APPENDICES

APPENDIX A

Task 1 Summary: Tracking Connecticut's Coast Using Aerial Infrared Photography

Overview

The effects of Superstorm Sandy significantly altered Connecticut's coast. It sustained considerable damage as a result of the storm's interaction with existing infrastructure and natural features occurring along the shoreline. As the frequency and intensity of these coastal storms increase, the ability of the state's coastal communities to prevent such events from turning into long-term community- and statewide disasters is essential. Thus, documenting the features of Connecticut's shoreline and how those features change in response to past and future storms is integral to making informed planning and investment decisions on coastal resilience and hazard mitigation.

Aerial infrared photography is an effective tool for monitoring and assessing the natural and man-made features of the Connecticut shoreline. This technique results in high resolution images, which simplifies the process of distinguishing different land uses and natural features. The Land & Water Resources Division ("LWRD") in Connecticut's Department of Energy and Environmental Protection ("DEEP"), which administers the state's Coastal Management Program, frequently uses aerial photographs in regulatory, land use planning, and resource management activities. LWRD has conducted coastal aerial photo flights at roughly 5 year intervals beginning in 1974. The most recent iteration in 2016 was accomplished through this project grant.

The resulting digital aerial photographs provide a means of inventorying and assessing environmental and human-use conditions along the coast and major riverine systems that support the regulatory and policy objectives of Connecticut's Coastal Management Program. They also provide a valuable time-series of data to members of academia, local government, the Federal government, non-governmental organizations, businesses and the general public. Continuation of this aerial photo time series is also extremely valuable for assessing storm impacts and provides a key resource for land use planning and hazard mitigation activities.

This project included interpretation of the 2016 coastal aerial photos to examine areas of tidal wetlands for internal water features and, through comparison with U.S. Fish & Wildlife Service National Wetlands Inventory ("NWI") data, digitize them within a new Geographic Information System ("GIS") layer. While the 2010 NWI captured the extent of tidal wetlands in Connecticut, this geospatial data and previous mapping from the 1970s and 1990s often ignored or inconsistently captured the delineation of internal waterbodies and regularly saturated pannes, making no differentiation between vegetated and non-vegetated areas within wetlands. By digitizing these internal tidal marsh features, DEEP is able to derive more accurate values for the overall area of functioning tidal wetlands across the state.

Connecticut's tidal wetlands are dynamic ecosystems occurring at the land/ocean interface that provide significant ecological and economic value to the state.[1,2] Healthy tidal marshes help to

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[1] Warren Pinnacle Consulting, Inc. 2015. *Application of the Sea-Level-Rise Affecting Marsh Model to Coastal Connecticut. Executive Summary*. Connecticut Department of Energy and Environmental Protection Office of Long Island Sound Programs, eds. Hartford, CT. p.1.

[2] Dreyer, G.D. and Niering, W.A. 1995 *Bulletin No. 34: Tidal Marshes of Long Island Sound: Ecology, History and Restoration*. Connecticut College. New London, CT. http://digitalcommons.conncoll.edu/arbbulletins/34. p. 22.

mitigate flooding in coastal areas by reducing flood peaks and storing flood waters associated with coastal storms.[3] However, these marshes are also among the most susceptible ecosystems to climate change, especially accelerated sea-level rise.[4] Accordingly, tidal wetlands are important for coastal hazard mitigation and climate change adaptation.[5] Hence, quantifying areas of functioning tidal wetlands and areas of wetland loss using aerial photography and GIS can support development of resilience measures in response to coastal flooding and sea level rise.

Outcomes

LWRD utilized the NOAA Office for Coastal Management Coastal Geospatial Contract Vehicle, available to federal, state, and local agencies through memoranda of understanding, to access to the geospatial industry's prime contractors for infrared aerial photography. LWRD has used this vehicle for previous coastal geospatial data projects with great success. LWRD selected Woolpert, LLC, as the contractor to collect and process the digital aerial photographs. The same digital process as in 2010 was employed to procure the aerial photographs, where flight operations used multi-spectral 4-band (red, green, blue, and near infrared) digital cameras to create both color infrared and "true-color" images (Figures 1 & 2). These digital images were then compiled into orthoimages. Orthoimagery data, also referred to as orthorectified imagery, combine the visual attributes of high resolution aerial photographs with the spatial accuracy and reliability of a planimetric map.

Figure 1. Image with infrared color balancing.

Figure 2. Image with "true-color" balancing.

Coastal aerial flight parameters generally conformed to the following technical & environmental conditions:

- Flight operations utilized color infrared photography/imaging (https://pubs.usgs.gov/fs/2001/0129/report.pdf);

[3] Shepard, C.C., Crain, C.M., Beck, M.W. 2011. *The Protective Role of Coastal Marshes: A Systematic Review and Meta-analysis*. PLoS ONE 6(11): e27374. doi:10.1371/journal.pone.0027374. p. 2.

[4] Warren Pinnacle Consulting, Inc. 2015. p.1.

[5] Shepard, C.C., et al. 2011. p. 1.

- Photos are nominally at 1:12,000 (1" = 1000') scale; digital data resolution ranges from 1 foot to 6 inches;
- Photos were only taken during times of no/minimal cloud cover;
- Photos have an average side-lap (overlap between adjacent flight-lines) of 25% (+/- 10%) and an average end-lap (overlap between adjacent tiles in a flight-line) of between 57% & 62%;
- The solar altitude was more than 65 degrees and no less than thirty (30) degrees;
- The ground was not obscured by flooding;
- Foliage (salt marsh vegetation in particular) was fully developed;
- Flight window favoring maximum human use/recreation activities;
- Photo times used tide-controlled windows within one (1) hour window before or after a predicted low tide based on NOAA tide tables;
- Orthophotos have a horizontal accuracy positional of 8.28 ft. at the 95% confidence interval.

The basic geographic extent of the project area is defined by:

- All land areas within one-thousand (1000) feet of Mean High Water (MHW) and within one-thousand (1000) feet of state-regulated tidal wetlands;
- An area of at least two-thousand (2000) feet waterward of the immediate shoreline of Long Island Sound;
- All offshore islands within the territorial borders of the State of Connecticut; and
- The main stem of the Connecticut River up to the Massachusetts state line.

Woolpert collected the aerial photographs on September 9, 2016, and completed surveying of the existing ground control network for the geometric correction of the aerial imagery by the end of that month. By the end of the following month, they completed aerial triangulation using the latest light detection and ranging method and digital elevation model (LIDAR/DEM) available for orthorectification. Digital ortho and GIS file processing were completed in February 2017, along with the required reporting and data documentation. DEEP accepted the final deliverables (orthophotos, GIS data, and reports) in May 2017, and in the following month the orthoimage index was made publicly available through Connecticut's Environmental Conditions Online (CT_ECO), a joint partnership between DEEP and the University of Connecticut): http://www.cteco.uconn.edu/guides/Ortho_2016_Coast_4Band.htm.

LWRD staff conducted the photo interpretation of coastal orthoimages to address the internal wetland waterbody analysis requirement between June 2017 and January 2018. Quality analysis of the data was then completed in February 2018. LWRD staff digitized a total of 512 acres of internal features, which corresponds to 3% of the total tidal wetlands area in Connecticut captured by NWI. Selection criteria for digitization were based on staff's best professional judgement in balancing the ability to examine features via the 6 inch photo resolution with the time and effort required to complete a thorough assessment of these areas statewide. The GIS map layer resulting from this digitization is useful for examining periodic changes in tidal wetlands in order to develop strategies for their continued preservation and protection. Classes captured include:

"Stream/Ditch/Channel": an area connected to a primary or secondary stream waterbody that remains submerged during low tide and generally achieves a width of at least 10 feet along its reach.

"Pond/Pool": an isolated area within a wetland system that remains submerged during low tide and generally occupies at least 0.1 acres.

"Saturated wetland": an area within or adjacent to a wetland or stream that is exposed at low tide and is devoid of vegetation and generally occupies at least 0.1 acres.

"Upland Island": an isolated area of woodland (upland) surrounded by tidal wetlands that has been included in the NWI classification of estuarine and marine or freshwater emergent tidal wetlands.

Nearly 158 acres are classified as “stream/ditch/channel” (Fig. 1). About 20 acres are classified as “pond/pool” (Fig. 2). Just under one acre is classified as “upland island” (Fig. 3). Lastly, 333 acres are classified as “saturated, non-vegetated wetland” (Fig. 4).

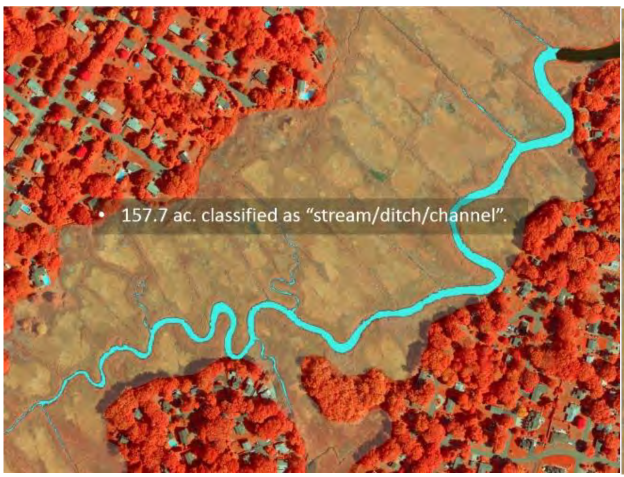

Figure 3. Digitization of a tidal stream.

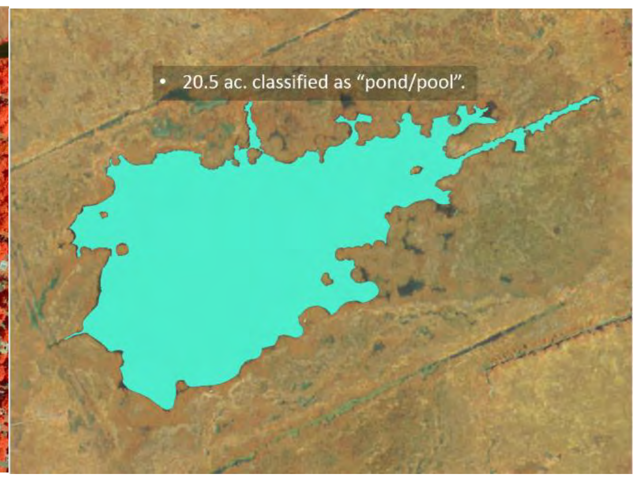

Figure 4. Digitization of a tidal pond.

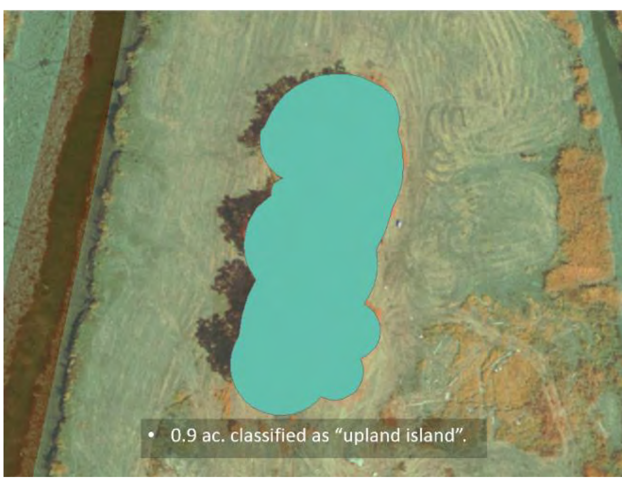

Figure 5. Digitization of an "upland Island".

Figure 6. Digitization of a saturated wetland.

Future Analysis

Using this enhanced tidal wetland data in combination with other GIS data can facilitate future policy development, as well as restoration planning for tidal wetlands, in part with other resilience measures. For example, the Sea Level Affecting Marshes Model identifies potential responses of intertidal and adjacent upland areas to anticipated increases in sea level along Connecticut's coast and tidal rivers. The model predicts long term changes as a function of land elevation, tide range, and sea level rise for 15-year increment scenarios between the year 2025 and 2100. The combination of quantifying areas of functioning tidal wetlands while investigating those areas for their probability of marsh migration in the event of sea level rise can assist municipal planning and conservation efforts towards developing more resilient coastal communities.

This data might also be used in conjunction with other neighboring state inventories to provide comparative analyses of change or to establish benchmarks for future management. For example, New York recognizes that, despite existing regulatory protection, salt marshes are presently losing ground due to a combination of factors including sea level rise and that the areas adjacent to many of their tidal wetlands are already developed and unavailable for marsh migration.[6] Consequently, they understand that a current and accurate accounting of shoreline conditions reveals how those conditions may change with sea level rise. The collected information provides a basis for coordinated coastal natural resource management strategies, which emphasize ecosystem-based management to promote effective resilience measures.[7]

This report is a product sponsored by the Connecticut Institute for Resilience and Climate Adaptation (more information about CIRCA can be found at circa.uconn.edu). The work is made possible through a grant from the State of Connecticut Department of Housing CDBG-Disaster Recovery Program and the US Department of Housing and Urban Development.

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[6] The Nature Conservancy. 2016. *Coastal Resilience: New York*. Retrieved from http://coastalresilience.org/project/new-york/.
[7] New York State Sea Level Rise Task Force. 2010. *Report to the Legislature*. p.30. Retrieved from https://www.dec.ny.gov/docs/administration_pdf/slrtffinalrep.pdf

APPENDIX B

Sea Level Rise in Connecticut
Final Report February 2019

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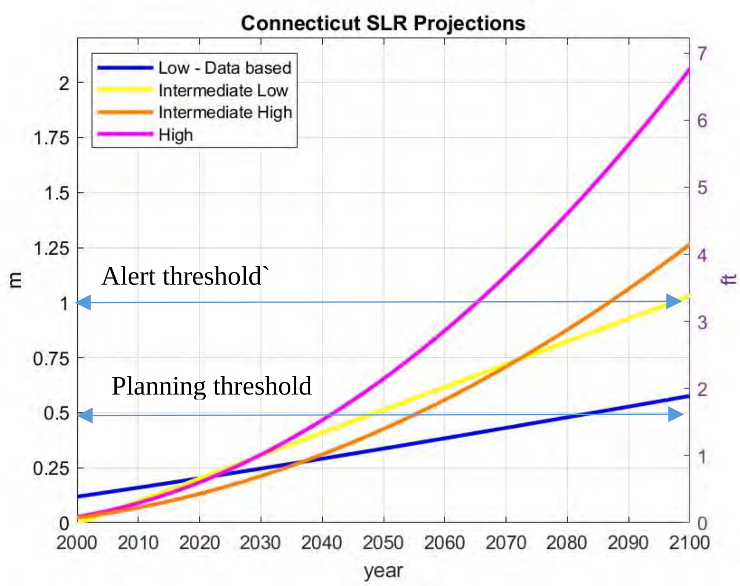
Measurements of sea level by instruments in the water and satellite altimeters provide unambiguous evidence that the annual mean level of the ocean surface is rising. Coastal communities should expect that the frequency of coastal flooding will increase. The National Oceanic and Atmospheric Administration (NOAA) report CPO-1 (Parris et al. 2012) provided guidance on the magnitude of potential changes in the global mean sea level based on analyses of both models and data. Four projections were shared so that managers could select what they judged to be appropriate. To provide more local guidance for Connecticut we have reviewed and modified the projections to include the effects of local oceanographic conditions, more recent data and models, and local land motion. A concise summary of the results are shown in Figure 1.



Sea level rise projections for Connecticut based on local tide gage observations (blue), the IPCC (2013) RPC 4.5 model simulations near Long Island Sound (yellow line), the semi-empirical models (orange line) and ice budgets (magenta line) as in CPO-1.

Though we show the results of four different approaches for forecasting future annual mean sea level in Long Island Sound in Figure 1, the differences between them are not great until after mid-century. We do not expect a significant refinement in the accuracy of longer term forecasts until the character of future emissions of greenhouse gases can be predicted. We note that the yellow line anticipates that emissions peak in 2040 and then fall rapidly, however, sea level late in the century is sensitive to emission between now and 2050. We recommend that planning anticipates that sea level will be 0.5 m (1ft 8 inches) higher than the national tidal datum in Long Island Sound by 2050. It is likely that sea level will continue to increase after 2050. We recommend that global mean sea level measurements and projections be monitored and new assessments be provided to towns at decadal intervals, or more frequently, to ensure that planning be informed by the best available science.

1. Introduction

The population of coastal counties in the United States increased by approximately 40% between 1970 and 2012. This trend is predicted to continue and lead to an additional increase of 8% by 2020 (NOAA, 2013). Recently, Neumann et al (2015) explored the likely changes the number of people living in low elevation coastal areas around the world under several plausible development scenarios. They found that even with the lowest growth rate assumptions the population in these areas could rise by more than 50% between 2000 and 2030 and double by 2060. The prospect of a substantial increase in population density at the coasts makes planning for the consequences of increased sea levels that are expected to accompany global warming (Parris et al, 2012; Church et al., 2013; Vermeer and Rahmstorf, 2009) a high priority.

The location where the ocean surface intersects the land has played an important role in public policy for centuries. So changes in the mean level of the ocean can have important economic and political consequences. Titles to property often extend to the Mean High High Water (MHHW) level for example, and in the many political jurisdictions the land and property below the level at which the estimated risk of flooding by seawater in a year exceeds 1/100 (commonly referred to as the hundred year flood elevation) are subject to use/development regulations that are restrictive. The land use in the zone below the level where the estimated risk exceeds 1/500 is also regulated. These levels are related to the Mean Sea Level (MSL).

Since there are periodic variations in water level due to the astronomical cycles and aperiodic variations due to meteorological forcing of the ocean, accurate determination of the mean level at any location requires time averaging of many measurements. The consequences of tidal variations can be removed when the measurements extend for 19 years and NOAA has defined the current National Tidal Datum Epoch (NTDE) as 1983 to 2001 to set the mean sea level. However, there are longer period oscillations in the ocean and atmosphere that cause sea levels to vary slightly. The spatial average of the time-mean sea level across the globe is termed the *global mean sea level* here. It changes as a consequence of the addition/loss of water to/from the ocean from land, the atmosphere or cryosphere and by thermal expansion/contraction. Since the ocean is in constant motion, measurement locations are sparse, and tectonic processes can move land vertically, measuring the global mean sea level is extremely difficult.

The United States Army Corp of Engineers (USACE, 2013) has recognized the need to include sea level rise in planning for all public works projects in areas influenced by tidal processes and has published guidelines that requires regional variations in rates of sea level change to be considered in every USACE activity. More specifically, they also require the consideration of "low," "intermediate," and "high" future rates of global mean sea level rise and provide guidance on how the global mean sea level will change until the year 2100 following recommendations of NOAA Technical Report OAR CPO-1 (Parris et al., 2012). Henceforward, we refer to this work as NOAA CPO-1. Similarly, the State of Connecticut in Public Act 13-179 requires that the state and municipal Plans of Conservation and Development, the state Civil Preparedness Plan, and municipal Evacuation and Hazard Mitigation Plans consider the effects of the anticipated sea level change scenarios published in NOAA CPO-1. This document recognized that there are processes in the ocean and lithosphere that cause the rate of change of sea level at a particular location to differ substantially from the global mean and outlined how this could be conducted. The Connecticut Legislature also recognized that the projections should be revisited at least once a decade and Public Act 13-179 also directed that this should be undertaken by The University of Connecticut. In this document we review recent observations at the NOAA water level gages at New London and Bridgeport and compare recent trends those published in the NOAA CPO-1 report. We then update and refine the information in the report as directed and provide recommendations on sea level rise projections that accounts for local conditions in southern New England to assist planning by coastal municipalities in Connecticut.

In the next section of this report we summarize the NOAA CPO-1 sea level rise projections of the potential trends in global mean sea level and their underlying rationale. We then describe the expected differences between global mean sea level and values in Long Island Sound at the shores of Connecticut. In Section 4 we present recent observation of sea level in Long Island Sound and evaluate whether changes have taken place. Since the NOAA CPO-1 projections were developed there have been considerable advances in the science of climate change and sea level rise so in Section 5 we summarize recent projections and their relationship to the earlier work. We conclude in Section 6 with recommendations for sea level trends and their uncertainty bounds for use in planning and provide recommendations for their use and review.

2. NOAA Global Mean Sea Level Projections

The primary goal of the NOAA CPO-1 sea level rise projections was to provide the first nationally coordinated guidelines for coastal planning and policy development in the United States. Though the report focused on projections for the global mean sea level, it acknowledged that regional variations associated with changes in ocean circulation and vertical land motions were important and provided advice on how users could to include these effects in their planning. A wide range of literature describing past, and possible future, changes in global mean sea level was considered in the preparation of the report. The evidence from direct measurements of water level is summarized by IPCC (2007), Kopp et al. (2009), Church, J. A. and N.J. White. (2011), and National Research Council (1987 and 2012).

Four approaches to the development of future projections were employed. The simplest was the extrapolation of observations. Using an extensive array of tide gage data, Church and White (2011) calculated that global mean sea level has been rising at a rate of approximately 1.7 mm/yr since 1900. Using the mean sea level during the National Tidal Datum Epoch (NDTE), the 19-year interval 1983 – 2001, as the datum and linearly extrapolating the rate from the middle of the NDTE (1992) to 2100 yields a value of 0.2m, or equivalently 0.7ft. This trend in shown by the blue line in Figure 1 and is termed the “Low” scenario in the NOAA CPO-1 report. The prediction formula is summarized in Table 1.

The second approach to prediction of the future sea levels is to use mathematical models to simulate how the earth’s climate system will change in the future under a range of plausible scenarios for emission of gasses that modify radiative transport in the atmosphere (greenhouse gases or GHGs). The International Panel on Climate Change (IPCC) developed six alternatives GHG emission reference scenarios in IPCC (2001) and then used many models to simulate the changes in environment that would result. The average and distribution of metrics like ocean and atmosphere temperatures and sea level were then reported. In scenario B1 the continued acceleration in the emission of GHGs was expected until 2050 when the reductions would begin. This scenario (IPCC, 2007) leads to a concentration of 650 PPM by 2100 (150% of the 2016 level) and a warming of the global average surface air temperature of between 1.1 and 2.9 C (the 5-95% range). The predicted rise in global mean sea level was 0.20 to 0.43 m (or 0.65 to 1.41 ft). The NOAA CPO-1 report adopted the 95% percentile value for the "Intermediate-Low" sea level rise prediction in 2100. To provide a time evolution in sea level estimates (z) they adopted the quadratic formulae parametrization

$$z(t) = s(t - t_0) + b(t - t_0)^2 \tag{1}$$

introduced in NRC (1987) were t represents the prediction year and $t_0 = 1992$, the middle of the NTDE. To ensure that this was consistent with the trend in observations for small $t - t_0$ requires $s = 0.17 \times 10^{-3}\ m/yr$ and if, in addition, $z(2100) = 0.5\ m$, then $b = 2.71 \times 10^{-5} m/yr^2$. This trend is shown by the yellow line in Figure 1.

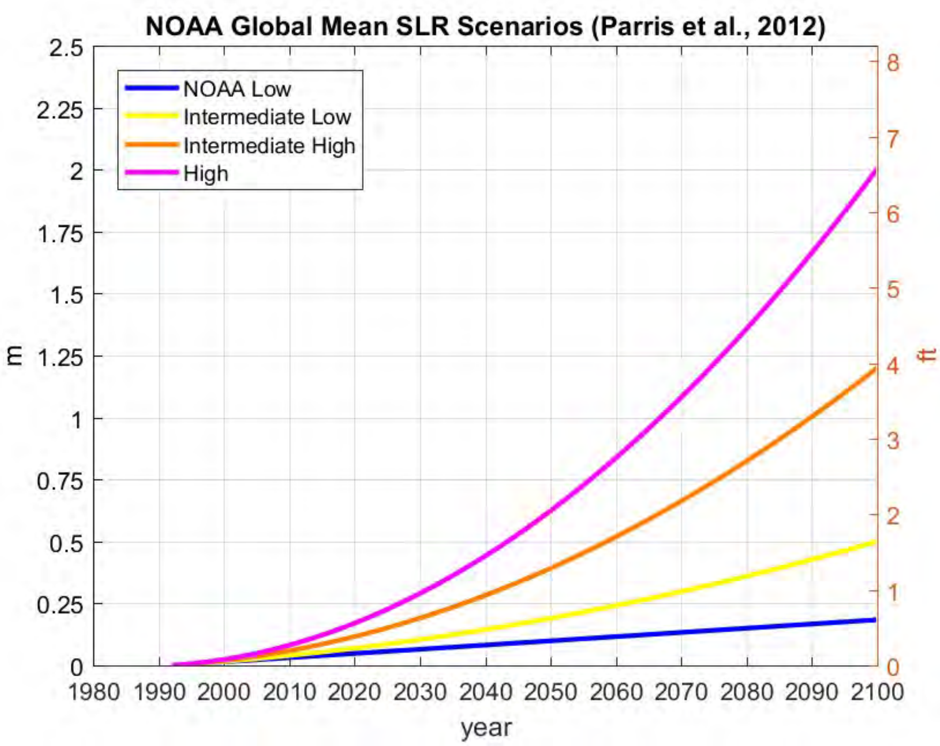


Figure 1. NOAA CPO-1 (Parris et al., 2012) sea level rise projections relative to mean sea level during the NDTE (1983-2001). The lines show four sea level rise scenarios and are computed from the formulae in Table 1.

Table 1. Prediction of future sea levels in the four scenario of NOAA CPO-1 (Parris et al., 2012) and shown in Figure 1 uses the formulae and coefficients listed below. Note that t represents the year the prediction is required and $t_0 = 1992$.

Scenario	**Formulae** $z = s(t - t_0) + b(t - t_0)^2$		**2100 level,** $z(2100)$	
	$s\ (meters/yr)$	$b\ (meters/yr^2)$	Meters	(feet
Low	1.7×10^{-3}	0	0.2	0.7
Intermediate Low	1.7×10^{-3}	2.71×10^{-5}	0.5	1.6
Intermediate High	1.7×10^{-3}	8.71×10^{-5}	1.2	3.9
High	1.7×10^{-3}	1.56×10^{-4}	2.0	6. 6

The models used to generate sea level rise predictions in the IPCC (2007) report were acknowledged to have elementary representations of the effects of warming of the ocean and atmosphere on the rate of melting of ice. Rahmstorf (2007) postulated that the rate of global mean sea level was linearly proportional to the global mean surface temperature and estimated the constant of proportionality from data. He then used the temperatures predicted by the global simulations of IPCC (2001) with the empirical relationship to estimate the global mean sea level. The results for 2100 ranged from 0.5 to 1.4 m above the 1990 level, substantially higher than the global model simulations. This third, semi-empirical, approach has been extended by several research groups. Horton et al. (2008) repeated the Rahmstorf (2007) calculation with the more sophisticated global models that were included in the IPCC (2007) report. The papers of Vermeer and Rahmstorf (2009), Grinsted et al. (2009) and Jevrejeva et al. (2010) subsequently improved the empirical model of the effect of temperature on sea level, augmented the data used in the analyses, and introduced technical improvements to the parameter estimation procedure. The ranges of the global mean sea level 2100 predictions for these semi-empirical models using temperature predicted in Scenario A2 in IPCC (2007) is provided in Table 2. The NOAA CPO-1 report adopted the mean of the upper and lower bounds, 1.2 m (3.8 ft), as the “Intermediate High” prediction for the year 2100. Using $b = 8.71 \times 10^{-5}\ m/yr^2$ in Equation (1) yields the trend shown by the orange line in Figure 1.

Since the results of the semi-empirical sea level forecasts require rapid melting of glaciers, Pfeffer et al. (2008) considered whether glacial flow rates in Greenland and the Antarctic Peninsula could provide sufficient water to augment thermal expansion and match the predicted rise in sea level. This forms the basis of the forth forecast approach. They found that increases in sea level between 0.8 and 2 m sea level by 2100 were plausible. The upper limit of this range was chosen as the “High” scenario for the NOAA CPO-1 report. The magenta line in Figure 1 shows the quadratic trend to this value using Equation (1) with $b = 1.56 \times 10^{-4}\ m/yr^2$

Table 2. Ranges of the global mean sea level predictions for 2100 using the semi-empirical models and temperatures from Scenario A2 in IPCC (2007).

Model	2100 Predictions and range			
	Lower (meters)	Upper (meters)	Lower (feet)	Upper (feet)
Vermeer and Rahmstorf (2009)	0.98	1.55	3.2	5.1
Grinsted et al. (2009)	1.25	1.8	4.1	5.9
Jevrejeva et al. (2010)	0.7	1.5	2.3	4.9
Horton et al. (2008)	0.7	0.9	2.3	3.0
Mean	**0.91**	**1.4**	**3.0**	**4.7**

3. Regional Variations in Changes in Mean Sea Level

The rate of change of mean sea level relative to the coast at any location is the results of the change in the global mean, changes in the level of the land and changes in the effect of ocean circulation and atmospheric circulation patterns. The vertical land movement at tide station with long records was estimated by Zervas et al. (2013). They assume that the effect of oceanic and atmospheric processes occur at a regional scale and then subtract the common trends in the data to reveal the underlying spatial structure of the vertical land movements. Table 3 shows the result of the analyses for stations in Long Island Sound. All the stations are becoming lower at approximately the same rate. The differences between the values are less than the width of the 95% confidence interval and all values are consistent with a Connecticut coast mean VLM of -0.7 mm/yr.

Table 3. The rate of vertical land movement (VLM) at tide station with long records in Long Island Sound estimated by Zervas et al. (2013).

Station Name	**NOAA Station Number**	**VLM (mm/yr)**	**95% interval (mm/yr)**
New London	8461490	-0.67	0.1
Bridgeport	8467150	-0.76	0.15
Kings Point	8516990	-0.67	0.07
Mean		**-0.70**	0.1

The current rate of relative sea level rise (that detected by the tide gages) should therefore be expected to be the global rate minus the VLM. In the future there may be a change to the ocean and atmosphere properties and that can only be detected by model simulations that resolve the critical processes accurately.

4. Recent Observations of Sea Level in Long Island Sound

The longest water level data records at the Connecticut coastline are located at New London and Bridgeport. The stations at Willets Point and Kings Point are close together in New York, at the eastern end of the East River. Water level data at the Willets Point station began in July, 1931 and terminated in November, 2000. The record at Kings Point started in November, 1998 and is continuing. The overlap in the data records allowed assessment of the differences in the mean levels and the records to be concatenated. The instruments are maintained by NOAA at the locations shown in Figure 2. The data from the stations is available at the web sites listed in Table 4. The level of the station datum and the mean sea level relative to the geodetic datum NAVD88 are listed in Table 4.

Table 4. Water level data sources (https://tidesandcurrents.noaa.gov/stationhome.html?id=XXXXXXX, where XXXXXXX is the Station Number below)

Station Name	Station Number	Lat. (Deg.)	Lon. (Deg.)	Station datum NAVD88 (m)	MSL relative to station datum	MSL relative to NAVD88
New London	8461490	41.355	-72.087	1.634	1.542	-0.092
Bridgeport	8467150	41.173	-73.182	1.774	1.708	-0.066
New Haven	8465705	41.283	-72.908	--	6.630	---
Montauk	8510560	41.048	-71.96	1.655	1.554	-0.101
Willets Point	8516990	40.81	-73.765	2.810	2.752	-0.058
Kings Point	8516945	40.81	-73.765	---	---	---

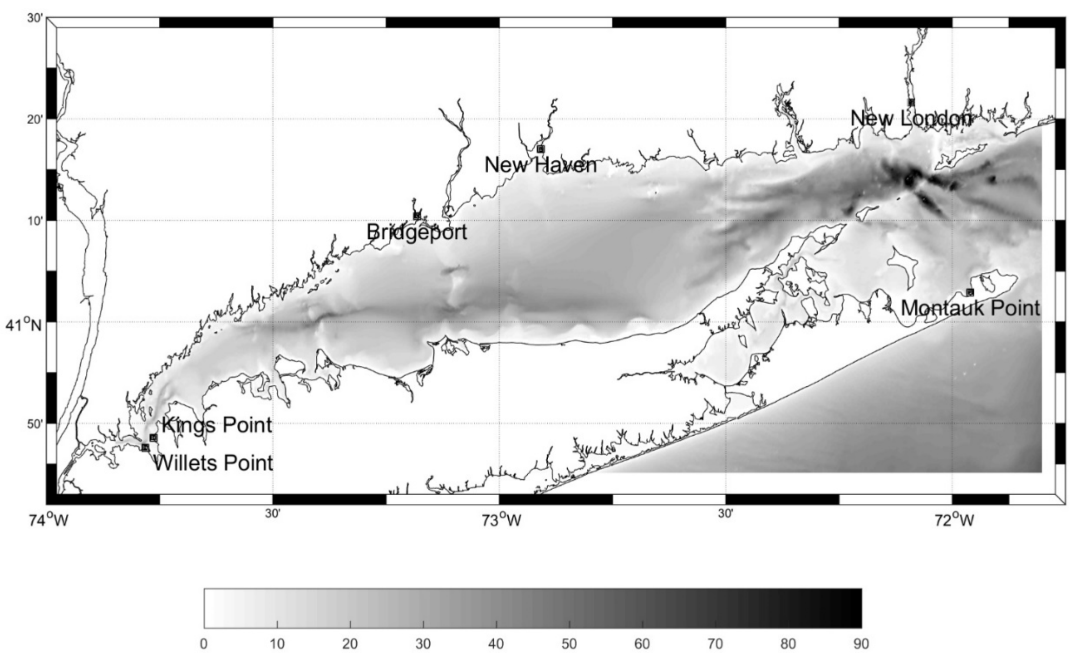


Figure 2. Coastal geometry and bathymetry of Long Island Sound showing the locations of the NOAA water level gages.

The longest records of water level measurements acquired in Long Island Sound are shown in Figure 3. The elevations in the Figure are plotted relative to the mean value at the station during the 19 year National Tidal Datum Epoch (NTDE) which is defined as the years 1983 to 2001. The elevation of the station datum and the elevation of the NDTE mean sea level are listed in Table 4. The blue lines show the monthly averages of hourly measurements, and the solid red lines show the annual averages. The seasonal variation in the monthly mean, as indicated by the two standard deviation interval is shown by the red dashed lines to vary between 10 and 20 cm.

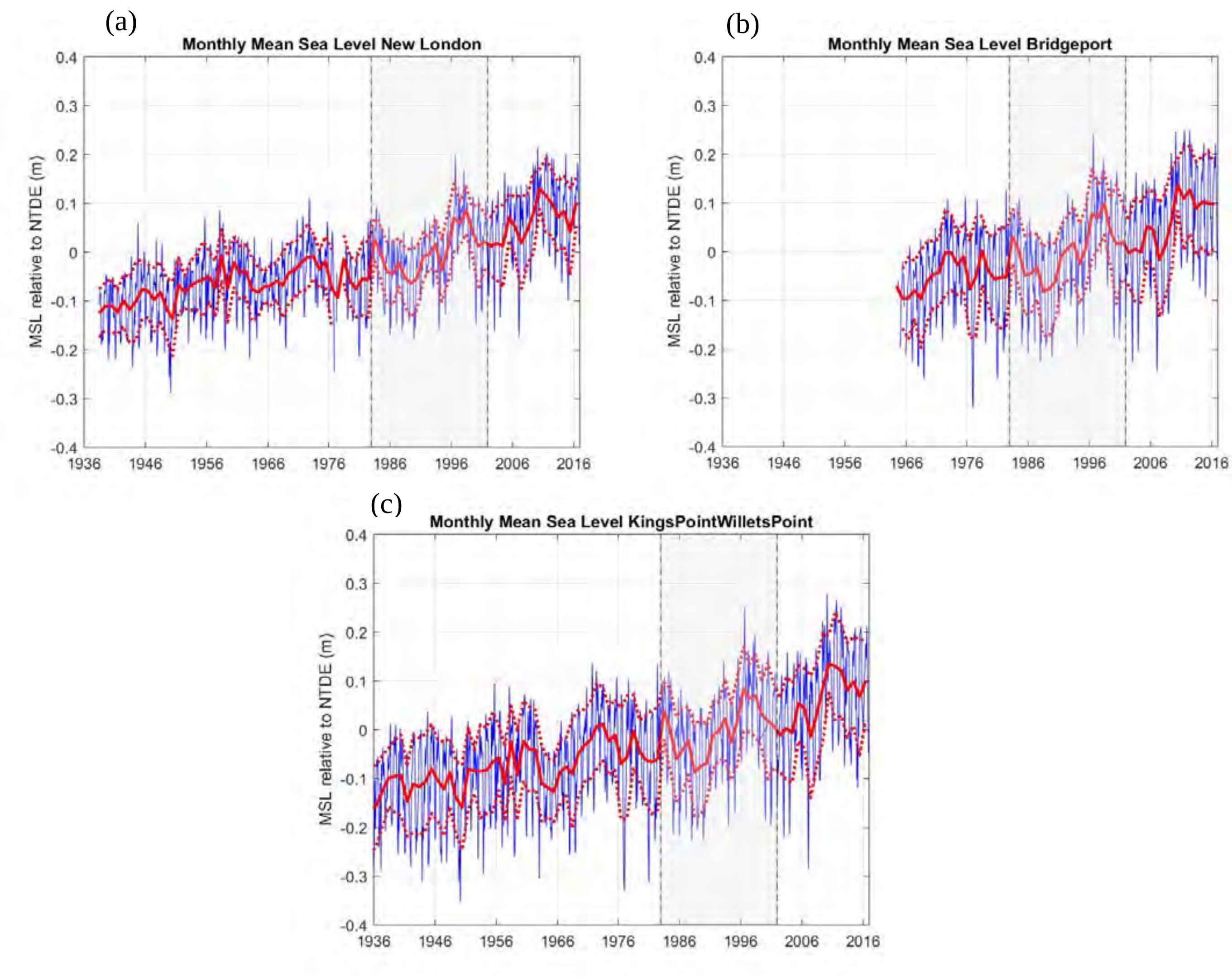


Figure 3. The time series of the monthly average of sea level observed at (a) Bridgeport, (b) New London, and (c) Kings Point – Willets Point are shown by the blue lines. The annual averages are shown by the solid red lines and the 68% confidence interval is bounded by the dashed red lines. Station locations are listed in Table 4 and shown in Figure 2. The grey stripe shows the period defined as the national tidal datum epoch (NTDE). The mean of each record during this interval is zero.

The red lines in Figure 3 clearly show the long term increasing trend in sea level underlying quasi periodic variations with a period of approximately 10 years. Note that these trends are measured relative to the individual station datums. It is well established that vertical land movements are common at tide gages due to tectonic processes and adjustment to the retreat of ice at the end of the last ice ages. Kopp et al. (2015) provide a cogent explanation of these processes and integrates estimates at a global network of observation stations. Zervas et al. (2013) provides estimates at the NOAA tide gages and Table 3 shows the values in Long Island Sound. The right-most column of Table 4 shows the observed mean sea level relative to the NAVD88 datum reported by NOAA. The difference in level from Montauk to Willetts Point is very small, only 4 cm, and shows that with the water level rises from the ocean to the East River.

The decadal scale oscillations in annual mean sea level that are evident in Figure 3 have amplitudes in the range of 5-10 cm. These cause the quantitative determination of the local rate of sea level rise to be uncertain and thereby limit detection of changes in the rate. Recently, McCarthy et al. (2015) showed that the oscillations in the annual mean difference between coastal water levels in southern New England and the South Atlantic Bight (south of Cape Hatteras) waters correlated with atmospheric forcing as indicated by the North Atlantic Oscillation (NAO) index (Hurrell et al, 2001). They also showed that they were coherent with fluctuations in the magnitude of the Atlantic overturning circulation and, consequently, the rate of northward heat transport. Temperature changes in the inter-gyre region of the North Atlantic determine the Atlantic Multi-decadal Oscillation (AMO) index which is well known to correlate with hemispheric-scale weather patterns. The sea level fluctuations are, therefore, manifestations of the coupling of atmospheric and ocean circulation variability.

Figure 4 shows the shows the annual mean sea level records from Bridgeport, New London and Willets Point. The differences between the records is very small and they are obviously highly correlated. Ordinary least-squares regression (following the method employed by NOAA in Storch and Zwiers, 2001) applied to the whole record of annual means at New London and Willets-Kings Point yields the rates of increase of relative mean sea level of 2.4 mm/yr and 2.8 mm/yr. Since the 95% confidence intervals of these estimates is 0.3 mm/yr, these are not significantly different. The Bridgeport observations did not begin until 1963 and so the record is 35% shorter than the others. The rate of sea level rise between 1963 and 2016 is 3.3 ± 0.7 mm/yr. When the data from 1976-2016 is used all three stations are consistent with values of 4.0 ($\pm$ 1.8), 4.1 ($\pm$ 2.6), and 4.1 ($\pm$ 2.4) mm/yr for the Bridgeport, New London and Willets Points stations. The confidence intervals for these estimates are larger because the data duration is shorter. These results are summarized in Table 5 and Figure 4 in which the red line indicates an increase of sea level relative to the gages at 4.1 mm/yr.

Table. 5. The results of linear regression analysis for the data shown in Figures 3 and 4. The second and third columns show the rate of change of mean sea level (relative to the gage datum) and the associated 95% confidence interval (CI). The confidence interval accounts for the serial correlation in the data following the approach of Storch and Zwiers (2001). To assess the possibility that the slope had changed the data was partitioned at 1976 and the regression repeated. The results are provided in the column on the right of the table.

Station Name	Whole record		Pre 1976		Post 1976	
	Rate mm/yr	95% CI	Rate mm/yr	95% CI	Rate mm/yr	95% CI
New London	2.4	0.3	2.3	0.6	4.1	1.8
Bridgeport	3.3	0.7	-	-	4.0	2.6
Willets Point	2.8	0.3	3.2	1.3	4.1	2.4

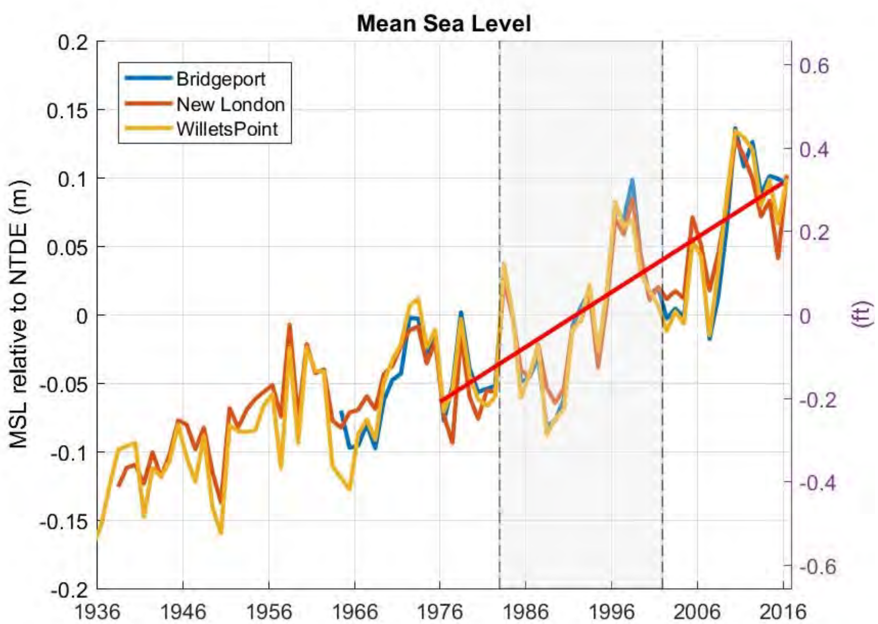


Figure 4. The annual average sea level observed at Bridgeport, New London, and Willets Point between 1936 and 2016. The grey strip defined the National Tidal Datum Epoch (NTDE) and the average of the observations at each station in this interval is set to zero to define the datum. These curves are the same as shown in Figure 3a-c. The red line shows the trend of 4 mm/yr since 1976.

5. Recent Analyses of Global Mean Sea Level

The rate of sea level rise at the Connecticut shore since 1976 shown in Figure 4 is much larger than the 1.7 mm/yr used in NOAA CPO-1. This can be compared to the recent estimates of the global average mean sea level reported by Church and White (2011). They used the global network of sea level gage data and an averaging approach that compensates for the heterogeneity of sampling in time and space. They have also provided several updates to the analyses at the web site http://www.cmar.csiro.au/sealevel/sl_data_cmar.html. The blue line in Figure 5 shows their annual global mean sea level estimates with the average in the NTDE (1983-2001) set to zero. The light blue stripe show the 68% confidence interval of the estimate obtained from their averaging process. The band is wider in the 19th and early 20th century as a consequence of the observation network being sparser in the early period of the record. The spatial averaging results in a series with much less decadal-scale variability than in Long Island Sound (Figure 4). Church and White (2011) pointed out that the analysis shows an obvious increase in the rate of increase in the global mean sea level between the first to the second half of the series. From 1880 to 1935 global mean sea level rose at the rate 1.1$\pm$ 0.7 mm/yr and from 1936 to the end of the record the trend was 1.8 $\pm$ 0.3 mm/yr. Several short periods of falling mean sea levels are noticeable and Church and White (2011) propose explanations for these. For example, the cooling in the ocean after the eruptions of Mount Agung (Indonesia) in 1963, El Chichon (Mexico) in 1982, and Mount Pinatubo (Philippines) in 1991, may have contributed the dips in the mean sea level trend a few years after these eruptions (Church et al. 2005; Gregory et al. 2006; Domingues et al. 2008). They also pointed out that at the end of the record available to them the rate of change increased to 2.8 $\pm$ 0.8 mm/yr for the interval 1993 to 2009.

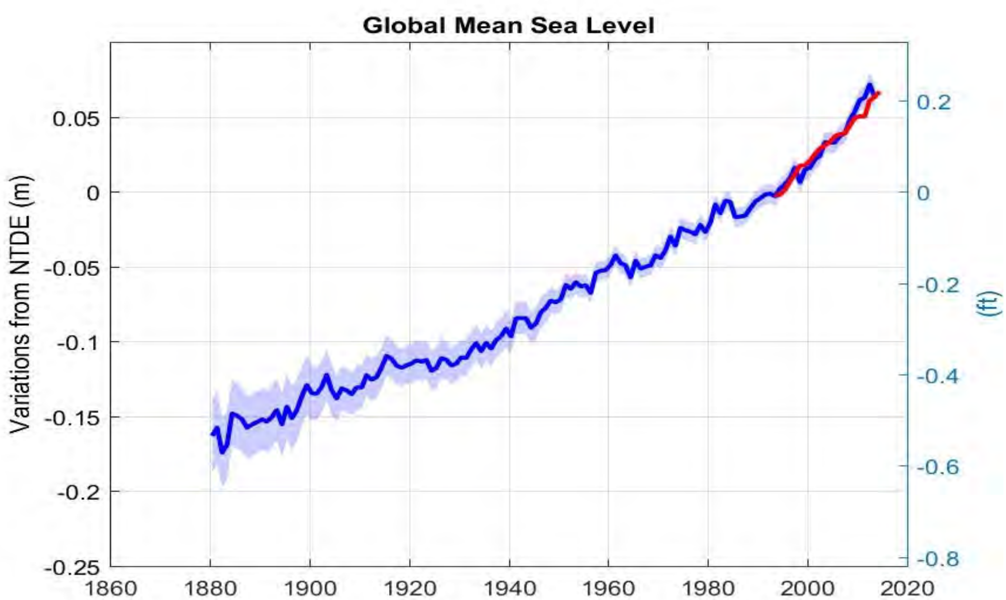


Figure 5. The blue line shows estimates of the annual average global mean sea level estimated from measurements from a global array of tide gages. Annual mean values smoothed with a 7 point box-car filter are shown. The red dashed line shows the 68% estimation interval. The black line on the right shows the trend obtained from altimeter data. Note that the elevation datum is the mean level in 1990. Adapted from Church and White (2011) using data from http://www.cmar.csiro.au/sealevel/sl_data_cmar.html.

Since 1993 the water surface level across much of the ocean have been observed by satellite-borne altimeters. The spatial coverage of these measurements complement the long records available at tide gages and directly avoids the aliasing of the spatial variability. Church and White (2011) also analyzed available data and the results of their calculation of global average mean sea level shown by the red line in Figure 5. They found that the rate of increase in the global mean sea level, after correction for GIA, was 3.2 ± 0.4 mm/yr. This was slightly higher than the 2.8 ± 0.8 mm/yr yielded by the analyses of tide gage data, but not significantly different.

A synthesis of available estimates of the trends from satellite observations is described by Nerem et al. (2010). The comparison is regularly updated at (http://sealevel.colorado.edu/) and their results are summarized in Table 6. When the confidence intervals are taken into account the results of the various analyses are consistent. The mean value weighted by the inverse of the variance is 3.4 ± 0.4 mm/yr. The Church and White (2011) tide gage analysis has also been updated (the data is included in Figure 5) and for the period 1993 to 2015 the rate of change is 3.5 ± 0.4 mm/yr in agreement with the altimeter-derived results.

Table 6. A compilation of estimates of the rate of change of the global mean sea level obtained from satellite-borne altimeters from http://sealevel.colorado.edu/.

Altimeter Derived Rate of Change of Global Mean Sea Level	Rate mm/yr	CI (68%) (mm/yr)
Univ. of Colorado http://sealevel.colorado.edu/	3.4	0.4
Centre National D'Estudes Spatiales (France) http://www.aviso.altimetry.fr/en/data/products/ocean-indicators-products/mean-sea-level.html	3.4	0.6
CSIRO (Australia) http://www.cmar.csiro.au/sealevel/sl_hist_last_decades.html	3.3	0.4
NASA Goddard http://podaac-ftp.jpl.nasa.gov/dataset/MERGED_TP_J1_OSTM_OST_GMSL_ASCII_V3	3.4	0.4
NOAA https://www.star.nesdis.noaa.gov/sod/lsa/SeaLevelRise/	3.3	0.4

6. Observation-Based Projections for Connecticut

It is evident that the observation of sea level in Long Island Sound shown in Figure 4, the analyses of the global network of tide gages and the satellite measurements shown in Figure 5 agree that the trend that should be anticipated for mean sea level at the shoreline of Connecticut is much higher than the 1.7 mm/yr used in NOAA CPO-1 and shown by the blue line in Figure 1. Further, since the uncertainty in the trends can also be estimated these should be used be included in planning guidance.

Since the effects of decadal scale variability is substantially reduced in the analyses of the global mean sea level the uncertainty in the trend is much smaller than that obtained from the analyses of the measurement obtained in Long Island Sound. However, the local rate of vertical land motion, -0.7 ± 0.1 mm/yr (see Table 3), must be subtracted from the global trend of 3.4 ± 0.4 mm/yr to yield 4 ± 0.4 mm/yr as the expected rate. Note that this is equivalent to the trend obtained from the observations from tide gage data from Long Island Sound between 1976 and 2016 and shown in Figure 4.

In Figure 6 we show an extrapolation of the relative mean sea level in Long Island Sound based on the 4.0 mm/yr trend to 2100 by the solid black line. This is substantially higher than the data-based projection of Parris et al. (2012) which is shown by the yellow line. The thin dashed lines show the 95% interval of the estimate of the sea level rise rate and the thick dashed line show the 95% interval of the prediction of the annual mean values until 2100. This is substantially wider than the trend uncertainty since the amplitude of the decadal-scale variability due to local factors exceeds 10cm.

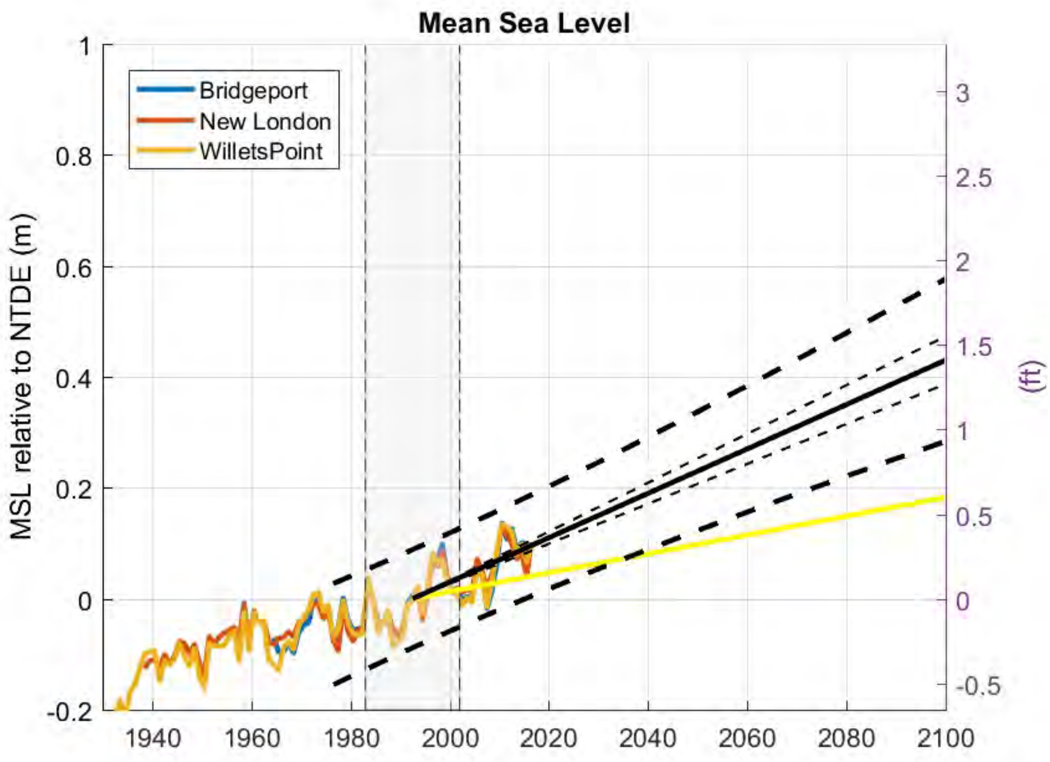


Figure 6. The annual average sea level observed at Bridgeport, New London, and Willets Point between 1936 and 2016 are shown using the same colors as in Figure 4. The solid black line shows the trend of 4 mm/yr and the thin dashed lines show the ± 0.4 mm/yr range of the predicted slope based on the global mean tide gage and altimeter observations. The thicker dashed lines show the 95% prediction interval for the annual mean sea level in Long Island Sound extrapolated to 2100. The yellow line shows the projection of global mean sea level published by NOAA CPO-1 and shown as the blue line in Figure 1. Note that the axis on the right shows the level in feet.

The information in Figure 6 is repeated in Table 7 to assist in planning calculations. The expected value (the solid black line in Figure 6) for the years shown in the leftmost column are listed in the second column. The upper bound of the 95% confidence interval for the annual mean sea level (the upper thick black line in Figure 6) are listed in the third column. For comparison, the projections of NOAA CPO-1 are shown in the fourth column (yellow line in Figure 6). The values on the units of feet are repeated in the three column on the right of the Table. This projection anticipates that water level gages in Long Island Sound should in 2050 be expected to record a mean values that is 0.23 m above the mean of the NTDE. Further, there is a 97.5% likelihood that the annual mean sea level will be less than 0.39m.

Table 7. Predictions of the change in mean sea level at the coast of Connecticut relative to the mean value during the NTDE. For the years shown in the first column, the second column show the expected (mean) value and the third column shows the upper bound of the 95% confidence interval. The fourth column show the "low" projection from NOAA CPO-1 for comparison. The three columns on the right show the same information in units of feet. The values are also shown by the solid black line in Figure 6.

Year	Mean (m)	Upper 95% (m)	NOAA (m)	Mean (ft)	Upper 95% (ft)	NOAA (ft)
2030	0.15	0.25	0.06	0.5	0.81	0.21
2040	0.19	0.29	0.08	0.63	0.96	0.27
2050	0.23	0.34	0.10	0.76	1.11	0.32
2060	0.27	0.39	0.12	0.89	1.27	0.38
2070	0.31	0.43	0.13	1.02	1.42	0.43
2080	0.35	0.48	0.15	1.15	1.58	0.49
2090	0.39	0.53	0.17	1.29	1.74	0.55
2100	0.43	0.58	0.18	1.42	1.9	0.60

7. Model Projections of Sea Level

The NOAA CPO-1 “intermediate low” future sea level projection (yellow line in Figure 1) were based on process models of the climate system that are utilized the results of the IPCC (2007) fourth assessment report (AR4). The IPCC simulations adopted a range of assumptions about the future trajectory of the rate of global emissions of radiatively active gases, or greenhouse gases (GHGs). These assumptions were termed “emission scenarios” and the various options are discussed in detail by van Vuuren et al. (2011). The NOAA CPO-1 report used the results of scenario B1 in which the rate emissions of CO_2 (and other GHGs) were assumed to continue to increase until approximately 2050 after which technological innovation would lead to decreases. The IPCC process aggregated the results of 58 simulations from 14 different mathematical models of the earth’s climate system for each GHG emissions scenario. This were termed an “ensemble” of simulations. The mean and distribution of the critical variables were then computed and archived. The ensemble global mean surface air temperature change between the baseline interval (1980 to1999) and 2090 to 2099 in scenario B1 was 1.8 C. The corresponding 95% confidence range was 1.1 to 2.9 C. The change in the global mean sea level between these intervals was predicted to be 0.28 m and the 95% confidence rage was 0.18 to 0.38.

The IPCC AR4 report has recently been superseded by IPCC (2013), the fifth assessment report (AR5), which was based on improved models that incorporated more recent advances in climate science. The character of future GHG emissions considered in AR5 were also slightly revised and termed “representative concentration pathways” or RCPs. The simulation in which the emissions were most similar to scenario B1 in terms of both GHG emissions and their effect on the earth’s heat budget is RCP4.5. Figure 7 shows the assumed variation in the rate of emissions by the blue lines. The IPCC (2013) report project that the RPC will lead to the global average surface air temperature in the last two decades of the 21st century (2081-2100) being 2.2 C warmer than the average between 1886 and 2005. The 90% confidence interval of this estimate is 1.4 to 3.1 C.

The IPCC (2013) report contrasts the projections of RCP4.5 with those of more aggressive emission reduction (RCP2.6, magenta line in Figure 7) in which emissions are assumed to peak, and begin to reduce, earlier, and RPC6.0 (yellow line in Figure 7) in which the peak occurs in 2075 at a higher level before reductions occur. A continuing growth in emissions is simulated in RPC8.5 (red line in Figure 7). The projected effects of the RPCs on global mean sea level, and that near Connecticut are discussed in this section.

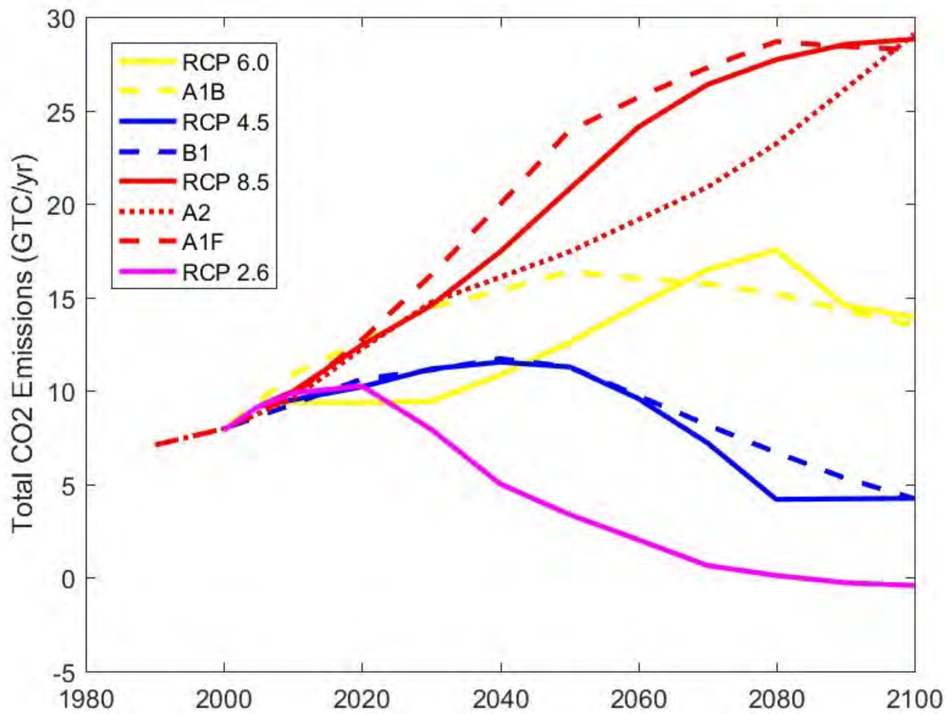


Figure 7. A Comparison of the trajectory of global emissions of greenhouse gases considered in the IPCC's AR4 and AR5. The blue dashed line shows scenario B1 of AR4 which is the basis of the "intermediate low" sea level rise scenario in the NOAA CPO-1 report. The solid blue line shows the emissions in representative concentration pathway RPC 4.5 of AR5. (Based on data from http://sres.ciesin.org/final_data.html and http://tntcat.iiasa.ac.at:8787/RcpDb).

In Figure 8 we show the predicted evolution of the global mean sea level for four RCPs. The solid lines show the ensemble means and the surrounding shaded bands indicate the 5-95% confidence intervals. The four graphs share similar characteristics. In each the mean sea level increases monotonically with time. The confidence intervals also widen with time at approximately the same rate so that by 2100 the 5-95% range is approximately 30 to 40cm. The main differences are in the sea level at 2100 and that in RPC 6.0 and 8.5 the rate of change of the sea level increases noticeably after 2050.

The differences in the sea level trends are clearer in Figure 9 which shows the results of all four scenarios and the confidence interval for the RCP 4.5 projection. Figure 9(a) demonstrates that,

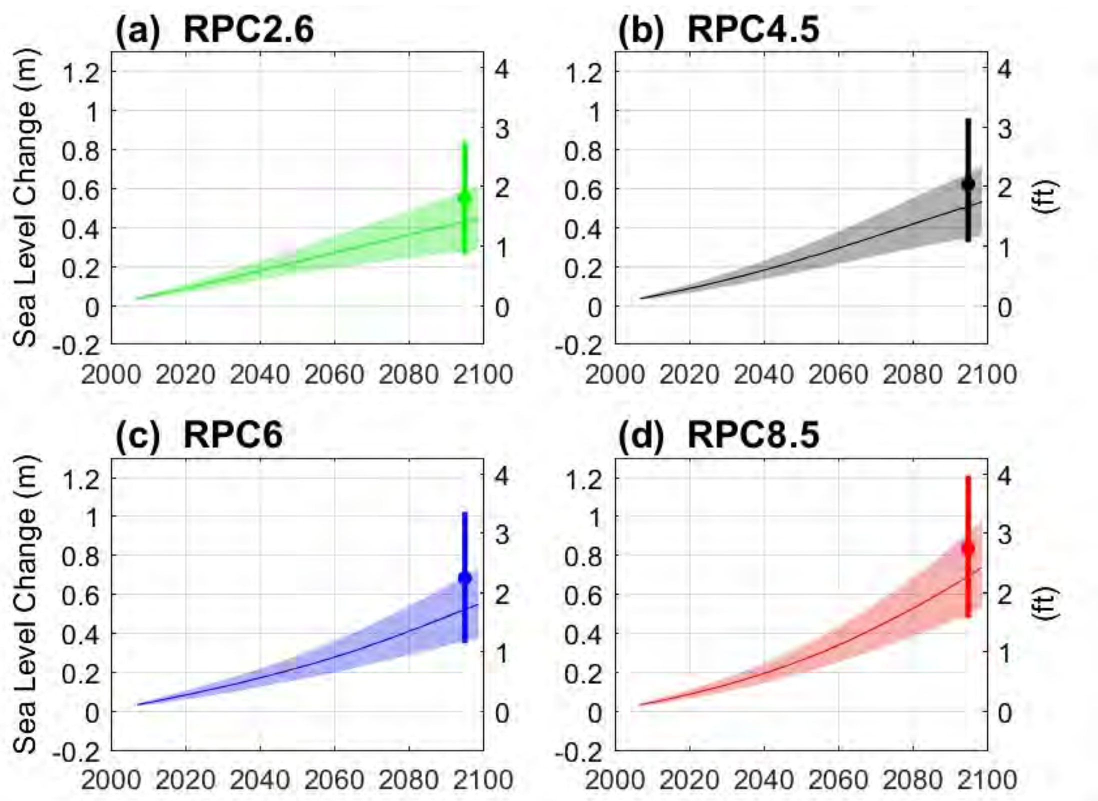


Figure 8. The evolution of the ensemble mean (solid lines), and 5-95% confidence interval (shaded bands) for the global mean sea level predicted by the IPCC (2013) models for RCPs (a) 2.6, (b) 4.5, (c) 6, and (d) 8.5. In each graph the circle and bar shows the ensemble mean and 5-95% confidence interval for the predicted sea level at the model grid point shown in Figure 9 averaged between 2090 and 2100.

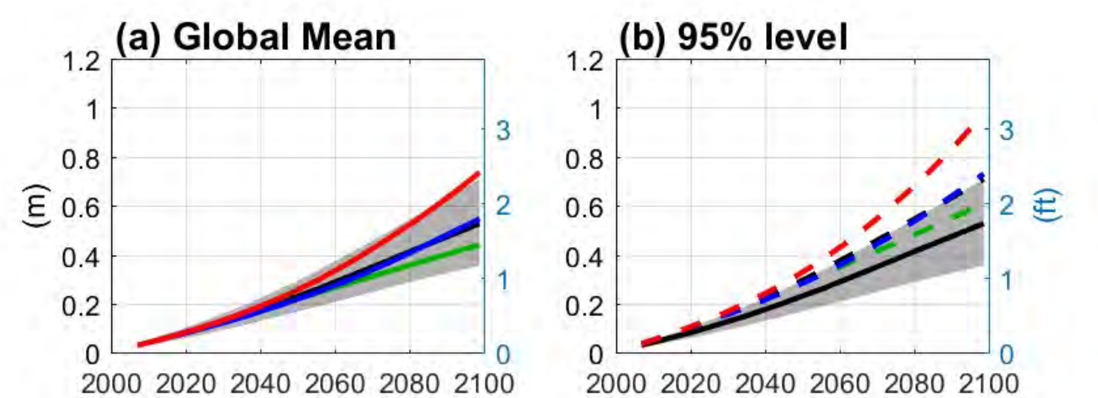


Figure 9. (a)The IPCC (2013) predicted trends in global mean sea level (green, black, blue and red represent RPC 2.6, 4.5, 6.0 and 8.5 respectively) with the 5-95% confidence interval for RPC 4.5 shaded grey. (b) The 95% confidence bound for each RCP using dashed lines with the same color code as (a). The RPC 4.5 mean (solid black line) and 5-95% confidence interval (grey stripe) are also shown for reference.

as far as mean sea level is concerned, the solutions for RPC 4.5 and 6.0 (black and blue lines) are indistinguishable between in the interval shown. As is evident in Figure 7, these two RPC have very similar GHG emissions until 2050 and Figure 9(a) suggests that the reduction in GHG emissions that is anticipated in RPC 4.5 after 2050 has little effect on sea level until after 2100. The long lag between changes in the rate of emissions and the effect on sea level is also reflected in the difference between the RPC 4.5 and 8.5 (black and red lines). Even though the rate of emissions in RPC 8.5 is 50% larger than in RPC 4.5 by 2050, the difference in the change in global mean sea level is small, both the RPC 4.5 and 8.5 solutions are within the 5-95% confidence interval of the RPC4.5 value.

The NOAA CPO-1 "intermediate low" sea level change projection was based on the 95% values in the IPCC (2007) AR4 simulations. The 95% bound on the confidence intervals of the four projections in the IPCC (2013) AR5 are shown in Figure 9(b) and these are all very similar until after 2050 when the RPC 8.5 become higher than 4.5 and 6.0. Table 8 lists the values of the change in global mean and upper bound of the 5-95% confidence interval for RCP 4.5 and 8.0. In 2050 the difference in the 95% level of the expected rise in global mean sea level is only 5 cm, however, by 2100 it is 35 cm.

Table 8. The predictions of the change in global mean sea level averaged in decades surrounding the year listed in the leftmost columns. Columns 2 and 3 list the means and upper 95% values from the RPC 4.5 simulation and columns 4 and 5 show the same results from RCP 8.5. The four columns on the right show the same information in feet.

	RCP 4.5		RCP 8.5		RCP 4.5		RCP 8.5	
Year	Mean (m)	Upper 95% (m)	Mean (m)	Upper 95% (m)	Mean (ft)	Upper 95% (ft)	Mean (ft)	Upper 95% (ft)
2030	0.13	0.16	0.13	0.17	0.42	0.54	0.44	0.56
2040	0.17	0.22	0.19	0.24	0.57	0.73	0.63	0.79
2050	0.22	0.28	0.26	0.33	0.72	0.93	0.84	1.07
2060	0.27	0.35	0.33	0.43	0.87	1.14	1.09	1.4
2070	0.31	0.41	0.42	0.54	1.02	1.35	1.38	1.78
2080	0.36	0.48	0.52	0.68	1.17	1.58	1.72	2.23
2090	0.40	0.55	0.64	0.84	1.33	1.81	2.09	2.74
2100	0.43	0.60	0.72	0.95	1.43	1.97	2.36	3.12

It is very important to note that the dynamics of the atmosphere and ocean cause the mean sea level change resulting from warming to be spatially variable. The details of the mechanisms that cause the differences are summarized clearly by Kopp et al. (2014). Changes in the ocean circulation and the rate of northward transport of heat in the northwestern Atlantic Ocean have a significant impact of mean sea level in southern New England. Figure 10(a) shows the global variation of the changes in mean sea level in 2100 in RCP 4.5. The purple shades in the northwest Atlantic show that the warming leads to a much greater increase in the mean sea level around New England and the Canadian Maritime Provinces thane almost anywhere else in the world. The magnitude of the change is sensitive to the climate model and parameter set that is used as is shown in Figure 10(b) which displays the standard deviation (approximately the 68% interval) of the ensemble of predictions of the projected mean sea level in 2100.

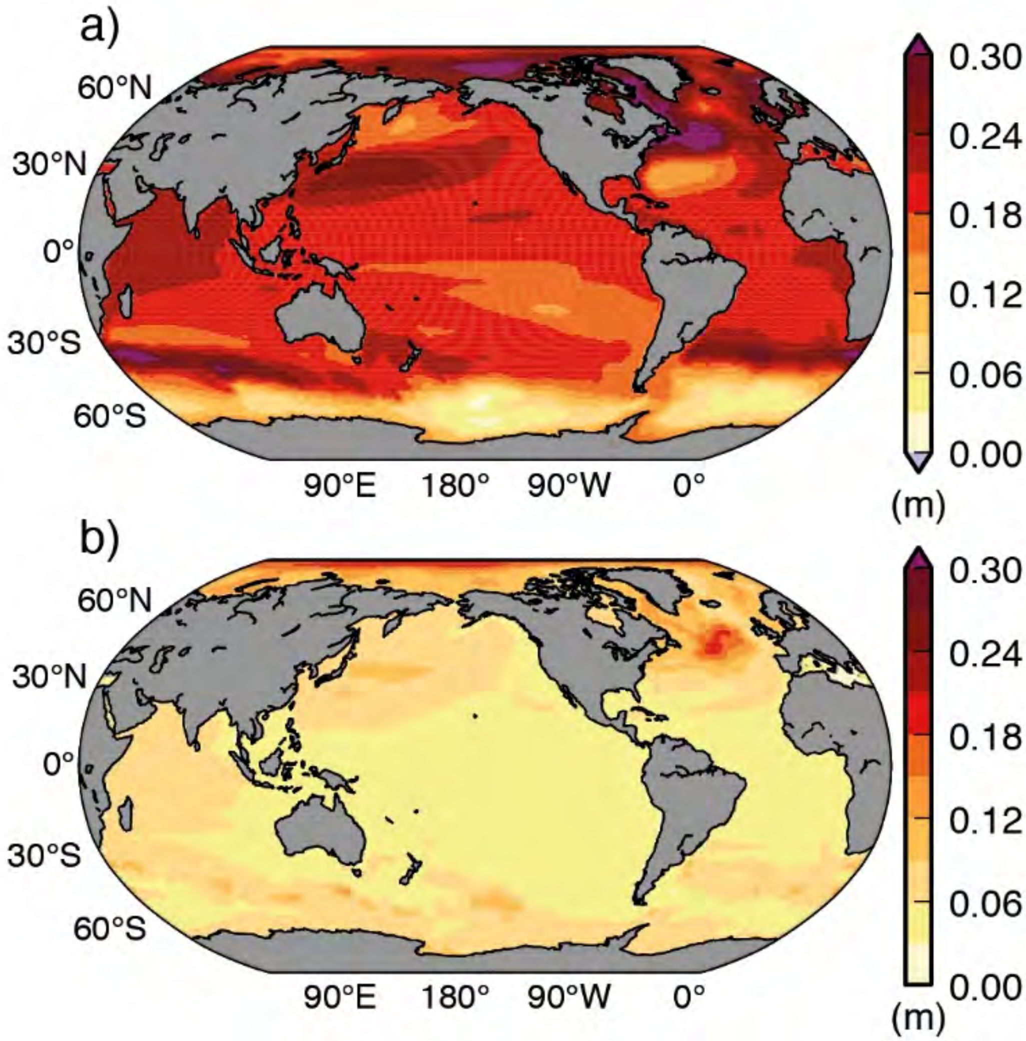


Figure 10. (a) Ensemble mean sea level changes for the period 2081–2100 relative to the reference period 1986– 2005 for RCP 4.5. (b) The root-mean square deviation about the ensemble mean (meters). Reproduced from Figure 13.16 of IPCCC (2013).

The expected sea level change around New England in 2100 is shown in Figure 11. This is simply an expanded view of the information in Figure 10(a). At this scale the resolution of the analysis is clear. Note that though the models used to construct the ensemble have higher resolution, the solutions are averaged to the common 1× 1 degree grid shown. Consequently, variations on the scale shorter than the length of Long Island Sound can't be resolved. The mean and 5-95% confidence intervals for the mean sea level change for the interval 2090 to 2100 in each of the four RCPs at the grid point shown by the green square in Figure 11 near the southern New England shore is shown in Figure 8 by the circles and bars. The ensemble solutions for all four RPCs near the coast of southern New England are almost equal to the 95% confidence interval of the global mean. In addition, the width of the confidence interval the coastal solutions are significantly wider than that for the global mean. Planning for sea level rise in southern New England should, therefore, be based on the mean and 95% of the local ensemble values.

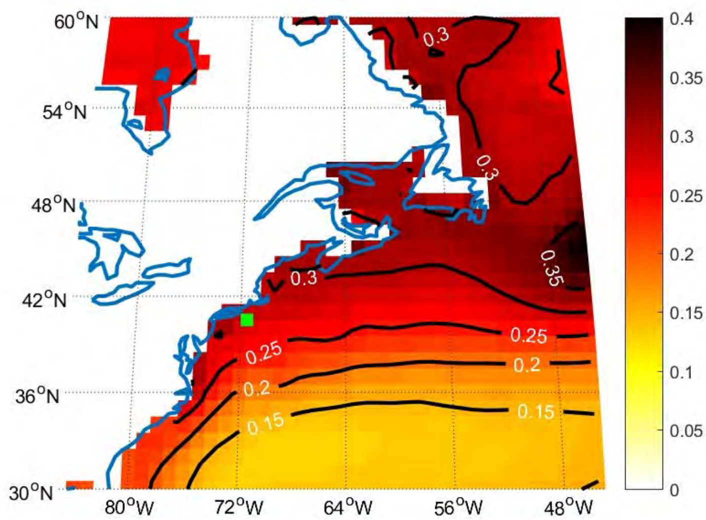


Figure 11. A close up of the IPPC ensemble mean sea level projection for 2100 in the northwest Atlantic. The coastline is shown in blue. The unit for the contour lines and color scale is meters. The green square shows the location chosen to represent the sea level near the southern New England shore.

To use the results of the IPCC simulations as guidance for the expected change in sea level in Connecticut the difference in the vertical datums used in the IPCC models and in the NOAA tide gages, and the consequences of vertical land movement must be taken into account. The IPCC (2013) used the mean of the interval 1986-2005 as the datum for sea level. Since the data from the NOAA gages discussed in Section 4 used the NTDE (1983 to 2001), a small, -4 mm, adjustment must be added to the IPCC sea level projections. The vertical land motion in coastal Connecticut is shown in Table 3 to be -0.7 mm/yr (subsidence) and this requires an increase in the sea level projection. Figure 12 shows the evolution of the ensemble mean and 5 to 95% confidence interval for RPC 4.5 at the location of green cell in Figure 11 near the coast of southern New England with the correction for vertical land motion. The variation is remarkably linear and the rate of change of the mean is 6.6 mm/yr and the trend in the 95% increases at 9.7 mm/yr. The values for each decade are listed in Table 8.

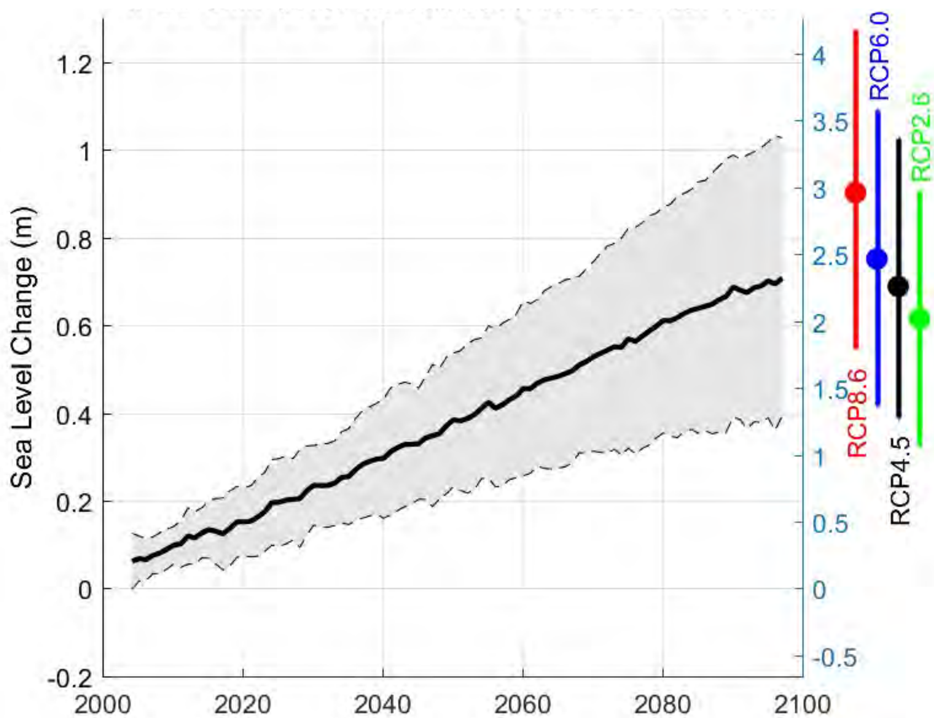


Figure 12. Sea level projection from IPCC (2013) for RCP 4.5 at the cell shown by the green cell in Figure 11 with the rate of vertical land motion added are shown by the solid black line. The 5 to 95% confidence interval is represented by the grey stripe. On the right of the figure the average sea level, and 5 to 95% range, for the interval 2090 and 2100 is shown for the 4 RCPs in IPCC (2013).

Table 8. Predictions of the change in mean sea level at the coast of Connecticut relative to the mean value during the NTDE based on the IPCC (2013) RPC 4.5 simulations. For the years shown in the first column, the second column show the expected (mean) value and the third column shows the upper bound of the 95% confidence interval. The fourth column show the intermediate low projections from NOAA CPO-1 for comparison. The three columns on the right show the same information in units of feet. The values are also shown in Figure 6.

Year	Mean (m)	Upper 95% (m)	NOAA (m)	Mean (ft)	Upper 95% (ft)	NOAA (ft)
2030	0.25	0.36	0.1	0.83	1.19	0.34
2040	0.33	0.47	0.14	1.07	1.53	0.47
2050	0.4	0.57	0.19	1.31	1.87	0.62
2060	0.47	0.67	0.24	1.55	2.21	0.79
2070	0.54	0.78	0.3	1.79	2.55	0.98
2080	0.62	0.88	0.36	2.02	2.89	1.18
2090	0.69	0.98	0.43	2.26	3.23	1.4
2100	0.76	1.09	0.5	2.5	3.57	1.64

8. Semi-Empirical Models.

An important weakness of the models used in the IPCC (2007) report and, consequently, the CPO-1 report, to simulate the impact of higher concentrations of CO_2 in the atmosphere on warming the ocean and increasing mean sea level, was is the representation of the effect of warming on the rate of melting of ice sheets. Observations were very limited and the mechanisms not well understood. Rahmstorf (2007) showed that there was a correlation between observations of the global average surface air temperature and the rate of sea level rise observed between 1881 and 2001. He then exploited this correlation to translate the temperatures predicted by a climate system model to obtain what he termed a semi-empirical estimate of the mean ocean level. Though this approach intrinsically assumed that the mechanistic links between a warming atmosphere and melting ice would remain the same, he showed it predicted a significantly higher mean sea level than the model.

Vermeer and Rahmstorf (2009) followed up this work by refining the correlation and applying it to translate the temperature predictions of the models used in IPCC (2007) to semi-empirical sea level forecasts. These were again substantially higher than the predictions of the process models. Grinsted et al. (2009) used a similar approach that exploited a much longer record of sea level and temperature proxies, but the conclusion was again that the sea level rise predictions made by the process models were too low to be consistent with the empirical link between mean air temperature and sea level.

To create the "Intermediate High" projection, the orange line in Figure 1, the CPO-1 report averaged the results of Vermeer and Rahmstorf (2009) and Grinsted et al. (2009). They then approximated the time evolution by a quadratic function $E(t) = m(t - t_o) + b * (t - t_0)^2$ where $t_0 = 1992$, $m = 1.7 \times 10^{-3}$, and $b = 8.71 \times 10^{-5}$.

To localize this estimate for applications at the shore of Connecticut the effect vertical land motion (subsidence) must be included. We therefore introduced the estimate from Table 3 and modified the CPO-1 equation to $E(t) = (m + 0.0007)(t - t_o) + b * (t - t_0)^2$.

9. Ice Budget Models

A large source of uncertainty in sea level forecasts arises from our limited understanding of the rate of melting of ice in Greenland and Antarctica. The CPO-1 report used estimates of the highest, physically plausible, rates of glacier motion presented by Pfeffer et al. (2008) to estimate the upper bound on sea level rise rates. They approximated the trend by the same quadratic function as in Section 8, but with $b = 15.6 \times 10^{-5}$. To include the effect of land subsidence in Connecticut we added 0.0007 the value of m.

10. Summary and Conclusions.

To provide planning advice for sea level rise that accounts for local conditions and follows the approach of CPO-1 we assemble in Figure 13 revised versions of the NOAA projections. Instead of projecting the best fit line through the observations of the annual estimates of global mean sea level, the blue line (the Low projection) is the upper bound of the prediction interval of the linear regression through the data from tide gages in Long Island Sound. This accounts for the substantial decadal-scale variability that occurs in the region. Note that the line doesn't intersect the other lines at 2000 since the best fit line (see Figure 6), which is at the center of the prediction interval, does. If the best fit line was used, as in CPO-1, then even if the trend estimate was correct, there would be a 50% probability each year that the mean sea level would exceed the estimate. The upper bound of the range is therefore a much more prudent planning tool.

The orange line in Figure 13 is the upper bound of the ensemble of projections in the IPCC (2013) model forecasts for the annual mean sea level near southern New England in scenario RCP 4.5. It is a localized and updated version of the Intermediate Low projection in CPO-1. Note that Figure 12 show that the mean and range of the other scenarios at 2100 and that the difference in the upper bounds of RPC4.5 and RCP 8.6 at that time is only 0.25 m. At 2050 it is approximately half of that.

The orange and magenta lines in Figure 13 are Intermediate High and High projections of CPO-1 adjusted for the local vertical land motion and so they result in slightly higher values in 2100.

The main difference between Figure 13 and Figure 1 (from CPO-1) is that the lower two curves in Figure 13 are higher than in Figure 1. This is because the IPCC (2013) models (yellow line) included an improved representation of ice melting, and the data-based projection shows the upper bound of the likely interval rather than the median, and only data since 1980. An important feature of the graph is that the projections diverge rapidly after 2050. The difference between the lowest and highest lines is approximately 0.3 m at 2050 and almost 1.5 m at 2100.

A common and useful planning outlook in many applications, e.g. home mortgages, is 30 years. Since 0.5 m (approximately 20 inches) is the mid-point of the projections at 2050, shown in Figure 13 as a red line, it provides a reasonable and prudent guideline for planning purposes. Figure 13 makes clear that the mean sea level will increase after 2050. This is a very robust prediction. So instituting a planning threshold using 2050 projections only makes sense if future reassessment is anticipated. However, alerting the public with property in the altitude zone impacted if a 1.0 m increase in mean sea level was to occur is also prudent.

It is important to emphasize that the model-based projection (yellow) line is the upper bound of the ensemble predictions and it assumes that the models are correct. If future scientific discoveries require models to be updated then the projections will have to be revised. Similarly, on-going data collection programs may show that the data-based projection may also require adjustment. This also motivates a periodic reassessment of the planning threshold. Since science moves slowly, and it is likely that a decade of data will be required to detect changes to recent rate of change in means sea level, updates at a minimum of 10 year intervals would be wise.

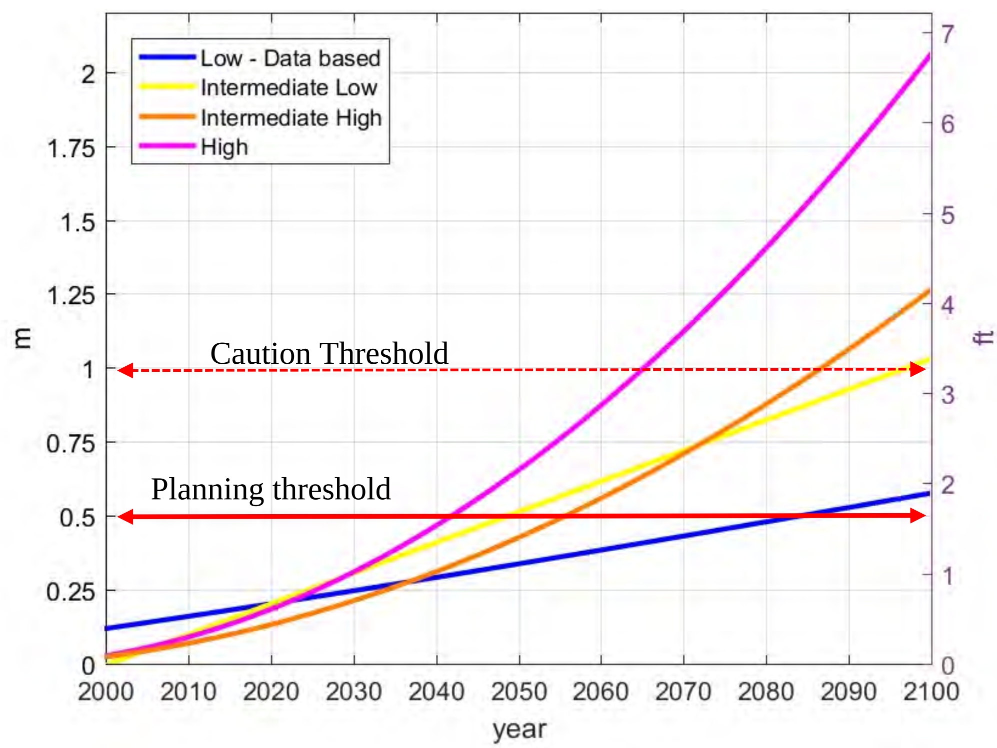


Figure 13. The blue line shows the upper bound on the prediction interval for the extrapolation of the annual average sea level at the Long Island Sound tide gages as shown in Figure 6. The yellow line shows the upper bound of the ensemble of predictions of the mean sea level off southern New England in simulations of RCP4.5 from IPCC (2013) and shown in Figure 12. The Orange and Magenta lines are the same as in CPO-1, but with the effect of vertical land movement included. The thick red line shows the 0.5 m level which is the center of the range of predictions at 2050.The red dashed line is the upper bound of the model predictions at 2100.

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An Assessment of the Long Island Sound Circulation and Storm Surge Model

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1. Introduction

The prediction of the effects of climate change on the statistics of coastal flooding is essential to the development and evaluation of designs for risk reduction. Though the physical processes that link tides and wind forced motions to sea level variations are well established and understood, computing solutions to the equations is difficult because of their intrinsic nonlinearity and the complex, and wide variations in scales in, the geometry of the coastline. In addition, the coastal ocean is inherently linked to the global ocean and the conditions imposed at the edges of the smaller domain inherently have errors. The forcing imposed by the wind is also approximate. Many choices and judgements are therefore built into coastal models and the consequences of these need to be assessed empirically. In this document we describe the assessment of a model we have develop to guide the projection of sea level rise on coastal flooding in Connecticut.

In the next section we summarize the development of the model of Long Island Sound (LIS) and the initial tests we conducted using NOAA tide gage data. We then describe a more detailed examination of the model performance in prediction of currents in a complex area. We then show the performance of the model when realistic winds are used to force the motion and then summarize the results.

2. Model Development and Preliminary Calibration

We have developed a high resolution model of the circulation and hydrography in Long Island Sound (LIS) and Block Island Sound (BIS) in collaboration with Prof. C. Chen of University of Massachusetts, Dartmouth. The domain of the model and the resolution in the study area are shown in Figure 1. The model is an implementation of FVCOM (Chen et al., 2007) and is designed to exploit forecasts of the northwest Atlantic regional model operated as the Northeast Coastal Forecast System. This approach is computationally efficient since it allows the effect of the larger-scale processes to be simulated at coarse resolution and allows UConn's computing resources to focus on the smaller scale structures in LIS and BIS. In this section we outline the model forcing, the process of calibration and the model performance, and then comparison to measurement collected in the study.

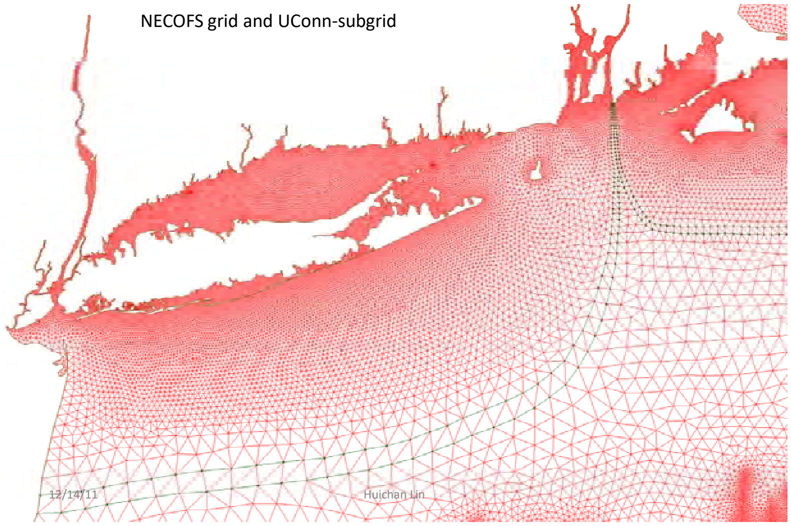

Figure 1. Map of southern New England shore showing the model grid (red). Blue cells show the boundary locations where the regional model NECOFS and the nested LIS-BIS sub-domain overlap.

FVCOM was initialized using a temperature and salinity climatology dataset derived via objective interpolation (OI) from CTDEEP station and offshore buoy records. This climatology has been constructed for times representing four seasons: 15 Oct, 15 Jan, 15 Apr, and 15 Jul. In order to be input into FVCOM, these OI fields are interpolated from sigma level depths to a set of standard depth levels. The standard depths were chosen as: [0. -2. -4. -6. -8. -10. -12. -15. -20. -25. -30. -40. -60. -80. -100.m]. The model simulations are started in the fall for the subsequent year in order to provide an adjustment period.

FVCOM is forced at the open boundaries by sea level variations. We employ constituents derived from the from the TOPEX model using the Foreman algorithm. These boundary conditions are then iteratively adjusted to achieve an optimal representation of the amplitude and phase at each tidal frequency using NOAA tidal height observations from 2012 at Montauk, New London, CT, New Haven, CT, Bridgeport, CT, and King's Point, NY. Each constituent amplitude was adjusted by the mean of the relative amplitude. Fig 2 shows an example of the result of this procedure on the observed and predicted level at the NOAA Bridgeport tide gauge. The mean tidal skill, defined using the model tidal height errors normalized by the tidal amplitudes, was improved from 88% to better than 96%. Figure 3 show a comparison of the predicted and observed sea level variation at a NOAA ADCP near Hammonassett Point.

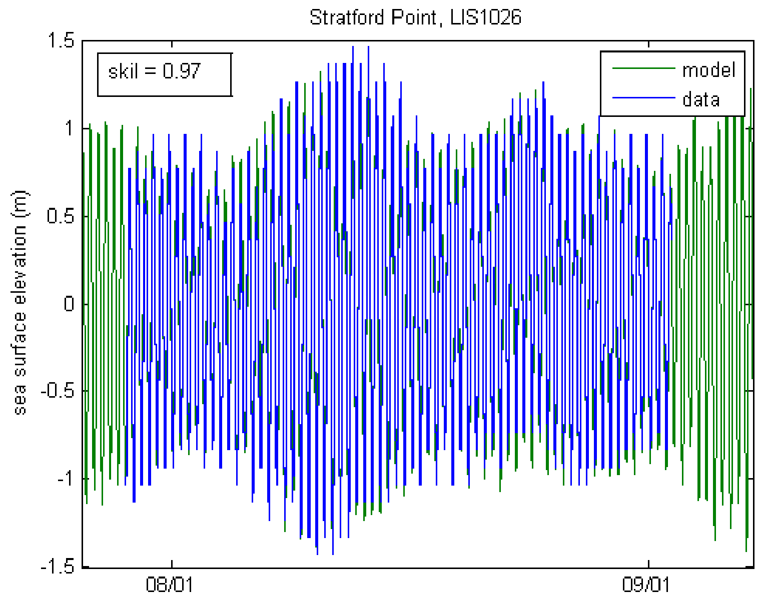

Figure 2. Comparison of model prediction and observation of sea level at the NOAA ADCP LIS1026.

Although the calibration procedure did not involve ADCP current observations, the model captures tidal currents and tidal constituents of depth-averaged currents well. Minor differences appear where the topography is steep or the data did not cover a full spring-neap tidal cycle. Time series comparisons (below) between field measurements and model simulations of the same time period demonstrate the model successfully predicts tidal currents. (See Fig. 3.)

Heat fluxes in FVCOM are prescribed; the model makes no internal calculations of these fluxes. FVCOM can be linked to an atmospheric model and thereby calculate surface heat fluxes in a coupled ocean/ atmosphere manner, but we have not implemented this capability yet. The model is therefore sensitive to the heat fluxes imposed. Domain-uniform fluxes are derived using the WHOI/USGS air-sea toolbox, and then iteratively tuned so as to reproduce the water temperature climatology. The heat flux forcing used is thus neither year nor location specific, but replicates the annual warming and cooling cycle near Stratford Shoals well. Figure 4 shows a comparison of the FVCOM prediction for bottom temperature in the study area for the interval Oct 2012 - Oct 2013 and compares it to the temperatures measured by the bottom frames.

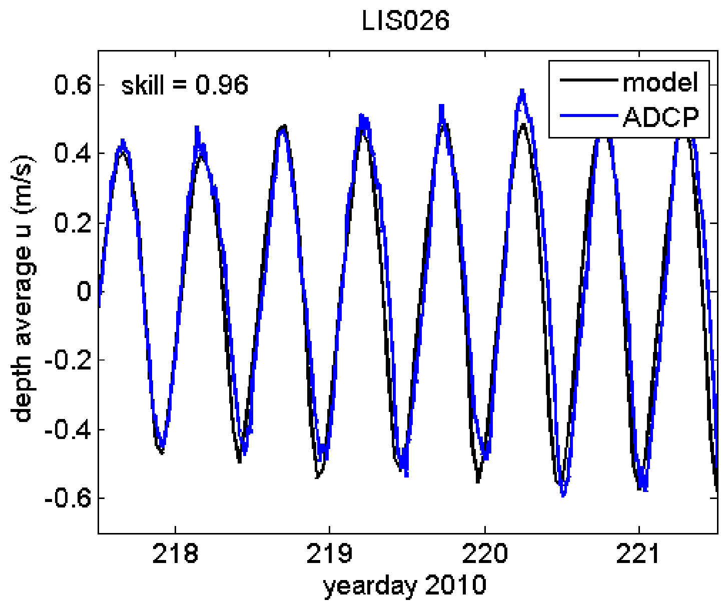

Figure 3. ADCP deployment (blue) compared to those predicted by the FVCOM model (black).

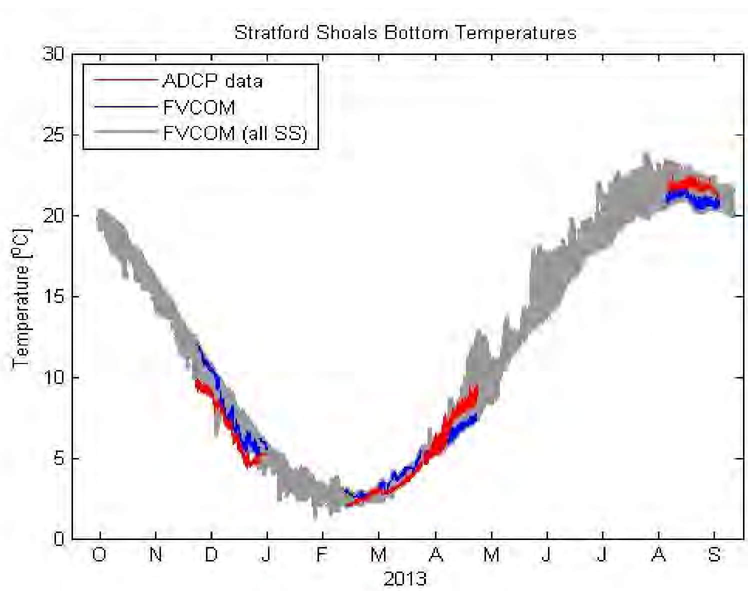

Fig. 4. Comparison of bottom temperatures (°C) in the FVCOM model with those measured during the six ADCP deployments at Stratford Shoals (SS). The temperatures measured by the ADCP sensors are shown in red; shown in grey are the FVCOM model solutions for the entire year at all six SS deployment sites; the FVCOM results at the individual sites for each deployment period are shown in blue. Based on these six data sets, the overall model skill with respect to bottom temperatures in this region is 98%. (Calculated as $l = 1 - \frac{1}{N}\sum_{1}^{N}\frac{(model-data)^2}{\sigma^2}$)

Freshwater is input into the LIS FVCOM domain at 5 points corresponding to the locations of the Rivers Thames, Niantic, Quinnipiac, Housatonic, and Hudson rivers. The fluxes are gauged flows measured by USGS and increased by 20% to account for below-gauge watershed. The gauged flows are lagged by one day to account for the distance between the head of the Connecticut River in our model and Thompsonville. Each river, R_i, is adjusted using the USGS Thompsonville data as $R_i = 1.20\frac{R_{CT}}{\overline{R_{CT}}}\overline{R_i}$ where R_{CT} is the day-specific Connecticut River flow, $\overline{R_{CT}}$ is the mean Connecticut River flow, and $\overline{R_i}$ is the mean flow for river *i*. An additional fixed input of 40 $m^3\ s^{-1}$ was added to the East River to represent the freshwater fluxes from the Bronx River and New York City Sewage Treatment Plants. Fig. 5 shows a comparison of the model salinity in the western LIS at the LISICOS ARTG buoy location (near CTDEEP station E1) with climatology derived from the CTDEEP surveys and with the 2013 buoy measurements.

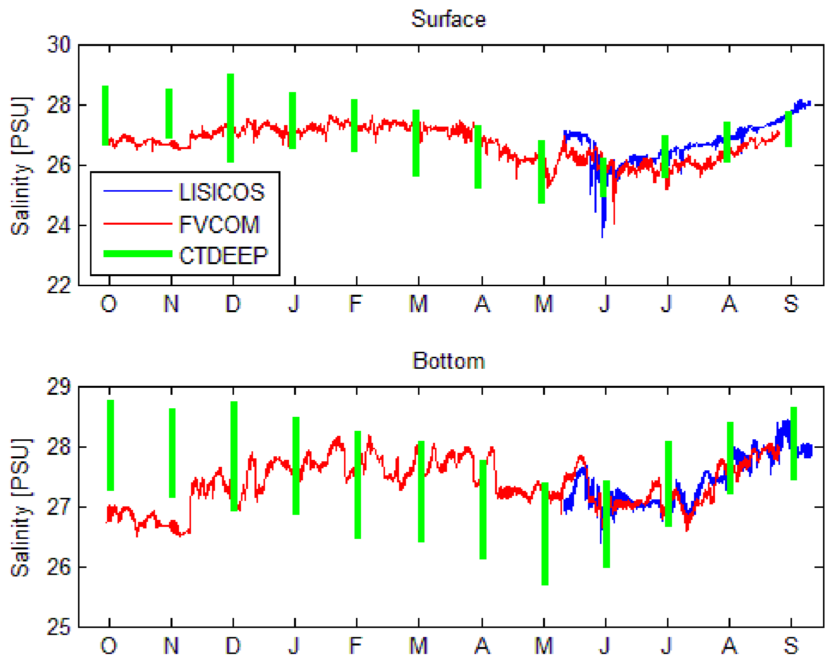

Fig.5. 2012-2013 salinity at ARTG/ E1 for the near surface (top panel) and near-bottom (bottom panel). The FVCOM model predictions are shown in red. Shown by the green bars are the means ± one standard deviation of the CTDEEP data at station E1 binned by month for 1993-2012. Shown in blue are the salinities measured by the LISICOS ARTG buoy for water year 2013. Note that the model is closer to the buoy observations for the near-bottom observations than the climatology is, indicating that the model has a positive Brier skill compared to the climatology at this location.

The model is forced with domain-uniform winds obtained from the LISICOS Western Sound Buoy. Because FVCOM expects 10 m wind speeds, while the buoy winds are measured at 3.5 m, the wind speeds in the buoy record are converted to W_{10} values as $W_{10} = W_{3.5}\frac{\log(10\mathrm{m}/z_0)}{\log(10\mathrm{m}/z_0)}$ using z_0=0.01 m. Gaps in the buoy record are then filled in using W_{10} data from Bridgeport/ Sikorsky airport (BDR). Because of the disparity in the observational locations, contemporaneous data from both the buoy and BDR were regressed using a total least squares methodology and the regression results were applied to the BDR data for those periods where the buoy data was missing. Fig. 6 shows a comparison of the subtidal bed stresses predicted by the model during two wind events in 2013 with those calculated from the ADCP deployment data.

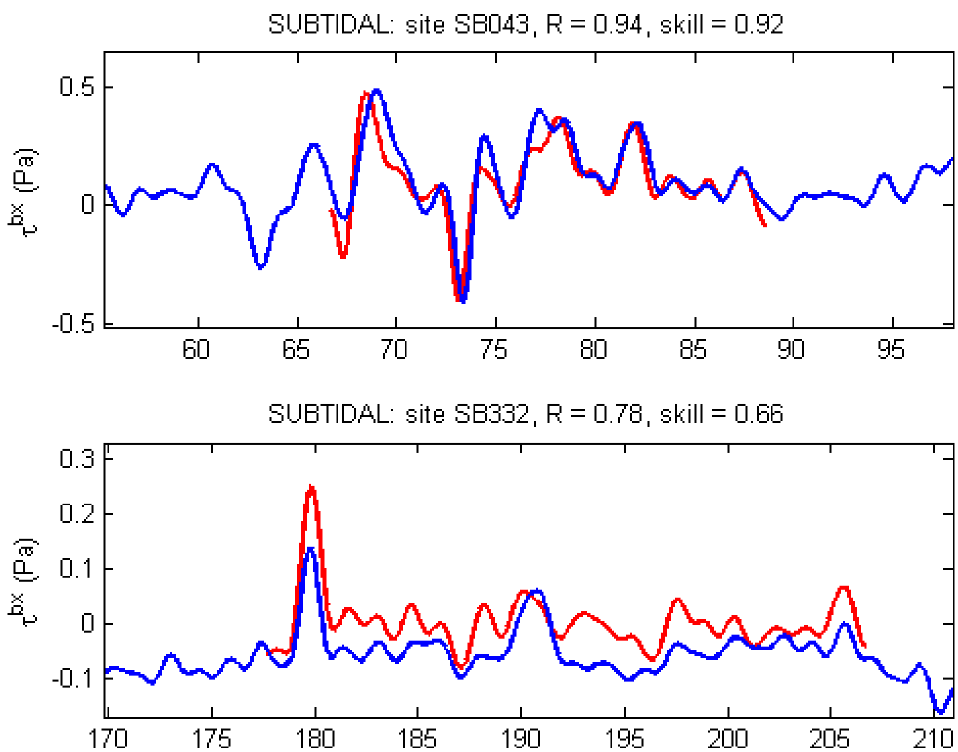

Fig. 6. Subtidal bottom stresses calculated from ADCP records (red) using the SB043 (top) and SB332 deployment data compared with those calculated from the FVCOM model predictions (blue) during wind events (wind speed > 15 m s^{-1}).

The model captures the spatial variation in the amplitude of the M2 tidal component very well. The M_2 is the primary tidal frequency in LIS and is responsible for the bulk of the semi-diurnal tide. Figure 7 shows a comparison of the M_2 amplitudes at the four LIS tidal gauges from the model (green) with those estimated from NOAA gauge data (blue.)

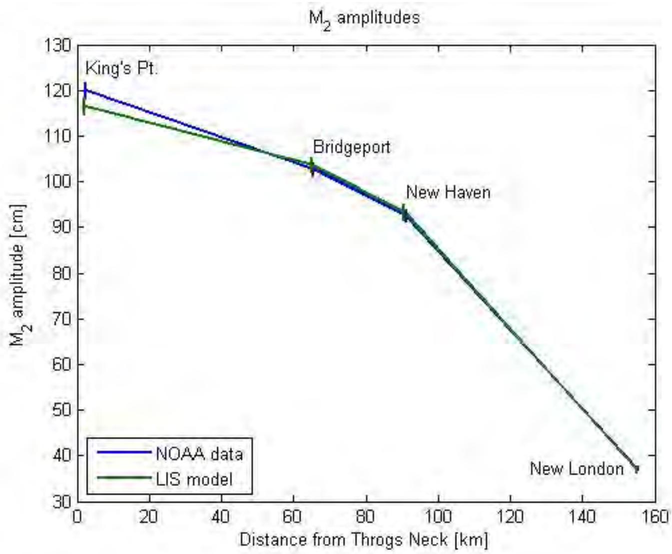

Figure 7. M_2 amplitudes plotted by along-Sound distance from the Throg's Neck estimated from NOAA tide gauge observations (blue) and from the LIS-FVCOM model results (green) using T_TIDE (Pakolwicz et al, 2002). The error bars show the uncertainties in the T_TIDE harmonic analyses.

The model also captures the along-estuary SSH gradient that results from the along-Sound density gradient as well as the mean wind stress. This is a result that is difficult to obtain from data. Figure 8 shows a plot of the model mean along-Sound model sea level predictions referenced to MSL at New London.

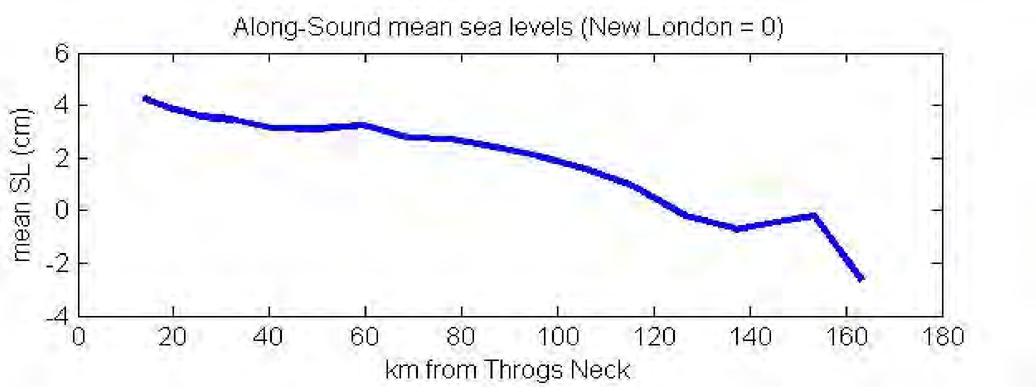

Figure 8. Mean model sea-level predictions (blue) along an along-Sound transect plotted by distance from the head of the Sound at the Throg's Neck.

3. **Simulation Evaluation of the Stratford Shoals Area**

To evaluate the performance of the model in the prediction of currents and stress in the study area, in Figure 9 we compare the M2 tidal current ellipses for the vertically averaged flow computed from the data acquired by the moored RDI ADCPs, to that estimated from the model. Note that the northern (SB043) and southern (SB332) most deployments are in excellent agreement with the observation-based ellipses and that the discrepancies in direction and amplitude are slightly larger at the station in the region of the most complex bathymetry.

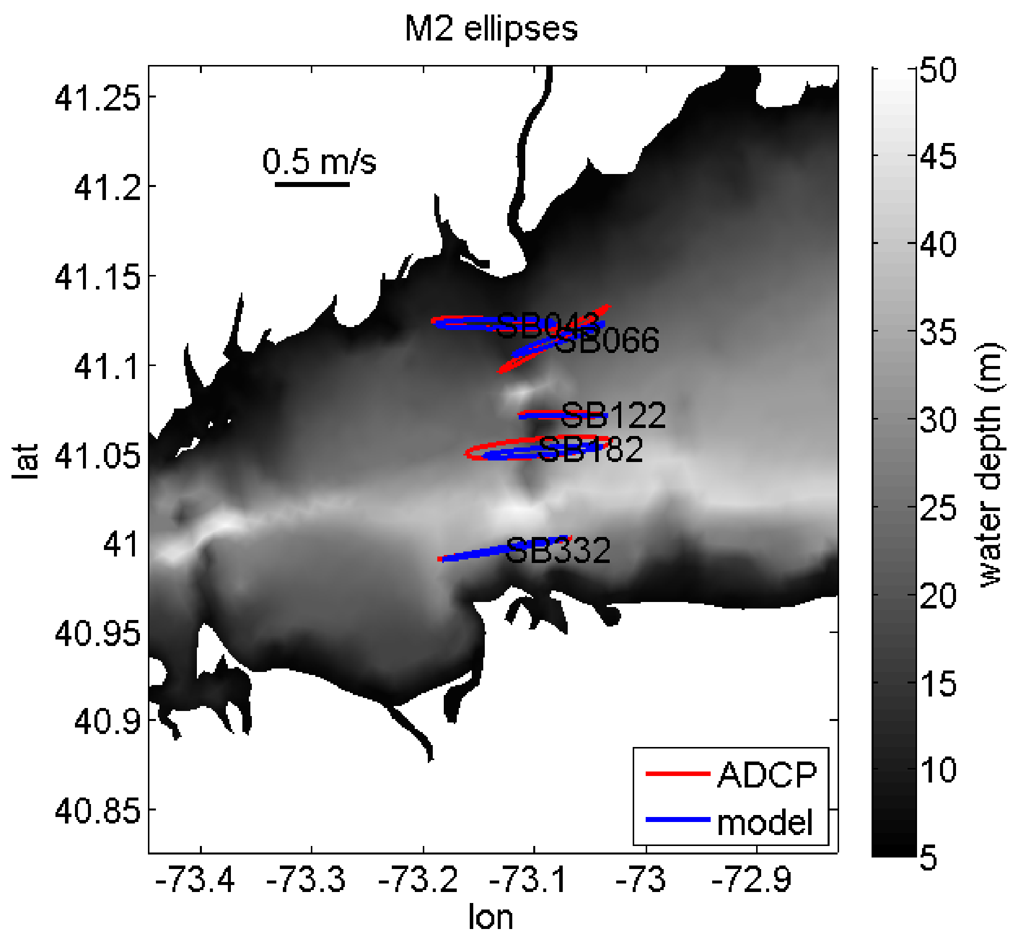

Figure 9. M2 ellipses for depth-average velocities from ADCP measurements (red) and FVCOM model (blue) at 5 sites on Stratford Shoals. ADCP deployments ranged from 13-44 days duration in the summer of 2013. Model ran from fall 2012 to fall 2013. The grey shading represents mean water depth.

Perhaps the most ecologically relevant parameter after temperature is the bottom stress. In Figure 10 we compare the model's estimate of the near bottom stress at the M2 frequency to that estimated by the moored instruments. The agreement at the northern and southern boundaries of the study area are within 10%, however, in the center the error is closer to 20%. This is clearer in

Figure 11 which shows a comparison of the time series of the stress components in the principle axis directions. There scale is chosen to clarify the intra-tidal variations. Stress magnitudes vary from -1.5Pa to 1.5Pa at the northern station and by substantially less at the central stations. The model resolves this spatial structure well. Skills are all over 90% and correlations vary from 80 to 92%.

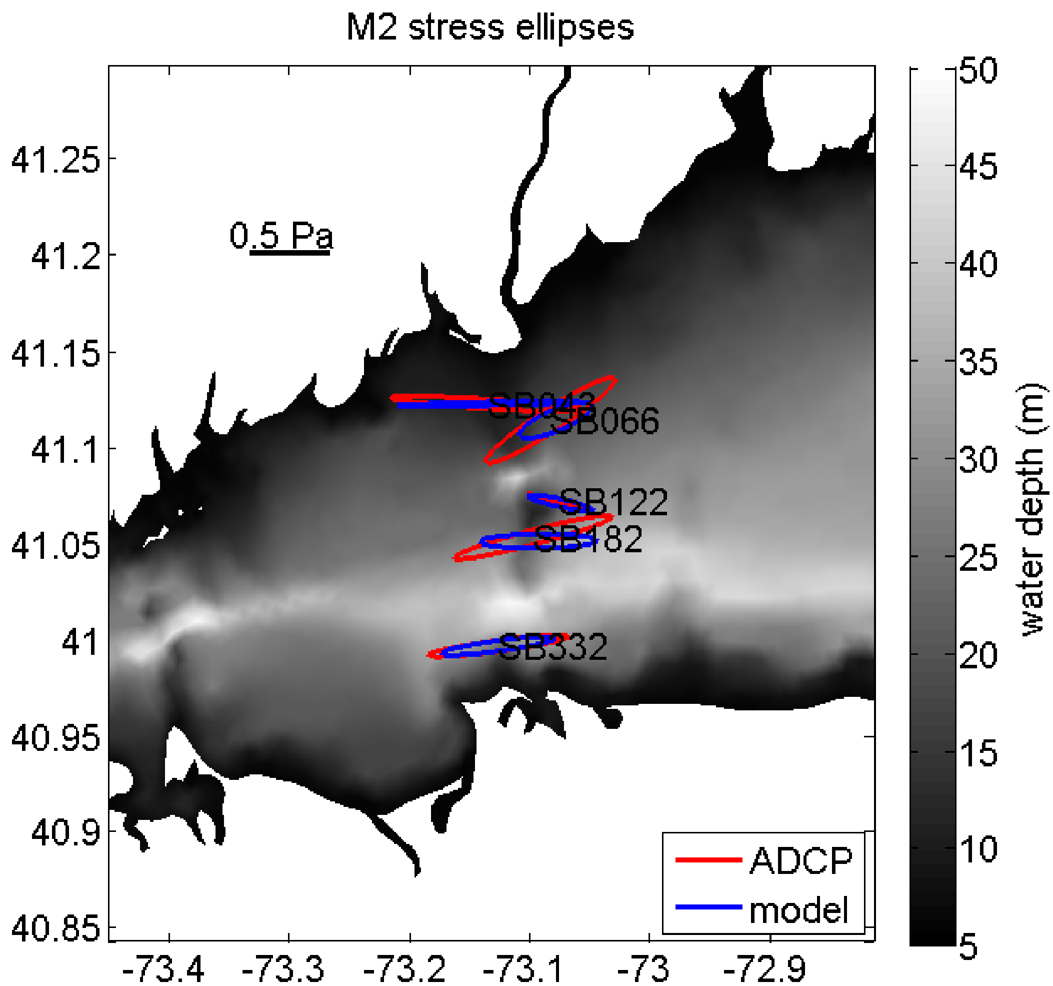

Figure 10. M2 ellipses for bottom stresses, calculated from lowest ADCP velocity measurement (red) and FVCOM model at similar elevation (blue) at 5 sites on Stratford Shoals. ADCP deployments ranged from 13-44 days duration in the summer of 2013. Model ran from fall 2012 to fall 2013.

The performance of the model in simulation of the longer term evolution of the bottom stress is demonstrated in Figure 12 which compares the low pass filtered observation and predictions at

SB043 (northern station) and SB332 (southern station) during times when the wind was strong (greater than 15 m/s). The results are very good in that the correlations are high and the magnitude as very close. There appears to be a slight low bias in the southern station.

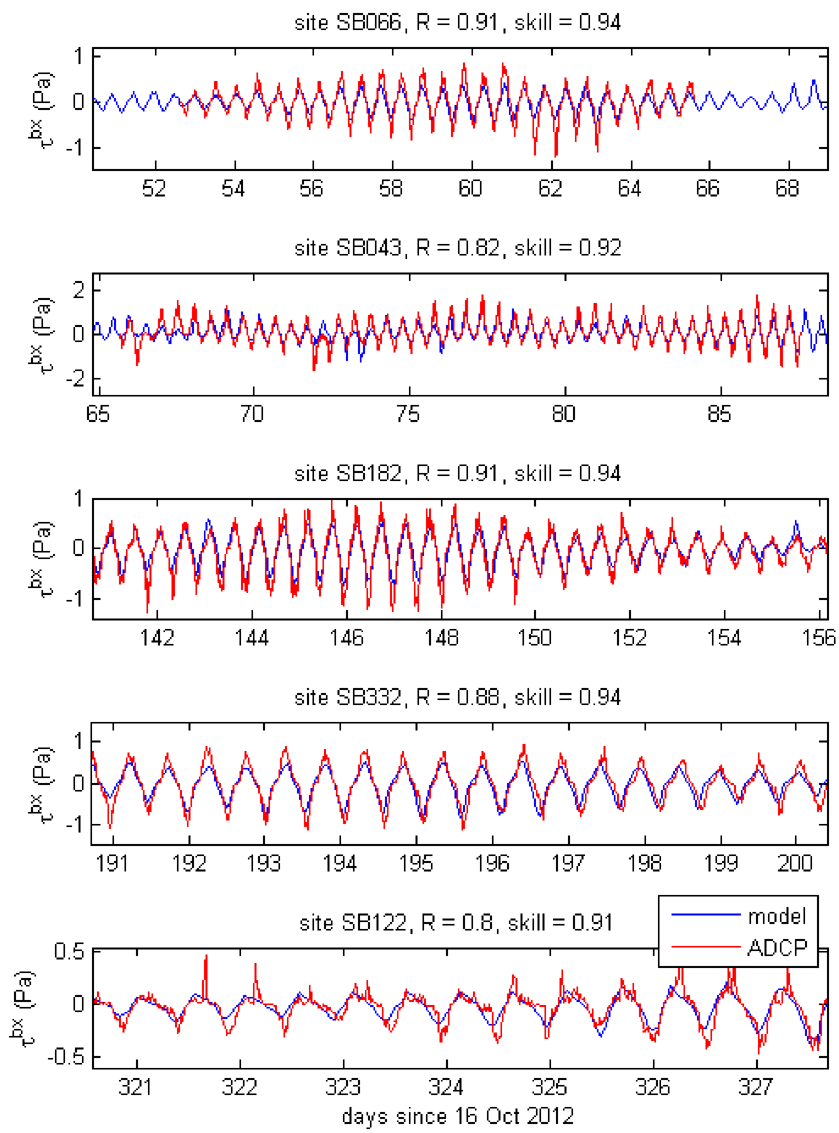

Figure 11. Time series of bottom stress at 5 sites on Stratford Shoals from the summer of 2013 calculated from ADCO (red) and FVCOM model (blue) velocity data.

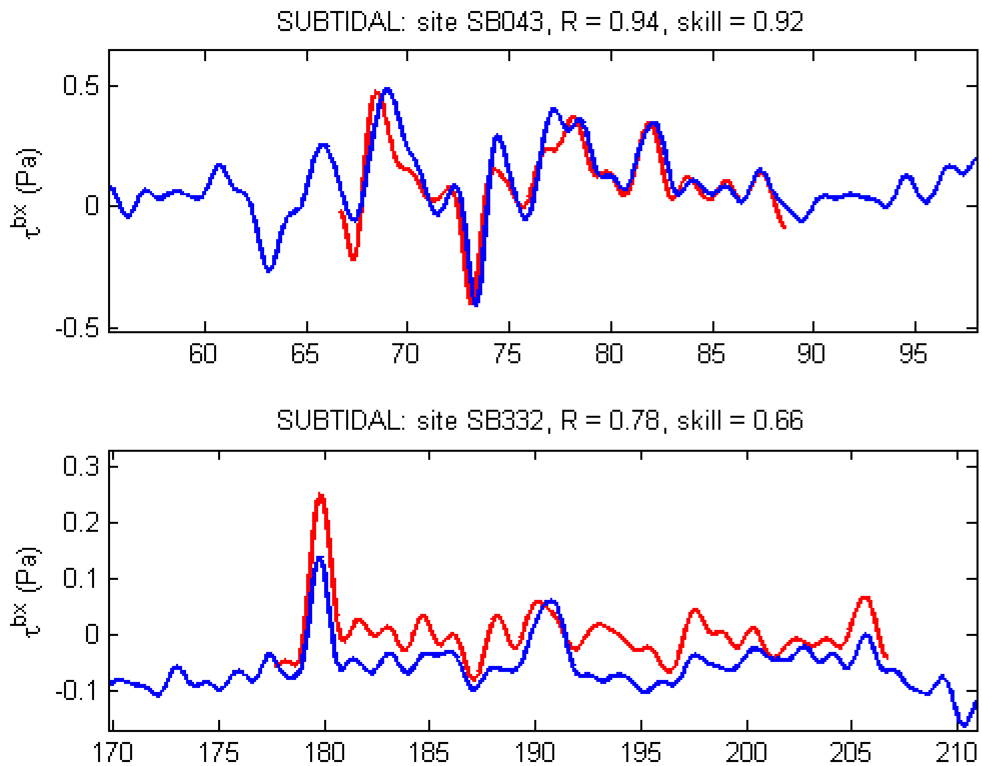

Figure 12. Subtidal bottom stresses calculated from the ADCP (red) and model (blue) at two sites on Stratford Shoals that experienced wind events (speed > 15 m/s) while the ADCP was deployed there.

4. Model Performance Summary

The comparison of the model simulations to temperature, salinity, current and bottom stress measurements are all show excellent agreement. The discrepancies between predictions and observations may be improved in the future to better represent high frequency fluctuations but the model results clearly support the model's use as a tool to interpolate spatially between the observations for the purpose of making maps of the characteristics of the bottom environment that are ecologically important.

LIS-FVCOM is forced at the seaward boundaries by sea level variations. The sea level is initially prescribed using tidal constituents derived from the global tidal model (Egbert et al., 1994). Since the Egbert et al. (1994) constituents are not precise in shelf areas, the amplitudes and phase of the major constituents were iteratively adjusted to achieve an optimal representation of the amplitude and phase at each tidal frequency using NOAA tidal height observations from 2010 at Montauk (NY), New London (CT), New Haven (CT), Bridgeport (CT), and King's Point (NY). Each constituent amplitude and phase was adjusted by the proportional amplitude error and phase error to optimize the model. Subtidal fluctuations at the open boundary are incorporated from the NECOFS system by de-tiding and low-pass filtering the NECOFS solution at the open boundary locations using t-tide (Pawlowicz et al., 2002) and a 25-hour raised cosine low-pass filter. The model's subtidal performance was further optimized by removing the low-passed error in the NECOFS subtidal forcing as determined by comparing the NECOFS solution with NOAA sea-surface height (SSH) gauges at Newport, RI and Atlantic City, NJ. These station are near the open boundary of the LIS model. The detided and adjusted NECOFS subtidal solution was then combined with a time series of tidal heights generated using the optimized tidal constituents.

To evaluate the performance of LIS-FVCOM, we use the "skill," s, statistic defined as (von Storch and Zwiers, 1999)

$$s_f = 1 - \frac{\langle (f_m - f_d)^2 \rangle}{\langle (f_d - \langle f_d \rangle)^2 \rangle} \quad (1)$$

where f_m and f_d represent the model and data values and the $\langle\,\rangle$ notation represents the mean of the argument over the simulation interval (e.g., $< f_d >$ is the mean of the data).

Table 1 shows the model sea-surface-height (SSH) skill (Eq 1) from a realistic simulation of the year 2017 compared to hourly measurements at the four NOAA tidal gauges in LIS: New London, New Haven, Bridgeport, and King's Point. The first row shows the skills when simulated sea surface heights (relative to MSL) are compared to the raw observations. The second and third rows shows the skills when the model and data series are divided into tidal and weather components using harmonic analysis (Pawlowicz et al, 2002). The errors in the simulation of tides are small - the skills all exceed 93%. The errors in the simulation of the total water level (SSH) mainly arise from the errors in the simulation of the meteorologically driven motions and are, to a large extent due to inadequacies in the atmospheric model used to prescribe winds.

In conclusion, though this model is not perfect and some aspects can be improved, it is an excellent tool with which to develop guidance for the effects of sea level rise on tides, storm surges and flooding. The errors are bounded in this project and so the uncertainties that are inherent in the simulation can be considered in design guidance.

Table 1: Model skills (Eq 1) when model elevations are compared to NOAA gage data at New London, New Haven, Bridgeport, and Kings Point. The first row (Total SSH skill), shows the skills when sea-surface heights (relative to MSL) are compared, the second row shows the skills at tidal frequencies, the third row shows the skills for the subtidal residuals.

	New London	New Haven	Bridgeport	King's Point
Total SSH skill	91%	92%	93%	93%
Tidal skill	94%	93%	94%	94%
Subtidal skill	77%	75%	77%	54%

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Pawlowicz, R., B. Beardsley, and S. Lentz. 2002. Classical tidal harmonic analysis including error estimates in MATLAB using T_TIDE. *Computers and Geosciences* 28:929-937.

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Wave and Storm Surge Flooding in a Small Marsh System

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1. Introduction

The coastline of Connecticut is incised by numerous inlets where the streams and rivers carrying runoff from land towards the ocean and the saline tidal waters of Long Island Sound intrude into the channels. Salt marshes have formed in many of these inlets and have become critical habitat for numerous species of insects, birds and fish. Coastal settlements, and the routes between them, have general skirted the inland limits of the salt marshes and many bridges and culverts have been constructed to allow the water and transportation network to co-exists. Rising sea levels will cause segments of roadways to become more vulnerable to flooding in the future. Assessing the most cost effective and appropriate adaptation strategy to reduce the frequency of flooding to an acceptable level requires analysis of the flow of water through the inlets. In this report we develop an approach to the assessment of the current flood risk and the estimation of the future risk as sea level rises. The study site is Sybil Marsh in Branford, CT. This area provides a good example of several issues that are important in the region. It is densely developed with residential housing, it is surrounded by roads, and the flow into the marsh has been controlled by a tide gate for many decades. During "Super Storm Sandy" much of the area was flooded and some data on water levels and flow paths was acquired. Residents reported that water was flowing over the bridge at Linden Avenue and into the marsh. Other reported that breaking waves were overtopping the road at Limewood Avenue that the splashover was flowing northward along Waverly Avenue and into the marsh as well.

In the following sections we first address the flow through the tide gates using observations and a model. We describe the geometry of the region, the observation program and the use of models we have developed to assess flood risk and the effects of sea level rise. Since it is unlikely that we could acquire data on severe events during the contract period, we then address the wave overtopping and flow into the marsh at Limewood Avenue with just model simulations. We conclude with a discussion of the likely effects of sea level rise.

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2. The Geography of the Sybil Creek

The Sybil Creek area of the Town of Branford, CT, is shown in the GoogleEarth Image in Figure 1. It is an affluent town with a mixture of year round residences and some large vacation homes along the shoreline of the Sound. The promontory that extends into Long Island Sound has some rocky high ground and it connected to the mainland by a sandy spit at the area shown by the yellow arrow. The main coastal state highway (RT 146) runs parallel to the shore in the spit and is named Limewood Avenue there. It turns north and crosses Sybil Creek on a bridge-tide gate structure near the junction with Linden Avenue.

Figure 1. The coastline of Branford is shown using a GoogleEarth image with some locations of flooding on RT 146 indicated by the blue and yellow arrows. To understand how the water level in the Sound drives flooding we deployed instruments to measure sea level at the 3 locations shown by the red diamonds. We also deployed a wave sensor at approximately the location of the yellow *.

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A bridge and tide gate carry RT 146 across the Sybil Creek in Branford. Figure 2 shows the topography and bathymetry in the area of the bridge and the location of 4 moored instruments that were deployed to observe water level fluctuations. Flooding have been reported on both Sybil and Linden Avenue to the east of the bridge. The magenta square in Figure 2 includes BR1 and BR2 and surrounds the area prone to flooding. A high resolution map of the area is shown in Figure 3 where the elevation range displayed is restricted to -0.5 m to 2m to reveal the subtle variations in topography around the level of the top of the bridge. The red dots in Figure 3 indicate the locations of measurements of elevation by RTK GPS on the road surface of the tide gate-bridge structure.

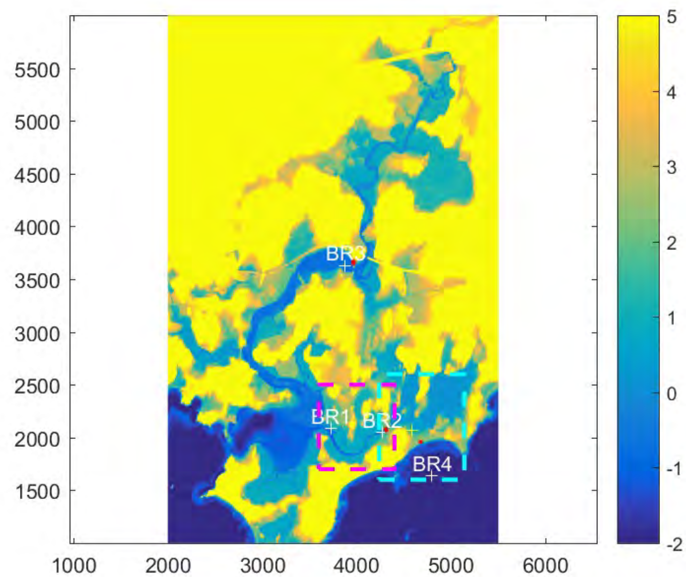

Figure 2. The topography and bathymetry of Branford, CT. The color codes are shown on the right. The square defined by the dashed magenta line surrounds the junction of Sybil and Linden Avenue and defines the area shown in higher resolution in Figure 45. The white + symbols show the location of moored instruments. The area surrounded by the cyan square is discussed in the next section.

The black line in Figure 4 displays the elevation along a north-south line through the red points in Figure 3 using both LIDAR estimates and the direct RTKGPS measurements. The data show that the top of the tide gate is at 1.9 m NAVD88 and the level of the bottom of the channel near the structure is 0.7 m. These measurements are clearly consistent with each other. It is worthy of note that the bridge is scheduled for replacement and the design (90% final) shows it to be at the level 1.96 m (NAVD88).

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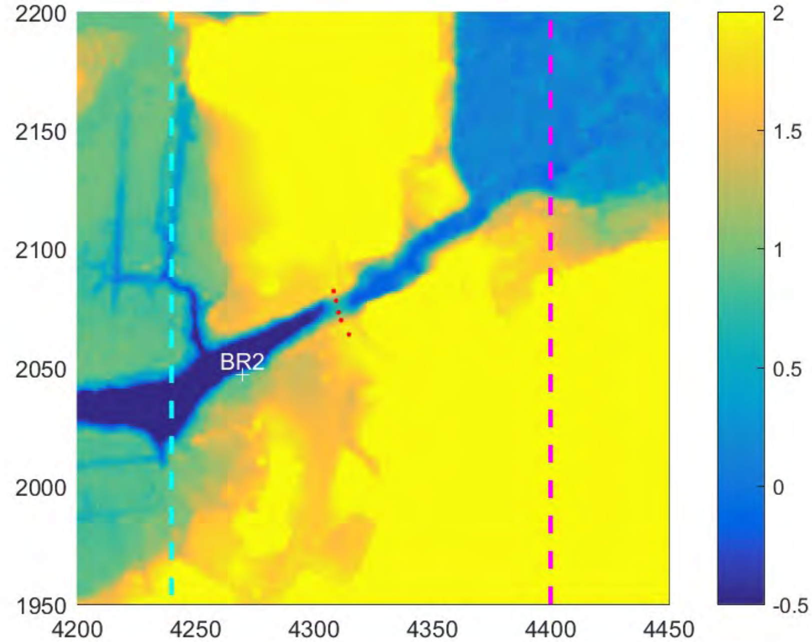

Figure 3. A high resolution map of the elevation in the area of Linden and Sybil Avenue. The color range is set to vary from -0.5 to 2.0 m NAVD to highlight the variation in the elevation in this range. The red dots show the locations where elevation on the road surface at the tide-gate and bridge structure at Linden Avenue was measured with an RTK GPS system.

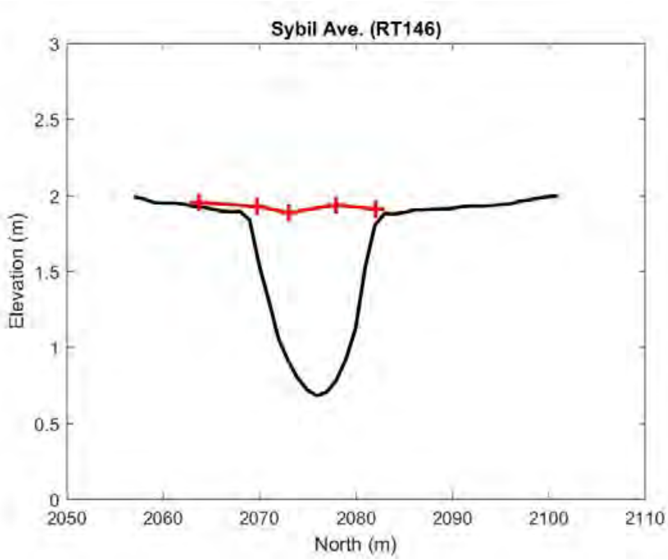

Figure 4. The black line shows elevation estimates along Sybil Avenue from the LIDAR shown in Figure 45, and the red + symbols and line shows measurements by RTK GPS at the locations shown by the red points in Figure 3.

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2 The Observations

The observations from sites BR1, BR2 and the sea level measurements from the NOAA tide gage at New Haven are shown in Figure 5. The mean over the common period of observation of the New Haven and BR1 series was set to -0.08 NAVD, which is the mean sea level reported by NOAA when they maintained a station in Branford (8465233). This was necessary because the NOAA gage in New Haven is not referenced to NAVD directly, and because measuring the water level at the sensors during the deployment was difficult and the consequent uncertainties were too large for the datum to be useful. In Figure 5 (a) we show the evolution of the total water level for all three series. The magnitude of the tidal oscillations, the spring-neap cycle, and the irregular meteorologically forced motions are all evident. but since the differences between the records are so small, the different lines are difficult to distinguish. In Figure 5 (b) we show the same series after the semidiurnal tidal oscillations have been removed by a 5^{th} order Butterworth filter with a 48 hour cut-off period. The New Haven (cyan) and the BR1 (red) series are again almost coincident demonstrating that the low frequency variations propagate from the Sound into Branford harbor with little variation. The dark blue line shows the BR2 record. This record has been adjusted to the NAVD88 datum (approximately) by minimizing the difference between the peaks in the low-pass filtered series at BR1 and BR2. This allows the tidal

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frequency variations, see Figure 5 (c), to be influenced by the bathymetry, but not the low frequencies.

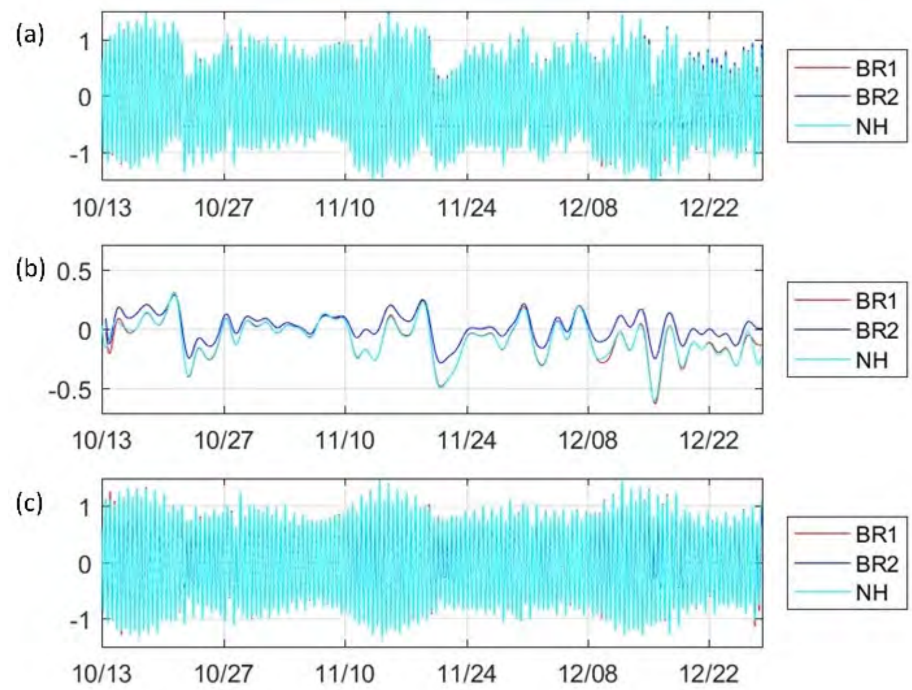

Figure 1. (a) Time evolution of the water level observed at BR1 (red), BR2 (blue) and New Haven (cyan) in the fall of 2016. (b) The low pass filtered series and (s) show the high frequency signal.

To compare the observations more clearly we show in Figure 6 a seven day segment of the same data as in Figure 5. The only noticeable difference in the raw series shown in Figure 6 (a) is that the BR2 series (blue lines) doesn't fall below -0.6 m which is the elevation of the bottom a at the station location. The low frequency variation shown in Figure 6 (b) also shows that the BR2 series (blue) varies from the others, it usually higher, largely as a consequence of the higher minimum value that it can reach.

The maxima in the total water level records from BR2 and New Haven during the observation period are compared in Figure 7. The root mean square difference in the maxima is 0.05 m and the correlation coefficient is 0.98. This demonstrates that there is little difference between the two levels and there is, therefore, no need for a model of the flow in the lower Branford River to link the two levels.

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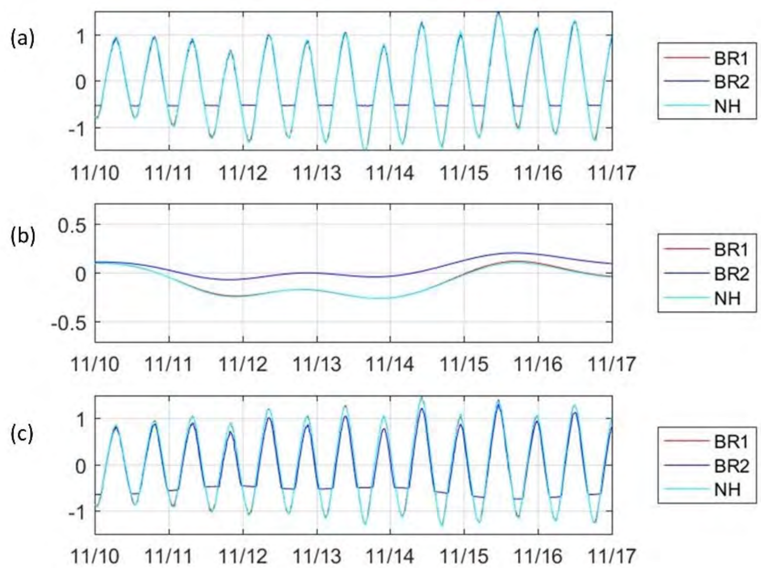

Figure 2. The same data as in Figure 4 but for a 7 day interval in November 2016.

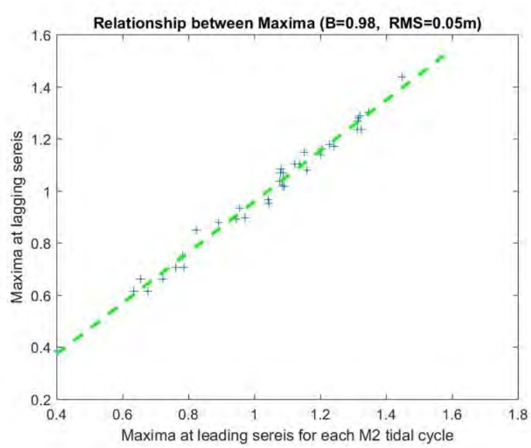

Figure 7. The correlation between the magnitude of the peaks observed in the New Haven (horizontal axis) and BR2 (vertical axis) series shown in Figure 4 (a).

3. Analysis of Observations

The measurements described in the preceding section demonstrate the water level at BR2 and the junction of Linden and Sybil Avenues can be accurately represented by the NOAA water level at New Haven. The analysis of the LIDAR and RTK GPS elevation measurements indicate that the roads are subject to flooding by seawater when the water level exceeds 1.9 m NAVD88. Figure 14 shows the record of sea level reported by NOAA at New Haven in the seventeen years since January, 1999, with the 20 highest levels (separated by at least 48 hours) highlighted by the red

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circles. These values are shown in descending rank order by the red squares in Figure 8. Note that these level assume that the mean sea level at New Haven (and BR1) is -0.08 m NAVD and this may introduce an error of approximately ± 0.1 m. The largest two values exceed 2 m and occurred during Hurricane Irene in August, 2011, and super-storm Sandy in October 2012. The rest of the peaks were due to the much more frequent extra-tropical storms. The dashed black line shows the level of the roadway at Linden and Sybil Avenues where it crosses Sybil Creek. This graphic suggests that the roadway was flooded during the hurricanes and perhaps the next two largest water level peaks. The levels reached by the peaks ranked 5 and higher lie below the road level in a narrow range between 1.7 and 1.9 m. That the level of the roadway was reached or exceed four times in seventeen years confirms that the area is at risk from coastal flooding. The red dashed line shows the levels that the water level peaks would have reached if mean sea level had been 0.25 m higher, a level that could plausibly occur by 2050. Comparison of the red and the black dashed lines demonstrates that all 20 storm could cause road flooding in the future.

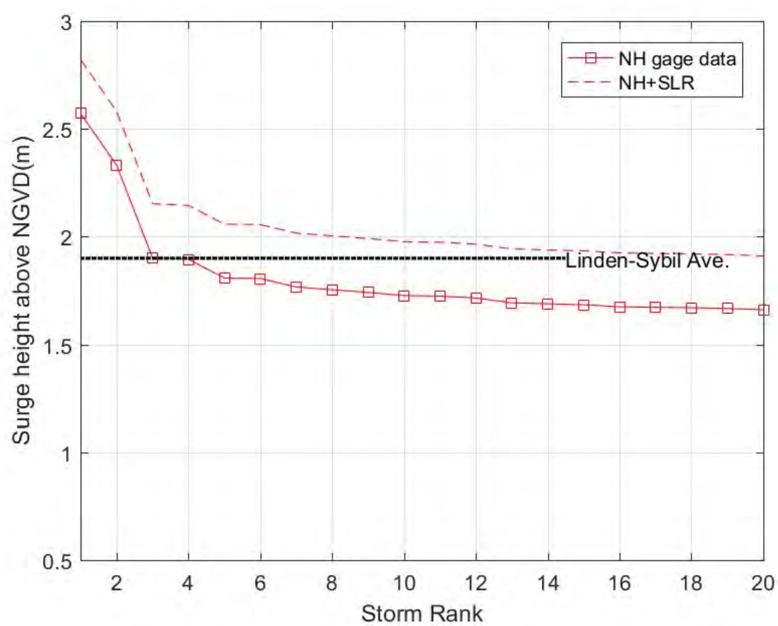

Figure 3. The red squares show the levels of the 20 highest water levels observed at New Haven since January 1999. The dashed black line shows the level 1.9 m, which is the elevation of the road surface at the bridge across Sybil Creek. The dashed line is the levels that the water levels would have reached of the means sea level was 0.25 m higher.

To more clearly show the extent of the area vulnerable to flooding now and in the future, at water levels of 1.9 m we show in Figure 9 (a) the topography of the study area again but with the 1.9 m contour indicated by the black line. The same line is shown in cyan in Figure 9 (b) on a GoogleEarth geo-rectified aerial photograph. It is evident that there are few buildings below the 1.9 m elevation in the area near the junction of Linden and Sybil Avenues. If the mean sea level was to increase by 0.25 m then the same risk of flooding would occur at the 2.15 m contour. This

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elevation is shown by the green lines in Figure 9 (a) and (b). The separation of the two contours is remarkably small and so the area subject to an increased risk of flooding is small.

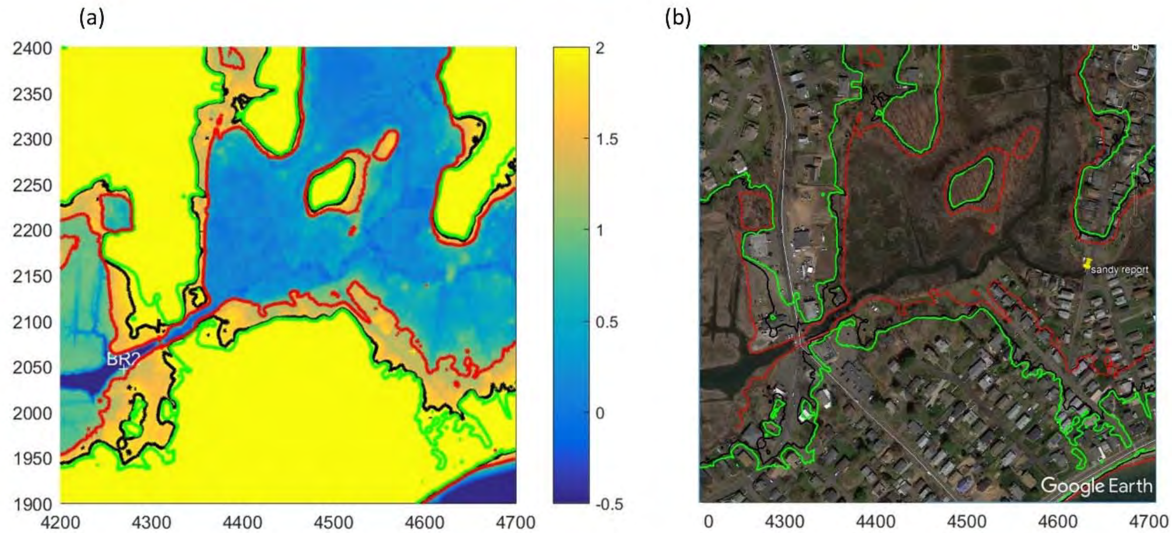

Figure 4 (a) Topography of the study area shown by the colors using the key on the right. The black line shows the 1.9 m contour and the green line shows the 2.15 m contour. (b) GoogleEarth display of the 1.9 m (black) and 2.15 m (green) contours in the study area overlaid on aerial photography. The red line shows the 1.1 m contour which was the maximum level reported during super storm Sandy at the location shown by the yellow pin.

When the water level exceeds 1.9 m at BR2, as it did during the two largest events shown in Figure 8, flow over Sybil Avenue into the large marsh complex to the east can occur. The volume transport into the marsh is largely determined by the elevation above the road, which determines both the vertical cross section and wetted perimeter of the flow. Since the surface extent of the marsh is large, the water level in the marsh and the flooding of the neighborhood in the low lying areas in the vicinity of Waverly Road, will be impacted by the duration of the high water level.

The latter show that the water levels at the bridge are almost equal to those reported at the NOAA tide gage at New Haven. The longer data record available there allows us to characterize the longer term variability of the water levels and to describe the vulnerability of the area to flooding by water from Long Island Sound. We show that in the last 17 years only two major hurricanes raised the water level above the road and two other storms were very close to the 1.9 m road level. However, the next biggest 16 peaks all caused water levels above 1.7 m so that an increase in mean sea level of just 0.25 m would lead to the road being flooded much more frequently. Since the slope of the topography at the 1.9 m level is relatively large in most of the study area, the 1.9 and 2.15 m contours are very close together. Consequently, the area of the study that is subject to an increase flooding risk is small. In addition to the increased frequency of closures of the Sybil Avenue Bridge, the main increase in flooding vulnerability will occur in the low lying areas near Waverly Road, when flow across the Sybil Avenue Bridge into the marsh to the east will occur more often.

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4. Wave Effects at Limewood Avenue (RT 146)

RT 146 in Branford has a short section, Limewood Avenue, that follows the shoreline of Long Island Sound before turning north where it changes name to Sybil Avenue. During super-storm Sandy, the waves that impacted the shoreline from Long Island Sound overtopped the road. The water on Limewood Avenue then flowed down Waverly Road into the marsh surrounding Sybil Creek. The water in the marsh largely is isolated form the Branford River, and Long Island Sound, by the tide-gate at the Sybil Avenue Bridge. Unfortunately there were no direct measurements of the wave characteristics during the storm or of the water levels in the marsh. However, the USGS post storm high water mark surveys did locate a station in the marsh, see (https://stn.wim.usgs.gov/STNPublicInfo/#/HWMPage?Site=19322&HWM=18220). This will be used as an assessment of the effectiveness of the model predictions.

Figure 10 shows the elevation and bathymetry of the region derived from the USGS (2017) digital elevation model. The dotted magenta line along the shore in Figure 10 show the location of RTK GPS elevation measurement along the Limewood Avenue and the solid white line shows the location of Waverly Road. The dashed line from Limewood Road to BR4 shows the location of the water depth section in Figure 11.

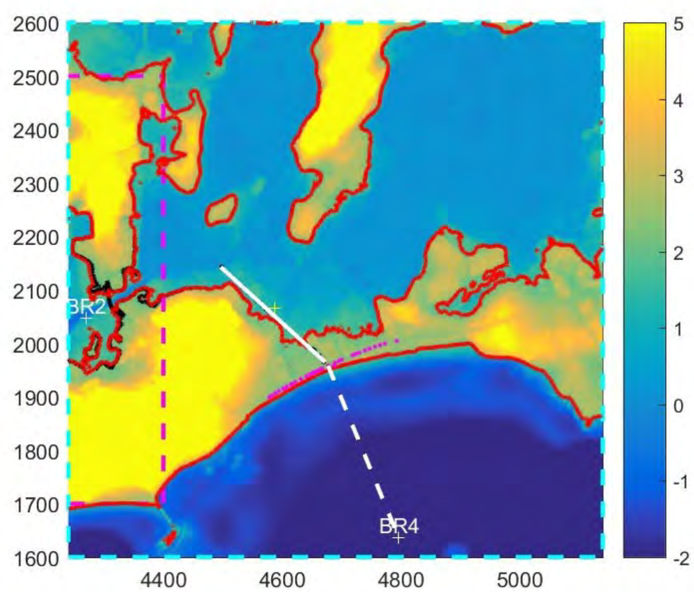

Figure 5. Topography of the Limewood Avenue –Waverly Road area. The color scale show the elevation in the range -2 to 5 m using the color scale on the right. The location of the water level and wave sensors at BR 4 is shown by the white + symbol. The magenta points lie on Limewood Avenue and the solid white line shows Waverly Road.

In Figure 11 (a) we show the water depth and land elevation along a line from BR4 to Limewood Avenue and then along Waverly Avenue. The black line shows the LIDAR estimates and the red + symbols show the RTK GPS measurements along Waverly Road. From the crest of the road to the -1 m level the topographic slope is steep (approximately 10%). Further from shore the slope reduces to 1%. Figure 10 (b) shows the elevation of the roadway at Limewood. The difference between the LIDAR and the RTK GPS estimates is approximately 0.1 m. This is likely due to the spatial averaging employed in the LIDAR processing and the slope of the road surface. The measurements agree that the road is at approximately 2.3 m elevation though slightly lower to the west of Waverly. This alongshore slope likely funneled the water that reaches the road from splash-over towards the junction of Waverly Road and Limewood Avenue.

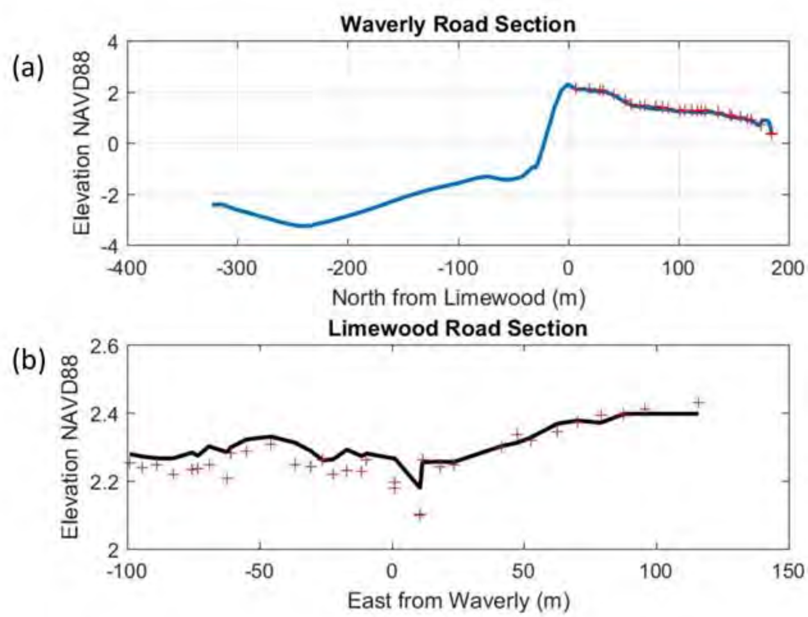

Figure 6. (a) The variation of water depth and land elevation along the dashed white line from BR4 to Limewood Avenue, and along the solid while line that shows Waverly Road in Figure 10. (b) The variation of elevation along Limewood Avenue. The zero of both graphs is at the junction of Limewood and Waverly. The red + symbols show measurements by RTKGPS

4. Wave Observations

We showed in Section 5, using measurements of water level, that the sea level at BR4 was almost the same as at the NOAA tide gage at New Haven. We also measured the amplitude, period and direction of high frequency surface gravity waves at BR4 which was located approximately 300 from the shore in water of 3 m depth. The observations are summarized in Figure 12 where (a) shows the significant wave height, (b) the period at the peak of the spectrum, and the direction of the peak period is shown in (c). The maximum significant wave height during the observation period was 0.6 m. During intervals when the wave heights were in excess of 0.3 m the period was between 4 and 5 seconds and the waves were propagating from the southwest (225 deg). Note that when wave heights were small, the direction was unstable.

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5. Wave Model Performance

Whether or not coastal flooding occurs on Limewood Avenue and Waverly Road is determined by the mean water level and the height and period of the storm driven waves. We have demonstrated in Section 5 that the water levels at Branford and New Haven are effectively the same. However, wave measurements close to shore in the area are limited and long records are only available at two buoys in the center of the Sound. To estimate the wave conditions during major storms we developed a mathematical model of the generation and propagation of waves in Long Island Sound and evaluated it with measurements at a variety of location. A summary of the project and results can be found at http://circa.uconn.edu/crest/wave-research/. The fundamental goal was to establish that the model adequately reproduced observations during major storm events at the buoy locations where data was available for 12 years. We then evaluated how well the model performed at several coastal sites where data had been acquired for several months. When the model was performing well in both tests we used it to generate statistics for waves that occurred at near shore location and published the results on the circa.uconn.edu web site. For this project we also tested the model at the BR4 site using the data shown in Figure 12.

A comparison of the model predictions to the observations at BR4 is provided in Figure 13. The black lines in Figure 13 (a) and (b) show the model significant wave height and the peak period, respectively, and the blue points show the observations. The root mean square error for the December 2016 simulation was 0.87 s for the dominant period, and 0.21 m for the significant wave height. The correlations were both very high as is evident in the figures. The significant wave height was biased low as we have found to be the case at other sites when the wind and waves were in the moderate range, however, at higher wind speeds the bias is less.

To summarize the wave amplitudes and periods that may be expected during severe storms, we simulated 20 storms with the high winds speeds. We used the wind speed data to rank the storms and constructed the return interval diagram shown in Figure 14 using the rank of the wind speed used in the model forcing for the return interval. Table 2 lists the maximum significant wave heights dominant periods in the simulations. The largest significant wave height occurred during Hurricane Carol in 1954 which produced a significant wave height of 3.84 m. Since the waves generated in Long Island Sound are generally fetch limited, the amplitude and period are correlated. Our simulation of super storm Sandy in 2012 was produced maximum significant wave heights near BR4 of 1.89 m with a dominant period of 7.4 s. Figure 14 suggests that the probability of exceeding this significant wave height value in any year is approximately 1/7.

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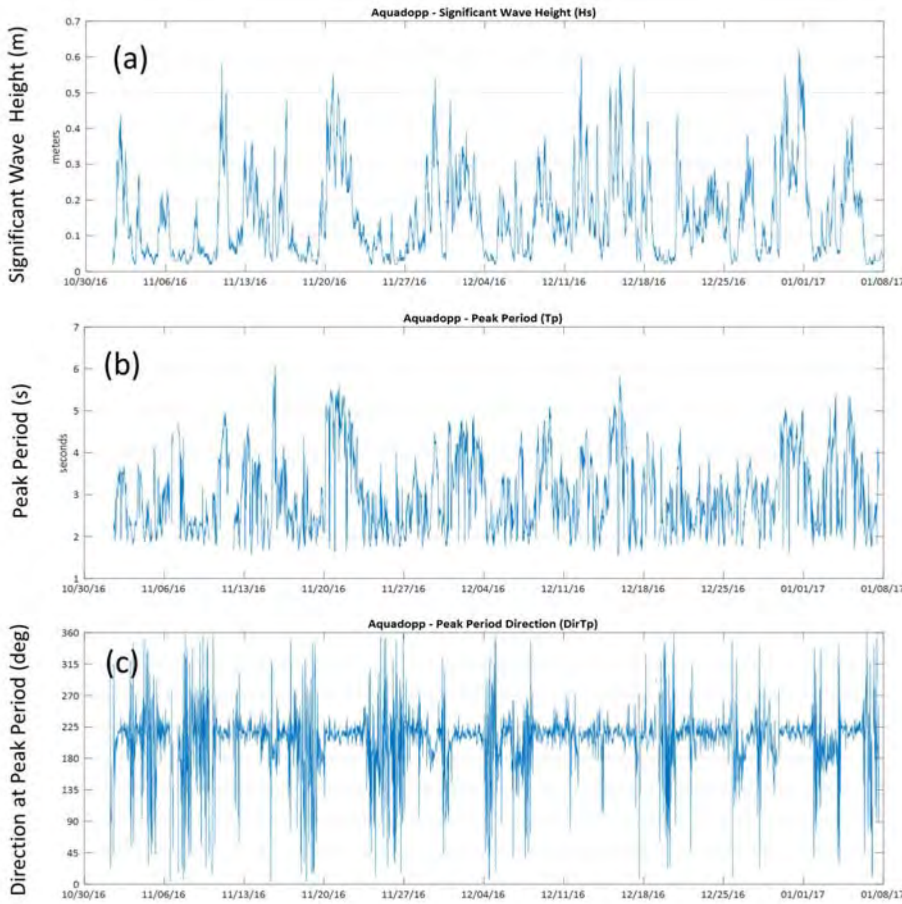

Figure 7. Wave observations at BR4 from October 30, 2016 to January 8th, 2017. (a) shows the significant wave height (m), (b) the peak wave periods (s) and (c) shows the direction (degs.) the waves at the peak period were traveling from.

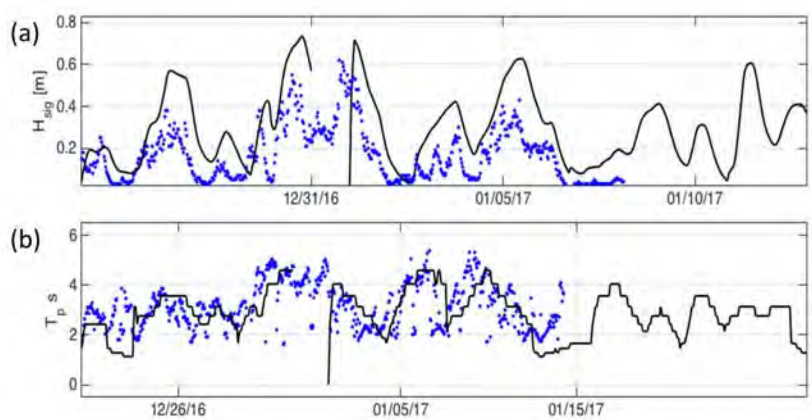

Figure 13. Results of the simulation of the (a) significant wave height at BR4 and (b) the peak wave period.

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Table 2. Results of the simulations of significant wave height, H_s and dominant period T_p near Branford, CT.

Year	[m]	T_p [s]
1985	3.84	8.83
1954	2.38	9.67
2012	1.89	7.37
2011	1.45	6.73
2017	1.41	6.75
2008	1.31	4.68
2014	1.21	5.92
2006	1.06	5.12
1991	0.93	4.61
2015	0.76	5.61
1978	0.75	5.61
2013	0.62	4.27
2007	0.61	4.05
2005	0.59	4.05
2016	0.51	2.26
2003	0.48	4.05
2009	0.41	3.56
2011	0.37	4.68

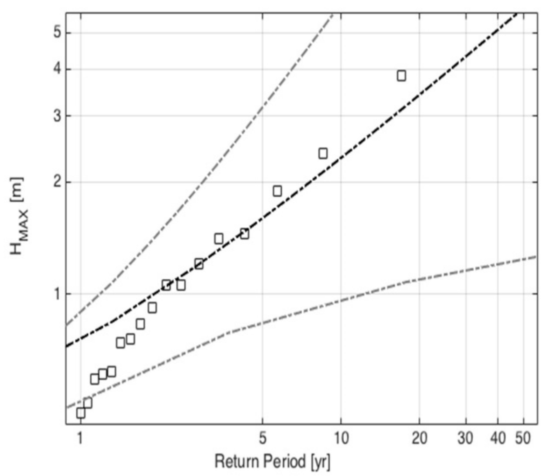

Figure 8. Return period of significant wave heights Branford, CT. The dashed black line corresponds to the best-fit GEV function and the grey dashed lines mark the 95% confidence interval. The black squares show the maximum significant wave height (m) in the simulations at the site.

6. Overtopping

To link the water level and wave predictions to road flooding, a model must be formulated. The EurOtop II report (Van der Meer et al., 2016) provides a comprehensive summary of the empirical relationships that have been established to quantitatively estimate the volume flow rate over a coastal embankment due to both splash-over from waves (Q_{SO}), and the over-bank flow (Q_{OF}) that occurs when the mean water level exceeds the level of the crest of the structure. Figure 10 (a) shows the water depth and elevation profile offshore of Limewood Avenue. To

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apply the results of the EurOtop II approach we approximate this geometry as shown in Figure 15. Using the data shown in Figure 10 (a) we take the slope of the bottom near the road as $s = tan\,\alpha = 0.1$. We also define the elevation of the road surface relative to the mean water level, R_c in the schematic, as the difference between the water level measured at New Haven and the elevation of the low region of Limewood Avenue which Figure 10 (b) shows is 2.3 m.

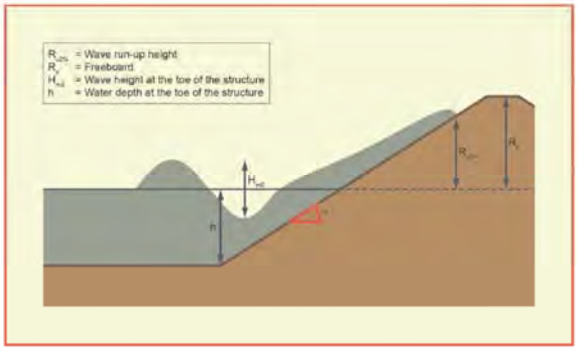

Figure 9. Schematic of an idealized coastal dyke or embankment defined in the EurOtop II report (Van der Meer et al., 2016). The

During super storm Sandy the mean water level exceeded the level of the Limewood Avenue, implying $R_c < 0$, and when that happened seawater flowed directly from the Sound across the road and then down Waverly Road. Following the empirical work of Hughes and Nadal (2009), the EurOtop II report recommends the volume flux per meter of shorefront of the over-bank flow be estimated by a version of the weir formula (White, 2003)

$$Q_{OF} = 0.54\sqrt{g|R_c^3|}$$

where $g = 9.81$ m/s^2 is the acceleration of gravity. Before, during, and after the peak water level, wave splash-over was likely delivering sea water onto the road as well. The volume flux per meter of shorefront can be estimated by the EurOtop II over-topping formula

$$Q_{SO} = \sqrt{gH_0^3}\; a\, exp\left\{-\left\{b\frac{R_c}{H_0}\right\}^c\right\}$$

where H_0 is the spectral significant wave height and the empirical constants are: $c = 1.3$, $a = \frac{0.023}{s}\gamma_b\zeta_p$, and $b = 2.7/\zeta_p\,\gamma_b\gamma_f\gamma_\beta\gamma_V$ where s represents the bottom slope at the coast, $\zeta_p = s/\sqrt{H_0/\frac{gT_0^2}{2\pi}}$ is $the\ Iribarren\ Number$, T_0 is the spectral peak period, and the four parameters $\gamma_{f,b,\beta,V} \cong 1$, are factors that can be used to account for the effects of rough bottom, the presence of a berm, wave propagation direction, and vertical sea walls at the road. Note the upper bound on the splash-over flux uses $a = 0.09$ and $b = 1.5/\gamma_f\gamma_\beta\gamma^*$ where $\gamma^*$is used to account for additional geometric effects. We assume the γ coefficients are 1 at the moment to estimate the upper bound on the flux.

Figure 16 (a) shows the water level measurements from the tide gage at New Haven during super storm Sandy with the level of the Limewood Avenue road surface near the Waverly Road

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intersection shown by the thick dashed black line. It is clear from comparison of the levels of the water and road that the mean (averaged over many wave periods) water level was above the road for several hours. There is uncertainty inherent in this analysis since the water levels at Limewood Road and New Haven are not exactly the same. Wave conditions are likely to be different and, consequently, the wave induced mean set-up is different. The magnitude of the error is likely to be 10 to 20% of the difference in the significant wave heights at the two locations and in the range of 0.1 to 0.2 m. The green and red lines in Figure 16 (A) show the water level ± 0.15 m to illustrate our estimate of the uncertainty in the water level.

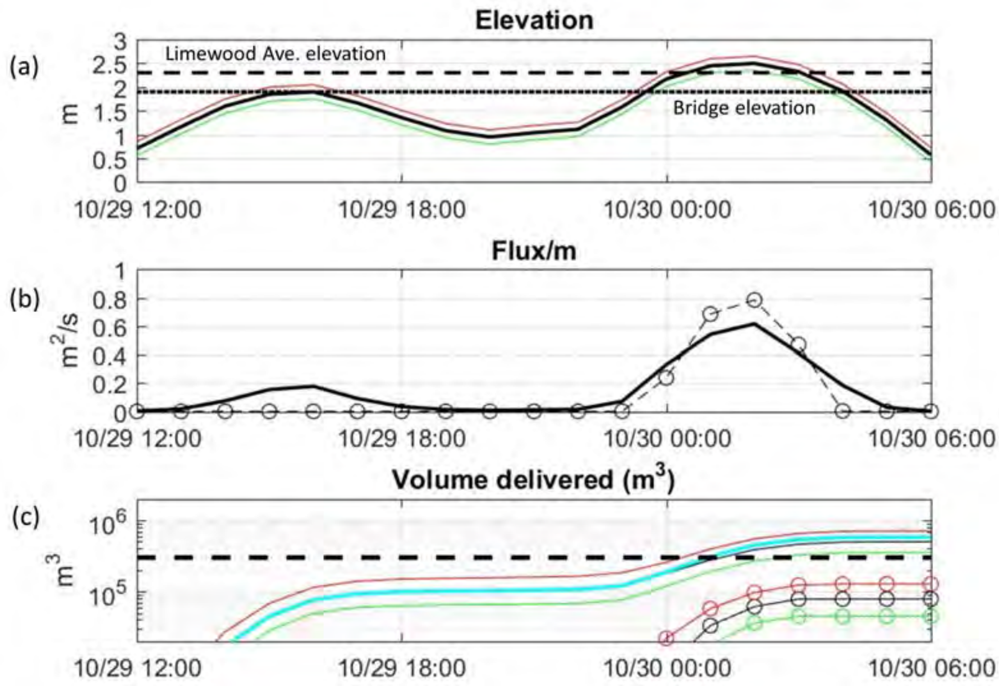

Figure 10. (a) The evolution of the water level at New Haven during super storm Sandy is shown by the solid black line and the level of Limewood Avenue is shown by the thick black dashed line. The red and green lines show the 0.3 m interval surrounding the measured value to represent the uncertainty interval. The dotted black line show the level of the top of the bridge at Sybil Avenue. (b) The thick black line show the estimate of the water flux per meter of shore front (m^2/s) due to both splash over and over-bank flow at Limewood Avenue. The dashed line with circles shows the estimate of the flow over the road at Sybil Avenue. (c) The thin black line and the line with black circles show the accumulated volume (m^3) of seawater delivered into the marsh surrounding Sybil Creek by the flow over Limewood Avenue and Sybil Avenue respectively. The red and green lines show the volumes computed with the higher and lower water level bounds. The thick cyan lines shows the sum of the volume from both sources. The thick dashed line shows our estimate of the volume accumulated in the marsh based on the USGS water level report.

The fluxes on to the road computed using the EurOtop II over-topping formula during super storm Sandy are shown in Figure 16 (b) by the solid black line. During the first high tide the peak flux per meter of shore front was 0.2 m^2/s and at the second peak was 0.6 m^2/s. These are very large fluxes. Van der Meer et al. (2010) suggested upper bounds on allowable limits for low speed vehicles on a road along a well-drained dike of 0.05 m^2/s.

Roads are generally capable of draining with rain rates of several inches per hour. If the extent of Limewood Avenue where the flooding was occurring was 200 m, then the volume flux would be 120 m^3/s. For this to be delivered to a 5 m wide road by rainfall, then the rate would 17,000 inches per hour. Even flux values as small as 3.5×10^{-4} m^2/s (10 inches/hour in the example) would lead to significant road flooding.

There are no direct water level measurements with which we can test the accuracy of these estimates. However, the U.S. Geological Survey (2017) surveyed the levels of high water marks in the area impacted by super storm Sandy and one site was located in the marsh drained by Sybil Creek. The location is shown by the yellow push-pin symbol in Figure 17 (a). The elevation recorded was 1.1 m relative to the NAVD88 datum. To estimate the volume of sea water required to fill the marsh complex to that level, we assumed that the surface was uniform across the marsh complex and processed the USGS LIDAR data in the same manner as in Section 2. The results are shown in Figure 19 (b).

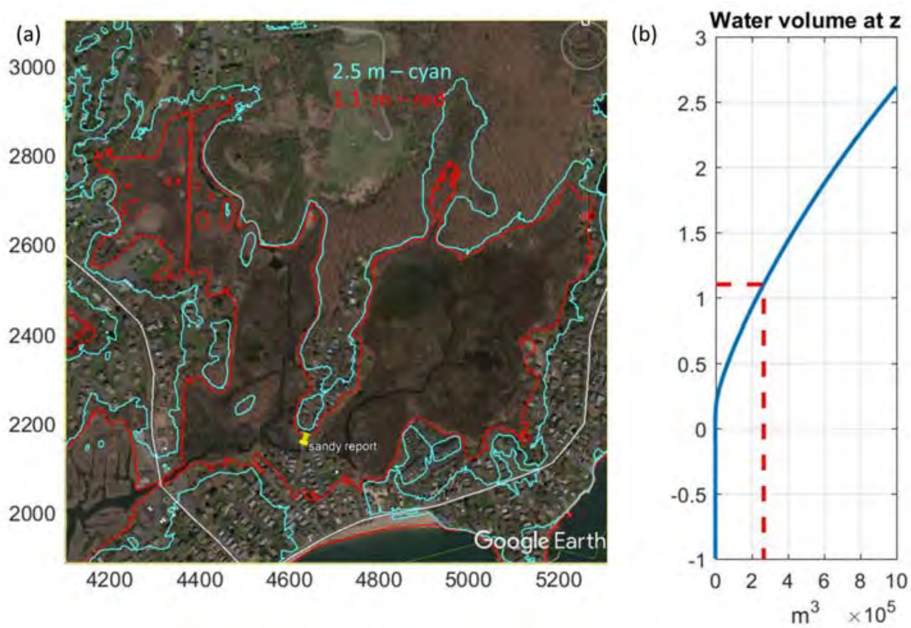

Figure 17. (a) A GoogleEarth map with the location of the USGS high water mark (site CTNEW19322) shown by the yellow push-pin. The 1.1 and 2.5 m elevation contours are shown by the red and cyan lines respectively. The volume required to fill the basin to the 1.1 m elevation is shown in (b).

Figure 16 (c) shows the total volume that would be accumulated in the marsh (horizontal axis) as a function of the water depth. To fill the marsh to 1.1 m would require 2.7×10^5 m^3 of sea water. This water may have come over the tide-gate and bridge at Sybil Avenue as well as over Limewood Avenue. The level of the road surface at the bridge (1.9 m) is shown in Figure 16 (a) by the black dotted line. In Figure 16 (b) we show an estimate of the volume flux per meter to bridge width using the same weir formula as at Limewood Avenue using the water elevation minus 1.9 m as water layer thickness. We neglect splash over since the waves in the Branford River are unlikely to be significant. Since the water level didn't exceed the bridge level in the first high tide during the storm the flow was zero. However, during the second high water the flow per unit width into the marsh from the Branford River was comparable to that at the beach.

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To compare the contributions to the volume in the marsh we integrated the fluxes from both sources, the curves in Figure 16 (b), in time and assumed the flow across the beach occurred in a 50m wide swath and that the width for the flow across the bridge was 10m. In Figure 16 (c) we show the sum of the two volumes as the broad cyan line and the black line, and the black line with circles show the contributions form Limewood Avenue and the Sybil Avenue bridge. The latter is 16% of the flow over the beach.

The sum of the two fluxes is greater than the volume accumulated in the marsh as estimated from the USGS water level measurement. The ratio of the two values is 1.77. The red and the green lines in the Figure 16 (c) show the estimates of the volume transported into the marsh using the EurOtop II formulae but with ± 0.15 m added to the sea level observations. The lower value is 30 % larger than the estimate based on the high water mark and marsh geometry. Since we have assumed that the waves were approaching the beach from a normal angle, that the dissipation factors in the overtopping formula were unity, and that the wave height was at the maximum value for the entire storm, a high bias in our estimate is to be expected. Laudier et al. (2011) used a similar approach to calibrating the splash-over formula at a natural beach and found that the product of the γ coefficients in the range 0.64 to 0.72 produced estimates consistent with their observations. It is possible to refine this model further by carefully assessing the geometry and using the time evolution of the wave height from out model, however, the conclusions that a principle factor in the flooding of Sybil Creek marsh was the splash-over at Limewood Avenue, and that the risk of road flooding there can be usefully estimated by a simple model, are unlikely to change.

7. Analysis.

Using the link we have established between the water levels at Limewood and New Haven, then Figure 50 suggests that the mean water level has only exceeded the level of the road (2.3 m) once, during super storm Sandy, which created the highest storm surge in the available 18 year record. At the New London tide gage where the data record spans 80 years, super storm Sandy created the third highest water level. This suggest that at current mean sea level, flooding like that experienced in super storm Sandy has an annual probability in the range of 4% to 6%, or equivalently, a return interval in the range 18 to 26 years.

The risk of flooding on Limewood Avenue is much higher because of wave driven splash-over. The magnitude of the splash-over sea water volume flux is determined by the vertical distance between the mean water surface and the road level, the slope of the beach, and the significant wave height and period. Since the mean water level and significant wave height jointly determine the extent of flooding at Limewood Road, and around the Sybil Creek marsh, quantifying the risk requires estimation of the joint probability distribution. Since both waves and sea level are largely driven by wind the fluctuations are not independent. Estimation of the most appropriate probability distribution function requires further study.

The EurOtop II model can provide guidance on the range of conditions that will lead to significant flooding at Limewood Road. In Figure 18 we plot the estimated flux to Limewood Road per meter of shore front as a function of the sea level (the average over many waves) for a

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range of wave conditions. For these illustrative examples we use $\gamma_f = 0.65$ in the EurOtop II formula, a value in the range suggested by the results of Laudier et al. (2011). Example peak wave periods between 4 and 9 seconds were prescribed and the results of the model simulations listed in Table 2 were used to estimate the significant wave height associated with each period. The values are listed in the left of Figure 18. Three flux thresholds are indicated by the horizontal red lines. The lower (dotted) line shows 3.5×10^{-4} m^2/s which is the equivalent water flux to a 5m wide road at a rainfall rate of 10 inches per hour. This would overwhelm the drainage capacity on most roads and result in water accumulation. An over-topping flux that is one tenth smaller (3.5×10^{-5}) would be equivalent to a one inch per hour rainfall rate, a high, but not uncommon, rate in Connecticut. Van der Meer et al. (2010) suggested that vehicles on a highway along a coastal dyke with effective drainage would be in jeopardy for overtopping fluxes in the range 10 to 50 $\times$ 10^{-3} m^3/s. The upper end of the range is shown by the red dashed line in Figure 18. The maximum value that is estimated to have occurred at Limewood Road during super storm Sandy is shown by the red dot-dashed line.

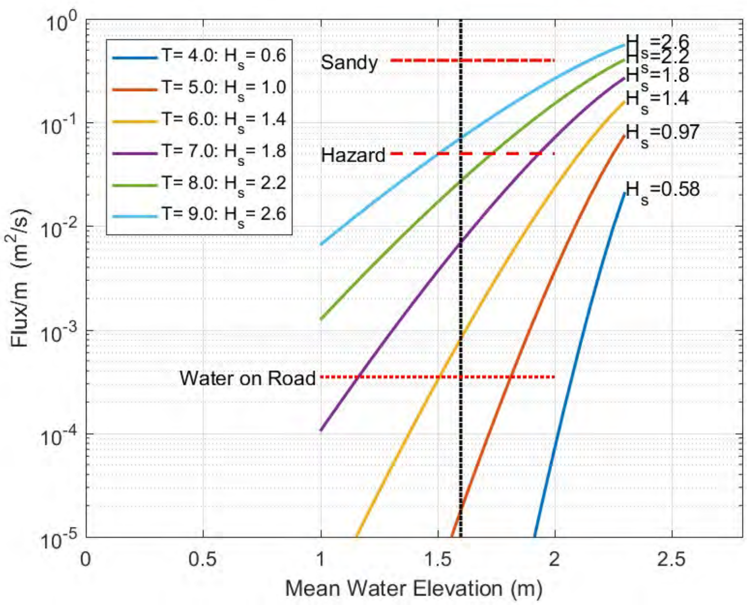

Figure 11. The over-topping flux predicted at Limewood Road as a function on water elevation for 6 different wave conditions that span the range predicted in Figure 7. The red horizontal lines show values that result in significant impacts. The red dotted line is the rate that would be equivalent to equivalent to a 10 inch/hour rainfall rate on a 5 m wide road. The red dashed line shows 0.05 m^2/s which would pose difficulty for vehicles according to Van der Meer et al. (2010), and the red dot-dash line show the level that is estimated during super storm Sandy.

High tide at Branford is approximately 1 m and the purple line in Figure 18 shows that we should expect substantial road flooding at high tide when the significant wave height is between 1.8 and 2.2 m (the purple and green curves). Figure 14 suggests that the probability of waves exceeding the higher range is only 1/7 per year but the lower level is more likely with an annual probability of 1/2. The black dotted vertical line shows the 1.6 m water elevation which, as Figure 8 shows, is characteristic of the highest water level at Branford each year. The orange line in Figure 18 show that when the water level is at 1.6 m, a significant wave height in excess of 1.4 m will

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result in significant water on the road surface. The figure also shows that a significant wave height of 1 m would produce a water flux comparable to a 1 inch per hour rain storm. The green and cyan lines show that the waves would need to be in excess of the conditions during super storm Sandy (1.9 m) for the vehicle hazard level to be exceeded during a “normal” storm.

The dependence of the overtopping fluxes on the wave conditions near high tide and in typical storm (one that should be expected each year) is demonstrated in Figure 19 (a) and (b), respectively. The intersection of the solid black curve and the red dotted line shows again that at high tide a 1.845 m significant wave height will result in severe road flooding. The intersections of the red dotted line with the black dashed, and dot-dashed lines are to the left indicating that at higher water levels, lower wave elevations (1.57 and 1.37 m) are required for splash-over to result in severe flooding. Figure 14 shows that the probability of waves in excess of 2 m is approximately 1/6.5 and that for 1.73 and 1.37 m are 1/4.8 and 1/38. It is plausible that by 2050 or 2100, the mean sea level could increase by 0.25 or 0.5 m. Assuming storm and wave statistics don’t change much over that time, then these relatively small changes in level would increase the risk of severe road flooding at high tide by approximately 134% to 172%.

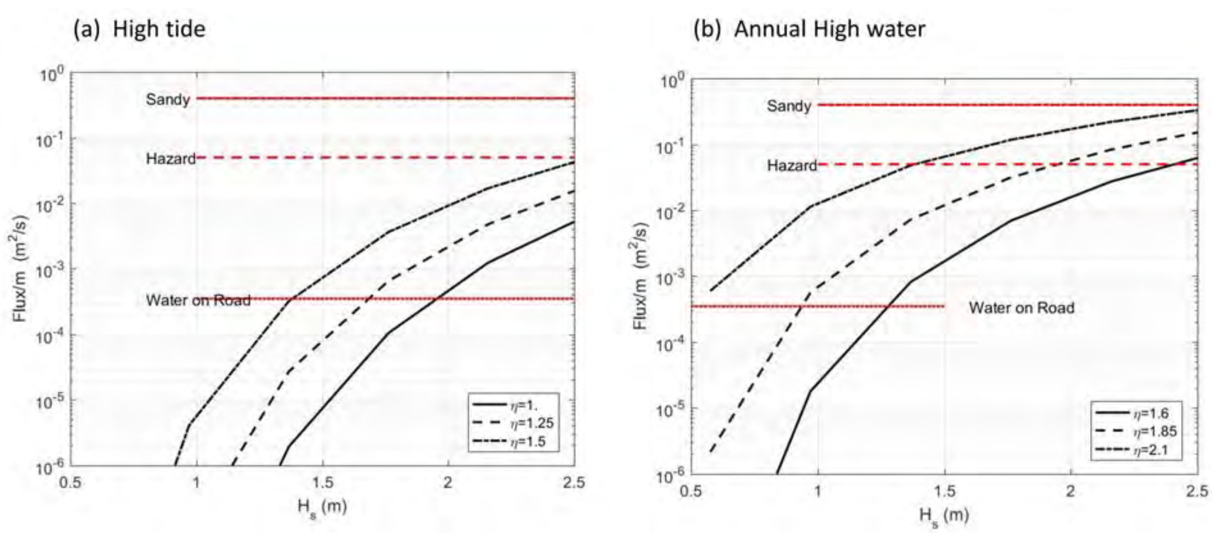

Figure 12. (a) The dependence of the over-topping flux on the significant wave height (and period) at a typical high tide ($\eta = 1$ m) is shown by the solid black line. The variation at .25 and 0.5 m higher levels are shown by the dashed and dot-dashed lines respectively. The variation during high tide in a storm ($\eta = 1.6$) is shown in (b), where again the 0.25 and 0.5 m higher levels are shown by the dashed lines.

A similar analysis for the potential for severe flooding during high tide during normal storms can be developed using Figure 19 (b). At a sea level of 1.6 m (solid black curve) a significant wave height of 2.36 m leads to hazard level (red dashed line) flooding, however at 1.85 m and 2.1 m, significant wave heights of 1.90 and 1.38 m will have the same consequences. Note that the effect of the 0.25 and 0.5 m sea level change has a large impact on the change in wave height required to have the same flooding consequences at higher water levels because the first derivatives of the curves decrease at higher water levels and higher wave heights (they are flatter

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on the right side of the graphs). The wave statistics in Figure 56 imply that the 2.36 m significant wave height has a probability of exceedance of 1/10.2 and that the smaller wave heights have probabilities of 1/6.9 and 1/2.7 respectively. Consequently, the increase in risk of hazard level flooding for .25 m and 0.5 m increases in sea level are 148% and 267%.

It is worthy of note that the substantial increase in risk predicted by the analysis is mainly due to two factors: the dependence of the over-topping flux on the water to road elevation separation, and the exponential shape of the wave exceedance diagram (Figure 56). Though the values reported above are estimates that are based on available data and models have uncertainty associated with them, the most important result (the substantial increase in the risk of flooding associated with small changes in mean sea level) are robust.

To evaluate the consequences of the combined effects of mean sea level changes on the flooding of the area around the Sybil Creek marsh, see Figure 19 (a), we repeated the calculations that led to Figure 15 but incrementally increased the mean sea level from 0 to 0.5 m in 0.05 m increments. We assumed that the sea level at New Haven was 0.15 m higher that Branford during the storm, and used a value of $\gamma_f = 0.65$ in the EurOtop II formula in to make the model predictions more consistent with observations. We did not allow the significant wave height to evolve through the storm. We converted the predicted volume in the marsh using the relationship between volume and elevation computed from the LIDAR based topography and shown in Figure 17 (b). The black solid line in Figure 20 (b) shows the elevation in the marsh at the end of the simulated storm or when the elevation reached 2.5 m. At that catastrophic level the model of the flow into the marsh is not as reliable.

In Figure 20 (a) the green contour shows the 1.1 m contour which is the level of the high water mark surveyed and reported by the USGS (2017) in the Sybil Creek marsh to the east of the Sybil Avenue (RT 146) bridge and tide-gate. The blue line shows the 2.5 m level. This is a good estimate of the high water level during super storm Sandy. The area between the blue contour (2.5 m) and the red contour (1.1 m) were protected from flooding during super storm Sandy by the presence of the Sybil Creek marsh, the berm carrying Limewood Avenue (RT 146) and the tide-gate. The black line in Figure 20 (b) shows how a rise in the mean sea level will influence the maximum water level in in the area surrounding the marsh. A 0.28 m increase in the sea level is predicted to increase the high water level from 1.1 to 1.9 m and reduce the range of the elevations protected from flooding. The 1.9 m contour is shown in green in Figure 19 (a). Note that the .28 m increase in mean sea level leads to the high water level in the marsh areas increasing by 0.8m, a factor of 2.85 larger. This is rapid erosion of the flood protection value by rising sea level continues until at 0.42 m the high water level would reach 2.5 m. Worse still, areas that are between 2.5 and 2.92 m elevation would then be vulnerable to flooding.

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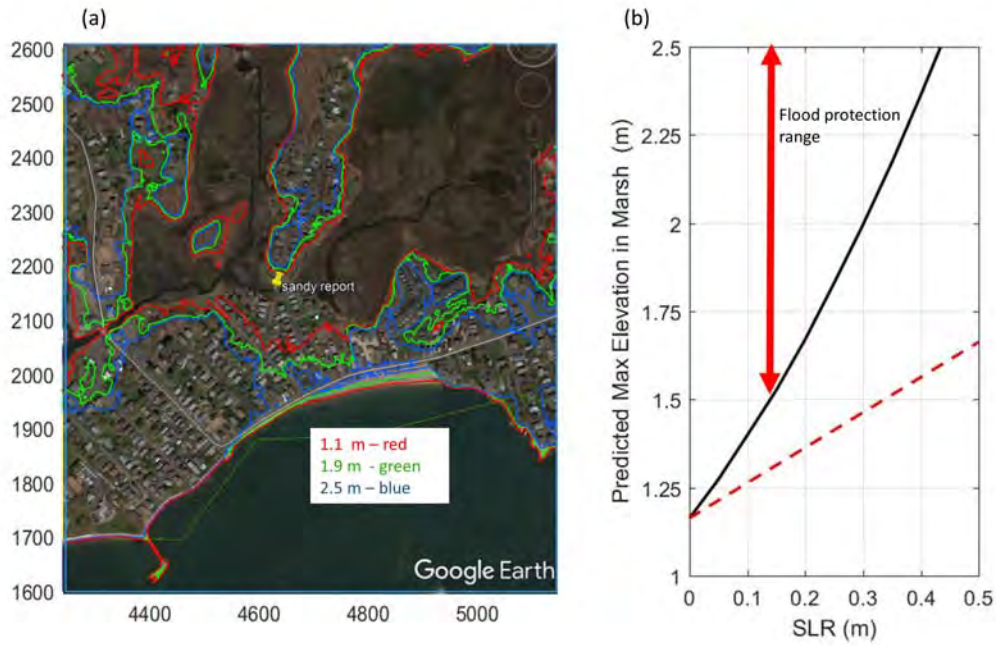

Figure 13. (a) A GoogleEarth map of the coastal area near Limewood Avenue. The white line show the location of RT 146 and the red, green and blue lines show the 1.1 m 1.9, and 2.5 m elevation contours. (b) The black solid line shows the elevation in the marsh that corresponds to the maximum predicted volume transported into the marsh. The red dashed line shows the change in sea level in the marsh if it was just do to sea level rise.

8. Summary

We have described the geography of the area of Branford between Limewood Avenue and the marsh surrounding Sybil Creek that is susceptible to coastal flooding. Using a combination of simple models of wave driven transport over the beach at Limewood, and the bridge at Sybil Avenue, we conclude that most of the flooding around the marsh during super storm Sandy was due to flow over the beach. Without an estimate of the joint probability of wave heights and sea level it is not possible to estimate the risk of future flooding adequately. This should be addressed in the future. However, the model allows us to assess what conditions would likely lead to flooding. At normal high tide levels, significant wave heights in the range of 1.37 to 1.57 m will lead to significant flooding on Limewood Avenue. During severe storm the high tide level increases to 1.6 m and significant wave heights in the range 1.0 to 1.5m will lead to substantial road flooding.

The models we developed also allow us to estimate the effects of sea level rise on the change in the risk of flooding in the area surrounding the Sybil Creek Marsh. It is clear that the land and properties are protected from high water by the tide gate and bridge at Sybil Creek, and by the berm that carries Limewood Avenue along the coast. When the water level in the Sound was 2.5 m during super storm Sandy, the water level in the marsh was only 1.1 m. Our model results show that an increase in sea level of 0.25 m allows flooding to 1.9 m, an increase of 0.8 m, and

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shrinks the width of the flood protection zone from 1.4 m to 0.6 m. This rapid loss of flood risk protection is a robust characteristic of the model, especially at low sea level change values where the model is most reliable. The same analysis has the more positive result that small increases in the elevation of Limewood Avenue would reduce the flood risk considerably.

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Simulation and Observation of Wind driven Waves in a Fetch-Limited Urban Estuary: Long Island Sound

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Abstract

We have evaluated the wave module of a hydrodynamic-wave coupled numerical model inside an urban estuary. We performed four numerical experiments using different forcing scenarios in order to test the ability of the model to capture the wave field statistics inside the estuary. The geometry of the estuary renders the wave field fetch limited and leads to marked difference between western and eastern areas. We were able to capture the local wave statistics after tuning the wave growth and breaking spectral parameterizations. This allowed the model to differentiate stages of wave development and better capture wave statistics inside the estuary. Although modifications were linked to a bias high relative to the buoy observations under weak and fetch limited circumstances we deemed the modifications necessary for moderate to strong forcing. Finally, the last numerical experiment was forced with Superstorm Sandy 2012, considered an extreme weather event for the region. For this simulation we also tested different bottom boundary closure schemes for a hydrodynamic-wave coupled simulation; a classic log-layer and a wave perturbed bottom boundary (Madsen 1994). The fully coupled simulation was able to capture the maximum values of significant wave height and period recorded at the Western and Central locations of the estuary.

1. Introduction

The non-negligible interaction between waves and currents at different time, frequency and spatial scales, has driven the ocean modeling community to incorporate wave dynamics into hydrodynamic ocean models. Studies have ranged from exploring global wave effects to the ocean mixed layer (e.g. Belcher et al. 2012) down to local impacts on circulation at coastal environments (e.g. Davies and Lawrence 1995; Xie et al. 2008). Relevant wave induced effects include modification of the surface stress (e.g. Donelan et al. 1993; Drennan et al. 2003), injection of Turbulent Kinetic Energy into the ocean surface layer by wave breaking (e.g. Terray et al. 1996;Drennan et al. 1996; Scully et al. 2016) and wave driven Langmuir turbulence, which ultimately alters the mixed layer depth (e.g. Sullivan et al. 2007; Belcher et al. 2012; Kukulka and Brunner 2012) potentially having a substantial impact on air-sea interaction. Furthermore, the presence of waves adds momentum to the water column via radiation stresses (e.g. Mellor 2003 and 2005). Finally bottom interaction between currents (low frequency) and orbital velocities (high frequency) and the subsequent wave induced enhancement of bottom drag (e.g. Grant and Madsen 1984) with direct consequences to the currents structure.

To account for these effects, classic hydrodynamic models such as the Princeton Ocean Model (POM), the Regional Ocean Modeling System (ROMS), and the Advanced Circulation (ADCIRC) model have been coupled with wave models such as Wave Watch III (WWIII) and Simulating Waves Near Shore (SWAN). To date, most efforts to incorporate these effects into numerical models have been mainly purely scientific in nature; however, there is considerable relevance to coastal communities, municipalities and coastal cities in the advancement of hydrodynamic-wave coupled models. For example, understanding wave-current interaction in coastal environments aids in the prediction of storm impacts (e.g. flooding risk and structural damage), particularly with a changing climate, and can inform future mitigation and adaptation efforts. This is one of the reasons why modeling efforts are being targeted to capture and evaluate the coupled effects between storm surge and surface gravity waves under severe forcing (e.g. Xie et al. 2007; Bunya et al. 2009; Roland et al. 2009; Chen et al. 2011; Dietrich et al.2011) and the implications on flooding at coastal areas and the consequences with a rising sea level. For example, modeling results indicate that waves can increase water levels by 5-20% depending on the local bathymetry (e.g. Sheng et al. 2004; Fukanoshi et al. 2008; Dietrich et al. 2010), with enhancements of 35% in regions with a steep slope (Dietrich et al. 2010). Furthermore, wave-induced effects can account for up to 30% of the peak storm surge (e.g. Sheng et al. 2004) where hydrodynamic-wave coupled simulations by Xie et al. (2008) suggested a strong wave-induced effect on the overall flooding area, with the most dramatic effects observed in the shallow water river estuaries of the Charleston Harbor, SC.

Therefore, we have conducted an evaluation of the wave module in the Finite Volume Community Ocean Model, hereafter FVCOM (Chen et al. 2006; Huang et al. 2008; Chen et al. 2008; Chen et al. 2011). The FVCOM model is currently being implemented in a small urban estuary, Long Island Sound (LIS) (Fig. 1), to quantify the response of the system to severe weather events in a changing climate. FVCOM uses a 3-D unstructured grid, free-surface and primitive equations to calculate hydrodynamics. FVCOM was coupled with the SWAVE wave module (Qi et al. 2009), which uses an unstructured finite version of the Simulating Waves Nearshore (SWAN; the Delft University of Technology), to resolve smaller coastal scales, where shallow water processes predominate. The hydrodynamics and waves are coupled via radiation stresses, bottom boundary layer, and surface stress (e.g., Wu et al., 2011). The work presented here summarizes the evaluation of the modeled wave statistics for a range of forcing conditions (e.g., $5 < U_{10} < 26$ m s^{-1}, with and without fetch limitation) in order to check the model's capacity to recreate observed and previously documented wave dynamics inside the estuary under fully hydrodynamic-wave coupled runs. Fetch limitation, strong tidal currents, a complex bathymetry and fragmented coastline, features common among estuaries and to LIS in particular; produce a large range of deep to shallow water dynamics. To our knowledge this is the first effort to implement and validate a fully coupled high-resolution hydrodynamic-wave model in LIS. Finally, the model simulations were compared and analyzed relative to observations in an effort to shed some light on wave dynamics across the estuary.

1.1 General circulation and winds in LIS

The LIS is a tidally driven estuary, where the sea surface displacement on the adjacent continental shelf is responsible for the observed barotropic driving force impacting the general circulation. The strong tides inside LIS are resonant with the M_2 tidal constituent, with the strongest tidal currents located in the eastern section of the estuary (i.e. at the mouth of LIS). In this area, tidal axes are oriented across sound at the surface with an along isobath direction near bottom (Bennett et al. 2010; O'Donnell et al. 2014). As an estuary, the LIS does receive fresh water input, although a large fraction of fresh water discharge happens close to the mouth of the estuary via the Connecticut River. This renders the LIS unusual relative to other estuaries. The main source of fresh water is the Connecticut River (Fig. 1), with a contribution of 75% of the total gauged flux (e.g. Gay et al., 2004). The wind forcing over the estuary exhibits a marked periodicity with consistent seasonal variability, both in wind magnitude and direction (e.g. Isemer and Hasse 1985, O'Donnell et al. 2014). Studies have focused on wind measurements collected at the Western, Central and Eastern areas (WLIS, CLIS and ELIS metocean buoy stations) to explore wind and stress distributions in the LIS. Data shows wind stresses pointing to the northeast during summer and southeast during winter, with an overall stronger forcing during the winter months (e.g. Klink 1999; Lentz 2008). Annual means of stresses are dominated by the winter months and the CLIS and WLIS are significantly different with annual means of 0.026 N m^{-2} and 0.012 N m^{-2} respectively (O'Donnell et al. 2014). The seasonality and strength of the wind forcing has direct implications on surface currents and wave generation, where the directionality of the forcing plays into the fetch limitation of the system (Fig.2).

1.2 Oceanographic observations for the validation exercises

We relied on the metocean buoy stations at the Western and Central LIS (lisicos.uconn.edu) for wave statistics inside the LIS, which are maintained and operated by the University of Connecticut. Both of these buoys are equipped with met packages from R.M. Young and include wind speed and direction, air temperature, barometric pressure, and relative humidity. The Central Sound buoy is equipped with a directional wave sensor manufactured by Axys Technologies sampling every 30 minutes for 22 minutes at 4 Hz. A non-directional wave module by Neptune Sciences is installed on the Western Sound buoy, sampling every 30 minutes for 17 minutes at 2 Hz.

We also relied on a wave observations at the Block Island Sound (BLIS) region which were collected with an upward looking 600 KHz RDI Teledyne Acoustic Doppler Current Profiler. The sampling frequency was set at 1 Hz with a burst duration of 20 minutes occurring every 30 minutes. The instrument provided measurements of the frequency and direction for surface gravity spectra based on the surface pressure measurements. This signal was partially processed with the proprietary RDI software WavesMon.

2. The FVCOM-SWAVE Numerical Model

The model was forced at the open boundary with eight harmonic tidal components for the region (e.g. Foreman 1978), which were tuned based on observations inside the estuary (i.e. New London, Bridgeport and New Haven tide gauges) Riverine discharge was limited to the Connecticut River. The atmospheric forcing was based on the North American Mesoscale (NAM) and the Weather Research and Forecasting (WRF) model simulations, where at this point only the wind field was included (i.e. no heat fluxes and no precipitation). The spin up for the model ranged between 1 – 2 days. The horizontal grid resolution (Δx, Δy) was set at 250 m with 11 sigma layers in the vertical (z). The turbulent closure model corresponds to the *q-ql* Mellor and Yamada (1982) level 2.5 (i.e. MY-2.5), where *q* is the turbulent kinetic energy and *l* is the turbulent scale. The bottom boundary layer follows a *law-of-the-wall* classic behavior, where the bottom drag coefficient follows by matching a logarithmic profile at height z_{ab} (depending on model resolution) and the aerodynamic roughness length (z_o). The SWAVE module is a direct adaptation from SWAN and the reader is referred to the SWAN user manual and also to Qi et al., (2009) and the FVCOM User Manual for further details on the numerical approach to the solution of the wave action equation. The SWAVE spectral frequency range was set in the range 0.05 – 1 Hz with 32 logarithmically spaced frequencies and an angular distribution resolution of 10º (Δdeg) with 36 equally spaced angles with a $f^{-4.0}$ Hz spectral tail roll off. It is relevant to note that the spectral tail roll off needs to be modified depending on which wave growth parameterization is used. Spectral sources and sinks of wave energy were slightly modified to better capture the wave dynamics inside the estuary.

2.1 Atmospheric Forcing: Wind Energy Input

The SWAVE wave module was run as a third generation wave model (GEN3), where both, the Snyder et al. (1981) (e.g. Komen et al. 1984) and the Janssen (1991) wave growth parameterization were initially evaluated. The total wind input from wind forcing was prescribed to have a linear and exponential growth component, where the total wind input (S_{in}) follows from the addition of the two growth parameterizations:

$$S_{in}(f,\theta) = A + B\,F(f,\theta) \qquad (1)$$

where $F(f,\theta)$ is the frequency-direction sea surface spectrum. The *B* parameterization corresponds to the Snyder et al., (1981) or to the Janssen (1991) and *A* represents the linear growth by Cavaleri and Malanotte-Rizzoli (1981) The linear wave growth by Cavaleri and Malanotte-Rizzoli (1981) was active during all simulations.

2.2 Energy Dissipation: Wave Breaking

This energy sink term is not well understood and available parameterizations are highly empirical. The model was run using the generalized Komen et al. (1984) wave breaking parameterization to complement the Snyder et al. (1981) wave growth parameterization and the Janssen (1991) breaking parameterization when the same wave growth parameter was used. The spectral source term can be stated as (Ris 1997; Booij et al., 1999):

$$S_{diss}(f,\theta) = \Gamma\, f_m \left(\frac{k}{k_m}\right) F(f,\theta) \qquad (2)$$

where Γ is a steepness (*s*) dependent coefficient (e.g., Janssen 1992) :

$$\Gamma = C_{ds}\left[(1-\delta) + \delta\left(\frac{k}{k_m}\right)\right]\left(\frac{s}{s_m}\right)^n \qquad (3)$$

where C_{ds} is an empirical coefficient of proportionality, *s* corresponds to the overall steepness parameter, *n* is a numerical constant and the subscript *m* denotes an average where k_m follows from:

$$k_m = (\langle 1/\sqrt{k} \rangle)^{-2} \quad (4)$$

and the steepness parameter s follows from:

$$s = E(k_m)^2 g^{-2} \quad (5)$$

where E is the zero order moment of the spectrum ($F(f, \theta)$).

2.3 Energy Dissipation: Bottom Friction

The spectral dissipation function due to bottom friction effects (S_{bf}) can be written in the general form (Weber 1991a,b):

$$S_{bf}(k) = -C_f \frac{k}{\sinh(2kH)} G(k) \quad (6)$$

where k is the magnitude of the wavenumber, H is the water depth and C_f is a friction coefficient with units of velocity i.e. m s $^{-1}$, $G(k)$ is the wavenumber spectrum where $G(k) = F(f)\, df/dk$. The Madsen wave friction coefficient (f_w) follows from equation (6):

$$f_w = \begin{cases} 0.15 \;;\; \frac{a_b}{k_N} < 1.57 \\ \frac{1}{4\sqrt{f_w}} + log_{10} \frac{1}{4\sqrt{f_w}} = m_f + log_{10} \frac{a_b}{k_N} \quad ; \quad \frac{a_b}{k_N} > 1.57 \end{cases} \quad (7)$$

where the roughness element length (k_N) corresponds to the actual physical roughness length (i.e. associated to the sediment size and distribution), a_b is the bottom excursion amplitude ($a_b = u_b\, \omega_b^{-1}$), where u_b is the bottom orbital velocity, ω_b the bottom wave frequency and m_f is a constant of value -0.08. Then the friction coefficient follows from:

$$C_f = \sqrt{2}\, f_w \langle u_b^2 \rangle^{1/2} \quad (8)$$

2.4 Quadruplet non-linear interaction

Quadruplet non-linear interactions were activated using the default settings for DIA (Hasselmann et al. 1985). Triad non-linear interactions were not active during these simulations.

3. Results

We performed a few numerical tests to compare the two wave growth parameterizations (i.e. Snyder et al. 1981 and Janssen 1991) and concluded that the Janssen (1991) wave growth parameterization, with default coefficients produced lower significant wave heights relative to the Snyder et al. (1981) parameterization (all other spectral parameterizations held constant). This was the case particularly at low wind speeds and was consistently biased low when compared to observations. The Snyder et al. (1981) performed better, but when compared to observations of significant wave height and dominant period at the WLIS (fetch limited location) it was also biased low. The Snyder et.al (1981) wave growth did perform well at the CLIS and BLIS and we therefore attempted to slightly modify it to better represent the underdeveloped wave field conditions at the Western end of LIS. Modifications to the wave growth parameter coefficients are displayed in Table 3.1 where we enhanced the coefficients C and D. Further fine-tuning was needed for the severe weather simulation were we introduced one more modification to the Snyder et al. (1981) wave growth parameter aside the enhancement of the C and D coefficients. Writing the full expression for B from equation (1) we have:

$$B = max\{0, C\frac{\rho_a}{\rho_w}\left[D\ \frac{u_*}{c}\cos(\theta_{wave} - \theta_{wind}) - X\right] * f\right\} \quad (9)$$

where $(\theta_{wave} - \theta_{wind})$ is the difference between wave and wind direction, u_* is the atmospheric friction velocity and c is the phase speed of the waves. The term *X* in equation (9) has a default value of 1. This induces a negative energy flux at frequencies that are lower than the spectral peak. This accounts for the assumption of a minimized or even negative wind-wave coupling when waves are travelling faster than the wind. In the underdeveloped WLIS we reduced X to 0.85. This value minimizes the energy reversal at lower frequencies and enhances the wind energy input at the peak. The reduction of X from 1 to 0.85 enhances the wave growth at WLIS with a minimum impact on CLIS and the Eastern locations. For example, by solely enhancing C and D (and leaving X = 1) the model overestimates the wave growth at CLIS during the high forcing (U_{10} > 25 m s^{-1}) with a bias high of 29% whereas this modification in combination with the tuning to the wave breaking coefficients leads to a bias low of 6% at CLIS and better captures the maximum significant wave height at the CLIS and WLIS.

Modifications to the breaking coefficients were also explored and applied. Default coefficients appear to overestimate the dissipation due to breaking inside the estuary. We found that to better capture significant wave height and dominant wave period observations, the coefficient $C_{ds,}$ had to be modified from its default value (Table 3.2) with best results in the range: 1.10 x 10^{-5} –1.18 x 10^{-5} (Table 3.2) The exponent *n* was kept constant at 1.0. In the underdeveloped seas inside LIS, breaking should be theoretically distributed across all frequencies (e.g. Gemmrich et al. 2008), whereas equation (2) heavily weights dissipation at the peak based on default values. We hypothesized that this was leading to an overestimation of the actual breaking and attempted to reduce the weight of the spectral dissipation at the dominant frequencies. At this point this is somewhat speculative, as we do not have wave breaking observations aside from anecdotal observations from several field campaigns.

The modifications presented in Table 3.2 reduced the spectral dissipation at the peak, but maintained an active dissipation at higher frequencies. This was achieved by increasing the delta (δ) parameter and by reducing the C_{ds} coefficient. The overall reduction in dissipation by breaking once the coefficients were fine-tuned was estimated at approximately 52% across the frequency domain, where approximately 75% of the reduction happens at frequencies in the 0.05 – 0.3 Hz. The other relevant dissipative term is the bottom friction parameterizations, where at this time we did not perform a full evaluation of it. The Western end has shallow waters (~20 m deep), which can certainly interact with the wave field in a severe event such as Sandy. Here, we have chosen a roughness element length (k_N) of 0.02 m to estimate the Madsen et al. (1988) spectral parameterization, which was used during our last simulation. During all simulations triad non-linear interactions were turned off and the quadruplet non-linear interactions were solved using default DIA coefficients.

The model was compared against observations and the performance was evaluated based on the root-mean-squared-error (Eq. 10) the model bias (Eq. 11), which states the under-over prediction (%) and the index of agreement, which is a parameter of the skill of the model (Eq. 12).

$$rms = [\langle (X - x)^2 \rangle]^{1/2} \tag{10}$$

$$bias = 100 \frac{\sum_{i=1}^{N}(X_i - x_i)}{\sum_{i=1}^{N}|X_i|} \tag{11}$$

$$IA = 1 - \left[\sum_{i=1}^{N}(X_i - x_i)^2 / \sum_{i=1}^{N}(|X_i - \langle x \rangle| + |x_i - \langle x \rangle|)^2\right] \tag{12}$$

where brackets denote temporal averages and X and x correspond to model and observations respectively.

3.1 Case 1: Response to fetch limited weak wind forcing

The first simulation corresponds to a period of weak atmospheric forcing conditions, which are commonly observed in the LIS during the summer months. The strength of the forcing was defined in terms of the wind speed where a low mean wind speed (U_{10}< 5.0 m s^{-1}) was satisfied in combination with a relative constant wind direction assuring a limited fetch during the model run (i.e. Westerly and South-Westerly winds). The period selected was June 19-24, 2013. Observations from the CLIS (lisicos.uconn.edu/clis) buoy showed an average wind speed of 4.97 m s^{-1} with a dominant wind direction of 212° making the forcing predominately from the southwest. Wind conditions at the WLIS (lisicos.uconn.edu/wlis) buoy were similar with the same mean wind speed of 4.95 m s^{-1} and wind direction of 212° (SW).

During this simulation the model was biased high at the Western and Central sound locations (Fig 1). The significant wave height at WLIS showed a 48% bias high and an index of agreement (Eq. 10) of 0.59. The significant wave heights at the CLIS location were biased high by 43% with an index of agreement of 0.61. Modeled significant wave heights were biased low relative to observations at BLIS with and index of agreement of 0.36 (Fig. 3-a). At the CLIS the dominant period comparisons (Fig 3-b) had a 0.96 correlation coefficient with a bias high of 4%. Nonetheless the index of agreement was only 0.40 as the model had a delayed response to changes in local wind conditions only capturing the mean behavior, but not fully capturing the dynamic range of the dominant period. Dominant periods at the WLIS exhibited a high correlation coefficient 0.92 and were bias low by 15% with an index of agreement of 0.50. At BLIS wave scales were not well captured, where the model overestimated the dominant period by 37% with an index of agreement of 0.30.

By complementing the wind forcing (i.e. wind speed) distribution over the LIS with the dominant phase speed, we explored the difference in the wave field evolution at CLIS relative to the WLIS. In order to do so we rely on the inverse wave age parameter; defined as the ratio of wind speed at the reference height of 10 meters (U_{10}) to dominant phase speed (c_p), which follows from the dispersion relation once the peak period is identified. The inverse wave age can be stated as: ${U_{10}}/{c_p}$. The inverse wave age is relevant to the wave growth parameterization and was used to estimate the dominant wave scales and the potential differences in developing stages across the LIS wave field. For ${U_{10}}/{c_p} < 1.2$ the wave field is defined as a mature or developed state, whereas for ${U_{10}}/{c_p} \geq 1.2$ the sea state is said to correspond to a young or developing sea. For example, during this simulation the CLIS had an observed inverse mean wave age (i.e. ${U_{10}}/{c_p}$) of 1.26 and an inverse mean wave age of 1.22 at WLIS. Modeled inverse mean wave ages were 1.21 and 1.22 at CLIS and WLIS respectively.

The wind forcing at both sites was correlated and of comparable magnitudes, leaving the developing differences to the capacity of the waves to react to the forcing. On average the model was able to capture the overall wave field structure across the LIS for a fetch limited scenario. Modeled waves were shorter and smaller at WLIS than at CLIS based on significant wave heights (sigH) and dominant periods (T_p) (Table 3.4). Average significant wave height distribution and dominant period are shown in Figures 4-a and 4-b. Observations at BLIS show a mean ratio $\langle {U_{10}}/{c_p} \rangle = 0.87$, suggesting a more mature state with waves coming from the shelf (non-locally generated swell). Modeled inverse wave age at BLIS was close to one (i.e. $\langle U_{10}/c_p \rangle = 1$). Modeled waves at BLIS were not able to capture the dominant peak period. This could be improved by modifying the open boundary conditions (OBC) to include swell propagating into the estuary.

4.1.2 Case 2: Response to fetch limited moderate forcing

The second case considered rapid changes in wind magnitude, but with a relatively constant and dominant westerly wind direction (average wind direction 268°) making the system fetch limited again. The maximum wind speed was observed to be 14 m s^{-1} at CLIS and 13 m s^{-1} at WLIS, both during the beginning of the simulation, followed by a period of calm (U_{10} < 5.0 m s^{-1}) and a final ramp up in wind speed (U_{10} > 10.0 m s^{-1}) The average wind speed during the simulation was 5.1 ± 0.15 m s^{-1}. The model run covered four days from February 16-20, 2015. Once again, the wind forcing was highly correlated at both sites and we associated the observed and modeled differences between sites to behavior of the wave field.

The physical conditions during this run kept the model at an average underdeveloped stage at CLIS and WLIS with a mean inverse wave age of 1.01 and 1.26 respectively (i.e. $\langle U_{10}/c_p \rangle$. The modeled scenario was consistent with observations resulting in the CLIS and WLIS exhibiting a developed state with an average inverse wave age of 0.97 and 1.14 respectively

This difference in development can also be seen in Fig. 5 and Table 4.5 where significant wave heights and dominant periods at CLIS and WLIS were found to be on average different with larger waves observed at CLIS. Figure 5 shows the 1:1 comparison for significant wave height and dominant period in CLIS and WLIS. The model shows high correlation coefficients between hindcast and observations of significant wave height and dominant period with low *rms* errors (Table 3.5). Mean dominant periods were well captured at both central and western locations (Table 3.6). The dominant wave period at CLIS had a correlation coefficient of 0.93 and an *rms* of 0.9 s and was biased low by 8.5% with an index of agreement of 0.85. At WLIS the model estimates of dominant wave period where also biased low (by 13%) with an index of agreement of 0.60. Significant wave heights were also well captured during this simulation, with an index of agreement of 0.86 and bias high of 5% at the CLIS and an index of agreement of 0.87 with a bias high of 17% at the WLIS.

The average structure of the wave field is shown in Figure 6, where there is a marked difference between the CLIS and WLIS environments. This model simulation showed a more severe contrast between CLIS and WLIS relative to the previous case. We attribute this to the strong wind dependence of the system. The strong forcing registered on February16 and17 and at the end of February19th (U_{10} > 10.0 m s^{-1}) rapidly develops the wave field at the CLIS, but the fetch limitation at WLIS keeps this region underdeveloped with overall shorter waves. The significant wave height difference under strong forcing (U_{10} > 10.0 m s^{-1}) between the CLIS and WLIS was on average twofold. The overall average (Table 3.6) and significant wave height and wave scale distribution was well captured by the model hindcast.

This simulation exhibited a wide dynamic range of conditions (Table 3.6) leading to a sharp contrast in wave energy between the Central, Western and coastal areas (Fig. 6a).

4.1.3 Case 3: Response to unlimited fetch under moderate forcing

The third case corresponds to an unlimited fetch scenario with moderate to strong forcing. The simulation was run for seven days between January 1-8 2014 with a mean wind speed of 7.47 ± 3.4 m s^{-1} and an average wind direction of 100º (easterly wind). In Figure 7 we show the comparison across the sound from BLIS, CLIS to WLIS of significant wave heights (Fig 7-a) and dominant period (Fig. 7-b).

At the WLIS location the modeled dominant period was bias high by 11% with an *rms* of 1.2 s (Table 3.7) with an index of agreement of 0.54. The dominant periods at CLIS showed good agreement and were biased high (2.8%) and had an index of agreement of 0.61. The modeled significant wave height at WLIS had an index of agreement of 0.79 and was biased high by 20% with an *rms* of 0.29 m. At the CLIS location the modeled significant wave height had an index of agreement of 0.74 with a bias high of 11%, but missed the maximum observed significant wave height. Correlation coefficients were high (Fig 7) at both locations inside the estuary, particularly for the dominant period comparison. At BLIS the index of agreement dropped to 0.38 with a bias low of 14% for the dominant period. Significant wave heights had an index of agreement of 0.61 and were bias low by 17%.

During the simulation, the WLIS observations exhibited on average underdeveloped seas, with an inverse wave age of: $\langle U_{10}/c_p \rangle$= 1.76. The average inverse wave age at CLIS was observed to be: $\langle U_{10}/c_p \rangle$= 1.47. The Block Island Sound site showed an average inverse wave age of 1.20. Modeled inverse wave age at CLIS, WLIS and BLIS were 1.43, 1.64 and 1.30 respectively. The spatial distribution of significant wave heights and dominant periods is shown in Figure 8, where the model shows a more homogeneous distribution of wave energy inside the LIS.

The overall wave field structure appears to be rather homogeneous throughout the LIS with differences constrained at the coast (Fig. 7).

4.1.4 Case 4: Response to a severe weather event: Unlimited fetch under extreme forcing

The severe weather event was chosen to be the Superstorm Sandy 2012. The model simulation covered ten days between the 21 and 31 of October 2012. The maximum wind intensity inside the estuary was recorded at 22:00:00 on Oct -29 with wind speeds in excess of 24 m s^{-1} at the CLIS. Although the wind magnitude was not particularly high e.g. Hurricane Gloria reached 33 m s^{-1} at the same location, the long duration of the storm in addition to the direction of the forcing made it an exceptional event. For example, wave heights in the continental shelf reached over 9 m with dominant periods in excess of 12 seconds at Long Beach, NY. Inside the estuary reported observations of significant wave heights were 4 m at the central buoy location and reached an excess of 3 m at the western end.

4.1.4-a Hydrodynamic- Wave Coupled simulation with a Logarithmic Bottom Boundary Layer

First we run a simulation with a classic log-layer as the bottom boundary. The modeled dominant periods and significant wave height comparisons showed high correlation coefficients at both locations and acceptable *rms* errors (Table 3.9). For this longer simulation we present a time series of the significant wave heights (Fig. 9) and dominant period (Fig. 10) in order to give an idea of the build up of the storm and how the model captured the evolution inside the estuary.

The index of agreement at CLIS was 0.91 for the dominant period with a bias low of 10%. The index of agreement at CLIS was 0.94 for the significant wave height comparison with a bias low of 8%. At the WLIS location the significant wave height hindcast had an index of agreement 0.84 and had a bias low of 41%, as the model failed to capture the full evolution of the wave energy in the WLIS area with the spectral parameterizations despite the previous calibration. The dominant period at the WLIS was better captured by the model, with an index of agreement of 0.84 and a bias low of 18% (Table 3.10)

The modeled wave field at the CLIS location was on average underdeveloped ($\langle U_{10}/c_p \rangle =$ 1.63) and reached a peak inverse wave age value of 3.4 at the storm maximum consistent with observations. In the WLIS region, the wave field was also on average underdeveloped ($\langle U_{10}/c_p \rangle$=1.84) with a maximum inverse wave age value of 4.57. Observations at CLIS and WLIS showed an average inverse wave age of 1.79 and 1.73 respectively. During the storm maxima, observations reported $\langle U_{10}/c_p \rangle = 3.23$ and $\langle U_{10}/c_p \rangle = 4.33$ at CLIS and WLIS respectively. Maximum significant wave heights and periods are presented in Table 3.11. These results show how the wave field inside LIS evolved under a severe (long duration, high wind) event (Fig).

The WLIS region remained underdeveloped, where wave growth was mainly limited by the local bathymetry and surface dissipation by wave breaking and bottom friction. This is also true within CLIS, but to a lesser degree. The deeper bathymetry at CLIS allowed longer and faster waves to develop (Table 3.11) yielding a more mature sea.

4.1.4-a Hydrodynamic- Wave Coupled simulation with Wave-Current interaction at the Bottom Boundary Layer.

Finally, this simulation was run using the sediment module available in FVCOM, where the Madsen (1994) bottom boundary layer (BBL) scheme was implemented. This allowed the waves to be fully coupled with the hydrodynamics at both boundary layers and through the radiation stresses in the water column.

The index of agreement at CLIS was 0.90 for the dominant period with a bias high of 5.4% (Fig. 10) and 0.88 for the significant wave height comparison with a bias high of 38.8% (Fig. 9). At the WLIS location the significant wave height hindcast had an index of agreement 0.91 and was biased low by 16%. The dominant period at the WLIS was better captured by the model, with an index of agreement of 0.88 and a bias low of 5.3% (Fig. 10). Although the maximum peak period recorded at the WLIS was missed by the model (~40% bias low) This simulation yields lower *rms* at WLIS compared to a log-layer BBL (Table 3.12)

Maximum significant wave heights and periods were better captured during this simulation (Table 3.13). Despite the improvement from the previous simulation, the WLIS was biased low relative to the maximum observations recorded during Sandy 2012.

5.0 Discussion

We have performed a series of numerical experiments to test the model's sensitivity in capturing the structure of the wave field inside a fetch limited urban estuary under different forcing scenarios. First we evaluated the performance of the Janssen (1991) and the Snyder et al. (1981) wave growth parameterizations. We found that at low to moderate wind speeds ($2 \leq U_{10} \leq 8$ m s^{-1}) the Janssen (1991) parameterization had the tendency to produce significant wave heights that were biased low relative to observations. The default Snyder et al. (1981) parameterization behaved better exhibiting lower *rms* relative to observations. Nonetheless, both parameterizations were biased low. Under stronger forcing ($U_{10} > 10$ m s^{-1}) the Janssen (1991) improved its performance and both parameterizations exhibited little difference relative to observations. Under very strong forcing ($U_{10} > 20$ m s^{-1}) the Janssen (1991) exhibited better agreement with the data, although further evaluation is deemed necessary at this stage. Under strong forcing ($U_{10} > 15$ m s^{-1}) both default parameterizations were biased low. Furthermore, the iterative nature of the Janssen (1991) makes it computationally more expensive than the Snyder et al. (1981). Based on these considerations, we opted to run our numerical simulations based on a modified version of the Snyder et al. (1981) parameterization. We did this by fine-tuning the parameterization coefficients (Table 3.1) to improve modeled significant wave heights (sig_H) and dominant periods (T_p) inside the estuary. Finally under the severe forcing event we also explored a modification of the X term in equation (10), which allowed for an enhancement of energy in (i.e. wind input) at lower frequencies. The enhancement in energy input grows as the forcing becomes larger. For example this leads a 2% increase in the integrated spectral energy for a 15 m s^{-1} and 9% enhancement at wind speeds larger than 24 m s^{-1} with less than a 1% enhancement for wind speeds lower than 10 m s^{-1}. This was useful during the last simulation of Superstorm Sandy (2012), where we improved the modeled maximum significant wave height and peak wave period. Further enhancement can be achieved by enhancing the coefficients C and D, but the effects on the CLIS and ELIS suggested this is not a good alternative.

Regarding the wave dissipation inside LIS, observations suggest that the wave field inside the estuary remains underdeveloped and therefore we opted to tune the wave breaking down from default value of C_{ds} of 2.36 x 10^{-5}. We find that the default breaking coefficients overestimate dissipation, with a heavy weight on the dominant frequencies. In doing so we enhanced the energy input (wind driven) into the system. We found that the best results were in the 1.10 x 10^{-5} - 1.18 x 10^{-5} range, with even lower values yielding good results at WLIS. Further work and observations on the subject are required to further improve breaking parameterizations inside the LIS estuary,

The bottom friction parameterization selected was the Madsen (1994) formulation with a roughness length (k_N) of 0.25 m. The FVCOM-SWAVE model was not run with bottom wave-current interaction and during these simulations a bottom log-layer was in place. Therefore the bottom friction parameterization became relevant only at coastal areas where the wave field was able to directly interact with the bottom.

The first sets of numerical simulations were fetch limited under varying forcing conditions. For both of these cases (i.e. Case 1 and Case 2), the modeled significant wave heights inside the LIS showed a significant bias high for Case 1 with improved agreement in Case 2 (Tables 3.4, 3.6 and 3.8). Modeled peak periods (T_p) and therefore peak wave scales were better captured giving good estimates of wave field development stages. The bias high could be due to a lack of dissipation, although during these simulations waves behave like deep water waves making bottom friction less relevant of a dissipation mechanism. Enhancing dissipation through wave breaking could solve the issue, although during weak forcing and young seas, the expectation of breaking was low. The overall bias high exhibited by the model inside the LIS for fetch limited cases was associated with too strong of a dependency on wind forcing, potentially due to the modified wave growth parameter. For example, during the weak and fetch limited forcing (i.e. Case 1) the modeled significant wave heights within CLIS exhibited a 0.66 zero-lag correlation with the x-component of the wind (along LIS wind) and a 0.63 zero-lag correlation with the y-component of the wind (across LIS wind). Observations on the other hand show a 0.64 and 0.47 zero-lag correlation respectively. During this low forcing scenario, observations suggest a max correlation between wind and waves (along the sound) to be 0.67 and lagged approximately 2 days (with the waves trailing the weak wind forcing), where the magnitude of the lag was not fully captured by the model (0.6). At the WLIS the model hindcasted a 0.57 zero-lag correlation between significant wave heights and the x-component of the wind and a 0.50 zero-lag correlation with the y-component of the wind. Observations at WLIS suggest a 0.38 and 0.20 zero-lag coefficient for the x and y wind components. At both locations the model appears to significantly overestimate the resulting correlation between waves and the wind forcing.

Model results during the moderate and limited fetch scenario (i.e. Case 2) the x-component of the wind forcing shows a 0.93 zero-lag correlation, whereas the observations at CLIS suggest a 0.70 correlation (at zero-lag). The y-component of the wind (across sound component) showed a modeled 0.74 zero-lag compared to a 0.49 zero-lag correlation in the observations. The behavior at WLIS was similar, where the model captures the overall behavior of the correlation coefficient in time, but overestimates its magnitude. Nonetheless, the modified parameterization was needed to improve model performance inside the LIS under moderate to stronger forcing. This was the case for the latter two simulations. For example, during the unlimited fetch scenario under moderate forcing (i.e. Case 3), the model showed that the zero-lag correlation coefficient of x and y-component of the wind forcing with significant wave heights were respectively 0.7 and a 0.10 at CLIS with observations suggesting a 0.50 and a 0.21 zero-lag correlation coefficient for the x-component and y-component of the wind with significant wave heights. At the WLIS the overall structure of the correlation was well captured, with differences within 10% in the correlation coefficient magnitudes at zero-lag up until the zero correlation was reached by observations and model at approximately 4 days. We associate the improvement in the correlation between wind and significant wave height as a key component of the improvement of the model in the Western end of the estuary. This was further confirmed during the Superstorm Sandy simulation. For example, the y-component of the wind forcing and the significant wave height had a modeled correlation coefficient of 0.31with a 15-hour lag at the CLIS. Buoy observations showed a 0.28 correlation coefficient at the 15-hour lag at the same location. At the WLIS the max correlation was observed and modeled at 21 hr lag with a correlation coefficient of 0.38. Overall the modeled runs were able to differentiate the local wave climatology existing in LIS (Fig. 2), with short and long waves during summer and winter respectively under moderate to strong forcing. Nonetheless, in the presence of weak forcing (U_{10} < 5.0 m s^{-1}) the model was not able to capture adequate wave growth rates and at this point we recommend further evaluation of the spectral terms in the wave action equation. Nonetheless, under moderate to strong forcing under limited or unlimited fetch the model has the capacity to differentiate different stages of wave development (i.e. inverse wave age) and growth accounting for the different Easter and Western regions inside the LIS.

6.0 Conclusions

We have performed several simple numerical experiments to evaluate the FVCOM-SWAVE model inside the Long Island Sound urban estuary. For moderate to strong forcing an enhancement of the Snyder et al. (1981) wave growth was necessary in combination with a reduction of the breaking intensity. Our modifications succeeded in better capturing the short wave scales in a commonly underdeveloped state at the WLIS. We found the wave field within the WLIS region to remain consistently underdeveloped and unable to fully develop given the geometry of the estuary and the nature of the wind forcing tested so far. Waves within WLIS remain short (relative to the forcing) and in comparison to those within CLIS under severe events (i.e. Super Storm Sandy of 2012). Under more moderate cases the CLIS and WLIS regions can reach the same level of development and ultimately similar wave statistics if the wind forcing exhibits a North-East/ East direction.

The modeled bias high was attributed to the modified wave growth coefficients. For weak forcing hindcast or forecasting (U_{10} < 6 m s^{-1}) we recommend default wave growth coefficients with modified wave breaking coefficients (reduced). Finally, we concluded that the FVCOM-SWAVE coupled model works well in such an environment. Although significant wave heights were biased high for weak forcing scenarios, the wave scales were on average well captured by the modified growth coefficients. These results can be used in combination with observations to further explore the differences between the CLIS, BLIS and WLIS regions of the Sound from a wave field development stand point (wave age). The model proves to be a valuable tool in providing wave field evolution and information within the LIS with acceptable uncertainty.

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An Assessment of Two Models of Wave Propagation in an Estuary Protected by Breakwaters

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Abstract: Breakwaters influence coastal wave climate and circulation by blocking and dissipating wave energy. In a large harbor, these effects are combined with wave generation, refraction and reflection. Accurate representation of these processes is essential to the determination of coastal circulation and wave processes. MIKE21SW and SWAN are two third-generation spectral wave models which are used widely in coastal research and engineering applications. Recently improved versions of the models are able to consider the influence of breakwater structures. In this study, we used available observations to evaluate the accuracy of model simulations of waves in New Haven Harbor, Connecticut, USA, an estuary with three detached breakwaters near the mouth. The models were executed on their optimum unstructured triangular grid. The boundary conditions were derived from a bottom mounted Acoustic Doppler Current Profilers (ADCP) on the offshore side of the breakwaters. Wind forcing was applied using data from the Central Long Island Sound buoy. We found that both models were largely consistent with observations during storms. However, MIKE21SW predicted some of storm peaks slightly better. SWAN required the finer grid to achieve the optimum condition, but as it uses a fast, fully implicit algorithm, the computational times were similar. Also, the sensitivity analysis represents that wind forcing and the breakwaters have significant impact on the results.

Keywords: wave hindcast; breakwater; harbor; estuary; SWAN; MIKE21SW; unstructured grid

1. Introduction

Breakwaters are used to protect harbors and shorelines from waves and to limit coastal erosion. In harbors, breakwaters provide tranquility behind them to ease both navigation and berthing for vessels. Breakwaters influence coastal wave climate by breaking, reflecting, and diffracting wave energy. In a large harbor, the fetch may be sufficient for the local generation of waves to be important. Studying these influences in situ poses a challenge. In recent years, spectral wave models have become more widely used and are important in describing coastal wave behavior. However, the performance and precision of the spectral models in real harbors in the presence of the breakwaters has not been well examined.

SWAN, MIKE21SW, and Wavewatch III are three commonly used spectral wave models in coastal and ocean communities. Wavewatch III is mostly used for deep ocean and open sea applications and is not able to include breakwater structures. On the other hand, the recent versions of SWAN and MIKE21SW are equipped to handle breakwaters.

Although parabolic and elliptic mild slope models as well as Boussinesq models may be more appropriate for the simulation of waves in small harbors, where diffraction is the most important phenomenon, in large embayments and harbors wind-wave generation can be important and spectral models are useful. However, some circumstances should meet to use spectral for wave simulation in harbors [1,2].

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In recent years, unstructured grid models have become more popular for modeling complex geometries and are an effective alternative to the grid nesting approach [3,4]. In this study, we employ unstructured SWAN (v41.20) and MIKE21SW (v2017) to simulate the effects of three coastal breakwaters on the wave field in New Haven Harbor, Connecticut, and then assessed their accuracy and efficiency.

There have been previous comparisons of these models. Strauss et al. [5] compared simulations of waves on a narrow continental shelf in Gold Coast, Australia using SWAN and MIKE21SW. SWAN was executed in the fully spectral mode with a structured grid, while MIKE21SW was executed in decoupled parametric mode with an unstructured grid. The results indicated that both models overestimated significant wave height. Moeini and Etemad-Shahidi [6] applied SWAN and MIKE21SW for hindcasting waves in Lake Erie. The study suggested SWAN simulated significant wave height better, while MIKE21SW simulated wave period and direction better. Fonseca et al. [7] suggested that MIKE21SW, SWAN, and STWAVE had similar precision when examining performance on the Portuguese coast. Hoque et al. [8] evaluated SWAN and MIKE21SW in the Mackenzie Delta, Beaufort Sea, Canada. They found that the results of the models were almost identical, but in water shallower than 2.7 m for wave heights between 2 and 3 m, SWAN simulated significant wave height better, though the peak period from MIKE21SW was more accurate.

In all previous studies, SWAN was executed on a structured grid and MIKE21SW on an unstructured grid. In this study, both SWAN and MIKE21SW were run on their optimum unstructured grids and evaluated inside New Haven Harbor which is separated from Long Island Sound by substantial breakwaters (Figure 1). The model results are compared to data from two bottom mounted Acoustic Doppler Current Profilers (ADCP) in the harbor for storm events, one outside the harbor for storms with northerly winds. The sensitivity of the model results to the wind forcing, and the representation of diffraction, reflection, and the breakwater are discussed. The simulation skill and the efficiency of the models are summarized and possible explanations for these differences were discussed.

Figure 1. Locations of breakwater structures in front of New Haven Harbor are highlighted by white lines and ADCP locations inside and outside the harbor are identified by yellow boxes and labels. Image Source: "New Haven Harbor". 41°15′03.79″ N and 72°55′20.36″ W. Google Earth. 23 September 2017. 18 June 2018.

2. Model Descriptions

MIKE21SW is a proprietary model developed by DHI Company. It is one of the most widely used wave models in coastal and marine engineering projects around the world. It has a graphical user interface (GUI) that makes it simple to set up the model and visualize the results. SWAN is an open source model developed by the Delft University of Technology. It is often used in academic coastal research and has been integrated to community circulation models. For simplification and clarification, we introduce the models by summarizing their similarities and differences.

SWAN [9] and MIKE21SW [10] are both third generation fully spectral wave models. The models solve the wave action balance equation, described by Mei [11], Komen et al. [12], and Young [13]. In Cartesian coordinates, the wave action balance equation can be written as

$$\frac{\partial N}{\partial t} + \nabla .\left(\left(\vec{c}_g - U\right)N\right) = \frac{S}{\sigma} \tag{1}$$

where $N(x, \sigma, \theta, t)$ is the wave action density, $\vec{c}_g = (c_x, c_y, c_\sigma, c_\theta)$ is the wave group velocity, U is ambient current, σ is relative frequency, θ is wave direction, t is time, and S is the total source and sink terms which represent generation, dissipation, and redistribution of wave energy. ∇ is the four-dimensional differential operator with respect to x, y, σ, and θ.

The source terms in both models are almost the same. Wave dissipation terms such as bed friction, wave breaking, whitecapping, nonlinear quadruplet interactions, nonlinear triad wave interactions, and diffraction are essentially the same. However, in some cases such as wind input, whitecapping and quadruplet wave interaction, SWAN provides a wider range of parameterizations and coefficients.

SWAN can be run on both structured and unstructured grids, while MIKE21SW only uses unstructured grids. The spatial discretization method differs between the models. SWAN's spatial discretization is based on a vertex-centered method while MIKE21SW uses a cell-centered method. This implies that wave action N is stored at the grid cell vertices in SWAN and at the cell center in MIKE21SW. Thus, the control volume in SWAN is a polygon, while in MIKE21SW it is triangular.

The numerical methods used in structured and unstructured SWAN are different. In the structured mode of SWAN, a first order upwind-space backward-time (BSBT) scheme, or a second order SORDUP scheme (default for stationary mode), and second order Stelling and Leendertse scheme (default for nonstationary mode) may be selected. In unstructured SWAN the only option is the BSBT scheme which is fast but diffusive [14]. MIKE21SW uses a first order upwind difference and second order accurate scheme in space. The first order scheme is usually sufficient for small-scale domains dominated by local wind. In the case of swell propagation, the second order scheme should be applied [10].

The major difference between the numerical methods is that SWAN uses a fully implicit method time integration whereas MIKE21SW is an explicit approach. Consequently, MIKE21SW avoids solving a large system of equations with the drawback that the temporal step is limited by the Courant number. SWAN's fully implicit scheme eliminates the stability constraint on the temporal step but requires a large system of equations must be solved to achieve a solution. To improve efficiency SWAN uses a point-by-point multi-directional Gauss-Seidel iteration technique that circumvents the need to construct and solve a large system of simultaneous equations as is typical in implicit methods [14]. This technique highly improves the computational efficiency of the SWAN model.

3. Methods

In this study, the model domain is New Haven Harbor, Connecticut, USA. New Haven Harbor is located in Long Island Sound, a large estuary on the northeast coast of the United States. There are three detached breakwaters in front of the harbor to reduce the effects of waves during extreme storms. The area is frequently affected by strong winds during winter, from January to March, and occasionally by hurricanes in the summer and early fall. The significant wave height in central Long Island Sound, where New Haven Harbor is located can exceed two meters. Also, the maximum distance from New

Haven breakwaters to end of estuary is 7 km, sufficient fetch for local wave generation to be important. This is the main reason that the spectral wave models, rather than mild slope or Boussinesq wave models, were employed in this study.

To observe the effect of breakwaters on waves in extreme storms, we deployed two ADCPs, one outside the harbor (NH1) and one inside (NH2), during the winter of 2015 from 21 January to 5 April. The wind data were gathered during the same period by the Central Long Island Sound Buoy (CLIS) which is located 25 km from New Haven. CLIS wind data are a good representative of New Haven wind, particularly when the winds are southerly. Northerly winds may be more influenced by the roughness of the land surrounding the harbor. However, the topography of the New Haven area does not contain features that could cause substantial influence on wind direction. Depths and locations of the observations can be found in Table 1, and Figure 1 illustrates the field site.

Table 1. Location and depth information for the observations used for modeling

Station ID	Latitude (N)	Longitude (W)	Depth (m)	Location
NH1	41°13.44′	72°53.15′	10.4	Outside Harbor
NH2	41°14.64′	72°56.96′	5.2	Inside Harbor
CLIS	41°8.28′	72°39.30′	27	Outside Harbor

Instead of applying a nesting approach, which uses results from a large-scale model to force the boundaries of the local wave model, we used the observed wave spectrum at NH1 to force the open boundary of the models. In this way, we reduce the uncertainty that arises from simulation of the large-scale wave field. The possible variation of the wave field along the boundary was neglected since Long Island Sound is fetch limited and the bathymetric variations near the study site were small. The models were also forced by a uniform wind stress over the domain at half-hour intervals using observation from the CLIS buoy. Mean sea level variations were prescribed in the simulation using observed water level data at the NH2 station.

For the results from the models to be comparable, both models were set up with the same forcing and the optimum time step and grid size for each model were determined by comparison to observations. In MIKE21SW, the user selects a range for time steps (the minimum and maximum) and the model automatically determines the optimum time step based on the grid size, wave propagation speed, and Courant number. The minimum time step must meet the Courant number restriction. In SWAN, the numerical scheme is unconditionally stable but it is critical to ensure that the solution has converged. Using a grid with the resolution range $dx_{max} = 350$ m and $dx_{min} = 35$ m, we found that a time step $dt = 60$ s provided the same solution as a range of smaller time steps, Figure 2a,b compare the solutions at the location of NH2 for two 24 h intervals together with the observations.

We also examined the effect of the grid generation choices. Using a grid converter, available in the MIKE21 package, and the grid generation software in the surface-water modeling system package (SMS v12) we created grids for the models using the same spatial smoothing ratio. Figure 2c,d shows the sensitivity of SWAN solutions for different grid sizes and time steps. As the grid size is decreased, the time step also must be decreased by the same factor to avoid accumulation of numerical computation errors. For the majority of storms, the grid size $dx_{max} = 350$ m and $dx_{min} = 35$ m was adequate (Figure 2c), but some storms required finer grid, (Figure 2d). Refining the grid size and time step by the factor of $\sqrt{2}$ increases the computational time at least by the factor of $\left(\sqrt{2}\right)^3 = 2.8$; therefore, it is vital that the optimum grid size be selected very carefully. The grid size $dx_{max} = 250$ m and $dx_{min} = 25$ m with time step $dt = 42$ s was found to provide the optimum condition for SWAN.

Figure 2e,f illustrates the sensitivity of the MIKE21SW solutions to grid size. Since MIKE21SW selects the optimum time step based on the grid size automatically, it is easier and faster to get to optimum condition by MIKE21SW. MIKE21SW also showed less sensitivity to grid size than SWAN, (Figure 2e,f). The result was converged for grid size with $dx_{max} = 500$ m and $dx_{min} = 50$ m.

The optimum unstructured triangular grid for each model is presented in Figure 3. The grids were smoothly refined around the breakwaters and inside the harbor.

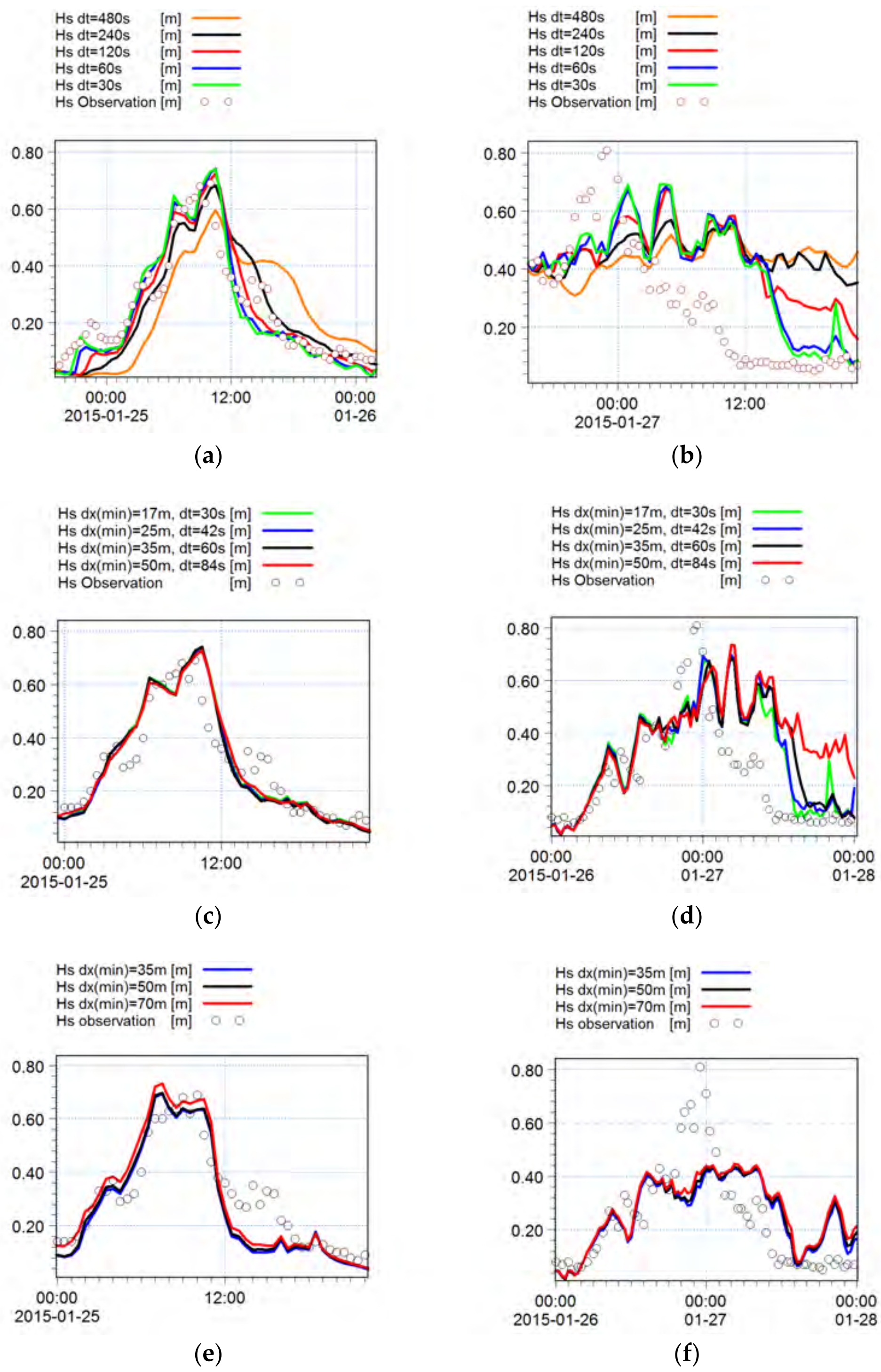
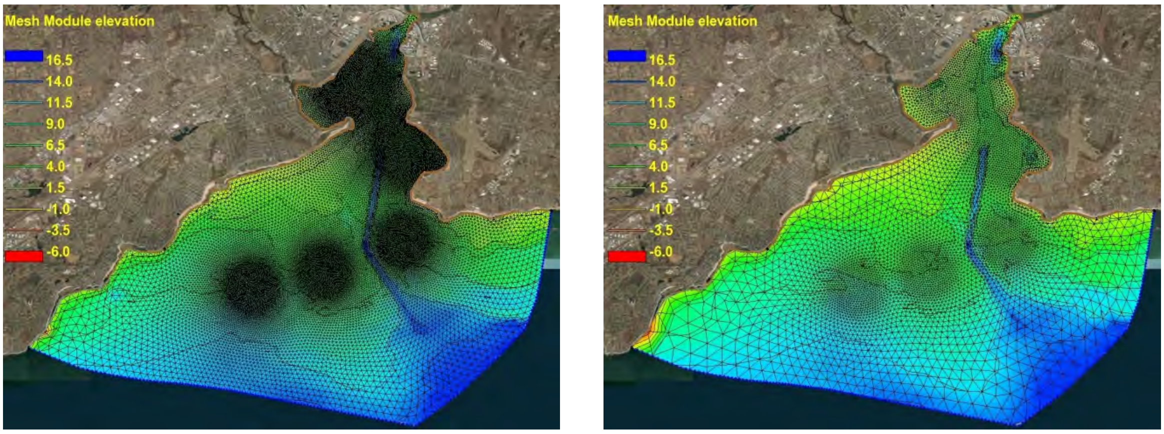


Figure 2. **(a,b)** Wave height at NH2 from SWAN time step sensitivity analysis using a grid size range dx_{max} = 350 m and dx_{min} = 35 m. The results indicate that solutions with time steps of 30 s (green) and 60 s (blue) are almost identical for this grid size. **(c,d)** SWAN solutions for grid size and time step sensitivity analysis, the solution for grid sizes less than dx_{max} = 250 m and dx_{min} = 25 m are almost indistinguishable; **(e,f)** MIKE21 SW solutions is less sensitive to grid size and with larger grid size dx_{max} = 500 m and dx_{min} = 50 m.



(a) (b)

Figure 3. The optimum unstructured triangulate grids used for (**a**) SWAN with $dx_{max} = 250$ m and $dx_{min} = 25$ m and (**b**) MIKE21SW with $dx_{max} = 500$ m and $dx_{min} = 50$ m. SWAN required a finer grid to reach the optimum condition. The spatial smoothing of the grids is the same. The grids were refined around the breakwaters, three densification zones, and in the harbor.

The models were calibrated using data from the period of 23 to 28 January. For each model, we tested settings and coefficients, and applied the set that achieved the best agreement with the observations. Both models were executed in third generation fully spectral and non-stationary mode. The same spectral discretization (25 frequencies and 16 directional discretizations) were applied to SWAN and MIKE21SW with a minimum frequency of 0.06 Hz and a maximum of 0.59 Hz. The results of MIKE21SW were tested for both first and second order numerical scheme, and no significant difference was observed between the first order and second order schemes. Consequently, in order to save computational time, MIKE21SW was run on first order. As mentioned in Section 2, the only available numerical scheme in unstructured SWAN is first order BSBT.

Options for representing the wind input source and whitecapping dissipation functions are different in the models. SWAN is configured to use the wind input source function of Janssen [15,16], as implemented in WAM cycle 4 [17]; the method of Komen [18], as implemented in WAM cycle 3 [19]; and method of Yan [20]. MIKE21SW only supports Janssen's method. Dissipation through whitecapping is based on the development of Hasselmann [21] in both Janssen's and Komen's methods; however, the coefficients are different (see Komen [12,18]). Yan's wind input method is combined with saturation-based whitecapping as described in Van der Westhuysen [22,23]. Moeini and Etemad-Shahidi [6] suggested that Komen's method led to more accurate significant wave height than Janssen's method for Lake Erie. Hoque [8] indicated Westhuysen's formulation tends to have better significant wave height in the Mackenzie Delta. We tested all three methods with SWAN. We found that Janssen's method provides the best wave height simulations in the harbor. Therefore, Janssen's wind input method was used for both models with the tunable coefficients set as $C_{ds}^* = 4.5$ and $\delta = 0.5$.

Wave dissipation due to bottom friction was represented in both models by the empirical JONSWAP [24] approach. The friction coefficients introduced by Zijlema et al. [25] were used: $C_b = 0.038\ m^2s^{-3}$ for SWAN and $c_{fw} = 0.0077\ ms^{-1}$ for MIKE21SW.

Waves breaking in shallow water was taken into account in the models using the Battjes and Janssen [26] formulation with $\alpha = 1$ and $\gamma = 0.8$. Also, triad wave–wave interactions were enabled in both models. Triad interactions in MIKE21SW are calculated based on Eldeberky and Battjes [27] and in SWAN based on Eldeberky [28], a slightly modified version of the former. Quadruplet wave–wave interactions were also enabled in the models. In both models, the quadruplet wave–wave interactions are computed with the Discrete Interaction Approximation (DIA) as proposed by Hasselmann et al. [29].

When breakwaters are present in the model domain, diffraction computations become important. Diffraction is taken into account in the models using a phase-decoupled refraction-diffraction approximation proposed by Holthuijsen et al. [1]. Diffraction computation in the models is almost the same, but a wave field smoothing technique for the computation of the diffraction parameter that is not available in SWAN with an unstructured grid.

The reflection coefficients for breakwaters were calculated using the method proposed in the Coastal Protection Manual: Part VI, [30], and originally developed by Seeling [31], for non-overtopped slopping structures with the parameter values of Davidson [32]. The reflection coefficient for the type of structure and wave climate in the study area varied from 0.47 to 0.52. Therefore, the average reflection coefficient of 0.493 was selected.

Spectral wave models adequately simulate the effects of diffraction when breakwaters are far from the coastline and have a low reflection coefficient [1]. In addition, the breakwaters should not cover the down-wave view substantially, [1]. In New Haven harbor, the distance between the breakwaters and coastline varies 4 to 5.2 km, and the separation of the breakwaters is 700 m to 1000 m, which much larger than the threshold distance [2] of twice the dominant wavelength (here $2L \cong 100$ m, where L is wave length). Also, the rubble mound breakwaters with low reflection coefficient, 0.493, create incoherent wave reflection.

The spectral wave models such as SWAN simulate wave diffraction better for the wider directional spectrum of wind-waves than for swell [2]. The wave spectra for the important storms are shown in Figure 4. The wave spectra in the harbor are directionally broad, similar to those obtained in Long Island Sound. Therefore, New Haven harbor is considered a suitable case for simulating waves using the spectral models.

4. Results

The results of SWAN and MIKE21SW models were compared and assessed inside the harbor at NH2 during all storms and at NH1 for northerly storms. We divided the observations into five storm periods, detailed in Table 2. Each of these periods is discussed separately, and then the results are summarized. The statistical parameters used for data validation are

$$Bias = \frac{\sum_{i=1}^{n}(Y_i - X_i)}{n}, \tag{2}$$

$$RMS = \sqrt{\frac{\sum_{i=1}^{n}(Y_i - X_i)^2}{n}}, \tag{3}$$

$$m = slope\ of\ the\ best\ fitted\ line, \tag{4}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(Y_i - Y_i'\right)^2}{\sum_{i=1}^{n}\left(Y_i - \overline{Y}\right)^2}, \tag{5}$$

where Y_i, with mean $\overline{Y}$, are the observed values, X_i are the simulated values, and n is the number of data points. RMS is the root mean square error, R^2 is the fraction of the variance in the data explained by the model, Y_i' is the estimated value by regression, and $\overline{Y}$ is the mean of the observed values.

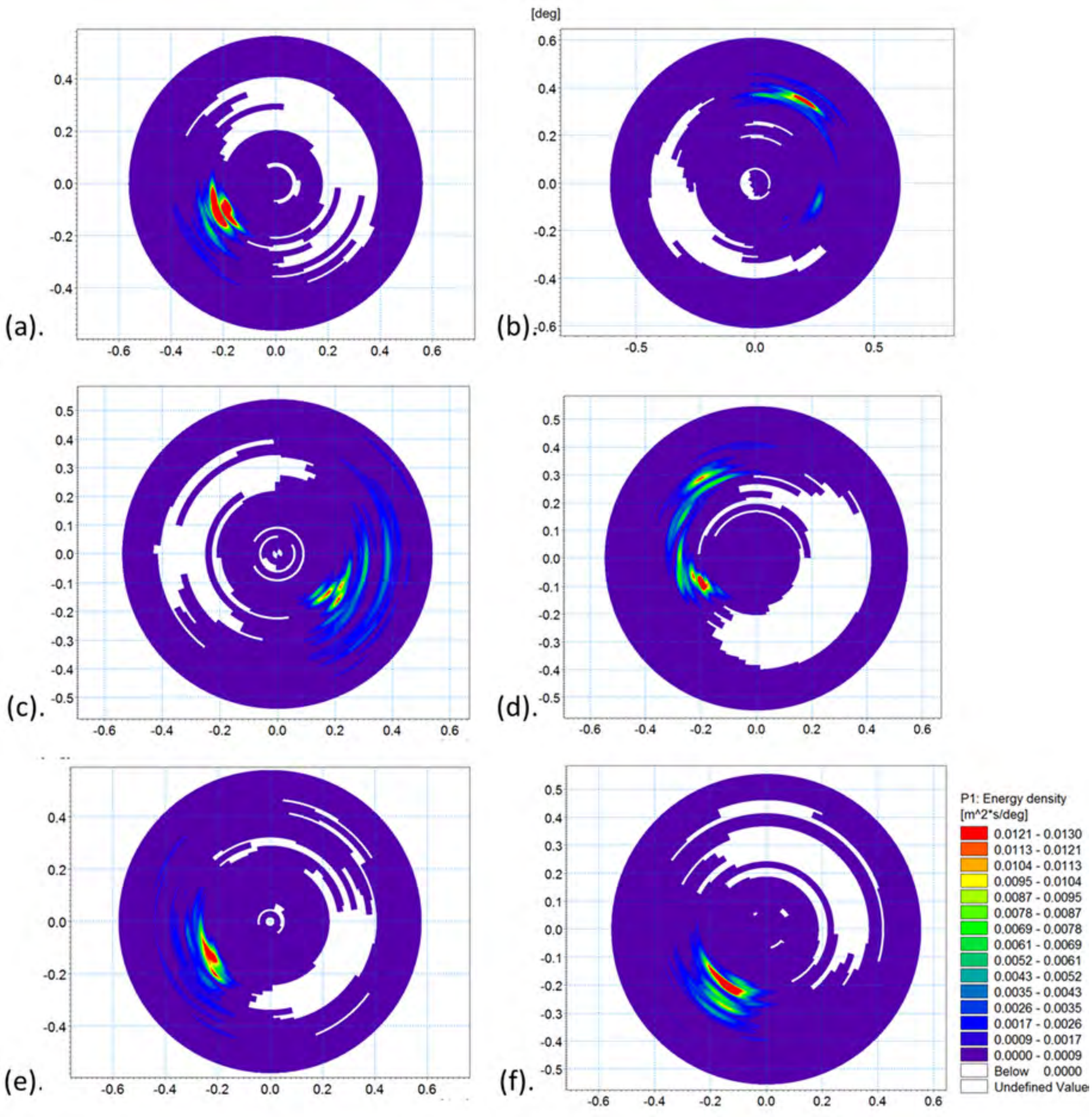


Figure 4. The two-dimensional wave spectra for important storms at NH1. As the majority of waves generates with local wind in central Long Island Sound, the spectrums are directionally wide. (**a**) 25 January; (**b**) 27 January; (**c**) 2 February; (**d**) 15 February; (**e**) 7 March; and (**f**) 2 April. The spectral wave models simulate wave diffraction for directionally wide spectrum better than directionally narrow spectrum, [2].

Table 2. Storm periods used for analyzing and assessing the models

No.	Storm Period
1	23 to 28 January
2	1 to 10 February
3	14 to 21 February
4	6 to 8 March
5	2 to 5 April

Three consecutive high wind intervals occurred during the first storm period, 23 to 28 January. Wave boundary condition and wind input data, as well as comparisons between observations and the model predictions of the significant wave height, peak wave period and wave direction for Storm

Period 1 are presented in Figure 5. The noise in observed wave periods and directions in low significant wave heights events were not included in the assessments. In this storm period, the first two storms had winds from the west and southwest. In the first storm, the predicted significant wave height (H_s) series were very similar to each other. Both missed the first part of the storm peak and under-predicted the second part by 5% (Figure 5b). Both models were able to simulate wave period and direction correctly (Figure 5c,d). In the second storm, both models reproduced the storm's entire wave height peak very well. Simulated wave period and direction for the second storm also agreed well with the observations. For the third storm, the models did not perform well. On 26 January, the storm caused easterly winds, then on 27 January, wind stress vectors suddenly turned by 90 degrees and a very strong wind (in excess of 15 m/s) blew from the north. This strong wind was adequate to generate wave in a very fetch limited area as New Haven estuary. The models showed different behavior during this storm. Simulated peak wave periods were in consistent with observations. Modeled wave directions for the first part of the storm completely agreed with observation, but after the wind vector rotated on 26 January 10 p.m., there was a 25 to 40 degrees difference between observed and simulated wave direction. The observation showed a wave direction from northeast (50 degrees), while simulated wave directions were from north. The statistical parameters show that SWAN results were slightly better than MIKE21SW for this period, (Table 3). The *Bias* in significant wave heights obtained from SWAN was 0.03 m less than that in MIKE21SW. R^2 for SWAN was 0.60 versus 0.57 for MIKE21SW. The *RMS* values were the same (0.13) and the slope of best fitted line was better for MIKE21SW (0.89) than SWAN (0.72).

Comparison of the results of the models and observations from Storm Period 2, 1 to 10 February, are shown in Figure 6. Both models showed similar behavior during this period though SWAN overestimated the strongest storm significant wave height on 2 February by 50% (Figure 6b). There was a high wind event from the north on 5 and 6 February (Figure 6a), and the models simulated the significant wave height very well (Figure 6b). In other storms, the models had very similar behavior, both missed some small oscillations and overestimated others. The models correctly simulated the peak wave period and mean wave direction, (Figure 6c,d). Statistical parameters for this period did not present any substantial preference of the models, *Bias* and R^2 were better for SWAN and *RMS* and m were better for MIKE21SW (Table 3).

Three storms occurred in the third period, from 14 to 21 February. As shown in Figure 7, the models accurately simulated the first storm. The second storm started with a wind from north to south and it then rotated to the east. MIKE21SW accurately simulated significant wave height in the first part of the storm but later produced overestimates. In contrast, SWAN overestimated significant wave height over the whole storm duration. Both models provide poor estimates of the wave period for the second part of the storm. For the third storm, both models successfully simulated the wave height, period, and direction, however, MIKE21SW slightly under-predicted the first part. Overall, *RMS* error was 0.03 lower, the slope of the best-fitted line was 0.11 higher, and R^2 was 0.01 higher for MIKE21SW. The magnitude of *Bias* values were the same (0.02) but with opposite signs, (Table 3). Therefore, MIKE21SW results were slightly more accurate than SWAN for this time period, mostly due to better simulation of the second storm.

In the fourth storm period, both models failed to correctly simulate significant wave height variations between 6 and 8 March, as shown in Figure 8. The storm includes two peaks in significant wave height, but the models underestimated both (Figure 8b). However, they correctly estimated wave periods and directions (Figure 8c) and the statistical parameters show similar model performance. There was two hours delay in storm growth in both models. The storm started at 3 March 03:00 p.m., according to observations, but 05:00 p.m. in the models. Also, there was no difference between wind speed at 03:00 and 05:00 p.m. (both around 5 m/s, Figure 8a). Some statistical parameters, such as R^2, were better for MIKE21SW and others, such as *Bias*, for SWAN (Table 3).

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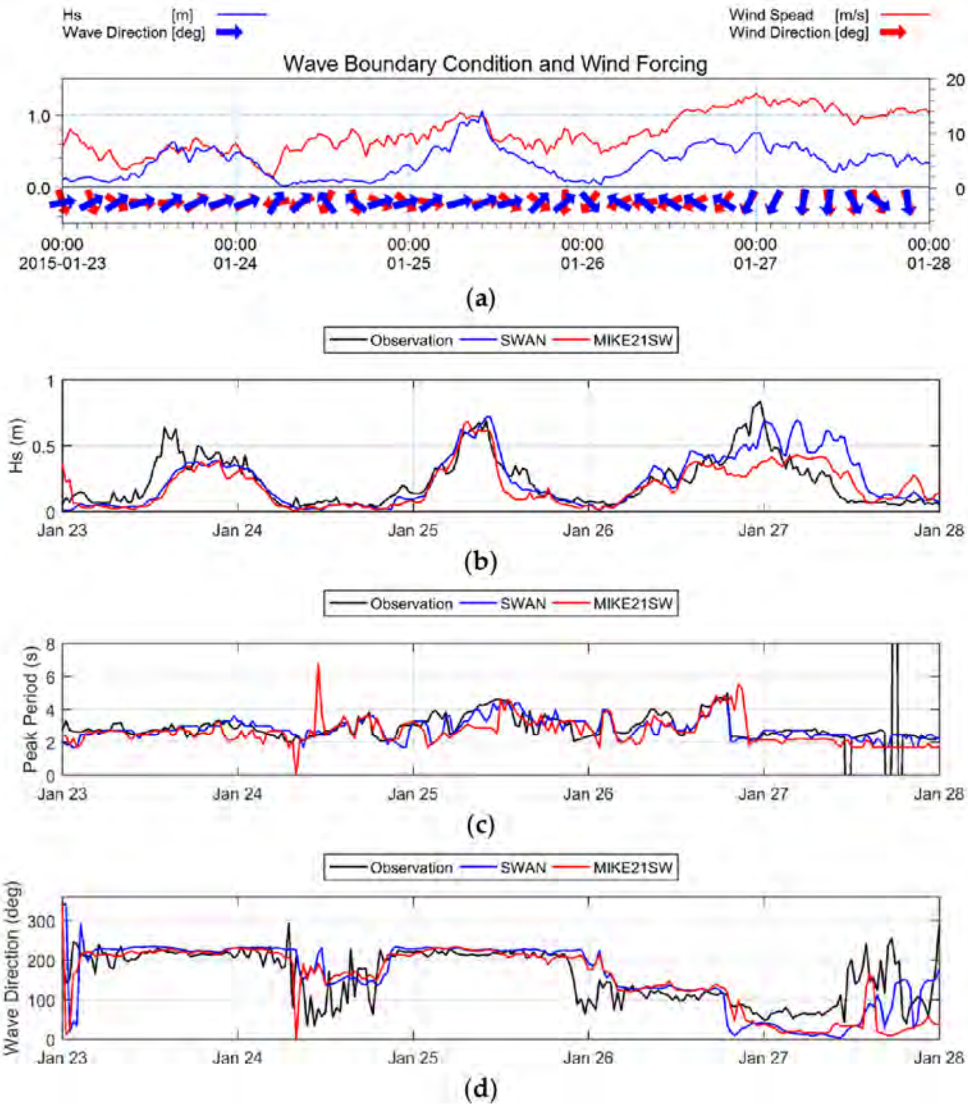

Figure 5. (**a**) Wave boundary condition and wind input for the time interval of 23 to 28 January. Blue: significant wave height (left axis), blue arrow: wave direction at the boundary, red: wind speed (right axis), red arrow: wind direction. (**b–d**) Comparison of SWAN (blue), MIKE21SW (red), and observation (black) at NH2 for the time interval of 23 to 28 January. (**b**) Significant wave height. (**c**) Peak wave period. (**d**) Mean wave direction. The models had good performance for the first two southerly events but not for the third event which was from the north.

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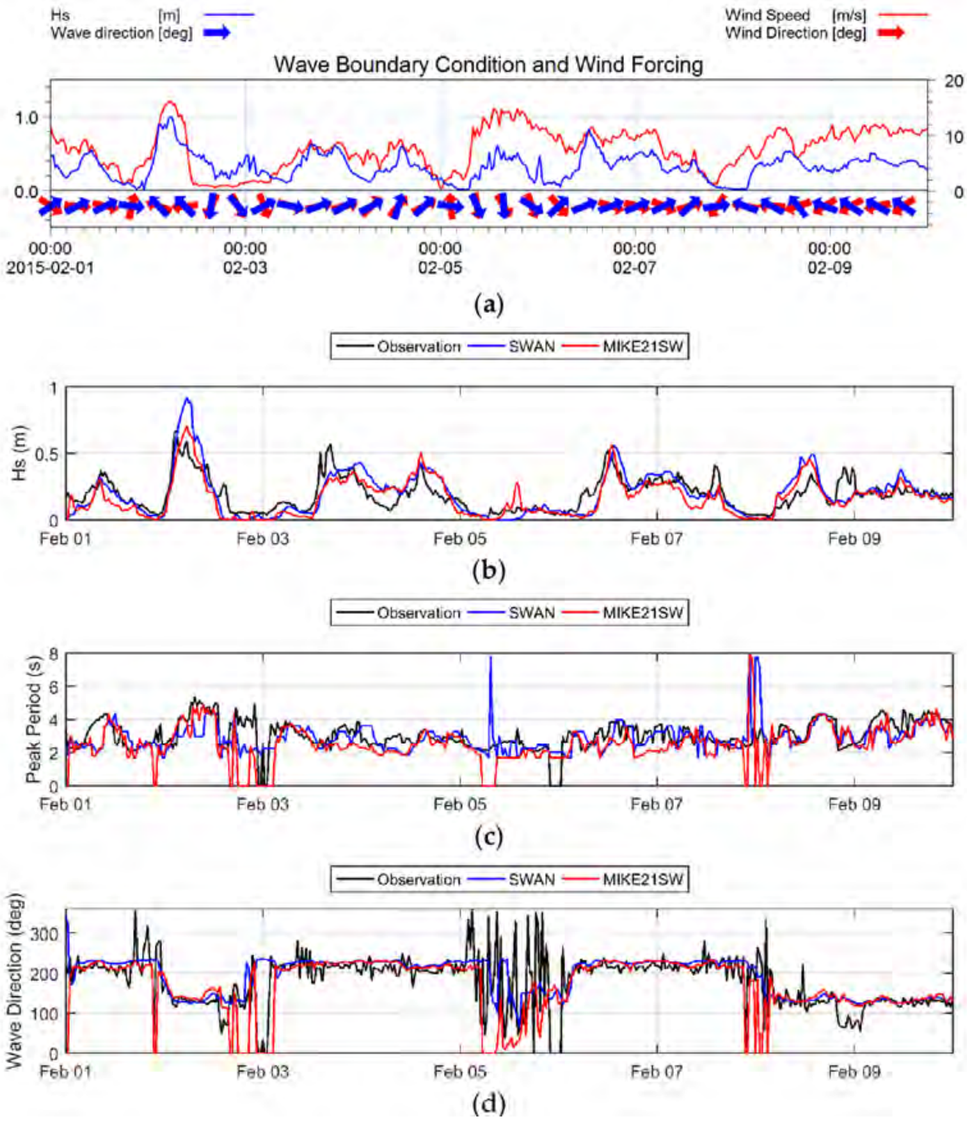

Figure 6. (**a**) Wave boundary condition and wind input for the time interval of 1 to 10 February. Blue: significant wave height (left axis), blue arrow: wave direction at the boundary, red: wind speed (right axis), red arrow: wind direction. (**b**–**d**) Comparison of SWAN (blue), MIKE21SW (red), and observation (black) at NH2 for the time interval of 1 to 10 February. (**b**) Significant wave height. (**c**) Peak wave period. (**d**) Mean wave direction. The models had good performance for this period though SWAN overestimated the strongest storm on 2 February.

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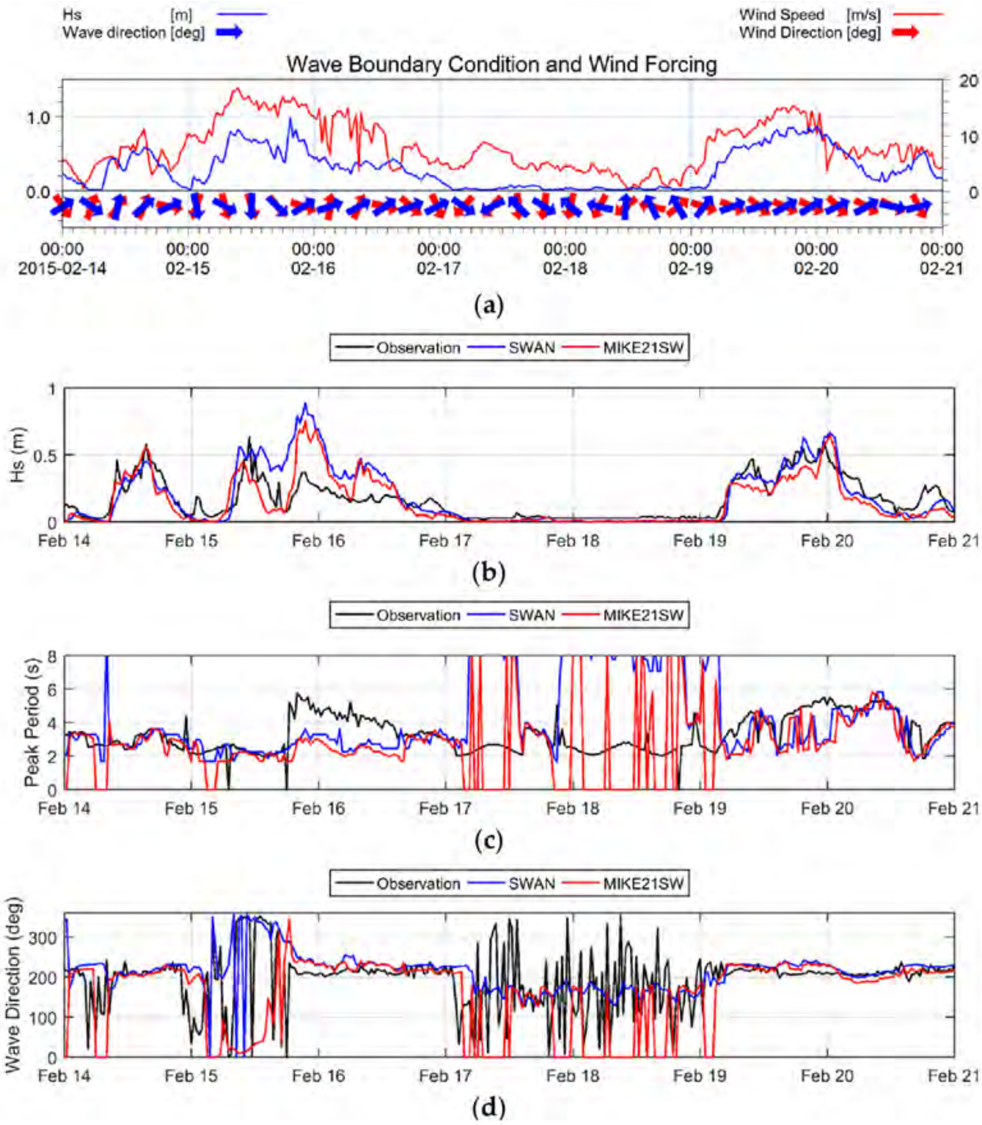

Figure 7. **(a)** Wave boundary condition and wind input for the time interval of 14 to 21 February. Blue: Significant wave height (left axis), blue arrow: wave direction at the boundary; red: wind speed (right axis); red arrow: wind direction. **(b–d)** Comparison of SWAN (blue), MIKE21SW (red), and observation (black) at NH2 for the time interval of 14 to 21 February. **(b)** Significant wave height; **(c)** Peak wave period; **(d)** Mean wave direction. During the second storm, when the wind direction changed from north to south to east to west, the simulations were poor.

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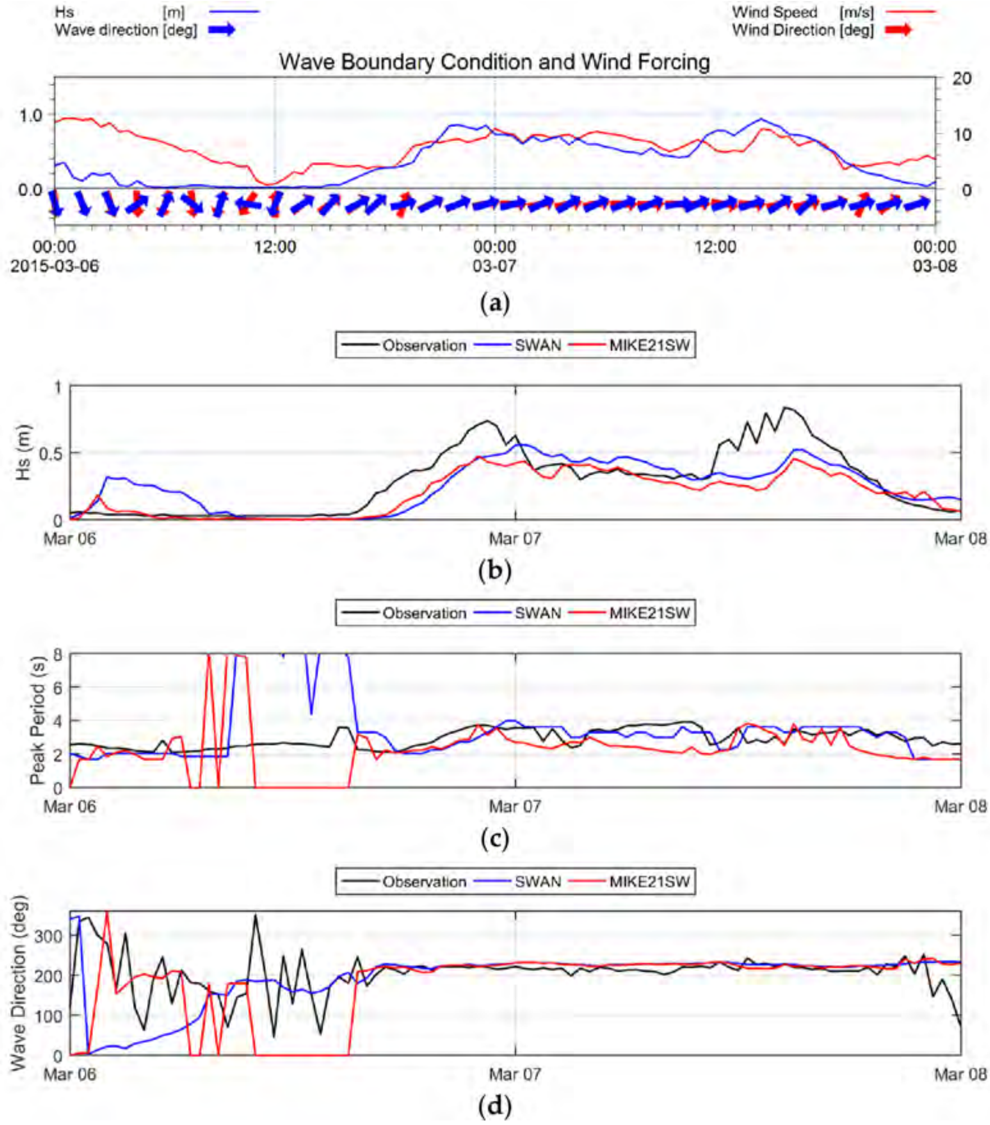

Figure 8. (**a**) Wave boundary condition and wind input for the time interval of 6 to 8 March. Blue: significant wave height (left axis), blue arrow: wave direction at the boundary, red: wind speed (right axis), red arrow: wind direction. (**b**–**d**) Comparison of SWAN (blue), MIKE21SW (red), and observation (black) at NH2 for the time interval of 6 to 8 March. (**b**) Significant wave height. (**c**) Peak wave period. (**d**) Mean wave direction. Both models did not do well during this time interval. A two-hour delay in storm growth was significant in models results.

Results from Storm Period 5 are illustrated in Figure 9, showing the assessment of the models results during the storm took place on 2 and 3 April. MIKE21SW was able to catch the storms highest wave height and correctly computed wave period and direction during the storm. SWAN slightly underestimated the first part of the storm and there was a short delay in storm growth (Figure 9b). Statistical parameters were slightly better for MIKE21SW with $R^2 = 0.81$ versus SWAN results with $R^2 = 0.77$. RMS was better for MIKE21SW and the slope of best-fitted line was better for SWAN (Table 3).

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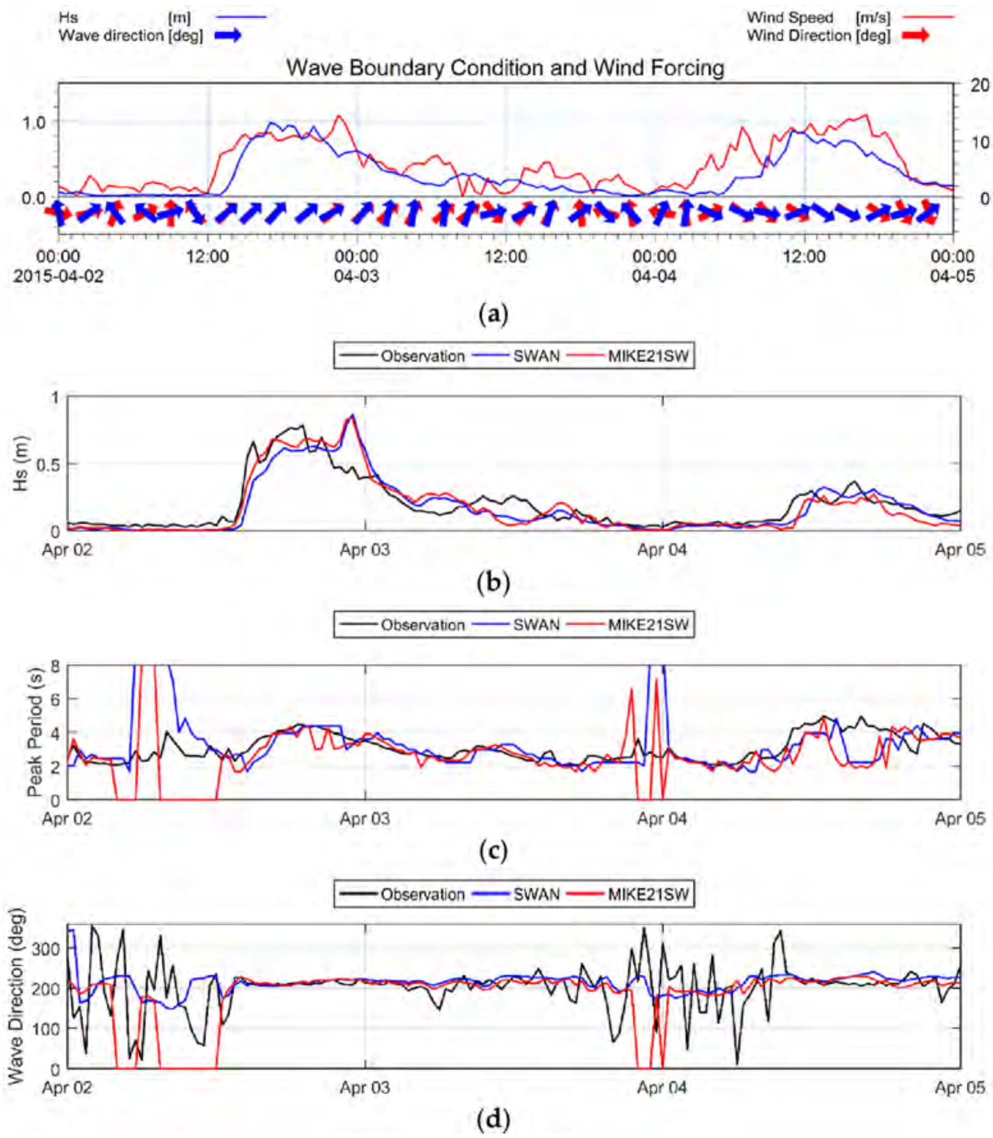

Figure 9. (**a**) Wave boundary condition and wind input for the time interval of 2 to 5 April. Blue: significant wave height (left axis), blue arrow: wave direction at the boundary, red: wind speed (right axis), red arrow: wind direction. (**b**–**d**) Comparison SWAN (blue), MIKE21SW (red), and observation (black) at NH2 for the time interval of 2 to 5 April. (**b**) Significant wave height; (**c**) Peak wave period; (**d**) Mean wave direction. Both models performed well for this storm period, but MIKE21SW was slightly better during the first part of the storm on 2 March.

We compare all storm simulations to data in Figure 10. *Bias* was better for SWAN. *RMS* of MIKE21SW was 0.01 lower than *RMS* obtained from SWAN results. The slope of best-fitted line for MIKE21SW was closer to one. R^2 of the models' results were almost the same, 0.61 for MIKE21SW versus 0.60 for SWAN. Therefore, the statistical parameters suggest the performance of both models were good and the models' results had a lot of similarity.

The model predictions did not agree with observation at NH2, inside the harbor, for two northerly storms, 27 January and 15 February. To assess whether the errors were due to the wind speed magnitude being too high, we compared the results of the models to data obtained at NH1, at the boundary of the model domain (Figure 11). Note that since wave energy was propagating out of the domain during northerly wind the boundary observations were not influencing in the predictions. Both model results were biased high relative the observation at NH1 with the SWAN results having a larger bias (Figure 11a). However, both models were more correlated with observations at NH1 than at NH2. Both models did a better job for the second northerly event on 15 February. SWAN showed lower errors early in the simulation but both models overestimated the

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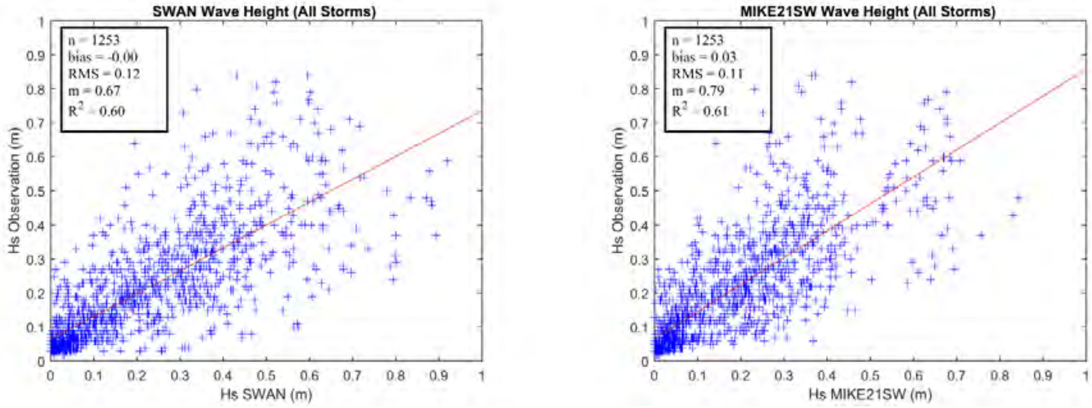
than at NH2. Both models did a better job for the second northerly event on 15 February. SWAN showed a lower bias early in the storm, but both models overestimated the significant wave heights later in the storm just as they did in the interior of the Harbor at NH2. This may be a consequence of overestimation of the wind stress, however, the reduced correlation in the model and data time series cannot be explained by the magnitude bias alone.

Table 3. Comparison of statically parameter between SWAN and MIKE21SW. Statistically, there was no substantial difference between the performance of the models. SWAN performance was better for the storm periods 23 to 28 January while MIKE21SW for 14 to 21 February and 2 to 5 April.

Storm Period	SWAN					MIKE21SW				
	n	$Bias$	RMS	m	R^2	n	$Bias$	RMS	m	R^2
23 to 28 January	241	−0.01	0.13	0.72	0.60	241	0.04	0.13	0.89	0.57
1 to 10 February	433	0.00	0.10	0.60	0.62	433	0.03	0.09	0.69	0.60
14 to 21 February	337	−0.02	0.14	0.55	0.60	337	0.02	0.11	0.66	0.61
6 to 8 March	97	0.03	0.16	1.03	0.56	97	0.09	0.16	1.33	0.73
2 to 5 April	145	0.02	0.10	0.83	0.77	145	0.02	0.09	0.79	0.81
All Storms	1253	0.00	0.12	0.67	0.60	1253	0.03	0.11	0.79	0.61



(a) (b)

Figure 10. Comparison of scatter plot and statically parameter between observed and simulated significant wave heights from SWAN (**a**) and MIKE21SW (**b**) for all storms. There was no substantial difference between the performance of the models. $Bias$ was better for SWAN and RMS, the slope best fitted line and R^2 were better for MIKE21SW.

Figure 12 displays the variation of significant wave height over the model domain for three storms on 25 January (wind from the southwest), 27 January (wind from the north), and 2 February (wind from the southeast). Unfortunately, as the output format of the models were different, we were not able to plot them with the same tools, therefore, the color bars scales are slightly different. The models had similar behavior over the domain on the southern storms (Figure 12a,b), but different on the northern storm (Figure 12c,d). Also, it can be implied that MIKE21SW dissipates wave energy around the breakwaters more than SWAN, it may be the reason of the SWAN overestimation on 2 February.

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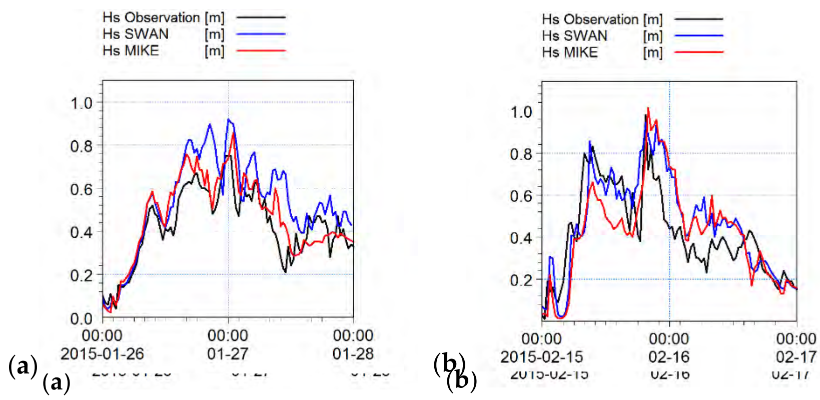

Figure 11. Comparison of significant wave height for two northerly storms at NH1 station outside the harbor. SWAN (blue), MIKE21SW (red), and observation (black) (**a**) 26 to 28 January. (**b**) 15 to 17 February.

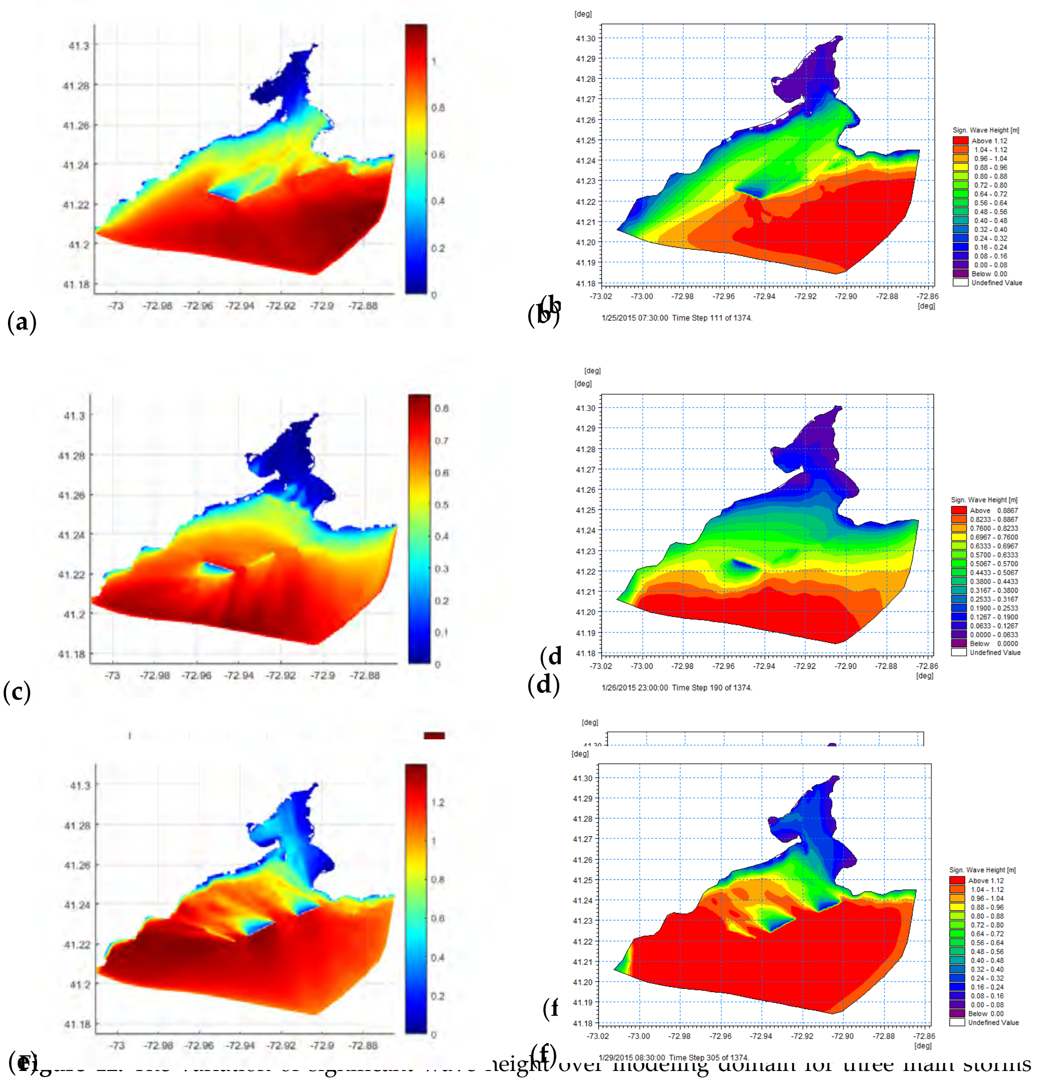

Figure 12. The variation of significant wave height over modeling domain for three main storms from the southwest, north, and southeast. (**a**) SWAN, 25 January, storm from the southwest; (**b**) MIKE21SW, 25 January, storm from the southwest; (**c**) SWAN, 27 January, storm from the north; (**d**) MIKE21SW, 27 January, storm from the north; (**e**) SWAN, 2 February, storm from the southeast; (**f**) MIKE21SW, 2 February, storm from the southeast. Note: the color bar scales are slightly different for SWAN and MIKE21SW, as they were plotted by different tools.

5. Discussion

In total, 14 storms occurred in New Haven harbor during the observation period in the winter of 2015 and the models simulated similar wave fields in most of them. Both models had very good statistical performance when storm winds blew from the south, when the breakwaters are most influential. SWAN predicted the peak significant wave height for one storm (on 18 February) better than MIKE21SW, while MIKE21SW simulated three storms (on 2 February, 15 February, and 3 April) better than SWAN. The worst performance during southerly wind storms was the SWAN results for 2 February when the model overestimated the peak significant wave height by 50%. Figure 12e suggest that the wave sensor was close to a region of high spatial gradient in the significant wave height during this storm and, therefore, slight differences in diffraction and propagation led to large differences in model solution values. The worst performance of MIKE21SW was on 18 February when the peak significant wave height was underestimated by 25%. In other storms the models had similar behavior. Notably, both models underestimated the storm peak on 7 March by 60%.

To further understand the sensitivity of the models results to different physical processes we ran the simulations with the wind forcing eliminated; zero reflection from the breakwaters; with diffraction disabled; and with the breakwaters entirely removed. Figure 13 shows the results of these simulations at NH2.

Figure 13a,d show the observations (+symbols) and solutions at NH2 for the 25 January storm with SWAN and MIKE21SW when the wind blew from the south. The agreement between the black lines and the +symbols shows that both models performed well. The differences between the black and blue lines shows that the influence of the wind over the harbor is significant and increases the peak significant wave height during the storm by 50%. Comparison of the black line to the magenta, green, and red lines show that the next most important process is the presence of the breakwaters. Eliminating them increases the peak significant wave height by approximately 15% in SWAN and 30% in MIKE21SW. Figure 13b,e shows the same properties for the 2 February storm period when the wind was from the south east. Since the performance of both models were not as good, due to high spatial gradients near the location of the wave sensor, the comparison of the result with (black line) and without local wind forcing (blue line) shows again that the local wind can increase the peak significant wave height by approximately 50%. Similarly, removing the breakwaters increases the peak wave heights as in Figure 13a,d, by comparable amounts. We note that the presence of breakwaters appears to be more significant in MIKE21SW than SWAN. The spatial distributions of wave height in Figure 12 also indicate this difference in model performance.

Comparison of the green and red lines with the black lines in Figure 13a,b,d,e illustrates that the effects of diffraction and reflection influenced the significant wave height at NH2 by less than 5 percent in both models. NH2 is approximately 2 km (or 40L, where L is the dominant wave length) away from the breakwaters. This is consistent with [2] which concluded that reflection and diffraction effects are insignificant far away the breakwaters.

Figure 13c,f show the data and solutions for the 27 January storm when the wind was from the north. As expected, comparison of the black and blue lines shows that in the absence of wind forcing the significant wave height drops to zero. The other effects do not play a large role in the model predictions though reflection, also, has a maximum effect of 7%. These results highlight the importance of wind in this case study, which is a large harbor with fetch length varies from 5 km to 7 km.

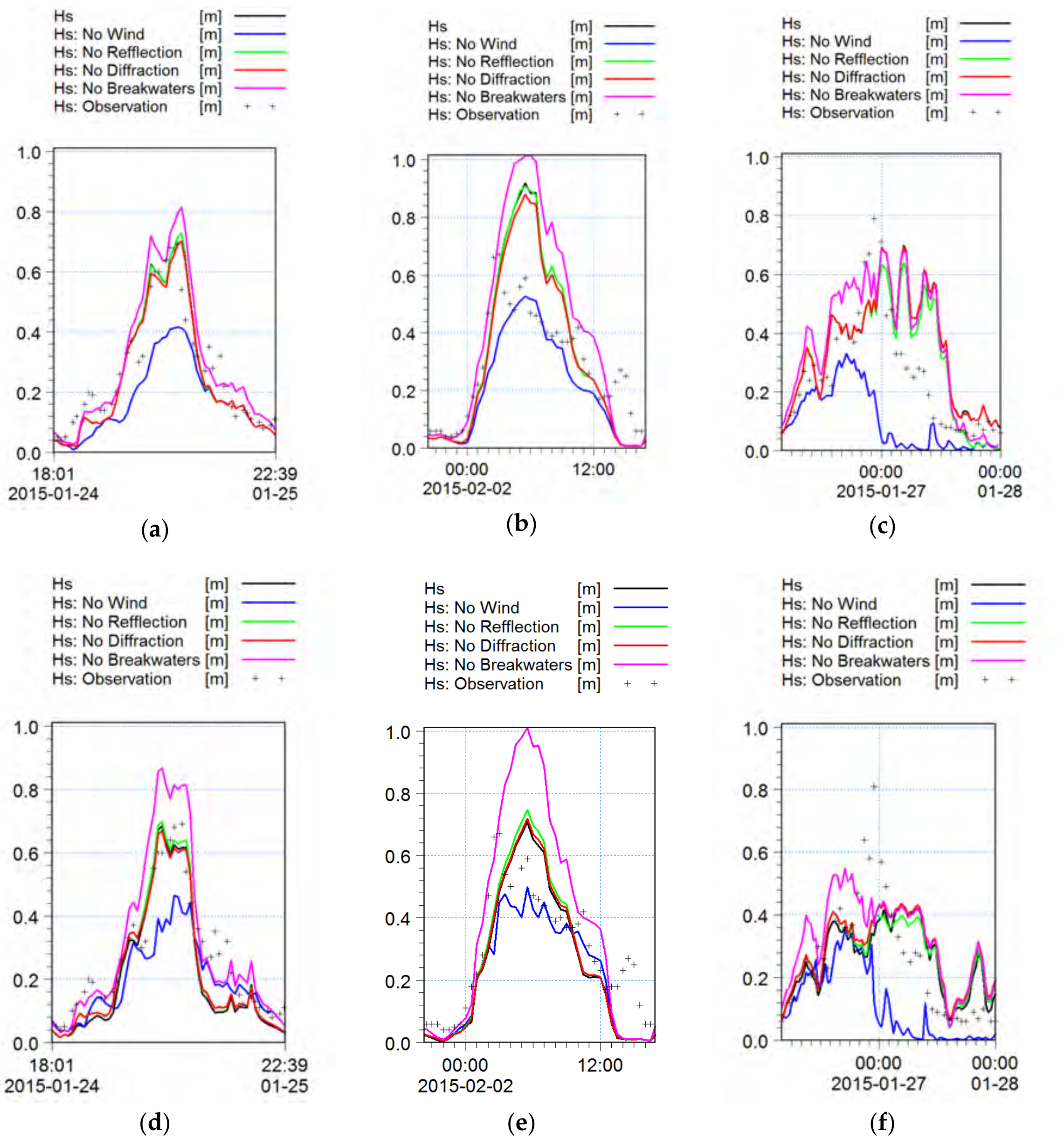

Figure 13. Sensitivity of the models to wind, reflection, diffraction module, and the breakwaters. Black: the model results considering all processes. Blue: The model results without wind forcing. Green: the model results without reflection from the breakwaters. Orange: the model results with disabling diffraction module. Pink: the model results with removing the breakwaters. (**a**) SWAN, 25 January; (**b**) SWAN, 2 February; (**c**) SWAN, 27 January; (**d**) MIKE21SW, 25 January; (**e**) MIKE21SW, 2 February; (**f**) MIKE21SW, 27 January.

In some events, such as 6 April and 6 March, a delay in the growth of the waves was observed in the models results, however, the delay in SWAN results was about one hour more than MIKE21SW results. There were three events (27 January, 5 February, and 15 February) with high winds from the north and the models did not deliver good simulations in two, 27 January and 15 February. These events were accompanied with 90-degree rotation of wind vectors during the storm. This inconsistency may be a consequence of the uncertainty in the difference between the wind observed at the buoy and that over the harbor. The wind observation station is located about 20 km away from the coastline. When wind blow from the coast (from the north), the wind boundary layer near the coastline become very complex. This complexity may not be observed at the wind station located 20 km away from the coastline. In addition, the significant wave height evaluation outside the harbor for northerly storms, Figure 11, demonstrates that the models overestimate the significant

Figure 11, demonstrates that the models overestimate the significant wave height when winds were from the north. It implies that, for northern storms, winds at CLIS are more intensive than New Haven. Also, New Haven estuary has a complex geometry. Consequently, a small change in wind direction can change the fetch length drastically. For example, for NH2 station, a wind blowing from 10 degrees has more than double fetch length of the wind from the north, (Figure 1). The inconsistency of the models with observation for a very small fetch length with strong wind condition needs more investigation. This requires a local high frequency wind and wave observation to record precisely oscillation in wind speed and direction.

Another possible source of error is that a spectral wave model cannot simulate wave resonance due to reflected waves from the harbor edges and breakwaters. Figure 4b,d show spectra for 27 January and 15 February, when the models failed to accurately simulate the wave field, there were two waves, a low frequency wave from the south and high frequency waves propagating from the north. In this situation, reflection could have significant role. To observe these effects more accurately, multiple high frequency wave observation stations in the harbor would be required. The wave spectra shown in Figure 4 are not confined to a narrow range of directions and, in some events such as 2 February, the spectrum has multiple peaks. For this storm SWAN overestimated the wave height by 50%. Both models under-predicted significant wave heights during the storm on 7 March. In this event, the wave spectrum, also, have two peaks (Figure 4e). The models had good performance for the two-peak storm on 25 January, however, this storm had two peaks from the same direction but different frequency. The models may have lower accuracy in the events that the wave spectrum have multiple peaks at different directions, but that is not always the case as MIKE21SW well predicted the storm on 2 February with multiple spectrum peaks. Further investigation is required.

The influence of currents on waves was not considered in this study. Current can be considered in the modeling using a coupled hydrodynamic-wave models such as FVCOM-SWAVE, ADCIRC-SWAN, XBEACH [33,34], and MIKE21 Coupled Model. This effect should be considered in modeling in forthcoming studies. Another uncertainty in the results can be due to uncertainty in the model wave boundary condition. Though we used the observed wave spectra, instead of a model or parametrization, to prescribe the open boundary condition, it is possible that there are periods when there is variation in wave conditions along the boundary. Multiple wave sensors would be needed to assess that possibility and we hope to evaluate it in the future.

Besides the accuracy of the model, the efficiency and simplicity of the models are important in assessment of the model utility. SWAN is much more efficient computationally than MIKE21SW. SWAN executes the same model grid and configuration using the same computational engine much faster than MIKE21SW. Although SWAN is equipped with a fast-computational algorithm, the total computational time of the models in the optimum conditions was almost the same. SWAN requires much finer mesh to reach the optimum condition. In this study, the grid size of the mesh used for SWAN ($dx_{max} = 250$ m and $dx_{min} = 25$ m) was half of the grid size of the mesh used for MIKE21SW ($dx_{max} = 500$ m and $dx_{min} = 50$ m). Getting to the optimum condition with MIKE21SW was faster than SWAN. MIKE21SW automatically selects the optimum time step based on the grid size. User just needs to assign the minimum and maximum time steps. In addition, MIKE21SW showed less sensitivity to grid size than SWAN. Therefore, finding the optimum condition in MIKE21SW needs fewer number of sensitivity simulations than SWAN.

The time integration and spatial discretization method employed in SWAN and MIKE21SW play the main role in determining the differences in the results and efficiency. MIKE21SW uses an explicit Euler scheme for time integration with cell-centered finite volume when computing wave propagation while SWAN uses a fully implicit method for time integration with finite difference first order BSBT scheme. This study suggests that the method used in SWAN is computationally much faster but it is more sensitive to spatial resolution and requires much finer mesh.

The application of the spectral models for simulation of waves inside the harbor in the presence breakwater is questioned by some authors [1,2,35]. This implies that the spectral models are not suitable for small ports with narrow connections to the ocean. However, in situations in which breakwaters have low reflection coefficients, are far enough the shoreline and do not shade a significant portion of the basin [1] spectral models may be useful as we have demonstrated in this work. In situ observations and sensitivity analyses are extremely valuable in assessing model effectiveness at all sites.

6. Conclusions

SWAN and MIKE21SW are two spectral wave models that solve the wave action balance equations. Although there are lots of similarities in both the main equations and wave source terms, they have some minor differences in the algorithms used to obtain solutions that impact both the results and efficiency of the models. SWAN and MIKE21SW were assessed on the unstructured grid and inside a harbor in the presence of three detached breakwaters. This study suggests the results of the models were consistent with observations during the storms which were affected by breakwaters. The R^2 was approximately 0.6 for both models. Considering the complexity of the modeling domain, the results are quite acceptable. The models behaved similarly in most events, MIKE21SW slightly better simulated significant wave height at storm peaks in some events. SWAN required the finer grid to get to the optimum condition, but as it uses the faster computational algorithm, the total computational time for their optimum condition was almost the same. MIKE21SW automatically selects the efficient time step based on grid size and it was less sensitive to grid size than SWAN. Therefore, the optimum condition of MIKE21SW was reached with fewer sensitivity simulations. Both models performed poorly for when high wind blew from the coast to sea. It is likely that this was a consequence of inadequate resolution of the wind field, though further observations and investigations will be required to fully understand that result. The sensitivity analysis demonstrates the wind effect was significant on the results due to large fetch length in the harbor. This is also the reason for using the spectral models for this case study. Also, it has been shown that, in MIKE21SW simulation, the breakwaters dissipate wave energy slightly more than the breakwaters in SWAN simulation.

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Coastal Storm Surge and Precipitation in Coastal Connecticut: a Preliminary Assessment

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Abstract

We examine observations of sea level and precipitation at Bridgeport, CT, to characterize the likelihood of flooding resulting from both precipitation and coastal storm surge. Data obtained from national archives show that anomalous sea level and precipitation levels are uncorrelated. High values (greater than the 10% per year return levels) of rainfall have not been observed to co-occur with his sea levels since the joint probability is low. However, likely sea level rise will substantially increase the frequency of high sea levels and, even without changes in the precipitation, substantially increase to probability of the joint probability of high sea level and high precipitation. A careful reassessment of the effectiveness of existing storm water management systems in coastal towns will be necessary, especially in areas that have recently been subject to flooding by rainfall..

1. Introduction

Climate change and sea level rise will lead to increases in the risk of flooding in all coastal areas. The designs of strategies and choices among plausible options, for flood risk reduction must be informed by statistics of sea level fluctuations and precipitation rates. The level, H_{100}, that has a likelihood of 1/100 of being exceeded in any year is frequently used for design and planning. At Bridgeport, CT, for example, NOAA (https://tidesandcurrents.noaa.gov/est/stickdiagram.shtml?stnid=8467150) estimate that $H_{100} = 9.08\ ft$, relative to the datum NAVD88. Similarly, a variety of rainfall statistics are published by the National Weather Service (NWS) at https://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html?bkmrk=ct for Connecticut and at Bridgeport the a daily rainfall total of 7 inches has a 1/100 probability of being exceeded.

The design of coastal flood defenses often include the construction of walls or berms around the coastline. However, that may reduce the rate of runoff of rainwater and resilience projects must then include storm water management. Whether retention ponds or pumps are required, and their design and capacity, will generally depends upon the joint probability of the exceedance of thresholds in both precipitation and sea level. There have been few studies of these statistics. This paper use observations from Bridgeport, CT, to develop a methodology to characterize the risk of coastal flooding. In the following section we describe the data sources and the character of the observations. We then present an analysis, summarize the results and discuss implications and priorities for further work.

2. Sea Level and Precipitation Data

Observations of sea level have been acquired at hourly intervals at Bridgeport harbor by the National Oceanic and Atmospheric Administration (NOAA), and predecessor agencies, since 1968 and are shared through a convenient interface at https://coastwatch.pfeg.noaa.gov/erddap/tabledap/. The observations were adjusted to the North American Vertical Datum of 1988 (NAVD88) and displayed in Figure 1. The highest value reached in each calendar day were identified and these are shown in by the red '+' symbols. The long-term trend associated with increasing global mean sea level was estimated by linear regression and is shown by the thin red line. The trend was then subtracted from the daily maxima for the return interval analyses. Note that the elevations should be adjusted for future mean sea levels when used to evaluate future risk.

The $M = 17965$ daily maxima, η_i, constitute 49.2 years of observations. These were indexed by increasing magnitude (i.e. $i = \{1, \dots M\}$) and then plotted in Figure 2 as $\eta_i(T_i)$, where $T_i = 49.2 \times (i + 1)/M$ in order to construct an empirical return interval diagram. The inverse of the return interval T_i represents the probability of that the sea level will exceed η_i in any year. NOAA's Mean High High Water (MHHW) is shown by the dashed red line and the 1 and 10 year return elevations are shown by the green triangle and the blue diamond. Since data at long return intervals are sparse, mathematical functions are generally used to smooth and extrapolate $\eta_i(T_i)$. Zervas (2013) explains this approach in great detail. The red square on the right of Figure 2 shows the NOAA, Zervas (2013), extrapolated estimate of $\eta(T = 100)$, i.e. the hundred year or 1% flood level. Note that a variety of choices for the smoothing and extrapolation function are in use and these lead to small differences between the levels adopted by the Federal Emergency Management Agency (FEMA) and NOAA. An alternative method was employed by O'Donnell and O'Donnell (2012). Since the uncertainty in large at the 100 year level, differences between these methods is not significant.

The NOAA National Climatic Data Center archives precipitation observations are numerous stations in the United States. Menne et al. (2012) describes the data validation procedures and the database format. Figure 3 shows the measurements of the 24 hour precipitation totals available at the Sikorsky Memorial

Airport in Bridgeport, CT. A total of 24660 values, P_i, equivalent to 67.6 years, are shown. No precipitation was reported on 68% of these days. Using the same approach as discussed above, the return interval diagram for daily precipitation, $P_i(T_i)$ where $T_i = 67.6 \times (i+1)/M$, was constructed and is shown in Figure 4. The red square shows the NWS estimate of $P(T = 100)$ and the green triangle and blue diamond again show the P(T=1) and P(T=10) year 24 hour precipitation totals.

3. Joint Probability Analysis

To examine the co-occurrence of high precipitation at times of anomalously high water the overlapping interval of two series, shown in Figures 1 and 3, were identified and plotted in Figure 5. Note that the maximum sea level on days when the rainfall was zero are shown on the horizontal axis by red squares and the level of the Mean High High Water (MHHW) is shown by the green line. A total of 16805 days (46 year) are plotted. The data evidently cluster between daily maximum elevations of 2 and 6 feet and below 2 inches of daily precipitation. There is little evidence in Figure 5 that there is correlation between the occurrence of precipitation and high water levels.

Rainfall was recorded on only 22 days in which the sea level exceeded the 1 year return interval of 6.1 ft. These points are to the right of the dashed red vertical line in Figure 5. The data, therefore, suggest that the probability of rainfall on days when the sea level exceeds 6.2ft NAVD is approximately 0.1 % each year. The maximum value of the precipitation on those days was less than 2 inches. It is also clear in Figure 5 that on all the days during which the precipitation exceeded the 1 year return level (points above the dashed horizontal red line) the high water level was below the 1 year return level (i.e. to the left of the dashed red vertical line).

4. Discussion and Conclusions

This data analysis shows that there is no evidence in the observational record at Bridgeport, CT, a station that has long data records and is representative of coastal Connecticut, that the occurrence and extreme values of high sea level and 24 hour precipitation are correlated. All days with anomalously high precipitation occur when the maximum sea level is in the normal range (i.e. less than the annual return level). This suggests that the design for high rainfall events should not necessarily anticipate the need to accommodate a very high sea level as well. Further, this result suggest that the construction of an empirical joint probability distribution function, analogous to that developed in O'Donnell and O'Donnell (2012) would be useful. It must be noted that though the data records at Bridgeport, CT, are quite long relative to most other sites, they are inadequate to describe low probability events. It is also important to note that high precipitation rates do not lead to flooding everywhere. The local geomorphology and development patterns play important roles. Project plans should consider the potential consequences of extremely unlikely events.

There is strong scientific evidence that the global mean sea level is likely to rise in the future as the climate warms. O'Donnell (2018) studied data from the Connecticut shoreline and the results of global change models and recommended that coastal towns anticipate that the mean sea level in 2050 will be up to 20 inches above the mean of the interval 1983-2001 (the National Tidal Datum Epoch). Similarly, the Connecticut Physical Science Assessment Report (Seth et al., 2019) examined the predictions of a wide range of models for future precipitation and temperature changes in Connecticut. They found that the mean of the model projections for the annual precipitation in Connecticut in 2050 to be 4 inches per year above current levels. They also used downscaling approaches to project changes in the 24 hour precipitation level with a 10 year return interval and found that an increase of 2 inches per day.

If we assume that the statistics of the variability of sea level remain unchanged as the mean level increases, we can estimate the increase in the probability that the sea the level will exceed the current 10 year return level (7.4 ft) by simply adding 20 inches to the observed data and constructing a revised return interval diagram. The result is that the 7.4 ft level will be exceeded 2.5 times per year. Further, the probability that it will rain on days that the sea level exceeds 7.4 ft increases from 0.1% to 5.7%. Note that this factor of 50 increase in the probability occurs even without an increase in rainfall. This will require an assessment of the effectiveness of existing storm water management systems in the coastal zone.

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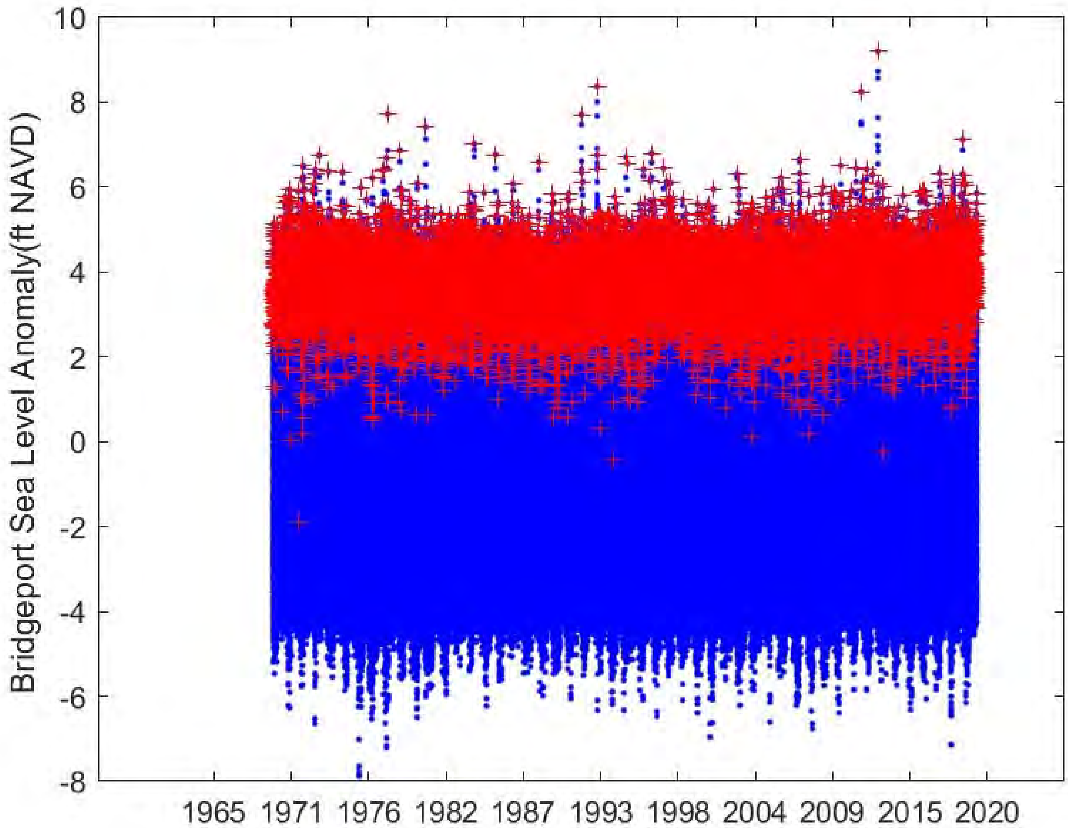

Figure 1. Observations of the sea level at the Bridgeport, CT, tide gage at hourly interval (blue) and referenced to NAVD 88 obtained from https://coastwatch.pfeg.noaa.gov/erddap/tabledap/. The daily maxima are shown by the red '+' symbols.

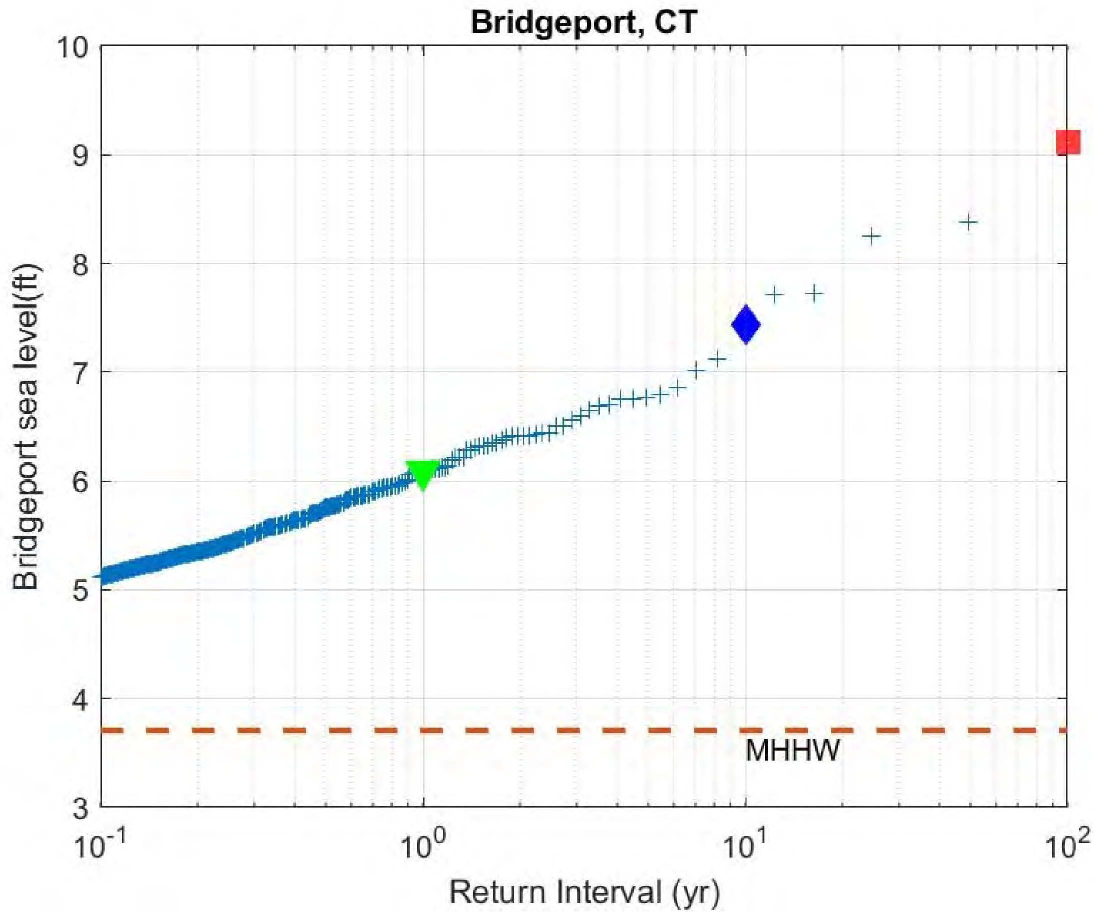

Figure 2. A "return interval diagram" for the daily high water elevation relative to NAVD 88 measured at Bridgeport, CT. The green triangle and blue diamond show the 1 and 10 year return levels (6.1 ft, and 7.4 ft) obtained by interpolation of the data. The red square at 100 years is the elevation with a 1% risk of exceedance reported by NOAA at https://tidesandcurrents.noaa.gov/est/stickdiagram.shtml?stnid=8467150.

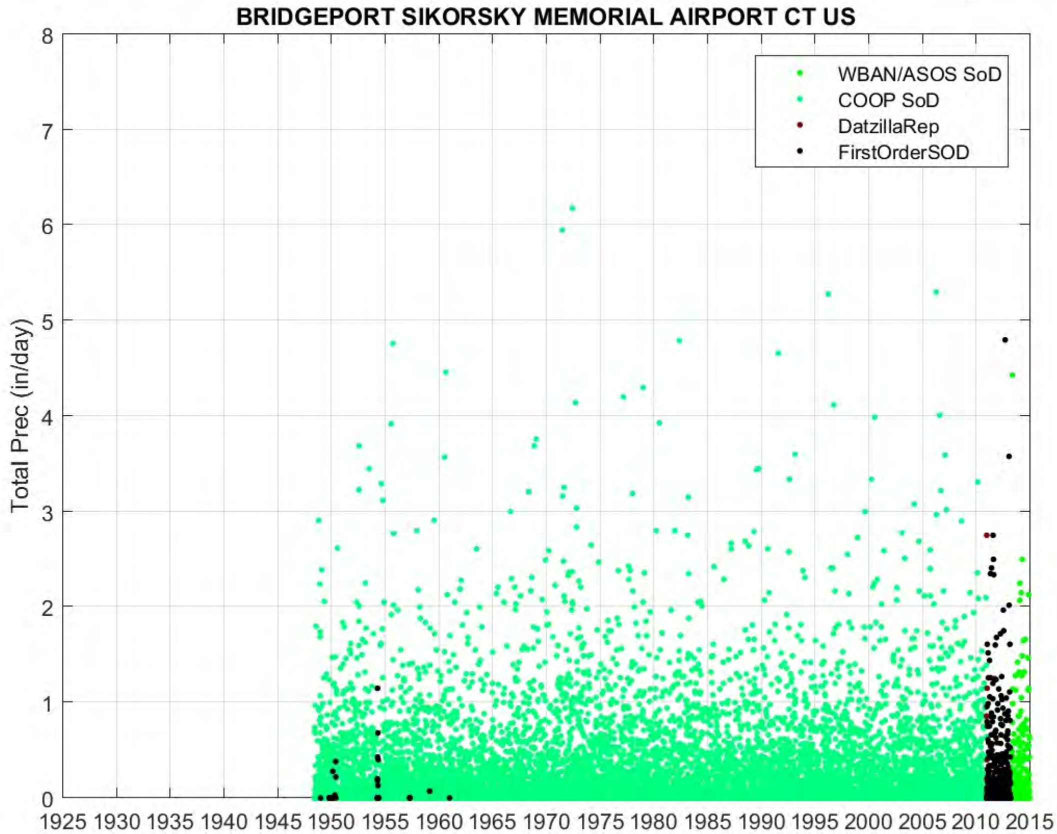

Figure 3. Observations of the daily total precipitation at the Bridgeport (Sikorsky Memorial Airport) gage obtained from the (green) the NOAA National Climatic Data Center (see Menne et al. 2012).

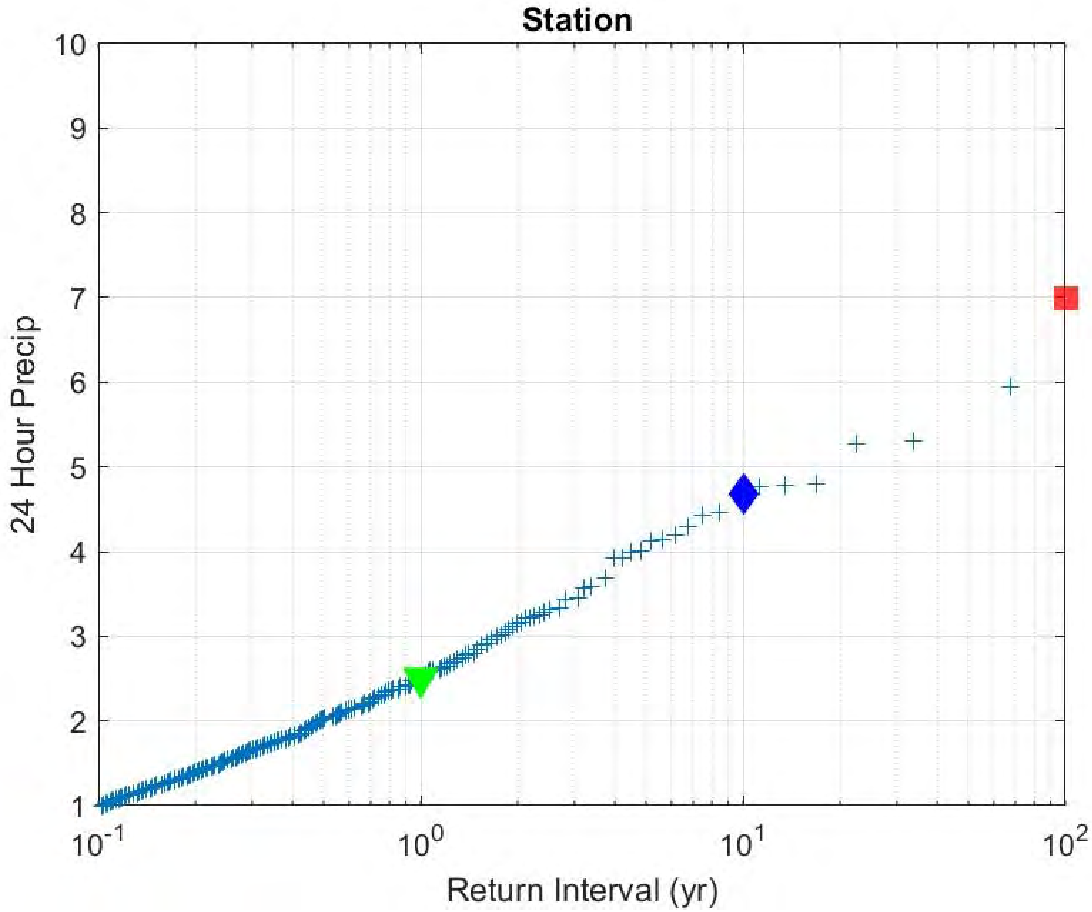

Figure 4. The "return interval diagram for the daily total precipitation at the Bridgeport, CT, precipitation gage at Sikorsky airport. The green triangle and blue diamond show the 1 and 10 year return levels (2.5 in, and 4.7 in) obtained by interpolation of the data. Data were obtained from the NOAA National Climate Data Center.

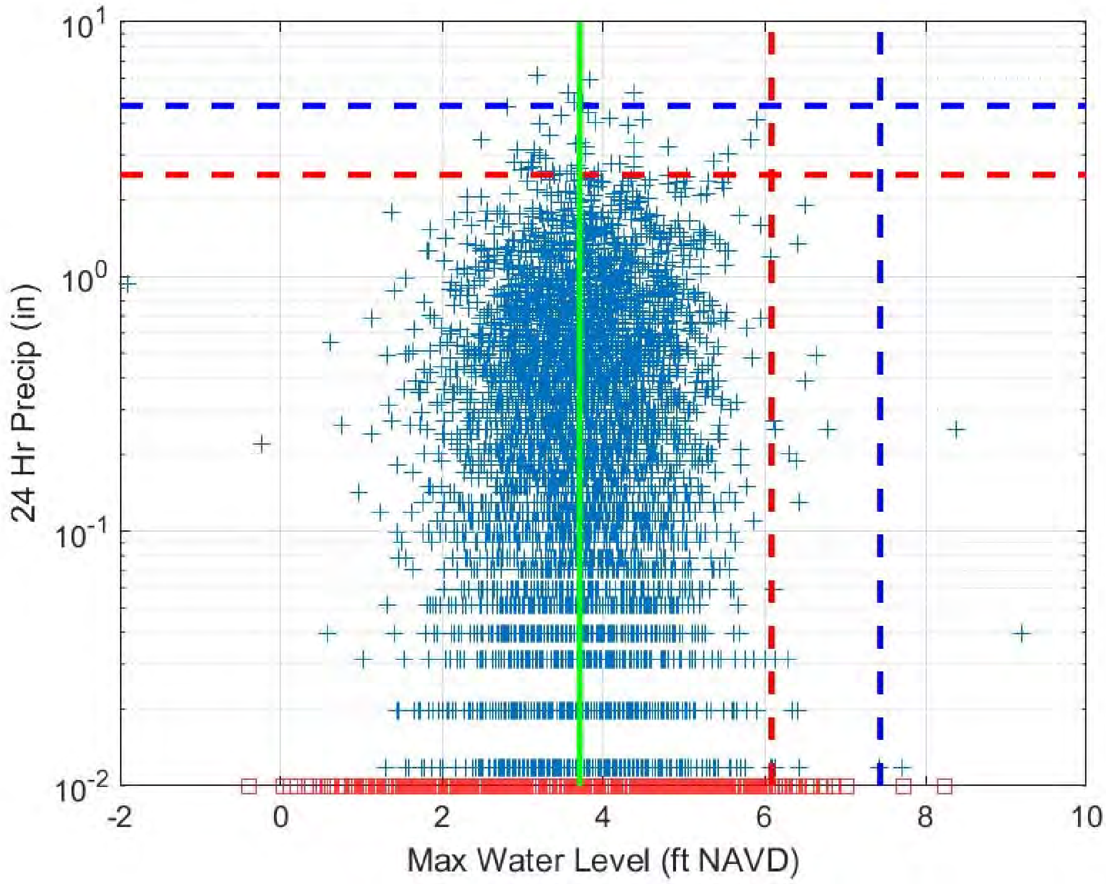

Figure 5. The variation of 24-hour precipitation rates are Bridgeport, CT, with sea level. The red squares show the range of sea level maxima on days when the precipitation was zero .The red and blue vertical dashed lines show the annual and decadal exceedance values for sea level and the horizontal dashed lines show he same thresholds but for 24-hour precipitation. These levels were estimated using Figures 2 and 4.

APPENDIX C

Task 5-6 summary

Task 5 - Statewide Mapping Tool for Projections of Sea Level Rise and Storm Surge Inundation Impacts on Municipal Infrastructure.

Task 6 - Floodplain Mapping Based for Projections of Future Precipitation Events and High Resolution Topographic Data.

Brief task overview

Models for selected locations (Milford and New London) have been set up and used to produce synthetic flows for events in the period 1979-2016. For these locations, we integrated the different model simulations for selected storm events to compute the total impact from coastal and river flooding. We provided updates on the combined flood inundation simulations based on the coastal and riverine models including results on flood frequency (2 to 200 year return period daily peak flows) for the entire CT river network.

Outcomes

We developed a hyper resolution distributed hydrological model, named Coupled Routing and Excess Storage- Soil-Vegetation-Atmosphere-Snow (CREST-SVAS), emphasizing the physical coupling of energy and water balances to accurately simulate the water cycle in mid and northern latitude basins where snowmelt causes significant spring flooding. Reference to the publication of CREST-SVAS[1] in the Journal of Hydrology is given in Appendix C. It was found in our study that the flow simulation accuracy and efficiency is significantly improved compared with existing hydrological models in the Connecticut River. A flood frequency analysis algorithm was then implemented following Bulletin 17B. The resultant flood frequency map of Housatonic, Connecticut and Thames Rivers as well as small coastal watersheds that were modeled based on this work are shown in *Figure 1*. Using the flood frequency analysis from this study and a static culvert model, we estimated overtopping risks of large number of road crossings during different flood scenarios for the Housatonic Valley Association (HVA) in Salmon Kill, Hollenbeck, Kent, Macedonia, Mill, Sandy brooks, as well as Tenmile, Seymour and Oxford. Those watersheds are shown in *Figure 1*.

The capacity to simulate the effects of river flow on coastal water levels was built into the FVCOM model developed and tested in Tasks 3 and 4.

Highlighted tables/figure(s):

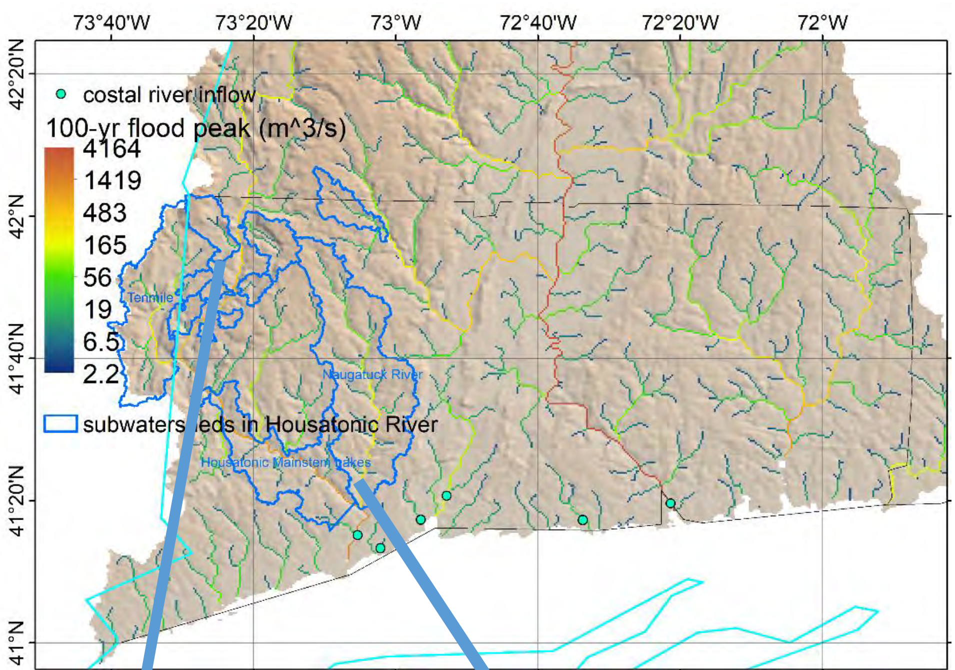

Figure 1. Estimated 100-year flood map

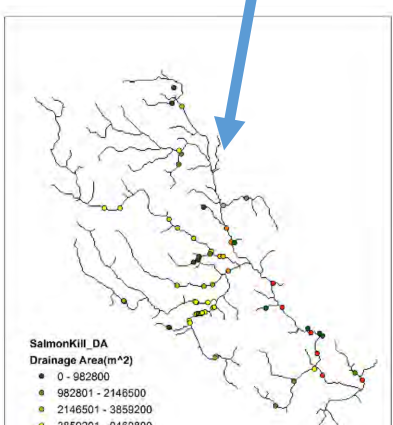

Figure 2. Road Crossings in Salmon Kill

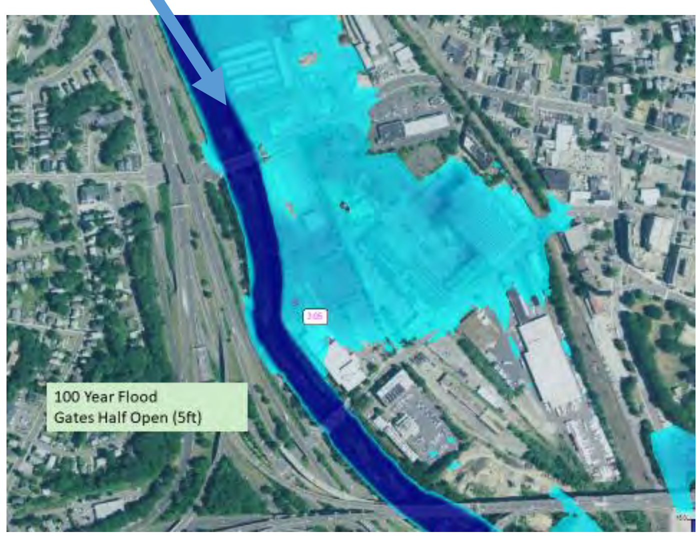

Figure 3. 100-year inundation over Freight St. Waterbury, Eversource owned critical utility substations

Description of Tools Used for Decision Making

1. CREST-SVAS, a distributed hydrological model to compute long-term and fine spatiotemporal resolution stream flows.

2. A flood frequency mapping tool to compute flood frequency from multi-decadal synthetic stream flow time series.

3. A hydrological-hydrodynamic (based on HEC-RAS) framework to construct synthetic hydrograph from estimated flood frequency (magnitude) and historical flood events (timing structure), and map the inundation extent and depth. HEC-RAS is a hydrodynamic software that is open source and maintained by Army Corps. More information can be found at: here http://www.hec.usace.army.mil/software/hec-ras/.

4. A culvert model to compute overtopping risk at small road crossings (above culverts).

Issues/analysis for future consideration

Flood frequency analysis (FFA) is based on using multi-decade synthetic annual peak flows provided by hydrological simulation. However, even a very well performed simulation can exhibit bias in the simulated peak values in the range of 30 to 50%. On the other hand, observational data have relatively short records and are sparsely distributed, therefore cannot be used for ungauged locations. Although USGS is advocating an in-house developed statistical FFA regionalization method based on regression applied to proximity stations, the reported error of the method ranges from 24% to 67%. In the future, researchers plan to improve the Regional FFA (RFFA) using jointly synthetic (from model simulations) and USGS observation network data.

Task 5-6 Reports

Publication - Describing a flood frequency analysis model

Shen, X. & Anagnostou, E. N. A framework to improve hyper-resolution hydrological simulation in snow-affected regions. *J Hydrol* **552**, 1-12 (2017).

Publications - High resolution flood-inundation extent/depth mapping techniques

Shen, X., Anagnostou, E. N., Allen, G. H., Brakenridge, G. R. & Kettner, A. J. Near Real-Time Nonobstructed Flood Inundation Mapping by Synthetic Aperture Radar. *Remote Sensing of Environment* **221**, 302-335, doi:https://doi.org/10.1016/j.rse.2018.11.008 (2019).

Xinyi Shen, Dacheng Wang, Kebiao Mao, Emmanouil Anagnostou, and Yang Hong. (2019) "Inundation Extent Mapping by Synthetic Aperture Radar: A Review", *Remote Sensing*, 11, 879, DOI: 10.3390/rs11070879.

Publications – Hydrological-hydraulic technique to evaluate vulnerability of infrastructure (Naugatuck-one of the two tributaries of Housatonic River)

Sage Hardesty, Xinyi Shen, Efthymios Nikolopoulos, Emmanouil Anagnostou, "A Numerical Framework for Evaluating Flood Inundation Risk under Different Dam Operation Scenarios", *Water,* 10 (12), 1798, DOI:10.3390/w10121798.

Planning for Climate Resilient and Fish-Friendly Road-Stream Crossings in Connecticut's Northwest Hills, May 2018.

remote sensing

MDPI

Article

Inundation Extent Mapping by Synthetic Aperture Radar: A Review

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Abstract: Recent flood events have demonstrated a demand for satellite-based inundation mapping in near real-time (NRT). Simulating and forecasting flood extent is essential for risk mitigation. While numerical models are designed to provide such information, they usually lack reference at fine spatiotemporal resolution. Remote sensing techniques are expected to fill this void. Unlike optical sensors, synthetic aperture radar (SAR) provides valid measurements through cloud cover with high resolution and increasing sampling frequency from multiple missions. This study reviews theories and algorithms of flood inundation mapping using SAR data, together with a discussion of their strengths and limitations, focusing on the level of automation, robustness, and accuracy. We find that the automation and robustness of non-obstructed inundation mapping have been achieved in this era of big earth observation (EO) data with acceptable accuracy. They are not yet satisfactory, however, for the detection of beneath-vegetation flood mapping using L-band or multi-polarized (dual or fully) SAR data or for urban flood detection using fine-resolution SAR and ancillary building and topographic data.

Keywords: flood inundation mapping; synthetic aperture radar; microwave remote sensing; natural hazard

1. Introduction

Near-real-time (NRT) inundation extent mapping during flood events using remote sensing data is vital to support rescue and damage recovery decisions and to facilitate rapid assessment of property loss and damage. It also provides a two-dimensional reference for validating and calibrating real-time numerical modeling, including flood risk analysis at a regional to global scale [1–3]; flood event prediction at a small scale [4–7]; and the tradeoff evaluation between the accuracy and complexity of hydrodynamic simulation [8–11]. It is, moreover, a validation source for geomorphological analysis of flood vulnerability [12–16]. Retrieved inundation extent can also be converted to inundation depth [17–20].

Both optical sensors and passive and active microwave sensors can be used for inundation mapping, offering different levels of capacity, accuracy, and solution difficulty. By means of water indices, optical remote sensing data can be used to extract water surfaces straightforwardly and reliably. As long-term, fine-resolution satellite data (such as Landsat data) are accumulated and new satellites (such as Sentinel-2) are started to serve, optical remote sensing methods are contributing significantly to the delineation of global and regional water surfaces [21–24]. The validity of optical observations is limited, however, by clouds and unclear weather conditions, which are common during flood events.

Microwave remote sensing techniques, on the other hand, have good penetration through the atmosphere and therefore can provide more efficient measurement. Pixel water fraction estimated from passive microwave measurement—the brightness temperature—features low spatial (~25 km, $\frac{1}{4}$ degree) but fine temporal resolution (daily) [25,26]. The result is, therefore, usually downscaled up to 90 meters by topography [27] and/or optical sensor-derived water probability [28]. Such downscaling mechanisms may be valid for fluvial inundation at global and regional scale but can be problematic for small pluvial flooding at local scale.

By detecting the scattering mechanism, synthetic aperture radar (SAR) can be used to map inundation under almost any weather condition at fine to very fine spatial resolution (from 30 m to <1 m). As an active sensor, SAR works nocturnally as well. The retrieval algorithms using SAR data are more difficult to design than the sensors discussed above, and purely automated algorithms that require zero human interference are so far rare. With the growing availability of remote sensing data and the development of retrieval techniques, the automation and reliability of SAR data are expected to emerge soon.

This study focuses on evaluating existing inundation mapping algorithms, using SAR data developed from 1980 to the present. Given that the data, study areas, and validation methods vary among studies, we primarily evaluate algorithms, along with some recently emergent approaches, according to four criteria: automation, robustness, applicability, and accuracy.

2. Techniques to Produce SAR Inundation Maps

2.1. Principles

Change in surface roughness is the key to detecting inundation using SAR data. Where the ground surface is covered with water, its low roughness exhibits almost ideal reflective scattering, in strong contrast to the scattering of natural surfaces in dry conditions. Consequently, different scattering mechanisms can cause two opposing changes in the total backscattering intensity: dampening and enhancement.

In the case of an open flood where water is not obscured by vegetation or buildings, dampening occurs because most of the scattering intensity is concentrated in the forward direction, whereas the back direction is very weak. In vegetated areas, different scattering mechanisms can happen, depending on the vegetation structure and submerge status. In fully submerged locations, scattering dampening occurs as in an open flood, while scattering enhancement is observed in partially or unsubmerged locations because the dihedral scattering dominates. The backscattering components of vegetation (with a canopy layer) are derived in the enhanced Michigan microwave canopy scattering (enhanced MIMICS) model by Shen et al. [29] from the first-order approximation of the vectorized radiative transfer (VRT) equation [30,31].

As shown in Figure 1, the vegetation-ground system can be conceptualized by three layers from top to bottom: the canopy layer (C), the trunk layer (T), and the rough ground surface (G). Term 1 (G-C-G) in the figure, for instance, refers to the wave scattered by the ground surface after it penetrates the canopy, which is then scattered by the canopy back to the ground and is finally scattered back to the sensor after penetrating the canopy. Term 7 (direct scattering) indicates that the scattering process on the ground surface only occurs once between the two penetrations of the canopy.

A trunk is usually modeled by a cylindrical structure whose length is much greater than its diameter. Term 4a (T-G-C) in Figure 1 represents the scattering wave that consecutively penetrates the canopy layer first, is scattered forward by the trunk, is scattered back in the antenna's direction, and, finally, penetrates the trunk and canopy layer. Term 4b (C-G-T) represents the scattering wave in the reverse order; under physical optical approximation, its forward scattering (in all azimuth directions) dominates. As a result, in 4a and 4b, only the forward scattering from the trunk is retained. If G is rough, the ground scattering energy is distributed to the upper hemisphere, and the forward direction is not very strong. When flooded, the ground surface is close to ideally smooth, and the forward scattering is significantly enhanced, which, in turn, significantly enhances 4a and 4b.

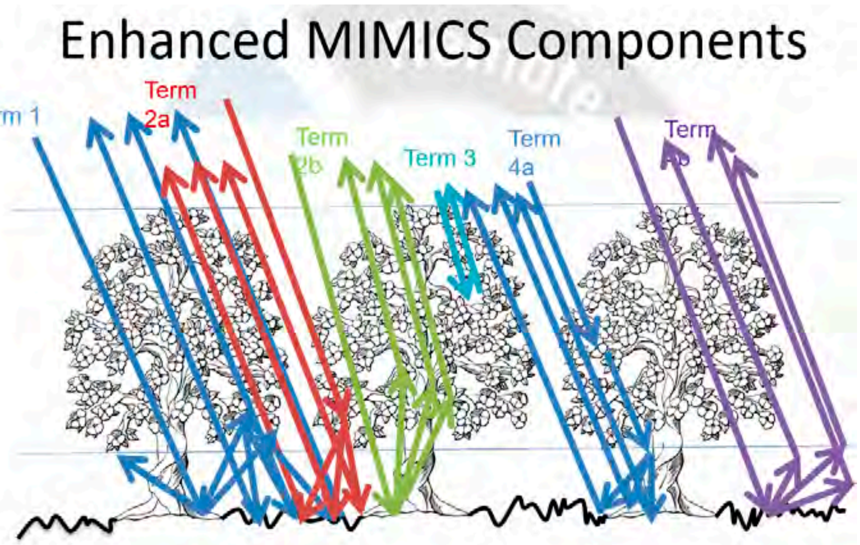

Figure 1. Backscattering components from vegetation with a canopy layer in enhanced MIMICS.

Figure 1. Backscattering components from vegetation with a canopy layer in enhanced MIMICS.

Another principle is to utilize interferometric SAR (InSAR) formed from repeated passes to detect non-obstructed flooded areas by identifying the loss of coherence over water surfaces [32–35]. However, coherence may only be used as the primary indicator where the background exhibits strong coherence, such as in highly developed urban areas whereas can only be used as a complementary source because the surface of a water body is not the only kind of area that loses coherence—the background is full of low-coherence areas, such as vegetation, shadow [36]. Similarly, utilizing differential InSAR (DInSAR) pairs from repeated tracks to detect inundation depth may only be feasible over background areas of strong coherence, which is not the case of beneath-vegetated inundation or non-obstructed inundation in natural areas.

Both non-obstructed flood and beneath-vegetation inundation can occur in natural areas; in urban areas, both non-obstructed-flood dampening effects and L-shaped-caused enhancement can be observed. A horizontal smooth inundated surface together with a vertical building can form an L-shaped corner reflector [37], which can be a strong scatterer when illuminated by the radar antenna. In addition, more areas can be shadowed by buildings than by natural terrain, resulting in greater uncertainty about flood detection in urban areas.

2.2. *Error Sources*

We attribute commonly seen errors to three sources: water-like surfaces, noise-like speckle, and geometric correction.

Water is not the only surface that exhibits close-to-specular scattering. Smooth surfaces at the scale of the measuring wavelength and shadowed areas share almost identical scattering properties with water surfaces; we refer to them hereafter as water-like surfaces. Water-like surfaces vary slightly with frequency and flood mapping algorithms. With sufficiently little roughness relative to wavelength, even bare soil can be misidentified as water. In procedures to detect non-obstructed water, water-like surfaces can create "false positives", or "over-detection."

Noise-like speckle is encountered for almost all SAR applications and, in many, is considered a major disadvantage of SAR images over optical images. For example, unlike optical images, noncommercial SAR images with 5–10 m resolution, may not be suitable for detecting headwater

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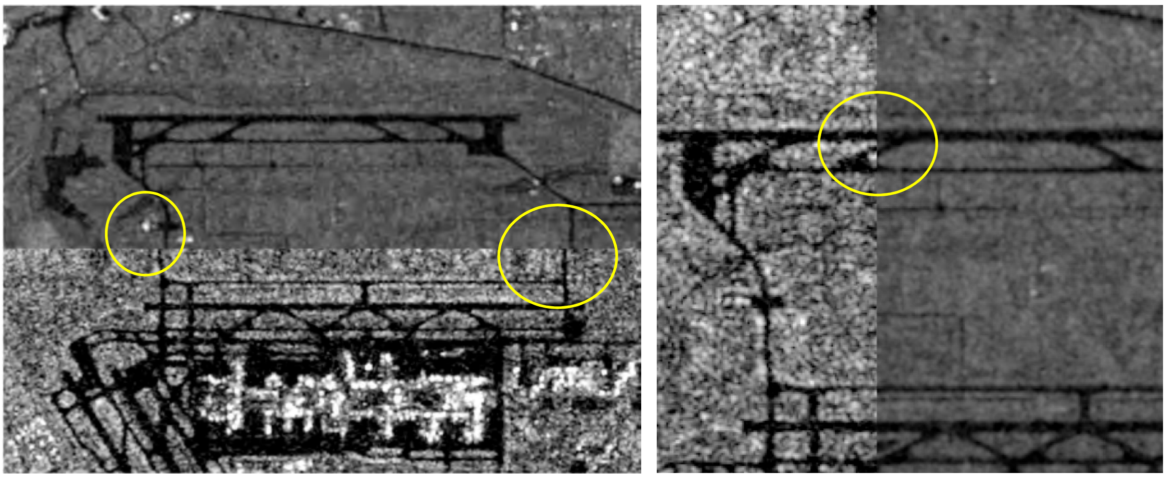
Noise-like speckle is encountered for almost all SAR applications and, in many, is considered a major disadvantage of SAR images over optical images. For example, unlike optical images, noncommercial SAR images with 5–10 m resolution, may not be suitable for detecting headwater flood. Since the floodplain of headwater may be only one or a few pixels wide, the water pixels can be contaminated severely by speckle and surrounding strong scatterers. Speckle is not real noise. The formation of speckle was well explained by Lee and Pottier [38] (p. 101): As "the distances between the elementary scatterers and the radar receiver vary due to the random location of scatterers, the received waves from each scatterer, although coherent in frequency, are no longer coherent in phase. A strong signal is received if wavelets are added relatively constructively, while a weak signal is received if the waves are out of phase." As a result, homogeneous and continuous areas exhibit strong inhomogeneity in SAR images. As the sample number decreases with the improvement of spatial resolution, the backscattering of a pixel may not be represented well by a known fully developed speckle model, which increases the difficulty in classification. Although many SAR filtering techniques are developed, most of them reduces noise at the price of damaging image details, which can also propagate to inundation mapping. Modern techniques such as the selection of the optimal filter [39] and machine learning may offer some advanced way in suppressing speckle.

The original geometry of SAR images is range-azimuth. To be georeferenced, SAR images are often corrected to ground distance before high-level products are generated. Limited by the accuracy of input elevation data, the geometric correction algorithm, and orbit accuracy, it is common to see location errors at the level of a few pixels, as demonstrated in Figure 2. The offset in 10-pixel order in Figure 2 reflects the cumulatively geometric error of using Sentinel-1 images from different orbits, which can be significantly reduced using image pairs from the same orbit.



(a) (b)

Figure 2. (**a**) Vertical and (**b**) horizontal swipe demonstration of the geometric error (circulated tracks) between two Sentinel-1 SAR images georeferenced by Range-Doppler algorithm in Sentinel Application Platform (SNAP) 6.0 software using the Shuttle Radar Topography Mission (SRTM) 3″ DEM data. The background and foreground images were obtained, respectively, over George Bush International Airport, Texas.

3. Relative Strengths and Limitations of Existing Techniques

3.1. Approaches

SAR-based inundation mapping methods are usually more complex than those based on optical sensors because of the processes added to mitigate the error propagated from one or more of the error sources mentioned above. Consequently, one study may consist of several different approaches introduced in the following.

3.1.1. Supervised Versus Unsupervised Methods

Mapping water extent is a matter of classification using supervised or unsupervised approaches. Supervised classification methods require a training set consisting of labeled inundated areas or core water locations and their corresponding pixels extracted from SAR data. Using training sets, mappers can achieve better accuracy without deeply understanding the physics of the data signal before designing an algorithm [40–46]. Drawbacks are at least twofold, however, the generation of training sets cannot be automated, and the algorithm has local dependence—that is, a classifier well-trained over one area may not work well in another.

Pulvirenti et al. [47] developed an "almost automatic" fuzzy logic classifier, which used fixed thresholds determined by a theoretical scattering model to classify pixels automatically or to use human-labeled samples. This method has proved reasonably accurate, but the automatic classification requires a microwave scattering model and introduces modeling uncertainty, while the human labeling of samples is time consuming. These drawbacks of supervised methods may be circumvented through the use of three unsupervised methods: threshold determination, segmentation, and change detection.

3.1.2. Threshold Determination

The specular reflective properties of non-obstructed water have driven many efforts [48–51] to determine a threshold below which pixels are identified as water. A single threshold may not hold well in large-area water bodies [52] or for the whole swath of a SAR image since it suffers from the heterogeneity of the environment, caused by wind-roughening and satellite system parameters [53]. Martinis and Rieke [54] demonstrated the temporal heterogeneity of the backscattering of permanent water bodies, implying the temporal variability of the threshold. To address the spatial variability, Martinis, Twele and Voigt [53] applied a split-based approach (SBA) [55], together with an object-oriented (OO) segmentation method [56]. Matgen et al. [51] introduced a histogram segmentation method, and Giustarini et al. [49] generalized the calibration process.

Essentially, a threshold-based approach needs to have either a bimodal image histogram (Figure 2 in Matgen, Hostache, Schumann, Pfister, Hoffmann and Savenije [51]) or some sample data to initialize the water distribution. To deal with non-bimodal histograms, manually drawing regions of interest (ROIs) is the most straightforward solution, but it impedes automation. For automation, SBA [53] ensures that only the splits showing a bimodal histogram (of water and non-water pixels) are used to derive a global threshold. On the other hand, Lu et al. [57] loosened the bimodal histogram restriction by initializing the water distribution using a "core flooding area" automatically derived from change detection, using multi-temporal SAR images. As change detection using only a single dry reference is sensitive to speckle and location error (see the subsection on change detection), the method may be affected. Furthermore, the threshold globalization of the method can be difficult.

More recently, dual-polarized (the common configuration of many active sensors) and fully polarized SAR data are utilized for threshold segmentation. After sampling pixels of high water probability from the global water occurrence map [58], and then removing out-of-bound samples by matching the peak, and 99% confidence interval of the sample histogram and the χ^2 distribution, Shen et al. [59] automatically optimized the Wishart distribution and the probability density threshold of water in the dual-polarized domain. Since the water class is initialized before the threshold determination, this method is not restricted to bimodal histograms.

3.1.3. Segmentation

In contrast to pixel-based threshold determination, image segmentation techniques that group connected homogeneous pixels into patches can provide information at the object level—that is, at a higher level than the pixel—and are therefore believed to be more resistant to speckle because they utilize morphological information instead of radiometric information alone. The active contour method (ACM; [60,61]) allows a certain amount of backscattering heterogeneity within a water body and incorporates morphological metrics, such as curvature and tension. Martinis et al. [53] have applied OO segmentation [56] with SBA to reduce false alarms and speckle. Heremans et al. [62] compared the ACM and OO and concluded that the latter delineated the water areas more precisely than the former, which tend to overestimate their extension. Pulvirenti et al. [63] developed an image segmentation method consisting of dilution and erosion operators to remove isolated groups of water pixels and small holes in water bodies, which are believed to be caused by speckle. Giustarini et al. [49], Matgen et al. [51] and Lu et al. [57] employed the region growing algorithm (RGA) to extend inundation areas from detected water pixels. RGA starts from seeding pixels and then keeps absorbing homogenous pixels from neighbors until no more homogenous pixels exist in neighboring areas.

3.1.4. Change Detection

Change detection approaches traditionally refer to techniques for comparing pre- and in-flood backscattering intensities to detect changes in pixels caused by flooding [48,50,57,64,65]. One or more prior- and post-flood SAR image or images are needed; we refer to this hereafter as "dry reference." The principle behind change detection techniques is straightforward, and the techniques should, theoretically, be effective in overcoming the first source of error—over-detection on water-like surfaces—as was shown by Giustarini et al. [49,51]. In the past, however, limited by their availability, change detection traditionally used only two SAR images. As a result, the aforementioned second-geometric error can only be avoided by limiting the using SAR images obtained from the same orbit or by indireclty evaluating the change from binary water mask; and the third error sources—speckle-caused noise—could compromise the effectiveness [66]. Shen et al. [59] have proposed an improved change detection (ICD) method that employs multiple (~5) pre-flood SAR images and a multi-criteria approach to reject false positives caused by water-like bodies and to reduce the effect of speckle.

More generally, change detection can be extended to the use of multiple dry references [59,67], the comparison of binary water maks [59], or InSAR coherence. The loss of InSAR coherence might be a more promising signature than the enhancement of intensity to detect buildings surrounded by inundation [33–35]. We refer to buildings surrounded by inundation as flooded buildings for simplicity, which should not be understood as flooded building floor or basement because satellite remote sensing images cannot detect the internal of buildings.

Besides isolating inundated areas from permanent (or, more precisely, preexisting) water areas, change detection techniques have been used to initialize water pixel sets before thorough detection [53,57], especially when full automation is an objective and no a priori water information is available. Change detection methods can also be used to detect flood beneath vegetation, as described in the next section.

3.1.5. Visual Inspection/Manual Editing Versus Automated Process

As discussed above, SAR-derived inundation results are affected by many error sources, which can hardly be eliminated by most algorithms. Visual inspection and manual editing could help in drawing training ROIs [42] and reducing false positives/negatives. As manual editing requires an overwhelmingly large workforce, it however, cannot be applied to rapid response to flood disasters, especially during back-to-back flood events. Studies aiming to improve automation include Pulvirenti et al. [47], Giustarini et al. [49], Matgen et al. [51], Martinis et al. [53], Horritt [60]; Horritt et al. [61], Pulvirenti et al. [63], Horritt et al. [68]; and Pulvirenti et al. [69].

3.1.6. Unobstructed, Beneath-Vegetation Flood Versus Urban Flood

Inundation detection over vegetated areas, partially submerged wetlands, and urban areas has gained attention recently. Theoretically, scattering is enhanced during flood time if a trunk structure exists. Ormsby et al. [70] evaluated the backscattering difference caused by flooding under canopy.

Martinis and Rieke [54] analyzed the sensitivity of multi-temporal/multi-frequency SAR data to different land covers and concluded that X-band can only be used to detect inundation beneath sparse vegetation or forest during the leaf-off period, while L-band, though characterized by better penetration, has a very wide range of backscattering enhancement, which also obscures the reliability of the classification. Townsend [44] utilized ground data to train a decision tree to identify flooding beneath a forest using Radarsat-1 (http://www.asc-csa.gc.ca/eng/satellites/radarsat1/Default.asp). Horritt et al. [68] input the enhanced backscattering at C-band and phase difference of co-polarizations (HH-VV) to the ACM to generate water lines from selected known open water (ocean) and coastal dryland pixels. The area between the dry contour and open water was considered as flooded vegetation. Pulvirenti et al. [42] trained a set of rules using visually interpreted ROIs to extract flooded forest and urban areas from COSMO-SkyMed SAR data. Pulvirenti et al. [69] combined a fuzzy logic classifier [47] and segmentation method [63] to monitor flood evolution in vegetated areas using COSMO-SkyMed (http://www.e-geos.it/cosmo-skymed.html).

Given its potential for flood detection under vegetation, most studies have adopted a supervised classification, which can hardly be automated. Specifically, the enhanced dihedral scattering of vegetation cannot be considered as a single class because of different vegetation species, structure, and leaf-off and leaf-on conditions. Such heterogeneity makes it difficult to determine automatically a threshold of backscattering enhancement. In other words, the issue in detecting floods beneath vegetation is identifying multiple classes from an image, the automation of which is more challenging than identifying a single class.

Until now, few studies have been made available on flood mapping in urban areas [33–35,49,53,71,72], and only a handful [33–35,73] investigated the use of dihedral scattering to extract flooded buildings using either the intensity enhancement or the loss coherence. Because of the vertical structure of many buildings, the challenges in detecting urban inundation using intensity enhancement share some similarities with those of identifying floods under vegetation. An additional challenge arises from asymmetric building structure as compared to the symmetric structure of vegetation. Such enhancement only occurs when the radar line of sight (LoS) is orthogonal to the horizontal alignment of the building face [33,35]. Consequently, utilizing intensity enhancement cannot guarantee complete detection of flooded buildings and requires to know the geometry, orientation, and even material of buildings, and the direction of illumination [74]. Such more ancillary data may not always be available. In contrast, the loss of coherence, though can be created by the dihedral scattering, may still work when the LoS moves away from the orthogonal direction. Either the enhancement or the presence of water, breaks the original backscattering arrangement of building pixels, causing the decrease of coherence. Moreover, smooth artificial surfaces and shadowing areas may also create over-detection which need to be masked out from detection. At present, the major challenge to an operational system for urban flood mapping is still data availability. Ultra-fine resolution data (~1 m) such as TerraSAR-X (https://directory.eoportal.org/web/eoportal/satellite-missions/t/terrasar-x) and COSMO-SkyMed (http://www.e-geos.it/cosmo-skymed.html) are less accessible than free datasets.

3.2. Selected Studies of Combined Approaches

Many operational agencies are dedicated to providing NRT flood maps based on SAR, including the International Charter Space and Major Disasters (https://disasterscharter.org/web/guest/home), the United Nations Institute for Training and Research (UNITAR, https://unitar.org/unosat/), the Copernicus Emergency Management Service (EC EMS, https://emergency.copernicus.eu/mapping/ems/emergency-management-service-mapping), the European Space Agency (ESA, http://www.esa.int/Our_Activities/Observing_the_Earth/Copernicus/Sentinel-1), the German Aerospace Center (DLR https://www.dlr.de/), the Centre d'Etudes Spatiales de la BIOSphère (CESBIO, http://www.cesbio.ups-tlse.fr/index_us.htm), and the Canada Space Agency (CSA, http://www.asc-csa.gc.ca/eng/satellites/disasters.asp). Despite this, past studies have only partially addressed the operational demands of real-time inundation mapping in terms of automation and accuracy. Often, tedious human intervention to reduce over-detection, as well as filtering to reduce under-detection caused by strong scatter disturbances and speckle-caused noise, are needed when using satellite SAR data for inundation mapping. As our space is limited, we selected from the studies mentioned above some representative ones for in-depth analysis to show how and why different methods can be combined and the strengths and limits of such combinations. These are summarized below.

Martinis et al. [53] applied SBA [55] to determine the global threshold for binary (water and non-water) classification. In SBA, a SAR image is first divided into splits (sub-tiles) to determine their individual thresholds using the Kittler and Illingworth (KI) method [75], global minimum, and quality index. Then, only qualified splits showing sufficient water and non-water pixels are selected to get the global threshold. The OO segmentation algorithm (implemented in e-cognition software) is used to segment the image into continuous and non-overlapping object patches at different scales. Then the global threshold is applied to each object. Eventually, topography is used as an option to fine-tune the results.

SBA is employed to deal with the heterogeneity of SAR backscattering from the same object in time and space. The intention of applying the OO segmentation algorithm is to reduce false alarms and speckle noise. OO was, however, originally designed for high-resolution optical sensors, which have no consideration of noise like speckle and water-like areas. The fine-tuning procedure can only deal with floodplain extended from identified water bodies, leaving inundated areas isolated from known water sources. To avoid the drawback of fixing tile size to SAR images of different places and resolution [53,55,76], Chini et al. [77] propose the hierarchical SBA (HSBA) method with variable tile size, and they post-processed the binary water mask derived by HSBA using RGA and CD, similar to Giustarini et al. [49], Matgen et al. [51].

The ACM, also known as the snake algorithm [60], was, to the authors' knowledge, the first image segmentation algorithm designed for SAR data. It allows a certain amount of backscattering heterogeneity, while no smoothing across segment boundaries occurs. A smooth contour is favored by the inclusion of curvature and tension constraint. The algorithm spawns smaller snakes to represent multiple connected regions. The snake starts as a narrow strip moving along the course of a river channel, ensuring it contains only flooded pixels. Overall, it can deal with low signal-to-noise ratio.

Horritt et al. [68] used ACM to map waterlines under vegetation. They started from known pure ocean pixels to map the active contour of open water and then to map the second active contour, which was the waterline beneath vegetation. Two radar signatures—the enhanced backscattering at C-band and the HH-VV phase difference at L-band—forced the ACM. Unlike the OO method, which aggregates objects from the bottom (pixel level) to the top, the segmentation in ACM requires seeding pixels, whose detection is difficult in an automated approach. In addition, similar to RGA, ACM cannot detect inundated areas isolated from a known water body.

To assess flooding beneath vegetation, Pulvirenti et al. [63] developed an image segmentation method using multi-temporal SAR images and utilized a microwave scattering model [78] that combines matrix doubling [30,31] and the integral equation model (IEM) [31,79] to interpret the object backscattering signatures. The image segmentation method dilutes and erodes multi-temporal SAR images using different window sizes. Then, an unsupervised classification is carried out at the pixel level. The object patches are formed based on connected pixels of the same class. Eventually, the trend of patch scattering can be compared with canonical values simulated by a scattering model to derive the flood map.

Pulvirenti et al. [47] proposed a fuzzy logic–based classifier to incorporate texture, context, and ancillary data (elevation, land cover, and so on), as an alternative to thresholding and segmentation methods. Eventually, they combined the segmentation and fuzzy logic classifier [69] by using backscattering change and backscattering during flooding as input for densely vegetated areas. The thresholds of the membership functions were fine-tuned with a scattering model. The use of image segmentation reduces the disturbance by speckle; the use of multi-temporal trend takes into account the progress of the water receding process, and the comparison with a scattering model sounds more objective and location independent than a supervised classification or empirical thresholds. The adopted image segmentation may, however, reduce the inundation extent detail, and it does not guarantee the removal of speckle. Scattering models require detailed vegetation information (moisture, height, density, canopy particle orientation and size distribution, trunk height, and diameter) and ground soil information (moisture, roughness) as input; these data are heterogeneous in space and usually not available.

Pulvirenti et al. [33] and Chini et al. [34] argued the advantages of utilizing the loss of coherence as the primary signature of flooding buildings over the enhancement of intensities [73], as has been briefly summarized in Sections 2.1, 3.1.4 and 3.1.6. To rule out false positives created by vegetated areas, Chini et al. [35] first identified buildings by thresholding temporally averaged intensities using the HSBA method, in conjunction with (via logical OR) thresholding temporally averaged coherence. Then they masked out layover and shadowed areas by using the local incidence angle to prevent false alarms there. As stated in [80] both polarized intensities and coherence exhibit contrasting behaviors over built-up and vegetated areas. Over vegetated areas with naturally distributed scatterers, as modeled by the Freeman-Durden three-component decomposition [38,81], volume scattering contributes significantly to both co- and cross-polarized intensities while the dihedral scattering only contributes to co-polarizations. Whereas over built-up areas, modeled by the Yamaguchi four-component decomposition [38,82], the helix component contains the correlated contribution from dihedral scattering to both co- and cross-polarizations. For coherence, buildings show persistent strong values, while vegetation does not.

Toward automation, Matgen et al. [51] developed the M2a algorithm to determine the threshold that makes the non-water pixels (below the threshold) best fit a gamma distribution—a theoretical distribution of any given class in a SAR image. They then extended flooded areas using RGA from detected water pixels using a larger threshold—99 percentile of the "water" backscatter gamma distribution—arguing that flood maps resulting from region growing should include all "open water" pixels connected to the seeds. Then they applied a change detection technique to backscattering to reduce over-detection within the identified water bodies caused by water-like surfaces, as well as to remove permanent water pixels.

Based on the same concept, Giustarini et al. [49] developed an iterative approach to calibrate the segmentation threshold, distribution parameter, and region growing threshold (M2b). They applied the same segmentation threshold to the dry reference SAR image to obtain the permanent water area. They claimed, however, that if the intensity distribution of the SAR image were not bimodal, the automated threshold determination might not work.

Lu et al. [57] used a changed detection approach, first to detect a core flood area that contained a more plausible but incomplete collection of flood pixels, and then to derive the statistical curve of the water class to segment water pixels. The major advantage of this approach is that a bimodal distribution is not compulsory. In practice, a non-bimodal distribution often occurs. The change detection threshold might be difficult to determine and globalize.

Assuming even prior probability of flooded and non-flooded conditions, Giustarini et al. [83] computed probabilistic flood maps that characterize the uncertainty of flood delineation. The probability reported in this study, however, related to the uncertainty neither in extent nor in time. Rather, it was the uncertainty of a SAR image classification based on backscattering.

Taking advantage of big earth observation (EO) data, the two most recent studies—Cian et al. [67] and Shen et al. [59]—implemented full automation of inundation retrieval. With the CD principle underpinning both methods, they employed multiple dry references instead of one supported by operational satellite SAR data for multiple years.

Cian et al. [67] developed two CD-based flood indices, the Normalized Difference Flood Index (NDFI) and the Normalized Difference Vegetated Flood Index (NDVFI), assuming a number of revisits for each pixel in dry conditions was available:

$$\mathrm{NDFI} = \frac{mean\langle\sigma^0_{ref}\rangle - min\langle\sigma^0_{ref},\ \sigma^0_{flood}\rangle}{mean\langle\sigma^0_{ref}\rangle + min\langle\sigma^0_{ref},\ \sigma^0_{flood}\rangle} \quad (1)$$

$$\mathrm{NDFVI} = \frac{mean\langle\sigma^0_{ref}\rangle - max\langle\sigma^0_{ref},\ \sigma^0_{flood}\rangle}{mean\langle\sigma^0_{ref}\rangle + max\langle\sigma^0_{ref},\ \sigma^0_{flood}\rangle} \quad (2)$$

Empirical thresholds 0.7 and 0.75 were reported sufficiently stable for generating the inundation mask from NDFI and NDFVI, respectively. In the post-processing, Cian et al. [67] applied dilation and closing morphological operators, a larger than 10-pixel size limit, and a smaller than 5-degree slope limit to the inundation mask to further reduce speckle-caused noise. They concluded the potential for detecting inundation under vegetation was limited.

Shen et al. [59] developed a four-step processor, as shown in Figure 3, the Radar Produced Inundation Diary (RAPID), which makes use not only of time series of SAR data, but also the abundance of available high-resolution ancillary satellite products, including land cover classification (LCC) maps from Landsat [84,85], water occurrence from 30-year Landsat images [58], global river width from STRM [86] and Landsat images [87], and fine-resolution hydrography [88,89]. The four steps are as follows:

First, SAR images are classified into water and non-water masks (WMs), based on statistics from polarimetric radar. This binary classification step was inspired by the auto-optimization method by the m2b method [49] and extend to utilizing the dual-polarized SAR data. It removes the assumption of a bimodal distribution made in of m2b by initializing the water PDF using the water occurrence map.

Second, morphological processing runs over the mask, consisting of two operators, water source tracing (WST) and improved CD (ICD), to form inundated water bodies while to remove false positives caused by water-like surfaces. WST and ICD are also designed to detect fluvial and pluvial inundation, respectively. This morphological procedure is different from the post-processing methods in Matgen et al. [51], Chini et al. [77], and Twele et al. [90] in three aspects: (1) in RAPID, a pixel needs either to be accepted by WST or ICD while, in the other studies, the change detection is used to measure the pixels accepted by the RGA, which cannot capture pluvial inundated areas; (2) both WST and ICD utilize object-level information instead of pixel-level information to evaluate whether a detected water body is a false positive; and (3) to prevent the disturbance of calibration error among different SAR images, the change is detected from a binary mask instead of backscattering.

Third, a multi-threshold compensation step is applied to reduce the under-detection within water areas, and, fourth, a machine learning–based refinement is used to remove false negatives created by strong scatterers and to reduce further the noise level in the result. These final two steps in RAPID reduce the error caused by speckle and strong scatterers by utilizing the PDF and physically integrating multi-source remote sensing products instead of brutally applying a filtering technique. Thus, RAPID reduce the noise level without sacrificing resolution to mapping quality.

Among available satellites with SAR sensors, Sentinel-1 is the most popular because it is free to use and has relatively short revisiting intervals (six days in Europe and the Hawaiian islands and twelve days everywhere else in the world), three-day in average revisiting tracks (the revisiting intervals of the satellites (S1A and S1B) without the promise of producing the data), and a multi-year data archive dating back to 2014. During an event, the satellites may add extra revisits. As illustrated in Figure 4, for instance, for Hurricane Harvey six revisits were acquired from 27 August to 10 September 2017 in Seabrook area, and for Hurricane Irma eleven revisits from 12 September to 2 November 2017.

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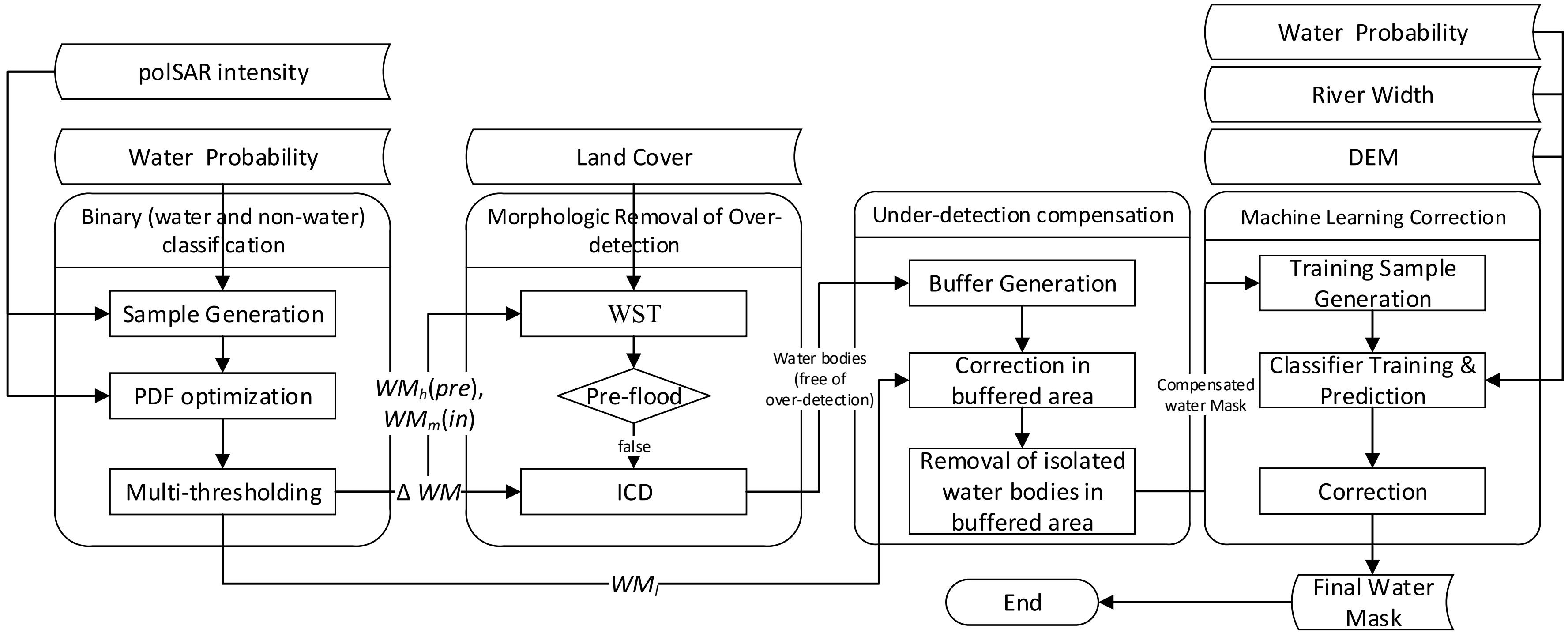

Figure 3. The workflow of RAPID. From the left to the right panels are step 1 (binary classification), 2 (morphological processing consisting of water source tracing (WST) and improved change detection (ICD)), 3 (multi-threshold compensation) and 4 (machine learning based correction), respectively.

Figure 3. The workflow of RAPID. From the left to the right panels are step 1 (binary classification), 2 (morphological processing consisting of water source tracing (WST) and improved change detection (ICD)), 3 (multi-threshold compensation) and 4 (machine learning based correction), respectively.

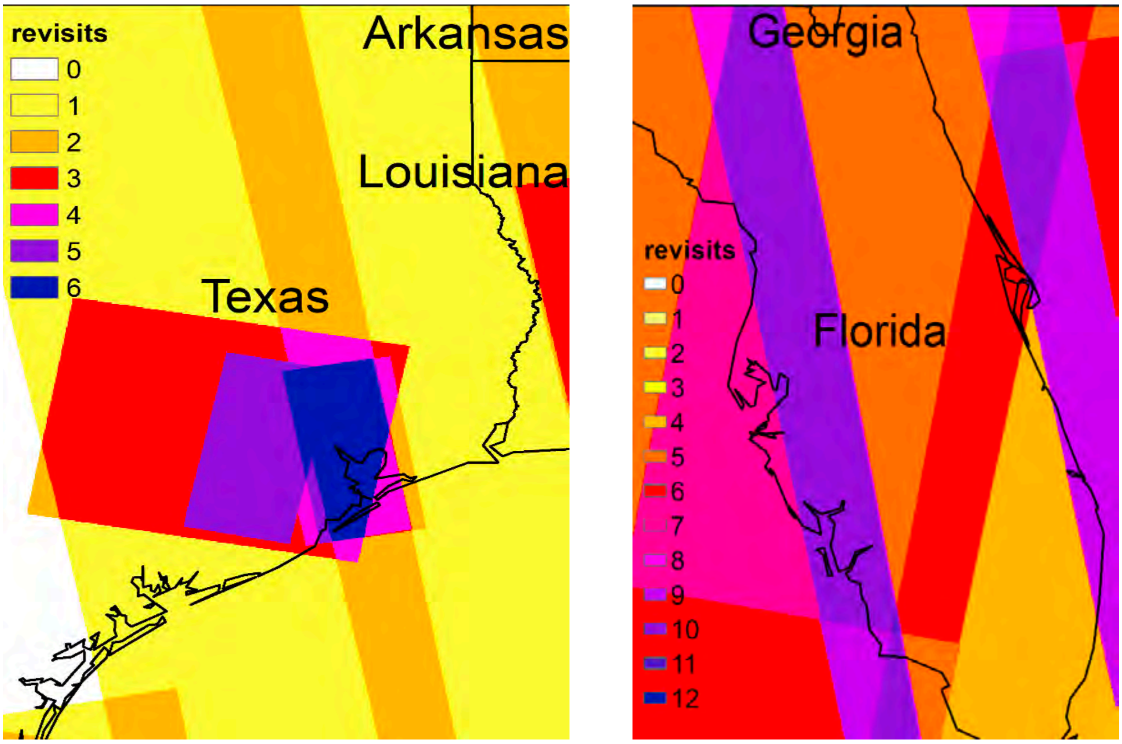

Figure 4. During Harvey, (a) Sentinel-1 SAR data availability days and coverage in Texas and (b) the inundated times of the Seabrook area.

4. Summary

This study has reviewed existing principles and methods for inundation mapping using SAR data. As microwave measurements are significantly less disturbed by weather than measurements from optical sensors, SAR has the greater potential for high-resolution flood mapping. Efforts to automate the process leave a number of common errors unaddressed by most of the reviewed studies:

(1) The argument that flood maps resulting from region growing should include all "open water" pixels connected to the seeds may be untrue and lead to instances of under- and over-detection. If captured after the apex, large isolated and scattered flood pockets disconnected from the pre-flooded water bodies can develop at times due to variability in surface elevation and barriers. Limited by image resolution, narrow water paths or paths covered by vegetation may also appear isolated from known core water zones. Water-like areas can be connected to real water bodies as well; airports built, respectively, in Boston along the Atlantic Ocean and in San Francisco along the Pacific Ocean, for example, may be identified as water areas because they are water-like (smooth) and connected to real water bodies.

(2) Change detection at pixel level can eliminate false positives caused by water-like surfaces, but it is sensitive to noise-like speckle and geometric errors. In SAR applications, change detection approaches need to be applied with caution. Change in shadow areas, for instance, can be caused by change in the looking direction. Most studies that have used change detection models (including those reviewed here) have compared backscattering of collocated SAR pixels within and outside the flood period. Backscattering exhibits large heterogeneity in space and time, however, indicating that in a single object (water or non-water), the direct difference in backscattering might have led to erroneous interpretations. In addition, change detection was carried out from the output of RGA. Consequently, isolated inundation areas could not be detected.

(3) Although a speckle model has been taken into account by most studies, false positives and negatives caused by speckle pixels are not effectively reduced by other than brutal filtering techniques. More advanced approaches target on reducing the noisy effects without damaging image

details, including selecting the optimal filter, simple morphological operators, multi-thresholding compensation, machine learning refinement and utilization of big EO data.

(4) Most approaches have not been tested in large areas, and their validation is usually limited to small areas along rivers. In particular, the limit of SAR-based mapping in terms of river width has not been reported. Limited by the 5–10 m resolution of noncommercial SAR satellites and the presence of speckle, one should not expect a successful rate in delineating inundation in headwater regions.

In the past decades, measurements based on satellite SAR have shifted from data scarcity to abundance. At present, Sentinel-1 enables new approaches taking advantage of big EO data by offering free and global SAR measurements from a large number of repeated observations. With its six-day revisiting intervals, however, Sentinel-1 alone cannot provide sufficiently frequent revisits for floods of short duration. More frequent scanning of the earth will be implemented by the constellation of SAR satellites (e.g., the four-satellite constellation of Cosmos SkyMed can provide revisits within a few hours) and planned SAR satellites (e.g., the NASA-ISRO SAR Satellite Mission (NISAR), planned to launch in 2020, is designed to provide spatiotemporal resolution of 5–10 m and four to six times per month). Consequently, newly emerging studies utilizing the big EO data have advanced to reduce the summarized error to a great extent.

As the automation of non-obstructed inundation extent has been fully addressed by previous studies, three topics may need further investigation: (1) the retrieval of inundation under vegetation; (2) the retrieval of urban inundation; and (3) the estimation of inundation depth from extent.

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Near-real-time non-obstructed flood inundation mapping using synthetic aperture radar

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ABSTRACT

In the event of a flood disaster, first response agencies need inundation maps produced in near real time (NRT). Such maps can be generated using satellite-based information. In this study, we developed mapping techniques that rely on synthetic aperture radar (SAR) on-board earth-orbiting platforms. SAR provides valid ground surface measurements through cloud cover with high resolution and sampling frequency that has recently increased through multiple missions. Despite numerous efforts, automatic processing of SAR data to derive accurate inundation maps still poses challenges. To address them, we have developed an NRT system named RAdar-Produced Inundation Diary (RAPID). RAPID integrates four processing steps: classification based on statistics, morphological processing, multi-threshold-based compensation, and machine-learning correction. Besides SAR data, the system integrates multisource remote-sensing data products, including land cover classification, water occurrence, hydrographical, water type, and river width products. In comparison to expert handmade flood maps, the fully-automated RAPID system exhibited “overall,” “producer,” and “user” accuracies of 93%, 77%, and 75%, respectively. RAPID accommodates commonly encountered over- and under-detections caused by noise-like speckle, water-like radar response areas, strong scatterers, and isolated inundation areas—errors that are in common practice to ignore, mask out, or be filtered out by coarsening the effective resolution. RAPID can serve as the kernel algorithm to derive flood inundation products from satellites—both existing and to be launched—equipped with high-resolution SAR sensors, including Envisat, Radarsat, NISAR, Advanced Land Observation Satellite (ALOS)-1/2, Sentinel-1, and TerraSAR-X.

1. Introduction

Near-real-time (NRT) inundation mapping during flood events is vital to support rescue and damage recovery decisions and to facilitate rapid assessment of property loss and damage. NRT is here defined as a lag of no more than one day from the conditions mapped to the publication of the map. Unlike optical sensors, synthetic aperture radar (SAR) provides its own illumination of the Earth's surface and thus can image day and night, as well as through cloud cover. In addition, SAR's spatial resolution can be very high (~1–2 m), so its potential for flood inundation mapping during storms and hurricanes is also very high, indeed.

The major constraint up to now on using SAR for NRT inundation mapping has been the inability to process quickly the obtained imagery into reliable flood maps. Flood water detection using SAR data can be categorized into six approaches: (1) unsupervised versus supervised; (2) threshold determination; (3) segmentation; (4) change detection; (5) visual inspection and manual editing versus fully automated processes; and (6) open water/closed water detection beneath vegetation or in urban areas blocked by buildings.

While several studies have combined several of these methods to detect flooded areas, most can be classified as supervised, due to the required training of the processing algorithm (Borghys et al., 2006; Kussul et al., 2008; Pulvirenti et al., 2010; Song et al., 2007; Töyrä et al., 2002; Townsend, 2001; Zhou et al., 2000). Although reported to be more accurate, supervised classification is tuned to local circumstances, and its accuracy is affected by the levels of expertise available during training-set selection. Most importantly, the supervised

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approaches cannot be readily automated (Manavalan, 2017). This remains a major challenge.

2. SAR imagery classification to water and land

Different from the estimation of surface parameters (such as soil moisture), inundation mapping is simply the identification of a highly accurate binary mask of water and non-water. Below we provided a complete review of previous work on inundation mapping, most of which has involved methods for which an automated approach was difficult or impossible.

The specular reflective properties of open still water in SAR sensing motivated several efforts (Giustarini et al., 2013; Hirose et al., 2001; Matgen et al., 2011; Yamada, 2001) to determine a threshold below which pixels are identified as water. It was understood that a single threshold might not hold well with large-area water bodies (Tan et al., 2004) or the entire swath of SAR images due to the variability of the environment with regard to, for example, wind roughening and satellite system parameters (Martinis et al., 2009). Martinis and Rieke (2015) produced spatial and temporal backscattering heterogeneity, even for permanent water bodies.

To address spatial variability, Martinis et al. (2009) applied a split-based approach (SBA), together with object-oriented (OO) segmentation (Baatz, 1999). Martinis et al. (2015) further combined SBA with fuzzy logic–based refinement to construct an automated processing chain (Twele et al., 2016). Matgen et al. (2011) developed a histogram segmentation method, and Giustarini et al. (2013) automated the calibration process for segmentation and region-growing thresholds. Essentially, threshold-based approaches need either a bimodal histogram of the pixels or some sample data to initialize the water distribution. For more general situations, when the histogram of the pixels is not bimodal, a straightforward option is to draw training regions of interest (ROIs) manually; but, again, this impedes automation. The SBA method, on the other hand, ensures that only the splits that show a bimodal histogram (water versus non-water pixels) are used to derive the global threshold; and Lu et al. (2014) loosened the restriction to bimodal histograms by initializing the water distribution using a "core flooding area," automatically derived from change detection using multi-temporal SAR images. Change detection (Bazi et al., 2005; Giustarini et al., 2013; Hirose et al., 2001; Lu et al., 2014; Matgen et al., 2011; Santoro and Wegmüller, 2012; Yamada, 2001) is also used to select only significantly changed pixels as inundation candidates to reduce false classification of water (hereafter referred to as "false positives").

In contrast to pixel-based threshold determination, image segmentation–based techniques identify water bodies on continuous and non-overlapping objects. The active contour method (ACM) (Horritt, 1999; Horritt et al., 2001) allows a certain amount of backscattering heterogeneity within a water body and incorporates morphological metrics, such as curvature and tension. Martinis et al. (2009) applied OO with SBA to reduce false positives and speckle. In a comparison of the ACM and OO, Heremans et al. (2003) concluded that the latter delineated more accurately while the former tended to identify large water areas better. Pulvirenti et al. (2011a) provided an image segmentation method that consisted of dilation and erosion operators and employed a microwave scattering model (Bracaglia et al., 1995), which coupled matrix doubling (Fung, 1994; Ulaby et al., 1986) and the integral equation model (IEM) (Fung, 1994; Fung et al., 1994) to interpret the backscattering signature at object level. (Giustarini et al., 2013; Lu et al., 2014; Matgen et al. (2011)) employed a region-growing algorithm to extend the inundation area from detected water pixels.

Inundation detection also encounters vegetated areas, partially submerged wetlands, and urban areas. Theoretically, dihedral scattering is enhanced during a flood if a vegetal stalk structure exists. Ormsby et al. (1985) evaluated the backscattering difference caused by flooding under vegetation. Martinis and Rieke (2015) analyzed the sensitivity of multi-temporal/frequency SAR data to flooding conditions under different land cover conditions and concluded that the X-band radar is only suitable to detect inundation beneath sparse vegetation or forest during leaf-off period, whereas L-band, though with better penetration, has a wider range of backscattering enhancement, which reduces the reliability of the classification. Kasischke et al. (2003) analyzed the backscattering change of ERS-2 SAR from a dry to an inundated situation by comparing with a scattering model and concluded the decrease was not as great as predicted. Townsend (2001) utilized ground truth to train a decision tree to identify flooding beneath forest using Radarsat-1 SAR. Horritt et al. (2003) used two radar signatures as input for the ACM, the enhanced backscattering at C-band and the HH-VV phase difference, to generate two water contours from selected known open-water (ocean) and dry-land (coastal) pixels. Then the area between the two contours was labeled "flooded vegetation." Pulvirenti et al. (2010) trained a set of rules using visually interpreted regions of interest (ROIs) to extract flooded forest and urban areas from COSMO-SkyMed SAR data. Also using COSMO-SkyMed, Pulvirenti et al. (2013) combined their fuzzy logic classifier (Pulvirenti et al., 2011b) and segmentation method (Pulvirenti et al., 2011a) to monitor flood evolution in vegetated areas.

Given the potential for flood detection under vegetation using SAR data, most of these efforts were based on supervised classification, which is almost impossible to automate. One explanation for the preference for supervised classification over an automated threshold determination method is the vegetation heterogeneity: the enhanced dihedral scattering of vegetation cannot be considered as a single class because of the presence of different vegetation species and structure and leaf-off and leaf-on conditions. Such heterogeneity makes it difficult to find a threshold of backscattering enhancement automatically. In other words, detecting flooding beneath vegetation requires identification of multiple classes from an image, but current automatic methods based on threshold determination are only able to discern one.

Segmentation methods present other difficulties. The initial seeds (water lines) needed by the ACM may not be identified for inundated areas that are not connected to a known water source; image dilation and erosion-based methods can smooth out details while reducing speckle; and the OO algorithm, besides the subjective process of determining the scaling factor, was not designed for SAR and is therefore not resistant to speckle. Comparison to microwave scattering models can be affected by the models' poor accuracy, caused by the lack of ground truth (soil and vegetation parameters) (Pulvirenti et al., 2013).

Only a few studies are available on flood mapping in urban areas (Giustarini et al., 2013; Martinis et al., 2009; Mason et al., 2012; Mason et al., 2010), and only one (Mason et al., 2014) investigated the use of dihedral scattering to extract flooding in areas enhanced by buildings. The vertical structure of buildings can resemble vegetation in SAR images, but it is rotationally asymmetric in comparison with a canopy trunk, which prohibits enhancement from occurring from all directions of sight. As a result, scattering enhancement only occurs at some orientations. In addition, smooth impervious surfaces and shadow areas in cities may cause over-detection. More accurate detection of water, therefore, requires knowledge of geometry, the orientation and materials of buildings, and the direction of radar illumination (Ferro et al., 2011)—information that is challenging to acquire for many cities. Another consideration is expense. Ultra-high-resolution SAR data (~1 m) such as TerraSAR-X and COSMO-SkyMed, which are suitable for inundation mapping in urban areas, are commercial and, therefore, costly.

3. Issues for an automated flood mapping system

Existing algorithms to detect flooding unobstructed by structures or vegetation have, as yet, only partially addressed the operational demands of NRT inundation mapping in terms of automation and accuracy. We summarize the issues as follows:

1) Manual labor is needed to reduce over-detection caused by smooth surface and shadow areas (referred to hereafter as water-like surfaces) and under-detection resulting from strong scatter disturbances and speckle-caused noise. Skilled operators are needed to accomplish such manual editing.
2) Assembled segmentation using a region-growing algorithm (RGA) cannot capture the large isolated and scattered flooded areas that may, at times, become disconnected from the pre-flooded water bodies due to variability in surface elevation and barriers after the flood peak. Water paths too narrow to detect or covered by vegetation may appear isolated from known water sources—a limit of sensor spatial resolution. Bottom to top segmentation is affected by speckle. Neither method works where actual water areas are connected to water-like areas.
3) Change detection, designed to eliminate over-detection, may contain significant errors caused by noise-like speckle, geometric dislocation, or shadow areas that change with the direction of radar sight. Expected location error can be a few (1–3) pixels after georeferencing of SAR data. Exact-repeat images (from the same orbits and, thus, radar sight direction) reduce these errors, however.
4) Comparison with a scattering model might be inaccurate because ground parameters of vegetation are required by these models but are not available. Scattering models are also complicated to use by those with less applicable technical training.
5) Spatial filtering, which was used in most of the aforementioned studies, will coarsen the resolution of the result and reduce valuable details along water boundaries.

To address these issues, we developed a fully automated, radar-produced inundation diary (RAPID) system to detect open flood extent. Operating in NRT, RAPID fully integrates radar polarimetry, SAR statistics, morphology, and machine-learning methods to address the identified issues in detecting open flood water. No individual operator attention is needed, although RAPID does not detect flooding under vegetation due to difficulties outlined in Section 2. Section 4 details the four automated processing steps and shows the advantage of synergies of multisource ancillary data, including high-resolution topography, high-resolution water occurrence, land cover classification (LCC), and river width, hydrography, and water type databases. Section 5 provides case studies, including used data, study region, and flood events, followed by Section 6 on quality assessment. Finally, we examine possible applications and also the limitations of the system design.

4. Methodology

Fig. 1 details the four-step framework of RAPID: (A) binary classification of water and non-water at pixel level, (B) morphological processing, primarily to reduce over- and under-detection at object level, (C) multi-threshold compensation to reduce speckle noise; and (D) machine learning–based correction, utilizing topography and the knowledge of stream network and water type.

Based on a fundamental understanding of developed SAR speckle, we know that noise-like speckle is not real noise (Lee and Pottier, 2009; Ulaby et al., 1982); it is, rather, a strong overlap between water and non-water classes. Consequently, conventional single-threshold methods inevitably cause noisy classification results (Matgen et al., 2006; Matgen et al., 2004), and the common-practice strategy to filter speckle as noise at the price of reducing effective resolution is not recommended as a solution. For this study, therefore, we proposed a multi-threshold scheme to reduce the speckle effects.

Since water-like surfaces share identical scattering properties with water bodies, they cannot be eliminated by only using radar statistics. Using the water masks generated by the three automatically optimized thresholds, we found the morphological and compensation procedures significantly suppressed over- and under-detection. In principle, water sources for large water bodies can be found on a high-resolution LCC map, but they may not be found for small water bodies. To prevent over-detection, we applied morphological processing to trace floodplain inundation from known water sources. To prevent the under-detection of isolated water bodies, we improved change detection (ICD).

Finally, we used a machine learning–based approach to refine the detected water areas. Strong scatterers within water bodies, such as infrastructure and vehicles, can cause significant identification errors in surrounding areas due to long synthetic aperture and wide-band range compression. These errors cannot be addressed by the previous processing steps. To reduce the error caused by strong scatterers and remaining speckle, the machine-learning step integrates information on topography, river network, and water probability and type.

Although a machine-learning procedure usually requires manual collection of training samples, this is not the case in the RAPID system. Since correctly identified pixels dominate the water mask generated by previous steps, the pixels collected for training within a buffered area of water bodies (to include both water and non-water pixels) can be used directly as the training set.

A. Binary classification

The first step in binary classification is to cluster water pixels from the whole swath of polarimetric SAR images. All water bodies in one swath are hypothesized as homogeneous areas with fully developed speckle. Assuming the measuring surface is reciprocal, the PDF of multi-look backscattering amplitude matrix, A, for a given category can be

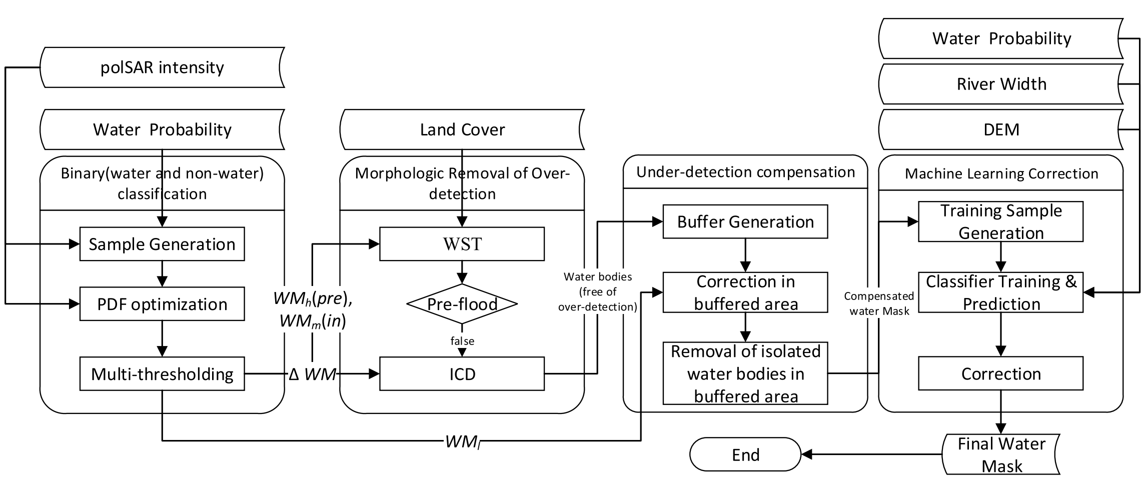

Fig. 1. Framework of RAPID. Individual modules are detailed in the methodology section.

characterized by the Wishart distribution (Lee and Pottier, 2009),

$$p(A) = \frac{|A|^{n-q}}{K(n,q)\ |C|^{n}} \exp(-nTr(C^{-1}Z)), \tag{1}$$

where n is the equivalent number of looks (ENL), $Tr\langle\cdot\rangle$ and $|\cdot|$ are the matrix trace and determinant, and the multi-look covariance matrix, Z, is computed by averaging multiple 1-look covariance matrices,

$$\boldsymbol{A} = n\boldsymbol{Z} = \sum_{k=1}^{n} \bar{u}(k)\bar{u}^{H}(k), \tag{2}$$

where H represents the conjugate transpose operator, and $\bar{u}$ is the 1-look complex scattering vector (Kostinski and Boerner, 1986),

$$\bar{u} = [S_{HH}, \sqrt{2}S_{HV}, S_{VV}\ ], \tag{3}$$

and

$$K(n,q) = \pi^{\frac{1}{2}q(q+1)}\Gamma(n), \ldots\Gamma(n-q+1), \tag{4}$$

where q is the dimension of vector $\bar{u}$ and takes the value of 3 in reciprocal condition.

C is the expectation of the covariance matrix,

$$C = E\langle \bar{u}\bar{u}^{H}\rangle, \tag{5}$$

where $E\langle\cdot\rangle$ stands for the expectation of a stochastic variable.

In practice, the most available data formats are dual-polarized intensities:

$$I_{1,2} = \frac{1}{n}\sum_{k=1}^{n} |S_{i,j}(k)|^2,\ i, j \in \{HH, HV, or\ VV\},\ i \neq j. \tag{6}$$

Carrying out the integral with respect to other variables in Eq. (1), we have the PDF of dual-polarized intensities (Hagedorn et al., 2006; Lee and Pottier, 2009),

$$p(I_1, I_2) = \frac{n^{n+1}(I_1I_2)^{\frac{n-1}{2}} exp\left[-\frac{n(I_1/C_{11}+I_2/C_{22})}{1-|\rho_c|^2}\right]}{(C_{11}C_{22})^{\frac{n+1}{2}}\Gamma(n)(1-|\rho_c|^2)|\rho_c|^{n-1}} \mathrm{I}_{n-1}\left(2n\sqrt{\frac{I_1I_2}{C_{11}C_{22}}}\frac{|\rho_c|}{1-|\rho_c|^2}\right), \tag{7}$$

where $\Gamma(\cdot)$ and $\mathrm{I}_n(\cdot)$ stand for the Gamma function and modified Bessel function, respectively. Although Eq. (7) is used as the starting point of water extraction in this study, the RAPID framework is not restricted to the dual-polarization case, as one can simply replace Eq. (7) with other PDFs according to the polarization availability. The distribution parameters of Eq. (7) are

$$C_{ii} = E\langle |S_i|^2\rangle \tag{8}$$

and

$$|\rho_c|^2 = Cov\langle I_1, I_2\rangle = \frac{E\langle (I_1 - E\langle I_1\rangle)(I_2 - E\langle I_2\rangle)\rangle}{\sqrt{E\langle (I_1 - E\langle I_1\rangle)^2\rangle E\langle (I_2 - E\langle I_2\rangle)^2\rangle}}. \tag{9}$$

In this step, we try to find the optimal value of $(C_{11}, C_{22}, |\rho_c|)$ for a given SAR image and then find the best probability density threshold. Unfortunately, due to the nature of SAR calibration, we cannot assume $(C_{11}, C_{22}, |\rho_c|)$ to be constant over either time or space across different scenes of imagery. We developed an iterative optimization procedure for dual-polarized SAR data that shares similar principles with the single-band optimization method proposed by Giustarini et al. (2013).

A single threshold is not applicable in a dual-polarized intensity space. Instead, we use a probability density threshold, th_{PD}. A pixel is classified as water if

$$p(I_1, I_2) > th_{PD}. \tag{10}$$

In this way, the intensity domain is segmented into two regions: the central part and the marginal part, which correspond to water and non-water, respectively. If accumulative probability, th_P, of water pixels needs to be retained, then

$$th_P = \iint_{p(I_1,I_2) > th_{PD}} p(I_1, I_2)dI_1dI_2. \tag{11}$$

Using Eq. (11), th_{PD} can be uniquely determined by th_P and PDF. We can then derive our iterative optimization procedure:

1. Compute the initial value of distribution parameters, $(C_{11}, C_{22}, |\rho_c|)$, from sampled water pixels.
2. Set $th_P = 0.82$ as the minimum retaining probability.
3. Solve for th_{PD} using Eq. (11).
4. Classify the entire image by substituting th_{PD} into Eq. (10). Note that the seeding pixels are unconditionally classified as water to prevent the parameters from deviating due to trimming of the tailing region of the probability domain.
5. Update $(C_{11}, C_{22}, |\rho_c|)$ using all pixels classified as water.
6. If the change of $(C_{11}, C_{22}, |\rho_c|)$ is within 0.1%, the iteration under the current th_P converges; if the change is too large—say, twice the original value—the iteration under the current th_P fails; go to step 9. Otherwise, go to step 3.
7. Save the current $(C_{11}, C_{22}, |\rho_c|)$ and th_{PD} as the converged parameter set and classification threshold for the current th_P. Compute the Nash-Sutcliffe efficiency coefficient,

$$NSE(th_P) = 1 - \frac{\iint [p(I_1, I_2) - p_{obs}(I_1, I_2)]^2 dI_1dI_2}{\iint [p_{obs}(I_1, I_2) - \bar{p}_{obs}(I_1, I_2)]^2 dI_1dI_2}, \tag{12}$$

where p and p_{obs} stand for the probability density computed by Eq. (7) and the probability density aggregated from all water pixels in the image, respectively. p_{obs} is derived by a grid area–normalized 2D histogram.

8. Increment th_P by 0.01. If th_P is smaller than the upper limit, 0.99, set $(C_{11}, C_{22}, |\rho_c|)$ to the original value. Then go to step 3.
9. The th_P and $(C_{11}, C_{22}, |\rho_c|)$ corresponding to the maximal NSE are selected as the optimal values.

Automated Sampling and the Determination of ENL

Similar to Lu et al. (2014)'s strategy of detecting "core" flooded areas, we removed the requirement of bimodal histogram by initializing the PDF of water class from seeds needed in step 1. But, as discussed in the introduction, change detection is sensitive to speckle and geolocation error, and the threshold is difficult to globalize, so we chose to use a different approach. For sampling to be completely automated, the generation of seeds for step 1 needs to be automated. We proposed to obtain seeds automatically by collecting pixels of high water probability value (> 95%) from the TM-derived global water probability map (Pekel et al., 2016). In this step, the high probability requirement ensures that most sampled pixels are water in SAR images. One potential complication is that we may still sample a very small portion of non-water pixels with strong backscattering. The magnitude of a single pixel of a strong scatterer can be many orders greater than water pixels in a radar image and is thus able to deviate the PDF significantly. Non-water pixels other than strong scatterers can broaden the scattering range, preventing us from deriving reasonable intervals to compute the histogram of the water class. To remove these non-water samples before initializing the PDF, we need to determine a pair of upper and lower thresholds, I_u and I_d, for each polarization. The PDF of water pixels of a single polarization follows the χ^2 distribution (Lee and Pottier, 2009),

$$p\left(\frac{nI}{C_{ii}}\right) = \chi^2_{2n}\left(\frac{nI}{C_{ii}}\right),\ i = 1, 2 \tag{13}$$

We require (I_u, I_d) to represent a confidence interval of no < 99% and let I_p stand for the peak density. Then $\frac{nI_d}{C_{ii}}$, $\frac{nI_u}{C_{ii}}$, and $\frac{nI_p}{C_{ii}}$ can be estimated from Eq. (13). As I_p, can be estimated from the histogram of sampling pixels and n is provided by the user guide the SAR data, even in the presence of strong scatterers and other non-water pixels, C_{ii}, I_d and I_u can finally be derived. The following steps outline the method to estimate I_u and I_d and to refine n

1) Find the intensity of the peak density, I_p, from the initial samples.
2) Find the x_u, x_d whose the cumulative probability of value ${\chi_{2n}}^2$ are 0.5% and 99.5%, and x_p which yields the peak ${\chi_{2n}}^2$ value

where n is initialized using values from the Sentinel-1 user guide (https://sentinel.esa.int/web/sentinel/user-guides/sentinel-1-sar/resolutions/level-1-ground-range-detected)—i.e., 4.4 and 29.7 for the interferometric wide swath (IW) and strip map (SM) modes, respectively.

3) Initialize I_u and I_d using Eq. (14),

$$I_{u,d} = \frac{x_{u,d}}{x_p} I_p \tag{14}$$

4) Iteratively refine I_u by increasing I_u by half a time until the sample number of the excluded tailing region, $[I_u, 5I_u]$, is smaller than 0.5% of the included region, $[I_d, I_u]$. Refine I_d similarly.
5) Using remaining samples, refine ENL by Eq. (15):

$$n = \frac{\sqrt{E\langle (I - E\langle I\rangle)^2\rangle}}{E\langle I\rangle} \tag{15}$$

Water mask generation by multiple thresholds

We generated three water masks, WM_h, WM_m, and WM_l, from a single SAR image using multi-level probability density thresholds (high, moderate, and low) and later combined them through morphological and compensation procedures to suppress the severe over- and under-detection of current automated algorithms. The idea was to let WM_h have the optimal PDF, WM_m have a balanced over- and under-detection, and WM_l have a low level of under-detection but a high level of over-detection. The high threshold was the optimal th_{PD}. Then we divided th_{PD} by 30 and 300 to get the moderate and low thresholds, respectively.

B. Morphological processing

The objective of the morphological processing is to use body-level rather than pixel-level features to reduce over-detection and prepare for the next compensation step to reduce under-detection. We begin by acknowledging the following facts:

1. Disconnected inundation areas may exist. Therefore, not all water sources are identifiable from "dry date" SAR images and the LCC map.
2. Water-like radar responses from non-water surfaces can exist in any SAR image (pre-flood or in-flood).
3. Geometric error and noise-like speckle may "confuse" a change detector over targets with thin shapes, such as streets and small creeks.

We then design for the RAPID system a robust morphological module consisting of two steps: water source tracing (WST) and improved change detection (ICD).

WST utilizes the RGA to form water bodies from known water sources—that is, pixels that are classified as water on both the LCC map and the radar-derived water mask WM_h (under processing). We then impose a size limit ($th_{size} > 50$ pixels) on all water body pixels, and a fraction limit of highly developed classes, developed ratio ($r_{dev} < 30\%$) on water body pixels without the permanent water pixels overlapping with the LCC data. The argument is that false detected water bodies consist of speckle and unchanged non-water smooth surfaces.

WST has little chance of introducing over-detection caused by non-water smooth surfaces and blocked areas, but it has a high chance of neglecting water areas charged by narrow water paths invisible to the images' resolution. To identify these overlooked water areas further, we use ICD, but only for in-flood water masks.

We implemented ICD by running RGA again over the remaining water pixels (after muting all water pixels identified by the WST) in $WM_m(in)$, using the positive pixels in the difference water mask, $\Delta WM = WM_h(in) - WM_m(pre)$, as seeds. For derived water bodies, we loosened the developed ratio to $r_{dev} < 80\%$ and added two over-detection criteria to th_{size} and r_{dev} used in WST: the inundation ratio ($r_{inund} > 30\%$) and high probability ratio ($r_p > 50\%$). For each water body, we defined the inundation ratio as the difference area—the number of pixels that are classified as water in WM_m(in) but as non-water in WM_m(pre)—over the total area and the high probability ratio as the number of water pixels in WM_h(in) over that in WM_m(in). The reason for running the morphological processing over WM_m rather than WM_h for in-flood images is to reduce under-detection caused by speckle and to facilitate accurate estimation of r_{inund} and r_p. Note that speckle and changing shadow areas may severely affect the accuracy of change detection. To overcome them in ICD, we are forced to use, respectively, at least four dry references and satellite data of the same track (mode and orbit number). With identified water pixels (actual water or water-like) on multiple pre-flood dates forming the maximal pre-flood water mask, the probability of misidentifying seeding pixels and over-estimating inundation ratio is reduced significantly. Since pre- and in-flood SAR data obtained in the same track share the same illumination geometry at any given pixel, they share similar water-like surfaces as well.

The ICD is different from traditional change detection (Giustarini et al., 2013; Lu et al., 2014; Matgen et al., 2011) in three ways: (1) ICD runs over all remaining non-water pixels after WST. It does not require inundated pixels to be connected to a known water source and, therefore, is capable of detecting inundation of disconnected lowland. (2) Complete water bodies rather than just changed pixels are formed by running RGA in ICD, while changed pixels, ΔWM, only serve as seeding pixels. Therefore, r_{inund} and r_p can be calculated at object level. Consequently, whereas traditional change detection algorithms measure whether the backscattering of a pixel is significantly changed, ICD measures whether a water body's area is changed significantly to evaluate its inundation severity. And Eq. (3) ICD detects changed pixels from a binary water mask instead of from an image of SAR backscattering. In practice, r_{inund} and r_p were effective to avoid introducing blocked (shadow) areas. The joint use of all four criteria at object level—that is, a water body must satisfy all the criteria to be accepted—made ICD resistant to classification error, noise-like speckle, and geometric error of SAR data. Although the threshold values of the four criteria are empirical, they all have clear physical interpretations, and users do not need to adjust them to different events and regions.

WST and ICD each overcomes the drawbacks of the other: the under-detection of inundation areas with unidentifiable water sources by WST and the exclusion of river-extended flood plains (usually of low r_{inund} values) by ICD. Overall, the sophisticated morphological processing makes RAPID robust to common errors of ancillary and SAR data.

C. Compensation

Through morphological processing, most over-detection is removed and the location of all water bodies is determined. The under-detection within and surrounding water bodies is dealt with through compensation, as detailed in the following:

1. Generate a buffer region (extending 15 pixels) by swelling from the morphologically processed water mask.
2. Label a buffered pixel as water if it is identified as water in the WM_l to generate WM_{comp}.

3. Using all water pixels identified before step 2 as seeds, apply the RGA to WM_{comp}. The grown water pixels form the final water mask.

The buffered area contains outside pixels to a certain distance and most inside pixels. Misclassified non-water pixels inside of each water body are a result of speckle; equivalently, pixels distributed in the marginal area of the water PDF, lower down the threshold of probability density, will reduce the error inside of each water body while not significantly altering the true boundary, as shown in Fig. 3(d) and (e).

D. Machine Learning–Based Correction

Errors caused by noise-like speckle and strong scatters can occur inside of water bodies in WM_{comp}. Although filtering approaches dominate SAR processing, they sacrifice the effective resolution and change the statistics of the signal without completely eliminating the error. For this reason, we did not employ a local filter in RAPID. Instead, we constructed an automated correction step based on machine learning. This step assumes that (1) given the noise, the majority of pixels are correctly classified; and (2) high-resolution terrain, river bathymetric, and network data also can provide the possibility ranks of water pixels.

In this correction step, a logistic binary classifier (LBC) is trained to predict the water probability of pixels in all water bodies and their buffered areas. Water coverage–related features are extracted as input variables, and the water result from the compensation step (described in Section 4C, above) is used as a “prediction result” to train the LBC. Finally, user-defined thresholds are applied to the predicted water probability to correct the water mask. Unlike in usual machine-learning procedures, the pixels for training and correction in RAPID are in the same set, and neither cross-validation nor optimization is needed in the training.

The correction algorithm is depicted in Fig. 2. The reasons whether a pixel can be water within these two categories of water bodies—-standing water bodies (SWs, hereafter referred to as lakes, wetlands, ponds, and reservoirs) and water bodies in movement (MWs)—differ between the categories. For SWs, a pixel is in water because its elevation is lower than the overland area. Elevation dominates the water coverage with the regulation of gates for some reservoirs. For MWs, elevation is only balanced within a cross section. The overland elevation of a downstream segment, for example, can be lower than the in-channel elevation of an upstream segment within a single river body.

Consequently, factors that contribute to the expansion of river bodies are more complex than those affecting SWs, so in constructing the correction step we needed to separate the two categories and construct different feature spaces for them.

Unfortunately, no existing algorithm can accurately separate standing and flowing water bodies because manmade standing water bodies, such as reservoirs and canals, can be made in a wide variety of shapes or within any part of the fluvial system. Instead of developing an automatic algorithm, we relied mostly on existing datasets based on survey or visual interpretation. For the identification of SWs, we jointly used the HydroLakes dataset (Messager et al., 2016), US detailed water bodies (USDWB, optional, provided by ESRI), and water probability. HydroLakes is mostly accurate for SWs larger than 10 ha, USDWB labels a lake/pond or stream to each segment of the water central line. The two datasets may help identify > 90% of water bodies, with those remaining unidentifiedsmall SWs. We used a simple rule to identify th remaining SWs—that is, a small water body is an SW if its P_{50} (water probability that ranks at 50 percentile) and compactness (the square root of area over the perimeter) are > 45% and 25, respectively. Improving the classification of SW and MW is beyond the scope of this study, but deep learning methods may be applied for this purpose in the future.

Training samples

To train the classifier, we generated buffering regions from existing water bodies so both true (water) and false (non-water) pixels would be included. For an LB, we simply swelled the water area by 15 pixels. For river cross sections, we connected a given number (3 to 5) of adjacent central channel pixels, then generated a buffered polygon using twice their maximal river width. We needed, therefore, a river width dataset. Since we lacked this information, water pixels not contained in the training set of SWs or river bodies would not be processed (trained, predicted, or corrected).

Feature selection

A water unit is a group of water pixels that theoretically share the same limit of a given feature. For an SW, the entire water body is a water unit, whereas for an MW, each cross section is an individual water unit. Table 1 gives the feature spaces of SWs and river cross sections (RCs). Each pixel has two types of features: uniform, which are constant for all pixels belonging to a water unit, and distributed, which are different for each pixel. Within a water unit, for example, the elevation of all pixels (a distributed feature) should be smaller than the maximal elevation (a uniform feature) of the water unit.

Ideally, the minimal probability and maximal elevation of an SW set the limits for all pixels within the SW. Due to the relatively coarse resolution and low frequency (15 days) of Landsat images, however, using minimal (0% rank) probability as the lower limit may result in a non-informative zero value of this feature for many SWs. We added, therefore, 1–20% rank probability values. Similarly, since the elevation

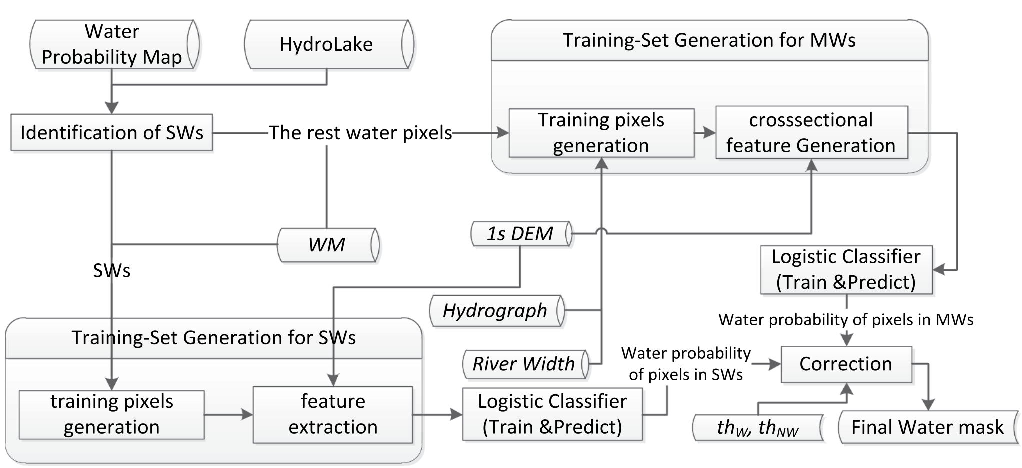

Fig. 2. Machine-learning correction schema.

Table 1
Feature space of water bodies.

Feature description	Reason to select	Water type	Feature type
Central channel pixel (CCP) FAC	River width is related to drainage area.	RC	Uniform
Maximum distances from both sides to CCP	Greater distance indicates smaller chance of being inundated.	RC	Uniform
Distance from CCP		RC	Distributed
Maximal elevation difference to the lowest pixel	Elevation difference should be below the upper limit.	Both	Uniform
Elevation difference ranked at 99%, 97%, 95%, and 90%		SW	Uniform
Elevation difference to the lowest pixel		Both	Distributed
Elevation ratio to the highest pixel		RC	Distributed
Minimal probability	Probability is higher for river and SW centers than for edges (works better for drier situations).	Both	Uniform
Probability ranking at 1%, 2%, 5%, 10%, and 20%		SW	Uniform
Probability		Both	Distributed

of an SW can be controlled by a gate, the maximal elevation difference may not be representative of the floodplain boundary. We included, therefore, 90–99% elevation differences, as well. For a river water unit, we simply used the minimal probability or maximal elevation difference, due to the limited number of pixels within each cross section. As coastal areas have less pronounced topography per stream cross section than most inland areas, we included an elevation ratio as a supplement to elevation difference.

Correction thresholds

Typically, a single threshold is applied to the probability result to generate the binary classes. To prevent over-correction and not rely purely on the trained results, we used double thresholds, 0.1 and 0.8. A water probability lower than 0.1 or higher than 0.8 indicated that a given pixel should be labeled as non-water or water class, respectively. Otherwise, if the probability falls in between, the class of the pixel will not change.

5. Test event, data, and processing

We selected two flood events to test the efficiency and robustness of RAPID. Typhoon Nepartak caused flooding of the Yangtze River in 2016, and Hurricane Harvey caused flooding in Texas in 2017. The two events were large enough to be observed by satellite multiple times. Moreover, they occurred outside of and within the United States, respectively, thus allowing us to test the robustness of RAPID using different input data, in different locations and climatic conditions. Table 2 describes the events and data.

We acquired Sentinel-1 level-1 dual-polarized (VH + VV or HV + HH) SAR data for Nepartak in IW mode and for Harvey in IW and SM modes in Ground Range Detected (GRD) format. After pre-processing using Sentinel Application Platform (SNAP), the ESA-released toolbox, the resulting pixel spacing was 10 × 10 m. The pre-processing included four steps:

1) Orbit correction
2) Radiometric calibration
3) Range-Doppler geometric terrain correction
4) Incidence angle normalization

Steps 2 and 3 are sometimes referred to as radiometric terrain correction (RTC). For simplicity, we used the algorithm provided by Mladenova et al. (2013) to run step 4. The total processing times for IW mode (~33,000 × 21,000 pixels) images are around 6 h and 1 h for in- and pre-flood images, respectively. For the SM mode (~12,000 × 17,000 pixels), processing takes around 2 h and 30 min. We processed images of the events on the University of Connecticut's high-performance computer (HPC) in parallel, making the total processing time about 6 h. We used Matlab and Microsoft R Enterprise (RRE) to implement, respectively, the Steps A–C and the machine learning step.

Table 3 provides ancillary data options. Categorized by type, they comprise LCC, water occurrence, hydrographic, water type, and river width products. Of the Landsat-based LCC products, the National Land Cover Database (NLCD) (Fry et al., 2011; Homer et al., 2007; Homer et al., 2015; Vogelmann et al., 2001) is available in the United States at five-year intervals, and the Finer Resolution Observation and Monitoring of Global Land Cover database (FROM-GLC) (Gong et al., 2013) (http://data.ess.tsinghua.edu.cn/) has been available all over the globe since 2010. In NLCD taxonomy, water types are coded 90, "water bodies," and 95, "wetland," while highly developed types are coded 23, "built-up area with medium density," and 24, "built-up area with high density." In FROM-GLC taxonomy, water types are 50, "wetland," and 60, "water bodies," while the highly developed type is 80, "artificial surfaces." For water occurrence, the only available dataset is produced by Pekel et al. (2016). For river width, two products, the Global River Width (GRWidth) (Allen and Pavelsky, 2018) and the Global Width Database for Large Rivers (GRD-LR) (Yamazaki et al., 2014) are available. The latter will be available in the future for global applications. For hydrography, the National Hydrography Dataset (NHD) plus v2 (Simley and Carswell, 2009) (www.horizon-systems.com/NHDPlus/NHDPlusV2_home.php) is available at 30 m resolution in the United States and the global GRD-LR at 90 m resolution globally. We used GRWidth as river width for both the Nepartak and Harvey events; as LCC we used FROM-GLC for Nepartak and NLCD for Harvey; and as hydrography we used GRD-LR for Nepartak and NHD for Harvey.

6. Case study results

Fig. 3 shows the concept for processing steps for the SAR image obtained for the July 17, 2016 event, over a zoomed-in area containing combined water-like surfaces (roads and an airport) and inundated areas. Fig. 3c provides an example area affected significantly by noise-like speckle and strong scatterers, as identified through binary classification (Section 4A, above). As shown, it is difficult to delineate the boundary of floodplain or flooded fields due to the antenna synthesis and range compression, strong scatterers for the Yangtze River, infrastructure, and vehicles radiating strong backscattering to surrounding

Table 2
Data and test events.

Event	Location	Data availability of pre-flood dates	Data availability of in-flood dates
Nepartak	Hubei, China	May 6, 18, 23, and 30, 2016	Jul. 5, 17, and 22, 2016
Harvey	Texas, USA	Jun. 25, Jul. 18, 24, 30, and 31, and Aug. 05, 11, 12, 18, and 23, 2017	Aug. 29 and 30, and Sept. 4, 5, and 10, 2017

Table 3
Input data to the RAPID kernel algorithm.

Name	Source/type	Producer	Time span	Coverage	Spatial res.	Revisiting intervals	Needed by step
Sentinel-1	SAR	ESA	Since 2014	Global	3.5/10 m	~2 days	A
NLCD	TM/LCC	USGS	1992–2011	US	30 m	5 years	B
FROM-GLC	TM/LCC	Tsinghua Univ.	2010 only	Global	30 m	One time	B
Water occurrence	TM/water probability	ESA	1984–2015	Global	30 m	Static	A & D
Hydrography	NHD	Horizon Systems Co.	N/A	US	30 m	Static	D
DEM	STRM	USGS	N/A	Global	30 m	Static	D
GRWidth	TM/River Width	George Allen	N/A	Global	30 m	Static	D
GWD-LR	STRM/River Width and Hydrography	Dai Yamazaki	N/A	Global	90 m	Static	D
HydroLakes	STRM	WWF	N/A	Global	90 m	Static	D
USDWB	Multiple	Esri, USGS, and USEPA	2018	US	4 m	Static	D

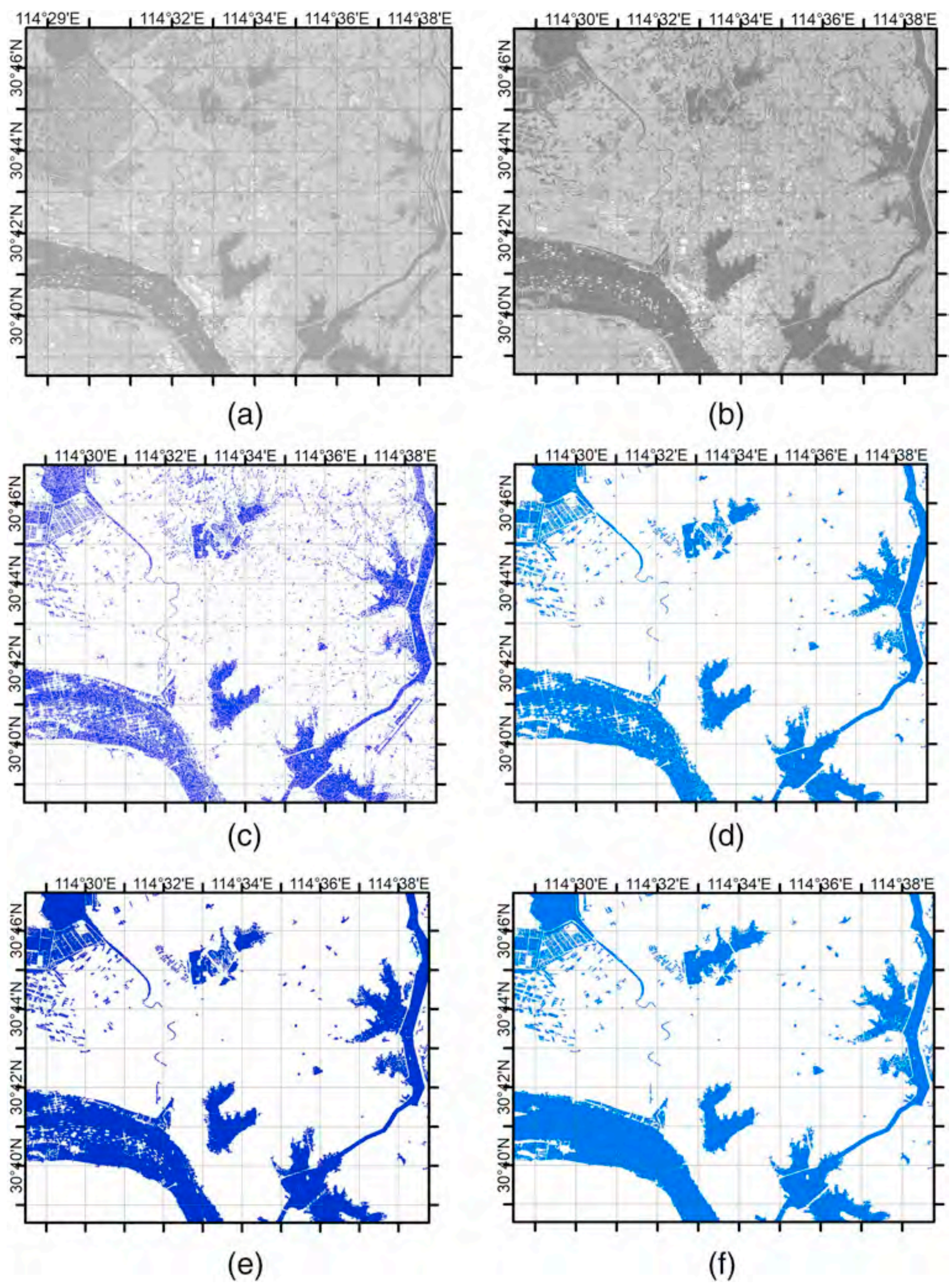

Fig. 3. Demonstration of the major processing steps (see A–D in the methodology section) using the water mask during the flooding of Yangtze River, July 17, 2016. (a) SAR data of July 17, 2016 (b) ESRI map, (c) water mask, $WM_{h,}$ derived from the binary classification using the optimal threshold, step A (d) water mask from step B, morphological processing, (e) water mask from step C, compensation, and (f) final water mask from step D, machine-learning correction.

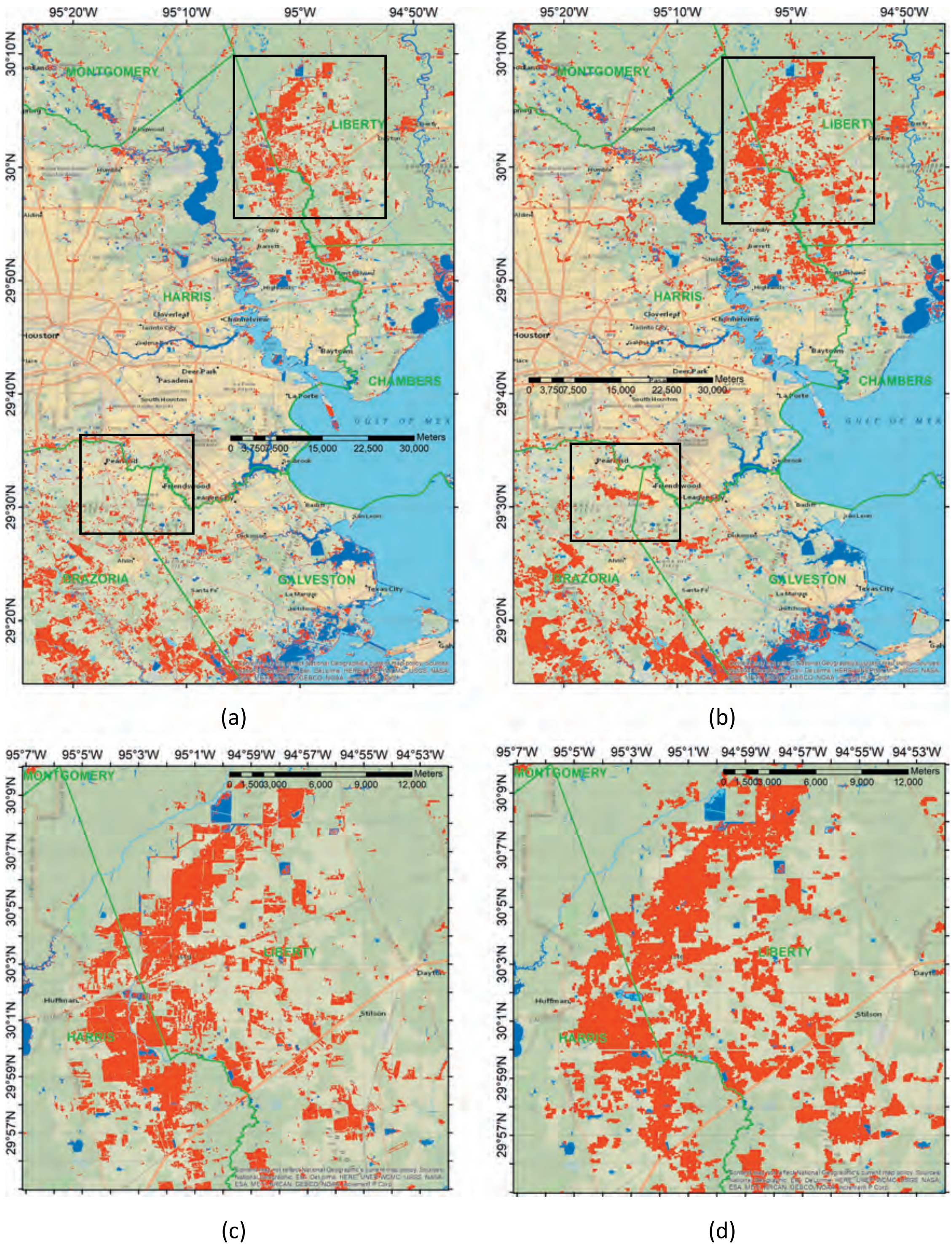

Fig. 4. Comparison of RAPID inundation map (a), (c), and (e) with EE (b), (d), and (f). (g) and (h) are pre- and in-flood Sentinel-1 data collocated with (e) and (f).

areas along the azimuth and range directions (the cross-shaped underestimated areas). Over-detection is observed over the airport in the bottom right corner of Fig. 5c, with speckle over most overland areas. The morphological processing eliminated most over-detection and slightly reduced under-detection, as shown in Fig. 3d. The compensation steps further reduced the under-detection caused by the PDF overlapping between water and non-water classes, as shown in Fig. 3e. The remaining issue—under-detection caused by strong scatterers and speckle—was corrected by the machine learning–based method, as shown in Fig. 3f.

The chance of having synchronized optical and SAR data of comparable resolution for the same area is rare, especially during a given flood period. To carry out quantitative validation, we compared the RAPID-generated inundation result with an expert, hand-derived inundation delineation (referred to as EE hereafter), intuitively using Sentinel-1 and World-View data. Fig. 4a and b show strong agreement between RAPID and EE. The confusion matrix, M, between RAPID and EE is given by Table 4. It shows overall agreement, with $M_{11} + M_{22}$ being 93% pixels, with producer accuracy, $M_{11}/(M_{11} + M_{21})$, being 77%, and user accuracy, $M_{11}/(M_{11} + M_{12})$, being 75%, respectively.

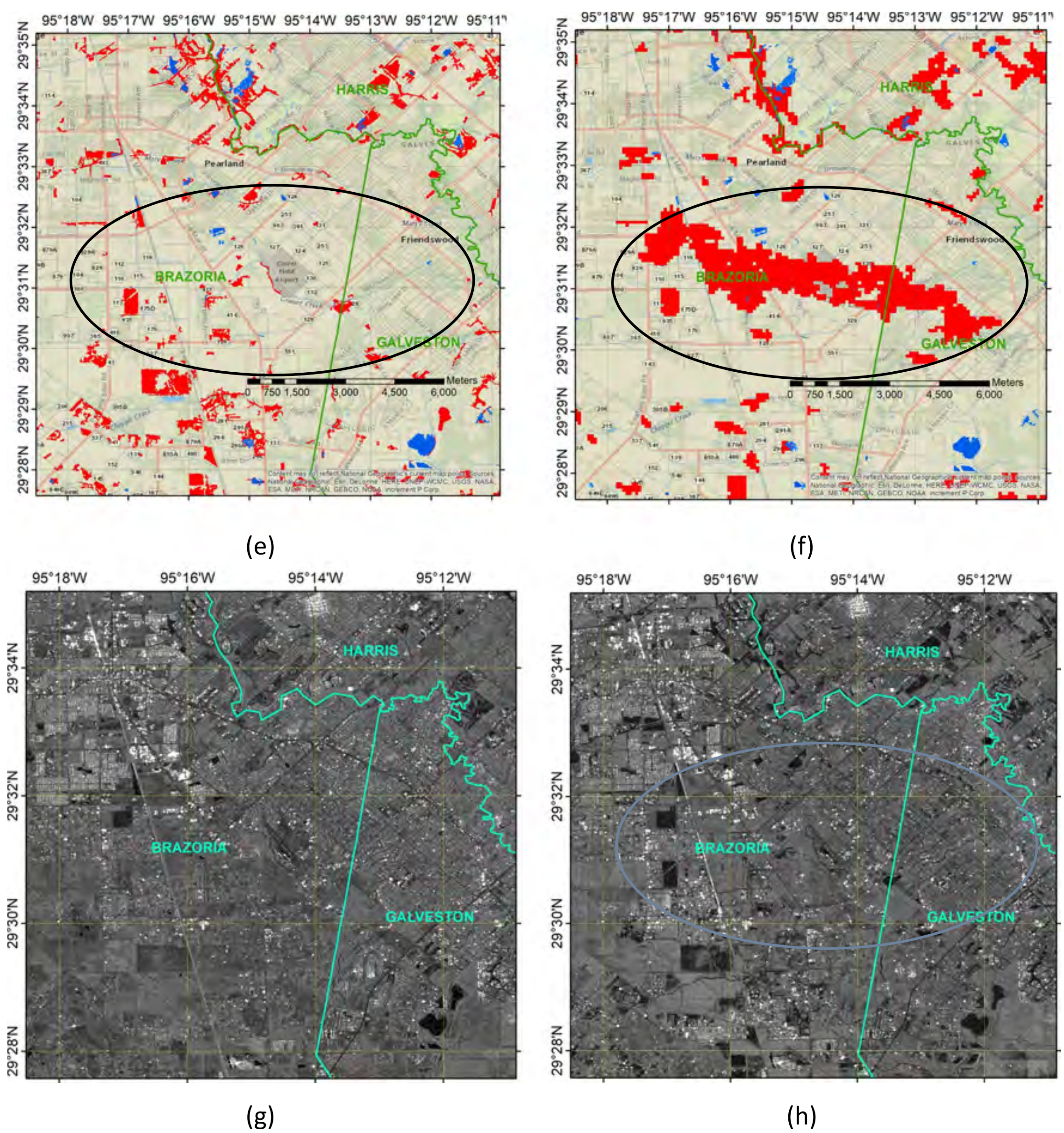

Fig. 4. (*continued*)

Table 4
Confusion matrix of inundation mapping.

Confusion matrix		EE	
		Wet	Dry
Retrieval	Wet	12,992,348 (11.09%)	3,853,426 (3.29%)
	Dry	4,367,647 (3.73%)	95,979,615 (81.90%)

Although the EE map is the best obtainable reference, RAPID did not necessarily produce false positives or negatives among pixels that disagreed. The major portion of "under-detection" by RAPID, for example, is given by Fig. 4e and f. By comparing the pre-flood and in-flood SAR data in 4g and h, we concluded the circled part of 4f was not, in fact, flooded. Indeed, the EE map was generated by compiling inundation results from other SAR images and from performing Dartmouth Flood Observatory (DFO; http://floodobservatory.colorado.edu) in-house classification algorithms on optical data, to deliver comprehensiveness overall flooding during a prolonged event. In this case, SAR images from more than one satellite were used. The "flooded" area in the circle originated from the result published by Copernicus Emergent Management Service using Cosmos SkyMed SAR data. Since the data acquisition time were different, the inundated area in the EE map might have been caused by fast-vanished or generated inundation that was "observed" by Cosmos SkyMed but not by Sentinel-1. Moreover, Fig. 4c shows more detailed dry terrace than 4d because, in the generation of EE, filtering and the manually editings of the polygons inevitably sacrificed some details.

Fig. 5 shows a map of the times an area is inundated in a region that is within all Sentinel-1 revisits. The fact that permanent water bodies exhibit the greatest number of wetted times verifies the correctness of RAPID procedure.

For Typhoon Nepartak, RAPID results generated from SAR data on July 17, 2016 are given by Fig. 6. Although no reference data were available for this event, we provided in the first and second column the pre (on May 6) - and in-flood SAR data for visual validation. Fig. 6d and g show that RAPID accurately captured the inundated area, and that false positives and noise were reduced without sacrificing, respectively, detectability or resolution. Where the LCC map was wrong, pre-existing water pixels derived from SAR data could, infrequently, either be

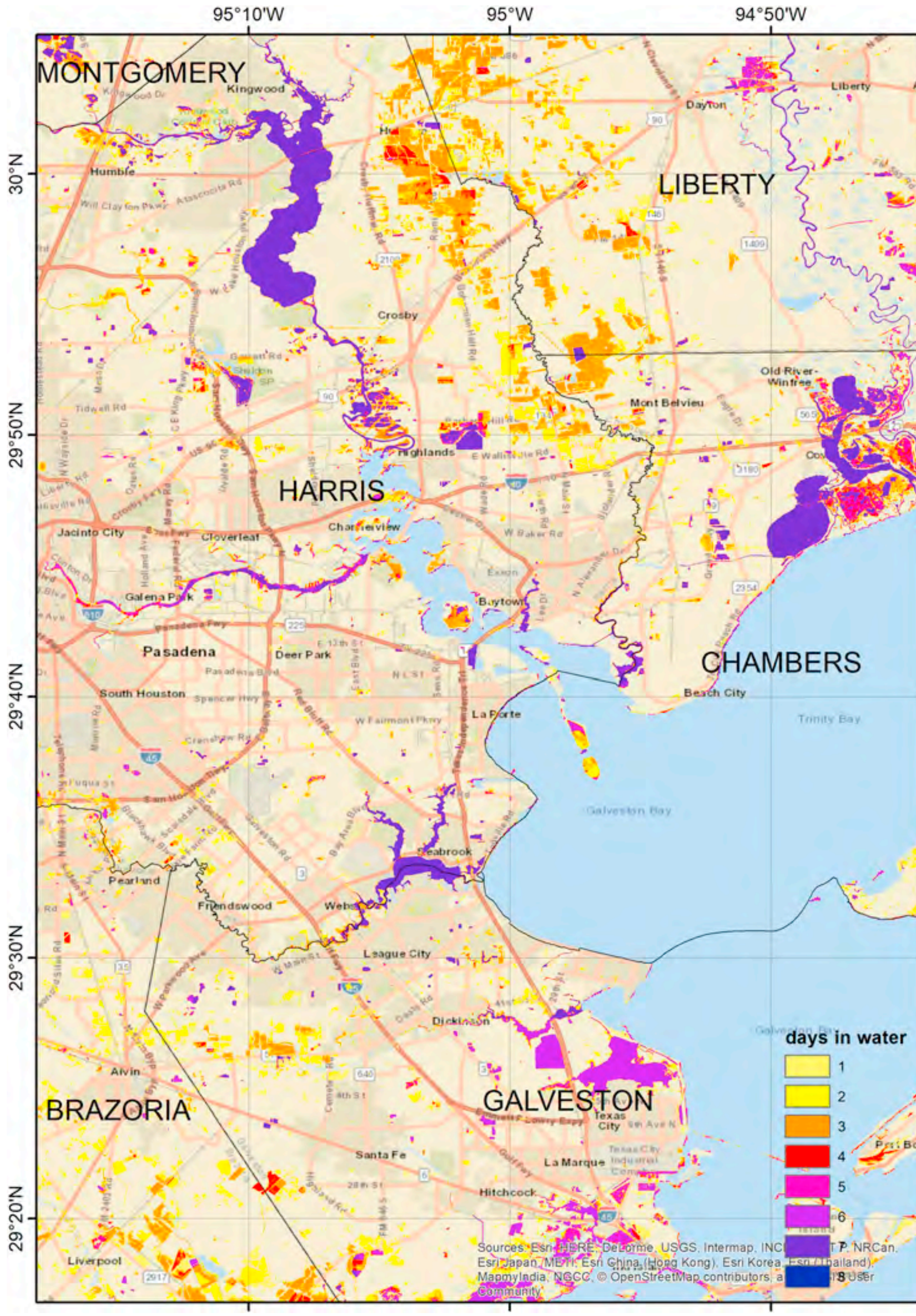

Fig. 5. The observed times of inundated areas during Sentinel-1 revisits. Data from both Sentinel 1A and Sentinel 1B satellites are available for some of the dates from different orbits.

misidentified as inundated if they were connected to a floodplain (as shown in the circular area in Fig. 6a) or as non-water if they were not connected. In practice, both misidentifications will be eliminated in the final result because pre-existing water areas can be accurately created by overlaying water masks extracted by revisits of high-resolution optical remote-sensing satellites (such as Landsat or World View).

7. Conclusions

We have developed an NRT inundation mapping system, named RAPID, driven by SAR data of dual polarization, which requires no human interference. By combining statistical classification, morphological processing, multi-threshold compensation, and machine learning–based correction, RAPID extracts at high spatial resolution (~10 m) inundated areas that have been flooded from existing water bodies and isolated lowlands and reduces over- and under-detection and speckle noise without applying any filtering techniques, which cause severe problems using existing algorithms. By combining the strength of state-of-art technologies, such as radar polarimetry and machine learning, with information from multi-source remote-sensing datasets and products at high resolution (≥30 m), including LCC, water probability, terrain data, and river bathymetry, RAPID achieved full automation and accuracy, as validated by selected flood events in Hubei, China, and Texas, United States, caused by Typhoon Nepartak (2016) and Hurricane Harvey (2017), respectively.

The datasets we used are all freely available globally. RAPID is designed to be resistant to low-level source data error, such as misclassification and low updating frequency of LCC data, less-

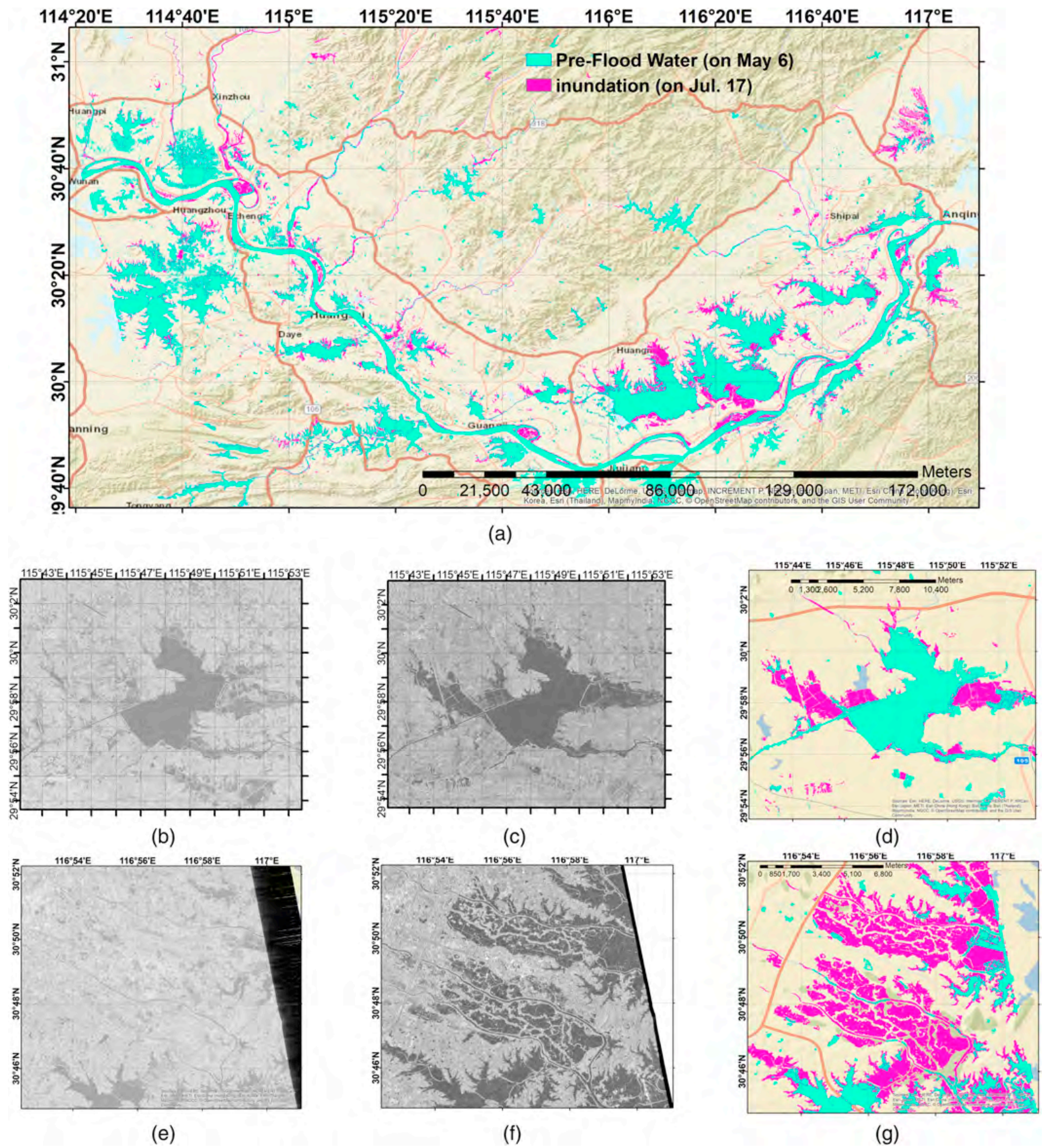

Fig. 6. Inundation detection of a segment of the Yangtze River (centered at Poyang Lake) using July 17, 2016 (b, e, in-flood) vs. May 06, 2016 (e, f, pre-flood). (a) is the overview with circular denoting the misidentification from pre-existing water bifurcation to inundated, and (d) and (g) are the zoomed-in inundation maps.

representative water probability (of flood extremity), and limited resolution of terrain data. In addition, RAPID is open to integrating newly emerging datasets and products to produce more accurate inundation results. Overall, the RAPID system processing time is similar to that of regular SAR processing techniques to detect water and is of low cost and high quality in both effective resolution and accuracy.

RAPID is limited in three ways:

1) The accuracy of the machine-learning step depends on the resolution and accuracy of the Digital Elevation Model (DEM) and the hydrographic and river bathymetric data.
2) Inundated areas that are out of floodplains (extending from rivers and SWs) will not be processed by the machine learning–based correction.
3) RAPID currently can only detect open flooding, where the line of sight is not obstructed by vegetation or other objects.

The first limit can be mitigated or eliminated once higher-quality ancillary data become available. The second will be partly mitigated when high-quality crop data (Xiong et al., 2017) become available in the near future. As analyzed in the introduction above, current theories of delineating vegetation flooding can less easily be automated. It is possible for RAPID to include vegetation flooding in the future, when more L-band SAR data become frequently available.

Recently, the abundance of free available SAR data has boosted the ability of the flood-monitoring community to detect inundated areas accurately, often during events. High-resolution inundation maps can be produced without any budgetary concerns regarding, for example, airborne photography missions, as data are freely available from satellites. The RAPID system liberates flood observers from tedious processing work requiring expertise that might not be available during an event. The system can be operationally applied to derive global inundation mapping at intervals of two days (in midlatitude regions) to four days (near the equator) using satellites—both existing and to be launched—equipped with high-resolution SAR sensors, such as Sentinel, the Advanced Land Observation Satellite (ALOS), the Surface Water and Ocean Topography (SWOT) satellite, and the NASA-ISRO SAR Satellite Mission (NISAR).

Besides the advantages of NRT monitoring, the low cost of manpower associated with RAPID facilitates the use of miscellaneous applications, including retrospective investing historical flood events stored in inventory like Shen et al. (2017b) and the DFO using archived SAR data, and the evaluating accuracy of Federal Emergency Management Agency (FEMA) flood-zone maps. With global or regional flood inundation databases populated in the future, the use of RAPID will also benefit the calibration and validation of hydrological, hydrodynamic modeling (Bates et al., 1997; Havnø et al., 1995; Schumann et al., 2005; Shen and Anagnostou, 2017; Yamazaki et al., 2011) and studies of inundation risk caused by geomorphological factors (Shen et al., 2017a; Shen et al., 2016). Besides inundation extent, floodwater depth can be inferred with available high-resolution DEM (Cohen et al., 2017).

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APPENDIX D

water

MDPI

Article

A Numerical Framework for Evaluating Flood Inundation Hazard under Different Dam Operation Scenarios—A Case Study in Naugatuck River

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Abstract: Worldwide, many river floodplains contain critical infrastructure that is vulnerable to extreme hydrologic events. These structures are designed based on flood frequency analysis aimed at quantifying the magnitude and recurrence of the extreme events. This research topic focuses on estimating flood vulnerability at ungauged locations based on an integrative framework consisting of a distributed rainfall–runoff model forced with long-term (37 years) reanalysis meteorological data and a hydraulic model driven by high-resolution airborne LiDAR-derived terrain elevation data. The framework is applied to a critical power infrastructure located within Connecticut's Naugatuck River Basin. The hydrologic model reanalysis is used to derive 50-, 100-, 200-, and 500-year return period flood peaks, which are then used to drive Hydrologic Engineering Center's River Analysis System (HEC-RAS) hydraulic simulations to estimate the inundation risk at the infrastructure location under different operation strategies of an upstream reservoir. This study illustrates the framework's potential for creating flood maps at ungauged locations and demonstrates the effects of different water management scenarios on the flood risk of the downstream infrastructure.

Keywords: flood frequency analysis; hydrologic and hydraulic modeling; flood inundation; LiDAR; HEC-RAS; Synthetic Hydrograph

1. Introduction

Floods are among the most damaging natural disasters, with increasing impact and frequency in Northeastern United States [1]. In the United States alone in recent decades floods have accounted for thousands of deaths and tens of billions of dollars in annual losses. Additionally, many utilities rely on critical infrastructure located on floodplains that are vulnerable to these extreme hydrologic events, allowing disturbances to extend beyond the floodplain. In flood resilience, we seek to quantify and mitigate the flood risk, as well as expedite recovery from the consequences after a flooding event occurs [2]. Resilience can be improved in many ways, including land use management, flood infrastructure management and operation, storm water withholding, more effective flood emergency preparedness, and flood response policy. However, before policy actions can be put in place, the risk must first be systematically quantified.

In relation to flood design, engineers use historical flow observations to derive information relative to the expected recurrence (i.e., return period) and magnitude (i.e., return level) of a flood event. The observed frequency is modeled using a probability distribution that can further be used to estimate the return period of event magnitudes that are generally unobserved (e.g., flood event with

500 years return period). Distributions used in frequency analysis vary, but in the U.S.A. engineering practice relies on the use of Log-Pearson Type III, which is recommended by the U.S. Water Resource Council [3]. Information regarding magnitude and frequency of occurrence of flooding events gathered through flood frequency analysis (FFA) is instrumental in mitigating losses associated with floods, particularly when designing hydraulic structures such as reservoirs and dams.

Hydrologists have developed a number of methods to conduct FFA. These methods can broadly be classified into two groups: statistical approaches and rainfall-runoff modeling. For statistical approaches, statistical analysis or hydrological regionalization are used to analyze hydrological data within a basin, or transfer hydrological information from one or more homogenous gauged catchments to a neighboring or geographically/hydrologically similar basin [4–6]. However, the quality of the estimation in the basin is subject to the continuous length of flow observations of the basin or neighboring gauged basins, and potential nonstationarity of the historical flood trend. In an alternate approach, observed precipitation combined with various other meteorological forcing parameters are used to drive physically-based hydrologic and flood routing models to simulate surface flows [7], which can have longer time spans but can be affected by the biased peak estimation. Surface flows are made up of both overland and channel flow routing, which can either be handled separately by two models [8,9], or combined through a coupled model [10,11]. Hydrodynamic routing models simulate surface flows based on solutions to simplified shallow water equations like the kinematic wave [12] or diffusion wave equations [9]. Solutions to these equations rely on parameters directly derived from physical watershed characteristics rather than empirically estimated coefficients. Specifically, physically-based distributed hydrologic models are able to capture the spatial variability of hydrologic parameters, and thereby better characterize the heterogeneity of certain complex hydrologic processes within catchments [13–15]. In inland watersheds, flooding is caused by rainfall, snowmelt, or a combination of both. Distributed hydrologic models have the capacity of accounting for the intra-basin variability of runoff-producing mechanisms by integrating gridded meteorological forcing with land cover, vegetation, terrain, and soil data. Furthermore, with the availability of high-resolution reanalysis forcing datasets like the North American Land Data Assimilation System (NLDAS), hydrologic models can now make use of quality controlled, temporally and spatially consistent datasets at a fine spatiotemporal resolution, often in areas that were previously uncovered by ground-based measurement networks. This study used The Coupled Routing and Excess Storage–Soil–Vegetation–Atmosphere–Snow (CREST-SVAS) model driven by NLDAS forcing data to simulate flows in basins of Northeastern United States [13].

The objective of this study is to demonstrate a numerical framework for evaluating flood vulnerability in terms of inundation at a site of interest in the Naugatuck River basin featuring critical utility infrastructure and different operation scenarios for an upstream dam. In the past, artificial intelligence (AI) has been used for the forecast of flood inundation [16,17] and dam-controlled reservoir water level [18]. Applying the AI techniques to assess flood vulnerability at this site of interest is however difficult because of the lack of necessary long-term observations at the site of interest and the existence of a major flood control dam upstream. This paper presents an integrative framework, involving atmospheric reanalysis driven hydrologic and hydraulic simulations that provide long-term flow data based FFA, and examine the impact of dam operation on the downstream floodplain under varying flood return periods.

2. Materials and Methods

2.1. Study Area

Located in Western Connecticut, the Naugatuck River is the largest tributary of the Housatonic River. Entirely confined within the state's borders, the Naugatuck River spans over 63 km south from Torrington to Derby, 19 km north of the Long Island Sound. The stream features quick flows for the majority of its length, due to its fairly steep gradient of 2.46 m per kilometer. This steep gradient causes the runoff from precipitation in the basin to be rapid. In this study basin, considerable floods occur in the spring, where heavy rainfall can trigger snowmelt which then contributes significantly to the flood magnitude and volume. Previous models have failed to capture flood peaks in this region due to the complexities of this hydrologic interaction [19,20]. At its outlet, the river has an average annual streamflow of 15.86 cubic meters per second (cms), while minimum baseflows are approximately 2.27 cms. The river's watershed is an approximate 805.5 square kilometers covering 27 different towns. The watershed contains a variety of land uses, including but not limited to rural, dense urban, suburban, agricultural, and undeveloped forested areas.

For this study, two separate river reaches were selected to investigate, primarily because of the presence of critical infrastructure in these areas. One infrastructure, just 1.5 km north to Thomaston, and at approximately the midway point of the Naugatuck River is the Thomaston Dam. A flood control dam built and operated by the U.S. Army Corps of Engineers in 1960, the Thomaston Dam is 43.3 m high, 609.6 m long, horseshoe-shaped earth fill dam with two 3.048 m adjustable gates. While the Dam is normally empty, it has the potential to utilize 3.88 square kilometers to store up to 1.8 billion cubic meters of water [21]. The other critical infrastructure is located in Waterbury, an urbanized and industrialized portion of the river and 14.5 km downstream of the Dam. This area features sections (henceforth known as critical infrastructure "A" and "B") both in close proximity to the Naugatuck River (Figure 1c).

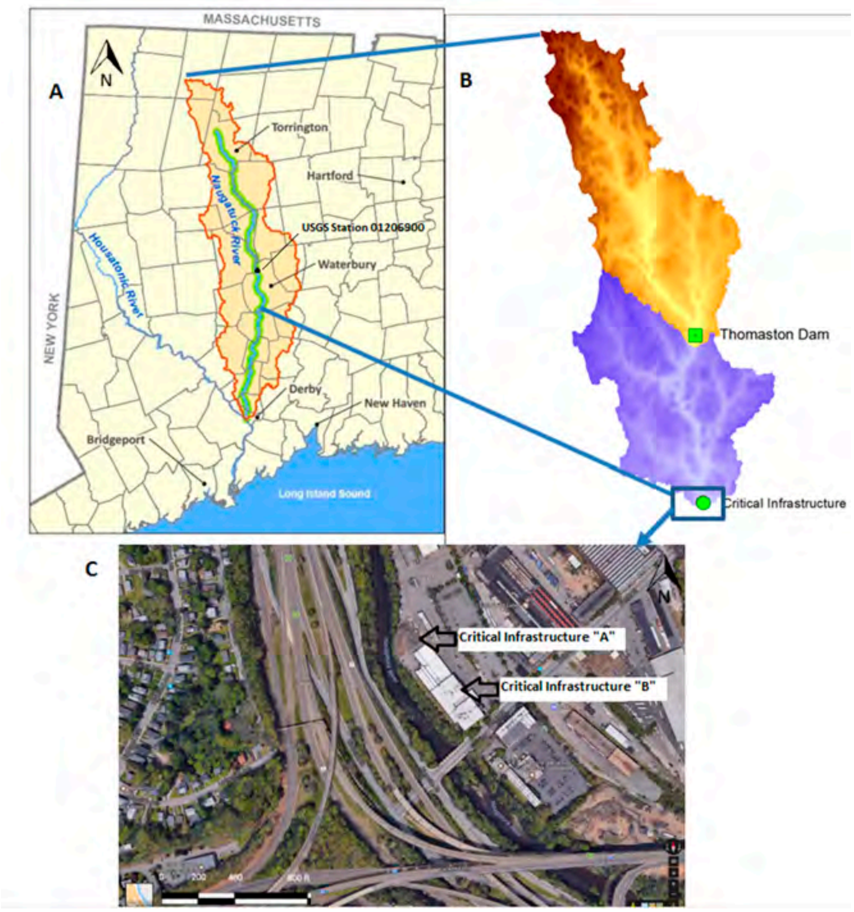

Figure 1. (**a**) The Naugatuck River Basin, (**b**) the subdivision of the Naugatuck River Basin, (**c**) satellite imagery of critical infrastructure in Waterbury, Connecticut.

Figure 1. (**a**) The Naugatuck River Basin, (**b**) the subdivision of the Naugatuck River Basin, (**c**) satellite imagery of critical infrastructure in Waterbury, Connecticut.

2.2. Data

Within the context of this study, the Naugatuck River Basin was split into two sub-basins, with the dividing point located at the Thomaston Dam (Figure 1b). The upstream portion will henceforth be referred to as river reach "U", and the downstream portion being river reach "D." This separation

2.2.1. LIDAR Terrain Elevation Data

For this study, Light Detection and Ranging (LIDAR) data was provided by the Connecticut Environmental Conditions Online (CTECO). The LIDAR data is available statewide, representing approximately 13,571 square kilometers in the form of USGS Quality Level 2, and point density of 2 points per square meter, hydro-flattened bare earth 1 m resolution. The LIDAR flights took place between March 11, and April 16, 2016. These flights occurred during a low flow season when the was done to help isolate streamflow contributions at the outlet of the dam from contributions of overland runoff, and, thus, attempting to re-create the influence of dam regulations on downstream floodplains. The average slope of the upstream and downstream basins are 0.0937 and 0.0923, respectively. For validation purposes, simulated flows were compared to the only United States Geological Survey (USGS) stream gage in the area located upstream (USGS 01206900) in the Naugatuck River at Thomaston, CT (Figure 1a) as well as a stream gage at the inlet of the Thomaston Dam.

2.2. Data

2.2.1. LIDAR Terrain Elevation Data

For this study, Light Detection and Ranging (LIDAR) data was provided by the Connecticut Environmental Conditions Online (CTECO). The LIDAR data is available statewide, representing approximately 13,571 square kilometers in the form of USGS Quality Level 2, and point density of 2 points per square meter, hydro-flattened bare earth 1 m resolution. The LIDAR flights took place between March 11, and April 16, 2016. These flights occurred during a low flow season when the depth of the river's water can be considered negligible compared to water depths during flood events. The horizontal datum is North American Datum of 1983 (NAD83), and the vertical datum is North American Vertical Datum of 1988 (NAVD88). The LIDAR surface was evaluated using a collection of 181 GPS surveyed checkpoints [22].

However, LIDAR is still subject to its own errors. Streambed profiles measured through LIDAR techniques tend to be incorrect. This is due to the backscatter effect, which is the inability of LIDAR pulse to penetrate water surfaces. These uncertainties have the potential to propagate, leading to an underestimation of water held in the stream channel, or an overestimation of water in the surrounding floodplain. In an investigation done by Hilldale et al. (2007) [23] on the accuracy of LIDAR bathymetry for the Yakima River in Washington State, mean vertical errors between remotely sensed and survey data were in the range of 0.10 and 0.27 m, with standard deviations from 0.12 to 0.31 m. Nevertheless, LIDAR Digital Elevation Models (DEMs) have enormous potential for application in various areas including land-use planning, management, and hydrologic modelling. Specifically, in regards to hydraulic modeling, making using of a fine-resolution LIDAR based DEM profiles of stream cross-sections at critical locations with the closest spacing moves the model set-up towards being more spatially distributed in nature, likely resulting in performance improvements.

2.2.2. NLDAS Reanalysis Forcing Data

The North American Land Data Assimilation System (NLDAS-2) is a collaborative project involving several groups: National Oceanic and Atmospheric Administration and National Centers for Environmental Prediction's (NOAA/NCEP) Environmental Modeling Center (EMC), NASA's Goddard Space Flight Center (GSFC), Princeton University, the University of Washington, the NOAA/National Weather Service (NWS) Office of Hydrological Development (OHD), and the NOAA/NCEP Climate Prediction Center (CPC). The dataset is in 1/8th-degree grid resolution, hourly temporal resolution, and is available from 1 January 1979 to the present day. The non-precipitation land-surface forcing fields are derived directly from the analysis fields of NCEP's North American Regional Reanalysis (NARR). The precipitation field in NLDAS results from a temporal disaggregation of a gauge-only CPC analysis of daily precipitation over the continental United States [24]. This analysis is performed directly on the NLDAS 1/8th-degree grid and includes an orographic adjustment stemming from the long-established Parameter-elevation Regressions on Independent Slopes Model (PRISM) climatology [25]. The hourly disaggregation weights for this precipitation field are derived from either 8-km CPC MORPHing technique (CMORPH) hourly precipitation analyses [24], NARR-simulated precipitation, or WSR-88D (Weather Surveillance Doppler Radar) Doppler radar-based precipitation estimates [26].

2.3. Methodology: Flood Vulnerability Framework

A numerical framework that incorporates high-resolution terrain data, flood frequency analysis (FFA), synthetic events construction, and simulation of dam operation and inundation has been developed within the study (Figure 2). We tested the method in the Naugatuck River of Connecticut. Specifically, peak flows of the Naugatuck River were simulated using the CREST-SVAS model forced with 37-year NLDAS data. Flood frequencies with 0.02, 0.01, 0.005, and 0.002 exceedance probabilities (50, 100, 200, and 500 return year periods, respectively) were estimated by fitting the Log-Pearson Type III distribution. For a given location, the timing structure dictating the shape of flood events was estimated from flood simulation or historical records following a methodology proposed by Archer (2000) [27]. The synthetic hydrograph of flood events of desired return periods was constructed by combining the timing structure and flood magnitude from the FFA. Based on LIDAR-derived high-resolution DEM, these synthetic hydrographs forced HEC-RAS to generate flood inundation maps in a downstream region controlled by a dam.

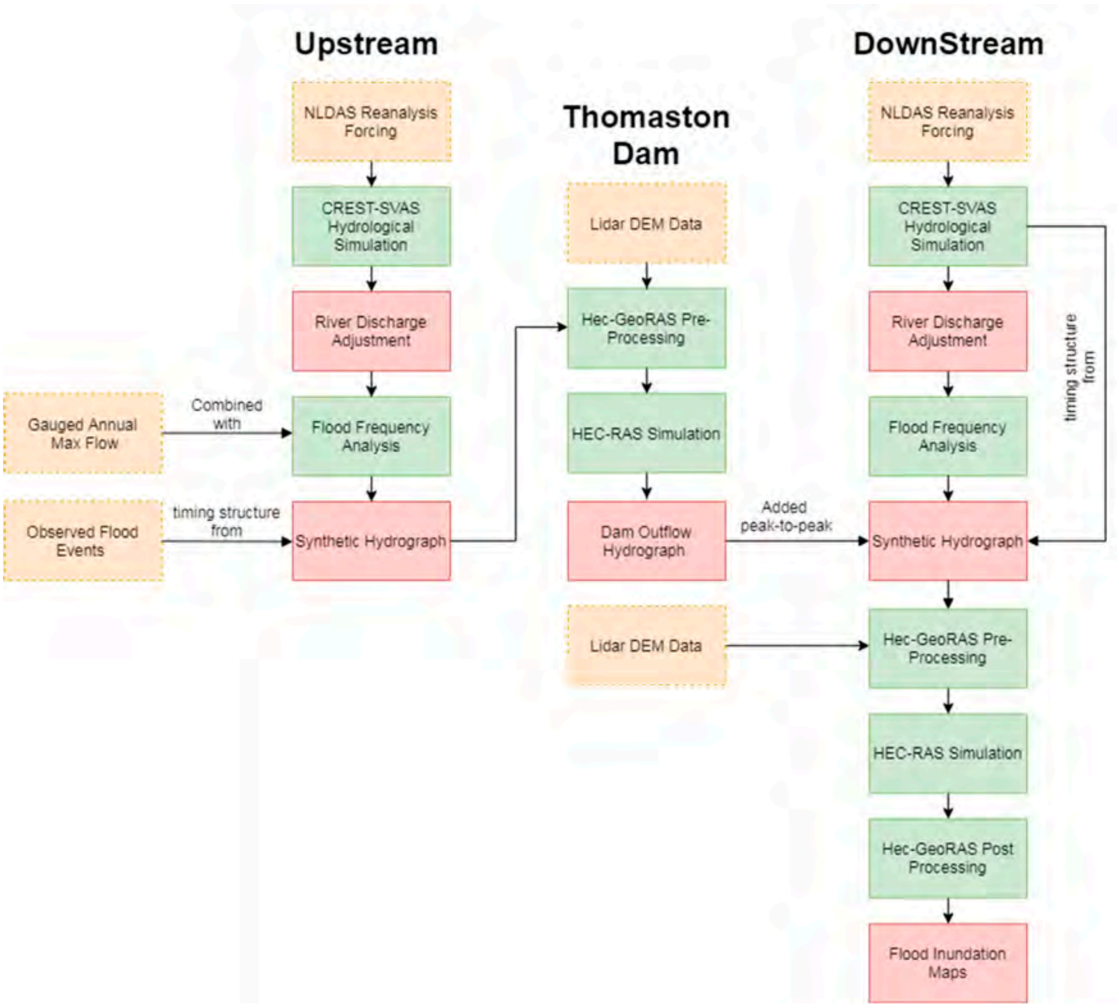

Figure 2. Structure of analysis framework.

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2.3.1. Hydrological Simulation

2.3.1. Hydrological Simulation

This study utilized the newest Coupled Routing and Excess Storage model, version 3.0 with soil–vegetation–atmosphere–snow extension (CREST-SVAS) [13]. CREST-SVAS is a computationally efficient, fully distributed hydrological model designed to simulate flow discharges for large watersheds at a fine spatiotemporal resolution (30 m to 1 km spatial grid resolution and hourly time steps). CREST-SVAS integrates a runoff generation module to simulate vertical fluxes with a routing module to simulate channel discharge at each time step. The runoff generation model couples energy and water balances in four different mediums: atmosphere, canopy, layered snowpack, and soil by solving water and energy balances coupled equations simultaneously. It takes dynamic (precipitation, radiation, humidity, wind speed, leaf area index) and static (land cover, soil properties, impervious ratios) input variables. To best represent the total 37-year timeframe, static maps of land cover and imperviousness from the median year of 2003 were chosen. Due to its strong physical basis a routing module to simulate channel discharge at each time step. The runoff generation model couples energy and water balances in four different mediums: atmosphere, canopy, layered snowpack, and soil by solving water and energy balances coupled equations simultaneously. It takes dynamic (precipitation, radiation, humidity, wind speed, leaf area index) and static (land cover, soil properties, impervious ratios) input variables. To best represent the total 37-year timeframe, static maps of land cover and imperviousness from the median year of 2003 were chosen. Due to its strong physical basis and computational efficiency, CREST-SVAS is capable of producing long-term, high-resolution hydrological simulations. Additionally, by physically coupling the snow accumulation/ablation with other water and energy exchanges in the SVA structure, CREST-SVAS gains improved simulation accuracy in situations previously considered difficult mid to high latitude basins with mixed phase precipitation [13]. The mesh size of the hydrological model was 500 m for the land surface simulation while the output variables were resampled to 30-m resolution for routing. In a given flood return period, CREST-SVAS performed hydrological simulations for both the upstream and downstream basins. The flow contribution of the downstream sub-basin is summed with the outflow of the dam, explained later, to calculate the total flow in the downstream area of interest.

2.3.2. Flood Frequency Analysis

Adjustment Technique for Flood Frequency Estimation

As introduced earlier, gridded forcing data of 1/8th-degree (~14 km) spatial resolution is used in this study to force CREST. Our forcing data sacrifices their spatial resolution to obtain relatively high temporal resolution (hourly). Therefore, local extreme precipitation may often be smoothed. Model dependency introduces additional biases. Consequently, it is expected that the simulated flow peak cannot fully capture the reality. In other words, underestimation of flood peaks constantly exists, which in turn, biases the estimation of flood frequency. To address such bias, we applied quantile-based matching technique to post process CREST flow output only to improve the quality of flood frequency estimation. Since the frequency estimation applied here depends solely on maximum annual peak values of the flow time series, only the top-ranked flow rate will affect this estimation. Therefore, we adjust top percentiles values using Equation (1).

$$Q^{obs}(p) = a\left[Q^{sim}(p)\right]^{b},\ p \geq p_0 \tag{1}$$

where $Q^{obs}(p)$ and $Q^{sim}(p)$ stand for observed and simulated flow at p percentile and p_0 is the lowest percentile of all annual peaks. Equation (1) is established on the stable relationship of top ranked flow value between observation and simulation.

LPIII Method

Flood frequency analysis is the process of evaluating peak magnitudes and frequencies of past floods to estimate the exceedance probabilities of similar floods. This probability information is vital to the accurate delineation of flood zones and safe design of hydraulic structures [28]. Bulletin #17B of the U.S. Water Resource Council recommends Log-Pearson Type III as the statistical distribution technique to determine peak-flow frequency estimates. Log-Pearson Type III utilizes three statistical parameters: the mean, standard deviation, and skew coefficient to describe the theoretical distribution of the peak-flow data [3]. Flood frequency analysis (LPIII Method) was performed on annual max peaks from the CREST-SVAS simulation in the Naugatuck River basin to generate the necessary flood return period peak flows. The logarithm of simulated annual peak flows was fit following Equation (2):

$$LogQ = \overline{X} + KS \tag{2}$$

where $\overline{X}$ mean logarithm of annual peak flows and S is the standard deviation of logarithms. K is a factor that depends on the skew coefficient and selected exceedance probability. Values of K can be found in Appendix 3 of Bulletin 17B. The values of $\overline{X}$, S, and skew coefficient were 1.5002, 0.2140, and −0.5098, respectively

2.3.3. Constructing Synthetic Hydrograph

Flood frequency analysis only gives flood peak magnitude information. To credibly model the flood propagation, the hydraulic model requires a complete realistic flood hydrograph rather than assuming a constant flow using the peak value for the entire flood event period.

Construction of appropriate synthetic design hydrographs (SDH) is an old topic (e.g., Snyder 1938) that has been revisited over the time by applying several different approaches (Sokolov et al., 1976; Yue et al. 2002; Serinaldi and Grimaldi 2011 among others) [29–32]. In this work, we adopted a procedure described in Archer et al. (2000), which is, in fact, similar to the typical hydrograph method (Sokolov et al. 1976) but utilizes information from more than just a single hydrograph for the construction of SDH [27]. A similar approach for defining the shape of SDH was also followed by Sauquet et al. (2008) [33]. Archer's proposed method has the benefit of neither requiring the separation of base flow and storm runoff nor assuming the hydrograph is symmetric, but instead considers the hydrographs in its totality by creating a normalized median flood hydrograph from observations (Figure 3). The synthetic hydrograph was produced by analyzing only hydrographs corresponding to the highest flow peaks. Specifically, hydrographs with peak flows greater than 100 m^3/s (~1-year return period) were considered. This method was used to construct synthetic hydrographs for flood events at 50-, 100-, 200-, and 500-year return periods used as upstream boundary conditions for river reaches "U" and "D". The same procedure is conducted for both upstream and downstream except that no observation is available for the flow contributed by the downstream drainage area alone. Therefore, the flow contributed by the downstream drainage area alone is retrieved from simulated flow. The constructed synthetic hydrographs are finally inputted to HEC-RAS to simulate inundation.

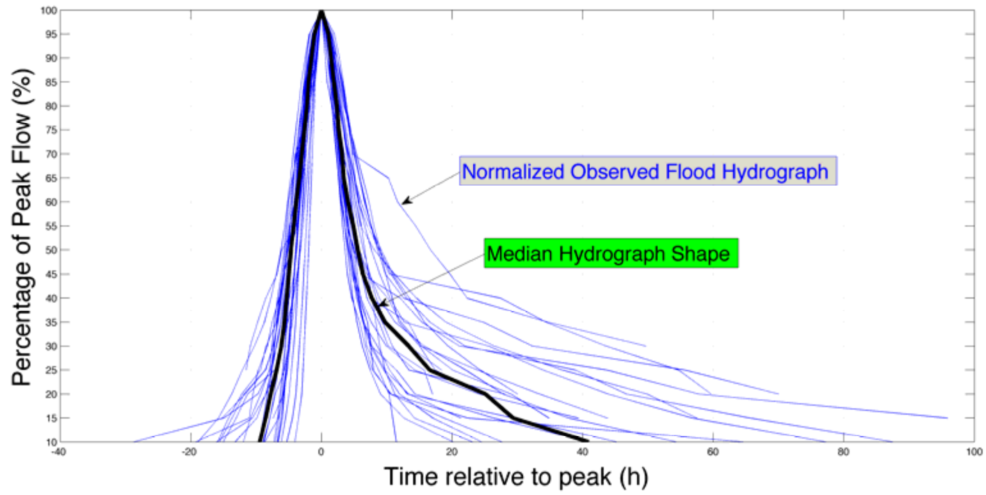

Figure 3. Deriving median durations for each exceedance percentile to determine median hydrograph shape.

2.3.4. Hydraulic Simulation

To quantify flood risk and identify flood-prone areas, a one-dimensional hydraulic model is used to simulate the spatial distribution of hydraulic variables like water depth and flood inundation extent. Two main forcing factors are required in HEC-RAS: the flood event's streamflow time-series and bathymetry of the river channel and surrounding floodplain. HEC-RAS is fully compatible with ArcGIS and accepts vector and raster data formats, therefore, the model gains access to one or two-dimensional representations of measured/computed hydraulic parameters at a fine spatial scale. High-resolution topographic data is necessary to capture the finer-scale heterogeneous features of a river and its floodplain and their effects on flood propagation. Airborne LIDAR-based observations provide topography at a finest resolution (1 m) over regional scale. Simulation accuracy is sensitive to DEM resolution. This improvement in resolution directly translates to the model's ability to two-dimensional representations of measured/computed hydraulic parameters at a fine spatial scale. High-resolution topographic data is necessary to capture the finer-scale heterogeneous features of a river and its floodplain and their effects on flood propagation. Airborne LIDAR-based observations provide topography at a finest resolution (1 m) over regional scale. Simulation accuracy is sensitive to DEM resolution. This improvement in resolution directly translates to the model's ability to accurately map flood inundation extent. Cook et al. (2009) [34] demonstrated that for a given flow and geometric description, HEC-RAS-predicted inundated area decreased by 25% when forced with 6 m LIDAR DEM instead of the 30 m National Hydrographic Dataset (NHD).

In the preprocessing, river cross-sections were extracted from airborne LIDAR-derived. Stream centerlines, river bank lines, predicted flow paths, inline structures, and river and terrain cross-sections were digitized. To accurately capture the meandering river characteristics, cross-section spacing was less than 45 m. These pre-processed river profiles were then exported to HEC-RAS to be used as a basis for one-dimensional hydraulic simulation. Two separate stream sections from the Naugatuck River were modeled and exported to HEC-RAS, one for the upstream section containing the Thomaston Dam (river reach "U"), and the other for the downstream section containing the critical electrical infrastructure (river reach "D") (Figure 4). Manning's roughness coefficients were computed from land cover type following Table 3-1 listed in the HEC-RAS 4.1 Reference Manual [35]. Specifically, the Naugatuck river is straight and clean. Thus, a Manning's "n" value of 0.032 was used for the main open channel. Since the downstream area surrounding the critical infrastructure is highly urbanized and paved, a roughness coefficient of 0.013 was used.

for the main open channel. Since the downstream area surrounding the critical infrastructure is highly urbanized and paved, a roughness coefficient of 0.013 was used.

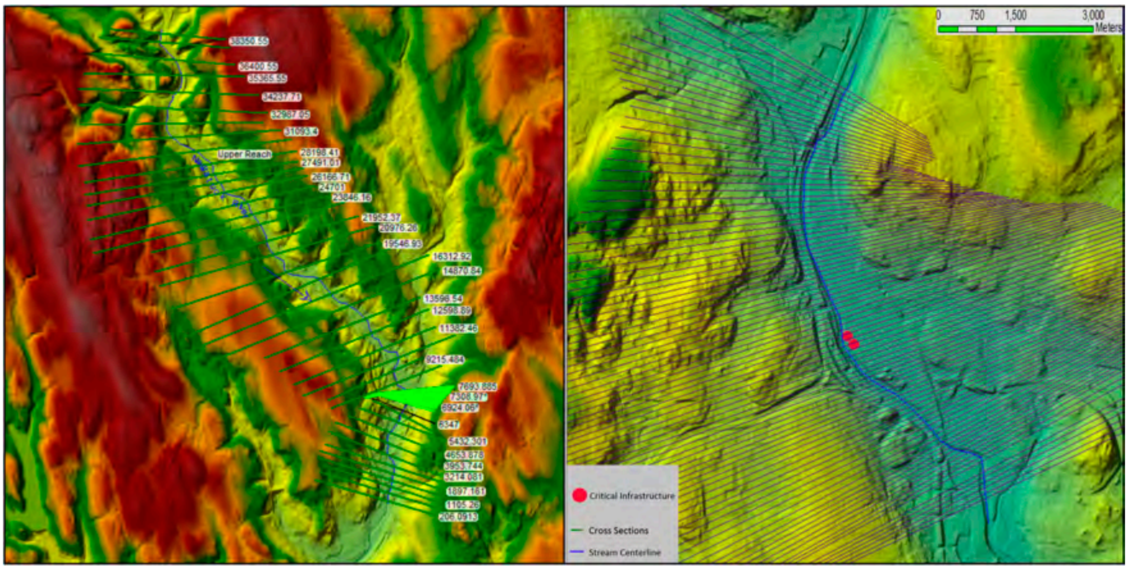

Figure 4. Upstream river reach "U" and downstream river reach "D" modeled in the HEC-RAS domain displayed over LIDAR derived DEM.

Figure 4. Upstream river reach "U" and downstream river reach "D" modeled in the HEC-RAS domain displayed over LIDAR-derived DEM.

The next step was to incorporate the flood-control dam on the delineated flood plain within HEC-RAS by utilizing the high-resolution topographic data and supplementary building design information (gate characteristics, construction materials, etc.) gathered from correspondence with Thomaston Dam engineers. The Thomaston Dam controlling the upstream reach "U", is featured by two sluice gates, which are hoisted to limit the flow passing underneath. These gates are 1.73 m wide, can open to a maximum of 3.05 m, and were assigned a typical energy loss coefficient of 0.6. Additionally, this dam is featured by a spillway 4.3 m below the crest to reduce the pressure to the dam and release water in an extreme flooding scenario. In all tested flooding scenarios, flood stages were far below the level to activate the spillway, and, thus, the spillway played no role in downstream inundation and will not be discussed in the scope of this paper.

The next step was to incorporate the flood-control dam on the delineated flood plain within HEC-RAS by utilizing the high-resolution topographic data and supplementary building design information (gate characteristics, construction materials, etc.) gathered from correspondence with Thomaston Dam engineers. The Thomaston Dam controlling the upstream reach "U", is featured by two sluice gates, which are hoisted to limit the flow passing underneath. These gates are 1.73 m wide, can open to a maximum of 3.05 m, and were assigned a typical energy loss coefficient of 0.6. Additionally, this dam is featured by a spillway 4.3 m below the crest to reduce the pressure to the dam and release water in an extreme flooding scenario. In all tested flooding scenarios, flood stages were far below the level to activate the spillway, and, thus, the spillway played no role in downstream inundation and will not be discussed in the scope of this paper.

Multiple plans were simulated in the following flooding scenarios: a 50-year flood event, 100-year flood event, 200-year flood event, and 500-year flood event. In river reach "U", each simulation was forced by a corresponding synthetic hydrograph with different initial depth conditions and gate operational plans. The plans include fully-open (3.05 m gate openings) and half-open gates (1.525 m gate openings). The conditions include under normal low flow (base flow conditions) and a half-full reservoir. In the first condition, the dam is set to empty when the simulation begins. In the second condition, the reservoir of the dam starts with 50% capacity filled. Water depths and stream velocities

Multiple plans were simulated in the following flooding scenarios: a 50-year flood event, 100-year flood event, 200-year flood event, and 500-year flood event. In river reach "U", each simulation was forced by a corresponding synthetic hydrograph with different initial depth conditions and gate operational plans. The plans include fully-open (3.05 m gate openings) and half-open gates (1.525 m gate openings). The conditions include under normal low flow (base flow conditions) and a half-full reservoir. In the first condition, the dam is set to empty when the simulation begins. In the second condition, the reservoir of the dam starts with 50% capacity filled. Water depths and stream velocities were finally output in a total of 16 flooding cases in the upper modeled river reach "U". The simulated hydrograph's output from the dam in river reach "U" was then added to the synthetic hydrographs of the same return period for river reach "D". The hydrographs were added "peak to peak", where the maxima of upstream hydrograph were combined directly with the maxima of downstream hydrograph with no time delay. This was done to simulate the "worst case scenario" of maximum flooding. The newly altered synthetic hydrographs forced the hydraulic simulation in river reach "D". Depending on the flood scenario, the outflow from the dam with fully or half-opened gates contributed from 7–20% of the peak streamflow at the outlet of the river reach "D" (Table 1), demonstrating the significance of accurate overland runoff simulation from the hydrological model.

Table 1. Thomaston Dam outflow contribution to downstream basin outlet peak streamflow.

Dam Peak Streamflow Contribution (cms)		
Flooding Scenario	Half Open Gates	Fully Open Gates
50 Year		
Empty Reservoir	649.3 (9.94%)	704.8 (16.90%)
Half Filled Reservoir	661.7 (11.52%)	732.3 (20.07%)
No Dam	969.4 (66.89%)	
100 Year		
Empty Reservoir	722.5 (9.20%)	780.4 (15.78%)
Half Filled Reservoir	734.0 (10.52%)	805.7 (18.45%)
No Dam	1088.1 (66.86%)	
200 Year		
Empty Reservoir	797.6 (8.56%)	857.7 (14.80%)
Half Filled Reservoir	808.4 (9.67%)	881.1 (17.07%)
No Dam	1210.5 (66.83%)	
500 Year		
Empty Reservoir	900.8 (7.83%)	963.5 (13.68%)
Half Filled Reservoir	910.7 (8.73%)	984.7 (15.52%)
No Dam	1379.2 (66.78%)	

Accompanying the 16 cases simulated in river reach "U" two scenarios, closed dam and no dam, were simulated solely in river reach "D". The closed dam scenario assumes the dam completely congests all upstream contribution, so the hydraulic simulation is forced only by the downstream synthetic hydrograph (thus, having no dam streamflow contribution). The no dam scenario illustrates the potential flooding that would occur if the protection provided by the dam was removed. To simulate this situation, the dam inflow synthetic hydrographs were combined "peak to peak" with the downstream synthetic hydrographs of the same return period. This adds an additional eight flooding cases modeled exclusively in river reach "D". A table illustrating all of the separate dam operation plans and return periods simulated in river reaches "U" and "D" for this study can be found in Table 2 below.

Table 2. Dam operation scenario diagram.

<table>
<tr><th>Return Period</th><th>Dam Operation</th><th>Reservoir Level</th><th>Results</th></tr>
<tr><td rowspan="4">50 years</td><td>No Dam</td><td rowspan="2">N/A</td><td rowspan="16">24 FLOOD INUNDATION MAPS</td></tr>
<tr><td>Closed Dam</td></tr>
<tr><td>Half Open Gates</td><td rowspan="2">Both: Empty and Half Filled</td></tr>
<tr><td>Fully Open Gates</td></tr>
<tr><td rowspan="4">100 years</td><td>No Dam</td><td rowspan="2">N/A</td></tr>
<tr><td>Closed Dam</td></tr>
<tr><td>Half Open Gates</td><td rowspan="2">Both: Empty and Half Filled</td></tr>
<tr><td>Fully Open Gates</td></tr>
<tr><td rowspan="4">200 years</td><td>No Dam</td><td rowspan="2">N/A</td></tr>
<tr><td>Closed Dam</td></tr>
<tr><td>Half Open Gates</td><td rowspan="2">Both: Empty and Half Filled</td></tr>
<tr><td>Fully Open Gates</td></tr>
<tr><td rowspan="4">500 years</td><td>No Dam</td><td rowspan="2">N/A</td></tr>
<tr><td>Closed Dam</td></tr>
<tr><td>Half Open Gates</td><td rowspan="2">Both: Empty and Half Filled</td></tr>
<tr><td>Fully Open Gates</td></tr>
</table>

3. Results

3.1. Validation of Stream Flow Simulations

CREST-SVAS hydrologic model simulated streamflows in the watershed upstream of the Thomaston Dam. These streamflows were validated against observed discharges measured by a stream gauge at the inlet of the dam maintained by USACE (U.S. Army Corps of Engineers). A total of 45 events were used for calibration/validation of the model, with nine of the events used for validation. A mosaiced hydrograph of all the events is shown in Figure 5. CREST-SVAS runoff simulations exhibited good agreement with stream flow measurements, with Nash-Sutcliffe coefficient of efficiency (NSCE) [36], Pearson correlation coefficient, and relative bias (see Equations (3)–(5)) being 0.7, 0.85, and −6.3%, respectively.

$$NSCE = 1 - \frac{\sum_{t=1}^{T}\left(Q_m^t - Q_o^t\right)^2}{\sum_{t=1}^{T}\left(Q_o^t - \overline{Q_o}\right)^2} \quad (3)$$

Q_o is the mean of observed discharges, Q_m is modeled discharge, and Q_o^t is observed discharge at time t. In addition to NSCE, we computed the correlation coefficient and relative bias, defined as:

$$CC = \frac{\sum_{t=1}^{T}\left(Q_m^t - \overline{Q_m}\right)\left(Q_o^t - \overline{Q_o}\right)}{\sqrt{\sum_{t=1}^{T}\left(Q_m^t - \overline{Q_m}\right)^2}\sqrt{\sum_{t=1}^{T}\left(Q_o^t - \overline{Q_o}\right)^2}} \quad (4)$$

$$Bias = \frac{V_m - V_{obs}}{V_{obs}} \times 100 \quad (5)$$

where V_m is the total measured volume and V_{obs} is the total observed volume.

CREST-SVAS is only calibrated in the sub-basin upstream to the dam. The calibrated routing parameters are applied to both upstream and downstream sub-basins because there is no downstream gauge observation for calibrating these parameters. Please note that CREST-SVAS model uses distributed and physically derived parameters for the simulation of the land surface process (rainfall-direct runoff) and the simulation of the land surface process does not require any calibration. Only the routing parameters that primarily control the time-delay and velocity of flows are needed to be calibrated [13,37].

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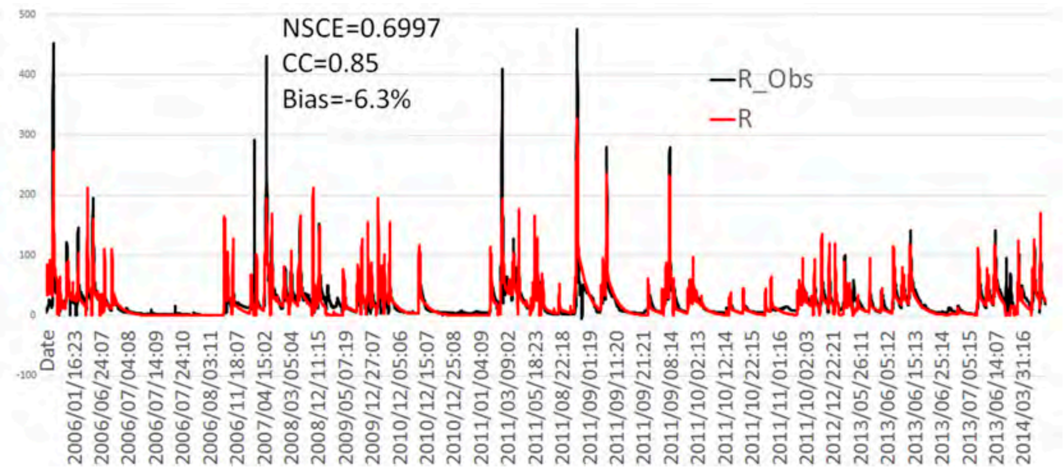

Figure 5. The Coupled Routing and Excess Storage-Soil-Vegetation-Atmosphere-Snow (CREST-SVAS) daily streamflow validation against observation for Naugatuck River Basin at the inlet of Thomaston Dam.

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3.2. Validation of Hydraulic Simulations

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Simulated dam outflow from the 27 August 2011, the largest recent flooding event in river reach "U", were validated against flow rates computed using gate rating curves posted by the U.S. Army Corps of Engineers (see Figure 6). Hydrographs recorded by a stream-gage at the inlet to the dam were used for the model's upstream boundary condition. The measured flood-control gate height time-series from the Thomaston dam for this same event were used as the operation of the dam in the simulation. During this event, a maximum flood stage of 22.8 m was reached, producing outflow rates of 21.3 cms and 35.2 cms when the gates were half and fully open, respectively. The model displayed good agreement with these two outflow rates, with minor gate discharge discrepancies of only 2.2 cms (10% error) and 4.7 cms (13% error) for the two operational scenarios. Additionally, simulated stream flow rates for the same flooding event in river reach "U" were compared against observed hydrographs from a stream gauge (USGS station 01206900) residing 2.4 km downstream of the Thomaston dam on the Naugatuck River (Figure 7). As seen in the figure, the hydraulic model did well in capturing the overall hydrograph shape; however, it consistently underestimated total streamflow. This underestimation can be explained by overlooking the contributing area between the dam and the USGS gauge location.

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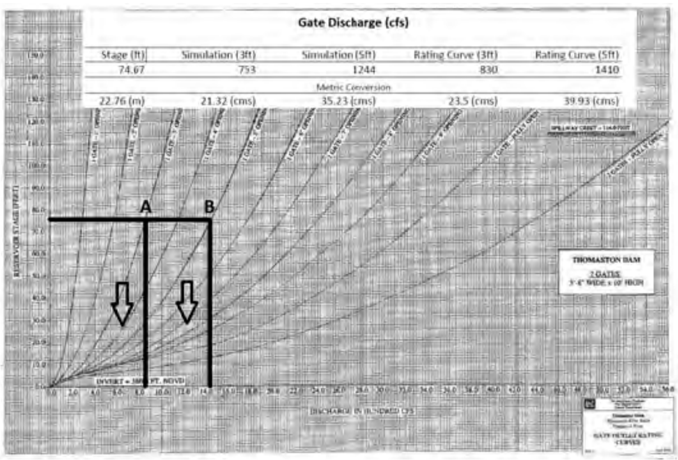

Figure 6. Model simulated gate discharge validated against Thomaston Dam posted ratings curves. Line A represents the intersection between the maximum flood stage (22.76 m or 74.67 ft) and the rating curve for one gate that is 3 ft open. Line B represents the intersection between the maximum flood stage and the rating curve for one gate that is 5 ft open.

Figure 6. Model simulated gate discharge validated against Thomaston Dam posted ratings curves. Line A represents the intersection between the maximum flood stage (22.76 m or 74.67 ft) and the rating curve for one gate that is 3 ft open. Line B represents the intersection between the maximum flood stage and the rating curve for one gate that is 5 ft open.

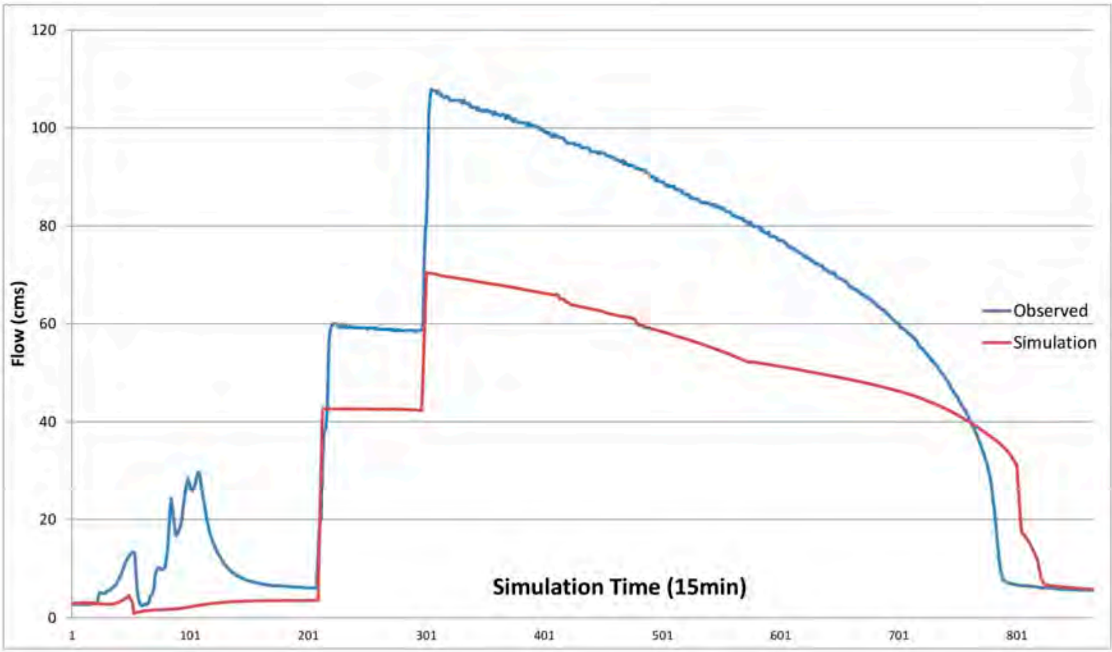

Figure 7. Model simulated dam output streamflow validated against observations from USGS station (01206900) Naugatuck River at Thomaston, CT, USA.

4. Discussion

Maximum inundation depth and extent maps simulated by the HEC-RAS model for each of the 24 flooding scenarios in the downstream river reach "D" are illustrated in Figures 8–11. Flood extent was determined by subtracting the underlying ground elevation from the LIDAR-derived Triangular irregular networks (TINs) from the water surface profile elevation. If the result was positive, then the area is classified as inundated and assigned a flood depth. Simulated water depths and extents have been co-displayed over satellite imagery to visualize the susceptibility of certain urban areas in Waterbury-CT. A high-end limit of 2 m was utilized in the inundation maps so that the spatial variability of flood depths could be more clearly represented. The majority of flood occurred in the floodplains on the eastern side of the Naugatuck River. An elevated highway that runs along the western edge of the river prevents floods from propagating in that direction.

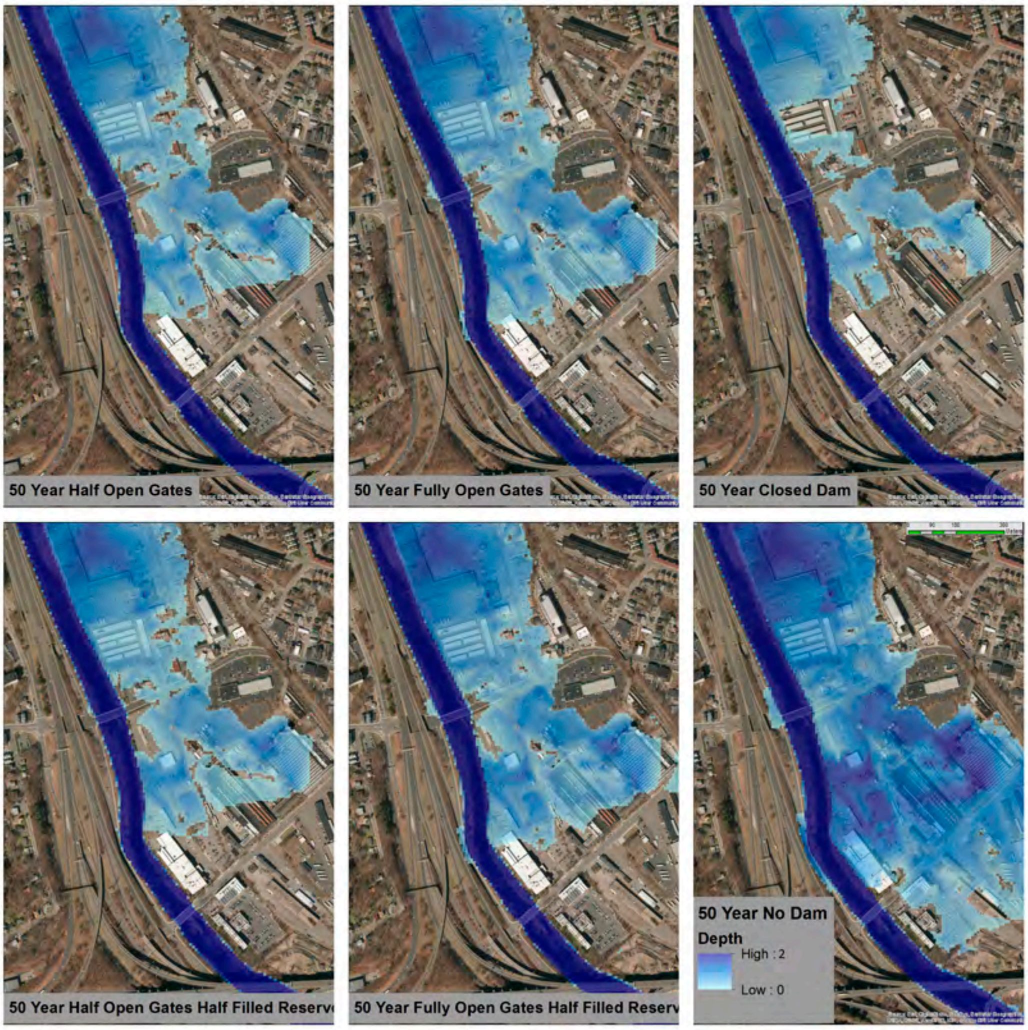

Figure 8. Simulated maximum 50-year flood inundation in various dam operation scenarios.

Figure 8. Simulated maximum 50-year flood inundation in various dam operation scenarios.

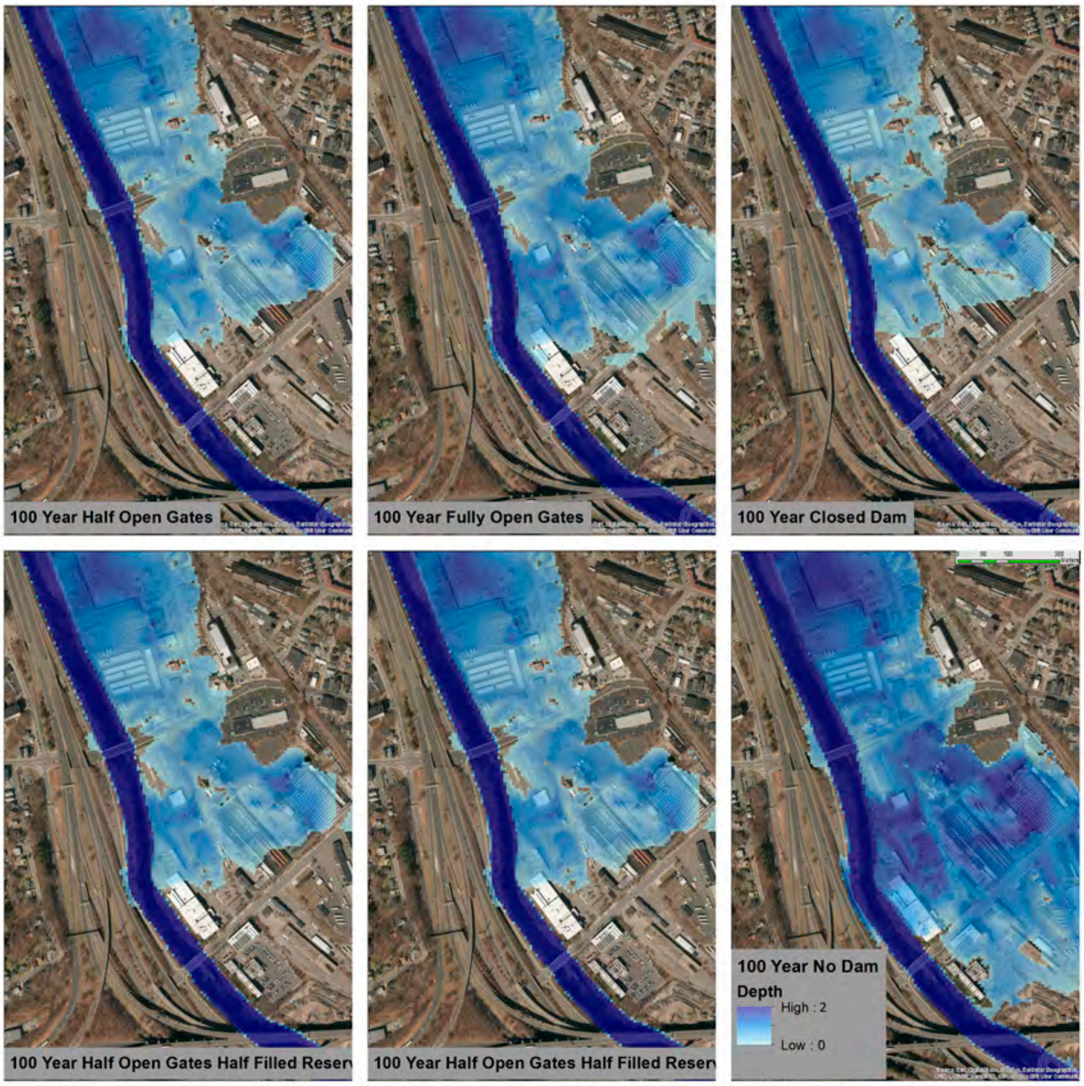

Figure 9. Simulated maximum 100-year flood inundation in various dam operation scenarios.
Figure 9. Simulated maximum 100-year flood inundation in various dam operation scenarios.

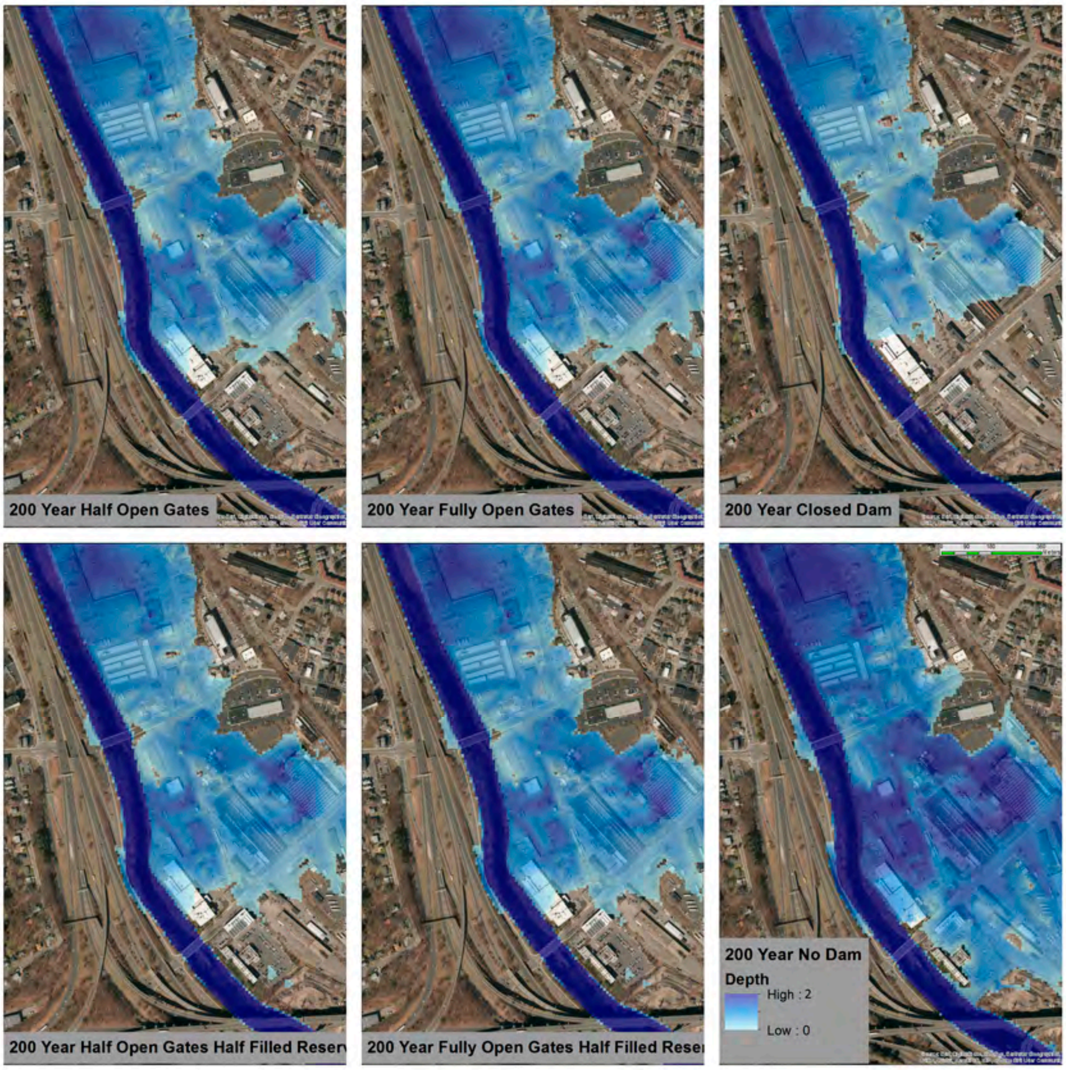

Figure 10. Simulated maximum 200-year flood inundation in various dam operation scenarios.

Figure 10. Simulated maximum 200-year flood inundation in various dam operation scenarios.

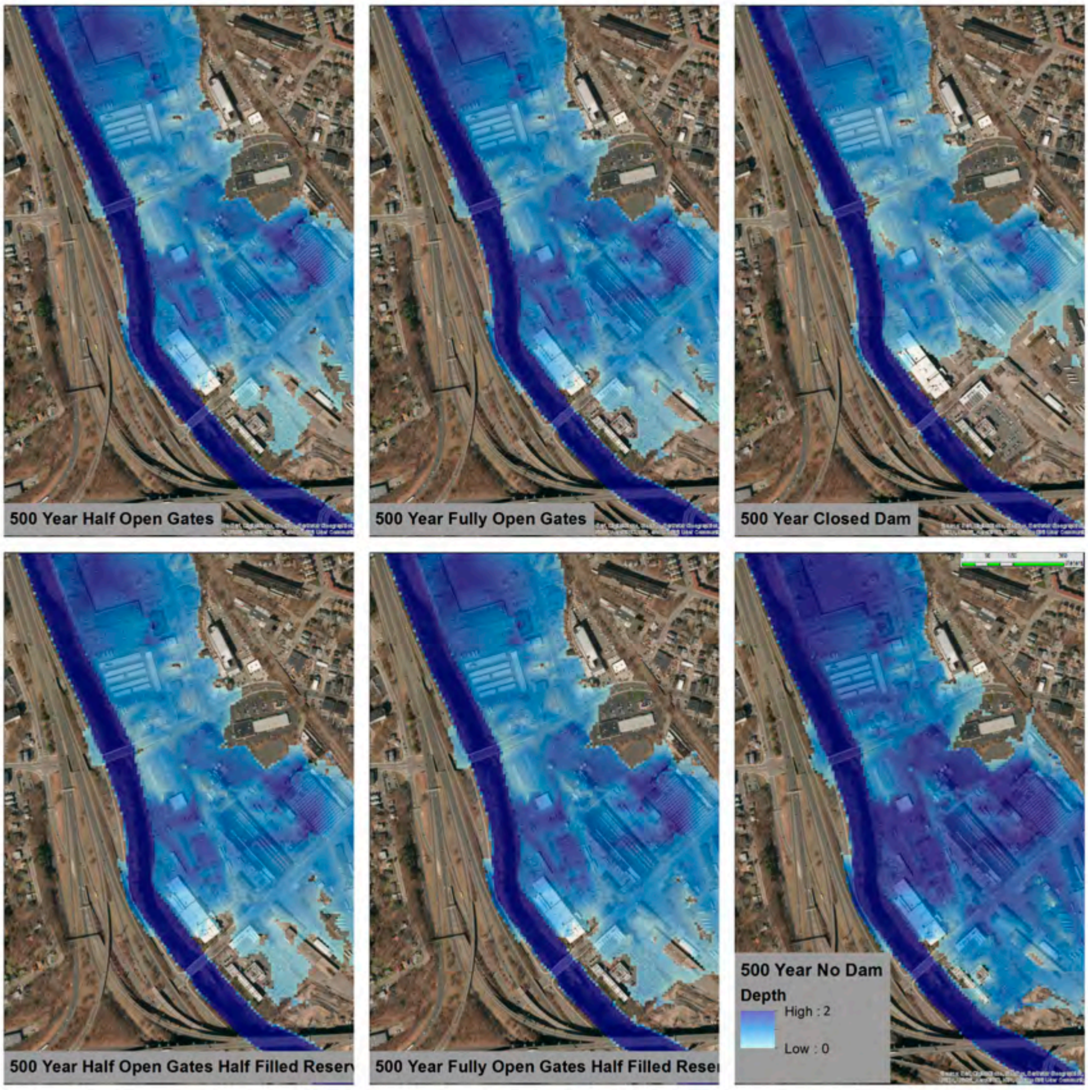

Figure 11. Simulated maximum 500-year flood inundation in various dam operation scenarios.
Figure 11. Simulated maximum 500-year flood inundation in various dam operation scenarios.

As shown in the results, a portion of the area of interest, more specifically critical infrastructure “A”, is partially or fully inundated in all flood scenarios. The maximum flood depth in each scenario at critical infrastructure “A” as well as critical infrastructure “B” can be seen in Figure 12. During the “worst case scenario” with the protection of the dam, a 500-year flood with the upstream dam’s reservoir initially half-filled and both flood control gates fully-open, the area of interest experienced an estimated 1.40 and 0.82 m of inundation at critical infrastructure “A” and “B”, respectively. When the dam was removed, these same locations experienced a greatly increased 1.93 (+36.5%) and 1.34 (+79.5%) meters of inundation. However, when the dam was closed, and only the downstream watershed contributed to flooding, critical infrastructure “A” and “B” experienced a decreased 0.82 (−42%) and 0.052 (−94%) meters of flood inundation, respectively. Comparing the no dam and fully-open dam operational scenarios provides direct insight on the role the dam plays in protection by delaying voluminous flood waters from reaching downstream floodplains. Analyzing the closed dam scenario provides an understanding of how upstream streamflow contributes to downstream flood depth, and demonstrates dam’s potential to control inundation, further illuminating the substantial dampening effect the dam has on downstream flood propagation under different dam operational scenarios. The remaining flood return periods (50-year, 100-year, 200-year) experienced similar increases in flood depth when the protection of the dam was removed and decreases in flood depth when the dam was closed. In all scenarios critical infrastructure “A” was more severely scenarios, critical infrastructure "A" was more severely affected by flooding than critical infrastructure "B", likely due to its close proximity to the river's bank.

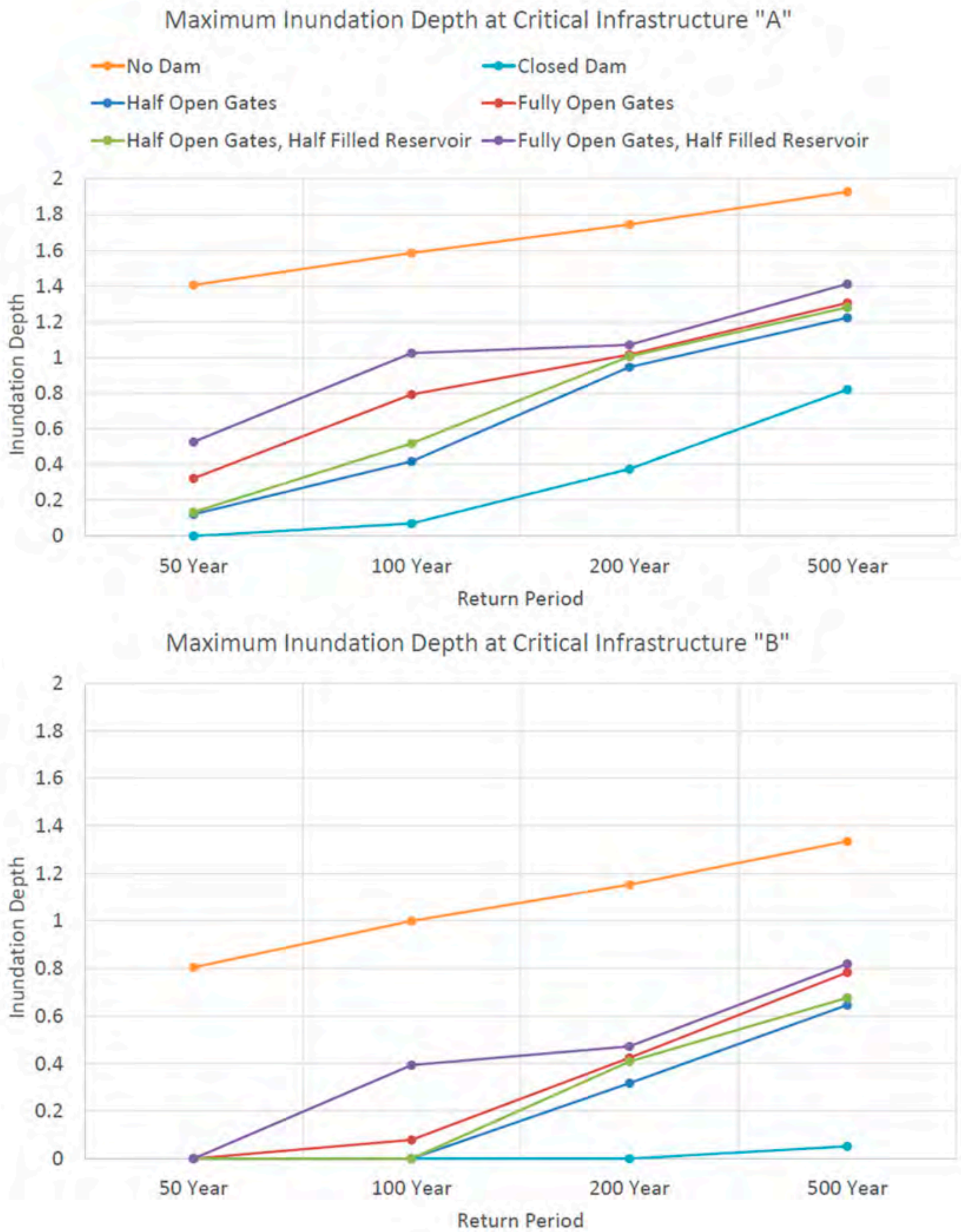

Figure 12. Simulated maximum water depth (meter) at critical infrastructure "A" and "B" for the various flooding and dam operation scenarios examined.

This study also examined how different flood infrastructure management strategies impact downstream floodplain areas. The manipulation of the flood control dam's gate height had a recognizable influence on both estimated maximum flooding extent and flood depth. This influence was more substantial during the 50-year and 100-year higher probability flooding events. With an initially empty dam reservoir, moving from half open to fully open gates produced 165%, 90%, 7%, and 6% increases in maximum water depth at infrastructure A for the 50-, 100-, 200-, and 500-return period simulated extreme flood events. While infrastructure B was dry for the 50- and 100-year flood scenarios, it too saw increases of 33% (200-year) and 21% (500-year) in flood depth when simulated with the same initial empty reservoir conditions.

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Comparing the simulated results from model runs with and without an initially filled reservoir illuminates the dam's ability to dampen the flooding effects in downstream floodplains when hit with a large volume of water from two extreme events in close temporal proximity. During an extreme event, this extra water will likely find its way over the banks and into the downstream floodplain. These results can be seen in Figure 12. Much like the relationship between gate height and maximum water depth and inundation extent, increased effects are found during higher probability, more frequent flood events. When changing from an initially empty reservoir to an initially half-filled reservoir, the model predicted increases in maximum water depth at critical infrastructure "A" of 10% and 63% for a 50-year flood and increases of 24% and 29% for a 100-year flood in maximum water depth at critical infrastructure "A" with gates half and fully-open, respectively. The increases during lower probability extreme events are less severe, resulting in increases of only 6%, 5%, 5%, and 8% (200-year half and fully, 500-year half and fully) maximum water depth at the outside transformer. The initial reservoir stage affected not only water depth but increased the inundation extent, which can be seen in all of the inundation maps.

The results from our study indicated that the existence of the dam served as a major factor in controlling simulated inundation extent and water levels depths downstream. Similar to the trends with gate height and initial water levels in the dam's reservoir, these effects are more significant in more frequent floods with higher probability (50- and 100-year), increasing maximum simulated water depths at critical infrastructure "A" by 10%, 63%, 24%, and 29% for the 50-year flood return period.

5. Conclusions

Accurate information regarding flood depth and inundation extent are invaluable to the assessment of potential flood risk. In this paper we presented a comprehensive framework for producing flood inundation maps of extreme event scenarios at ungauged locations, and it was demonstrated through a case study at the Naugatuck River in Connecticut. Our methodology links flood frequency analysis with synthetic flow simulations from a physically based, fully distributed hydrologic model, and a one-dimensional hydraulic model. To improve model performance, we utilized long-term atmospheric reanalysis (i.e., NLDAS) to drive ultra-high resolution hydrologic simulations, and a methodology using measured streamflows to create long-return-period flood peak quantiles and synthetic hydrographs at ungauged locations, and fine resolution LIDAR terrain elevation data to construct accurate stream channel profiles.

As a case study, our framework was employed to investigate flood hazard by creating flood inundation maps at the electric utility infrastructure location at the Naugatuck River under four extreme flood events (50-,100-,200-,500-year return period events), two dam operation procedures (gates half- and fully-open), two distinct dam protection setups (closed dam and no dam), and two separate initial dam reservoir conditions (empty reservoir and half-filled reservoir), resulting in a total of 24 flood cases for the electric infrastructure. These inundation maps were combined with satellite imagery to better represent the extent of flooding and potential areas affected.

Our results reveal how the dam assists in improving the resilience of the downstream floodplain. As seen by examining the no dam scenario, the existence of the dam naturally serves to delay flood waters from reaching vulnerable downstream floodplains. Furthermore, by evaluating differing dam gate height and reservoir water level scenarios, we illustrate the ability dam engineers have to further control and delay flood waters from reaching downstream translating directly to reduced maximum flood inundation at downstream critical infrastructure.

We acknowledge that there are potential limitations to the elements of the framework presented. For example, a 2D hydraulic model could potentially offer a better choice to model the flood inundation. However, we should note that the main objective of this paper is to present an integrated framework for flood vulnerability analysis and examine the relative effect of dam operations on the inundation depth values. Therefore, under the assumption that the dynamics (not actual magnitudes) presented between dam operation and flood extent would not change significantly, the choice between 1D vs. 2D model does not affect the main findings of this study. Additionally, Horritt and Bates (2002) [38] pointed out that HEC-RAS at 1D can well predict inundated area. Most recently, Liu et al. (2018) [39] compared HEC-RAS 1D, HEC-RAS 2D, Bristol University's raster flood inundation model LISFLOOD-FP diffusive, and LISFLOOD-FP subgrid in generating flood inundation extents and concluded that overall, the performance of a 1D model is comparable to the 2D models used in the study, with the 2D models showing slightly better results. Certainly, one could adopt the proposed framework and substitute individual elements (e.g., hydrologic/hydraulic models) based on their own preferences.

Future development of this numerical framework will include, but not limited to integrating novel regional flood frequency analysis (RFFA) approaches that provide more accurate flood frequency estimates by combining flow observation network, satellite-derived flow observation, and high-resolution hydrological simulation, calibrating the hydraulic component using remote sensing retrieved inundation maps, utilizing newly emerging detailed river bathymetric data obtained by penetrating LIDAR and survey, and evaluating the reduction effectiveness of adding low-cost hydraulic infrastructure.

Author Contributions: S.H. compiled the necessary data, performed the hydraulic simulations, and contributed to the writing of the paper. X.S. administrated the project, performed hydrologic simulations, frequency analysis, and contributed to the writing of the paper. E.N. constructed the synthetic hydrographs and contributed to the writing of the paper and E.A. supervised the study and contributed to the writing of the paper.

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Conflicts of Interest: The authors declare no conflict of interest.

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Research papers

A framework to improve hyper-resolution hydrological simulation in snow-affected regions

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Flood

ABSTRACT

Snow processes in mid- and north-latitude basins and their interaction with runoff generation at hyper-resolution (<1 km and <hourly) pose challenges in current state-of-the-art distributed hydrological models. These models run typically at macro to moderate scales (>5 km), representing land surface processes based on simplified couplings of snow thermal physics and the water cycle in the soil-vegetation-atmosphere (SVA) layers. This paper evaluates a new hydrological model capable of simulating river flows for a range of basin scales (100 km^2 to >10,000 km^2), and a particular focus on mid- and north-latitude regions. The new model combines the runoff generation and fully distributed routing framework of the Coupled Routing and Excess STorage (CREST) model with a new land surface process model that strictly couples water and energy balances at the SVA layer, imposing closed energy balance solutions. The model is vectorized and parallelized to achieve long-term (>30 years) high-resolution (30 m to 500 m and subhourly) simulations of large river basins utilizing high-performance computing. The model is tested in the Connecticut River basin (20,000 km^2), where flooding is frequently associated with interactions of snowmelt triggered by rainfall events. Model simulations of distributed evapotranspiration (ET) and snow water equivalence (SWE) at daily time step are shown to match accurately ET estimates from MODIS (average NSCE and bias are 0.77 and 6.79%) and SWE estimates from SNODAS (average correlation and normalized root mean square error are 0.94 and of 19%); the modeled daily river flow simulations exhibit an NSCE of 0.58 against USGS streamflow observations.

1. Introduction

The water cycle has been extensively studied in terms of land surface modeling (Liang et al., 1994; Ludwig and Mauser, 2000; Wang et al., 2011), yet in mid- and high-latitude regions affected by heavy snow, acceptable performance with a hydrological model is difficult to achieve (Parr et al., 2015). The snow accumulation and melting process in these regions greatly affects both thermal and water budgets (Anderson, 2006, 1976; Bartelt and Lehning, 2002; Lehning et al., 2002a), which in turn control evapotranspiration, soil temperature, and soil moisture calculations. These processes that greatly impact spring flow simulations have been studied extensively by both hydrological and snow process modeling groups. In forested areas, great efforts have been exerted to simulate snow processes (Anderson, 1976; Andreadis et al., 2009; Bartelt and Lehning, 2002; Lehning et al., 2002a; Lehning et al., 2002b; Fu et al., 2014). Even after calibration, however, these model simulations and observations have agreed only on annual amounts, while the uncertainty in daily values is considerable (Fu et al., 2015). This land surface modeling uncertainty has a great impact on flow simulations (Essery et al., 2009). In addition, most aforementioned snow models are designed merely for one-dimensional simulations, while the distributed hydrological models are suitable for simulations at moderate (>5 km) to macro (>1/8°) scales.

Current hydrological models use concepts from snow models by fully or loosely coupling with their original land surface schemes. For this paper, we applied a strictly closed energy balance (EB) solution to represent snow-affected water cycle processes and interactions with vegetation in forested areas. The difficulty of solving EB lies in structuring the air-vegetation-soil layers under various land surface conditions, formulating thermal/water balance equations within layers and flux/mass exchanges between layers, deriving distributed parameters, and making the nonlinear system within every grid cell converge efficiently. The computations become more challenging when these processes are to be resolved over large regions (ranging from large basins to continents) and long periods (multiple decades) at fine spatiotemporal scales.

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Originating from lumped hydrological models, the linear reservoir routing (LRR) can also been extended to distributed hydrological models with promising efficiency and acceptable accuracy, such as the parallel linear reservoir (PLR) (Lázaro et al., 2015) and fully distributed linear reservoir (FDLRR) (Shen et al., 2016).

Here we describe the development and evaluation of a new model aimed at improving the accuracy of hydrological simulations in snow- and forest-covered regions at fine spatiotemporal resolution (30 m to 500 m and hourly time steps) and for long periods (35 years to 50 years). Specifically, we extended the distributed hydrological framework of the Coupled Routing and Excess STorage (CREST) model (Wang et al., 2011; Shen et al., 2016) to physically integrate hydrological and snow processes, including vegetation interception, evapotranspiration, soil infiltration and snow accumulation, melting, and refreezing. Furthermore, parameters of CREST's runoff generation module are distributed and can be physically derived, while the routing parameters are uniform and can be optimized based on observed stream flow data.

In the next section we describe the development of the model, including its land surface structure and the methodology implemented for coupling water and energy balances. In Section 3 we describe the model validation over the Connecticut River. We discuss the model performance evaluation in Section 4, and in Section 5 we present our conclusions and thoughts on future directions. Abbreviations used in this paper are defined in Table 1.

2. Methodology

2.1. Model overview

We selected the CREST hydrological model as the framework for this study because of its computationally efficient, fully distributed routing module (Shen et al., 2016) that can run large basin ($\sim 10^6$ km^2) simulations at fine spatiotemporal resolution (30 m to 1 km spatial grid resolution and hourly time steps) over long periods (a few decades). However, CREST's current simple runoff generation scheme does not explicitly account for vegetation structure or the energy balance—processes that are critical for mid- and high-latitude regions affected by mixed phase precipitation.

In this paper, we extended the CREST model implementing a physically-based runoff generation module that explicitly represents the different vegetation structures and snow processes, as depicted in Fig. 1.The runoff generation module solves for the coupled water and energy balances, using as input dynamic variables—namely, meteorological variables (precipitation, radiation, humidity, wind speed), and leaf area index (LAI)—and static parameters—land cover, soil properties, vegetation species descriptions, and impervious ratios. The new version of CREST is named CREST-SVAS to represent the model's extension in terms of soil-vegetation-atmosphere-snow (SVAS) processes.

Table 1
Abbreviations used in this paper.

Abbreviation	Full Name
CREST	coupled routing and excess storage
SVA	soil-vegetation-atmosphere
SVAS	soil-vegetation-atmosphere-snow
ET	evapotranspiration
SWE	snow water equivalence
EB	energy balance
LAI	leaf area index
NSCE	Nash-Sutcliffe efficiency coefficient
RMSD	root mean squared difference
NRMSD	normalized root mean squared difference
HPC	high performance computer
VIC	variable infiltration capacity

2.2. Characterization of the Soil-vegetation-atmosphere structure

To compute the redistribution of precipitation at the vertical dimension, water and thermal balances must be simultaneously solved. In a given layer, we solve water balance for the water availability, which in turn greatly affects the temperature we solve for in the thermal balance. Knowing the temperature change, we can then estimate the amount of energy that is spent in changing the phase and amount of water.

Accurate modeling of the water and temperature variables depends primarily on the characterization of soil-vegetation-atmosphere (SVA) interactions through coupling of the water and thermal balances. Conceptually, we classify plants into two categories: with canopy and without canopy. The former are able to intercept both snowfall and rainfall, while the latter can only intercept rainfall. Considering the thermal insulator property of snow, temperature differences may occur between the canopy layer, adjacent air and encapsulating air of the canopy layer. The SVA, therefore, is thermally divided into, at most, five layers, as shown in Fig. 1. The snowpack layer vanishes when the ground has no snow accumulation, as does the atmospheric layer when there is no intercepted snow. Snowpack is divided into two layers, the surface layer and pack layer, to mimic the thermal insulator function of a snow layer between soil and air. As in (Liang et al., 1999), soil is thermally divided into two layers and physically divided into three layers. The coupled water and energy balance computational steps based on this conceptual structure are depicted in Fig. 2.

2.3. Water balance

Water exchanges in the rainfall runoff generation module include the interception of precipitation and evapotranspiration (ET) by vegetation; the accumulation and melting of the snow pack, its refreezing, and, finally, the outflow of the pack water; and the percolation by water of multiple soil layers. When precipitation first reaches the SVA structure, it undergoes the interception process if vegetation is present. Then, through-fall triggers the snow accumulation or melting process on the ground if there is snow or if the though-fall itself contains snow. Finally, the outflow from the snowpack or, in a snow-free grid, the through-fall infiltrates soil layers. Meanwhile, ET is taking place, including the evaporation and/or sublimation and/or from intercepted water and transpiration by plants.

2.3.1. Interception by vegetation

Precipitation is partitioned into snowfall and rainfall as a function of surrounding air temperature (Anderson, 2006). Snow interception, then, consists of canopy area accumulation, the blowing of snow from the canopy by wind, and melting-triggered release. Based on previous findings on the dependence of snow interception on vegetation properties and climatic variables (Satterlund and Haupt, 1970), the maximal holding capacity of the canopy is proportional to the LAI (Kobayashi, 1987) and the canopy temperature (Ohta et al., 1993), and the increment of the interception during a time step is proportional to the snowfall (Storck et al., 2002). The snow blowing process is driven by wind speed, following Bowling et al. (2004). Similarly, liquid water interception capacity is affected by the intercepted snow, the LAI, and the temperature, following the method used by (Andreadis et al., 2009).

2.3.2. Snowpack accumulation and ablation

The precipitation remaining after the interception process, together with the released drips from the vegetation layer, form the through-fall precipitation. Solid water contained in the through-fall contributes to the formation of the snowpack on the ground surface, which may contain solid and/or liquid water (if

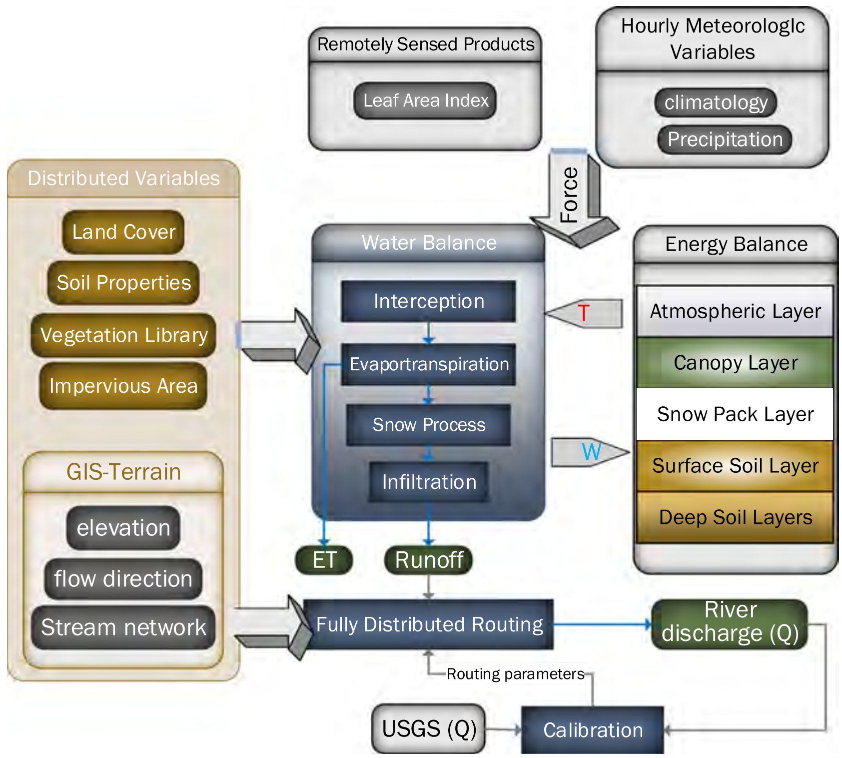


Fig. 1. Interface and structure of the model consisting of a runoff-generation and routing component.

the temperature of the given layer is at 0 °C). Depending on the solid amount, both layers have a certain capacity of liquid water storage that is modeled following Anderson (1976). For simplicity, the SWE boundary between the surface and pack layer is conceptually fixed at 125 mm. In other words, when solid water accumulation on the surface layer does not exceed this fixed SWE amount, no pack layer would exist.

Compaction, in which fresh snow is redistributed into the two-layer structure of the snowpack, is the first step of accumulation. It is followed by the evaporation, sublimation melting, or refreezing process. The amount of evaporation and sublimation is limited by the water availability and determined by the latent heat solved for by the thermal balance computation that is introduced in Section 2.4. Liquid precipitation through-fall first resides in the surface layer and then is drained into the pack layer if the storage reaches the holding capacity of the surface layer. Finally, outflow is generated if the liquid storage exceeds the holding capacity of both layers.

The microphysics of mass and phase change is complicated within the snowpack layer. To model it efficiently without losing overall accuracy, we propose a few rules for accounting for the mass and phase change in the accumulation and ablation process:

1) Sublimation only happens after liquid water is evaporated out, and both processes happen only at the surface layer.
2) Liquid water in the pack layer does not “go up” unless the capacity of the pack layer is not enough to hold it.
3) Melted water is added to the surface layer first. Therefore, ice in the pack is always consumed first during the melting season.

2.3.3. Infiltration

The outflow from snowpack or from through-fall in snow-free areas triggers the infiltration process. CREST uses the variable infiltration curve (Liang and Xie, 2001; Wood et al., 1992; Zhao, 1992; Zhao and Liu, 1995) to compute the infiltration process in the first moisture layer and the percolation algorithm of the Soil and Water Assessment Tool (SWAT) to account for the vertical moisture transport among soil layers. The variable infiltration curve is widely used in many hydrological models to account for the sub-grid variability of soil heterogeneity. Since the scope of this model development was to improve snowmelt-contributed flood processes, we considered unnecessary the use of a more physical but computationally expensive infiltration method (Richards, 1931; Ross, 1990; Van Dam and Feddes, 2000) at this point.

2.4. Thermal balance

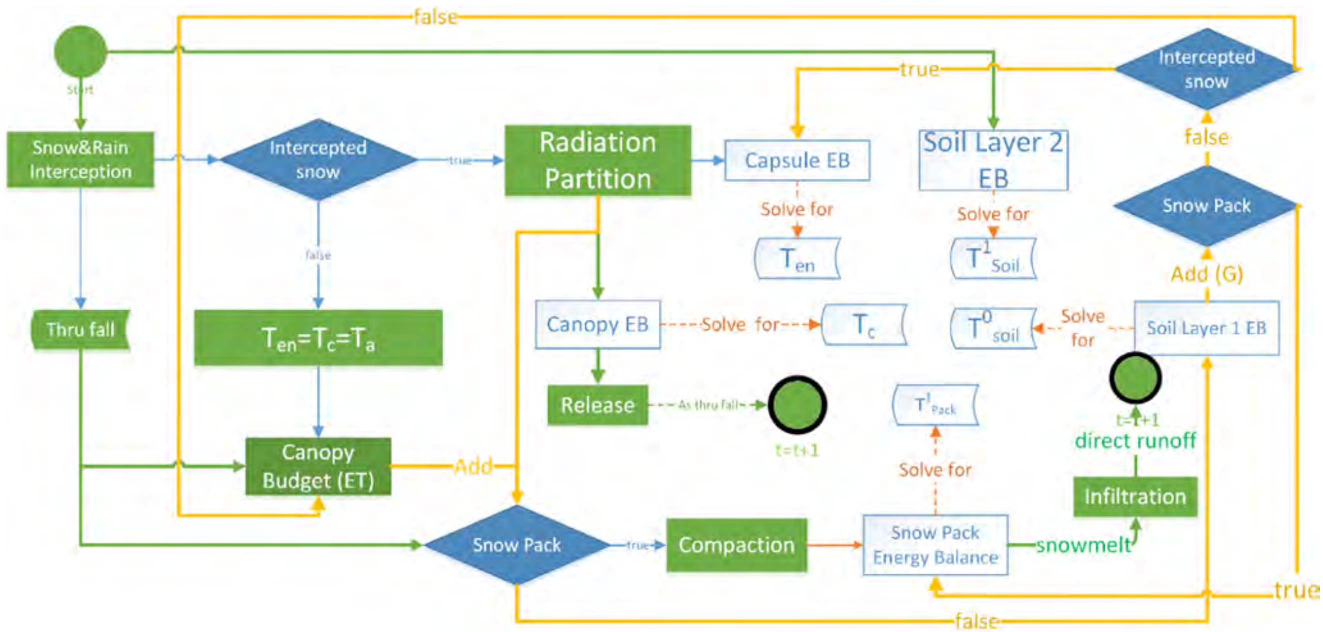
The energy balance (EB) represents the physical consistency but also the modeling complexity of a hydrological model. The complete form of EB in an arbitrary layer of medium can be formulated by Eq. (1),

$$R_n = H + E - G + \Delta H + \Delta M \quad (1)$$

where R_n is the net radiation (W/m^2), H is the sensible heat, E is the latent heat, G is the conductive heat flux, ΔH is the heat storage change of the medium, and ΔM is the heat induced by mass changes. Depending on different land cover and snow conditions, some terms vanish because of insignificance, and neighboring SVA layers (described in Section 2.2) may be combined into one to realize Eq. (1). Sections 2.4.1 through 0 and Fig. 2 describe the new model's realization of equation (1) in different layers and snow conditions.

2.4.1. Thermal balance in the canopy layer

2.4.1.1. Snow-free condition. As shown in Fig. 2(a), when the canopy layer is free of snow, H and ΔH are negligible, and ΔM does not exist. Consequently, the temperature of the canopy can be set to air temperature, and no energy balance needs to be solved. The canopy layer is combined with the layer beneath—namely, the soil



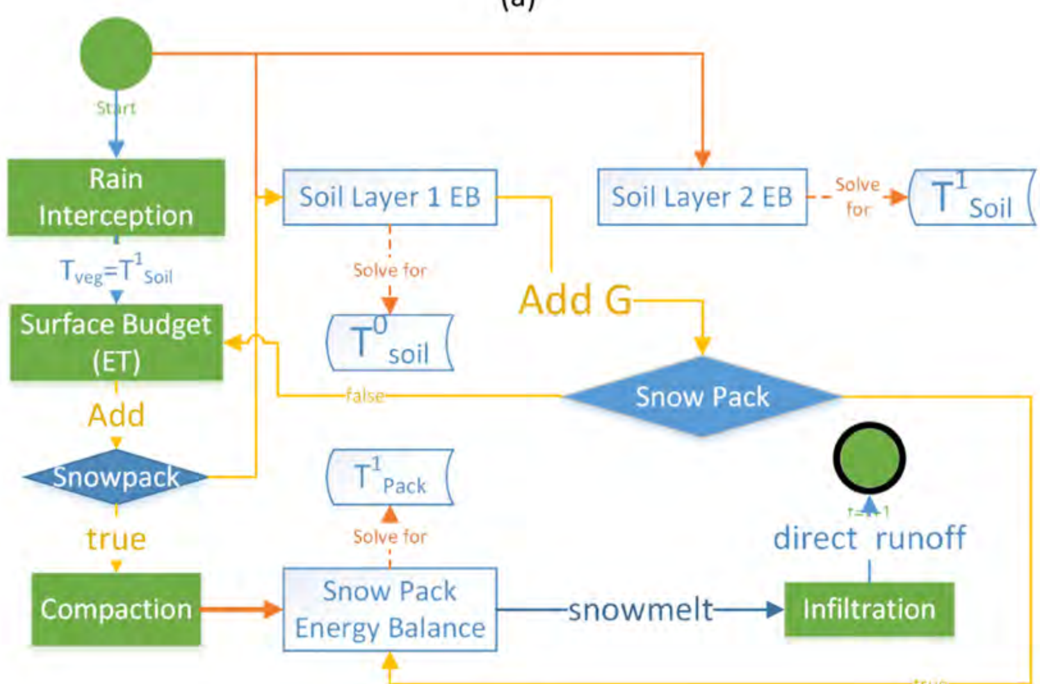


Fig. 2. Coupled Energy Water redistribution module integrated with a snow accumulation and ablation process in condition of (a) the land cover has a canopy layer and (b) the land cover is a short vegetation.

layer or the snowpack layer in the EB equation. The net radiation is given by Eq. (2),

$$R_n = (1 - \alpha_c)R_S + \varepsilon_c[R_L - 2\sigma(T_a + 273.15)^4] \quad (2)$$

where R_S and R_L are downward shortwave and longwave radiation, α_c and ε_c are albedo and attenuation of the canopy layer, $\sigma = 5.67 \times 10^{-8}\mathrm{W}/(\mathrm{m}^2\mathrm{K}^4)$ is Stefan-Boltzmann constant, and T_a (°C) is the air temperature. The first and second terms account for the net shortwave and longwave radiation, respectively. The coefficient 2 of the outgoing longwave radiation comes from the radiation of the canopy layer to both the hemispheres. The latent heat, E, contributed by the evapotranspiration (ET), can be directly computed by the potential ET (PET), which is given by the Penman-Monteith equation (Allen et al., 1998), and then adjusted by the availability of intercepted liquid water and soil moisture and the moisture resistance of vegetation roots (Liang et al., 1994). The conductive heat, G, represents the ground heat flux is caused by temperature difference between of the solid layers. It vanishes if the understory medium is snowpack—because ice and fresh snow have very little thermal conductivity—and is given by Eq. (21) if soil is right beneath. Since negligible heat storage can be used to balance Eq. (1), it can be unbalanced, that is,

$$B = R_n + G - E \neq 0 \tag{3}$$

B as the rest term is then cast to the understory layer, which represents the combination mathematically.

2.4.1.2. Snow condition. If snow is intercepted by the canopy layer, the temperature of the intercepted snow, T_{int} (°C), is solved for from EB in the canopy layer independently, and the temperature of the encapsulating air of the canopy layer, T_{en}, can be different from T_a and T_{int}. Note that it is valid to employ a one-layer snow model in the canopy layer with uniform temperature, T_{int}, because intercepted snow is always thin. To solve for T_{en}, the EB equation in the encapsulating air layer is formulated as described in Section 0.

As an alternative to Eq. (2), the net radiation of the canopy layer is given by Eq. (4),

$$R_n = \tau(1+\alpha_s)(1-\alpha_c)R_S + \varepsilon_c[R_L - 2\sigma(T_{int}+273.15)^4 + \varepsilon_s\sigma(T_{surf}+273.15)^4] \tag{4}$$

where c and s represent, respectively, radiation coefficients of the canopy layer and the understory surface. The sensible heat is proportional to the difference between T_{int} and T_{en},

$$H = \frac{\rho_a c_p}{r_a}(T_{int} - T_{en}) \tag{5}$$

where ρ_a, c_p, and r_a stand for density of air (kg/m^3), specific heat of air at constant pressure ($J{\cdot}kg^{-1}\,K^{-1}$), and wind-adjusted aerodynamic resistance to heat flow (s/m) between the snow surface and the atmosphere at the near-surface reference height, given by (Monteith and Unsworth, 2007).

The latent heat, E, given by Eq. (6), consists of the evaporation of liquid water, E_v, and the sublimation of solid ice, E_s, in the canopy layer upon neglecting transpiration in the snow covering condition,

$$E_{s,v} = L_{s,v}\rho_w\left[\frac{\rho_a}{P_a\rho_w r_a}(e_a - e_{surf})\right] \tag{6}$$

The second factor (in square brackets) of Eq. (6) stands for the maximal water evaporation rate in depth, which can be limited by the availability of water. In Eq. (6), ρ_a and ρ_w denote the density of air and water (kg/m^3), respectively; P_a is the atmospheric pressure (Pa), and $L_{s,v}$ stand for the specific latent heat of sublimation and evaporation (J/kg) that are computed by Eqs. (7) and (8):

$$L_v = 2.5008\times10^6 - 2.36\times10^3 T_{int} + 1.6T_{int}^2 + 0.06T_{int}^3 \tag{7}$$

$$L_s = 2.8341\times10^6 - 293T_{int} - 4T_{int}^2 \tag{8}$$

e_a is vapor pressure of the air which is a function of relative humidity and T_{en}, (or specific humidity and P_a); $e_{surf}(T_{int})$ is the vapor pressure (usually assumed saturated) on the surface of the intercepted snow surface. The computation of both can be found in (Allen et al. (1996); Allen et al. (1998)). Note that $E_{s,v}$ is typically negative when sublimation or evaporation occurs, but can be positive if condensation or liquefaction occurs, which indicates the formation of frost or dew, respectively.

ΔM is introduced by the heat deficit contained in intercepted precipitation,

$$\Delta M = \frac{\Delta D_H(T_a, P)}{\Delta t} \tag{9}$$

where P is total precipitation presented as SWE (m).

Heat deficit is defined as the opposite of the minimal energy the snowpack needs to return to isothermal status (0 °C):

$$D_H(T, SWE) = c_{ice}\times SWE\times T \tag{10}$$

The heat storage change in intercepted snow comes from two processes, the change of temperature and phase:

$$\Delta H = \frac{D_H(T_{int}, SWE) - D_H(T_{int}^-, SWE)}{\Delta t} + \frac{\rho_w\Delta_{ph}L_f}{\Delta t} \tag{11}$$

where T_{int}^- is the average temperature of intercepted snow during the last time step, SWE_{int} is the total depth of snow water equivalent (m) intercepted by the canopy, while $\Delta_{ph} < 0$ (or $\Delta_{ph} > 0$) is the depth of refrozen (or melted) water, ρ_w is the density of water (kg/m^3), Δt is the duration of the simulation time step (s) and $L_f = 3.337\times10^5$J/kg and $c_{ice} = 2.1\times10^6/m^{-3}{\circ}C^{-1}$ are the latent heat of freezing and specific heat of ice respectively. Physically, all liquid water must be refrozen if $T_{int} < 0$, and all solid water must be melted if $T_{int} > 0$, whereas when $T_{int} = 0$, the amount and direction of the phase change can vary within the limit of availability to balance the energy budget. This variability makes the energy budget as a function of T_{int} non-differentiable and therefore requires modification of the traditional numerical solvers, as described in Section 2.5.

The conductive heat, G, is computed in the same way as when the canopy is snow free.

2.4.2. Thermal balance in the snowpack

The physics of the EB in the snowpack layer is similar to that of the EB in intercepted snow. The difference originates from the two-layer structure of the snowpack and the heat exchange between the snowpack and the soil. The thermal insulator property of snow is utilized by setting thermal conductivity to zero in both the surface and pack layer. In other words, heat cannot be conducted either upward or downward via a layer of snow until the layer has been entirely melted. Therefore, it is valid to assume that both the surface and pack layer of snow are of uniform temperature—T_{pack}^1 and T_{pack}^2, respectively. Consequently, a concise way of accounting for the heat exchange in the two-layer structure is through the delegation of D_H. Compaction redistributes heat deficit in the two layers proportionally to the amount of mass it redistributes as following:

$$\Delta M_H^j = \frac{\Delta SWE^{i\to j}}{SWE^i}D_H^i - \frac{\Delta SWE^{j\to i}}{SWE^j}D_H^j + \frac{\Delta thru^j}{thru}D_H^{thru} \tag{12}$$

where superscript i and j stand for the surface and pack layer of the snow pack, respectively, and *thru* refers to the through-fall. Once the heat deficit of a snow layer is changed due to compaction, the new temperature is immediately obtained from Eq. (10).

In the EB of the surface snow layer, H, E, and ΔH can be computed using Eqs. (5), (6), and (11) by substituting T_{pack}^1 for T_{int}. The conductive heat, G, only exists when the pack layer vanishes and is computed by Eq. (21). The net radiation is given by

$$R_n = (1-\alpha_s)(1-\tau)(1-\alpha_c)R_S + \varepsilon_s\sigma\left[\varepsilon_c(T_c+273.15)^4 - (T_{pack}^1+273.15)^4\right] \tag{13}$$

where T_c is T_a if the canopy is snow-free, or T_{int} otherwise.

In the EB of the pack layer, R_n, E, and H vanish for the pack layer, and ΔH is computed in the same way as in the surface layer, using T_{pack}^2 instead of T_{pack}^1. G is computed by Eq. (21).

2.4.3. Thermal balance in soil layers

To solve the EB in the soil layers, a temperature profile is assumed. We adopted the two-layer thermal and three-layer moisture soil profile structure as described in (Liang et al., 1999), where temperature changes linearly with depth in the first thermal layer and exponentially below it, as in (14) and (15):

$$T(z) = T^0_{soil} + \frac{z}{d_1}(T^1_{soil} - T^0_{soil}), \quad 0 < z < d_1 \tag{14}$$

$$T(z) = T^2_{soil} + e^{-\frac{z-d_1}{d_p}}(T^1_{soil} - T^2_{soil}), \quad z \geqslant d_1 \tag{15}$$

where d_1, d_2, and d_p represent the thickness of the first and second thermal layers and the dampen depth, respectively.

The conductive heat flux within soil layers is given by Eq. (16),

$$G = -\kappa\frac{\partial T}{\partial z} \tag{16}$$

where κ is the thermal conductivity of the soil (in $Wm^{-1}K^{-1}$) and z is depth (in m).

Since conductive heat exchange exists only between soil layers, the temperature of the boundary between the first and second layers, T^1_{soil}, can be solved for using the EB in the second thermal layer, as given by Eq. (17),

$$T^1_{soil} = \frac{A \times T^{1-}_{soil} + B \times T^0_{soil} + C \times T^2_{soil}}{A + B + C} \tag{17}$$

where T^{1-}_{soil} is the boundary temperature between the first and second soil layer during the last time step and T^2_{soil} is the dampen temperature in the very deep soil, which does not change significantly with time; parameters A, B and C are defined below:

$$A = c^2_{p\_soil} \times d_p(1 - e^{-d_2/d_p})/\Delta t \tag{18}$$

$$B = \kappa^1/2d_1 \tag{19}$$

$$C = -\kappa^2(0.5 - e^{-d_2/d_p})/d_p \tag{20}$$

where $c^i_{p\_soil}$ and κ^i are the specific heat and thermal conductivity of the *ith* soil layer. Therefore, T^0_{soil} is the only unknown we need to solve for numerically, using the EB of the surface soil layer.

Substituting Eq. (14) for (16), the conductive heat (ground flux, $G\uparrow$) from the surface soil layer to the upper space is given by

$$G\uparrow = -\kappa\left(\frac{T^1_{soil} - T^0_{soil}}{d_1}\right) \tag{21}$$

The total conductive heat loss in the first layer is given by:

$$G = 0.5\left[G\uparrow - \frac{\kappa^2}{d_p}\left(T^2_{soil} - T^1_{soil}\right)\right] \tag{22}$$

The net radiation, R_n, and sensible heat, H, recede to zero when snowpack is present. Otherwise, R_n is computed by Eq. (13), and H is calculated by Eq. (5), replacing T_{int} with T^0_{soil} and recalculating the r_a value at the height of soil roughness. In case a vegetation cover exists, the energy consumed by ET has been accounted for in the canopy layer. Then the latent heat, E, in soil layers vanishes to zero.

In the bare soil case, soil water can be evaporated in two different ways: either from the first moisture layer at rate R_E, given by the Arno model (Franchini and Pacciani, 1991), and the consumed energy is calculated by the following equation:

$$E = L_s\rho_w R_E \tag{23}$$

or from three layers at different resistance, as in (Wang et al., 2011). We have created user options for these two different evaporation algorithms for bare soil.

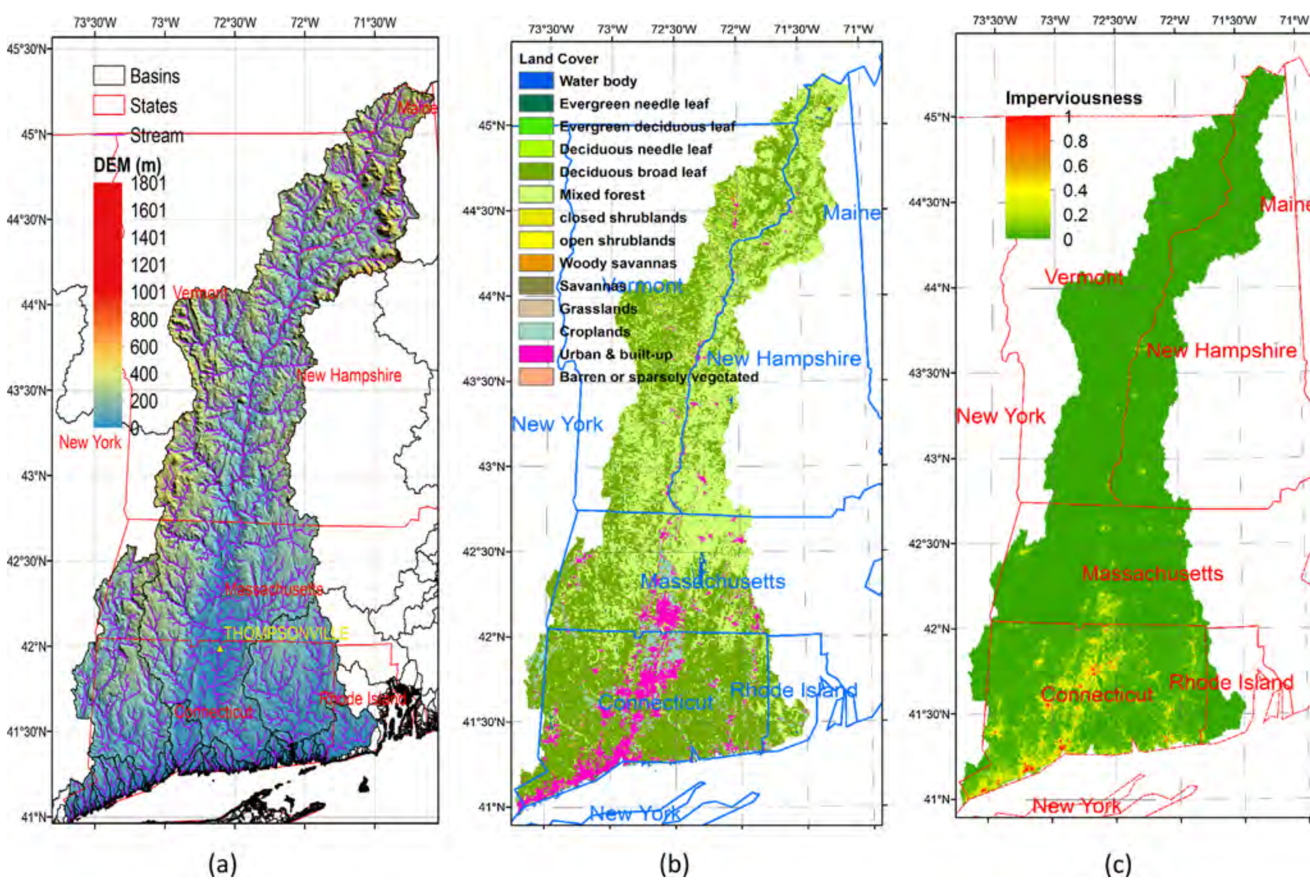


Fig. 3. Description of the testing basin region including (a) terrain, (b) land cover type and (c) imperviousness.

2.4.4. Thermal balance in the encapsulating atmosphere

As discussed in Section 2.4.1, the EB equation for the surrounding air needs to be solved when snow is intercepted. R_n, E, ΔM, and ΔH vanish in this air layer. The sensible heat in this layer is the sum of the sensible heat of the canopy, the understory, and the above air. If the ground is free of snow, G needs to be added to the EB of this layer.

2.5. Numerical solver of the EB equation-set

Each white block in Fig. 2 represents an EB equation to solve. Since sensible and conductive heat may be exchanged across layers, however, the temperature of neighboring layers affects the EB of the given layers. Therefore, solving EB is equivalent to solving a set of nonlinear equations.

As mentioned in Section 2.4.2, the non-differentiable EB as a function of the snow temperature cannot be solved by traditional numerical solvers. Consequently, we implemented the modified Broyden's method (Press, 2007). When snow exists only on the ground, T^1_{pack} and T^0_{soil} are the two unknown temperatures to solve for. We first set T^1_{pack} to zero and solve for T^0_{soil}. If the convergence is achieved within a limited number of iterations, the solution is found and the solver exits. Otherwise, it indicates that T^1_{pack} is not zero, and then we treat both T^1_{pack} and T^0_{soil} as unknowns and solve the equation-set again. Naturally, if snow exists both on the canopy and the ground, the EB system will be solved with up to four iterations. This modification successfully resolves the convergence problem and reduces the number of iterations. In practice, we set ten as the maximal iteration times for one trial. It usually takes four to five iterations to converge. Consequently, closed energy balance is always achieved in the simulation of a land surface process.

Applying the numerical solver at fine spatiotemporal resolution is computationally expensive. For this reason, we implemented the model on a high-performance computer (HPC) and used ~200 cores for simulating the land surface process. Parallel computation was implemented by evenly distributing basin grids to different cores. Moreover, within each core, vectorization was applied to optimize the computational efficiency of the equation solvers (Van Der Walt et al., 2011). Vectorization was implemented using the MATLAB platform, which further increased the computational efficiency (by around one to two orders) by avoiding looping over grids. Maximum efficiency can be achieved if each core has an independent cache.

2.6. Routing by modified FDLRR

The Fully Distributed Linear Reservoir Routing (FDLRR) method (Shen et al., 2016, 2014) developed for CREST has been demonstrated to accurately model channel flows. As the kernel of CREST v2.1, however, the FDLRR has not been tested over high-latitude basins affected by heavy snowfall.

Although the delay of the basin response to precipitation caused by snow accumulation and ablation has been addressed by the precipitation runoff module, it is difficult to physically model the consumed time by (1) the vertical drainage of liquid water in snowpack and (2) the refreezing of overland flow. Available methods (Anderson, 2006) significantly underestimate this delay by neglecting (2), thus resulting in underestimation of flow peak during snowmelt-contributing events. To address this issue empiri-

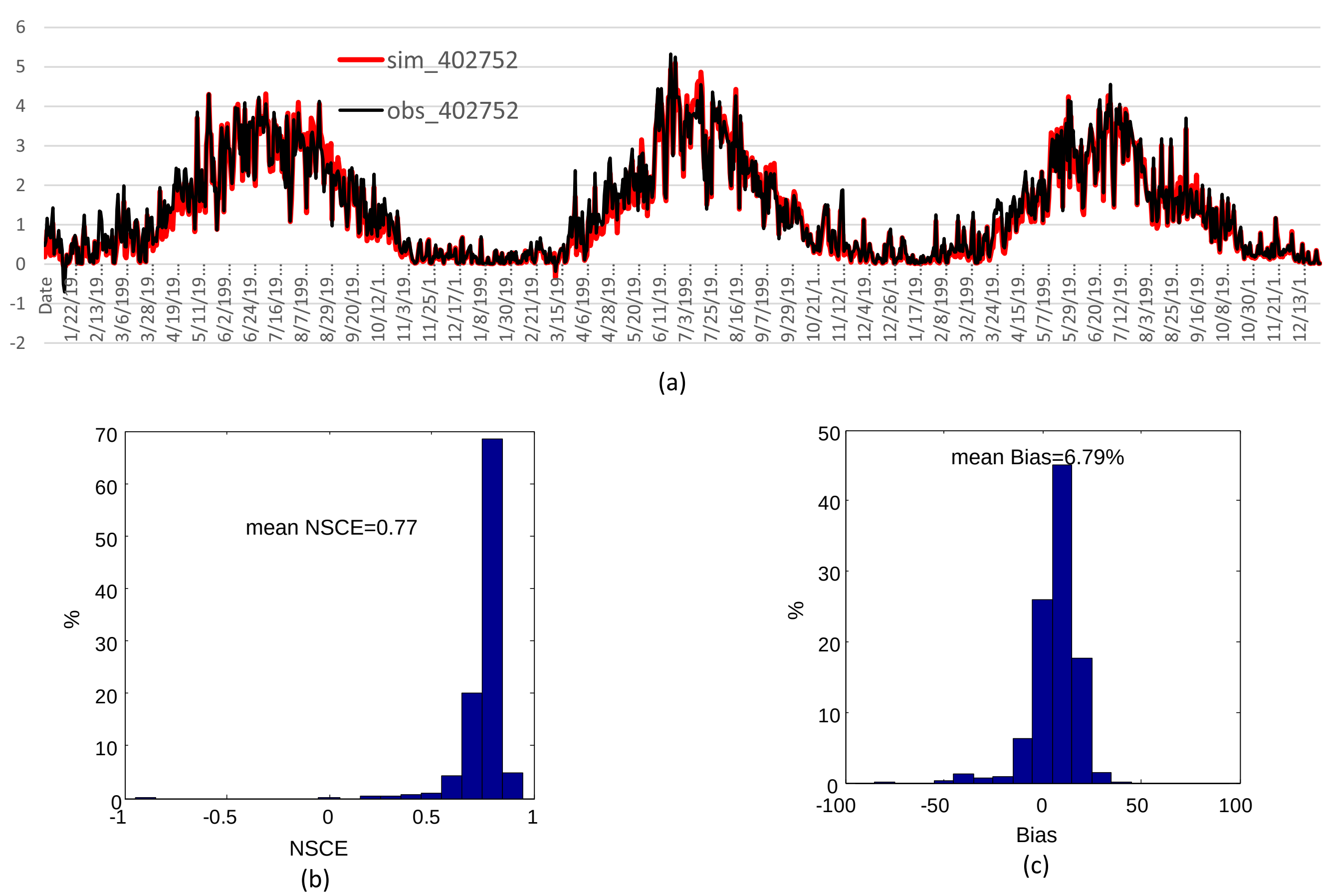


Fig. 4. Validation of the Actual ET. a) CREST simulation vs. MODIS retrieved ET product in daily scale over a randomly selected 8 km × 8 km grids. b)-c) gives the distribution of error metrics between the simulation and observation over all grids including: c) the NSCE value, d) the relative bias in (%).

cally, we added a time lag parameter (in time step) of snowmelt flow that can be optimized through calibration.

2.7. Error metrics

Pearson correlation (R), root mean squared difference (RMSD), and normalized RMSD (NRMSD), given by equations (24) and (25), are used as error metrics of SWE. The concentration at high R value (0.9–1) and low NRMSD (0.1–0.7), shown in Fig. 5(c)–(e), suggests good performance on simulating SWE. The Nash-Sutcliffe coefficient (NSCE), given by equation (26), and relative bias are employed to assess the ET simulation. Concentration at high NSCE (0.7–0.9) and low relative bias (−5% to 10%) indicates good performance on simulating ET.

$$R = \frac{\sqrt{\sum(Q_{sim} - \bar{Q}_{sim})(Q_{obs} - \bar{Q}_{obs})}}{\sqrt{\sum(Q_{sim} - \bar{Q}_{sim})^2}\sqrt{\sum(Q_{obs} - \bar{Q}_{obs})^2}} \tag{24}$$

$$NRMSD = \frac{RMSD}{mean} = \frac{\sqrt{N\sum(Q_{sim} - Q_{obs})^2}}{\sum Q_{obs}} \tag{25}$$

$$NSCE = 1 - \frac{\sum(Q_{sim} - Q_{obs})^2}{\sum(Q_{obs} - \bar{Q}_{obs})^2} \tag{26}$$

where Q_{sim} and Q_{obs} stand for the time series of interest given by simulation and observation, $\bar{Q}$ represents the mean value of the variable, and N is the number of the time steps.

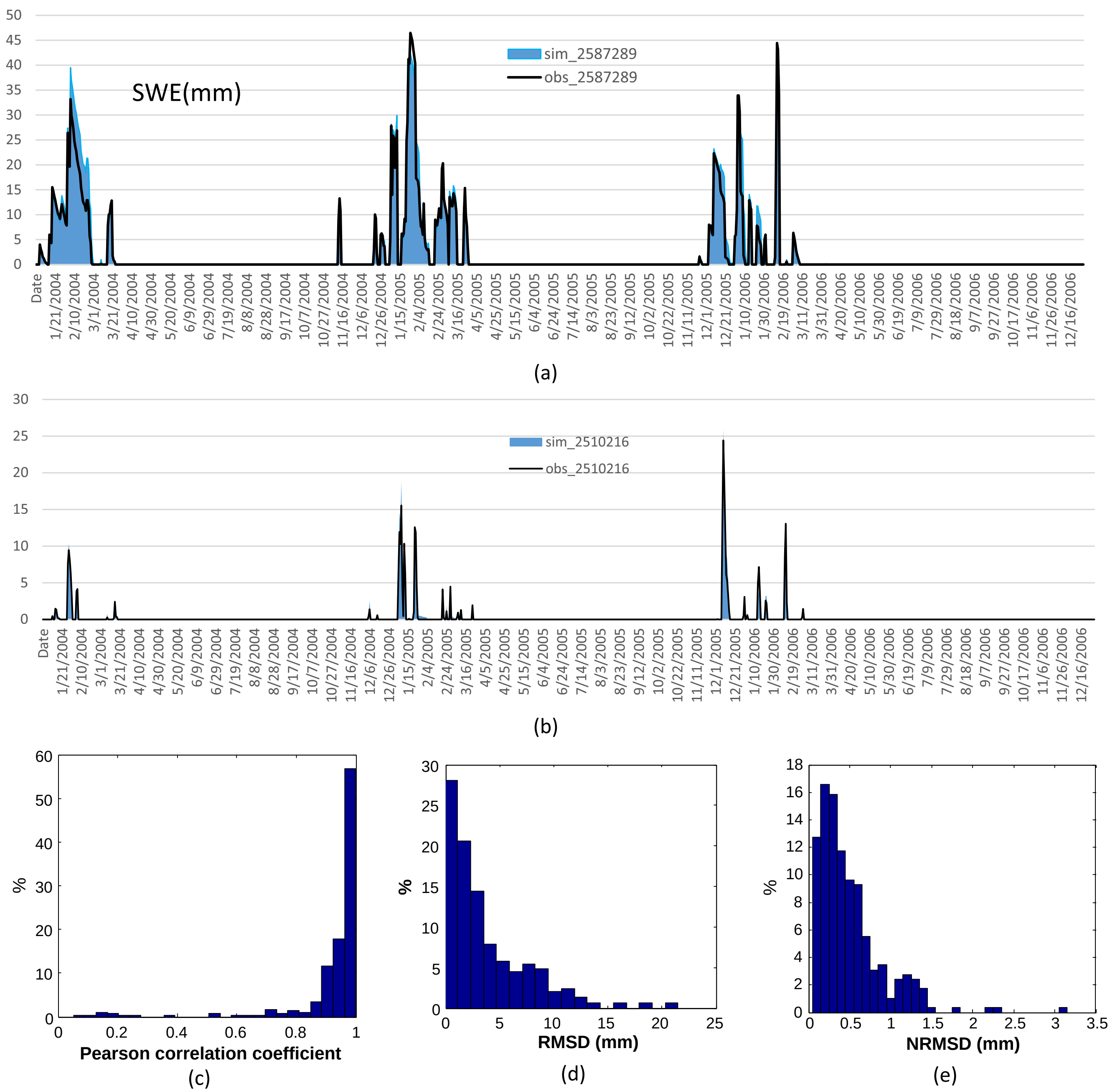


Fig. 5. Validation of SWE of the ground snowpack. a) and b) give CREST simulation vs. SNODAS "observation" in daily scale over two randomly selected 8 km × 8 km grids including a) a grid experienced heavy snow accumulation and b) a grid experienced light snow accumulation. c)-e) give the distribution of error metrics between the simulation and observation over all grids including: c) the Pearson correlation value, d) the root mean squared difference (RMSD) in millimeter and e) the normalized root mean squared difference, RMSD normalized by mean value.

3. Data, study area, and model parameterization

3.1. Input datasets and model parameters

Various meteorological and remote-sensing forcing data, and static model parameters, including vegetation, soil hydraulic, and land use parameters, are needed to run the precipitation-runoff module of CREST-SVAS. The datasets used in this study are listed in Table 2. The North American Land Data Assimilation System (NLDAS-2) meteorological dataset (Xia et al., 2012a,b) and the GLASS Leaf Area Index (LAI) have records of more than 30 years and were selected for this study to represent our forcing data. Land cover was obtained from the Moderate-Resolution Imaging Spectroradiometer (MODIS) land cover product, MOD12Q1, which defines the 500-meter grid resolution of the simulation. The impervious ratios were extracted from the Connecticut's Changing Landscape (CCL) and the National Land Cover Databases (NLCD) at 30 m resolution that are classified based on the Landsat surface reflectance, and then aggregated to the 500 m model-grid resolution. The vegetation parameter table (listed in Table 3) defines the vegetation properties that affect the ET rate and thermal aerodynamics and was obtained from (Calder and Maidment (1992), Ducoudré et al. (1993), Jackson et al. (1996)). Soil hydraulic properties were computed based on Saxton and Rawls (2006), using the 0–2 m (six-layered) soil characteristics from SoilGrids (Hengl et al., 2014). The study period supported by the atmospheric and LAI datasets is 1979–2012. Simulations were performed at hourly time step.

The routing module of CREST requires terrain data, including the digital elevation model (DEM), flow direction (FDR), and stream network. Global maps of these datasets at 3, 15, and 30 arc-secs can be obtained from maps based on SHuttle Elevation Derivatives at multiple Scales (HydroSHEDS) (Lehner et al., 2006). The U.S. maps can be obtained from the National Hydrographic Dataset (NHD) (Simley and Carswell, 2009) at 30 m spatial resolution. In this study, we used the 15 s (~500 m) version of the HydroSHEDS dataset. Routing parameters, except the newly developed snowmelt-runoff time lag (discussed in Section 2.6), are inherited from the previous version of CREST (Shen et al., 2016). Since routing parameters are either conceptual or difficult to derive on a physical basis, we optimized them using the automated Shuffled Complex Evolution University of Arizona (SCEUA) algorithm (Duan et al., 1993, 1992).

Table 3
Vegetation parameters. All parameters are cover-type dependent and parameters before h_{wind} changes every month.

Parameter	Description	Unit
α	Shortwave albedo	N/A
r	Roughness length	m
h	Displacement height	N/A
h_{wind}	Wind measured height	m
tr_0	Minimum incoming shortwave radiation to trigger transpiration	W/m^2
τ_R	Radiation attenuation factor	N/A
τ_{wind}	Wind speed attenuation factor	N/A
b_c	Whether the type Has a canopy layer	true|false
r_{trunk}	Trunk ratio	N/A
d_i, i = 1,2,3	Root zone thickness	m
f_i, i = 1,2,3	Root zone fraction	N/A
r_0	minimum stomatal resistance to evaporation	s/m
r_c	Architectural resistance to evaporation	s/m

3.2. Study area

We tested our modeling framework based on the Connecticut River Basin, a complex terrain that represents a drainage area of ~29,200 km^2 and the maximal, minimal and mean elevation of 1801 m, 0 m, and 303.97 m respectively, as shown in Fig. 3(a). The Connecticut River originates at the U.S. border between Quebec and New Hampshire; it then drains via Vermont, New Hampshire, Massachusetts, and Connecticut and discharges into the Long Island Sound. Snowmelt in the study basins significantly con-

Table 2
Distributed Parameters used in the CREST v3.0.

	Variable	Source	Spatial Resolution	Temperal Resolution
Dynamic Weather Forcing	total precipitation air temperature downward shortwave radiation downward long wave radiation humidity (specific or relative) pressure wind speed	NLDAS2 (http://ldas.gsfc.nasa.gov/nldas/NLDAS2forcing.php)	0.125°	1 h
Dynamic Surface Property	LAI	GLASS LAI (http://www.glcf.umd.edu/data/lai/)	0.05° (~5.5 km) (1982–1999) 1 km (2000-present)	8 days
Static Parameters	Vegetation Parameters Table	(Calder and Maidment (1992), Ducoudré et al. (1993), Jackson et al. (1996))	N/A	monthly periodic
	Land Cover	MCD12Q1 (https://lpdaac.usgs.gov/dataset_discovery/modis/modis_products_table/mcd12q1)	500 m	1 year
	Impervious Area Fraction	Connecticut's Changing Landscape (http://clear.uconn.edu/Projects/landscape/index.htm) National Land Cover Database (http://www.mrlc.gov/nlcd2011.php)	30 m	1 year
	Saturated hydraulic conductivity Field Capacity Wilting point soil moisture Saturated Soil Moisture Organic matter Bulk density	Soil hydraulic properties are computed by the Saxton's model (Saxton and Rawls, 2006)using soil texture and characteristcis downloaded from SoilGrids (https://soilgrids.org)	1 km/250 m	N/A
	Routing Parameters	Calibration. Definition please See (Shen et al., 2016; Wang et al., 2011)	Uniform	N/A

tributes to spring flows and flood events, while rainfall from storms primarily contributes to the floods occurring in summer and autumn. The climate type of the study region is humid continental. Over the basin, the average annual snowfall and rainfall are 164 mm and 1064 mm in equivalent water depth while rainfall spreads throughout the year. Therefore, solid, liquid, and mixed

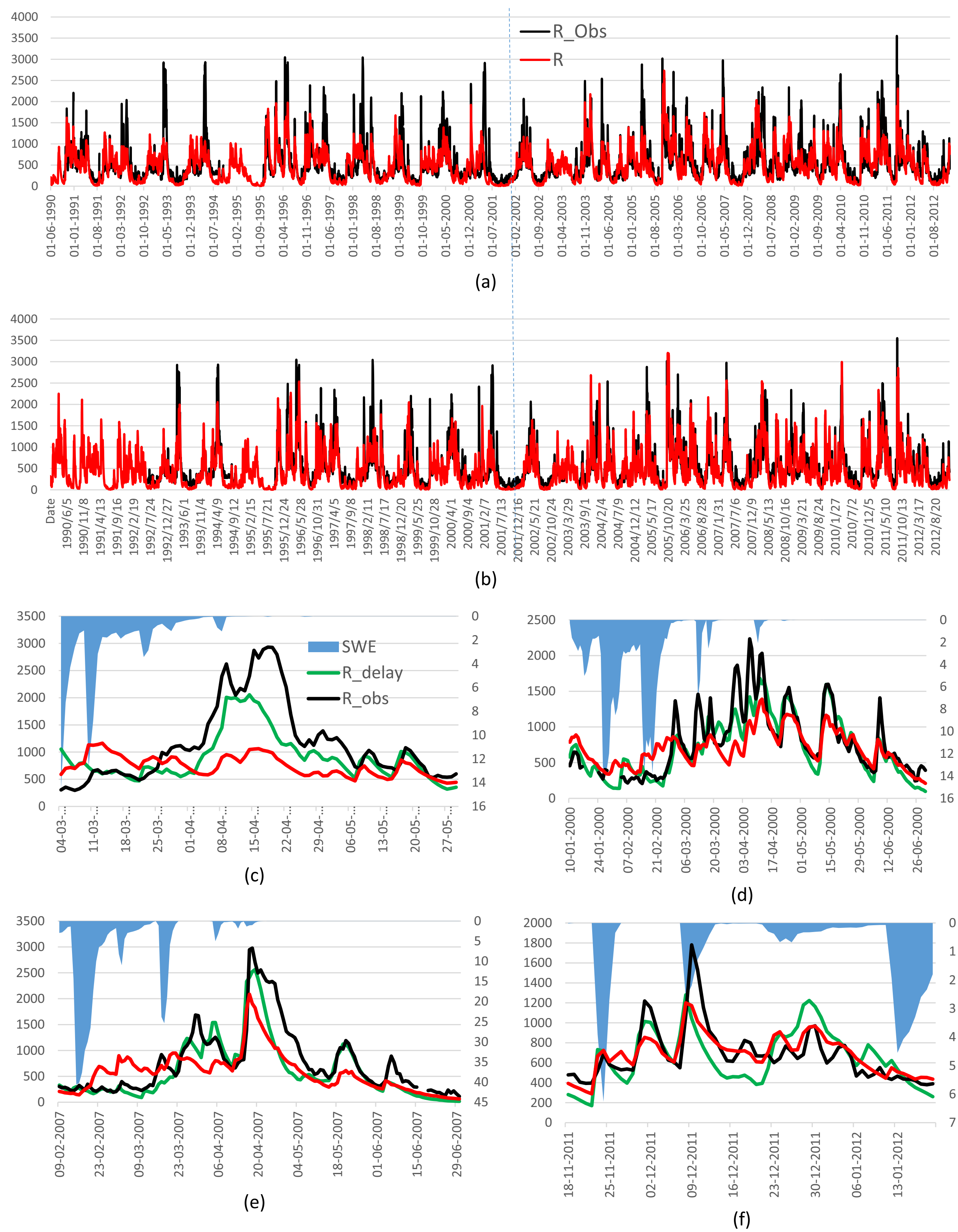


Fig. 6. Daily flow validation against observation including simulation (a) without and (b) with considering the time lag of snowmelt caused flow. (c) to (f) show four spring flood events contributed by snowmelt in 1994, 2000, 2007 and 2012.

precipitation are all experienced over the study area. Deciduous broadleaf and mixed forest dominate the overland area, buildings take up a large fraction along the downstream of the Connecticut River and coast, and agricultural lands are distributed along the Connecticut River, as suggested by Fig. 3(b). As the imperviousness in a given area depends on how built up the area is, it is high along the downstream of the Connecticut River and coast, as shown by Fig. 3(c). The densely distributed vegetation and canopy cover, as well as the meteorological conditions of the region, indicate a need to explicitly account for snow interception, accumulation and ablation, as well as evapotranspiration processes over the basin.

4. Results and model validation

Both the simulated land surface variables and stream flows were used in this study to evaluate the accuracy of the proposed model. Specifically, we used ET and SWE of the snowpack datasets (Section 4.1) retrieved from satellite observations and through data assimilation, respectively, and U.S. Geological Survey stream flow measurements in the Connecticut River (Section 4.2).

4.1. Validation of land surface simulations

The simulated ET and the snowpack in SWE were validated against third-party observations. The simulated ET was compared against the MODIS ET product (Zhang et al., 2010) and the simulated SWE of the snowpack against the SWE in the Snow Data Assimilation System (SNODAS) dataset (https://nsidc.org/data/g02158). Both are regarded as the best available gridded reference datasets for validation of the model ET and SWE parameters (Tedesco and Narvekar, 2010). To moderate random error effects, variables of the land surface process are conventionally validated at basin-average (or one-gauge point) and monthly time scale (Liang et al., 1994; Parr et al., 2015). With such averaging, however, one cannot evaluate the modeling skill at fine spatiotemporal resolution, which is critical to many applications, such as simulation of flood processes. In this study, we strictly validated our model's simulated ET and SWE parameters at high spatial resolution, namely 8 km $\times$ 8 km grid cells, which represents the spatial resolution of MODIS ET, and at daily temporal resolution. Since the model ran at 500 m spatial resolution and hourly time step, model outputs were averaged spatially within each 8 km $\times$ 8 km grid cell and aggregated to daily. The SWE outputs of the ground snowpack were also averaged within the same spatiotemporal scale.

The validation results of ET and SWE variables are given in Fig. 5 and Fig. 4, respectively. The average NSCE and average relative bias of simulated ET vs. the MODIS daily ET product are 0.77 and 6.79%. The average correlation of and normalized root mean square error of SWE estimates of simulation vs. SNODAS are 0.94 and 19%.

Using the HPC computational resources as introduced in Section 2.5, we were able to complete the computation over 180,000 grid cells and 298,008 time steps ($\sim$34 years at hourly time step) within 40.6 h. This performance is the combined effect of using parallel and vectorized computation.

4.2. Validation of the stream flow simulations

Fig. 6 compares the CREST stream flow simulations against the USGS observations at Thompsonville (gauge No. 01184000, denoted by the green triangle in Fig. 3) during 1990–2012, the period for which the USGS flow data are available. The model simulation with the snowmelt time-lag being optimized as 26 days (Fig. 6(b)) exhibits better agreement with USGS stream flows than the simulation without the lag parameter (Fig. 6(a)). The NSCE of the entire period increases from 0.42 to 0.58, while the NSCE of the timespan after 2002 increases from 0.60 to 0.63. The necessity of the snowmelt time lag adjustment parameter is consolidated by examining spring floods, shown in Fig. 6(c) and (f), when the snowpack is considerably melted. The simulation without the time lag adjustment (red line) tends to overestimate significantly the flow rate before the real floods are formed. As a consequence, during the actual peak time, the simulation underestimates the actual peak flow.

The time lag effectively addresses this problem, capturing the flood peaks during snowmelt periods (green line) without affecting the flood hydrographs during the summer and fall flood periods. The evidently low model performance shown in Fig. 6(a) from 1990 to 2001 is because the major floods during the first decade were mostly spring floods, whose peak values were significantly underestimated without delaying snowmelt-contributed flow. In the second decade (2002–12), due to possible global warming effects (warmer winters), autumn floods became dominant in most years, in which the model performance was not affected by the time lag. Fig. 6(c)–(f) not only verify that snowmelt-contributed flood events are well captured by the proposed model; they also demonstrate the value of introducing the snowmelt flow delay factor.

Due to the significant contribution of snowmelt, floods in the Connecticut River Basin have not been well captured by existing models (Dis et al., 2015; Parr et al., 2015). Most of these applications have reported NSCE scores of daily discharge simulations around 0.3. As shown in this section, the model proposed in this study improves simulation accuracy by physically coupling the snow accumulation/ablation with other water cycle processes in the SVA structure.

5. Closing remarks

In this paper, we presented the development of a high-resolution hydrological modeling framework aimed at improving simulations of snow-affected runoff generation processes, which are commonly expected in mid- and high-latitude regions. The model is physically based and integrates the most advanced energy balance concepts with remote sensing, atmospheric, soil survey, and GIS datasets. A new snowmelt flow delay parameter was introduced to better capture the magnitude and timing of snowmelt contributions to flood events. Without calibration, the precipitation-runoff module predicted ET and SWE variables with higher accuracy than what has been reported in past studies. This improved representation of snow processes in runoff generation improved the accuracy of stream flow simulations relative to performances reported in previous studies for this region.

Due to its computational efficiency and strong physical basis, this model can be used to conduct long term (>30 years) and high-resolution hydrological simulations at regional scale and for complex snow-affected basins. The accuracy reported in this study indicates that the model can be effectively applied to support physically-based estimations of flood frequencies of ungauged basins, by capitalizing on available long-term atmospheric reanalysis datasets that can span longer periods (35–50 years) than available hourly USGS flow datasets. Furthermore, the adaption of high resolution has prepared the model for future high-resolution meteorological data forcing in a comparable resolution (Zhang et al., 2016).

Acknowledgments

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APPENDIX E

Task 7 Summary: Vulnerability and Resilience of Municipal Wastewater Infrastructure

By Christine Kirchhoff, P.E., Ph.D., UConn Dept of Civil & Environmental Engineering and Amy C. Burnicki, ,Ph.D., UConn Dept of Geography and Dept of Civil & Environmental Engineering

Task Overview

Wastewater (WW) systems provide invaluable societal services and are critical to public and environmental health, economic vitality, and national security. Yet, they are sensitive to extreme winds, precipitation, and flooding. Past storms including Alfred, Sandy, and Irene exposed these sensitivities inflicting billions of dollars in damage to WW infrastructure in the Connecticut and across the Northeastern United States (U.S.). Changes in the economy, aging infrastructure, and an uncertain regulatory environment exacerbate these vulnerabilities as does accelerated sea level rise and more frequent extreme precipitation expected with climate change. To lessen the impacts of current extreme events and to withstand future climate changes requires WW managers to institute adaptation actions that lessen vulnerabilities and build resilience—the capacity to prepare for, cope with, recover, and learn. While WW managers must adapt and build resilience, very little is known about what WW managers are doing, what informs, motivates, supports, or impedes those actions, and if those actions are building resilience.

The purpose of this task is to understand the vulnerabilities WW systems in Connecticut face, the adaptation actions WW systems are taking, and what makes WW systems more (or less) resilient. Results from this research have helped inform state agencies (in Connecticut and Rhode Island) resilience building efforts and has been incorporated into the New England Interstate Water Pollution Control Commission WW Resilience Trainings.

This task was implemented by faculty from the Connecticut Departments of Civil and Environmental Engineering and Geography and was one of ten tasks comprising the Municipal Resilience Planning Assistance Project, funded by the U.S. Department of Housing and Urban Development in 2015 and coordinated by the Connecticut Institute for Resilience and Climate Adaptation. All ten tasks were focused on the coastal counties impacted by Superstorm Sandy in 2012.

Kirchhoff developed a quantitative survey and interview protocols and obtained Institutional Review Board approval prior to conducting the research (protocol X16-091). The survey questions were designed to assess experience with past storms, risk perceptions regarding future storms and climate change, the characteristics of the wastewater system (e.g., size, location) including the organization (e.g., leadership, culture, available science, etc.), and the broader context (e.g., public or political support, regulatory environment). To improve measurement reliability and validity, the survey was pilot tested in October 2015, revised based on feedback received, and then administered via email to 131 WW managers in Connecticut from November 2015 to April 2016. 86 completed surveys, 65.6% response rate, were used for analysis. In addition to the survey, Kirchhoff developed and tested an interview protocol including questions about the nature and severity of past storm impacts, the types of adaptive changes made, if any, and motivations for those changes, what helped or hindered making changes, and about adaptation to future climate change. Questions for the survey and interview drew on relevant theoretical literature on factors thought to drive adaptation actions including risk perceptions and organizational learning. 29 phone interviews were conducted from October 2016 to March 2017, and each interview lasted between 35 and 55 min.

In addition to the interviews, Kirchhoff and Burnicki worked with Milford, Connecticut to develop site specific sea level rise information for the Beaver Brook Wastewater Treatment Plant and Kirchhoff worked with Alejandro Cifuentes to produce more usable flood recurrence projections for Milford. Burnicki used ArcGIS to produce maps for Milford showing the water depth at the plant at the Mean Higher-High Water level (MHHW), Superstorm Sandy inundation levels, 100 year flood levels, and 100 year flood plus 1 to 7 feet of sea level rise. Figures were provided to Milford. Cifuentes analyzed tide gage data at Bridgeport and New Haven, Connecticut to produce flooding recurrence projections for Milford relative to the MHHW. Return periods of 1, 5, 10, 25, 50, and 100 year were developed. Kirchhoff shared a draft document with Milford Planning staff to obtain feedback and then used that feedback to help Cifuentes improve the usability of the summary document.

A GIS analysis was conducted to assess the potential impact of a 100-year flood event under varying sea level rise scenarios for all wastewater treatment plants in Connecticut. The analysis considered both the extent and depth of flooding within the wastewater treatment plant site and the impact of flood waters on plant accessibility, measured using a transportation network.

The data layers used in the analysis consisted of the following:

- wastewater treatment plants, provided by CT Department of Energy and Environmental Protection as a series of latitude / longitude coordinates
- wastewater treatment plant site footprints, digitized using 2016 orthorectified aerial imagery provided by CT Department of Energy and Environmental (0.25ft resolution)
- 2015 TIGER/Line files depicting roadways within the state of Connecticut, provided by the U.S. Census Bureau
- 100-year flood event water levels above Mean Higher High Water under varying sea level rise projections, provided by the Connecticut Institute for Resilience and Climate Adaptation (CRICA) as part of Task 2
    - SLR scenarios: 100-yr flood event, 100-yr flood event + 1ft SLR, 100-yr flood event + 2ft SLR, 100-yr flood event + 3ft SLR, 100-yr flood

event + 5ft SLR, 100-yr flood event + 7ft SLR

The projected 100-year flood event levels above MHHW under varying scenarios of sea level rise were overlaid onto the wastewater treatment plant site footprints to determine the extent and depth of flooding at wastewater treatment plant. The percentage of the site impacted by flooding, the mean water level observed within the site, and the maximum water level observed within the site were determined for each plant. The accessibility of each wastewater treatment plant was assessed by first determining all roadway segments and intersections within a 0.5-mile distance of each plant as measured along the transportation network. The projected 100-year flood event levels above MHHW under varying scenarios of sea level rise were then overlaid onto resulting roadway segments and intersections to assess site accessibility. For all intersections within 0.5 mile of a wastewater treatment plant, the percentage of intersections impacted by flooding, the mean water level observed over all impacted intersections, and the maximum water level observed over all impacted intersections was determined. For all roadway segments within 0.5 mile of a wastewater treatment plant, the percentage of the road network impacted by flooding, the mean water level observed over all impacted roadway segments, and the maximum water level observed over all impacted roadway segments was determined.

Outcomes

Four outcomes resulted from this work including: 1) two peer-reviewed publications one by Kirchhoff and Watson (2019) and a second by Mullin and Kirchhoff (2018), 2) a white paper entitled *Wastewater System Resilience: Learning from Connecticut Wastewater Systems* by Kirchhoff, Mullin, Utemuratov, and Tashev of resilience actions taken and lessons learned from wastewater systems in Connecticut, designed to supplement the NEIWPCC *Preparing for Extreme Weather at Wastewater Utilities: Strategies and Tips* guide, and 3) a GIS analysis of the vulnerability of WW systems to flooding/sea level rise.

Kirchhoff and Watson (2019) found that most WW managers (78%) are making changes to build resiliency to storms they have experienced in the past (e.g., extra fuel on site, extra staff on call, more training, better communication, adding generators, elevating components, adding capacity); most are not adapting to future climate change. This research suggests organizational leadership, concern about future climate-related impacts, and experiencing storm impacts drive resiliency changes while regulatory requirements drive adaptation to future climate change.

Mullin and Kirchhoff (2018) found the most resilient WW systems are those with high adaptive capacities that employ an adaptive management approach to make ongoing adaptation investments over time. Greater amounts of generic adaptive capacities (i.e., skilled staff and good leadership) help smooth both day-to-day and emergency operations and provide a foundation for adaptive management. In turn, adaptive management helps managers both build more generic adaptive capacities, and develop and employ greater amounts and diversity of specific adaptive capacities (i.e., soft and/or hard adaptations) that are especially important for enhancing and sustaining resiliency. Adaptive management also enables managers to better understand their system's vulnerabilities, how those vulnerabilities change over time, and what specific actions may reduce those vulnerabilities. Finally, this research suggests WW system resilience critically depends on the capacities of the human systems for building resilience as much as or more so than relying only on physical infrastructure resilience.

Kirchhoff et al. (2019) produced a resilience lessons learned guide entitled *Wastewater System Resilience: Learning from Connecticut Wastewater Systems*. The idea for the guide is to draw on the survey and interview data to derive practical advice for Connecticut wastewater system that compliments other resources available. For example, wastewater managers can use resources provided by the New England Interstate Water Pollution Control Commission (NEWIPCC) including their wastewater treatment plant design manual, *Guides for the Design of Wastewater Treatment Works* (also known as Technical Report 16 or TR-16), and a supplementary document, *Preparing for Extreme Weather at Wastewater Utilities: Strategies and Tips* (NEIWPCC 2016a,b). The Strategies and Tips document, intended for wastewater system managers and operators, synthesizes the experiences of Northeast wastewater utilities affected by recent major storm events and provides a set of strategies and tips for planning, preparing, coping with and recovering from major storm events. Our guide compliments these NEIWPCC resources to help wastewater systems build resilience to a broader range of stressors including not only resilience to extreme events and climate change but also resilience in day-to-day operations and to non-climatic stressors. The guide summarizes six strategies and tips used by Connecticut wastewater systems not previously discussed in the NEIWPCC Strategies and Tips document: 1) Promote Ongoing Learning and Experimentation; 2) Maintain and Improve Equipment and Infrastructure; 3) Transform where Possible; 4) Invest in Many Diverse Resilience Building Actions; 5) Take Advantage of New Technology but Beware the Technology Trap; and, 6) Monitor and Take Advantage of Regulatory Change.

We will share the lessons learned guide with Connecticut wastewater managers to not only be proactive in sharing lessons learned but also solicit feedback and input for refining the guide, should it be warranted in the future.

Alejandro Cifuentes produced draft and then revised flood recurrence projections for Milford showing the projected water depth relative to the MHHW for 1, 5, 10, 25, 50, and 100 year return periods. To improve usability, Kirchhoff suggested including a table showing sea level rise values in feet in addition to meters, revised figure scales, and a new figure to help explain how to interpret the information in the figures. In addition, Kirchhoff added clarifying text to help explain the analysis to a lay audience.

Eighteen out of 89 wastewater treatment plants (WWTP) were impacted by flooding at the plant site or with respect to plant accessibility. The impacted wastewater treatment plants were located along the coast and the southern portions of the Housatonic and Thames rivers.

System ID	System Name
1	Greenwich; Grass Island
2	Milford; Beaver Brook
3	West Haven
4	Stonington; Stonington Borough
5	City of Groton
6	Stratford
7	Stonington; Mystic
8	Norwalk
9	Bridgeport East
10	Fairfield
11	Branford
12	GNHWPCA; East Shore
13	Stamford
14	Bridgeport West
15	New London
16	Milford; Housatonic
17	Westport
18	Town of Groton

Table 1 illustrates the potential impact of a 100-year flood event under varying sea level rise scenarios with respect to the extent and depth of flooding within the site footprint.

- Without the addition of SLR, 9 of the 18 WWTP had greater than 90% of their site footprint impacted by flooding, with average water depths at each site ranging from 2.7-5.4 feet.
- With the addition of 3 feet of SLR, 13 WWTPs experienced flooding across greater than 90% of their site footprint, with average water depths increasing to a range of 2.8-8.3 feet.
- A more conservative projection of 1 foot of SLR results in 13 WWTP experiencing flooding across greater than half the site footprint with average water depths of 2.7-6.3 feet.

Tables 2 and 3 illustrate the potential impact of a 100-year flood event under varying sea level rise scenarios on the accessibility of a WWTP.

- Without the addition of SLR, 9 of the 18 WWTP experienced flooding at more than 50% of the *intersections* within 0.5 mile of their plant, with average water depths at nearby intersections ranging from 2.7-8.1 feet. For this same set of plants, 8 of the 9 WWTPs had greater than 50% of the *total roadway length* within 0.5 mile of the plant under flood waters, with average depths ranging from 2.2-7.2 feet.
- When 3 feet of SLR is factored into the analysis, 11 WWTPs experience flooding over more than 50% of the *intersections* within 0.5 mile of their

plant and 12 WWTPs experience flooding over more than 50% of the *total roadway length* within 0.5 mile of the plant.

Comparing the results across Tables 1-3, WWTPs fall into three general categories: a) plants that experience substantial flooding within their WWTP site footprint, but maintain site accessibility due to limited flooding along the road network within 0.5 mile of the plant (Figure 1); b) plants that experience severe limitations to site accessibility due to flooding along the road network within 0.5 mile of the plant, but the site itself is impacted by flooding to a lesser degree (Figure 2); and c) plants that experience a moderate impact to flooding both within the WWTP site footprint and along the road network within 0.5 mile of the plant (Figure 3).

Issues for Future Consideration

This research suggests that WW systems are not adapting to climate change unless there is a mandate to do so and that adaptive management together with generic and specific adaptive capacities can help systems be more resilient to a changing climate. This research provides actionable information that state agencies can use to encourage and support WW systems in their adaptation efforts. Moreover, the publications, guide, and GIS maps and tables provide specific strategies and data wastewater systems and local communities can use to make their systems more resilient.

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AMERICAN WATER RESOURCES ASSOCIATION

Are Wastewater Systems Adapting to Climate Change?

Christine J. Kirchhoff and Peter L. Watson

Research Impact Statement: Findings suggest wastewater managers are building resiliency to the past rather than adapting to future climate change except when regulations compel adaptation.

ABSTRACT: Wastewater (WW) systems are vulnerable to extreme precipitation events; storm-induced WW system failures pollute the environment and put public health at risk. Despite these vulnerabilities, we know very little about how WW managers are responding to current climate risks or to future climate change. This study aims to fill this critical gap in the literature. Data from surveys and interviews were used to understand what WW managers are doing to adapt to the current climate, what facilitates those adaptations, and if they are adapting to future climate change. Findings show most WW managers (78%) are making changes to build resiliency to storms they have experienced in the past (e.g., extra fuel on site, extra staff on call, more training, better communication, adding generators, elevating components, adding capacity); most are not adapting to future climate change. Our work suggests organizational leadership, concern about future climate-related impacts, and experiencing storm impacts drive resiliency changes while regulatory requirements drive adaptation to future climate change. Beyond advancing science, our work offers practical suggestions for building WW system resilience and for increasing WW system's consideration of future climate impacts in their resiliency building efforts.

(KEYWORDS: climate variability/change; sustainability; regulation or policy; resilience; climate adaptation.)

INTRODUCTION

Wastewater systems — including wastewater collection, pump stations, and wastewater treatment plants (WWTP) — play a critical function in society; yet, they are increasingly at risk of failing to protect public health and the environment because they are old, incredibly underfunded (EPA 2008; NACWA and AMWA 2009), and vulnerable to the impacts of extreme events and sea level rise (Patz et al. 2008; Campos and Darch 2015a; Howard et al. 2016). For example, hurricanes caused widespread power outages, flooding, and bypassing of billions of gallons of untreated or partially treated sewage into local waterways (Altimari 2011; Kenward et al. 2013; Wade et al. 2014). But, it is not just hurricanes. High winds and heavy rains are also enough to cause problems. For example, in 2007, summer floods in the United Kingdom overwhelmed wastewater systems putting hundreds of systems out of service (Campos and Darch 2015a) and in 2017, in Seattle, Washington a night of heavy rain sent 180 million gallons of wastewater into Puget Sound (Long 2018). Across the country that same year in Waterbury, Connecticut heavy rain washed five million gallons of raw sewage into the Naugatuck River (Blanks 2017). These failures suggest wastewater systems struggle to manage today's extreme storms; climate change is likely to make things worse with more frequent extreme precipitation events expected in the future (Bates et al. 2008).

To lessen the impacts of current extreme events and to withstand future climate changes requires wastewater managers to institute adaptation actions that

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lessen vulnerability and build resilience. For the purposes of this paper, we define resilience as the capacity to anticipate and prepare for, cope with, recover, and learn from a disturbance (Francis and Bekera 2014), and we define adaptation actions as specific and tangible actions intended to reduce vulnerability, increase resilience, and adapt to the impacts of climate change (Berrang-Ford et al. 2011; Lesnikowski et al. 2011). While scholars have advanced our understanding of how climate change will affect wastewater systems (Butler et al. 2007; Plósz et al. 2009; Langeveld et al. 2013; Campos and Darch 2015a; Weirich et al. 2015; Zouboulis and Tolkou 2015; Howard et al. 2016), how to design wastewater systems to withstand a changing climate (Smith 2009; Mailhot and Duchesne 2010), how to assess and enhance wastewater system resilience under a changing climate (Scott et al. 2012; Schoen et al. 2015; Faust and Kaminsky 2017; Juan-García et al. 2017; Sweetapple et al. 2017), and how wastewater systems might adapt to climate impacts (Gersonius et al. 2013; Campos and Darch 2015a, b; Zouboulis and Tolkou 2015), very little research that we know of aims at understanding what wastewater managers themselves are doing to reduce vulnerabilities, build resilience, and adapt to climate change. This lack of understanding of what wastewater managers are doing, what motivates those actions, and what supports (or impedes) those actions means we do not yet know how wastewater managers themselves are approaching this challenge or what possible entry points may exist to help wastewater managers implement more or different strategies to reduce vulnerabilities, build resilience, and adapt to climate change in practice.

This study aims to begin to fill this gap in the literature. We use an empirical mixed method approach including interviews and a survey of wastewater managers in Connecticut to understand: (1) How are wastewater managers responding to current extreme events? (2) What drives those changes? and (3) Are wastewater managers adapting to future climate change? The following sections include a brief review of the literature, description of Connecticut wastewater systems and the context of the study, the methods used to collect and analyze data, and present and discuss the results. We conclude with recommendations for how to facilitate adaptation to future climate change in wastewater systems.

LITERATURE REVIEW

Well-functioning wastewater systems provide a critical service to society by collecting and treating liquid organic wastes and discharging effluent water of sufficient quality to protect the environment and public health. The combined effects of aging infrastructure and extreme precipitation events contribute to wastewater system failures (Howard et al. 2016); wastewater system failures damage the environment and raise rates of gastrointestinal disease putting public health at risk (Wade et al. 2014; Jagai et al. 2017). Climate change is expected to aggravate these failures by increasing sewer overflows, changing treatment effectiveness, decreasing the absorptive capacity of receiving waters, and exposing more infrastructure to damage and inundation from sea level rise (Butler et al. 2007; Plósz et al. 2009; Nilsen et al. 2011; Arkell et al. 2012; Langeveld et al. 2013; Campos and Darch 2015a; Weirich et al. 2015; Zouboulis and Tolkou 2015; Sweetapple et al. 2017). Despite the prevalence of wastewater system failures and the prospect of more in the future, we know very little about the human dimensions of wastewater systems, especially what wastewater managers themselves are doing to combat today's challenges as well as adapt to future climate change.

While we lack understanding of the human dimensions of wastewater systems, an emerging body of literature explores how to physically engineer wastewater system resilience to the current climate and to adapt wastewater systems to the future. Resilience generally has to do with the capacity to anticipate and prepare for, cope with, recover from, and learn from a disturbance (Francis and Bekera 2014), while adaptation is defined as "the process of adjustment to actual or expected climate and its effects" (IPCC 2014, p. 118). In their review of this literature, Juan-García et al. (2017) found the most common suggested resilience improvements for wastewater systems are added capacity (buffering), equipment backup, maintenance and repair, and asset protection. Suggested adaptations include improved monitoring, planning, and maintenance of the wastewater system and conducting vulnerability analyses (Campos and Darch 2015a, b; Zouboulis and Tolkou 2015), installing more sustainable drainage systems, constructing floodwalls, and "dry-" or "wet-proofing" (Campos and Darch 2015a, b). Both resilience and adaptation suggestions are mostly derived from modeling of wastewater systems under different stresses (e.g., flooding, greater inflows, higher temperatures, etc.) and from reviews of the literature rather than empirical investigation of wastewater manager practices.

A great deal of research has quantified barriers to adaptation in different domains (for comprehensive review of this literature, see Biesbroek et al. 2013). Where adaptation has happened, researchers have quantified adaptation efforts globally (e.g., Adger et al. 2005; Berrang-Ford et al. 2011; Ford et al. 2011) and in individual countries (e.g., Tompkins et al. 2010; Bierbaum et al. 2013), in cities (Bowler et al. 2010; Measham et al. 2011; Dilling et al. 2017), in business and industry (e.g., Linnenluecke et al. 2013), in the transportation sector (e.g., Eisenack et al. 2012), and in the energy sector (Braun and Fournier 2016). The only published literature we found related to this subject for the wastewater sector is Rudberg et al. (2012). Rudberg et al. (2012) was limited in scope relying on interviews with only four wastewater systems in Stockholm, Sweden to explore how the adaptive capacity of wastewater systems influenced whether and how wastewater systems implement adaptive decisions in response to expected climate change. Rudberg et al. (2012) found the inability to justify the expense for the adaptation and the lack of rules requiring adaptation limit adaptation action while knowledge on climate change impacts supports adaptation. While Rudberg et al. (2012) provided a useful reference point, its limited geographic scope and small sample size make generalizations difficult. As such, there remains an urgent need for systematic, empirical investigation of wastewater systems to better understand what the wastewater sector is doing to build resilience and to adapt to climate change. This study aims to begin to fill this critical gap in the literature with a systematic investigation of the actions wastewater managers take to build resilience and adapt to climate change. In this study, we use the term adaptations (or adaptive changes) to mean specific and tangible actions intended to reduce vulnerability, increase resilience, and adapt to the impacts of climate change (adapted from Berrang-Ford et al. 2011; Lesnikowski et al. 2011). These actions may be temporary or permanent structural changes to wastewater infrastructure (e.g., to the collection system, pump stations, or the treatment plant) or they may be changes in practices and procedures resulting from organizational learning (Berkhout 2012).

CONNECTICUT WASTEWATER SYSTEMS

Connecticut has approximately 131 wastewater systems that provide wastewater services for over 2.38 million residents. Connecticut wastewater systems range in treatment capacity from about 5,000 gallons per day to 60 million gallons per day (MGD) with a median capacity of 1.2 MGD. Wastewater systems are regulated by the Connecticut Department of Energy and Environmental Protection (CTDEEP) which also administers the Clean Water Fund (CWF) (i.e., funding from the Clean Water Act) which provides loans to municipally owned systems. In 1998, the state legislature passed An Act Concerning Global Warming Solutions (Public Act 08-98) which led to the 2011 Connecticut Climate Preparedness Plan which recommended that CTDEEP require wastewater systems that receive funding from the CWF to "consider climate change as part of facility planning" (GSC 2011). In 2013, the state legislature made considering sea level rise a requirement of CWF recipients (Public Act 13-15).

Connecticut wastewater systems were chosen, following Flyvbjerg (2006) and Yin (2013), as a paradigmatic case study of wastewater system resilience and adaptation given the recent experience with extreme storms including Sandy and Irene and the state's support for adaptation. Given the support for climate adaptation, we would expect to encounter some adaptation activity among wastewater systems enabling a fuller exploration of the conditions that promote adaptation compared to states where adaptation is less supported.

METHODS

Data Collection

We sought and obtained Institutional Review Board approval for our research (protocol X16-091) that involved both a quantitative survey and qualitative interviews with wastewater system managers (hereafter wastewater managers) to understand wastewater managers' experience with past storms, what actions managers take to prepare, respond, or recover from storms, what facilitates those actions, and if they are adapting to future climate change. The survey questions were developed to assess experience with past storms, risk perceptions regarding future storms and climate change, the characteristics of the wastewater system (e.g., size, location) including the organization (e.g., leadership, culture, available science, etc.), and the broader context (e.g., public or political support, regulatory environment) drawing on relevant theoretical literature on factors thought to drive adaptation actions including risk perceptions and organizational learning (Berrang-Ford et al. 2011; Lesnikowski et al. 2011; Berkhout 2012). To improve measurement reliability and validity, the survey was pilot tested with nine individuals including wastewater managers not in the final survey sample, wastewater experts at the CTDEEP, and experts in questionnaire design in October 2015 (Schultz and Whitney 2005; Perneger et al. 2015).

The survey was revised using pilot testing feedback and the revised survey was administered via email to wastewater managers at 131 wastewater systems in Connecticut from November 2015 to April 2016 (Qualtrics, Provo, Utah, USA) with three email reminders to encourage a response (Dillman et al. 2014). The complete final survey is included as Supporting Information. In total, we received 86 completed surveys from the 131 surveys administered for a 65.6% response rate.

In addition to the survey, from October 2016 to March 2017, we interviewed 29 wastewater managers selected from among a stratified sample of survey respondents (i.e., stratified by inland vs. coastal location, impacted vs. not impacted by past storms, and made changes vs. did not make changes). The interview protocol was tested with four wastewater managers in July and August 2016 after which refinements were made to the protocol before initiating interviews with the final sample (Kirk and Miller 1986). Interviews were conducted by phone and each interview lasted between 35 and 55 min. Interviewees were asked questions about the nature and severity of past storm impacts, the types of adaptive changes made, if any, and motivations for those changes, what helped or hindered making changes, and about adaptation to future climate change. Question development for the latter three themes drew principally on factors thought to drive adaptation actions including risk perceptions, resources, and learning (Berrang-Ford et al. 2011; Lesnikowski et al. 2011; Berkhout 2012). See Supporting Information for survey and interview protocol.

Variable Construction and Analysis of Survey Data

One dependent and multiple independent variables were created from survey questions. The binary dependent variable *Changes* (where 0 = no change and 1 = made change) was constructed from responses to the question, "have you made changes to improve the resilience of your wastewater system." Independent variables were constructed to examine the influence of a range of factors on the dependent variable *Changes.* For example, several impact-related independent binary variables were created including: *Experienced impacts* (where 0 = not impacted and 1 = experienced impacts from past storms), *Lost power* (where 0 = did not lose power and 1 = lost power), *Experienced flooding* (where 0 = did not experience flooding and 1 = experienced flooding), *Bypassed* (where 0 = did not bypass and 1 = bypassed secondary treatment), *Lost access* (where 0 = did not lose access and 1 = lost access to one or more components of the wastewater system), and *Multipleimpacts* constructed as a sum of individual impacts experienced by the system. Other independent variables captured risk exposure *Coastal* (where 0 = not coastal, 1 = coastal) and risk perception (where 0 = not at all concerned, 1 = a little concerned, 2 = somewhat concerned, and 3 = greatly concerned) including for river and coastal flooding, storm surge, sea level rise, and climate change. A combined *Average concern* variable was also created from averaging the level of concern about future impacts across all five hazards. Other independent variables were created to capture organizational factors (*Available budget, Empowered, Organizational leadership, Aging infrastructure, Municipal partners, Up-to-date technology)*, sociopolitical factors (*Local/Regional Policies, State/Federal Policies, Local public support, Local political support*), and knowledge-related factors (*Incentives to learn*, *Climate science, Trusted information source*). These variables were created from Likert scale responses (where 0 = greatly hindered, 1 = somewhat hindered, 2 = neither helped nor hindered, 3 = somewhat helped, 4 = greatly helped) making changes. Finally, a system characteristic, *Average capacity* in MGD, was constructed to control for system size.

Survey data were analyzed using SPSS (SPSS Statistical software Version 22; SPSS, Armonk, New York, USA) using a 0.05 level of significance. Data analysis included descriptive statistics to summarize and explore the data, chi-square tests, independent samples *t*-test, and nonparametric Mann–Whitney tests to test for independence, differences in means, and differences in medians, respectively, between the dependent variable *Changes* and each independent variable (Noether 1991). Finally, to determine the most important predictors of change at wastewater systems, a logistic regression was performed (Agresti 2013).

Analysis of Interview Data

Interviews were recorded and transcribed (Galletta 2013) and then each coauthor independently reviewed and coded the transcripts using qualitative data analysis software NVIVO 11 (QSR International, Burlington, Massachusetts, USA) (Saldaña 2016). To answer the first two research questions, data were coded to identify (1) what changes wastewater managers implemented, (2) what motivated those changes, and (3) what helped or hindered making changes. To answer the third research question, data were coded for what wastewater managers think about (4) storms, (5) whether or not storms were changing, (6) climate change, and (7) climate change adaptation. Authors adjudicated differences in coding through multiple coding iterations to improve intercoder reliability (Brinkmann and Kvale 2015; Saldaña 2016). For these analyses, we compared systems that made changes to systems that did not make changes. Because anonymity was guaranteed, survey data are reported only in aggregated form and interviewees are referred to by code only.

ADAPTATION ACTIONS AT WASTEWATER SYSTEMS

According to our survey data, most (78%) wastewater managers made adaptive changes; interview data provide insight into the kinds of changes managers made. Nearly 30% (28.6%) of interviewees described several low-cost, temporary, adaptive changes to help prepare for and cope with storm events. These changes include fabricating and installing temporary flood gates and flood proofing doors in advance of storms, *... our local machine shop made up stop gates. ... we just drop them in and it holds back the water* (S24) and *... we went out and we took that foam that comes out in the can and we sealed the hatches as best we could* (S15). Another described purchasing and installing plugs for pump station vents to keep pump stations from flooding: *... we started seeing water entering from vent holes, so we did get plugs, and have them to this day, so we can plug those vent holes off* (S09). Others described topping off fuel tanks, *We'll fill up all the fuel tanks and make sure all the vehicles are fueled up* (S14) or stockpiling fuel in case of an extended power outage:

> A couple of our operators had some empty 55 gallon drums so when the fuel oil was able to be delivered, they filled two 55 gallon drums and left them at two of the stations in the building, which is good because we had to pump out of those barrels into the generator to keep them running. (O20)

Preparation and coping strategies concern not only temporary equipment or temporary modifications to equipment or structures but also temporary operational or staffing changes to help weather storm events. For example, a few interviewees described short-term changes they made to how they operate their WWTP that enables them to maintain permit limits despite receiving higher inflows to the plant during storm events (S32). Still others described how they prepare for storm events by keeping extra staff on call (S16) or on site, *... if there's going to [be] a hurricane ... or nor'easter. What we do is typically we'll leave guys here at the facility rather than risking not being able to get to work* (S14) in advance of a storm.

In addition to temporary changes, 62% of interviewees reported making permanent changes in how the system is run or permanent changes to physical components designed to improve resilience to extreme events. For example, some systems are conducting more or ongoing trainings (O20 and S16) to better prepare for and respond to storms when they occur. Others are saving more money to fund emergency repairs (DE18) as a strategy to improve resilience to extreme events. Still others made small-scale, permanent changes to reduce rates of infiltration such as sealing manholes that help them to cope with extreme events, [T]*here were some manholes that weren't sealed. ... we've addressed those, and that really helped us get through the major rains we've seen since then* (S06). Others described costlier changes including buying new pumps to have on hand for emergencies (DE18), buying new generators to provide backup power (S23), and buying new pumps that can withstand flooding, as described by this interviewee:

> [We changed to] the existing raw sewage pumps that we have right now because [they] are submersible pumps and if they do get submerged underwater, they're designed to operate the same. The ones we had prior to these were not submersible. (E17)

Other interviewees described elevating system components like generators, electrical systems, and control panels that experienced flooding in the past to make that equipment more flood resistant in the future:

> [W]ith the flooding ..., we did lose a few generators, and when we replaced them, ... one we put up on a cement pier using the high water mark from that [flood] event to at least if it happened again, our electrical service, and our generator wouldn't have that effect. (S09)

Finally, several interviewees described major changes undertaken at their facilities. These changes typically involved redesign and subsequent rebuilding of the entire WWTP costing the system many millions of dollars (S12, S13, S21, S22).

DRIVERS OF CHANGE AT WASTEWATER SYSTEMS

Statistical analysis of the survey data, summarized in Table 1, helped us understand what influences adaptive change at wastewater systems. Results show that managers who made changes had greater average concern about future climate-related risks (mean concern 2.48 vs. mean concern 1.36) and about climate change specifically (median 2, "somewhat or greatly concerned" vs. 0, "not at all concerned") than managers who did not make changes. Results also show that having local public support, strong organizational leadership, up-to-date technology, and aging

TABLE 1. Independent samples *t*-test, Mann–Whitney, and chi-square test results of wastewater managers that made changes.

Variables		Did not make changes (n = 19)	Made changes (n = 67)	Test statistic	*p*-Value
Average capacity (million gallons per day)	Mean (SD)	4.47 (5.31)	6.36 (7.65)	−1.005[1]	0.325
Average concern	Mean (SD)	1.36 (0.486)	2.48 (0.799)	−7.519[1]	<0.001
Concern for climate change	Median (SD)	0.0 (0.562)	2.0 (0.893)	193.00[2]	<0.001
Local public support	Median (SD)	2.0 (0.501)	3.0 (0.612)	67.000[2]	<0.001
Local political support	Median (SD)	2.0 (0.478)	4.0 (0.860)	87.000[2]	<0.001
Empowered	Median (SD)	2.0 (0.459)	3.0 (0.783)	81.000[2]	<0.001
Organizational leadership	Median (SD)	2.0 (0.577)	3.0 (0.704)	104.500[2]	<0.001
Up-to-date technology	Median (SD)	2.0 (0.452)	3.0 (0.687)	58.500[2]	<0.001
Aging infrastructure	Median (SD)	2.0 (0.772)	3.0 (0.839)	95.500[2]	<0.001
Experienced impacts	Median (SD)	2.0 (0.621)	4.0 (0.517)	69.500[2]	<0.01
Experienced flooding				16.877[3]	<0.001
Coastal				5.744[3]	0.017

[1]Independent samples *t*-test.
[2]Mann–Whitney test.
[3]Chi-square test.

infrastructure, and being empowered to make changes to the wastewater system were more helpful for managers who made changes compared to those that did not make changes (median = 3, "somewhat helped" vs. 2, "no effect"). Having local political support and experiencing impacts from past storms was more helpful for managers who made changes vs. those that did not make changes (median = 4, "greatly helped" vs. 2, "no effect"). Finally, survey results indicate experiencing flooding and being located along the coast were significantly associated with managers who made changes; treatment capacity was not significantly associated with making changes (i.e., larger systems were not significantly more likely to make changes compared to smaller systems).

While numerous factors were significant when tested individually, when controlling for other variables in a logistic regression, the most important predictors of change at wastewater systems were *experiencing impacts* from past storms, having strong *organizational leadership*, and expressing greater *average concern* about future climate-related risks (see Table 2). These three predictors explained 89% of the variance in the dependent variable made *changes* (for additional regression results, see Supporting Information).

Interview data help shed light on how impacts from past storms, leadership, and concern about future risks influence decisions to make changes to the wastewater system. First, among interviewees who made changes, most (78.6%) experienced disruptive, damaging impacts from past storms including significant flooding at the plant or at one or more collection system pump stations, high inflows at the plant that necessitated bypassing, and lengthy power outages. Often these systems experienced either multiple impacts from the same event (e.g., power loss and flooding, flooding of one or more pump stations and loss of access) or multiple impacts from separate events (e.g., experienced flooding and bypassing from one storm then experienced an extended power outage during a different storm). This connection between multiple impacts and change is echoed in the survey where managers who made changes experienced a median of three impacts compared to a median of one impact for those that did not make changes (Mann–Whitney $U = 297.5$, $p < 0.001$). Disruptive, damaging impacts from past storms helped to motivate change as indicated by these interviewees:

> It's been reactionary. We had a storm event at [that impacted] that station. After that first

TABLE 2. Final regression model with log odds, standard errors, and confidence intervals.

	Final model made changes				
	Coeff.	SE	*p*-Value	Exp(*B*)	95% CI for Exp(*B*)
Experienced impacts	2.194	0.925	0.018	8.973	(1.465, 54.973)
Average concern	4.667	2.272	0.040	106.394	(1.238, 9,141.495)
Organizational leadership	2.767	1.338	0.039	15.904	(1.156, 218.879)
Constant	−20.897				

flooding event, then we put in procedures to address that particular flooding. (O20)

We do our after action reports on each event, which is part of the closing up of the Emergency Operations Center. And we incorporate that into our training, or [into our] standard operating procedures ... anything that happens once to us ... we identify it and add it to our bag of tricks. (S23)

It [Hurricane Bob] did change a few things ... when the plant was upgraded in the 1990s they raised everything above 100 year flood plain ... and installed a new berm to keep plant from flooding. (S16)

Second, organizational leadership evident in two-thirds (66.7%) of systems that made changes enable wastewater managers to do what is needed to keep the system functioning well as conditions and demands on the system change. Organizational leadership manifests in these systems in two ways: wastewater managers are entrusted and empowered as leaders to make good decisions by those who oversaw the wastewater system (e.g., Water Pollution Control Authority [WPCA] or Town Council) and wastewater managers create a culture of continuous change within the wastewater management organization. Examples of wastewater managers entrusted and empowered to make good decisions include:

They're [the WPCA are] there in the background ... we do run everything by them, but they trust staff and the people they have working for them to make the best decisions for what's best for the facility. (S19)

We've got an eight member commission here ... we meet monthly. We go over what we're trying to accomplish and where we're going. But they really do leave that [the technical aspects] up to us. (S32)

In addition to being empowered to make decisions, mangers who made changes often create a culture of change that is geared toward continuous improvement. In this way, managers create an operating space open to new ideas and to experimentation (Wilby and Vaughan 2011) as illustrated by these interviewees:

I always tell people here if they want to try something, go ahead ... If it works, great. If not, we ditch it. I think it's helpful to the employees where we can show some trust or faith in giving them some opportunity to make an imprint in the facility. Make a change. (O20)

I've got my staff heavily involved ... because you get everyone's opinions and ideas and as a group collectively you come up with a lot more ideas or problems that you didn't know existed out there that you can try to correct. (S19)

Being empowered to make decisions and having a culture of continuous improvement means these wastewater managers tend to be proactive in making changes to keep the system functioning well as conditions and demands on the system change.

Finally, interview data were more mixed in terms of concern about future climate-related risks as a driver of change. On the one hand, future climate-related risks (e.g., climate change) was a concern for some (28.6%) interviewees — *we've got concerns about global warming* (O20) and *Climate change* [concerns me] *a little bit because if you get more severe storms, electrical interruptions* [may be more frequent]. *That's a bigger deal* (S16). This concern did drive some interviewees to make changes. For example, one interviewee said, ... *that* [storms getting more severe] *is one of the reasons we're doing the upgrade* [at the] *main pump station and the plant here. So we're hoping that'll help us* (S32). On the other hand, some interviewees explicitly said that future climate-related risk was not a motivator for making changes. For example, one interviewee said, *I mean global warming, all this stuff, good, it's all important in the big scheme of things but* [it is] *not relative to my plant* (W05) while another said, *I don't see it at this point in time ... if there were a pump station that were continuously flooded, yeah, I think you'd have to do something .... But it really has nothing to do with climate change* (DE18).

While concern about future climate-related risks was not a huge driver of change, interview data showed that more than half (57.1%) of the interviewees who made changes think there has been a change in the intensity of storms, whereas the majority (71.4%) of interviewees who did not make changes think storms are about the same as they have always been. To illustrate this point, interviewees who made changes and think storms are different now said the following:

It appears that the 50-year storms now seem to be the 25-year storms. And 100-year storms seem to be the 50-year storms type of thing. So we seem to be seeing more severity. (S06)

It just seems that storms that we're getting seem to be more intense. Maybe not as many of them but they seem to be more intense. (S12)

I think they [storms] are getting more severe and more regular. (W05)

I would have to say that the weather might be a little bit more extreme for this last thunderstorms ... in the past 10 years, we've had 500 year events, with regularity. (S23)

... they talk about the 100 year storm. Well, we're having 100 years storms every couple of years. (DE18)

Unlike interviewees who made changes, interviewees who did not make changes often expressed the belief that storms are about the same as they have always been as indicated by these interviewees: *I think they're probably about the same as they've always been* (E17) and *I think they are about the same in our area* (S27).

ARE WASTEWATER MANAGERS ADAPTING TO CLIMATE CHANGE?

Interview data reveal half (50%) of wastewater managers who made changes did so to improve resiliency to withstand the worst storm impacts experienced by the wastewater system to date. One interviewee put their resiliency efforts this way: *Our focus has been ... hardening facilities* to increase ... *survivability due to extreme weather events. I think we basically call it, the new buzz term is, resiliency* (S23). To improve resiliency and increase survivability often means thinking back to prior experiences and making the system more resilient to those events. For example, one interviewee described that they put a generator that had been flooded out in a prior storm *up on a cement pier using the high water mark from that event* (S09). Similarly, another interviewee said that when they replaced a generator that was flooded during Hurricane Sandy they ... *put the new one ... on three foot metal staging so it brought it up above that* [Hurricane Sandy flood] *line. They also raised control panels ... above the storm Sandy level* (S15). Other systems are sealing manholes or replacing sewer lines to reduce I&I (S06), adding generators (S21, S23), and stockpiling additional funds to pay for emergency repairs (DE18). Rather than proactive adaptive actions, these actions are reactive, incremental, and are aimed at sustaining capacity to provide reliable wastewater treatment and to meet permitting requirements (Berkhout 2012). While these changes likely will increase survivability to storms similar to those they have experienced in the past, the changes may not be sufficient to withstand future climate change.

When asked about making changes specifically to adapt to climate change, many wastewater managers responded in either of two ways. Some wastewater managers responded by saying that they are not doing anything specifically to adapt to climate change because they did not "see" climate change impacts as relevant to their system. For example, one interviewee said, *I associate climate change with increasing of the water* [sea level rise]*, and I'd say that it sounds more coastal to me* (S09) while another said, *I mean global warming. All this stuff. It's all important in the big scheme of things but* [it is] *not relative to my plant* (W05), and a third interviewee said, *right now I guess I don't look at it that long-term. I don't really see it* [climate change] *affecting it much unless it's at my door* (S15). For other wastewater managers, climate change could be relevant but they want to see some measurable climate change impact before they consider doing something in response to climate change. For example, one interviewee said, *there's no long term trend data that allows you to say,* [the increase in] *river levels* [is] *because of increasing ocean levels ...* (S21), while another said, *if there were a pump station that were continuously flooded, yeah, I think you'd have to do something* (DE18). While these wastewater managers are aware of climate change, they see it as a distant threat in time or space (Brügger et al. 2015). For these wastewater managers, there is no directly attributable climate signal relevant to their wastewater system that requires a specific adaptation — a necessary precursor to climate change adaptation for organizations (Berkhout 2012; Biesbroek et al. 2013).

About a third of interviewees who made changes are adapting to a changing climate; most (80%) are doing so because new state regulations require adaptation actions. These new regulations require that wastewater systems that receive CWF funds make wastewater infrastructure resilient to ... the effects from severe weather events and expected climate change impacts including, but not limited to, increases in the frequency and severity of precipitation events, flooding, storm surge, wave action, and sea level rise (CTDEEP 2017, p. 1). Specifically, all state-funded wastewater projects must adhere to minimum flood protection levels in *TR-16 Guides for the Design of Wastewater Treatment Works* (TR-16) (NEWIPCC 2016; CTDEEP 2017). TR-16 requires that critical wastewater equipment and structures are flood protected to the 100-year storm plus three feet or to the 500-year flood elevation (NEWIPCC 2016). Interviewees with state-funded projects mention the design guide (TR-16) or state regulations as the driving force for decisions to elevate infrastructure to required levels:

> Our upgrade that is in the planning stages and includes one hundred plus three is driven by state requirements. (S16)
>
> the state ... [is] requiring [us] to put in resilience flood measures. The plant itself has a berm around it. So currently it's protected for the 100-year [storm] ... Chemicals have to be five feet above the 100-year [storm]. Critical facilities like the headworks, primaries so that you can maintain primary treatment and not have the flood waters overwhelm the facility .... So that's kind of the driving force behind it. (S12)
>
> The facility is currently under design for a $15 million [upgrade] ... and I know that there's new

regulations for the [flood levels]. I think it's 100-year plus three. (S10)

Without state rules requiring projects that receive CWF funds be designed to withstand expected climate change impacts including sea level rise, it is unlikely these wastewater systems would be adapting to climate change. This relationship between regulation and adaptation action is consistent with the adaptation literature (Wilby et al. 2009; Wilby and Vaughan 2011). When rules require incorporation of climate change, utilities comply.

DISCUSSION AND CONCLUSION

We used a mixed method approach combining a quantitative survey and qualitative interviews with wastewater managers to understand what wastewater managers are doing to adapt, what facilitates those adaptive actions, and if they are adapting to future climate change. Our findings suggest that two-thirds of wastewater systems are adapting by implementing temporary and permanent structural changes within the collection system and treatment plants as well as changing practices and procedures to better prepare for, cope with, and recover from storms. Similar to other research that finds that the severity of prior negative experience with flooding matters as a driver of flood response (Berkhout 2012; Bubeck et al. 2012), the vast majority (~80%) of systems that made changes experienced disruptive, damaging impacts from storms. Besides past storm impacts, organizational leadership and a culture of learning helped wastewater managers implement changes consistent with characteristics of adapting organizations (Wilby and Vaughan 2011; Berkhout 2012). Finally, while nearly a third of wastewater managers expressed concern about future climate-related risks, fewer (20%) said future climate change specifically motivated the changes they made. Wastewater managers that made changes mostly did so to improve system resiliency to past extreme events.

Wastewater managers are concerned about building resiliency, but these actions are mostly reactive. Nearly two-thirds of wastewater managers who made changes are looking to past impacts to guide changes rather than thinking about what climate change may have in store for the future (Milly et al. 2008; Hallegatte 2009). So, while "building resilience" has taken hold in the wastewater sector as the new "buzzword" and a strong motivator for making changes, adapting to past storms may not protect wastewater systems from future climate risks. This suggests that language matters. "Building resilience" may be insufficient if what is really needed is "adaptation to climate change" or "climate resilience" (Hill and Kakenmaster 2018, p. 61).

Our results suggest that wastewater managers are aware of climate change but that managers generally see climate change as a distant threat in time or space (Brügger et al. 2015). For these wastewater managers, there is no directly attributable climate signal relevant to their wastewater system that requires a specific adaptation. Not perceiving a climate signal constrains climate change adaptations as perceiving a signal is thought to be a necessary precursor to climate change adaptation for organizations (Berkhout 2012; Biesbroek et al. 2013). While wastewater managers do not yet see a climate signal, this finding differs from Arnell and Delaney's (2006) study of UK water companies and Rudberg et al.'s (2012) study of Swedish wastewater organizations. In both of those studies, water managers in the UK and wastewater managers in Sweden recognized a climate change signal affecting the water supply and demand balance or the wastewater system.

Wastewater managers that are adapting to climate change are primarily driven by regulatory requirements tied to financing of wastewater system improvements. The positive influence of regulatory or policy drivers motivating adaptation to climate change has been stated elsewhere (Rudberg et al. 2012; Jordaan 2018); nevertheless, given policy and regulatory changes have influenced and made possible (with funding) adaptation in the wastewater sector, this is an important avenue to pursue to increase adaptation. With this recommendation, an important challenge is expanding the cadre of systems that pursue CWF funding (which triggers adherence to the new guidelines). Few systems benefit from these funds given the heavy administrative load and the requirement that municipalities must cover a portion of the costs. Alleviating these constraints may open up CWF funding to more systems and broaden support for climate adaptation. Beyond funding, wastewater systems may benefit from more exposure to information and training about potential climate changes and their impacts on wastewater systems. Such training may help overcome knowledge gaps about climate change that could be inhibiting adaptation (Rudberg et al. 2012) and help expose wastewater managers to resources and regulations for adaptation.

While this study has advanced what we know about wastewater systems and adaptation actions, more work is needed to more fully understand what drives or impedes climate change adaptation in the wastewater sector and to explore in more depth wastewater managers' understanding of and perceptions about resilience and climate change. In addition, more work is needed to investigate wastewater systems in other states and countries to understand how comparable these results are to other regions. Finally, more work is needed to explicitly compare resiliency and adaptation actions between infrastructure sectors to broaden our ability to derive theoretical and practical insights about what drives climate adaptation among water, wastewater, and other infrastructure systems.

SUPPORTING INFORMATION

Additional supporting information may be found online under the Supporting Information tab for this article: Survey instrument, interview protocol, and additional regression results.

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Marshaling Adaptive Capacities within an Adaptive Management Framework to Enhance the Resiliency of Wastewater Systems

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Research Impact Statement: Wastewater systems with many diverse adaptive capacities and managers that deploy those capacities within an adaptive management framework are more resilient to storms.

ABSTRACT: We assess adaptive capacity and adaptive management as measures of wastewater (WW) system resiliency using data from interviews with WW system managers (hereafter managers) impacted by past storms. Results suggest the most resilient WW systems are those with high adaptive capacities that employ an adaptive management approach to make ongoing adaptation investments over time. Greater amounts of generic adaptive capacities (i.e., skilled staff and good leadership) help smooth both day-to-day and emergency operations and provide a foundation for adaptive management. In turn, adaptive management helps managers both build more generic adaptive capacities, and develop and employ greater amounts and diversity of specific adaptive capacities (i.e., soft and/or hard adaptations) that are especially important for enhancing and sustaining resiliency. Adaptive management also enables managers to better understand their system's vulnerabilities, how those vulnerabilities change over time, and what specific actions may reduce those vulnerabilities. Finally, our work suggests WW system resilience critically depends on the capacities of the human systems for building resilience as much as or more so than relying only on physical infrastructure resilience. Our work contributes to filling an important gap in the literature by advancing our understanding of the human dimensions of infrastructure resilience and has practical implications for advancing resilience in the WW sector.

(KEYWORDS: climate variability/change; planning; flooding; precipitation; wastewater management; organizational learning; resilience; adaptive capacity.)

INTRODUCTION

While wastewater (WW) systems provide invaluable societal services and are critical to public and environmental health, economic vitality, and national security (Guikema et al. 2015), they are sensitive to extreme winds, precipitation, and flooding. Past storms including Alfred, Sandy, and Irene exposed these sensitivities inflicting billions of dollars in damage to WW infrastructure in the Northeastern United States (U.S.) (Baylis et al. 2016). Changes in the economy, aging infrastructure, and an uncertain regulatory environment exacerbate these vulnerabilities as does accelerated sea level rise and more frequent extreme precipitation expected with climate change (Horton et al. 2014; Wuebbles et al. 2017). Given these vulnerabilities, there is an urgent need for adaptation strategies that improve the resilience of WW systems. For the purposes of this paper, we define resilience as the capacity of a WW system to prepare for, cope with, recover from, and change to reduce vulnerability to stress, especially the impacts from extreme events and future climate change (IPCC 2007; Francis and Bekera 2014).

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Over the past several decades, scholars have increasingly focused on infrastructure resiliency including water (Falco and Webb 2015; Mugume et al. 2015; Shin et al. 2018), transportation (Eisenack et al. 2012; Bhamidipati 2015; Therrien et al. 2015; Mostafavi and Inman 2016; Donovan and Work 2017), and power (Reed et al. 2009; Ouyang et al. 2012; Lin and Bie 2016; Panteli and Mancarella 2017). Most studies of infrastructure adaptation efforts to build resilience focus on hard adaptation actions (e.g., digging impoundments, raising equipment). Recently, scholarship has embraced softer adaptations such as governance for adaptation to climate change and resiliency (Camacho 2009; Engle and Lemos 2010; May and Plummer 2011; Rijke et al. 2013; Boyd and Juhola 2015). Despite this focus on infrastructure resiliency broadly, WW system resiliency is largely unexamined in the literature. Moreover, related human adaptations (e.g., making changes to address behavioral, social, economic, and governance factors) that also influence WW system performance and resiliency are rarely considered (Juan-García et al. 2017). Of the studies that do exist, most are modeling-based or are literature reviews that provide frameworks or guidance on what WW systems should do to increase resilience (Schoen et al. 2015; Butler et al. 2016). To our knowledge, only one published empirical case study discusses what systems are actually doing in practice to increase resilience (Rudberg et al. 2012). We aim to fill this important gap in the literature by advancing understanding of what WW systems are doing to build resilience, especially how human systems help build (or not) resiliency.

We use the concepts of adaptive capacity and adaptive management as a means to assess WW system resiliency and how human dimensions influence the resiliency of WW systems. This builds on prior scholarship of measures of adaptive capacity, including both generic and specific adaptive capacities, and adaptive management (Folke et al. 2002; Yohe and Tol 2002; Brooks et al. 2005; Berkhout et al. 2006; Sharma and Patwardhan 2008; Hess et al. 2012; Rudberg et al. 2012; Eakin et al. 2014). Using data from 31 structured interviews with WW system managers (hereafter managers), we explore the following research questions: (1) How have WW systems been impacted by past storms and how do these impacts affect resilience? (2) What kinds of generic adaptive capacities improve resilience? (3) What kinds of specific adaptive capacities are managers implementing and how do these capacities influence resilience? And, (4) How do adaptive capacity and adaptive management interrelate to foster resilience?

In the following sections, we review the literature, describe the methodology, and present our results. Then, we explore how adaptive capacities and adaptive management influence WW system resiliency and the relationship between adaptive capacity, adaptive management, and resiliency more broadly. We briefly discuss what hinders or limits resiliency and conclude with future research suggestions.

LITERATURE REVIEW

Adaptive Capacity and WW System Resiliency

Our review of the literature suggests that only a small subset of resilience research directly addresses WW system resilience, and most are modeling-based or are literature reviews that provide frameworks or guidance on what WW systems should do to increase resilience (Schoen et al. 2015; Butler et al. 2016; Juan-García et al. 2017). Applying findings from the broader resiliency literature suggests that resilient infrastructure systems have high adaptive capacity and can reorganize, learn, and successfully adapt to stress or changing circumstances and maintain their desired state after significant disruption (Folke et al. 2005; Nelson et al. 2007; Pahl-Wostl 2007, 2009). Having high adaptive capacity increases resiliency by enhancing a system's ability to anticipate disturbances and reduce impacts, to take advantage of opportunities or cope with consequences, to recover more quickly, and to make adaptive changes (definition adapted from IPCC 2007). Building on prior scholarship, we use the concepts of generic and specific adaptive capacities (Folke et al. 2002; Yohe and Tol 2002; Brooks et al. 2005; Berkhout et al. 2006; Sharma and Patwardhan 2008; Hess et al. 2012; Rudberg et al. 2012; Eakin et al. 2014), and adaptive management as a means to assess the resilience of WW systems and how human dimensions influence WW system resilience.

Generic and Specific Adaptive Capacities. Eakin et al. (2014) explained there are two types of adaptive capacities: (1) those associated with basic human development needs (generic) and (2) those associated with managing, reducing, and responding to climatic threats (specific). Generic capacities including education, funding, knowledge, learning, information, skills, stability, and leadership (Berkhout et al. 2006; Pahl-Wostl 2009; Emerson and Gerlak 2014; Juan-García et al. 2017) provide the basic human capacity to respond to stress, and by extension the fundamental capacity of WW systems to respond to stress. Specific adaptive capacities are, "adaptation interventions and capacities," (Sharma and Patwardhan 2008, 820) such as climatic information use, adaptation funding, emergency planning, technology, human capital, and infrastructure (Eakin and Lemos 2006; Hess et al. 2012; Rudberg et al. 2012; Eakin et al. 2014) that are specifically geared to or that can be marshaled to reduce or cope with impacts from a particular hazard. Generic and specific adaptive capacities are interdependent. Being able to make adaptive decisions and enhance specific capacities effectively depends on the availability of generic capacities and vice versa (Haddad 2005; Eakin and Lemos 2006; Sharma and Patwardhan 2008). For instance, good leadership may compensate for low generic capacities such as insufficient funding, because good leaders establish helpful connections or they find creative funding solutions to manage problems when they arise (Moser and Ekstrom 2010). Generic and specific adaptive capacities also tradeoff (Eakin and Lemos 2006), especially in infrastructure systems. For example, because large and robust physical adaptations are costly and, as such, may not be socially or economically acceptable, less expensive investments in resiliency such as strengthening generic capacities may be more attractive than investing in new, expensive specific capacities (Dessai and Hulme 2007).

Few studies have examined adaptive capacity in WW systems. One study by Rudberg et al. (2012) found that increased knowledge on climate change and its impacts (generic capacity) helps WW systems justify spending money on adaptive actions (specific capacity) needed to improve resilience. Managers who were both aware of climate change and who understood the specific impacts climate change will likely have on their WW systems were better able to justify changing routines or investing in building specific capacities to adapt (Rudberg et al. 2012). Awareness and knowledge of climate change as well as funding (generic capacities) were the primary factors affecting managers' ability to build specific adaptive capacity and increase resiliency (Rudberg et al. 2012).

Adaptive Management. Classic adaptive management focuses on experimental learning by formally testing out different management techniques and carefully monitoring how they affect the resilience of ecological systems using controlled experiments (Holling 1978; Walters 1986; Allen et al. 2011; Westgate et al. 2013; Chaffin et al. 2016). In recent years, the term adaptive management has extended beyond ecological experiments to incorporate broader, more flexible learning-based approaches that improve the management and resilience of other types of systems including public health (Hess et al. 2012) and water resources management more broadly (Pahl-Wostl 2007; Kirchhoff and Dilling 2016). While adaptive management concepts have been applied more broadly in recent years, to our knowledge, adaptive management has not yet been applied to managing infrastructure systems to improve resilience.

Scholars suggest that rather than traditional, top-down management, managing infrastructure systems under changing conditions also requires a more adaptive approach (Pahl-Wostl 2007; Kirchhoff and Dilling 2016) that balances the short-term and long-term aspects of resilience. In this way, managing systems for resilience requires moving away from reactive, inflexible approaches that have led to complacency and inadequate attention to risk reduction and prevention (Baylis et al. 2016), to adaptive management approaches that foster ongoing learning, proactivity, and transformation especially in response to climate change (Hess et al. 2012).

METHODS

Data Collection

We use data from focused qualitative interviews with managers to understand impacts and responses from past storms and their implications for adapting to future climate change. The interviews addressed a range of topics and included questions about WW system characteristics (i.e., funding, size of system, location); the nature and severity of past storm impacts, what helped or hindered their emergency preparedness, response, and recovery; risk perceptions regarding climate change (i.e., future severe weather, sea level rise); the types of adaptive decisions and actions made (if any); what helped or hindered implementing adaptive decisions (e.g., availability of science, political support, leadership, adequate funding see, Moser and Ekstrom 2010); and what factors have the strongest impact on resiliency. The 31 interviewees were recruited from a random stratified (i.e., stratified by inland vs. coastal location, impacted vs. not impacted, and made changes vs. did not make changes) sample of 86 survey respondents (for more information on the survey, see Kirchhoff and Watson 2018). All interviewees are WW professionals comparable in age and education. The interview protocol was pilot tested with four managers not included in the final sample in July and August 2016, after which refinements were made to the protocol before initiating interviews for the study. Interviews were recorded and transcribed. See Supporting Information for the interview protocol.

Data Analysis

We sorted interview data into selective categories and themes (i.e., both predetermined and emergent) using a combination of both inductive (i.e., grounded theory) and deductive qualitative methodologies

(Creswell 2007). QSR International's NVivo 11 qualitative data analysis Software (QSR International Pty Ltd. Version 11, NVivo Pro edition, 2015; QSR International [Americas] Inc. United States, Canada and Latin America, Burlington, MA) was used to code interview transcripts for capacities (i.e., generic, specific, and adaptive management). The following adaptive capacities were coded: (1) skilled staff (i.e., flexible, dependable, knowledgeable, well trained, and resourceful); (2) good asset management (i.e., proactive and ongoing maintenance, repair, and replacement; monitoring and assessment; prevention of mechanical failures; and continual improvements); (3) good leadership (i.e., facilitates ongoing learning and change, proactivity, trust building, and useful connections); (4) sufficient funding (i.e., for both day-to-day and emergency operations); (5) soft adaptations: effective emergency preparedness, response, and recovery; (6) hard adaptations: temporary or permanent adaptations to increase resiliency; and (7) implementing adaptive management (i.e., continuous organizational learning, experimental adaptation, and transformation) to reduce vulnerability and increase resilience. In this study, we refer to 1–4 as generic adaptive capacities and 5–6 as specific adaptive capacities. Temporary storm resiliency interventions coded in Category 6 include hard adaptation actions implemented right before a storm hits aimed at increasing the WW system's ability to cope with and reduce impacts from that particular storm. These are typically removed after the event passes. Permanent resiliency interventions coded in Category 6 are permanent hard adaptations intended to reduce potential impacts and help the WW system cope with consequences and/or recover more quickly from future storm events. To explore how generic, specific, and adaptive management capacities relate to WW system resiliency, we controlled for the degree of historical impacts and tracked the amount and diversity of adaptations. We also considered WW system characteristics (i.e., funding availability, type and size of system, location) as potential drivers of WW system resilience.

PAST STORM IMPACTS AT WW SYSTEMS

Most (65%) managers said their systems were significantly impacted in some way by past storms such as Alfred, Irene, and Sandy; past impacts that managers attributed to the effects of severe weather are included in Table 1.

We found an association between location and the likelihood of storm impacts, particularly flooding. Most interviewees (81%) manage WW facilities located in a flood zone next to a river, tidal basin, or coastal area; most (76%) of those systems were impacted by storm surge, tidal, coastal, or river flooding in the past.

TABLE 1. Past storm impacts reported by WW systems.

Effects of severe weather	WW system impacts	# Systems
High winds, downed trees	Power loss	7/31
River, coastal, or tidal flooding, storm surge, sustained precipitation, high winds, hurricane	Power loss, water in and around facility, lost access to critical facilities, roads, or pump stations, bypassing,[1] broken equipment or controls, electrical system damage	19/31
Power loss	Bypassing, lost bacteria for treatment	5/31
Ice building up because of inflow and infiltration	Sewage backups, less flow	1/31
Trouble getting fuel or running out of fuel needed to power generators	Power loss	3/31

Note: Systems impacted by multiple effects of severe weather are included in the counts for each individual effect (i.e., double counted).
[1]WW systems with low flow capacities were forced to bypass large amounts of non-treated or partially treated sewage directly into nearby waterways.

GENERIC ADAPTIVE CAPACITIES

Skilled Staff

WW systems with skilled staff — these are staff who are experienced, knowledgeable, and involved and that can wear many hats — more effectively manage both day-to-day and emergency operations and have greater capacity to cope during and recover from emergencies. For example, one interviewee said, "... some of us have been here 15, 18 years, you know, I've got operators here with 25 years, so pretty much anything that goes on, whether it's flooding or a power pump or loss of power, you know, or toxic sludge coming in, somebody here has seen it and knows how to react" (W15). Having experienced staff is especially beneficial in reducing storm impacts. For example, regarding a 2012 storm, one interviewee said they experienced, "... torrential downpour for a couple of hours straight," (W13) that increased flow into their system from 10.3 million gallons per day to 25 million gallons per day. Without experienced staff, storm impacts would have been worse, "Yeah, if our staff had not known what to do. Our assistant plant manager is very hands on, really close to the training staff, and if he wasn't so hands on, if he wasn't so knowledgeable and then shared his knowledge with our staff, then it probably could have been terrible" (W13). Overall, having staff that can maintain and operate the system brings them closer to the equipment, and helps them understand what equipment is vulnerable. A manager said, "I like the idea of being involved and for our staff to be hands-on in these upgrades or these small incremental changes because it gives us real knowledge, some real knowledge of how did this go together" (W16). He also said, "If it fails, we're the ones who installed this so we're going to already have a leg up on how to fix it" (W16).

Good Asset Management

Resilient WW systems have managers who make continuous, incremental improvements to pump stations, plants, facilities, technology, generators, and pipes; both to make changes affordable, and to ensure equipment are dependable and work properly for day-to-day and emergency operations. One manager said, "... preventative maintenance can be an amazing thing" (S12). Proactive maintenance reduces vulnerability and increases a system's ability to cope during storms. For instance, one manager said they are better prepared to cope with disturbances because they proactively identify and fix their system's weaknesses — "[their town] ... is at least progressive in terms of looking out the future ... where other towns wait till something breaks before they even decide to fix it. We are being proactive and progressive looking. So that's a factor in our favor" (W31).

In addition to being proactive, managers are, "... chipping away at some of the infrastructure improvements on an ongoing basis" (W14). For example, "... instead of doing you know, a big upgrade every 20 years or so, you're doing small upgrades along the way" (W02). An interviewee said, we, "... continuously invest in our infrastructure here so it's an ongoing improvement process" (W10). Another manager said, "It's not good to you if it's not functionally operational" (W14). Ongoing maintenance, repair, and replacement of equipment is viewed as a necessity both to ensure good working order and affordability (see Sufficient Funding).

Additionally, because WW infrastructure is old, incremental maintenance is needed to reduce inflow and infiltration (I&I) in the collection systems. I&I and its impact on resiliency was a concern for most (74%) managers interviewed. I&I is problematic because when too much extra water enters the system, it overwhelms the plant and contributes to bypassing untreated or partially treated sewage, thereby lowering resilience. For example, one interviewee said, we bypass when, "... we get over an inch and a half of rain in less than 24 hours" (W19). Another said, "We're always concerned with I&I because a fact of the matter is that some of these old pipes ... we do know that for a fact, that they're leaking" (W14). Unfortunately, I&I is an ongoing maintenance issue for most WW systems — "You can't resist those roots. When you finish you have start all over again" (W07). To try and reduce I&I, a few managers are doing flow modeling and monitoring to try and identify problem areas (W19). A manager of a more resilient WW system said, "... to assist us in monitoring our collection system and pump stations we've developed a computer maintenance management system ... now we can readily identify areas in our system that need manhole inspections or line cleaning activities ... we finally have the resources at our fingertips that allow us to really keep a pulse on how efficient our collection system and pump stations are operating" (W31).

Good Leadership

Leaders who encourage staff to wear many hats, trust them to make decisions, and involve them widely in the design and installation of equipment help facilitate innovation and effective emergency management contributing to resilience. Having staff that wear many hats is important because, "... if somebody's out sick, there's enough cross-training that takes place so that anybody can step into any role and that facility will continue to run" (W06). Good leaders involve staff widely which helps build trust as indicated by the following interviewee, "They trust staff and the people they have working for them to make the best decisions for what's best for the facility or the city" (W15). For example, one manager said, "I think it's helpful to the employees where we can show some trust or faith in giving them some opportunity to make an imprint in the facility. Make a change" (W16). Building trust among the leadership and staff helps foster commitment, in turn committed staff care about the system's ability to withstand a storm and are willing to work long hours. A manager said, "probably half of the staff worked most of the hours through whatever, five, six, seven, eight, nine days" (W16). In addition, managers at more resilient systems are trusted by their funders (e.g., Water Pollution Control Authority) and are able to obtain needed resources — "If we need something, they know we're not lying about it" (W13).

Sufficient Funding

Having sufficient funds (i.e., budget for day-to-day, emergency reserve, and resiliency funding) increases managers' capacity to prepare for, recover from emergencies and make changes to increase WW system resilience. One interviewee said their, "... facility's plan spelled out 20 years of growth, capital projects, funding, sewer use fees, all that," which provides, "cash available if [they] need it in a pinch" (W12). Another manager said, "We have a reserve fund for treatment plant repairs or work that needs to be done ... [and] for the collection system repairs or work for capital improvement ... [while] ... emergency response would come out of [their] operation budget" (W08). Overall, managers that have funding for both day-to-day work and for emergencies are more resilient.

Generally, funding comes from the municipality — "... it's totally funded by the users of the sewer system," through sewer fees or from outside funding via state or federal grants and low interest loans (W24). For example, managers have used Environmental Protection Agency, "clean water funding," (W04) and, "USDA [U.S. Department of Agriculture] money" (W22, W24). Another system said they received a, "... 50% grant from the State of Connecticut," and paid, "... 50% from the facility" (W06). Some managers have taken advantage of these grant programs to make upgrades that increase the resiliency of their systems. Because they often lack, "... funds to maintain everything" (W20), making small incremental changes over a very long, extended period of time is the only way managers can afford to upgrade their WW systems. For example, a manager said, "... I guess they are small increments, but they're small increments over a very long, extended time. And that's the only way these small towns can afford these things" (W16).

While having sufficient funds helps increase resilience, lack of funding impedes many manager's ability to make changes to increase resilience. For example, a manager said, "I'd love to do all kinds of stuff but money's always the issue and how much can the ratepayer bear" (W25). Another interviewee said, "There are just aging infrastructures and old equipment everywhere, but no one's really stepping forward with the money to do it, so it stays how it is" (W13). Managers that struggle with their budget expressed that lack of public support for increasing sewer fees is a barrier to making changes to increase resiliency. For example, a manager said, "Nobody wants to spend millions of dollars on a sewer line that they never see" (W21).

SPECIFIC ADAPTIVE CAPACITIES

Soft Adaptations: Effective Emergency Preparedness, Response, and Recovery

Managers that have greater capacity to prepare their staff and equipment for issues that may arise during storms have more resilient WW systems. For example, "... once we find out these things are coming, we'll have conference calls with all our facilities with my area manager, and we'll go through planning, and what we're gonna have at the facility here, and who we're gonna have on staff, and make sure if it's a hurricane-type event or it's gonna be heavy rain, and winds, and stuff that everything's battened down" (W25). For other managers, keeping extra equipment on hand helps them weather the storm — "We have a few extra pumps, brand new, sitting on standby in case one burns, we can just plug in the next" (W09). Still others prepare equipment by fueling up and completing maintenance. For example, to prepare for a power outage, one manager said, "When we saw the storm coming we make sure the generators are operable. That fuel is filled up on them. Any maintenance that has been pending gets completed" (W02). Echoing this, another interviewee said, "... we make sure the generators, of course, are all full with fuel, especially in the winter time" (W11).

Managers with more staff available to work before, during, and after an emergency event are better able to prepare, cope, and recover from a storm or emergency event. For example, an interviewee said, "... staff definitely plays a big role in getting us going and making sure that everything is working properly ... we usually add one or two more personnel to the shifts so that they are available should we need them here" (W04). Another said, staff were available, "... to work extended hours by setting our own schedule up so that we could continuously monitor and take care of things as they occurred" (W05). When staff work through storms, they need to be prepared to potentially stay there for an extended period of time. For example, a manager said, we, "... have stuff available at the facility in case someone gets stuck here and they're working here by themselves or with a couple of guys by themselves, so we make sure we have food, and clothing, and stuff like that" (W25).

Effective emergency preparedness is also about establishing and maintaining lines of communication and relationships with the town, state, or other third parties (i.e., fuel providers, emergency contractors, and power companies) ahead of time to mitigate impacts and speed recovery. For example, one interviewee described how new communication pathways were established after a particularly harrowing event. In this case, miscommunication led to panic. To rectify this, he said his town hired a new emergency response leader. With the new Chief of Police, he said now, "We have a better chain of command for our emergency response ... we're going to get our information from that emergency control room at the police station from one man. We're not going to just be listening on the video or getting all this bad information that can cause us to panic" (W16). Lines of communication with the state help as well. One manager said that the state's online portal, "... where you could report what was happening each morning or afternoon or evening, or what you needed, or what you're experiencing through the storm," was helpful for coping with storm events (W02).

In addition to lines of communication with the town and state, resilient systems have established lines of communication and relationships with outside parties. An interviewee said, "As with any storm or single event ... establishing communication is the first goal, making sure the service provider is aware of the circumstances ... [and] fuel service providers also have to be contacted" (W03). Another said, "Reliance on third-party assistance is always part of the equation in meeting any weather-related event" (W03). Systems become more reliant on third-party assistance if the impacts from an event are long-lasting, meaning, "... any time the timeline of a storm impact reaches three, five, seven days or more the restoration is clearly determined by the third-party utility" (W03). More resilient systems have access to third-party assistance which helps them recover more quickly if they are impacted. For example, one interviewee said, "We do have emergency contractors so if there's a break or some kind of repair that needs to be made they're on board too" (W14). Another said they cannot always rely on emergency contractors because they are competing with other managers for assistance from the same resources — "Sometimes we do plan for that if something's coming and try to make arrangements, but everybody's vying for the same equipment when those type of events are on the way, so sometimes you need to make sure that you've planned ahead and you have that stuff in advance" (W25). Managers increase their WW systems resiliency by planning ahead and having additional options in mind in case they do not have access to assistance from third parties. Some managers seek assistance from other WW managers — for example, one manager said he has already agreed to help others by lending his equipment. Other managers ask, "... if we have an issue can we borrow your flusher truck so we can operate it? ... and we go okay fine, no problem" (W12).

Established lines of communication with power utilities are especially important to speed power restoration after an outage event. To improve power restoration rates, power companies may put WW systems on emergency power prioritization lists. For example, one manager said, "... they actually came to us and looked for priority sites throughout the community," (W14) and now, "... the stations are part of an overall list of facilities that are on a high priority with the utility provider" (W03). Another said, "We are priority facilities so we notify them and generally if we do lose power they get us fairly quickly" (W08). Finally, another said, "... we're considered a priority for them, so they're gonna make sure that we're back on primary commercial power as quickly as possible" (W20).

Hard Adaptations: Temporary or Permanent Adaptations to Increase Resiliency

Managers are making large or small, temporary or permanent infrastructure changes to increase WW system reliability and robustness. Regarding infrastructure changes, one manager said, "... we may have to try to do something intermittently and then something long term" (W14). Small or temporary changes can make a large difference in a system's ability to cope and recover from storms. For example, a manager with a WW system more resilient to storms said they mitigate I&I into their sewer system during storms by using, "... manhole structures [that] are built and secured with water tight covers" (W03). Another said they, "... have some manhole covers that have multiple holes in them ... [and they have] been changing those out as [they] can to manhole covers with no holes" (W02). He also said they are looking at using rubber stoppers to reduce inflow in the future instead of replacing covers because, "It is cheaper and easier to put in rubber stoppers ... [and replacing] the manhole covers [costs] over $100 apiece ... So it'd be cheaper to do quartz or rubber stoppers or something along those lines" (W02). Another system said they use plugs in a similar manner to prevent their pump stations from flooding — "... we did get plugs, and have them to this day, so we can plug those vent holes off, and it worked in some spots if the water didn't continue to rise and run in the cover in the top" (W05).

Being prepared to cope with power outages makes WW systems more resilient to severe storms where power loss is an issue. Generators are a good example of how managers reduce WW system impacts from power outages using either temporary or permanent backup power. In some cases, managers said they have permanent generators that can run their entire plant when they lose power — "We have a generator that runs the entire plant if something should happen" (W24). Another said, "... we're 100% generator-backed-up, so during Hurricane Irene and the October snowstorm [Alfred], we were off grid for about a week, running on backup generator. But it runs like a charm. You don't even notice any difference in the operation" (W18). Other managers said their WW systems and pump stations do not all have permanent backup power. These systems without permanent backup power cope with outages by moving temporary portable generators around as needed — "We have portable generators that we move out for the few small stations that don't have fixed standby generators" (W20). Another manager with a less resilient WW system said, "We don't have auxiliary power at every location. Although that would be the optimum condition, [but we] do have an auxiliary power facility now that we can take from place to place" (W14). If pump stations are located far away from each other, it is important for them to have their own generators, because road access may be limited during storms. For example, the manager of one less resilient system said, "We usually have backup power by a manual generator that we'd hook up to. But there was no access to it for a certain amount of time ... we actually got power back on before we had access to it" (W29). Many managers said the most important adaptive change they made to increase their capacity to cope was to get generators, or to increase the number of generators they have.

Managers tend to use temporary or small adaptations that are not cost intensive because they do not have sufficient funding to make large-scale changes — for example, one manager said, "... our major challenge is making sure that the electrical systems inside of the pump stations and the pumps themselves don't get flooded ... but short of raising them up which is not really an option in those locations, we take the approach that we will waterproof 'em ... basically we have large rubber mats that we put over the top of the Bilco doors ... it's surprising how effective a large rubber mat with a couple sandbags on it will make a Bilco door waterproof ..." (W01). When asked if more permanent adaptations were needed to ensure the pump stations do not get flooded, the same interviewee said, it is, "... gonna be a considerable expense that I don't know that I can justify because my methodology albeit some of my jury rigging, it works. So, if I could accomplish the same thing using duct tape and bailing wire do I really need to go out and have a whole new station rebuilt at considerable dollars for that rainy day?" (W01).

Permanent storm resiliency interventions tend to be large and expensive, and to increase resiliency, these must be completed before a storm hits. For example, a manager said, "... we're doing a lot of resiliency changes ... We're involved in a big project now, which will be taking our electrical distribution out of the basement and putting it on the first floor, well above the 100-year flood, probably closer to above the 500 flood. And then also we have a tunnel system underground, putting in the ability to have tunnel flooding protection" (W20). Another more resilient system said, they moved all of the electrical equipment way above the flood zone to increase their resilience to flooding — "All of the electrical rooms are above a 500-year flood. So even if this place were to have the dike overcame, we wouldn't really lose too much critical equipment" (W24). Pump stations and electrical equipment are vulnerable to flooding and during storms it may be difficult to access roads to drive to sites to monitor pump stations. Regarding a large change in technology that enhanced their resiliency, a manager said, "... what we learned from that is to incorporate remote sensing and basically be able to see the pump station from the comfort of the control room so we do not have to drive out there unless there truly is a problem" (W16).

While many managers are implementing hard adaptations, there may be limits to large-scale resiliency investments. A manager said, "... if we lifted the whole station, the whole area around it, four feet, then it would alleviate the problem totally. Right now, we just built a retainment around the whole thing ... I don't know if it's the best thing for it, but it works ... financially, it wouldn't be cost-effective to do that [lift the whole station]" (W29). Regarding investments to increase resiliency by reducing I&I, another manager said, "At some point, there is that law of diminishing return that we will start to identify and say that it's just not cost-effective for us to be throwing this kind of money into the system, if it's really not gonna make a significant difference" (W31). On the other hand, failing to invest in hard adaptations can also be costly, for instance, "For the amount of money we were doing on maintenance, [it] was cost-prohibitive. So, they decided to just put a whole new one in" (W18).

IMPLEMENTING ADAPTIVE MANAGEMENT

Managers of WW systems that have been impacted consistently or severely in the past are more likely to employ an adaptive management approach to understand, plan for, and mitigate anticipated risks than those who manage WW systems that have not been impacted, making their systems more resilient to future damage. By employing adaptive management, we mean these managers are promoting ongoing learning, experimentation, and innovation to enhance resilience. For example, regarding experimentation, one manager said, "Don't wait until it's going wrong and then try to figure it out. You're going to fail for sure. So the best time to make changes is when things are going pretty good. Not wholesale changes, but tinker around a little or, as I always tell people here if they want to try something, go ahead and monkey around with it and see what you can come up with. If it works, great. If not, we ditch it" (W16).

Regarding ongoing learning, he also said, "I try to mention to them all the time to make a list of all the things you've learned in the last six months that you didn't know," and, "Of course you don't want to have everybody at 65 years old, either. Sprinkle in some young people, too, so it can get passed on, that tribal knowledge. I think that gets missed sometimes, too" (W16). Managers who implement adaptive management are also able to learn from other WW systems' experiences. For example, after Hurricane Sandy hit Connecticut, one manager said, "We shared information after, kinda telling stories ... how did you make out?" (W05). In addition, when a storm hits, managers learn additional information about their WW system's vulnerabilities. For example, a manager said, "... we learned a few things during that event. And that was that, you know the generators, even though we test them monthly and keep them up and maintain them, that we had one go down on low oil pressure" (W28). He also said, "... the Department of Public Works learned a lesson there too cause some of the creeks had some grading [i.e., changes made to the ground elevation and side slopes of the stream channel to increase flow] that was part of it. So those were filled with debris from the high water" (W28).

Implementing adaptive management also involves transformation, which may include taking advantage of new technologies. One manager mentioned that a potential barrier to implementing new technologies is that operators in Connecticut, "... are not required to get continuing education credits each year," and that, "Other New England states require 25 tracked hours every two years, which sort of forces you to attend conferences and seminars and pick up on new technologies" (W06). Other managers learn about new technologies from other systems — "We definitely look to see what others have done in order to get to the point that we got here" (W04).

In addition to employing adaptive management, these systems and their managers implement more adaptations to mitigate future damage than systems that have not been impacted (see Figure 1).

The increasing amount of adaptations can be traced to having high amounts and diversity of adaptive capacities coupled with learning from past impacts to make improvements. For example, an interviewee said, "... historically it's been reactionary ... we had a storm event at that station ... [and] after that first flooding event then we put in procedures ... to address that particular flooding. So ... we have been able to reduce flooding impacts at that particular station and that is the only station that's at a position where it actually has flooded" (W08). Similarly, another interviewee said, "We prepare for a storm coming, and of course we learn from everybody after a storm happens, and we all try to get better from there" (W26). Another said, "We do our after action reports on each event, which are part of the closing up of the EOC [Emergency Operations Center]. And we incorporate that into our training, or standard operating procedures" (W19). These managers are employing adaptive management by fostering ongoing learning and change and thus are better

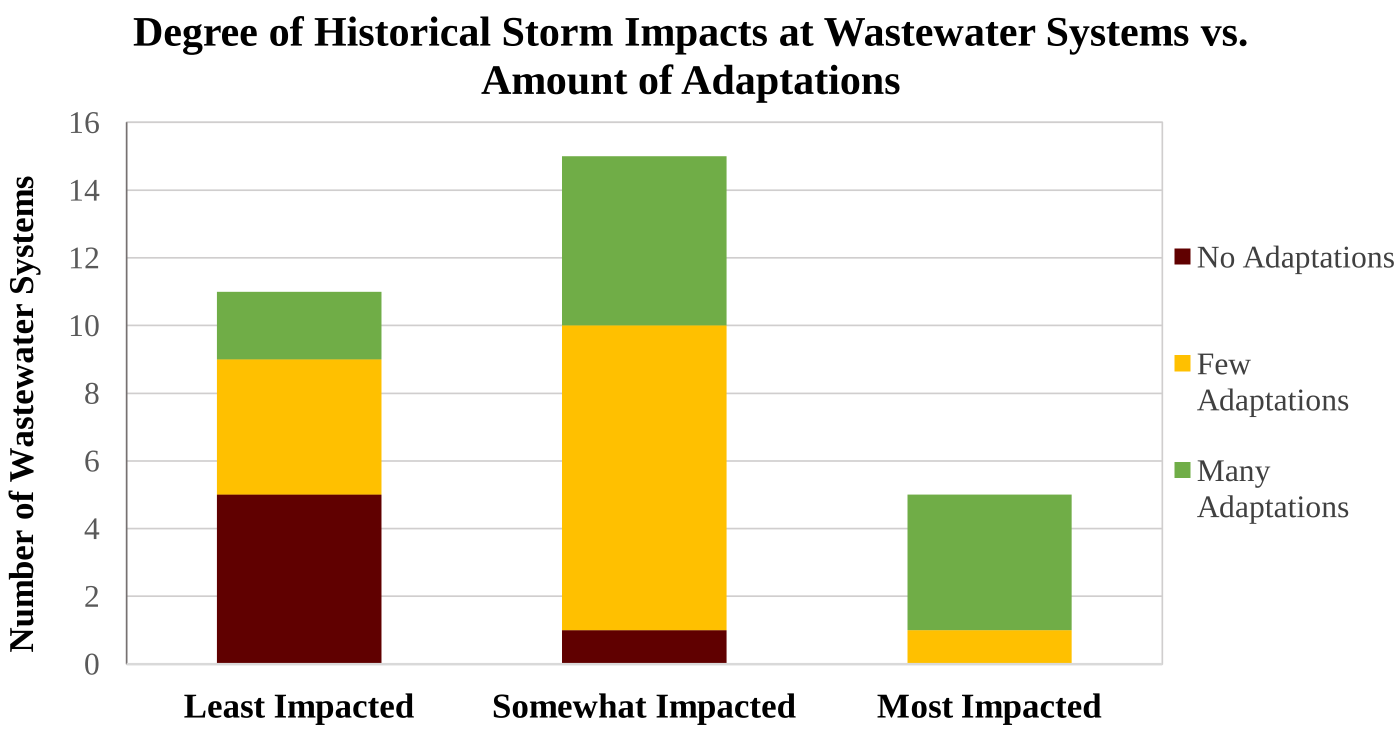

FIGURE 1. Chart showing the relationship between degree of historical storm impacts at wastewater (WW) systems and amount of adaptations. WW systems most impacted in the past have managers who are implementing the most adaptations to mitigate future storm damage.

able to understand and reduce vulnerabilities and increase their WW systems resilience to future storms. Adaptive management is especially important for enhancing and sustaining resiliency because it helps managers better understand their systems vulnerabilities, how those vulnerabilities change over time, and what specific countermeasures, if implemented, would reduce those vulnerabilities.

DISCUSSION AND CONCLUSION

Using data from 31 interviews with managers, we assessed WW system resiliency based on concepts of generic and specific adaptive capacities and adaptive management. This work builds on prior research on adaptive capacity measurement and extends our understanding of the influence of adaptive capacity and adaptive management on WW resilience in practice (Folke et al. 2002; Yohe and Tol 2002; Brooks et al. 2005; Berkhout et al. 2006; Sharma and Patwardhan 2008; Hess et al. 2012; Rudberg et al. 2012; Eakin et al. 2014).

Our results support previous findings that two of the most important generic adaptive capacities influencing a WW system's resilience is strengthening in-house staff expertise and good leadership (Rudberg et al. 2012). Staff that are reliable, flexible, knowledgeable, well trained, resourceful, and communicate effectively are able to do more work in-house and tend to build more resilient WW systems. Moreover, staff that are involved in the decision-making process are confident, committed, and trusted and work together well to make sense of complex situations, manage conflict, and build partnerships, knowledge, and support for change (Folke et al. 2005; Gunderson et al. 2006; Kenward et al. 2011; Pahl-Wostl et al. 2013; Emerson and Gerlak 2014). Good leadership helps foster staff that are more likely to engage in debates about the best adaptations to build resilience, more likely to care about the system's ability to withstand a storm, and more likely to be willing to work long hours. Additionally, we found good leaders build strong relationships with their customers, town, state, and/or other third parties, and thus are more likely to gain financial support for making changes to increase resilience. This is consistent with prior research that showed the importance of leadership for building trust, understanding, and communication pathways, increasing the ability to manage conflict, and facilitate adaptation to changing circumstances (Folke et al. 2005; Gunderson et al. 2006; Pahl-Wostl 2007; Pahl-Wostl et al. 2013; Emerson and Gerlak 2014; Peat et al. 2017).

Results also suggest WW systems with high generic adaptive capacities (i.e., skilled staff, good asset management, good leadership, and sufficient funding) are better able to understand what specific capacities or adaptation measures (e.g., soft and/or hard adaptations) should be implemented for a given context and time, and are more likely to have greater amounts and diversity of specific adaptive capacities making them more resilient. WW systems with high generic adaptive capacities and greater amounts and diversity of specific adaptive capacities also tend to have a better handle on the issues they face, the resiliency measures they can try out, and are better positioned to make investments over time. We also considered WW system characteristics (i.e., funding availability, type and size of system, location) as potential drivers of WW system resilience and found these factors do affect vulnerability and adaptive capacity, but do not affect the relationship between adaptive capacity and resiliency.

Managers that employed a "diversity of adaptations" strategy meaning building and deploying a mix of temporary and permanent, and a mix of hard and soft adaptations are on average more resilient. Building and deploying diverse specific capacities adds flexibility. Managers typically make small, temporary or intermittent changes to reduce WW system vulnerability first before shifting to larger, more expensive permanent changes. Similar to Hess et al. (2012), we found managers sometimes elect to rely on existing infrastructure and all-hazards preparedness rather than investing in innovations when increased risks have yet to materialize. Even for systems that have been impacted: at some point, the cost of storm resiliency interventions may outweigh the benefits, and, if a system manager does not have funds available and/or thinks that their temporary interventions are adequate for reducing storm impacts, larger permanent interventions are less likely to be done. Building on Dessai and Hulme (2007), this finding adds a new rationale for why managers may elect to forgo more expensive investments. Managers build resilience through smaller scale adaptations when managers know their system's vulnerabilities and whether or not and for how long these smaller temporary interventions will work.

While having high amounts of generic and specific adaptive capacities is necessary for resilience, they alone are not sufficient; more resilient WW systems also have high capacity for employing adaptive management to marshal those adaptive capacities and make informed adaptations. Having high capacity for adaptive management, including the capacity for ongoing learning, is needed to assess risks and make adaptive decisions. Prior studies found training and education form the basis for being able to understand risks and solve problems, and to make decisions and learn from them (Bruin et al. 2007) — all of which are crucial for adapting to climate change (Lutz and Muttarak 2017). Similarly, we found capacities to understand, learn, and make decisions (capacities for adaptive management) are fundamental to managers' abilities to make adaptive decisions and to build specific capacities that are critical for resilience. In addition, similar to Peat et al. (2017), we found that adaptive management is effective when WW systems have good leadership and that flexibility promotes experimentation. Finally, we found that WW systems that were impacted by storms consistently or severely in the past are more likely to employ adaptive management. This finding is consistent with prior research that found organizations learn, innovate, and change in response to outside pressures (Berkhout et al. 2006), and that strategies only begin to arise after systems have been impacted by extreme weather events (Berrang-Ford et al. 2011).

Adaptive management is helpful for resilience because it enables human systems to learn from disturbance (Holling 1996), recognize risks, and make continuous changes to improve resilience to climate variability and climate change. In addition, adaptive management provides a framework for continuing to build, evolve, and mobilize generic and specific adaptive capacities needed for resilience. Adaptive management's focus on continual learning, experimentation, and adjustment is critical for avoiding complacency and backsliding which undermines resilience gains. Despite these advantages, if climate change is abrupt and unexpected, incremental adaptive changes initiated in an adaptive management frame may be insufficient (Folke et al. 2004; Rudberg et al. 2012).

Finally, our results suggest that WW system resilience is more human-driven than the current literature suggests. Current literature on infrastructure resilience emphasizes structural resilience of the physical infrastructure including the ability of the WW treatment processes to withstand higher or lower temperatures and flows or the ability of WW system equipment and structures to withstand flooding (Juan-García et al. 2017). Our findings suggest that resilience of the physical infrastructure is only one aspect of resilience and that WW system resilience depends equally (or more so) on the capacity for resilience that the human systems that manage the physical system possess. That is, the most resilient WW systems are able to marshal, build, and deploy generic and specific adaptive capacities within an adaptive management framework to build resilience (see Figure 2).

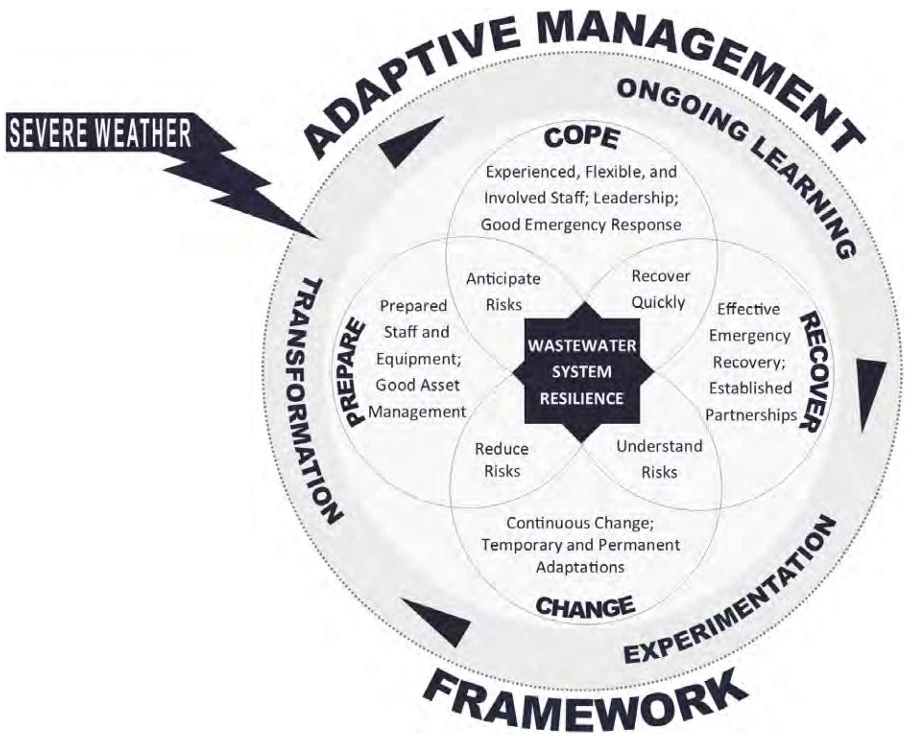

FIGURE 2. An adaptive management framework provides a means to learn from disturbances and to marshal adaptive capacities to make informed adaptations to reduce vulnerability. Adaptive management in turn depends on the amount and diversity of underlying adaptive capacities (i.e., generic and specific) needed for resilience, which is the capacity to prepare, cope, recover, and change.

Structural resilience remains an important contribution of overall WW system resilience, but it is embedded in and amplified by the adaptive capacities and adaptive decisions managers make as part of an adaptive management approach.

More work is needed to explore the limits of adaptive capacities and adaptive management for building resilience as well as to better understand what specific adaptive capacities help foster the kinds of transformations necessary to withstand more rapid climatic changes. In addition, more research is needed to better understand how generic and specific capacities interact leading to more or less desirable resiliency outcomes.

SUPPORTING INFORMATION

Additional supporting information may be found online under the Supporting Information tab for this article: Interview protocol.

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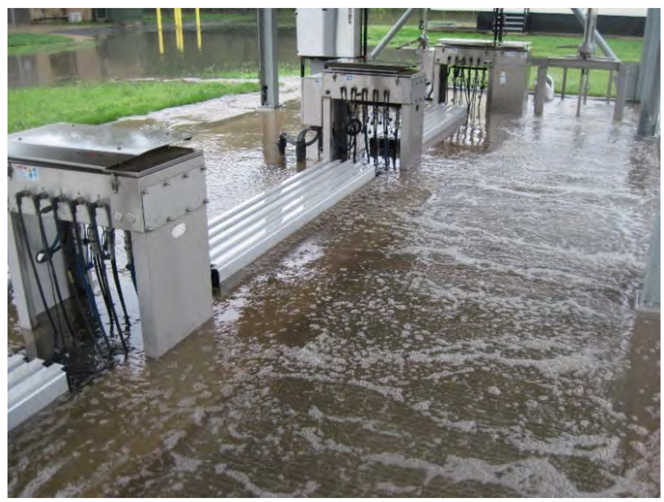

Wastewater System Resilience: Learning from Connecticut Wastewater Systems

Prepared By:

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May 2019

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We extend our appreciation to our collaborators, and especially to all of the hard working wastewater superintendents, managers, operators and local government pollution control authorities working together to increase the resilience of wastewater systems. We also wish to thank those who shared their time and experience with us by responding to the survey and participating in interviews so that we can share these lessons learned.

Foreword

Wastewater managers face many challenges from not only extreme storms but also from changes in the economy, aging infrastructure, an uncertain regulatory environment, and a changing climate. Given these challenges, wastewater managers in Connecticut are building resilience. For the purposes of this publication, we define resilience as activities to help prepare for, cope with, recover and learn from events that disrupt wastewater service provision whether during normal or emergency operations. The purpose of this document is to share lessons learned from Connecticut wastewater managers that are building resilience and through that sharing to help managers learn from each other and strengthen and support resilience building efforts.

Introduction

Approximately 130 municipal and private wastewater systems operate in the State of Connecticut with permitted treatment capacities ranging from less than one million gallons per day to 60 million gallons of wastewater per day. Extreme weather events, equipment failures or malfunctions, and other non-routine occurrences can result in sewage backups, overflows, and/or bypassing of untreated or partially treated into waterways. Storms can be particularly disruptive. A survey of Connecticut wastewater systems conducted from November 2015 to April 2016 revealed that 72 percent of systems experienced disruptive impacts from past storms such as power loss, flooding, bypassing, and loss of access from past storms (see Figure 1).

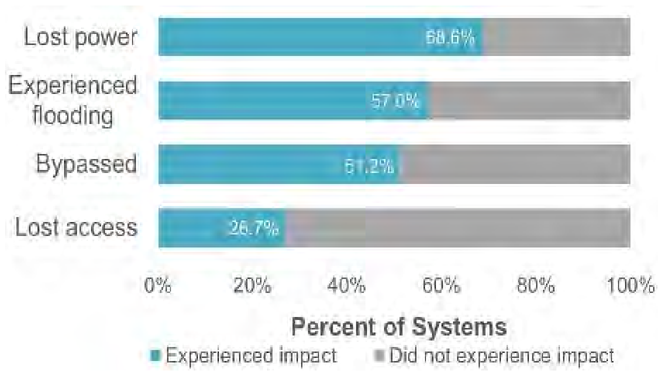

Figure 1 *Percent of Connecticut wastewater systems who experienced power loss, flooding, bypassing, or access loss from past storm events (n=86). For more information on the survey and for additional survey results see Kirchhoff and Watson (2019).*

Aging infrastructure, demographic shifts, economic crises, billions of unfunded capital needs (ASCE 2011), and cyber security could further increase vulnerability and undermine long-term sustainability and resilience of wastewater systems in Connecticut and across the USA. For the purposes of this publication, we define resilience as activities that help wastewater managers prepare for, cope with, recover, and learn from events that disrupt wastewater service provision whether during normal or emergency operations.

In the Northeastern USA, wastewater managers have resources available to help inform resilience building efforts. The New England Interstate Water Pollution Control Commission (NEWIPCC) provides a wastewater treatment plant design manual, *Guides for the Design of Wastewater Treatment Works* (also known as Technical Report 16 or TR-16), and a supplementary document, *Preparing for Extreme Weather at Wastewater Utilities: Strategies and Tips.* TR-16 focuses on wastewater treatment plant design including in the most recent addition, key concepts and design criteria related to flooding, storm surge, extreme weather, and climate change (NEIWPCC 2016a,b). While TR-16 is primarily for engineers and regulators, the audience for the supplementary *Strategies and Tips* document is wastewater system managers and operators. The *Strategies and Tips* document synthesizes the experiences of Northeast wastewater utilities affected by recent major storm events (e.g., Hurricane Sandy, Hurricane Irene, and winter storm Alfred) and provides a set of strategies and tips for planning, preparing, coping with and recovering from major storm events.

This publication—*Wastewater System Resilience: Learning from Connecticut Wastewater Systems*— compliments these NEIWPCC resources. Unlike the NEIWPCC publications that emphasize storm and climate resilience, this publication has broader but complimentary aims. Herein we provide ideas and concepts to help wastewater systems build resilience 1) in day-to-day operations, 2) to non-climatic stressors, 3) to extreme events, and 4) to a changing climate. This report also shares strategies and tips used by Connecticut wastewater systems not previously discussed in the NEIWPCC *Strategies and Tips* document. The intended audience for this document are the hard working wastewater superintendents, managers, operators and local government pollution control authorities working together to increase the resilience of wastewater systems in Connecticut and beyond.

Human Dimensions of Wastewater Resilience

In our conversations with Connecticut wastewater system managers, we found that the most resilient wastewater systems have excellent staff, good asset management, and effective leadership. Excellent staff are reliable, knowledgeable, well trained, resourceful and effective communicators. These staff are involved in the decision-making process and work well together to make sense of complex situations and build support for change. Good leaders support staff development and a 'learning culture'. In addition, good leaders create an environment that encourages staff to think about and work towards building resilience. They also cultivate strong relationships with their customers and town and state authorities to support making changes to increase resilience.

In addition to excellent staff, good asset management, and effective leadership, wastewater systems that employed a mix of resilience building approaches—both hard and soft, big and small, or temporary and permanent—are on average more resilient. For example, a typical resilient wastewater system had managers who made small, temporary or intermittent changes to reduce their systems' vulnerability first before shifting to larger, more expensive permanent changes such as adding plant capacity or undertaking large-scale flood proofing efforts. Building resilience through smaller scale adaptations is possible when managers know their system's vulnerabilities and whether or not and for how long these smaller temporary interventions will work.

Finally, while staff, asset management, leadership, and employing a diversity of resilience building approaches is necessary, alone they are not sufficient; resilient wastewater systems employ an adaptive management (AM) approach. By AM, we mean managers promote ongoing learning including learning from experimentation and trial and error as well as from other wastewater systems' experiences to enhance resilience. Ongoing learning helps wastewater systems assess risks and make adaptive, informed decisions. Implementing AM often involves transformation, which may include taking advantage of new technologies or reimagining or reconfiguring the wastewater system (see Figure 2). While many resilience resources stress the importance of flood-proofing and other physical measures for building resilience and while this is indeed important, lessons from Connecticut wastewater systems suggests wastewater resilience also depends on the capacity of the human systems to implement AM and build resilience.

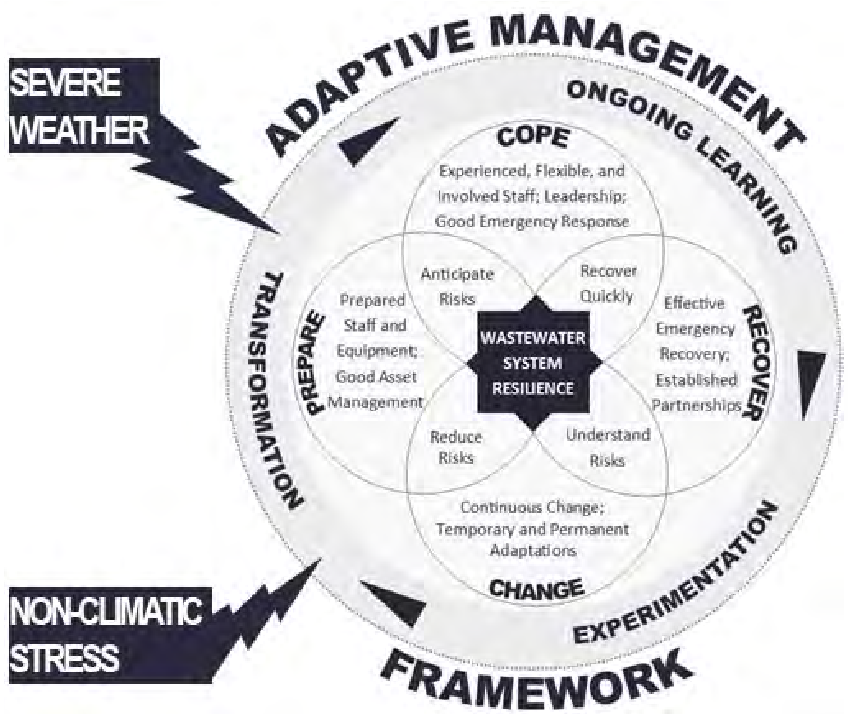

Figure 2 *An adaptive management framework to build resilience to climatic (extreme storms) and non-climatic stress. Adapted from Mullin and Kirchhoff (2018). To learn more about AM see (Mullin and Kirchhoff 2018).*

Strategies and Tips Used by Connecticut Wastewater Systems to Build Resilience

In addition to the survey, from October 2016 to March 2017, we interviewed 29 wastewater managers from across Connecticut to understand the nature and severity of past storm impacts, the types of adaptive changes made, what motivated those changes, and what helped or hindered making changes. We also asked managers about adaptation to future climate change. For a complete description of the interviews, analysis, and findings see Mullin and Kirchhoff (2018) and Kirchhoff and Watson (2019).

Connecticut wastewater managers employ a wide range of strategies to build resilience. Many of the strategies used for building resilience to extreme events align with the strategies and tips presented in the *Preparing for Extreme Weather at Wastewater Utilities: Strategies and Tips* (NEIWPCC 2016b). In addition to the strategies already included in the NEIWPCC *Strategies and Tips* document (NEIWPCC 2016b), on the next several pages we present six additional resilience building strategies and tips: 1) Promote Ongoing Learning and Experimentation; 2) Maintain and Improve Equipment and Infrastructure; 3) Transform where Possible; 4) Invest in Many Diverse Resilience Building Actions; 5) Take Advantage of New Technology but Beware the Technology Trap; and, 6) Monitor and Take Advantage of Regulatory Change. These are strategies used by Connecticut wastewater systems that are not included in other guides and that speak to a broader range of resilience building efforts including for: 1) day-to-day operations, 2) non-climatic stressors, 3) extreme events, and 4) a changing climate. Along with each strategy and tip, we present select quotes from Connecticut wastewater managers that illustrate each strategy referring to interviewees by code for anonymity.

1) Promote Ongoing Learning and Experimentation

Fostering ongoing organizational learning and change especially through a willingness to experiment and learn from new techniques that help wastewater systems reduce vulnerabilities and increase resilience.

- "*…we finally have the resources at our fingertips that allow us to really keep a pulse on how efficient our collection system and pump stations are operating.*" (S35)
- *"…if you don't have a good measurement process in place,* [you can't adjust or] *know how to portion it."* (DE18)
- "*Don't wait until it's going wrong and then try to figure it out. You're going to fail … the best time to make changes is when things are going pretty good. Not wholesale changes, but tinker around a little. I always tell people here if they want to try something, go ahead and monkey around with it and see what you can come up with. If it works, great. If not, we ditch it.*" (O20)
- *"I mention to them all the time to make a list of all the things you've learned in the last six months that you didn't know."* (O20)
- *"They come down to the plant frequently and have conversations with* [us] *on the ideas that they have or ideas that we may have for improvement."* (S11)
- *"…we definitely look at what others have done to get to where we are here."* (S08)
- *"Periodically you'll be at a conference or something. I'm always curious on how people are – especially after the last series of big storms over the last few years; people had a lot of problems with their emergency generators."* (S21)

2) Maintain and Improve Equipment and Infrastructure

Perform continuous and preventative maintenance and repair of equipment and infrastructure to ensure the best equipment performance. Perform regular inspections and cleanings (e.g., routine cleaning of collection systems and wet wells) to reduce future problems.

- "*We really did a really good job maintaining those generators through the years so that in the time of an emergency they all performed like they were supposed to. We didn't have any quit on us. The equipment held up*." (O20)
- "*Pump station maintenance gets done every week*." (S12)
- *"The money that's set aside for maintenance is spent on maintenance. What we don't spend this year will get carried over to next year, so there's nothing in it for us to not maintain the equipment."*(S29)

Implement continuous / incremental infrastructure improvements and split large capital improvement projects into a sequence of smaller chunks to the extent possible.

- "*…we're looking at chipping away at some of the infrastructure improvements on an ongoing basis*." (DE18)
- "*I guess it looks like small increments, but something as small or as minimal as getting these pump stations to the point that we can see them back here, it's been a process of probably eight or nine years*." (O20)
- "*…continuously invest in our infrastructure here so it's an ongoing improvement process. We typically invest between $50,000 and $100,000 annually in our collecting system and we've gone through $25 million in upgrades since 2008*." (S14)
- "*…looking at the capital projects projected over twenty years is the start, and then it all depends on what's breaking down or not breaking down, what needs repair, etcetera*." (S06)
- *"… we've been slowly replacing things but some of the generators are affordable. They're in the $20,000 to $40,000 range. So we can put that into our budget and save for it and the next year do it."* (O20)

3) Transform where Possible

Look for opportunities to make radical, cost effective changes that transform the system or operations where possible.

- *"Our impetus has been also to remove pumping stations. We're in the midst of reducing one, Savage Hill Road, so that it becomes a gravity. So we can get rid of that whole system frankly."* (DE18)
- "*We have a facility that's basically between solar, and their digester complex, and they have something else going on there where they're net zero energy use*." (S29)

4) Invest in Many Diverse Resilience Building Actions

Invest in small and large scale, temporary and permanent physical infrastructure resilience building actions as well as human dimensions actions (training, staffing, planning, etc.) to build resilience.

Stock extra pumps. Invest in submersible pumps and/or have auxiliary pumps available in case of an emergency.

- "*We have a few extra pumps, brand new, sitting on standby in case one burns, we can just plug in the next.*" (S13)
- "*…the ones we have now are submersible grinders and they're just all over better for wastewater and that's probably the biggest gains that we've made…*" (E17)

Add hydraulic capacity. Hydraulic capacity can be added at the plant or in the collection system.

- "*…our plant was redone … and it is oversized, over-engineered …we're able to handle* [excess flows] *with no problem…*" (S13)
- "*We have capacity, so the added hydraulic loading doesn't really affect us that much.*" (S14)
- "*…we put larger pipes underground … so we could handle larger flows…*" (S19)
- "*we have a tunnel system underground, putting in the ability to have tunnel flooding protection.*" (S24)

Implement temporary and/or permanent flood protection or damage control measures.

- "*…the station does have a berm around it but the driveway is not as high as the berm… So after the first one* [flood] *several years ago we staged sandbags for the driveway area…*" (S12)
- "*…put in permanent flood prevention barriers…*" (S12)
- "*…dykes and levees and floodgates, and we have two huge effluent pumps that have no problem pushing against the water that could be out there…*" (S13)
- "*I have a procedure in place to meet with electricians to actually pull a couple of pumps out, bring them to higher ground and hold them until things subside.*" (S06)

Prioritize team building and collaborative decision making. Collaborative decision making takes advantage of team experience and expertise.

- *"I've got my staff heavily involved … because you get everyone's opinions and ideas and as a group collectively you come up with a lot more ideas or problems that you didn't know existed out there that you can try to correct in the facility with the upgrade."* (S19)
- "*… exchanging information…ongoing day-to-day, keep people involved and let them hear the decision making.*" (S09)

Invest in training, cross-training, and building capacity to solve problems internally. Being able to do more with in-house staff expertise often improves resilience.

- "*We train constantly, exchanging information, and so I would say definitely training*" (S09)
- *"…we train them, you know, as they get more accustomed to the plant how to reset the facility when the power comes back on."* (S19)
- "*We actually had had the manufacturers come in and train us how to rebuild stuff and that's been able to save a lot of money in big downtime."* (S28)
- *"…so that if somebody's out sick, there's enough cross-training that takes place so that anybody can step into any role and that facility will continue to run…"* (S10)
- *"The problem becomes when everybody, all the other municipalities are relying on those same outside contractors, when there is an emergency we're all chasing after those same contractors."* (W05)

Bring new employees on early to aid in transfer of knowledge and experience from more experienced team members to newer team members.

- *"Probably half the staff has been here long enough. If you walked around and went to any piece of equipment here, they can tell you who made it, who is the rep, what type of lubricant is in it, what's the greasing schedule, how old it is. There are hundreds of pieces of equipment and everyone has this in their head."* (O20)
- *"Having an experienced staff. Of course you don't want to have everybody at 65 years old, either. Sprinkle in some young people, too, so it can get passed on, that tribal knowledge. I think that gets missed sometimes, too."* (O20)
- *"I don't see that workforce coming up behind us… replacing these 20 to 25-year employees. I have an employee that's gonna retire in ten years. I want to hire his replacement now. We don't make the investment in people coming up to be able to do this work."* (S10)
- *"Our assistant plant manager is very hands on, really close to the training staff, and if he wasn't so hands on, if he wasn't so knowledgeable and then shared his knowledge with our staff, then it probably could have been terrible, yeah."* (E17)

Establish and nurture mutual aid relationships. Having established lines of communication and relationships with others (e.g., wastewater systems, utilities, etc.) help systems improve resilience especially during emergency events.

- *"they call and say hey our flusher truck is down for a couple of days can you give me the number of a guy who's on call so that if we have an issue can we borrow your flusher truck so we can operate it and we go okay fine, no problem."* (S16)
- *"…it comes down to emergency preparedness and relying in case we need something that could be shared with other facilities or that other facilities may have something that could be shared with us, that type of planning."* (S08)
- *"But sometimes they'll need a line jetted. So they'll call us up and we'll send a guy out there. Work with them to get that line opened up."* (S32)

5) Take Advantage of New Technology but Beware the Technology Trap

New technologies can enable better day-to-day maintenance and monitoring and help identify problems. Technology can also help in emergency response by enabling remote monitoring and control.

- *"I did just invest in a new robotic camera."* (S24)
- "*…we're getting a GPS system, because we've got to have a GPS system for mapping…*" (S26)
- "*The biggest thing… we learned … is to incorporate remote sensing and basically be able to see the pump station from the comfort of the control room so we do not have to drive out there unless there truly is a problem.*" (O20)
- "*Something as simple as thinking about our cellular modems are 3G so we know we're going to have to go up to 4G modems at some point so we started buying now because each modem is somewhere between $300 and $400 and we're going to need 11 or 12 of them.*" (O20)

Figure 3 *Mission Control dialer. Photo courtesy of Kevin Cini, City of Groton WPCA.*

- "*Computerized Maintenance Management Systems. If you're gonna have the best equipment, you've gotta put the best maintenance in.*" (S30)

While technology has clear benefits, some systems noted that technology can also sometimes limit flexibility in response options.

- *Now we have installed all these new generators … they're brand new 2013 or 2014 models … but the flip side is they're all computer controlled, so if one of them doesn't start, there's not a damn thing we can do about it anymore until we can get the vendor in here to make a repair."* (S19)

6) Monitor and Take Advantage of Regulatory Change

Anticipate regulatory changes and make proactive adjustments. Early compliance may enhance wastewater system resiliency and speed recovery.

- "*…we did switch from diesel to propane in anticipation of more stringent air quality acts coming out.*" (S09)
- "*Any new things CTDEEP are going to require in the future… anticipate those…"* (S34)

References and Other Resources

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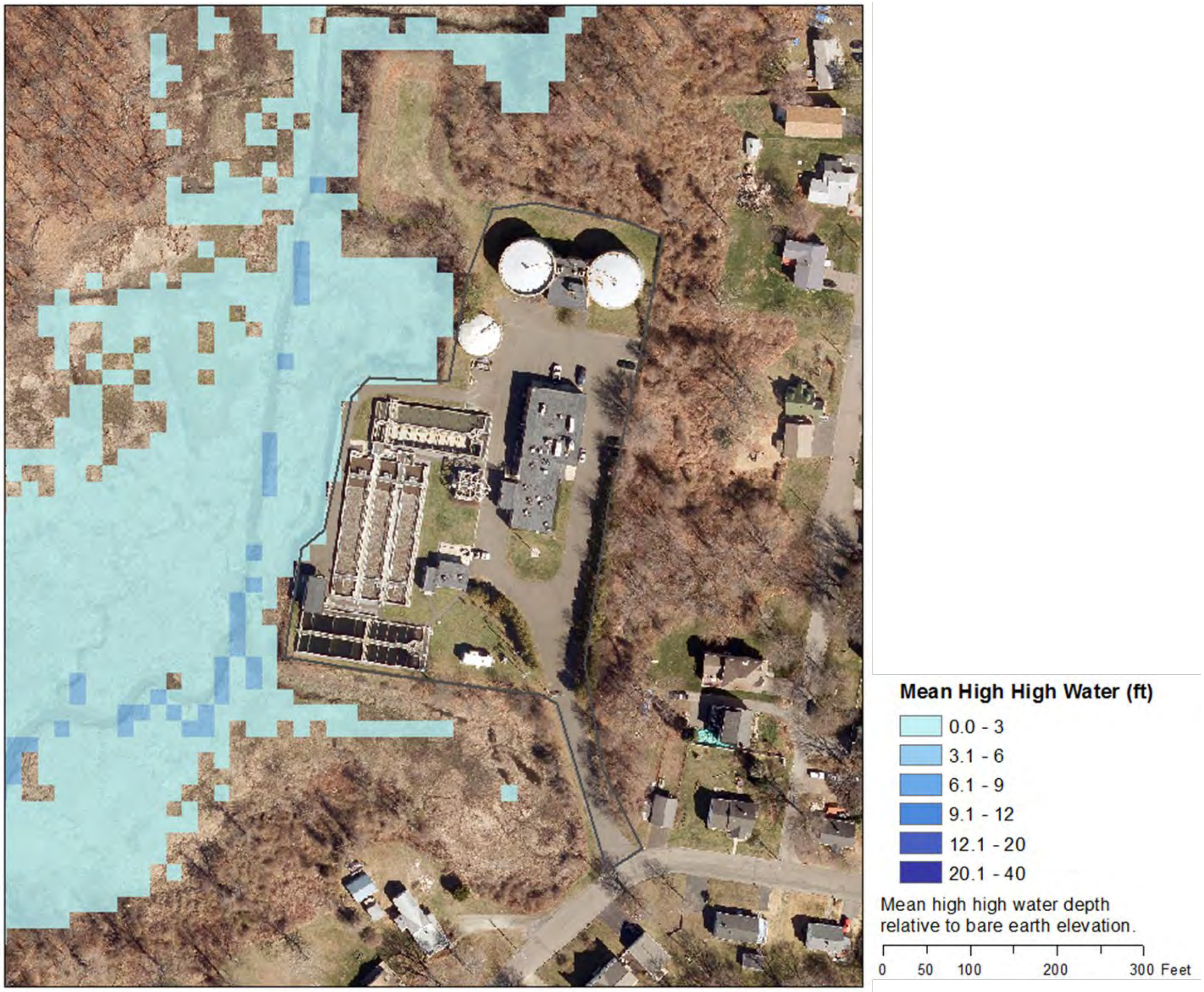
Flood Recurrence Analysis for Milford, CT



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We extend our appreciation to our collaborators, and especially to Milford, Connecticut Public Works, Planning, and GIS staff for their input.

SUMMARY

UCONN Marine Science researchers analyzed tide gage data at Bridgeport and New Haven, Connecticut to produce flooding recurrence projections for Milford relative to the MHHW. Return periods of 1, 5, 10, 25, 50, and 100 year were developed and are summarized in Table 1. Analytical details and backup materials are presented in the following ANALYSIS section.

UCONN Civil & Environmental Engineering researchers worked with UCONN Marine Science researchers and staff at Milford to revise the summary and backup materials. Changes resulting from this iteration included adding a table summarizing flooding recurrence projections in feet in addition to meters, changing the x-axis scale of Figure 1 and 2 from base 10 to 0, 1, 10, and 100 respectively, adding a figure to show how to interpret Figure 1 and 2 (new Figure 3), and adding additional explanatory text to the details and backup materials.

Table 1: Flooding Recurrence Projection at Milford, CT. Flooding reference is given relative to the Mean Higher-High Water levels (MHHW). Return periods for the 1, 5, 10, 25, 50 and 100 year are based on the GEV fit at Milford, CT (Fig. 2).

SLR [m]	MHHW [Milford, CT]	1-yr	5-yr	10-yr	25-yr	50-yr	100-yr
0	0	0.13	0.42	0.57	0.76	0.92	1.08
0.5	0.5	0.63	0.92	1.07	1.25	1.42	1.58
0.75	0.75	0.83	1.18	1.32	1.51	1.67	1.83
1	1	1.13	1.42	1.57	1.76	1.92	2.08
2	2	2.13	2.42	2.57	2.76	2.92	3.08

SLR [ft]	MHHW [Milford, CT]	1-yr	5-yr	10-yr	25-yr	50-yr	100-yr
0	0	0.43	1.38	1.87	2.49	3.02	3.54
1.64	1.64	2.07	3.02	3.51	4.10	4.66	5.18
2.46	2.46	2.72	3.87	4.33	4.95	5.48	6.00
3.28	3.28	3.71	4.66	5.15	5.77	6.30	6.82
6.56	6.56	6.99	7.94	8.43	9.06	9.58	10.10

ANALYSIS: Storm surge above MHHW for the Milford area

Storm Surge Summary for Bridgeport and New Haven, Connecticut Using Tide Gage Data

The following summary is based on analysis of tide gauge data at Bridgeport and New Haven, CT. The tide gages have 70 to 100 years of data (varies by gage); the focus of the analysis is on monthly maximum values as these values capture storm related surge levels at each location.

An Extreme Value Analysis was performed with each data set. The Extreme Value Analysis was based on the Generalized Extreme Value (GEV) fit of these data at both gauges (see Figure 1). The GEV probability distribution function (Cole 2001) is stated as:

$$G(x) = \exp\{-[1 + \zeta\left(\frac{x-\mu}{\sigma}\right)]^{-\frac{1}{\zeta}}\} \quad (1)$$

where the coefficients μ, σ and ζ are the location, scale and shape parameters respectively.

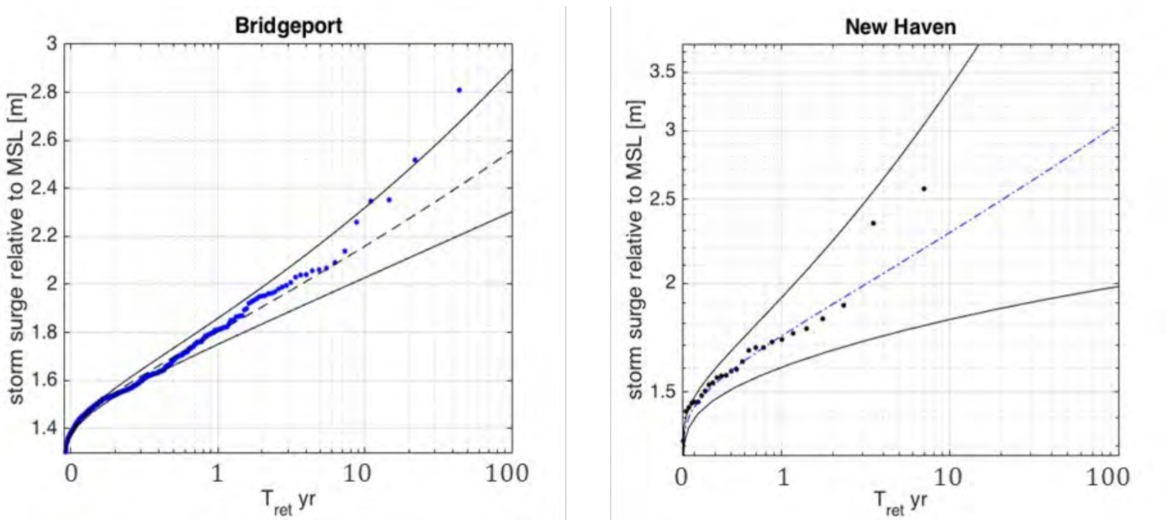

Figure 1: At left is the recurrence [return period] of water levels above mean sea level (MSL) (0 m relative to NAVD88) at Bridgeport, Connecticut and at right, the same information for New Haven, Connecticut. In both figures, the x-axis is the return period (1-year, 10-year, and 100-year) and the y-axis is the storm surge level relative to MSL in meters. The dashed line (black for Bridgeport and blue dash dot for New Haven) is the GEV fit line (Eq. 1). Blue (left figure) and black (right figure) dots are data points from the tide gauge, specifically monthly maximum values for all available years of data. Solid lines correspond to the 95% confidence interval. The width of the 95% confidence interval differs between the left and right. The New Haven data shows larger variance at larger return periods due to fewer observations available (shorter record, 70 years compared to 100 years for Bridgeport).

The GEV provides the probability of exceedance of a certain water level of interest. For example, using the Bridgeport plot, the probability of exceedance of an approximately 2.15 meter water level above MSL is 10 years (see Figure 2).

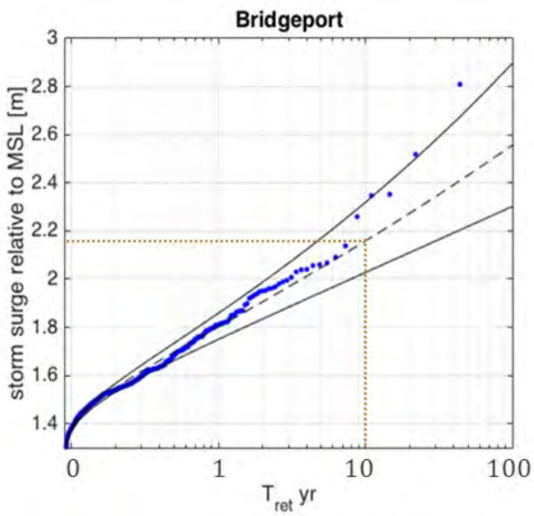

Figure 2: An example of using the GEV plot for Bridgeport to determine the probability of exceedance of a water level of interest. If a water depth of 2.15 meters above MSL was of interest, one could darw a horizontal line (shown as orange dotted line in graph) from the y-axis point corresponding to 2.15 meters to the GEV line (black dashed line) to determine the recurrence (return period) for that water level above mean sea level (MSL) (0 m relative to NAVD88) at Bridgeport, Connecticut. From the graph, drawing a vertical line from the intersection point down to the x-axis shows the return period for this water level is approximately 10 years. Note, there is uncertainty (reflected in the 95% confidence interval bands) for this value suggesting that the 10-year return period water level ranges from approximately 2 meters to 2.3 meters.

Storm Surge Summary for Milford, Connecticut Using Simulation and Observed Uncertainty in Tide Gage Data

Due to the lack of tide gauge data at the immediate Milford area, numerical simulation was used to evaluate the response of the system under an extreme weather event (i.e. Superstorm Sandy 2012). This initial validation exercise resulted in a 10% difference between simulations at Milford and local tide gauge observations of the maximum storm surge during Sandy 2012. Sea surface displacement observations from tide gauges at Bridgeport and New Haven recorded a maximum storm surge of 2.5 to 2.6 m during Superstorm Sandy. The hindcast simulation produced a maximum storm surge of 2.3 m in Milford bay corresponding to an 8% difference (low) compared to observed sea surface displacement at Bridgeport and a 13% difference (low) compared to New Haven [MSL 0 m]. To account for this difference in observation values, uncertainty of the observations and the GEV estimates from the numerical simulation were combined to give the expected range for the storm surge water level recurrence [return period] above mean sea level (MSL) (0 m relative to NAVD88) in Milford, CT (see Figure 3).

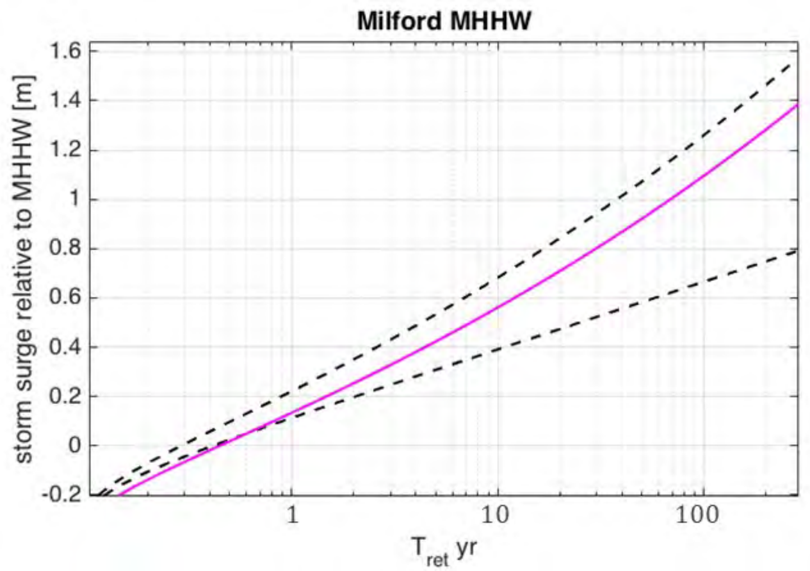

Figure 3: Recurrence [return period] of water levels above MHHW at Milford, CT. Dashed black lines correspond to the 95% confidence interval. The solid magenta is the GEV model used at Milford, CT. Note uncertainty increases (error bands widen) as the return period increases. However, uncertainty widens in the direction of lower probability of exceedance as it approaches the 100-yr event.

The information shown in Figure 3 was translated to a more usable summary table (see Table 1). In addition to the information shown in Figure 3, the effects of sea level rise (SLR) were also tabulated. Note, the SLR effects are not dynamic; rather they simply are added to the information derived from Figure 3 which accounts for the uniform rise in sea level. Figure 4 provides a plot of SLR at Milford using the same approach as the tabulated data but for all data values. Note, confidence intervals are not included. The uncertainty under SLR should be estimated from a joint probability distribution function based on both storm surge and SLR.

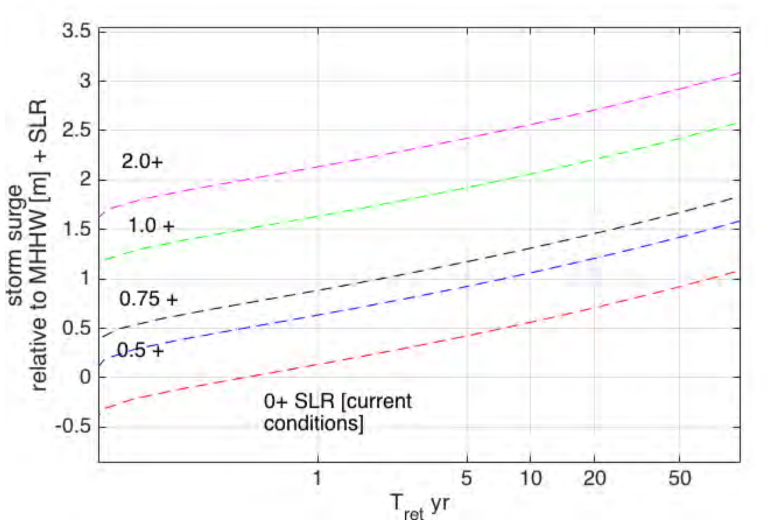

Figure 4: Recurrence [return period] of water levels above MHHW at Milford, CT. Dashed red line corresponds to the GEV model under current conditions (this is the same as the magenta line from Figure 3). The dashed blue, black, green, and magenta lines represent different SLR scenarios ranging from 0.5 meter to 2.0 meters (or 1.64 feet to 6.56 feet).

APPENDIX F

BANK STREET – SOUTH WATER STREET PROJECT
New London, CT

Final Report

December 2018
Community Research & Design Collaborative
UConn Landscape Architecture Program

Connecticut Institute for Resilience and Climate Adaptation

Sponsored by a grant from the Connecticut Institute for Resilience and Climate Adaptation (CIRCA). CIRCA is a partnership between the University of Connecticut and the State of Connecticut Department of Energy and Environmental Protection. More information can be found at: www.circa.uconn.edu

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CIRCA base data: Connecticut Institute for Resilience and Climate Adaptation

This report is a product sponsored by the Connecticut Institute for Resilience and Climate Adaptation (more information about CIRCA can be found at circa.uconn.edu). The work is made possible through a grant from the State of Connecticut Department of Housing CDBG-Disaster Recovery Program and the US Department of Housing and Urban Development.

UConn's Community Research & Design Collaborative (CRDC) is the umbrella organization for the outreach work of the landscape architecture faculty. Our mission is to be a regional leader in sustainable planning and design. We help our client's plan and design affordable, equitable, and ecologically healthy environments. Our mission is accomplished by providing our client's with objective, multi-disciplinary, state-of-the-art planning and design expertise. We promote and encourage academic-based collaborative research with an emphasis on "real world" projects as they apply to sustainable development.

Contents

INTRODUCTION

Situated on the Thames River and Long Island Sound, the city of New London has been historically vulnerable to flooding, and sea level rise projections depict even worse scenarios.

This project is an effort by the University of Connecticut's Community Research & Design Collaborative (CRDC), with support from the Connecticut Institute for Resilience & Climate Adaptation (CIRCA), to assist the city of New London, Connecticut to develop a community-based resiliency plan focused on sea level rise for the year 2100. It works with the city's Mayor's Office and the Business Owners Association to develop a science-based design to mitigate negative impacts of sea level rise while spurring economic growth along South Water Street.

South Water Street is on the edge of the Thames River. The area is historically vulnerable to flooding due to its low-lying topography.

The Role of CRDC

The CRDC was tasked to take CIRCA data on sea level rise, referenced by the recently introduced state-wide legislation on Climate Change Planning and Resiliency (Public Act 18-82), to graphically communicate the potential impacts of rising waters on the Bank Street area of New London. Based on this data, the CRDC team developed a series of design/planning scenarios envisioned to mitigate the negative consequences of sea level rise, while looking for opportunities to promote economic growth, create sustainable cultural/ natural systems and improve 'place-making/sense of place' of affected parts of the urban fabric.

This science guided approach began with the creation of three different design strategies. These were then presented to local officials and property owners to discuss potential solutions that would ensure a sustainable future for their community. Based on public input, designs were then revised, and a new meeting was held to ensure that multiple options were explored. The meetings were held to stimulate conversation with stakeholders, to ensure that consensus on a design was obtained, but also that concerns were expressed so that the proposed strategies aligned with the community's vision for the future.

Report Overview

The next five chapters go over the site inventory and analysis, the community engagement process, the proposed designs and the final outcomes. In the Flood Vulnerability section this report gives a brief overview of the history of the site and its current state, as it pertains to flood hazards. It goes on to describe future projections for sea level rise from 2018 to 2100 and beyond. In the Public Engagement Section, it goes over the meetings with the South Water Street business and property owners and addresses how the project sought to include the community in the design process. In the Proposed Design Section, this document depicts the three main designs proposed and alterations made based on public participation, it then moves on to the Final Design Section where it presents the design proposal that seems to best address the desires and needs of the Bank Street – South Water Street community. Finally, the report outlines future recommendations and the next steps needed for the implementation of the proposed final design.

FLOOD VULNERABILITY

Though there has been a lot of controversy over the future rate of sea level rise, and climate change in general, my experience of the past 4 years is that the science issues are the easy part of the problem. Determining how people want to adapt to the inevitable consequences have turned out to be much more of a challenge.[1]

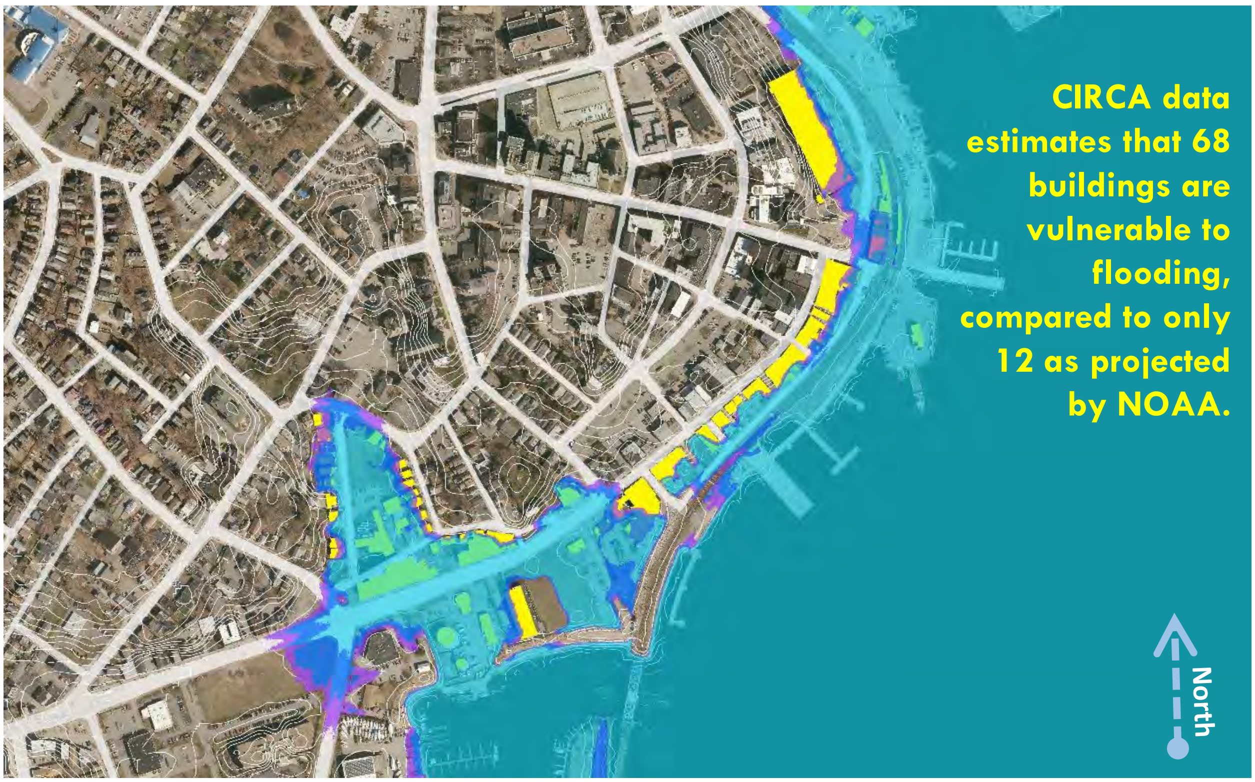
History and Current Conditions

Over the last 100 years, a total of eight hurricanes have hit the southern Connecticut shoreline (1903, 1938, 1944, 1954, 1960, 1972, 1985 and 1991). The strongest storms to hit the area so far have been Category 3 hurricanes with sustained winds of 110 to130 mph.

Great Hurricane of 1938
Boats and piers at New London, Conn., are a mess of broken wreckage after the hurricanes. Fire at the height of the storm added to the terror and destroyed a quarter of a square mile of the business district, Sept. 12, 1938. Sights like this were common all along the coast, as New England faced a cleanup job which took weeks.

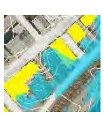
[1] James O'Donnell – CIRCA Executive Director

Sea Level Rise – Projections for the Future



Thames River


Aerial w/ structures, roads & contours


2018 - Structures affected by 100 Year Event


2050 - Structures affected by 100 Year Event Plus 1 foot

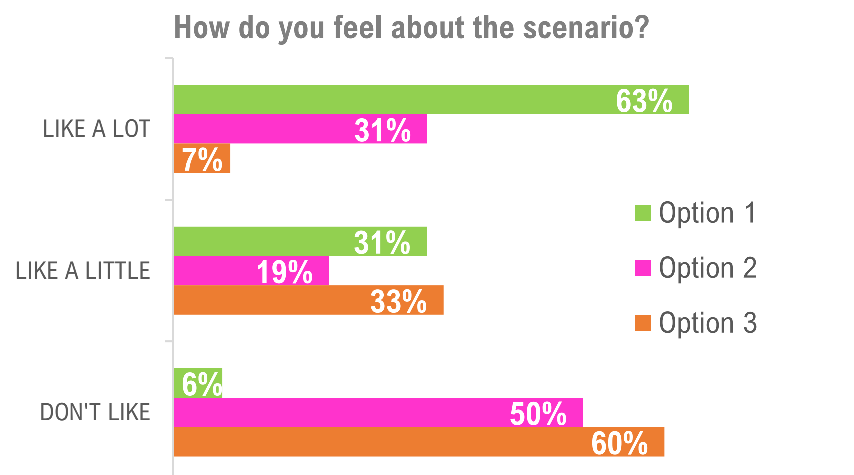

2050 – Structures affected by 100 Year Event Plus 20 inches

Using NOAA Long Island Sound tide gauge data, CIRCA estimated the 100 year flood event levels above MHHW. The preliminary data on sea level rise produced by CIRCA indicates that the 1%, or 100-year storm events will likely be 20 inches higher in 2050. Trends based on CIRCA projections estimate that approximately 68 buildings along the Thames River will be vulnerable to flooding in 2050. This is a significant increase when compared to current 100 year flood projections, which estimate only 12 buildings in danger.

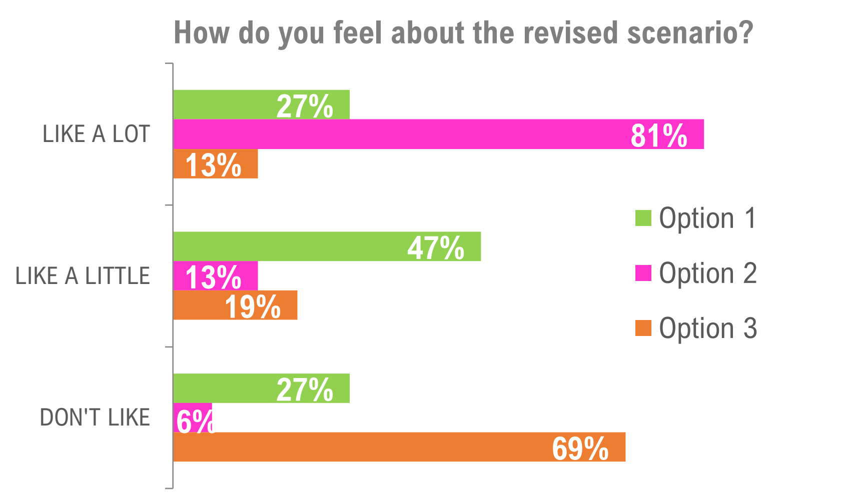
PUBLIC ENGAGEMENT PROCESS

The entire design process was founded on public involvement. To do so an expert in public engagement and communication participated in the meetings as a moderator. After designs were presented the moderator made sure that property and business owners, and city officials, were heard. The process also included an anonymous voting system, so that those less vocal could express their preferences. Participants were asked to comment on the pros and cons of all the design options, and revisions to the design were made based on the input gathered.

Input from 8.16.2018 meeting



Input from 10.04.2018 meeting

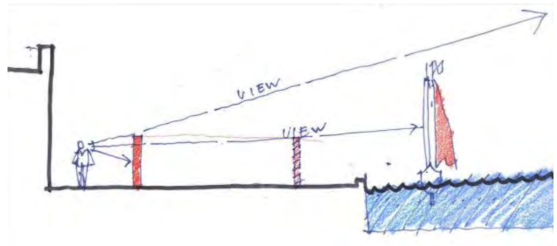


PROPOSED DESIGNS

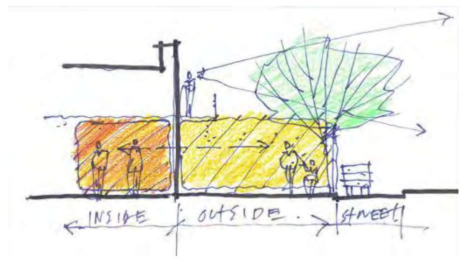
The proposed design should create or preserve settings for human activities that engage the mind and touch the heart, while allowing the original environment, both human and non-human, to sustain. We aim to create socially responsible landscapes which combine function with aesthetics.

The designs proposed are guided by three community planning principles:

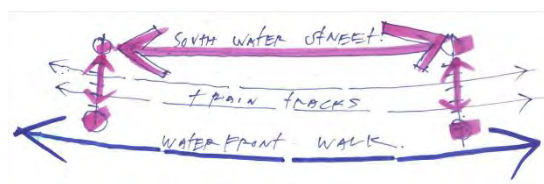
- **Do not block pedestrian views with landscape walls over 5' – 6' and in close proximity of the user.** High walls negate the concept of "defensible space" and can create a claustrophobic feeling in the user.



- **Building uses need to support the street level. The more uses in the buildings the better**. Roof tops and upper level balconies are great but do not substitute for street level activity.



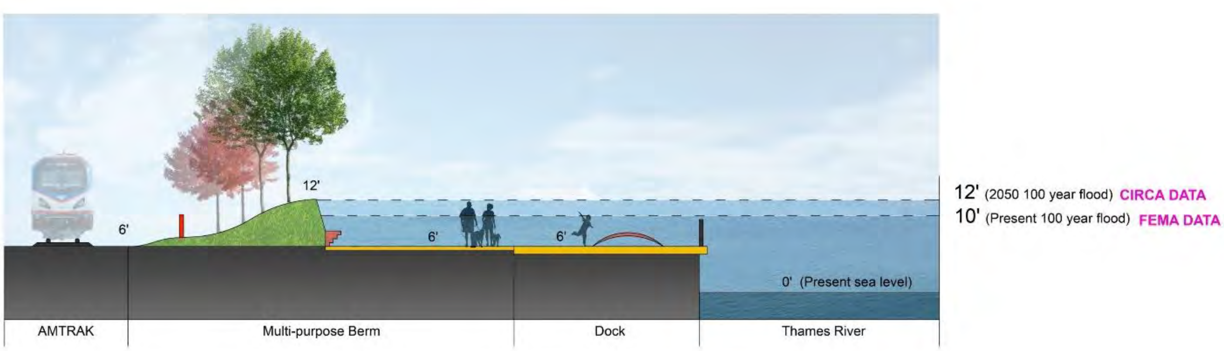
- **Successful streets function as both memorable pathways and landmark type of destinations.** This is especially critical for South Water Street because it connects the two crossing over the tracks to the waterfront.



This project uses a **General Model** that serves as an illustrative section along South Water Street used to depict the proposed design concepts. It cuts through Bank Street and South Water Street all the way to the riverfront.

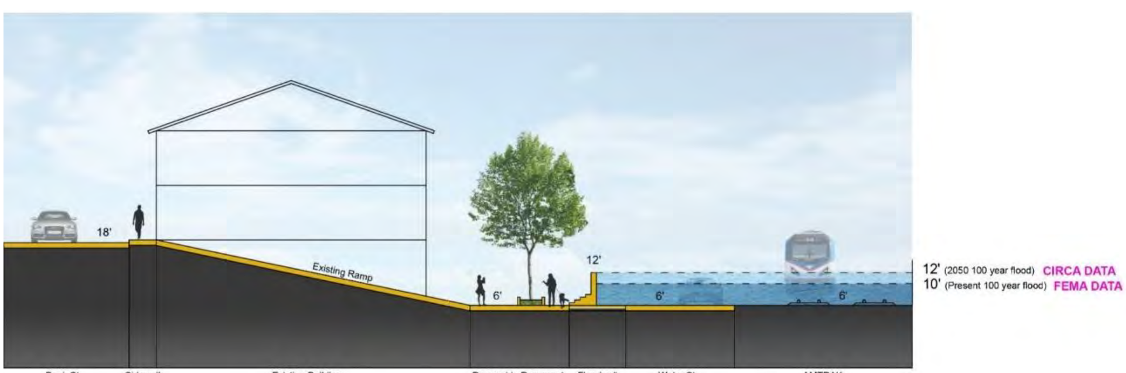
Design Option 1- Improvements on Public Lands

Option 1 proposed a series of berms/landforms running between the train tracks and river. It includes deployable gates to close the ends of the berm system. This alternative protects Amtrak, Water Street and buildings on eastside of Bank street from flood waters.



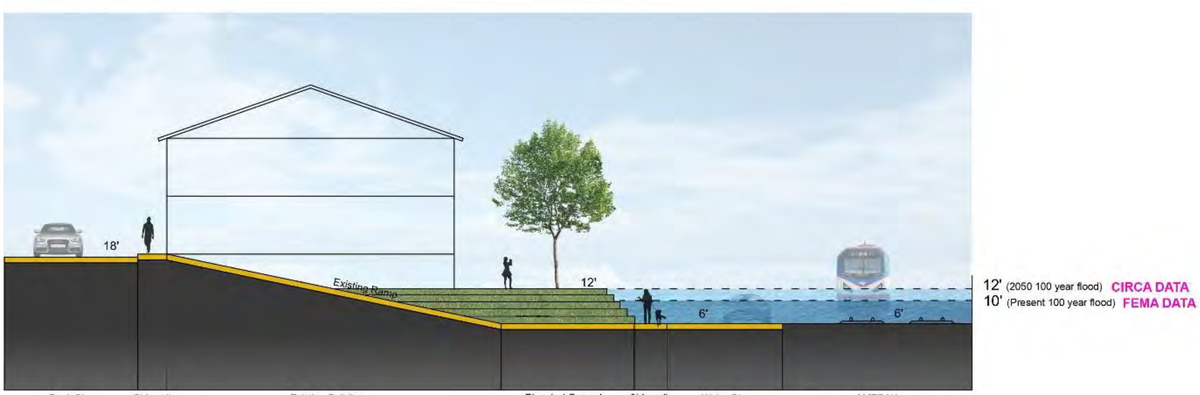
Design Option 2- Improvement on Public/Private Lands

In this option the design proposed that South Water Street be elevated 3’ with a 3’ glass wall added to the elevated plane, to protect both the street and buildings on the eastside of Bank Street from flood waters.



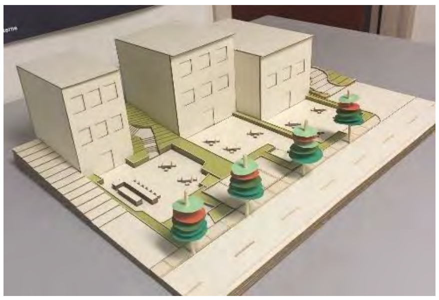
Design Option 3- Improvement on Private Lands

In this design proposal, the back of the buildings, facing South Water Street, are filled by 6'. This is intended to protect buildings on the eastside of Bank Street from flood waters. In some cases, the first floor would have to be converted to basement space.



FINAL DESIGN

UConn's studies depict conceptual ideas and are not intended to be authoritative regarding proposed development or preferred mitigations regarding sea level rise. Further study and coordination between interested parties will be required to further refine these concepts toward a viable proposal.



The final design further revises Design Option 2, based on requests gathered from the public engagement process during the second meeting. The community requested the incorporation of aspects of Design Option 1, so that a park is created on the edge between Amtrak and the Thames River, connecting the area to the river and creating a leisure space that would draw the community to South Water Street.

RECOMMENDATIONS AND NEXT STEPS

In order to elevate South Water Street, the project should expand to include the area to the east of the site, where Union Station is located. Grading will need to be done on the connections between State Street and Water Street so that the elevation of the road effectively addresses potential water rise. With that said, Union Station, a historic building siting just outside of the studied site, has come to our attention as particularly vulnerable structure that should be addressed in order to ensure the success of the plan. Additional studies on stormwater management and green infrastructure should also be produced to compliment the project. Finally, the community will need to support to secure funds for the construction of the final design.

APPENDIX G

Appendix G1

TASK 9 SUMMARY REPORT: LEGAL AND POLICY ANALYSES THAT SUPPORT STATE AND MUNICIPAL EFFORTS TO IMPLEMENT RESILIENCY MEASURES.

Charge from DEEP Contract # 15 DEP16120AA

Connecticut faces unique challenges in climate resilience planning and implementation. Statewide resilience planning may be challenged by the legal relationship between state and municipal governments, undergirded by home rule principles that ensure municipal autonomy. In addition, legal concepts that have filtered down through the common law into modern courts—such as the public's right to access the coastline and the constitutional rights of private property owners—may hinder adoption of resiliency.

While Tasks 2-8 address the maps and tools to identify and make decisions on infrastructure, there also needs to be more information available for Connecticut communities to implement resilience measures through law and public policy, which take Connecticut's unique challenges into account. To address this need, the Center for Energy and Environmental Law at the UConn Law School will conduct legal and policy analysis on critical topics in climate resilience, and conduct a targeted educational campaign for key decision-makers.

Justification

Laws and public policies are often cited as barriers to the adoption of resiliency measures. In Connecticut, key decision-makers often lack information about the scope of their legal authority. Over the course of two years, the Center for Energy and Environmental Law will direct research efforts toward identifying the laws and policies that are the biggest barriers and offering strategies to ensure that key decision-makers have tools they need to make sound planning decisions.

Center for Energy and Environmental Law faculty and research fellows will generate a series of deliverables aimed at educating both key policymakers and the general public on best practices in law and policy. These deliverables will include legal research white papers and drafts of model rules for adoption, with the overall goal of removing barriers to climate resilience efforts at the state and municipal levels. Topics suitable for analysis may include zoning regulations, building codes, coastal protection and armoring, takings jurisprudence, and the public trust doctrine, and will be finally determined in coordination with the Connecticut Department of Energy and Environmental Protection. In coordination with the community engagement described in Task 10, the Law School will host a conference and/or series of workshops for municipal and state leaders, and others, which will communicate the legal and policy recommendations of the project. The Center for Energy and Environmental Law has successfully hosted a number of these conferences in the past.

Task Overview

Task 9 was undertaken by the University of Connecticut Center for Energy and Environmental Law (CEEL). The goal of this task was to identify climate resilience opportunities for the Connecticut shoreline that could be implemented within the complex and unique legal structures that define the relationships between the state government, municipal governments, property owners and the general public. Limiting the scope of work to issues that had not been adequately addressed by others, the following subtasks were undertaken to meet this overall goal:

- The evaluation of coastal management programs in other oceanfront states to identify coastal management policies, legal structures, practices, and procedures that could be useful in Connecticut
- The examination of Connecticut legal structures to identify opportunities for, and obstacles to, climate resilience planning and implementation
- The identification of legal structures to support coastal and floodplain management based upon forward-looking sea level rise projections instead of the traditional backward-looking "100 year flood" events
- The communication of the results of this work to state and municipal leaders, regulators, officials, and other interested parties through white papers and outreach events

Over the course of this project, the overall goal of Task 9 was realized with the following accomplishments:

- The publication of four white papers on climate resilience issues

- The presentation of sixteen community outreach events that engaged 517 interested and influential parties
- The hosting of an all-day conference that attracted 128 registrants and served as a capstone outreach event for all of the tasks within the Municipal Resilience Planning Assistance Project
- The enactment of climate resilience legislation that was informed by the recommendations developed during this task

Initial Research

Task 9 research started with an in-depth study and analysis of Connecticut coastal and floodplain management law and policy, with particular attention to the roles of the state and municipal agencies. Concurrent with this study was a survey of coastal and floodplain management programs in other oceanfront states that focused on the key decisions associated with coastal and floodplain management, the laws and policies that enable these decisions, the entities responsible for making these decisions, and how these decisions incorporate the effects of sea level rise. The results of these initial areas of study were used to establish the direction and scope of the remaining research.

The scope of the remaining research was also informed by (1) the preliminary results of the municipal needs analysis conducted under Task 10 by the University of Connecticut (UConn) Center for Land Use Education and Research (CLEAR), (2) the preliminary results of the sea level rise projections developed under Task 2 by Connecticut Institute for Resilience and Climate Adaptation (CIRCA), and (3) an analysis of previous work related to shoreline climate resilience in general and Connecticut shoreline resilience in particular. The influence of these three factors is further described below.

Task 10 Municipal Needs Analysis. The full and final results of the Task 10 Municipal Needs Analysis are provided elsewhere in this report. These final results were not available at the start of the Task 9, but by then the Task 10 research team had nevertheless identified two common and recurring municipal concerns – one general and one quite specific. The general concern was a perceived need for some higher "standard of authority" to implement coastal and floodplain management programs and practices that exceeded the minimum requirements of existing laws and regulations. The specific concern was the apparently mundane - but practically important - issue of reconciling building height limits imposed by zoning regulations with building elevation requirements imposed by floodplain and coastal management programs.

Task 2 Sea Level Rise Projections. The full results of the Task 2 Sea Level Rise Projections are also provided elsewhere in this report. These final projections were not available the beginning of Task 9, but preliminary work made it clear that sea level rise in Long Island Sound would prove to be significant. Furthermore, the early work on Task 2 indicated that the rise of Long Island Sound will substantially increase the return rate of the flood levels associated with the historical "100 year flood," and that eastern sound communities would experience these floods at roughly twice the rate of western sound communities. This east-west disparity in flood return rates could prove to have important policy ramifications.

Analysis of Previous Works. By the time Task 9 started in 2016, a sizeable body of work had been amassed on the subject of shoreline climate resilience, so it was necessary to review this work in order to avoid repetition. Some of these works, such as the "Adaptation Tool Kit" published by the Georgetown Climate Center, were applicable to coastal climate resilience in any state or territory. Other works were more narrowly tailored to Connecticut needs, such as the summer 2012 special issue of the Sea Grant Law and Policy Journal addressing “Legal Solutions to Coastal Climate Change Adaptation in Connecticut” and a 2017 series of fact sheets published by UConn CLEAR that address “Legal Issues in the Age of Climate Adaptation.” In all, this initial analysis involved hundreds of works including research reports, guidance documents, codes, standards, law review articles, and scholarly works originating from a wide variety of organizations such as the Army Corps of Engineers, the Connecticut Institute for Resilience and Climate Adaptation, the Environmental Protection Agency, the Connecticut Department of Energy & Environmental Protection, the American Society of Civil Engineers, the Federal Emergency Management Agency, the National Association of Insurance Commissioners, the National Oceanic and Atmospheric Administration, the Nature Conservancy, the United States Geological Survey, Universities, and the National Sea Grant College Program.

The initial research identified a total of 19 areas of study that could lead to results consistent with the overall goal of Task 9. Further scrutiny narrowed the scope of our work to the following five areas of study that that had not been addressed by others and that could be adequately pursued with the resources allocated to this task:

- Coastal management programs in oceanfront states and how those programs address sea level rise,
- elevation standards for buildings in Connecticut coastal floodplains,
- zoning height restrictions on elevated residential buildings in Connecticut coastal floodplains
- municipal exemptions for flood and erosion control structures landward of the Connecticut coastal jurisdiction line, and

- statutory adoption of University of Connecticut sea level rise projections for Long Island Sound.

The outcomes of our work on these five areas of study are more fully described below.

Research Outcomes

Oceanfront State Coastal Management Programs.

State coastal management programs are interrelated with the federal Coastal Zone Management Act of 1972 (CZMA), which provides financial and other federal incentives for states to develop, implement, and maintain coastal management programs that advance national coastal management policies.

Our research determined that as of June 2017, eleven of the twenty-three oceanfront states had coastal management programs that included statewide statutes or regulations that addressed sea level rise. Three states (Maryland, Massachusetts, and Rhode Island) required the consideration of sea level rise during planning processes and when making *most or all* coastal management decisions. Four states (California, Florida, Maine and New York) required the consideration of sea level rise when during planning processes and when making *some* coastal management decisions. Four more states (Connecticut[1], New Hampshire, Texas and Virginia) require consideration of sea level rise during planning processes, but not during decision-making processes.

Our research also looked at coastal management jurisdiction in the oceanfront states. Of the oceanfront states with state coastal management programs, state governments exercise all

[1] Connecticut Public Act 18-82, enacted in June of 2018, requires the consideration of sea level rise for building projects conducted or funded by the state. This law puts Connecticut in the category of states that require the consideration of sea level rise during planning processes and during some coastal management decision-making processes. Prior to P.A. 18-82, Connecticut was included among the states that considered sea level rise during planning processes, but not during decision-making processes.

coastal management jurisdiction in six states. State and local governments share coastal management jurisdiction in sixteen of the oceanfront states. Of the states that share coastal management jurisdiction, Connecticut is the only one that does not require state approval of local coastal management plans.

Our research on this topic is reported in the white paper entitled, "Oceanfront State Coastal Management Programs." This white paper is reproduced in its entirety in Section One of Appendix G2.

Elevation Standards for Buildings within Connecticut Coastal Floodplains.

As of this writing, all Connecticut shoreline communities participate in the National Flood Insurance Program (NFIP) and have enacted floodplain building elevation requirements that meet or exceed NFIP requirements. Connecticut municipalities must also comply with the floodplain building elevation requirements of the Connecticut State Building Code, which in some cases exceed the minimum requirements of the NFIP.

Our research in this area of study started with a tabulation of shoreline community floodplain elevation requirements. This tabulation facilitated a comparison of floodplain elevation requirements between communities and a comparison of individual community floodplain elevation requirements to NFIP standards, state building code requirements, consensus standards, and sea level rise projections. This research indicated that all Connecticut shoreline communities have floodplain building elevation requirements that meet NFIP requirements, but that thirteen of these communities have floodplain management ordinances that are less restrictive than the current requirements of the Connecticut State Building Code. Our research also revealed that three shoreline communities have elevation standards that meet or exceed the more demanding requirements of ASCE 24-1, a consensus standard for “Flood Resistant Design and Construction” adopted by the American Society of Civil Engineers.

Our research also confirmed that shoreline communities have strong legal authority to enact municipal zoning ordinances that specify construction standards for buildings erected in floodplains. With that authority in mind, we were able to offer the following options for municipal action to enhance community resilience to flood coastal events:

- Increase building elevation and flood-proofing requirements above the NFIP minimums to meet state code requirements and to accommodate the projected sea level rise in Long Island Sound
- Establish “Coastal A" zones to allow for more protective standards in the portions of “A" zones that are subject to wave effects, velocity flows, and erosion
- Participate in the NFIP Community Rating System to improve overall floodplain resilience and to take advantage of NFIP premium discounts of up to forty-five percent

These enhancement options, as well as the results of our research and legal analysis, are further described in the white paper entitled, "Floodplain Building Elevation Standards - Current Requirements & Enhancement Options for Connecticut Shoreline Municipalities." This white paper is reproduced in its entirety in Section One of Appendix G2.

Zoning Height Restrictions on Elevated Residential Buildings in Connecticut Coastal Floodplains

As noted in the previous section, all Connecticut coastal communities participate in the NFIP and all have enacted floodplain regulations that meet or exceed the NFIP requirement to elevate habitable portions of new and substantially improved residential structures. Supplementing these NFIP requirements are mandatory elevation requirements under the

Connecticut State Building Code and incentives under federal disaster relief and flood insurance programs that make it attractive for homeowners to voluntarily elevate new and existing residential structures to levels even higher than the regulatory minimums.

Unfortunately, conflicts can arise when a requirement or desire to raise a floodplain building runs up against a zoning regulation that limits how high the building can rise above the surrounding grade. Our research showed that most Connecticut shoreline communities simply use their existing zoning variance process to resolve such conflicts on a case-by-case basis. However, eight shoreline communities were found to have floodplain zoning ordinances that accommodate some increase in height above the usual limit without going through the complicated, time-consuming, expensive and uncertain variance process.

Our research also showed that these eight communities used one of two methods to allow some increase in floodplain building height without invoking the variance process. The first method was to simply allow some additional height above the surrounding grade. The second method was to allow additional height above a specified floodwater elevation. Our research confirmed that Connecticut shoreline communities have strong legal authority adopt zoning ordinances that use either of these methods.

The results of our research on this topic are set forth in a white paper entitled, "Height Restrictions on Elevated Residential Buildings in Connecticut Coastal Floodplains." This white paper is reproduced in its entirety in Section One of Appendix G2.

Municipal Exemptions for Flood and Erosion Control Structures Landward of the Connecticut Coastal Jurisdiction Line

The Connecticut Coastal Management Act, or CMA, empowered shoreline communities to adopt municipal coastal programs for coastal areas landward of the mean high water mark,[2] and all coastal municipalities have done so. These municipal coastal programs are enforced through a coastal site plan review process whereby a local board or commission verifies that coastal area development is planned in accordance with the requirements of the CMA and other applicable municipal regulations.[3]

The CMA allows municipalities to exempt certain minimal-impact uses from coastal site plan review, including "construction of new or modification of existing on-premise structures including fences, walls, pedestrian walks and terraces, underground utility connections, essential electric, gas, telephone, water and sewer service lines, signs and such other minor structures as will not substantially alter the natural character of coastal resources or restrict access along the public beach."[4] Most shoreline communities adopted this language verbatim when developing their municipal coastal management programs.

Our research identified several occasions[5] where walls that were clearly a "shoreline flood and erosion control structure" under the CMA were nevertheless excluded from site plan review by this exemption. Shoreline flood and erosion control structures, such as seawalls, are known to have adverse effects on coastal resources, are highly regulated under the CMA, and are discouraged by the Connecticut Department of Energy and Environmental Protection (DEEP).[6] However, since most shoreline communities exempt "on-premise" walls from site plan review,

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[2] CONN. GEN. STAT. 22a-101
[3] CONN. GEN. STAT. 22a-105
[4] CONN. GEN. STAT. 22a-109
[5] *See, e.g.*, Guilford Planning & Zoning Commission: Regular Meeting & Public Hearing Approved Minutes (April 15, 2015).
[6] Office of Long Island Sound Programs, Fact Sheet for Shoreline Flood and Erosion Control Structures, *in* CONN. DEP'T OF ENVTL. PROT., CONNECTICUT COASTAL MANAGEMENT MANUAL (2000) *available at* http://ct.gov/deep/lib/deep/long_island_sound/coastal_management_manual/manual_08.pdf

they forgo the opportunity to regulate such walls even if they meet the definition of a "shoreline flood and erosion control structure."

The Connecticut DEEP is well aware of this issue, and has published a fact sheet that includes model regulations with wording that avoids this exemption of flood and erosion control structures from coastal site plan review.[7] To date, the towns of Madison and West Haven have wholly adopted the DEEP recommended language, and the city of Bridgeport and town of Westport have simply eliminated "walls" from the on-premise structures exempt from coastal site plan review.

Because this issue is addressed in the DEEP Coastal Management Manual, a white paper on this topic was not prepared under the auspices of Task 9. However, since twenty shoreline towns still exempted on-premise walls from coastal site plan review, this topic was addressed and emphasized during the outreach events presented under this task.

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[7] *Id.*

Statutory Adoption of University of Connecticut Sea Level Rise Projections for Long Island Sound

Our initial research into Connecticut coastal and floodplain management law and policy identified an important incongruence in Public Act 13-179. This 2013 act, and the statutes that were codified from the act, required state and municipal planners to consider the forward-looking sea level change scenarios published in NOAA Technical Report OAR CPO-1 (2102). Recognizing the rapid advances in the field of climate science, the legislature also included in the act a requirement for UConn to update the 2012 NOAA sea level rise scenarios at least once every ten years. However, the act did not mandate the use of these updated scenarios, nor did it specify a means by which the UConn updates should be promulgated. The result of this incongruence was that Connecticut state and municipal agencies were required to prepare for rising seas using increasingly outdated projections that were not particularly applicable to the Connecticut shoreline or Long Island Sound even though updated and sound-specific projections were readily available from UConn.

The Center for Energy & Environmental Law discussed this incongruity at length with the Commissioner of the DEEP and other DEEP officials during a meeting in May of 2017. The DEEP asked CEEL to fully explore this issue and to draft proposed legislation for further consideration.

The CEEL analysis of this statutory incongruence and the suggested legislation to correct it is set forth in a white paper entitled, "Statutory Adoption of Updated Sea-Level Rise Scenarios." This white paper is reproduced in its entirety in Section One of Appendix G2.

A draft of the Statutory Adoption of Updated Sea-Level Rise Scenarios white paper was provided to the DEEP in the fall of 2017. This draft provided the basis for the sea level change provisions of Governor's Bill S.B. 7, which was introduced into the 2018 legislative session and was enacted into law as Public Act 18-82. Among other things, Public Act 18-82 requires the use of UConn sea level rise projections wherever a "rise in sea level" or "sea level change" is invoked by Connecticut statutes, thus resolving the statutory incongruence identified by our research. The evolution and enactment of S.B. 7 and P.A. 18-82 is discussed later in this report.

White Papers

The charge for Task 9 recognizes that effective dissemination of research results is as important as the research itself. Legislators, elected officials, regulators and other influential parties interested in climate resilience efforts need to understand how Connecticut law and policy supports those efforts and, just as importantly, how Connecticut law and policy also impedes those efforts. Such an understanding facilitates the pursuit of climate resilience activities and helps avoid actions that are not supported by existing law. Understanding how current law and policy can impede climate resilience efforts may also inspire legislative or legal action to change those laws and policies.

The results of the Task 9 research were disseminated via white papers, community outreach events, and a final conference. The community outreach events and final conference are described later in this report. This section describes the four white papers that were prepared during this task.

Oceanfront State Coastal Management Programs

The white paper on Oceanfront State Coastal Management Programs explores the differences and commonalities of coastal management programs in the twenty-three oceanfront states to provide a foundation for understanding state implementation of the federal Coastal Zone Management Act. This paper analyzes and details the genesis of state programs, the exercise of coastal management jurisdiction within each state, and how state statutes and regulations address sea level rise. The Oceanfront State Coastal Management Programs white paper also provides an individual summary for each of the oceanfront states that describes the key features of that state's coastal management program. This white paper is provided in its entirety in Section One of Appendix G2.

Floodplain Building Elevation Standards - Current Requirements & Enhancement Options for Connecticut Shoreline Municipalities

The white paper on "Floodplain Building Elevation Standards - Current Requirements & Enhancement Options for Connecticut Shoreline Municipalities" presents the results of our research on elevation standards for buildings within Connecticut coastal floodplains. It surveys the current floodplain building elevation requirements of Connecticut shoreline municipalities and identifies changes that can improve municipal flood resilience within the limitations of legal authorities. This white paper also includes an appendix that provides a comprehensive tabulation of the elevation requirements of the NFIP, the current Connecticut State Building Code, the proposed 2018 Connecticut State Building Code, and Connecticut's twenty-four shoreline communities.

Floodplain Building Elevation Standards - Current Requirements & Enhancement Options for Connecticut Shoreline Municipalities is provided in its entirety in Section One of Appendix G2.

Height Restrictions on Elevated Residential Buildings in Connecticut Coastal Floodplains

The white paper on "Height Restrictions on Elevated Residential Buildings in Connecticut Coastal Floodplains" presents the results of our research on the conflicts that arise when a requirement or desire to elevate a floodplain building runs up against a zoning regulation that limits how high the building can rise above the surrounding grade. It explores the conflicts between zoning height limits and floodplain building elevation projects and offers options to resolve those conflicts using zooming ordinances. The paper describes the legal authority to use ordinances rather than the variance process to accommodate increased building heights in floodplains, and explains how eight Connecticut shoreline communities have done so. It also highlights some of the considerations involved when making decisions on a floodplain building height ordinance, and an appendix to the paper provides the text of regulations in the eight communities that use ordinances rather than the variance process to accommodate increased building heights in floodplains.

Height Restrictions on Elevated Residential Buildings in Connecticut Coastal Floodplains is provided in its entirety in Section One of Appendix G2.

Statutory Adoption of Updated Sea-Level Rise Scenarios

The white paper on "Statutory Adoption of Updated Sea-Level Rise Scenarios" presents the results of our research on an internal conflict among Connecticut sea level rise statutes. This white paper is summarized below and provided in its entirety in Section One of Appendix G2.

The Connecticut General Assembly acknowledged the threat of rising seas with Public Act 13-179. Signed into law on June 21, 2013, this act required state and municipal agencies to consider sea level rise when making critical plans for land use, hazard mitigation, and civil preparedness.

P.A. 13-179 helped Connecticut plan for rising seas, but the effectiveness of those plans were limited by a dissonance within the act that involved the source of the sea level data to be used by the planners. Among other things, the act required planners to use the sea level data in a specific 2012 NOAA report while simultaneously requiring the University of Connecticut to update the data in that report at least once every ten years. However, the act did not require - or even allow - the use of the UConn updates as they become available, nor did it specify a means by which the UConn updates are published. As a result, planners were obligated to consider the 2012 NOAA data even after newer, and presumably more accurate, updates were available from UConn.

Statutory Adoption of Updated Sea-Level Rise Scenarios describes the sea level rise scenarios in the NOAA Report, identifies the statutes that invoke the NOAA Report, explains the need to periodically update sea level change scenarios, and proposes statutory revisions that (1) require the use of the UConn updates in lieu of the scenarios in the 2012 version of the NOAA Report, and (2) specify the means by which the UConn updates are promulgated.

A near-final draft of Statutory Adoption of Updated Sea-Level Rise Scenarios was provided to the DEEP in the fall of 2017. This draft provided the basis for the sea level change provisions of Governor's Bill S.B. 7, which was introduced into the 2018 legislative session and was enacted into law as Public Act 18-82. Among other things, this legislation requires the use of UConn sea level rise projections wherever a "rise in sea level" or "sea level change" is invoked by Connecticut statutes, thus resolving the statutory incongruence identified by our research. The evolution and enactment of S.B. 7 and P.A. 18-82 is described later in this report.

Community Outreach Events

Community outreach events provided the second element of the Task 9 outreach triad. Most of these events were presented to government organizations such as planning and zoning commissions and councils of governments, or affinity groups with a special interest in shoreline climate resilience, such as the Connecticut Association of Flood Managers and the Connecticut chapter of the American Institute of Architects. These groups were solicited with direct contact via mail, email, or telephone, and through advertisements on the UConn-sponsored listserv for Connecticut Planning Professionals. A copy of the abstract that accompanied the solicitation for these presentations is provided in Section Two of Appendix G2.

Whenever possible, Task 9 community outreach events included a CIRCA scientist to present and explain the Task 2 sea level rise projections. In situations where time or resource restraints could not accommodate a presentation by a CIRCA scientist, the Task 2 sea level rise projections were introduced by CEEL. Either way, all of the community outreach events included a PowerPoint presentation, tailored to the audience and the available time, that addressed the five areas of study conducted under Task 9. Section Two of Appendix G2 of this report includes the CEEL PowerPoint slides from a typical "with CIRCA" presentation and from a typical "without CIRCA" presentation.

The CEEL Legal Research Fellow delivered the CEEL presentations at the community outreach events. When possible, the CEEL presentations were introduced by the CEEL Executive Director.

A total of sixteen community outreach events were organized and delivered under Task 9. These events were presented from March 28, 2017 through June 6, 2018, were delivered at sixteen different venues, and attracted a total of 517 attendees. A comprehensive tabulation of these community outreach events that includes dates, venues, presenters, duration, content and attendees is provided in Section Two of Appendix G2 to this report. The community outreach events were successful in reaching a diverse group of interested parties, including state legislators, municipal chief elected officials, state and municipal regulators, state and municipal officials, scientists, environmentalists, architects, engineers, flood managers, planners, lawyers, professors, students and members of the general public. Given the number and diversity of the attendees, it is not unreasonable to speculate that community outreach events were the most successful and influential deliverables of Task 9.

Capstone Conference

The capstone conference was the third and final element of the Task 9 outreach triad. This conference provided an all-day venue that presented the results from all of the tasks conducted under the Municipal Resilience Planning Assistance Project. This conference, entitled "Creating a Resilient Connecticut: A CIRCA Forum on Science, Planning, Policy & Law," included sessions that presented research results and applications, invited audience-based policy discussions with expert panelists, and described CIRCA-sponsored climate resilience projects.

Conference attendees were welcomed with remarks by Timothy Fisher, UConn School of Law Dean and Professor of Law and Joseph MacDougald, UConn Professor in Residence, Executive Director of UConn Center for Energy & Environmental Law, and CIRCA Director of Applied Research. This welcome was followed by opening remarks from Rob Klee, the commissioner of the Connecticut DEEP.

The first panel of the day presented the results of research conducted under the Municipal Resilience Planning Assistance Project. Dr. James O'Donnell, CIRCA Executive Director and UConn Professor of Marine Sciences, presented the results of his research on sea level rise in Long Island Sound. Dr. Manos Anagnostou, UConn Professor of Engineering , presented the results of a statewide riverine flood vulnerability assessment were presented by. The final presentation of this panel was on legal and policy analyses to support resilience measures, and was presented by William Rath, a Legal Research Fellow with the UConn Law Center for Energy & Environmental Law.

The morning session continued with a second panel of experts that presented the results of additional work conducted under the Municipal Resilience Planning Assistance Project. DeAva Lambert, an Environmental Analyst with the Connecticut Department of Energy & Environmental Protection Land & Water Resources Division, presented the results of, and applications for, the aerial photography conducted under Task 1 of this project. Dr. Christine Kirchhoff, UConn Assistant Professor of Engineering, presented the results of her research on the resilience of wastewater and drinking water systems. The morning sessions concluded with a presentation of vulnerability assessment and planning in New London, where UConn Associate Professor Landscape Architecture Peter Miniutti manipulated architectural models of the Bank Street waterfront as he described the various options that could improve the resilience of the waterfront while simultaneously enhancing the commercial prospects of this economically challenged section of the city.

The keynote speaker was introduced by Evonne Klein, Commissioner of the Connecticut Department of Housing. Ms. Klein spoke on the challenges of incorporating climate change considerations into strategic planning for Connecticut housing, and how these challenges present particular obstacles for affordable and low income housing.

Harriet Tregoning delivered the keynote address on “Connecticut's Future in a Disaster-Prone World.” As the Strategic Policy Advisor and Former Deputy Assistant Secretary of the Office of Community Planning and Development at the U.S. Department of Housing, Ms. Tregoning worked on homelessness and helped communities at the state to the local levels plan for resilience in the face of changing economic, social, and climate factors. Ms. Tregoning was also Director of the District of Columbia Office of Planning, where she oversaw the re-writing of the city’s zoning code and pushed for smart growth and a pedestrian and bike friendly city. She was formerly the Secretary of Planning in Maryland and Director of the Governors' Institute on Community Design. Ms. Tregoning also served as the Director of Development, Community and Environment at the United States Environmental Protection Agency where she launched the Smart Growth Network. In 2004, she was a Loeb Fellow at the Harvard Graduate School of Design. Ms. Tregoning's appearance was made possible through the UConn Law Center for Energy & Environmental Law, the conference's co-sponsor.

The afternoon session continued with an audience-based policy discussion with an expert panel. The panel was moderated by Harriet Tregoning, and was populated by George Bradner, Director, Connecticut Insurance Department, Sara Bronin, UConn Professor of Law and Hartford Planning and Zoning Commission, and Michael Piscitelli, AICP, Deputy Economic Development Administrator, City of New Haven and President, CT Chapter, American Planning Association. The panel focused on the keynote topic of "Connecticut's Future in a Disaster-Prone World," with a brief presentation from each panelist followed by questions from the audience.

The afternoon session concluded with a climate resilience project panel moderated by Katie Lund, the CIRCA Project Coordinator for the Municipal Resilience Planning Assistance Project. This panel presented the results of work funded by CIRCA with funds through the Municipal Resilience Planning Assistance Project. The presentation covered the following projects:

- "Southeastern Connecticut Critical Facilities Assessment," presented by Amanda Kennedy, Assistant Director, Southeastern Connecticut Council of Governments
- "Municipal Low Intensity Development Design and Enhancing Rural Resiliency in the Northwest Hills," presented by Joanna Wozniak-Brown, Regional Planner, Northwest Hills Council of Governments

- “Planning for Flood Resilient and Fish-Friendly Road-Stream Crossings,” presented by Mike Jastremski, Watershed Director, Housatonic Valley Association
- “Hartford Climate Stewardship Initiative and Green Infrastructure,” presented by Shubhada Kambli, Hartford Sustainability Coordinator
- “Coastal Road Flooding Study in Branford,” presented by Dr. James O’Donnell, CIRCA Executive Director and Professor of Marine Sciences

The conference attracted 129 registrants and a small number of walk-in attendees. Section Three of Appendix G2 provides a list of these registrants, the working agenda for the conference, the full conference program, and a copy of the CEEL PowerPoint presentation that was delivered at this conference.

Connecticut Public Act 18-82 - An Act Concerning Climate Change Planning and Resiliency.”

As described in the white paper on "Statutory Adoption of Updated Sea-Level Rise Scenarios,” the Task 9 research into Connecticut coastal and floodplain management law and policy identified an incongruence in the Connecticut statutes that mandate the consideration of sea level change during critical planning activities. Specifically, these statutes required state and municipal planners to use a series of 2012 NOAA sea level rise projections instead of the latest UConn updates to these projections. This was problematic because it required planners to consider global sea level rise projections developed in 2012 instead of the UConn updates to these projections which are specific to Long Island Sound and which, by law, must be updated at least once every ten years.

The Task 9 research also revealed that existing Connecticut statutes did not specify a means by which the UConn updates to the NOAA Report must be promulgated. This was problematic because the affected agencies need ready access to a controlled copy of the latest update, particularly if future use of the UConn updates was to be mandated by legislation.

The Center for Energy & Environmental Law brought these issues to the attention of the DEEP in May of 2017. The DEEP asked CEEL to fully explore this issue and to draft proposed legislation for further consideration. These issues were also brought to the attention of Connecticut state legislative leaders during an outreach presentation at the state capitol on September 6, 2017.

The Task 9 white paper on "Statutory Adoption of Updated Sea-Level Rise Scenarios" provides an in-depth examination of the incongruities in Connecticut sea level rise statutes and offered legislative language for their resolution. A draft of this white paper, provided to the DEEP in the fall of 2017, informed some of the basis for the sea level change provisions of a Governor's Bill entitled, “An Act Concerning Climate Change Planning and Resiliency." This bill was introduced to the Connecticut legislature as Senate Bill Number 7 in February of 2018. A copy of S.B. No. 7, highlighted to show the provisions that were advanced by Task 9, is included in Section Four of Appendix G2.

The Joint Environment Committee of the Connecticut legislature held a hearing on S.B. No. 7 on March 14, 2018. CEEL offered testimony at that hearing in support of the sea level rise provisions of the bill. Transcripts of the CEEL testimony on S.B. No. 7 are included in Section Four of F.

S.B. No. 7 received a "Joint Favorable" recommendation from the Environment Committee on March 22 and was filed with the Legislative Commissioners' office the following day. The bill was considered by the entire Senate on May 8, at which time an amended bill was offered by Senator Ted Kennedy, Jr. The scope of the amended bill was significantly narrower than the bill introduced by the governor, but nevertheless retained all of the sea level rise provisions inspired by the Task 9 white paper. The amended S.B. No. 7 passed the Senate by a vote of 34-2.

The House of Representatives took up the amended S.B. 7 on May 9 - the very last day of the 2018 legislative session. The amended bill passed the House without amendment by a vote of 137-11, and Governor Dannel Malloy signed the bill into law as Public Act 18-82 on June 6, 2016. A copy of P.A. 18-82, highlighted to show the provisions advanced by Task 9, is included in Section Four of Appendix G2

P.A. 18-82 resolves the statutory incongruence identified by our research. As enacted, this act refines the statute that requires UConn to periodically update Long Island Sound sea level rise projections by (1) clarifying the scientific basis for the update, (2) providing legislative authority for the promulgation of a single, time-referenced sea level change scenario, and (3) requiring the publication of the latest UConn update on the website maintained by DEEP. The act also specifies the use of the UConn sea level rise projections in all places where “a rise in sea level” or “sea level change” is invoked by Connecticut statutes. This legislative endorsement of the UConn sea level rise projections also resolves one of the issues identified in Task 10 by providing the highest possible "standard of authority" for municipalities that desire to implement coastal and floodplain management programs and practices based upon projected flood levels that exceed those associated with the historical "100 year flood."

Issues/Analysis for Future Consideration

Tabulation of Oceanfront State Coastal and Floodplain Management Decision Authority.

Early during the research for Task 9 it became apparent that when comparing state coastal and floodplain management programs, it would be useful to know how oceanfront states make coastal and floodplain management decisions. Specifically, it is useful to identify the elements of the management programs that require a decision, whether the decision falls under the coastal management program or the floodplain management program, whether the decision is legislative or administrative in nature, what party or organization is responsible for making the decision, and whether the administrative decisions must consider sea level rise.

For example, a coastal management decision item in Connecticut is whether a planned development will have an impact on coastal resources. Coastal resources seaward of the mean high water mark are under exclusive state jurisdiction, so legislative decisions regarding impact on coastal resources are made by the Connecticut state legislature and administrative decisions are made by the DEEP. Coastal resources landward of the Coastal Jurisdiction Line (CJL) are under exclusive municipal jurisdiction, so legislative decisions regarding these impact on coastal resources are made by the municipal legislative body, and administrative decisions are made by municipal authorities. The state shares jurisdiction with municipalities in the area between the mean high water mark and the CJL, so decisions affecting coastal resources in this area are made by combinations of the parties described above. None of the administrative decisions on this issue are required to consider sea level rise.

Our research identified a total of 23 important decision items associated with coastal and floodplain management programs, each one of which is likely to involve legislative and administrative decision makers at both the state and local level. Starting with Connecticut, these decision items were organized into a "Decision Authority Table" that identified each decision as coastal or floodplain management, identified the legislative decision and administrative makers, and noted whether the administrative decision maker was obligated to consider sea level rise when making the decision. The table was heavily footnoted to clarify decision items, account for jurisdictional issues, explain exceptions and conditions, and to provide statutory references.

The work under Task 9 produced draft Decision Authority Tables for eight of the twenty-two oceanfront states that have coastal management programs. Those tables, included in Section Five of Appendix G2 of this report, proved useful for the analysis and comparison of state programs and were particularly helpful to the understanding of the means by which coastal and floodplain management programs were implemented within the political and legal systems that are unique to each state. The resources available for Task 9 could not support the completion of these tables for all of the oceanfront states, but such a compilation would certainly be useful for future coastal management research and is recommended as a research task worthy of future consideration.

Implementation:

Subsequent to the conference which concluded the majority of the work of Task 9, several municipalities contacted CIRCA for help in implementing the recommendations from this Task. Many of these towns and cities used the white papers created for this task to inform the adoption of their regulations. To assist in the implementation, a professional architect was hired to work with CIRCA staff to develop individual, street scale, and neighborhood scale layered computer documents that depict illustrations of common resilience problems. These publicly available tools make reference to planning concepts developed throughout the project. The files contain computerized “layers” whose display can be toggled on and off. The documents are designed to assist town planners, engineers, and educators to communicate common resilience problems and solutions in a neutral setting that does not represent any single location but were developed by analyzing several Connecticut coastal communities and creating an amalgamation of their common challenges.

These files were used in a recent town meeting in a shoreline community. CIRCA staff presented them to a well-attended public meeting, to describe zones of shared risk and other planning concepts. The meeting included presentations of the scientific, planning, and legal work completed in this task and throughout the grant. Town officials and residents were highly receptive and, as a direct consequence of the presentation and information, formed a charter-level resilience committee to implement many of the concepts developed throughout this grant. A recent webinar, hosted by CIRCA, also, brought together two towns who are approaching this through different perspectives

Conclusion:

Task 9 began with policy and statutory research; Used that research to develop statutory and policy recommendations; Engaged in outreach to communication those recommendations; Assisted in statutory suggestions that changed the law of sea level rise; and, finally, held conferences and created tools to help towns adjust to the new statutory framework, adopt the Task 9 recommendations, and, finally, implement new regulatory and planning approaches to make their towns more resilient.

APPENDIX G2

TASK 9

Legal And Policy Analyses that Support State and Municipal Efforts to Implement Resiliency Measures

Section 1 – White Papers

- Floodplain Building Elevation Standards - Current Requirements & Enhancement Options for Connecticut Shoreline Municipalities
- Height Restrictions on Elevated Residential Buildings in Connecticut Coastal Floodplains
- Oceanfront State Coastal Management Programs
- Statutory Adoption of Updated Sea-Level Rise Scenarios

Section 2 – Community Outreach Events by the Center for Energy & Environmental Law (CEEL)

- Abstract and Speaker Biography
- Tabulation of Community Outreach Events
- Example Community Outreach Event PowerPoint Presentations
    - Typical CEEL Presentation When a CIRCA Scientist Presents Sea Level Rise Research Results
    - Typical CEEL Presentation When CEEL Presents Sea Level Rise Research Results

Section 3 – Capstone Conference - "Creating a Resilient Connecticut: A CIRCA Forum on Science, Planning, Policy & Law"

- Agenda
- Program
- CEEL Final Conference Presentation

Section 4 – An Act Concerning Climate Change Planning and Resiliency

- Governor's Bill S.B. No. 7
- Connecticut Public Act 18-82
- CEEL Testimony on S.B. No. 7

Section 5 – Tabulation of Oceanfront State Coastal and Floodplain Management Decision Authority

Section 6 – Summary of Task 9 Project Meetings

APPENDIX G2 - SECTION 1

WHITE PAPERS

Floodplain Building Elevation Standards - Current Requirements & Enhancement Options for Connecticut Shoreline Municipalities

Height Restrictions on Elevated Residential Buildings in Connecticut Coastal Floodplains

Oceanfront State Coastal Management Programs

Statutory Adoption of Updated Sea-Level Rise Scenarios

UCONN SCHOOL OF LAW
CENTER FOR ENERGY & ENVIRONMENTAL LAW

MUNICIPAL RESILIENCE PLANNING ASSISTANCE PROJECT

LAW & POLICY WHITE PAPER SERIES

Floodplain Building Elevation Standards

Current Requirements & Enhancement Options for Connecticut Shoreline Municipalities

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Connecticut Institute for Resilience and Climate Adaptation

Executive Summary

Elevating buildings above flood levels is a common and effective way to minimize damage from floodwaters, and is a key flood protection provision of the National Flood Insurance Program (NFIP). All Connecticut municipalities participate in the NFIP, and all have enacted floodplain regulations that meet or exceed NFIP requirements. Furthermore, Connecticut municipalities must also comply with the floodplain building elevation requirements of the Connecticut State Building Code, which in some cases exceed the minimum requirements of the NFIP.

The elevation requirements of both the NFIP and the Connecticut State Building Code are based upon the "BFE shown on federal flood insurance rate maps. These maps are prepared by the Federal Emergency Management Agency and the BFEs identified on the maps are based upon historical floods. This is problematic because the National Oceanic and Atmospheric Administration estimates that global sea levels could rise from one to more than eight feet above current levels by the year 2100. Locally, the Connecticut Institute for Resilience and Climate Adaptation recommends planning for a Long Island Sound sea level rise of one foot, eight inches by 2050. Given these projections for future sea level rise, elevating buildings to a BFE that is based upon historical flood levels is unlikely to keep them above damaging floodwaters.

Fortunately, the elevation requirements of the NFIP and the Connecticut State Building Code are expressed as *minimum* elevations, so municipalities are free to specify higher and more protective elevation requirements for floodplain buildings. As described in this paper, municipalities have the legal authority to mandate elevation in excess of the NFIP and Connecticut State Building Code minimums, and the incremental cost of adding additional height to an existing elevation project is low. Therefore, even though the NFIP and the Connecticut State Building Code do not consider sea level rise when establishing building elevation requirements, it is well within the ability and authority of shoreline communities to account for the effect of rising seas when establishing elevation requirements for buildings located within their floodplains.

This paper describes the following actions within existing municipal authority that will help Connecticut shoreline communities accommodate the Long Island Sound sea level rise projected for 2050, assure compliance with the elevation requirements of the Connecticut State Building Code, and enhance community resilience to flood events:

- increase building elevation and flood-proofing requirements,
- establish "Coastal A" zones to allow for more protective standards in the portions of "A" zones that are subject to wave effects, velocity flows, and erosion, and
- participate in the NFIP Community Rating System to improve overall floodplain resilience and to take advantage of NFIP premium discounts of up to forty-five percent.

These relatively minor changes to local floodplain regulations can help Connecticut shoreline municipalities comply with the State Building Code while improving resilience by adapting to the rising seas.

I. Introduction

Coastal flooding represents a tremendous threat to Connecticut infrastructure. According to estimates by the Federal Emergency Management Administration (FEMA), a "100 year flood" in Connecticut's four shoreline counties could cause property losses of more than $13 billion.[1] To further exacerbate this threat, climate scientists estimate that by 2050 this "100 year flood" will revisit the Connecticut coast, on average, not once every 100 years, but once every twelve-and-a-half to twenty-five years.[2]

The National Flood Insurance Program (NFIP) offsets some of the risk faced by floodplain property owners by reducing the probability of flood damage and by providing financial compensation should flood damage occur.[3] This program, administered by FEMA, makes federal flood insurance available to property owners in communities that impose a minimum standard of floodplain management regulation, generally imposed through zoning ordinances.[4] These floodplain management ordinances must adopt the FEMA Flood Insurance Rate Map (FIRM), implement a permit system for floodplain development, specify construction standards to ensure development does not interfere with natural flood and drainage patterns, and adopt building codes to assure that new and substantially improved buildings are protected from flood damage.[5] Every Connecticut municipality currently participates in the NFIP, and all have adopted at least the minimum floodplain management regulations required by the program.[6]

Among the building codes that must be adopted are requirements to elevate new and significantly improved structures above predicted floodwaters. Figure 1 identifies some of the key features of an elevated building, which start with a floodwater elevation called the *Base Flood Elevation* (BFE). BFE is the anticipated flood elevation that has a one percent chance of being equaled or exceeded any given year, and is sometimes called the "100 year flood."[7] The *base flood depth* is the distance between the grade and the BFE, where *grade* is the ground level immediately adjacent to the building. [8] The *building elevation* is the difference between the grade and the lowest floor of the building or, in areas subject to high velocity storm waves, the difference between the grade and the *lowest supporting horizontal structural member*. Finally, *freeboard* is any amount of building elevation above the BFE. [9]

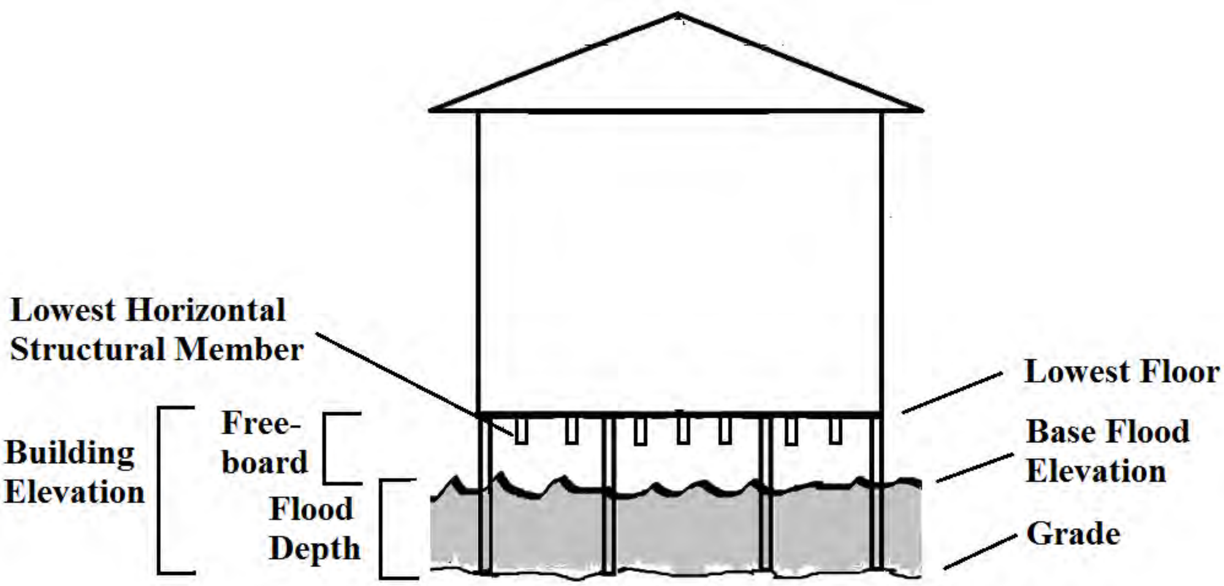

Figure 1 – Shoreline House Elevated on Pilings

The elevation requirements of the NFIP are relatively straightforward: habitable portions of new and substantially improved residential structures must be elevated to or above the BFE.[10] Non-residential structures must also be elevated to BFE or, as an alternative, flood-proofed to BFE. [11] In coastal areas subject to high velocity storm waves, both residential and non-residential structures are further protected by a requirement to elevate not just the lowest floor, but also the lowest supporting horizontal structural member to or above BFE. [12] Because all Connecticut towns participate in the NFIP, all shoreline towns have ordinances that meet these minimum elevation requirements for new and substantially improved structures.

In addition to the federal requirements of the NFIP, the state also specifies elevation requirements for floodplain buildings through the Connecticut State Building Code, which is the mandatory building code for all Connecticut cities, towns, and boroughs.[13] These code requirements vary depending on the use of the building and the severity of flooding, but the elevation and flood-proofing requirements of the Connecticut State Building Code are higher than BFE for all categories of buildings except for residential buildings in flood zones not subject to high velocity storm waves. [14] Interestingly, many shoreline communities still specify the less-restrictive NFIP elevation requirements in local floodplain management regulations, which may put them at odds with the minimum requirements of the state building code.[15]

It should be noted that both the NFIP and the Connecticut State Building Code identify *minimum* elevation requirements for new and substantially improved buildings in floodplains,[16] and that significant and cost-effective additional protection can be achieved by adding freeboard above these minimum requirements.[17] Studies indicate that adding freeboard at the time of initial construction is relatively inexpensive, with four feet of freeboard costing only about one to two percent more than the cost of elevating to BFE with a pile or masonry pier foundation.[18] Furthermore, adding freeboard significantly reduces insurance premiums, and FEMA estimates that the cost of adding freeboard can be recovered through reduced insurance premiums in six years in A Zones and in three years or less in V zones.[19] The significant benefits and low costs of adding freeboard are powerful incentives to increase municipal elevation requirements above the regulatory minimums.

This paper surveys the current floodplain building elevation requirements of Connecticut shoreline municipalities and identifies changes that can improve municipal flood resilience within the limitations of legal authorities. Section II starts this discussion with an evaluation of the legal authority that allows Connecticut municipalities to adopt floodplain management ordinances. Section III describes building elevation regulatory requirements and includes an explanation of the various types of flood zones that determine which of these requirements are invoked. Section IV identifies concerns related to sea level rise and Section V offers options that will allow Connecticut shoreline communities to accommodate sea level rise, assure compliance with the Connecticut State Building Code, and enhance the resilience of floodplain buildings. The conclusion in Section VI is followed by Appendix A, which identifies the elevation requirements of the NFIP, the current Connecticut State Building Code, the proposed 2018 Connecticut State Building Code, and Connecticut's twenty-four shoreline communities. Finally, Appendix B reproduces the FEMA definitions of the flood zones encompassed by the NFIP.

II. Legal Authority

The legal authority for communities to regulate land use through zoning ordinances is long and well established. The threshold case affirming this authority was in 1926, when the United States Supreme Court held that local land use zoning is a valid exercise of police power as long as the zoning ordinances are not "clearly arbitrary and unreasonable, having no substantial relation to the public health, safety, morals, or general welfare."[20]

In Connecticut, municipalities derive their zoning authority from the state through a general zoning enabling act passed in 1925 and revised and reenacted in 1949.[21] These acts, now codified in Title 8 of the Connecticut General Statutes, empower municipalities to establish zoning commissions, designate zoning districts, and enact zoning ordinances that, "regulate the erection, construction, reconstruction, alteration or use of buildings or structures and the use of land."[22] In fact, section 8-2 of the Connecticut General Statutes specifically allows zoning ordinances that regulate to "secure safety from … flood and other dangers."[23] This statutory language gives Connecticut municipalities the explicit authority to specify construction standards for buildings erected in floodplains.

Communities that adopt zoning ordinances must also establish a zoning board of appeals that is empowered to review municipal zoning decisions and grant variances where special circumstances unique to a particular parcel of land would cause "exceptional difficulty or unusual hardship" if the zoning ordinances were enforced as written.[24]

This variance process provides an important protection for land owners who, through no fault of their own, are confronted with unique circumstances that don't allow them to comply with certain provisions of local zoning ordinances.

The combination of explicit delegation of state authority and a guarantee of due process through the variance process provides a strong legal authority for municipal zoning ordinances that specify construction standards for buildings erected in floodplains. This authority is so strong, in fact, that it has never been challenged in the Connecticut Appellate or Supreme Courts.

III. Elevation Requirements

A. Overview and Flood Zone Terminology

The NFIP and the Connecticut State Building Code specify mandatory minimum elevation and flood-proofing requirements for all new and substantially improved buildings located in floodplains.[25] Non-mandatory consensus standards and FEMA guidelines recommend more protective elevation and flood-proofing levels that are above these mandatory minimums.[26] Connecticut municipalities are required to meet the mandatory requirements of the NFIP and Connecticut State Building Code, but because these requirements are minimums, municipalities are free to adopt more stringent standards for elevation and flood-proofing.[27]

All of these elevation and flood-proofing standards, irrespective of the source, specify different protective requirements for different types of flood hazards. These different types of flood hazards are conveniently identified as different categories of "flood zones" on a FEMA Flood Insurance Rate Map, or FIRM.[28] A copy of the FEMA definitions for the various types of flood zones identified on a FIRM is provided in Appendix B of this paper.

Flood zones on the FIRMs for Connecticut shoreline municipalities are categorized as "Special Flood Hazard Areas," "Coastal High Hazard Areas," or "Other Flood Areas." Special Flood Hazard Areas are areas with a one percent annual chance flood ("100 year flood zones"),[29] and are designated as zones AE and AO on FIRMs.[30] Coastal High Hazard Areas are Special Flood Hazard Areas along an open coast that are subject to high velocity wave action from storms,[31] and are designated as zone VE on FIRMs.[32] Other Flood Areas, also known as "Areas of Moderate Flood Hazards," are areas with a 0.2 percent annual chance flood ("500 year flood zones"), [33] and are designated zone X on FIRMs.[34]

The flood elevation in Special Flood Hazard Areas is called the "Base Flood Elevation" or, as noted earlier, "BFE."[35] This BFE is indicated on the FIRMs for AE and VE zones.[36]

In addition to the flood zones described above, NFIP communities may wish to adopt a "Coastal A" zone to provide greater protection for AE Zone structures that are subject to additional damage by wave action. If adopted, a Coastal A zone is the area on a FIRM that lies between the landward edge of the VE zone and an advisory line on the FIRM that indicates the limit of the predicted 1.5 foot wave height during the base flood.[37]

The remainder of this section describes the elevation requirements specified for these flood zones by FEMA under the NFIP, the Connecticut State Building Code, and Connecticut Shoreline Municipalities.

B. FEMA NFIP Elevation Requirements

The FEMA standards for floodplain building elevation and flood-proofing requirements are set forth in Title 44 of the Code of Federal Regulations. In AO zones, where BFEs are not specified, these regulations require the lowest floor of new and substantially improved residential structures to be elevated at least as high as the shallow flood depth shown on the FIRM or, if no flood depth is specified, at least two feet above the highest adjacent grade.[38] The lowest floors of non-residential structures in AO zones have the same elevation requirements, or, as an alternative to elevation, the lowest floors of non-residential structures may be flood-proofed to the same levels specified for elevation.[39]

In AE zones, the FEMA standards require the lowest floor of new and substantially improved residential structures must be elevated to or above the BFE.[40] The lowest floors of non-residential structures in AE zones are also required to be elevated to or above the BFE, or alternatively, flood-proofed to or above the BFE.[41]

In coastal high-hazard VE Zones, the same FEMA requirements apply to all structures, both residential and non-residential. In these zones, the lowest supporting horizontal structural member of the lowest floor must be elevated to or above the BFE.[42]

It should be noted that the mandatory elevation requirements set forth in Title 44 of the Code of Federal Regulations are regulatory minimums, and that FEMA encourages elevating buildings above these minimums. For example, the FEMA "Home Builder's Guide to Coastal Construction" recommends elevating new and substantially improved residential buildings to achieve three feet of freeboard above the freeboard specified in American Society of Civil Engineers standard ASCE 24-14, "Flood Resistant Design and Construction."[43] Implementing this recommendation will result in four feet of freeboard above BFE for most residential buildings.

C. Connecticut State Building Code Elevation Requirements for Residential Structures

The current Connecticut State Building Code, adopted in 2016, invokes the 2012 International Residential Code (IRC) for residential structures, which includes one- and two-family detached structures and townhouses.[44] The IRC elevation standards are based upon a "Design Flood Elevation" (DFE) that is equivalent to either the BFE or a higher elevation designated on a community's flood hazard map.[45] The DFE concept recognizes that flood-prone communities may want to enhance protection against floods by adopting flood elevations that exceed the BFE published on FIRMs.

In AO zones, the 2012 IRC requires the lowest floor of new and substantially improved residential structures to be elevated at least as high as the shallow flood depth shown on the FIRM, or if no flood depth is specified, at least two feet above the highest adjacent grade.[46] In AE zones, the lowest floor must be elevated to or above the DFE,[47] and in Coastal A Zones the lowest floor must be elevated to or above the DFE, or to the BFE plus one foot, whichever is higher.[48] In VE Zones, the lowest structural member of a residential structure must be elevated to or above the DFE if the member is parallel to the direction of wave approach, or if the member is perpendicular to the direction of wave approach, to or above the DFE or the BFE plus one foot, whichever is higher.[49]

The proposed 2018 Connecticut State Building Code invokes the 2015 revision of the IRC, [50] which increases the elevation requirements for AE, Coastal A, and VE zones above those specified by the 2016 Connecticut State Building Code. [51] The elevation requirements for AO Zones remain unchanged, but in AE zones the 2015 IRC requires the lowest floor of new and substantially improved residential structures to be elevated to or above the DFE, or to or above the BFE plus one foot, whichever is higher.[52] In this revision of the IRC, the elevation specifications for residential structures in Coastal A zones are now the same as for residential structures in VE zones, and the lowest supporting horizontal structural member in both zones must be elevated or above DFE, or BFE plus one foot, whichever is higher.[53]

D. Connecticut State Building Code Elevation Requirements for Non-Residential Structures

The current 2016 Connecticut State Building Code adopts the 2012 International Building Code (IBC) for all structures other than one- and two-family dwellings and townhouses.[54] For buildings and structures located in floodplains, the 2012 IBC invokes American Society of Civil Engineers standard ASCE 24-05, "Flood Resistant Design and Construction."[55] Included among the standards in ASCE 24-05 are elevation requirements for buildings and structures located in floodplains.

ASCE 24-05 identifies four different "Flood Design Classes" based upon the use and occupancy of buildings in flood hazard areas.[56] The information provided here for "Non-Residential Structures" is for "Flood Design Class 2" buildings, which represent the majority of non-residential buildings in flood hazard areas. Importantly, ASCE 24-05 specifies more stringent requirements for buildings and structures that pose a high risk to the public and for essential facilities necessary for emergency response and recovery. Refer to ASCE 24-05 for elevation requirements for those facilities.

ASCE 24-05 requires the lowest floor of most non-residential buildings in AE zones to be elevated to the DFE, or to the BFE plus one foot, whichever is higher.[57] Alternatively, such buildings have the option of flood-proofing to either the DFE, or to the BFE plus one foot, whichever is higher.[58] In high-velocity Coastal A and VE Zones, these non-residential structures are required to elevate the bottom of the lowest supporting horizontal structural member to or above the DFE if the member is parallel to the direction of wave approach, or if the member is perpendicular to the direction of wave approach, to or above the DFE or the BFE plus one foot, whichever is higher.[59] Flood-proofing in lieu of elevation is not an option for non-residential structures in Coastal A or VE zones.[60]

The proposed 2018 Connecticut State Building Code invokes the 2015 revision of the IBC,[61] which in turn invokes ASCE 24-14, an updated version of ASCE 24-05.[62] The non-residential building elevation and flood-proofing requirements invoked by ASCE 24-14 are similar to those invoked by ASCE 24-05 except that the Coastal A and VE zone elevation requirements are not dependent upon the orientation of the lowest supporting horizontal structural member. Under ASCE 24-14, and by extension the proposed 2018 Connecticut State Building Code, the lowest supporting horizontal structural member of non-residential buildings and structures in Coastal A and VE zones must be elevated to the DFE or to BFE plus one foot, whichever is higher, irrespective of the wave orientation of that member.[63]

E. Connecticut Shoreline Municipality Elevation Requirements

All Connecticut shoreline municipalities participate in the NFIP,[64] so by necessity each of those municipalities has floodplain building ordinances that meet the minimum NFIP elevation requirements. However, not all communities have updated their building elevation ordinances to remain current with changes in the Connecticut State Building Code. As a result, many shoreline communities specify NFIP elevation requirements in local floodplain management ordinances that do not meet the minimum requirements of the Connecticut State Building Code.[65]

Appendix A to this paper summarizes the elevation and flood-proofing requirements of the NFIP, the 2016 Connecticut State Building Code, the proposed 2018 Connecticut State Building Code, and Connecticut shoreline municipalities. Of the twenty-four shoreline municipalities shown on this summary, eleven have floodplain ordinances that meet or exceed the elevation standards of both the NFIP and the Connecticut State Building Code and thirteen have floodplain management ordinances that meet NFIP requirements but are less restrictive than the current requirements of the Connecticut State Building Code.

Most of the discrepancies between local ordinances and the Connecticut State Building Code are related to elevation and flood-proofing requirements for non-residential structures as specified in ASCE 24-05. The requirements of ASCE 24-05 are more stringent than the older FEMA NFIP standards, and apply to buildings in Connecticut floodplains because the current 2016 Connecticut State Building Code invokes the 2012 IBC, which in turn invokes ASCE 24-05.[66] Therefore, municipalities that have not updated their elevation requirements for non-residential buildings to the specifications of ASCE 24-05 have elevation requirements that are less stringent than those specified by the current Connecticut State Building Code.

The other point of discrepancy between local floodplain management ordinances and the Connecticut State Building Code is the elevation requirement for residential buildings in high velocity VE zones. The Connecticut State Building Code invokes the requirements of the 2012 IRC,[67] which requires the lowest supporting horizontal structural member to be elevated to the DFE if the member is parallel to the direction of wave approach, or to the BFE plus one foot or the DFE (whichever is higher) if the member is perpendicular to the direction of wave approach.[68] This elevation requirement is more stringent than the requirement of the FEMA NFIP, which calls for the lowest supporting horizontal structural member to be elevated to BFE irrespective of the direction of wave approach.[69]

IV. Sea Level Rise Concerns

The BFEs identified on FEMA FIRMs are based upon the flood levels associated with a historical "100 year flood."[70] These historical flood levels are a good starting point for flood planning, but there is scientific consensus that sea levels are rising above these historic levels. Tide gauge records indicate an average global sea level rise of 190 millimeters, or about seven-and-a-half inches, between 1901 and 2010.[71] Recent measurements with more sophisticated instruments indicate an average rise of 3.2 millimeters a year between 1993 and 2010, which is nearly twice the average annual rise of the entire period between 1901 and 2010.[72] Simply extrapolating this 3.2 millimeters per year out to 2100 indicates a sea level rise of another 262 millimeters - more than ten inches. When the latest climate science is factored in, the National Oceanic and Atmospheric Administration (NOAA) estimates that global sea levels could rise from 0.3 to 2.5 meters by 2100 – a rise from one to more than eight feet above current levels.[73] Locally, the Connecticut Institute for Resilience and Climate Adaptation (CIRCA) recommends planning for a Long Island Sound sea level rise of 0.5 meters – twenty inches - by 2050.[74] Given these predictions for future sea level rise, it is reasonable to expect that elevating buildings to historical flood levels is unlikely to keep them above damaging floodwaters in the future.

The local conditions of Long Island Sound also argue against using historical data as the sole basis for determining floodplain building elevation requirements. As noted above, studies by CIRCA indicate a 0.5 meter sea level rise in Long Island Sound by the year 2050.[75] These studies also indicate that this rise in sea level will increase the return rate of the "100 year flood" levels experienced by shoreline municipalities and, because of the geography and geometry of the Sound and the adjacent Connecticut shoreline, disproportionately affect municipalities depending upon their location east to west.[76] As shown in Figure 2, a 0.5 meter increase in sea level could result in a fourfold increase in flooding to the current "100 year flood" level in western sound communities, and an eightfold increase in floods to this level in eastern sound communities. These data suggest that flooding to the current BFEs, which are based upon the historical "100 year flood," will be revisited, on average, somewhere between once every twenty-five years to once every twelve-and-a-half years, depending upon where the community is located on Long Island Sound.

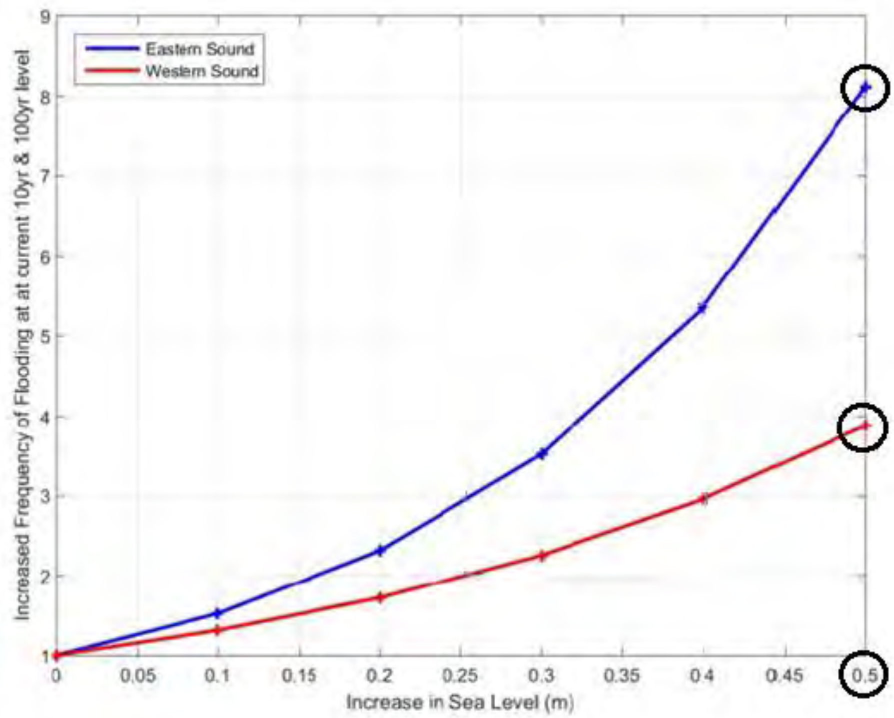

Figure 2 – Increase Flood Frequency with Long Island Sound Sea Level Rise[77]

Given the projected sea level rise in Long Island Sound and the increased frequency of flooding to the current "100 year" levels, it is reasonable to expect that elevating buildings to the current BFE will not provide adequate protection against likely future conditions

V. Enhancement Options

As described earlier in this paper, it is well within the legal authority of Connecticut municipalities to enact zoning ordinances that "secure safety from . . . flood and other dangers."[78] This paper describes the following municipal actions within that authority that can help Connecticut shoreline communities accommodate the Long Island Sound sea level rise projected for 2050, assure compliance with the elevation requirements of the Connecticut State Building Code, and enhance community resilience to flood events:

- increase building elevation requirements,
- establish a "Coastal A" zone, and
- participate in the NFIP community rating system.

These actions are further described below.

A. Increase Building Elevation Requirements

Elevating buildings above flood levels is an effective means of minimizing damage from floodwaters,[79] and FEMA regulations specify minimum elevation requirements for new and substantially improved buildings in communities that participate the NFIP.[80] FEMA recognizes, however, the limitations of these regulatory requirements and recommends elevating buildings above the NFIP minimums.[81] This paper offers three options for municipal actions to increase floodplain building elevation requirements above NFIP minimums: (1) Adopt the minimum elevation standards specified in the Connecticut State Building Code, (2) consider adopting the elevation standards specified in ASCE 24-14, and (3) consider adding at least two feet of freeboard above the FIRM BFE.

1. Adopt the Minimum Elevation Requirements of the Connecticut State Building Code

The Connecticut State Building Code is the mandatory building code for all Connecticut towns, cities, and boroughs.[82] Municipalities that have floodplain ordinances that do not meet current Connecticut State Building Code elevation requirements should consider revising those ordinances to comply with the requirements of the state code.

2. Consider Adopting the Elevation Standards Specified in ASCE 24-14

ASCE 24-14 is a consensus standard for "Flood Resistant Design and Construction" adopted by the American Society of Civil Engineers. This standard, which is revised at least once every five years, is a compilation of recognized engineering principles and is developed and adopted in accordance with a consensus standard process that has been accredited by the American National Standards Institute.[83] The flood protection requirements of ASCE 24-14 exceed the NFIP minimums and meet or exceed the minimum requirements of the Connecticut State Building Code. Municipalities should consider adopting the elevation and other requirements ASCE 24-14 because FEMA deems ASCE 24-14 to meet or exceed the minimum National Flood Insurance Program (NFIP) requirements for buildings and structures and notes that, "Buildings and structures designed according to ASCE 24 are better able to resist flood loads and flood damage."[84] The Connecticut shoreline towns of Clinton, Old Saybrook, and Waterford have already imposed elevation standards for new or substantially improved structures that meet the requirements of ASCE 24-14 for most floodplain buildings.[85]

3. Consider Adding at Least Two Feet of Freeboard Above the FIRM Base Flood Elevation

As noted in Section IV of this paper, FEMA building elevation requirements are based upon the flood levels associated with the historical "100 year flood," and those flood levels do not account for future conditions such as sea level rise.[86] Given that studies by the Connecticut Institute for Resilience and Climate Adaptation indicate a Long Island Sound sea level rise of twenty inches (0.5 meters) by the year 2050,[87] municipalities should consider adopting a freeboard requirement of at least two feet above the current FIRM BFE for residential structures with a service life of at least thirty years and even greater freeboard requirements for infrastructure facilities with longer anticipated service lives. The viability of such a freeboard requirement is demonstrated by the Connecticut shoreline city of New London, which has already adopted two feet of freeboard above the current BFE as the elevation standard for all new or substantially improved structures in flood hazard areas.

B. Establish a "Coastal A" Zone

Coastal A Zones encompass the area on FIRMs between the landward side of V or VE Zones and a further landward line denoting the "limit of moderate wave action." [88] Coastal A Zones are not marked on FIRMs because they are not a separate insurance zone under the NFIP,[89] but FEMA encourages communities to identify Coastal A Zones and regulate them in the same manner as V and VE Zones.[90] This is because ordinary A Zone construction standards do not provide adequate protection in areas that are subject to the wave effects, velocity flows, and erosion conditions that are typical of Coastal A zones.[91] Furthermore, the international codes invoked by the 2016 Connecticut State Building Code require the establishment of a Coastal A Zones and set forth elevation and other requirements for new and substantially improved building and structures within Coastal A Zones.[92] Shoreline communities that have not already done so should therefore consider establishing Coastal A zones to improve the resilience of A Zone buildings subject wave effects, velocity flows, and erosion and to support compliance with the requirements of the Connecticut State Building Code. Coastal A zones are already in place in the Connecticut shoreline communities of Clinton, Groton, Old Saybrook, Waterford, and Westbrook.

C. Participate in the NFIP Community Rating System

The Community Rating System (CRS) is a program designed to encourage communities to implement floodplain management and loss control activities that go beyond the minimum requirements of the NFIP.[93] Communities can earn flood insurance discounts of up to forty-five percent by accumulating "credits" for activities that improve floodplain mapping, tighten regulatory requirements, enhance public information activities, reduce flood damage, and improve flood preparedness.[94] Freeboard requirements alone can achieve a five percent discount on flood insurance,[95] so any community considering increasing floodplain elevation requirements above the BFE should consider the financial benefits of participating in the Community Rating System. The Connecticut shoreline communities of East Haven, East Lyme, Fairfield, Milford, Norwalk, Stamford, Stonington, Westbrook, and Westport currently participate in the Community Rating System.[96]

VI. Conclusion

Connecticut shoreline communities have adopted floodplain building elevation standards as a condition of participation in the NFIP. All of these communities meet the minimum elevation requirements of the program, but those minimums are unlikely to provide adequate protection in the face of rising seas and increasing flood return rates. Communities that increase floodplain building elevation standards beyond the minimums, adopt Coastal A Zones, and participate in the Community Rating System will be better prepared for a more resilient future.

APPENDIX A

MINIMUM ELEVATION AND FLOOD PROOFING REQUIREMENTS

(For New and Substantially Improved Construction as of September 1, 2017)

AUTHORITY	ZONE	RESIDENTIAL STRUCTURES	NON-RESIDENTIAL STRUCTURES	CODE, ORDINANCE, OR REGULATION
NFIP / FEMA	A / AE	Lowest Floor Elevated to BFE	Lowest Floor Elevated to BFE ***OR*** Flood-proofed to BFE	44 CFR 60.3.c.2, c.3
	V / VE	Lowest Horizontal Structural Member Elevated to BFE	Lowest Horizontal Structural Member Elevated to BFE	44 CFR 60.3.e.4
2016 Connecticut State Building Code **(IRC 2012)** **(IBC 2012)** (See Footnote [97])	A / AE	Lowest Floor Elevated to DFE	Lowest Floor Elevated to BFE + 1' or DFE (Whichever is Higher) ***OR*** Flood-proofed to BFE + 1' or DFE (Whichever is Higher)	
	Coastal A / AE	Lowest Floor Elevated to BFE + 1' or DFE (Whichever is Higher)	Lowest Horizontal Structural Member Elevated to: • DFE if Parallel to Wave Approach **OR** • BFE + 1' or DFE, Whichever is Higher, if Perpendicular to Wave Approach	
	V / VE	Lowest Horizontal Structural Member Elevated to: • DFE if Parallel to Wave Approach **OR** • BFE + 1' or DFE (Whichever is Higher) if Perpendicular to Wave Approach	Lowest Horizontal Structural Member Elevated to: • DFE if Parallel to Wave Approach **OR** • BFE + 1' or DFE (Whichever is Higher) if Perpendicular to Wave Approach	
Proposed 2018 Connecticut State Building Code **(IRC 2015)** **(IBC 2015)** (See Footnote [98])	A / AE	Lowest Floor Elevated to BFE + 1', or DFE	Lowest Floor Elevated to BFE + 1' or DFE (Whichever is Higher) ***OR*** Flood-proofed to BFE + 1' or DFE (Whichever is Higher)	
	Coastal A / AE	Lowest Supporting Horizontal Structural Member Elevated to BFE + 1', or DFE, Whichever is Higher	Lowest Supporting Horizontal Structural Member Elevated to BFE + 1' or DFE (Whichever is Higher)	
	V / VE	Lowest Supporting Horizontal Structural Member Elevated to BFE + 1', or DFE, Whichever is Higher	Lowest Supporting Horizontal Structural Member Elevated to BFE + 1' or DFE (Whichever is Higher)	
Branford	A / AE	Lowest Floor Elevated to BFE + 1'	Lowest Floor Elevated to BFE + 1' ***OR*** Flood-proofed to BFE + 1'	Branford Code of Ordinances 161-18
	Coastal A / AE	No Specific Standards for Coastal A / AE	No Specific Standards for Coastal A / AE	
	V / VE	Lowest Supporting Horizontal Structural Member Elevated to BFE + 1'	Lowest Supporting Horizontal Structural Member Elevated to BFE + 1'	Branford Code of Ordinances 161-19
Bridgeport	A / AE	Lowest Floor Elevated to BFE	Lowest Floor Elevated to BFE ***OR*** Flood-proofed to BFE + 1'	Bridgeport Code of Ordinances 15.44.150.B.1, B.3
	Coastal A / AE	No Specific Standards for Coastal A / AE	No Specific Standards for Coastal A / AE	
	V / VE	Lowest Supporting Member Elevated to BFE	Lowest Supporting Member Elevated to BFE	Bridgeport Code of Ordinances 15.44.150.C.2

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(For New and Substantially Improved Construction as of September 1, 2017)

AUTHORITY	ZONE	RESIDENTIAL STRUCTURES	NON-RESIDENTIAL STRUCTURES	CODE, ORDINANCE, OR REGULATION
Clinton	A / AE	Lowest Floor Elevated to BFE + 1’	Lowest Floor Elevated to BFE + 1’ ***OR*** Flood-proofed to BFE + 1’	Clinton Zoning Regulations 17.6
	Coastal A / AE	Lowest Supporting Member to BFE + 1'	Lowest Supporting Member to BFE + 1'	Clinton Zoning Regulations 17.8, 17.9
	V / VE	Lowest Supporting Member Elevated to BFE + 1'	Lowest Supporting Member Elevated to BFE + 1'	Clinton Zoning Regulations 17.8
Darien	A / AE	Lowest Floor Elevated to BFE + 1’	Lowest Floor Elevated to BFE + 1' ***OR*** Flood-proofed to BFE	Darien Zoning Regulations 825.d.6, 825.d.7
	Coastal A / AE	No Specific Standards for Coastal A / AE	No Specific Standards for Coastal A / AE	
	V / VE	Lowest Structural Member Elevated to BFE + 1'	Lowest Structural Member Elevated to BFE + 1'	Darien Zoning Regulations 825.f.2
East Haven	A / AE	Lowest Floor Elevated to BFE	Lowest Floor Elevated to BFE ***OR*** Flood-proofed to BFE + 1’	East Haven Ordinances 9-78(a)
	Coastal A / AE	No specific standards for Coastal A / AE	No specific standards for Coastal A / AE	
	V / VE	Lowest Horizontal Structural Member Elevated to BFE	Lowest Horizontal Structural Member Elevated to BFE	East Haven Ordinances 9-78(b)
East Lyme	A / AE	Lowest Floor Elevated to BFE	Lowest Floor Elevated to BFE ***OR*** Flood-proofed to BFE	East Lyme Zoning Regulations 15.5.2
	Coastal A / AE	No Specific Standards for Coastal A / AE	No Specific Standards for Coastal A / AE	
	V / VE	Lowest Horizontal Structural Member Elevated to BFE	Lowest Horizontal Structural Member Elevated to BFE	East Lyme Zoning Regulations 15.5.3
Fairfield	A			
	AE	Lowest Floor Elevated to BFE (See Footnote [99])	Lowest Floor Elevated to BFE ***OR*** Flood-proofed to BFE + 1'	Fairfield Zoning Regulations 32.3
	Coastal A / AE	No Specific Standards for Coastal A / AE	No Specific Standards for Coastal A / AE	
	V / VE	Lowest Structural Member Elevated to BFE	Lowest Structural Member Elevated to BFE	Fairfield Zoning Regulations 32.5
Greenwich	A / AE	Lowest Floor Elevated to BFE + 1'	Lowest Floor Elevated to BFE + 1' ***OR*** Flood-proofed to BFE + 1'	Greenwich Municipal Code §6-139.1.f.11
	Coastal A / AE	No Specific Standards for Coastal A / AE	No Specific Standards for Coastal A / AE	
	V / VE	Lowest Supporting Horizontal Member Elevated to BFE + 1'	Lowest Supporting Horizontal Member Elevated to BFE + 1'	Greenwich Municipal Code §6-139.1.f.12

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AUTHORITY	ZONE	RESIDENTIAL STRUCTURES	NON-RESIDENTIAL STRUCTURES	CODE, ORDINANCE, OR REGULATION
Groton	A / AE	Lowest Floor Elevated to BFE	Lowest Floor Elevated to BFE ***OR*** Flood-proofed to BFE	Groton Zoning Regulations 6.6-4
	Coastal A / AE	Lowest Floor Elevated to BFE + 1'	Lowest Floor Elevated to BFE ***OR*** Flood-proofed to BFE	Groton Zoning Regulations 6.6-5
	V / VE	Lowest Floor's Structural Members Elevated to BFE + 1'	Lowest Floor's Structural Members Elevated to BFE + 1'	Groton Zoning Regulations 6.6-7
Guilford	A / AE	Lowest Floor Elevated Above BFE	Lowest Floor Elevated Above BFE ***OR*** Flood-proofed Above BFE	Guilford Ordinances 174-18
	Coastal A / AE	No Specific Standards for Coastal A / AE	No Specific Standards for Coastal A / AE	
	V / VE	Lowest Supporting Horizontal Member Elevated to BFE	Lowest Supporting Horizontal Member Elevated to BFE	Guilford Ordinances 174-19
Madison	A / AE	Lowest Floor Elevated to BFE	Lowest Floor Elevated to BFE ***OR*** Flood-proofed to BFE	Madison Floodplain Management Ordinances 9-33
	Coastal A / AE	No Specific Standards for Coastal A / AE	No Specific Standards for Coastal A / AE	
	V / VE	Lowest Supporting Horizontal Member Elevated to BFE	Lowest Supporting Horizontal Member Elevated to BFE	Madison Floodplain Management Ordinances 9-34
Milford	A / AE	Lowest Floor Elevated to BFE	Lowest Floor Elevated to BFE ***OR*** Flood-proofed to BFE	Milford Zoning Regulations 5.8.13
	Coastal A / AE	No Specific Standards for Coastal A / AE	No Specific Standards for Coastal A / AE	
	V / VE	Lowest Supporting Member Elevated to BFE	Lowest Supporting Member Elevated to BFE	Milford Zoning Regulations 5.8.14
New Haven	A / AE	Lowest Floor Elevated to BFE + 1’	Lowest Floor Elevated to BFE + 1’ ***OR*** Flood-proofed to BFE + 1’	New Haven Flood Damage Prevention Ordinances 5.3.1
	Coastal A / AE	No Specific Standards for Coastal A / AE	No Specific Standards for Coastal A / AE	
	V / VE	Lowest Structural Horizontal Member Elevated to BFE + 1’	Lowest Structural Horizontal Member Elevated to BFE + 1’	New Haven Flood Damage Prevention Ordinances 5.3.4
New London	A / AE	Lowest Floor Elevated to BFE + 2’	Lowest Floor Elevated to BFE + 2’ ***OR*** Flood-proofed to BFE + 1’	New London Zoning Regulations 830.D.4, D.5
	Coastal A / AE	No Specific Standards for Coastal A / AE	No Specific Standards for Coastal A / AE	
	V / VE	Lowest Supporting Member Elevated to BFE + 2’	Lowest Supporting Member Elevated to BFE + 2’	New London Zoning Regulations 830.E.2

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MINIMUM ELEVATION AND FLOOD PROOFING REQUIREMENTS

(For New and Substantially Improved Construction as of September 1, 2017)

AUTHORITY	ZONE	RESIDENTIAL STRUCTURES	NON-RESIDENTIAL STRUCTURES	CODE, ORDINANCE, OR REGULATION
Norwalk	A			
	AE (See Footnote [100])	Lowest Floor Elevated to BFE + 1’	Lowest Floor Elevated to BFE + 1’ ***OR*** Flood-proofed to BFE + 1’	Norwalk Zoning Regulations Article 110.C.4, 5
	Coastal A / AE	No Specific Standards for Coastal A / AE	No Specific Standards for Coastal A / AE	
	V / VE	Lowest Horizontal Structural Member Elevated to BFE + 1’	Lowest Horizontal Structural Member Elevated to BFE + 1’	Norwalk Zoning Regulations Article 110.C.6
Old Lyme	A / AE	Lowest Floor Elevated to BFE + 1’	Lowest Floor Elevated to BFE + 1’ ***OR*** Flood-proofed to BFE + 1’	Old Lyme Zoning Regulations 4.4.6.4
	Coastal A / AE	No Specific Standards for Coastal A / AE	No Specific Standards for Coastal A / AE	
	V / VE	Lowest Horizontal Supporting Member Elevated to BFE + 1’	Lowest Horizontal Supporting Member Elevated to BFE + 1’	Old Lyme Zoning Regulations 4.4.6.5
Old Saybrook	A / AE	Lowest Floor Elevated to BFE + 1’	Lowest Floor Elevated to BFE + 1’ ***OR*** Flood-proofed to BFE + 1’	Old Saybrook Ordinances 128-20
	Coastal A / AE	Lowest Supporting Horizontal Member Elevated to BFE + 1’	Lowest Supporting Horizontal Member Elevated to BFE + 1’	Old Saybrook Ordinances 128-20
	V / VE	Lowest Supporting Horizontal Member Elevated to BFE + 1’	Lowest Supporting Horizontal Member Elevated to BFE + 1’	Old Saybrook Ordinances 128-20
Stamford	A / AE	Lowest Floor Elevated to BFE + 1’	Lowest Floor Elevated to BFE + 1’ ***OR*** Flood-proofed to BFE + 1’	Stamford Zoning Regulations 7.1.D.1
	Coastal A / AE	No Specific Standards for Coastal A / AE	No Specific Standards for Coastal A / AE	
	V / VE	Lowest Supporting Horizontal Member Elevated Above BFE + 1’	Lowest Supporting Horizontal Member Elevated Above BFE + 1’	Stamford Zoning Regulations 7.1.D.3
Stonington	A / AE	Lowest Floor Elevated to BFE + 1’	Lowest Floor Elevated to BFE + 1’ ***OR*** Flood-proofed to BFE + 1’	Stonington Zoning Regulations 7.7.8.2
	Coastal A / AE	No Specific Standards for Coastal A / AE	No Specific Standards for Coastal A / AE	
	V / VE	Lowest Supporting Horizontal Member Elevated to BFE + 1’	Lowest Supporting Horizontal Member Elevated to BFE + 1’	Stonington Zoning Regulations 7.7.8.3
Stratford	A / AE	Lowest Floor Elevated to BFE	Lowest Floor Elevated to BFE ***OR*** Flood-proofed to BFE	Stratford Ordinances 102-18
	Coastal A / AE	No Specific Standards for Coastal A / AE	No Specific Standards for Coastal A / AE	
	V / VE	Lowest Horizontal Supporting Member Elevated to BFE + 1’	Lowest Horizontal Supporting Member Elevated to BFE + 1’	Stratford Ordinances 102-19

APPENDIX A

MINIMUM ELEVATION AND FLOOD PROOFING REQUIREMENTS
(For New and Substantially Improved Construction as of September 1, 2017)

AUTHORITY	ZONE	RESIDENTIAL STRUCTURES	NON-RESIDENTIAL STRUCTURES	CODE, ORDINANCE, OR REGULATION
Waterford	A / AE	Lowest Floor Elevated to BFE + 1’	Lowest Floor Elevated to BFE + 1’ ***OR*** Flood-proofed to BFE + 1’	Waterford Zoning Regulations 25.3.5.D
	Coastal A / AE	Lowest Supporting Horizontal Member Elevated to BFE + 1’	Lowest Supporting Horizontal Member Elevated to BFE + 1’	Waterford Zoning Regulations 25.3.5.G
	V / VE	Lowest Supporting Horizontal Member Elevated to BFE + 1’	Lowest Supporting Horizontal Member Elevated to BFE + 1’	Waterford Zoning Regulations 25.3.5.G
West Haven	A / AE	Lowest Floor Elevated to BFE	Lowest Floor Elevated Above BFE ***OR*** Flood-proofed to BFE	West Haven Zoning Regulations 70.15
	Coastal A / AE	No Specific Standards for Coastal A / AE	No Specific Standards for Coastal A / AE	
	V / VE	Lowest Supporting Horizontal Member Elevated to BFE	Lowest Supporting Horizontal Member Elevated to BFE	West Haven Zoning Regulations 70.16
Westbrook	A / AE	Lowest Floor Elevated Above BFE	Lowest Floor Elevated to BFE + 1’ ***OR*** Flood-proofed to BFE + 1’	Westbrook Zoning Regulations 5.16.01
	Coastal A / AE	Lowest Floor Elevated to BFE + 1’	Lowest Floor Elevated to BFE + 1’ ***OR*** Flood-proofed to BFE + 1’	Westbrook Zoning Regulations 5.16.01
	V / VE	Lowest Horizontal Structural Member to BFE + 1’	Lowest Horizontal Structural Member to BFE + 1’	Westbrook Zoning Regulations 5.17.02
Westport	A			
	AE (See Foot-note [101])	Lowest Floor Elevated to BFE	Lowest Floor Elevated to BFE ***OR*** Flood-proofed to BFE	Westport Zoning Regulations 31-11.3.3, 11.3.4
	Coastal A / AE	No Specific Standards for Coastal A / AE	No Specific Standards for Coastal A / AE	
	V / VE	Lowest Horizontal Structural Member Elevated to BFE	Lowest Horizontal Structural Member Elevated to BFE	Westport Zoning Regulations 31-11.3.5

Municipal Participation in Community Rating System (October 2016) (Shoreline Towns Only)[102]

Municipality	CRS Class	Flood Ins. Discount (%)	Municipality	CRS Class	Flood Ins. Discount (%)
East Haven	10	0	Stamford	7	15
East Lyme	8	10	Stonington	10	0
Fairfield	8	10	Westbrook	10	0
Milford	9	5	Westport	8	10

Appendix B

FEMA FLOOD ZONE DEFINITIONS

Definitions of FEMA Flood Zone Designations

Flood zones are geographic areas that the FEMA has defined according to varying levels of flood risk. These zones are depicted on a community's Flood Insurance Rate Map (FIRM) or Flood Hazard Boundary Map. Each zone reflects the severity or type of flooding in the area.

Moderate to Low Risk Areas

In communities that participate in the NFIP, flood insurance is available to all property owners and renters in these zones:

ZONE	DESCRIPTION
B and X (shaded)	Area of moderate flood hazard, usually the area between the limits of the 100-year and 500-year floods. B Zones are also used to designate base floodplains of lesser hazards, such as areas protected by levees from 100-year flood, or shallow flooding areas with average depths of less than one foot or drainage areas less than 1 square mile.
C and X (unshaded)	Area of minimal flood hazard, usually depicted on FIRMs as above the 500-year flood level. Zone C may have ponding and local drainage problems that don't warrant a detailed study or designation as base floodplain. Zone X is the area determined to be outside the 500-year flood and protected by levee from 100-year flood.

High Risk Areas

In communities that participate in the NFIP, mandatory flood insurance purchase requirements apply to all of these zones:

ZONE	DESCRIPTION
A	Areas with a 1% annual chance of flooding and a 26% chance of flooding over the life of a 30-year mortgage. Because detailed analyses are not performed for such areas; no depths or base flood elevations are shown within these zones.
AE	The base floodplain where base flood elevations are provided. AE Zones are now used on new format FIRMs instead of A1-A30 Zones.
A1-30	These are known as numbered A Zones (e.g., A7 or A14). This is the base floodplain where the FIRM shows a BFE (old format).
AH	Areas with a 1% annual chance of shallow flooding, usually in the form of a pond, with an average depth ranging from 1 to 3 feet. These areas have a 26% chance of flooding over the life of a 30-year mortgage. Base flood elevations derived from detailed analyses are shown at selected intervals within these zones.
AO	River or stream flood hazard areas, and areas with a 1% or greater chance of shallow flooding each year, usually in the form of sheet flow, with an average depth ranging from 1 to 3 feet. These areas have a 26% chance of flooding over the life of a 30-year mortgage. Average flood depths derived from detailed analyses are shown within these zones.
AR	Areas with a temporarily increased flood risk due to the building or restoration of a flood control system (such as a levee or a dam). Mandatory flood insurance purchase requirements will apply, but rates will not exceed the rates for unnumbered A zones if the structure is built or restored in compliance with Zone AR floodplain management regulations.
A99	Areas with a 1% annual chance of flooding that will be protected by a Federal flood control system where construction has reached specified legal requirements. No depths or base flood elevations are shown within these zones.

Appendix B

FEMA FLOOD ZONE DEFINITIONS

High Risk - Coastal Areas

In communities that participate in the NFIP, mandatory flood insurance purchase requirements apply to all of these zones.

ZONE	DESCRIPTION
V	Coastal areas with a 1% or greater chance of flooding and an additional hazard associated with storm waves. These areas have a 26% chance of flooding over the life of a 30-year mortgage. No base flood elevations are shown within these zones.
VE, V1 - 30	Coastal areas with a 1% or greater chance of flooding and an additional hazard associated with storm waves. These areas have a 26% chance of flooding over the life of a 30-year mortgage. Base flood elevations derived from detailed analyses are shown at selected intervals within these zones.

Undetermined Risk Areas

ZONE	DESCRIPTION
D	Areas with possible but undetermined flood hazards. No flood hazard analysis has been conducted. Flood insurance rates are commensurate with the uncertainty of the flood risk.

From FEMA Map Service Center:
http://msc.fema.gov/webapp/wcs/stores/servlet/info?storeId=10001&catalogId=10001&langId=-1&content=floodZones&title=FEMA%20Flood%20Zone%20Designations

Endnotes

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2 James O'Donnell, Ph.D., Exec. Dir., Conn. Inst. for Resilience & Climate Adaptation, Presentation at the Connecticut Department of Energy and Environmental Protection (April 12, 2017) [hereinafter *O'Donnell DEEP Presentation*].
3 *National Flood Insurance Program*, DEP'T OF ENERGY & ENVTL. PROT., [hereinafter *DEEP-NFIP*], http://www.ct.gov/deep/cwp/view.asp?Q=446992 (last visited June 1, 2017).
4 *Id.*
5 44 C.F.R. § 60.3 (2017).
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26 *See, e.g.*, AM. SOC'Y OF CIV. ENG'RS, ASCE/SEI 24-14 FLOOD RESISTANT DESIGN AND CONSTRUCTION (2015); FED. EMERGENCY MGMT. AGENCY, HOME BUILDER'S GUIDE TO COASTAL CONSTRUCTION, TECHNICAL FACT SHEET SERIES P-499, TECHNICAL FACT SHEET NO. 1.6 1 (2010).
27 *See, e.g.*, CITY OF NEW LONDON, CONN., ZONING REGS. § 830.
28 *See, e.g.*, FED. EMERGENCY MGMT. AGENCY, FLOOD INSURANCE RATE MAP, NEW HAVEN COUNTY, CONN., PANEL 487 OF 635 (2013).
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30 *Id.* § 64.3.

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[33] *Flood Zones, Definitions / Descriptions,* FED. EMERGENCY MGMT. AGENCY, https://www.fema.gov/flood-zones (last visited June 8, 2017).
[34] 44 C.F.R. § 64.3 (2017).
[35] *Definitions*, FED. EMERGENCY MGMT. AGENCY, *supra* note 2.
[36] 44 C.F.R. § 64.3 (2017).
[37] FED. EMERGENCY MGMT. AGENCY, HOMEOWNER'S GUIDE TO COASTAL CONSTRUCTION, *supra* note 40, at 5-1.
[38] 44 C.F.R. § 60.3 (2017).
[39] 44 C.F.R. § 60.3 (2017).
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[41] *Id.*
[42] *Id.*
[43] FED. EMERGENCY MGMT. AGENCY, HOME BUILDER'S GUIDE TO COASTAL CONSTRUCTION, TECHNICAL FACT SHEET SERIES P-499, TECHNICAL FACT SHEET NO. 1.6 2 (2010)) [hereinafter *FEMA Home Builder's Guide*]..
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[46] *Id.* at R322.2.1.3.
[47] *Id.* at R322.2.1.1.
[48] *Id.* at R322.2.1.2.
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[50] CONN. DEP'T ADMIN. SERV., BUILDING AND FIRE CODE ADOPTION PROCESS, PROPOSED CODES, http://portal.ct.gov/DAS/Office-of-State-Building-Inspector/Building-and-Fire-Code-Adoption-Process (last visited September 13, 2017).
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[52] *IRC 2015, supra* note 51, at R322.2.1.1.
[53] *Id.* at R322.3.2.1.
[54] *Connecticut State Building Code*, *supra* note 44.
[55] INT'L CODE COUNCIL, INT'L BLDG. CODE, 1612.4 (2012) [hereinafter *IBC 2012*].
[56] AM. SOC'Y OF CIV. ENG'RS, ASCE/SEI 24-05 FLOOD RESISTANT DESIGN AND CONSTRUCTION (2015).
[57] *Id.*
[58] *Id.*
[59] *Id.*
[60] *Id.*
[61] CONN. DEP'T ADMIN. SERV., BUILDING AND FIRE CODE ADOPTION PROCESS, PROPOSED CODES, http://portal.ct.gov/DAS/Office-of-State-Building-Inspector/Building-and-Fire-Code-Adoption-Process (last visited September 13, 2017).
[62] INT'L CODE COUNCIL, INT'L BLDG CODE, 1612.4 (2015) [hereinafter *IBC 2015*].
[63] AM. SOC'Y OF CIV. ENG'RS, ASCE/SEI 24-14 FLOOD RESISTANT DESIGN AND CONSTRUCTION (2014) [hereinafter *ASCE 24-14*].
[64] *DEEP-NFIP*, *supra* note 3.
[65] *See infra* Appendix A.
[66] 44 C.F.R. § 60.3 (2017); *Connecticut State Building Code*, *supra* note 44; *IBC 2012, supra* note 55, at 1612.4.
[67] *Connecticut State Building Code*, *supra* note 44.
[68] *IRC 2012, supra* note 45, at R322.3.2.
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[75] *Id.*
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[78] CONN. GEN. STAT. § 8-2 (2017).
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[80] 44 C.F.R. § 60.3 (2017).
[81] *See, e.g.*, *FEMA Home Builder's Guide*, *supra* note 43.
[82] CONN. GEN. STAT. § 29-253 (2017).
[83] ASCE 24-14, *supra* note 63, at ii-iii.
[84] FED. EMERGENCY MGMT. AGENCY, HIGHLIGHTS OF THE ASCE 24-14, 1 (2005).
[85] The Clinton, Old Saybrook, and Waterford elevation standards meet the requirements of ASCE 24-14 for "Flood Design Class 2" buildings and structures, which include the majority of buildings and structures in flood hazard areas. Importantly, ASCE 24-14 specifies more stringent requirements for buildings and structures that pose a high risk to the public and for essential facilities necessary for emergency response and recovery, and these types of building and structures are not singled out by the standards in these towns. Refer to ASCE 24-14 for elevation requirements for Class 1, 3, and 4 facilities.
[86] *FEMA Home Builder's Guide*, *supra* note 43 at 1.
[87] *O'Donnell DEEP Presentation*, *supra* note 2.
[88] FED. EMERGENCY MGMT. AGENCY, NATIONAL FLOOD INSURANCE PROGRAM COMMUNITY RATING SYSTEM COORDINATOR'S MANUAL FIA-15/2017, 430–33 (2017) [hereinafter *FEMA Coordinator's Manual*].
[89] 44 C.F.R. § 60.3 (2017).
[90] *FEMA Coordinator's Manual*, supra note 88, at 430–32.
[91] *Id.*
[92] Section R322.2 of the 2012 International Residential Code specifically requires the establishment of Coastal A Zones (IRC R322.2) and establishes elevation requirements for those zones. *IRC 2012, supra* note 45, at R322.2. ASCE 24-14, as invoked by the International Building Code, does not specifically require the establishment of a "Coastal A Zone," but it does define "Coastal A Zone" (ASCE 24-14 § 1.2) and specifies construction requirements for zones with wave heights "greater than or equal to 1.5 feet." ASCE 24-14 §3.1.
[93] *FEMA Coordinator's Manual, supra* note 88, at 430–33.
[94] FED. EMERGENCY MGMT. AGENCY, NATIONAL FLOOD INSURANCE PROGRAM COMMUNITY RATING SYSTEM, A LOCAL OFFICIAL'S GUIDE TO SAVING LIVES, PREVENTING PROPERTY DAMAGE, REDUCING THE COST OF FLOOD INSURANCE, FED. EMERGENCY MGMT. AGENCY B-573, 3 (2015).
[95] *Id.* at 4-7.
[96] FED. EMERGENCY MGMT. AGENCY, COMMUNITY RATING SYSTEM (CRS) COMMUNITIES AND THEIR CLASSES CRS-7 (2016).
[97] The 2016 Connecticut Building Code invokes the 2012 International Building Code (IBC) for non-residential structures. The 2012 IBC invokes ASCE 24-05, "Flood Resistant Design and Construction" for design and construction of buildings and structures in flood hazard areas. ASCE 24-05 identifies four different risk categories for structures in flood hazard areas based upon the use and occupancy of those structures. The information provided here for "Non-Residential Structures" is for Risk Category II structures, which represent the majority of non-residential buildings in flood hazard areas. Importantly, ASCE 24-05 specifies more stringent requirements for buildings and structures that pose a high risk to the public and for essential facilities necessary for emergency response and recovery. Refer to ASCE 24-05 for elevation requirements for those buildings and structures.
[98] The Proposed 2018 Connecticut Building Code invokes the 2015 International Building Code (IBC) for non-residential structures. The 2015 IBC invokes ASCE 24-14, "Flood Resistant Design and Construction" for design and construction of buildings and structures in flood hazard areas, which is an update to the ASCE 24-05 invoked by the 2012 IBC and, by extension, the 2016 Connecticut State Building Code. In a manner similar to ASCE 24-05, ASCE 24-14 identifies four different "Flood Design Classes" for buildings and structures in flood hazard areas

based upon the use and occupancy of those buildings and structures. The information provided here for "Non-Residential Structures" is for Flood Design Class 2 buildings, which represent the majority of non-residential buildings in flood hazard areas. Importantly, ASCE 24-14 specifies more stringent requirements for buildings and structures that pose a high risk to the public and for essential facilities necessary for emergency response and recovery. Refer to ASCE 24-14 for elevation requirements for those buildings and structures.
[99] In A Zones, non-residential structures are only required to be flood-proofed to BFE.
[100] In A Zones, non-residential structures are only required to elevate the lowest floor or flood-proof to BFE.
[101] In A Zones, all non-residential structures are required to be flood-proofed at or above BFE.
[102] FED. EMERGENCY MGMT. AGENCY, COMMUNITY RATING SYSTEM (CRS) COMMUNITIES AND THEIR CLASSES 7 (2016).

MUNICIPAL RESILIENCE PLANNING ASSISTANCE PROJECT

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Height Restrictions on Elevated Residential Buildings in Connecticut Coastal Floodplains

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Executive Summary

Elevating buildings above flood levels is a common and effective way to minimize damage from floodwaters, and is a key flood protection provision of the National Flood Insurance Program (NFIP). Since all Connecticut municipalities participate in the NFIP, all have enacted floodplain regulations that meet or exceed the NFIP requirement to elevate habitable portions of new and substantially improved residential structures to or above the "Base Flood Elevation" (BFE) shown on federal flood insurance rate maps. The Connecticut State Building Code also specifies floodplain building elevation requirements, and in some cases the building code elevation requirements exceeds those of the NFIP. Supplementing these mandatory requirements are incentives under federal disaster relief and flood insurance programs that make it attractive for homeowners to voluntarily elevate new and existing residential structures to levels even higher than the regulatory minimums.

Unfortunately, conflicts can arise when a requirement or desire to raise a building above the BFE runs up against a zoning regulation that limits how high the building can rise above the surrounding grade. Most Connecticut shoreline communities simply use their existing zoning variance process to resolve such conflicts on a case-by-case basis. However, eight shoreline communities have adopted floodplain zoning ordinances that can accommodate some increase in height above the usual limit without going through the complicated and time-consuming variance process. These communities use one of two different methods to facilitate this accommodation:

- allow additional height above the surrounding grade, or
- allow additional height above a specified floodwater elevation.

This paper describes these two approaches and Appendix A provides the text of the floodplain height ordinances in the eight communities that make such accommodations. Shoreline communities interested in enhancing coastal resilience should consider whether similar ordinances are appropriate for their situations.

I. Introduction

Coastal flooding represents a tremendous threat to Connecticut infrastructure. The Federal Emergency Management Administration (FEMA) estimates that a "100 year flood" in the four Connecticut Shoreline counties could cause a staggering $3,571,200,000 in damage to residential structures alone.[1] To further exacerbate this problem, climate scientists estimate that by 2100 the inundation levels of this 100 year flood will revisit the Connecticut coast once every seventeen years if greenhouse gas emissions continue at current rates.[2]

The National Flood Insurance Program (NFIP) offsets some of the financial risk that these floods pose to homeowners.[3] This program, administered by the Federal Emergency Management Agency (FEMA), makes federal flood insurance available to communities that impose a minimum standard of floodplain management regulation, generally imposed through zoning ordinances.[4] Every Connecticut municipality participates in the NFIP.[5]

Under the NFIP, participating municipalities must create land use ordinances that require habitable portions of new or substantially improved residential structures within the Special Flood Hazard Area[6] to be elevated to or above the Base Flood Elevation (BFE)[7] shown on Flood Insurance Rate Maps (FIRM).[8] This elevation requirement is intended to minimize flood damage by keeping buildings above anticipated flood levels.[9]

The FEMA elevation specifications reflect the minimum requirements of the NFIP. Property owners may wish to raise their buildings even higher than these minimum elevations to further reduce the risk of flood damage and to reduce their flood insurance premiums.[10] Municipalities may also impose higher elevation requirements to minimize property loss during flood events that exceed historical highs or to accommodate projected sea level rise. Complicating the process of elevating buildings located in floodplains are zoning ordinance height restrictions that limit the distance between grade (ground elevation) and a high point on the building, such as ultimate roof height.[11] When floodplain property owners elevate existing buildings to or above the BFE, an otherwise compliant building may exceed the height limit set by a local zoning ordinance, squeezing property owners between two different regulatory requirements.

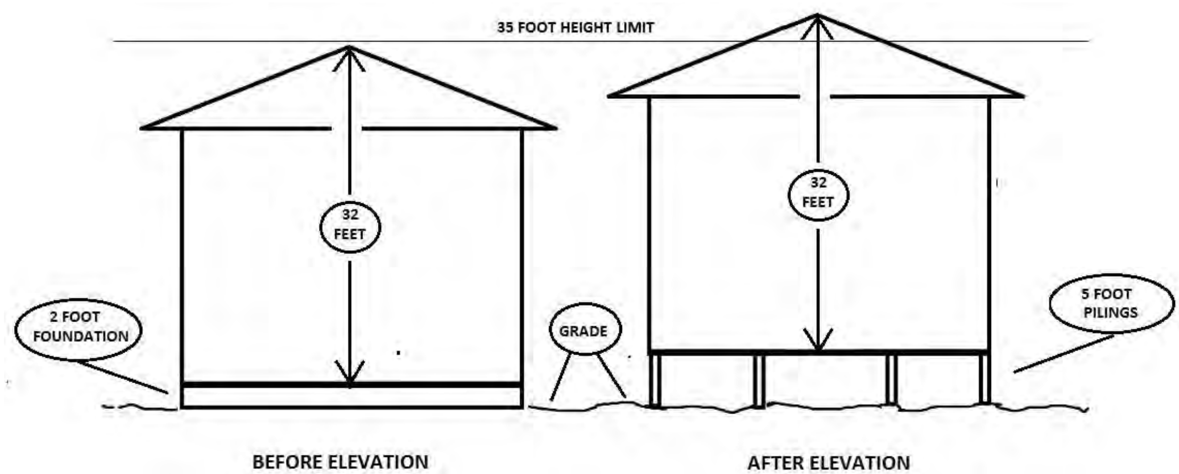

Figure 1 – Shoreline House Before and After Renovation

For example, assume the shoreline house in Figure 1 is located in a residential neighborhood where the zoning height limit is 35 feet above grade. This particular house is 32 feet tall from the bottom of the lowest habitable floor to the peak of the roof and rests upon a foundation that is two feet above grade. The top of the house is therefore 34 feet above grade, just below the 35-foot limit. To protect the house from flood damage, the owner wants to hire a contractor to replace the foundation with pilings and raise the lowest habitable floor to the BFE, which is five feet above grade. Unfortunately, the work would raise the peak of the roof to 37 feet above grade, in violation of the 35-foot zoning height limit. Without relief from this height limit, the owner would have to modify the roof of the house to raise the lowest habitable floor to the BFE. Such a modification would add to the expense of the project and could put the project out of financial reach.

To accommodate this situation, a municipality can either grant variances on a case-by-case basis or pass an ordinance raising the height limit for elevated buildings in floodplains. A municipality may prefer variances to retain control over individual circumstances, but the variance process is time consuming and can be expensive as it requires an individual analysis, a detailed application, and a formal public hearing.

Applicants for a variance must demonstrate to a zoning board of appeals that the variance will not substantially affect the comprehensive zoning plan and that strict adherence to the letter of the zoning ordinance will cause an unnecessary and unusual hardship.[12] The applicant must also demonstrate that the variance is required because of "some peculiar characteristic of his property."[13] These can be difficult requirements to meet when the applicant is one of many similarly situated floodplain property owners. Furthermore, the process can become even more expensive and time consuming for the owner if an aggrieved abutter contests a variance approval and appeals the board's decision to a superior court.[14] The possibility of appeal adds another degree of uncertainty for property owners as the court may find that the variance was improperly granted and reverse the decision of the board.[15]

If a municipality wishes to create a more efficient process it can enact an ordinance to accommodate the increased height of elevated floodplain buildings without going through the variance procedure. While such an ordinance many reduce the municipality's control over individual building elevation projects, it may represent a more efficient use of municipal resources. It will also reduce the time, expense, and uncertainties that the variance process imposes on floodplain building owners, which may encourage more owners to elevate floodplain buildings above dangerous floodwaters.

The remainder of this paper addresses the means by which shoreline communities can use ordinances accommodate increased building heights. Section II describes the legal authority that allows Connecticut municipalities to establish zoning ordinances and grant variances from those ordinances. Section III describes how Connecticut shoreline communities handle zoning height limits in floodplains and identifies the communities that have adopted ordinances to accommodate some increase in floodplain building height without resorting to the variance process. Section IV highlights some of the considerations involved when making decisions on a floodplain building height ordinance. Finally, the conclusion in Section V is followed by Appendix A, which provides the text of the regulations in the eight communities that use ordinances rather than the variance process to accommodate increased building heights in floodplains.

II. Legal Authority

The legal authority for communities to regulate land use through zoning ordinances is long and well established. The threshold case affirming this authority was in 1926, when the United States Supreme Court held that local land use zoning is a valid exercise of police power as long as the zoning ordinances are not "clearly arbitrary and unreasonable, having no substantial relation to the public health, safety, morals, or general welfare."[16]

In Connecticut, municipalities derive their zoning authority from the state through a general zoning enabling act passed in 1925 and revised and reenacted in 1949.[17] These acts, now codified in Title 8 of the Connecticut General Statutes, empower municipalities to establish zoning commissions and enact zoning ordinances that regulate land use and establish dimensional requirements, including building height.[18] In fact, Section 8-2 of the Connecticut General Statutes specifically allows zoning ordinances that regulate the "height, number of stories and size of buildings and other structures."[19]

Communities that adopt zoning ordinances must also establish a zoning board of appeals empowered to grant variances where special circumstances unique to a particular parcel of land would cause "exceptional difficulty or unusual hardship" if the zoning ordinances were enforced as written.[20] This variance process provides an important protection for land owners who, through no fault of their own, are confronted with unique circumstances that don't allow them to comply with certain provisions of local zoning ordinances.

The combination of explicit delegation of state authority and access to a variance process provides a strong legal authority for zoning ordinances that regulate building height. This authority is so strong, in fact, that the municipal authority to regulate building heights through zoning ordinances has never been challenged in the Connecticut Appellate or Supreme Courts.

III. Current Practices in Connecticut Coastal Municipalities

Eight of Connecticut's twenty-four coastal towns and cities have ordinances that work to reconcile NFIP elevation standards with building height zoning limits. These municipalities are Bridgeport, Fairfield, Greenwich, Guilford, Norwalk, Stamford, Waterford, and Westport. As shown in the text of the ordinances in Appendix A, these communities use one of two methods to accommodate the increased height of elevated buildings in flood zones:

- allow additional height above grade, or
- allow additional height above a specified floodwater elevation.

Both of these methods are described below.

Additional Height Above Grade

The simplest method used to reconcile height limits with elevation requirements in floodplains is to grant additional height above grade to elevated structures in those areas. The most straightforward example of this method is in Norwalk, where residential structures in flood zones are permitted an additional one foot of height.[21]

Other towns allow additional height above grade in a more conditional manner that may accommodate greater flood depths. In Westport, for every one foot between average grade and BFE, an additional foot may be added to building height, up to a maximum of five additional feet above the ordinary limit for height above grade.[22] Fairfield employs a similar system, where one foot of additional height is allowed for every two feet of difference between grade and BFE with no other limit on height above grade.[23]

Additional Height Above a Specified Floodwater Elevation

The municipalities described above measure building height in relation to the grade at the base of the building, which is the usual manner of measuring building height. However, some coastal municipalities have adopted a different starting point to measure the height of buildings in floodplains. Instead of starting at the surrounding grade, these municipalities start height measurements at an elevation related to the anticipated depth of floodwaters.

In Stamford, the starting point for floodplain building height measurement is BFE.[24] Therefore, if a residential building is in a coastal flood area with a zoning limit of thirty-five feet above grade and the BFE is three feet above grade, the building may be elevated until the highest point of the building is thirty-five feet above BFE, or thirty-eight feet above grade. There are limits, however, to how much extra height above grade can be granted under this ordinance. In Stamford, an elevated building in a floodplain may not exceed the prevailing above-grade height limit by more than five feet irrespective of the BFE.

Other towns have chosen different elevations related to the BFE as the starting point for building height measurement. In Guilford, the limits for floodplain building heights are measured from four feet below BFE or from grade, whichever is higher, with a maximum height of 40 feet above grade.[25] In Greenwich, the limits for floodplain building heights are measured from two feet below BFE or from grade, whichever is higher, with no separate limit on height above grade.[26]

The floodplain building height accommodations are more generous in Bridgeport and Waterford. In Bridgeport, the limits for floodplain building heights are measured from one foot above BFE or from grade, whichever is higher, up to a maximum of five additional feet above the ordinary height limit.[27] In Waterford, the limits for floodplain building heights are measured from two feet above BFE with no limit on height above grade.[28]

IV. Considerations

When choosing whether to enact an ordinance that will allow buildings in flood zones to exceed their local building height limits, a zoning commission's decision will likely be dictated by local preferences and concerns. Among those are the commission's preferences for how much variation to permit in maximum building heights. Some municipalities appear to take a more conservative stance in permitting variations in maximum building heights, while others are more generous. Additionally, municipalities may differ in elevation specifications for residential structures in floodplains. While a majority of shoreline communities specify the NFIP minimum elevation of requirement of BFE, a significant minority of municipalities have chosen to exceed the minimum requirements and specify elevation requirements one foot or more above BFE.[29]

Municipalities should also be aware that elevating a building increases the chance of wind damage to the building.[30] Municipalities considering ordinances related to elevating existing residential buildings in flood zones should also consider a recommendation or requirement to evaluate and, if necessary, retrofit these buildings in accordance with FEMA Publication P-804, "Wind Retrofit Guide for Residential Buildings."

V. Conclusion

Elevating residential structures above floodwaters is a common and effective measure to reduce flood damage, and elevation to at least the BFE is required for new construction and substantial improvements in communities that participate in the NFIP. However, property owners facing significant flood depths may encounter a regulatory impasse when elevating a structure above floodwaters violates municipal zoning height limits. Eight of Connecticut's shoreline municipalities have ordinances that bring some relief in such circumstances, either by allowing additional height above grade or by starting height measurements from an elevation related to flood depth instead of the surrounding grade. The other sixteen shoreline municipalities do not have ordinances that reconcile building height limits with floodplain elevation requirements. For property owners in those communities, a variance is the only relief when a floodplain building elevation project would cause building height to exceed zoning limits. These sixteen communities should consider height-accommodating ordinances to minimize the need for expensive, time-consuming, and uncertain variance applications and thus encouraging floodplain residents to elevate buildings above dangerous floodwaters.

Appendix A

Floodplain Building Height Accommodation Ordinances
(Effective September 1, 2017)

Connecticut Shoreline Communities

Bridgeport - BRIDGEPORT, CONN., ZONING & SUBDIVISION REG. Table 3, note 8 (2015).

> "In flood plain areas where the lowest floor of the building is elevated to meet the flood damage prevention standards, the maximum total building height shall be measured from the Base Flood Elevation (BFE)+1' elevation provided that the resulting height of the building is not more than five (5) feet greater than the maximum building height permitted in the RCC Zone."

Fairfield - FAIRFIELD, CONN., ZONING REG. § 5.2.2 (2017).

> "Two and one half (2 ½) stories or thirty-two (32) feet, whichever is less except that dwellings located within the 100 year flood zone are allowed one foot of additional height for every two (2) feet of vertical distance between existing average grade and the base flood elevation."

Greenwich - GREENWICH, CONN., BLDG. ZONE REG. § 6-139.1(c)(22.1) (2017).

> "Grade Plane, Flood Zone – A reference plane from which to measure the number of stories, height, and floor area of dwelling units in residential zones within the Flood Hazard Overlay Zone. The flood zone grade plane shall be measured from two feet (2') below the Base Flood Elevation, or the grade plane as defined under Section 6-5(a)(26), whichever is higher. If the structure complies with Section 6-139.1(f)(11)(A and D), the floor area below the flood zone grade plane shall be excluded. The area below the flood zone grade plane shall not count as a story provided there is no more than 7' from the flood zone grade plane to the top of the finished floor."

Guilford - GUILFORD, CONN., ZONING CODE § 273-91(O) (2016).

> "For buildings or structures in Flood hazard areas as defined by FEMA, average height shall be measured from the Base Flood Elevation minus four (4) feet or average grade whichever is higher. No building shall be higher than 40 ft. total height from average grade."

Norwalk - NORWALK, CONN., BLDG. ZONE REG (2017).

> *The Norwalk limits for building height and bulk are set forth in schedules that are not reproduced here. Those schedules add one foot to the height limits for residential structures in flood zones. See the Norwalk Connecticut Building Zone Regulations, Schedule limiting height and bulk of buildings - Residential (Part 1) (2017).*

Stamford - STAMFORD, CONN., ZONING REG. § 3(A)(16)(b) (2016).

> "Where a residential building is to be built, altered or reconstructed in order to comply with the Minimum Elevation Standard of Article III, Section 7.1 Flood Prone Area Regulations, and such building is located fully or partially within the Coastal Boundary as defined in Article III, Section 7(T) Coastal Area Management Regulations, building height may be measured from the Base Flood Elevation applicable to the residential building, provided that the resulting height of the building measured from average grade is not more than five (5) feet greater than the maximum building height permitted in the applicable Zoning District."

Appendix A

Waterford - WATERFORD, CONN., ZONING REG. § 1.11.2 (2017).

> "Buildings located in an F.E.M.A Designated Flood Zone AE and VE or both, the height shall be measured from the Base Flood Elevation (BFE) plus Two (2) feet as shown on the latest version FIRM (Flood Insurance Rate Map)."

Westport - WESTPORT, CONN., ZONING & SUBDIVISION REG. § 6-3.3 (2017).

> "Building Height for principal buildings may be increased by up to an additional five feet; (Maximum of 31') for an existing or new structure located within the Special Flood Hazard Area specifically, when such structure is proposed have its first finished floor elevated to at least the Base Flood Elevation has no basement or cellar below the BFE and in the AE Zone is designed to be fully compliant with §31-11.5.2 (Elevated Buildings). Structures in the VE zone shall comply with all the requirements in §31-11.3.5. One additional foot of Building Height as measured from average grade shall be permitted for each foot that the average grade is below the Base Flood Elevation up to a maximum of five feet. Wet flood proofed enclosed spaces below the first floor with a head room of five feet or less shall not be considered a story. (See §5-2 Definition of Crawl Space).

Endnotes

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DISCLAIMER: *This white paper addresses issues of general interest and does not give any specific legal advice pertaining to any specific circumstance. Parties should obtain advice from a lawyer or other qualified professional before acting on the information in this paper.*

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1 ADAPTATION SUBCOMM. TO THE GOVERNOR'S STEERING COMM. ON CLIMATE CHANGE, THE IMPACTS OF CLIMATE CHANGE ON CONNECTICUT AGRICULTURE, INFRASTRUCTURE, NATURAL RESOURCES AND PUBLIC HEALTH 88 (2010).
2 *Id.* at 86.
3 *National Flood Insurance Program*, DEP'T OF ENERGY & ENVTL. PROT. [hereinafter *DEEP-NFIP*], http://www.ct.gov/Deep/cwp/ view.asp?a=2720&Q=446992&deepNav_GID=1654 (last visited June 1, 2017).
4 *Id*.
5 *Id*.
6 Special Flood Hazard Area (SFHA) is an area having special flood, mudflow or flood-related erosion hazards and shown on a Flood Hazard Boundary Map (FHBM) or a Flood Insurance Rate Map (FIRM) Zone A, AO, A1-A30, AE, A99, AH, AR, AR/A, AR/AE, AR/AH, AR/AO, AR/A1-A30, V1-V30, VE or V. *Definitions*, FED. EMERGENCY MGMT. AGENCY, https://www.fema.gov/national-flood-insurance-program/definitions (last visited June 8, 2017). In common parlance, this is the area within the 100 year floodplain.
7 Base Flood Elevation (BFE) is the elevation of surface water resulting from a flood that has a 1% chance of equaling or exceeding that level in any given year. *Definitions*, *FEMA*, https://www.fema.gov/national-flood-insurance-program/definitions (last visited June 8, 2017). BFE is sometimes called the "100 year flood" elevation. *Designing for Flood Levels Above the BFE*, FED. EMERGENCY MGMT. AGENCY 1 (2010), https://www.fema.gov/media-library-data/20130726-1537-20490-8057/fema499_1_6_rev.pdf.
8 *Base Flood Elevation, Definition/Description*, FED. EMERGENCY MGMT. AGENCY, https://www.fema.gov/base-flood-elevation (last visited June 8, 2017).
9 *DEEP-NFIP*, *supra* note 3.
10 FED. EMERGENCY MGMT. AGENCY, DESIGNING FOR FLOOD LEVELS ABOVE THE BFE, TECHNICAL FACT SHEET 1.6, 1 (2010).
11 *See, e.g.*, Greenwich, Conn., Mun. Code, art. I, §§ 6-5(a)(9), 6-40(b) (2017).
12 Bloom v. Zoning Bd. of Appeals of the City of Norwalk, 658 A.2d 559, 564 (Conn. 1995).
13 *Id*.
14 CONN. GEN. STAT. § 8-8 (2012).
15 *See, e.g.*, Amendola v. Zoning Bd. of Appeals of the City of West Haven, 129 A.3d 743 (Conn. 2015).
16 Vill. of Euclid, Ohio v. Ambler Realty Co., 272 U.S. 365 (1926).
17 1925 Conn. Pub. Acts 4037.
18 CONN. GEN. STAT. § 8-2 (2017).
19 *Id*.
20 CONN. GEN. STAT. § 8-6 (2017).
21 Norwalk, Conn., Bldg. Zone Reg., Schedule Limiting Height and Bulk of Buildings, Residential (Part 1) (2017).
22 Westport, Conn., Zoning & Subdivision Reg. § 6-3.3 (2017).
23 Fairfield, Conn., Zoning Reg. § 5.2.2 (2017).
24 Stamford, Conn., Zoning Reg. § 3(A)(16)(b) (2016).
25 Guilford, Conn., Zoning Code § 273-91(O) (2016).
26 Greenwich, Conn., Mun. Code, art. X, § 6-139.1(c)(22.1) (2017).
27 Bridgeport, Conn., Zoning & Subdivision Reg. Table 3, note 8 (2015).
28 Waterford, Conn., Zoning Reg. § 1.11.2 (2017).
29 *E.g.*, Waterford, Conn., Zoning Reg. § 14a.5(8) (2017).

Endnotes

[30] Jeffrey Weston, Fang Pan & Wei Zhang, Resilience Study of Elevated Coastal Residential Buildings Subject to Strong Winds, The 13th Americas Conference on Wind Engineering (May 24, 2017) (unpublished), http://www.engr.uconn.edu/~wzhang/Pdf/C201705AAWEWestonBuilding.pdf.

Oceanfront State
Coastal Management Programs

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Executive Summary

Coastal management programs protect and restore coastal resources, manage coastal development, prioritize water-dependent uses, and facilitate access to public trust beaches, waters, and submerged lands. Contemporary state-level coastal management programs are progeny of the federal Coastal Zone Management Act of 1972 (CZMA), which provides financial and other federal incentives for states to develop, implement, and maintain coastal management programs that advance national coastal management policies.

To take advantage of CZMA incentives, state coastal management programs must comply with federal requirements. These federal requirements are functional in nature, and are intentionally designed to accommodate a broad range of implementing strategies. States are therefore free to select the legal structures and protective measures that best suit the unique political and geographical features of that state.

This white paper surveys the coastal management programs in the twenty-three oceanfront states. Individual state summaries describe the key features of the coastal management programs in each of the oceanfront states, while more detailed analyses address the genesis of state programs, the exercise of coastal management jurisdiction, and how state statutes and regulations address sea level rise. This paper specifically addresses the following questions:

Program Genesis: *How were the individual oceanfront state coastal management programs created?* Coastal management programs in four oceanfront states were established by executive orders that organized preexisting coastal management statutes into a program that was compliant with federal requirements. Meanwhile, new legislation was required to create coastal management programs in eight oceanfront states, though three of those states were careful to limit new legislation to the creation of a coastal management agency that relied entirely upon existing coastal management statutes. Finally, neither executive order nor new legislation was required to meet CZMA requirements in seven oceanfront states because existing statutes already provided the necessary legal authority.

Jurisdiction: *What authorities have jurisdiction over oceanfront state coastal management programs?* State government agencies exercise exclusive coastal management jurisdiction in six oceanfront states. Sixteen oceanfront states split jurisdiction between state agencies and local governments. The remaining oceanfront state, Alaska, does not have a federally-approved coastal management program.

Sea Level Rise: *How do states address sea level rise in state coastal management statutes and regulations?* Only three oceanfront states have statutes or state regulations that require the consideration of sea level rise when making all or most coastal management decisions. Four oceanfront states have statutes or state regulations that require the consideration of sea level rise when making some coastal management decisions. The remaining fifteen oceanfront states do not have coastal management statutes or state regulations that address sea level rise. However, four of those fifteen states have statutes or state regulations that require the consideration of sea level rise during certain planning activities.

Oceanfront state coastal management programs are as unique and diverse as the states themselves. This paper explores the differences and commonalities of these programs to provide a foundation for understanding state implementation of the CZMA.

I. Introduction

The vast and diverse coastlines of the United States provide attractive locations for residence, recreation, commerce, and industry. The magnitude of this attraction is revealed by the 2010 census, which shows population density in coastal shoreline counties is more than four times the national average.[1] This population density is complemented by robust economic activity, with nearly half of the country's gross domestic product generated in coastal counties that benefit from industries such as energy, tourism, and trade through some 360 seaports.[2] Coastal tourism alone contributes well over $200 billion a year to the United States' economy.[3]

Coastal areas provide valuable ecological and protective benefits as well. Coastal wetlands provide habitat for wildlife, nesting areas for waterfowl, spawning areas for fish and shellfish, and nutrient sources for marine fisheries.[4] They also protect coastal communities by providing buffers against storm surges and waves, enabling floodwater retention and drainage, and protecting the coastline from erosion.[5]

By the early 1970s, real estate and infrastructure development was placing unsustainable demands on the very resources that make coastal regions so valuable.[6] Congress recognized the adverse effects of these ever-increasing and competing demands and responded with the Coastal Zone Management Act of 1972 (CZMA).[7] This act made it the policy of the United States to "preserve, protect, develop, and where possible, to restore or enhance, the resources of the Nation's coastal zone for this and succeeding generations" and to "encourage and assist the states to exercise effectively their responsibilities in the coastal zone through the development and implementation of management programs to achieve wise use of the land and water resources of the coastal zone, giving full consideration to ecological, cultural, historic, and esthetic values as well as the needs for compatible economic development."[8]

The CZMA includes two powerful incentives to encourage states to adopt coastal management programs. The first incentive is financial, as states with approved state coastal management programs are eligible for four types of federal grants to support their programs. These grants include (1) matching grants for fifty percent of the annual program administration costs,[9] (2) matching grants for cost of certain nonrecurring resource management activities,[10] (3) matching grants for development of coastal nonpoint source pollution control programs,[11] and (4) outright grants to support attainment of one or more federally-approved coastal zone enhancement objectives.[12]

The second major incentive is the federal consistency provision of the CZMA. Under this provision, federal agencies engaged in activities affecting land, water, or other natural resources within a state coastal management zone must conduct those activities in accordance with the enforceable policies of the approved state coastal management program.[13] This requirement assures that state coastal management programs are not frustrated by federal activities not normally subject to state authority, and is a particularly effective incentive in states with a large federal presence.

These incentives have proven quite effective. By 2011, all thirty-five eligible states and territories were participating in the National Coastal Zone Management Program.[14] Alaska has since withdrawn from the national program, but all other eligible states continue to participate and take advantage of the federal program incentives.[15]

A state coastal management program must be approved by the United States Secretary of Commerce before a state can receive federal coastal management funds or require federal consistency with state coastal management policies. To receive federal approval, the Secretary must find that a state coastal management program has met a series of statutorily-defined requirements.[16] The program must articulate the boundaries of the coastal zone, permissible uses, areas of particular concern, applicable legislative authorities, priorities of uses within the zone, the organization of the management program, the term "beach" and how beaches will be protected, the planning process for energy facilities, and the planning process for dealing with shoreline erosion.[17] The program must also include mechanisms for protecting and restoring land, for implementing the state coastal nonpoint pollution control program, and for considering national interest – particularly when planning energy facilities and protecting coastal resources of national significance.[18] The state or territory must have the ability to review and approve uses within the coastal zone and state regulations must not unreasonably restrict uses of regional benefit.[19] The plan must have been adopted after full public participation and notice to interested parties and coordinated with any currently existing governmental plans applicable to the coastal zone.[20] The governor of the state must approve the plan and any changes and designate a single agency to receive all funds for the program.[21] Finally, the state must demonstrate its authority to regulate and acquire land, and detail how it will implement the program and ensure state agency compliance.[22]

This paper describes the essential features of the coastal management programs in the twenty-three oceanfront states. Section II of this paper describes the genesis of the state programs in terms of the organizing authority for each state program and the initial legal authorities invoked by those programs. Section III addresses the jurisdiction schemes deployed by state programs, differentiating between states that exercise state jurisdiction from those that share jurisdiction with local governments, and describes the level of state authority over local programs where jurisdiction is shared. Section IV discusses the need to incorporate sea level rise into state coastal management programs and identifies the states that meet this need through the statutory or regulatory components of their coastal management programs. Finally, Section V provides a summary of the coastal management program in each oceanfront state, with information on state and local jurisdiction, responsible state agencies, and the means by which sea level rise is addressed by statute or regulation.

II. Genesis of Federally-Approved State Coastal Management Programs

Oceanfront state coastal management programs approved under the CZMA were created in one of two ways: state legislation or gubernatorial executive order. The limitations on gubernatorial executive orders vary by state, but in most states the governor has the authority to organize executive branch agencies and to respond to federal programs.[23] Governors of states that already had the necessary coastal protection statutes in place could therefore use their executive authority to organize those statutes into a coastal management program without the need for new legislation. Such was the case in Maryland, North Carolina, Rhode Island, and Virginia, where federally-approved coastal management programs were created by executive orders that organized existing state agencies and programs into a coordinated coastal management program that met the standards for federal approval.[24]

Federally-approved coastal management programs in the remaining oceanfront states were created by program-specific state legislation. The nature of this state legislation fell into one of three categories: (1) existing legislation that met CZMA requirements without further modification, (2) new legislation that created a coastal management organization that relied entirely upon existing coastal management statutes, or (3) new legislation that created a coastal management organization as well as new coastal management statutes that supplemented existing coastal management statutes.

Several oceanfront states relied completely upon existing legislation for federal approval of a coastal management program. A good example is the Washington state program, which relied completely upon existing authorities embodied in comprehensive state coastal and environmental protection legislation passed in 1971, 1973, and 1974. With no further legislation or formal executive order, Washington's program was the first to attain federal approval in 1976.[25] Similarly, no additional legislation or executive orders were required for federal approval of the Alabama, Massachusetts, Maine, New Hampshire, New Jersey, or Oregon coastal management programs.[26]

Other oceanfront states created CZMA coastal management programs with new legislation. The state legislatures of Florida, Mississippi, and Texas were careful to limit new legislation to the creation of a coastal management agency that relied entirely upon existing coastal management statutes that, like the statutes invoked by the executive order states, already provided adequate legal authority and only required organization into a coastal management program to meet federal requirements.[27] The remaining oceanfront states of California, Connecticut, Delaware, Georgia, Hawaii, Louisiana, New York, and South Carolina enacted new coastal management legislation to supplement existing statutes as required to meet the criteria for federal approval of their coastal management programs.[28]

As noted above, many states did not wait for the 1972 CZMA and its associated incentives to create robust coastal management programs. A good example is Rhode Island, which passed legislation in 1971 that established a Coastal Resources Management Council with permit authority over all coastal development and certain inland development that could affect coastal resources.[29] That 1971 legislation, and regulations passed under that legislation, provided the basis for a 1977 executive order that organized the program for federal approval in 1978.[30] Rhode Island therefore represents a case where a formal state coastal management program was created by legislation, but the federally-approved program was created by executive order.

III. Jurisdiction in State Coastal Management Programs

All oceanfront state coastal management programs use some type of permitting system to control activities that affect coastal resources. The jurisdiction schemes for implementing these permitting systems are as varied as the states, and tend to reflect the laws, traditions and preferences of the state where the coastal management program was developed. These state-by-state variations notwithstanding, permitting jurisdiction schemes for coastal management jurisdiction generally fall into two broad categories: state-only jurisdiction or shared state and local jurisdiction.

In states with state-only jurisdiction, all permitting decisions required by the coastal management program are made by one or more agencies of the state. Oceanfront states with state-only jurisdiction are Delaware, Georgia, Mississippi, New Hampshire, New Jersey, and Rhode Island.[31] Section V of this paper identifies the state agencies responsible for coastal management decisions in states with state-only jurisdiction.

Most states share permitting jurisdiction with local governments. In these arrangements, state statutes identify the limits of jurisdiction and the permitting authority of state and local governments. Oceanfront states with shared state and local permitting jurisdiction are Alabama, California, Connecticut, Florida, Hawaii, Louisiana, Maine, Maryland, Massachusetts, New York, North Carolina, Oregon, South Carolina, Texas, Virginia, and Washington.[32] Section V of this paper identifies the state agencies and local governments responsible for coastal management decisions in states with shared permitting jurisdiction.

With one exception, states that share permitting authority with local governments require those local governments to obtain state approval of the local management plans or ordinances under which the local permits are issued.[33] The exception is Connecticut, where local coastal management plans and ordinances must be submitted to a state agency for review and comment, but state approval is not required.[34]

IV. Sea Level Rise Statutes and Regulations in State Coastal Management Programs

Sea level is rising. Tide gauge records indicate an average global sea level rise of 190 millimeters, or about seven and a half inches, between 1901 and 2010.[35] Recent measurements with more sophisticated instruments indicate an average rise of 3.2 millimeters a year between 1993 and 2010, which is nearly twice the average annual rise of the entire period between 1901 and 2010.[36] Simply extrapolating this 3.2 millimeter per year average out eighty-two years to 2100 indicates a sea level rise of another 262 millimeters - more than ten inches. When the latest climate science is factored in, the National Oceanic and Atmospheric Administration (NOAA) estimates that global sea levels could rise from 0.3 to 2.5 meters by 2100 - a rise from one to more than eight feet above current levels.[37]

The ramifications of this sea level rise cannot be overstated. About forty percent of all Americans live in coastal shoreline counties that account for only about ten percent of the land in the United States.[38] The rise in sea level since the start of the coastal development boom in the 1950s has led to a significant increase in tidal and storm surge flooding in most of these coastal counties.[39] The continued rise in sea level can only make things worse, by increasing the risk to coastal features, infrastructure, and inhabitants.

When it comes to protecting the coast, every oceanfront state except Alaska has a coastal management program that is designed to protect and restore coastal resources, manage coastal development, prioritize water-dependent uses, and facilitate access to public trust beaches, waters, and submerged lands. These state programs are progeny of the Federal Coastal Zone Management Act of 1972, and comply with the requirements of that Act and ongoing guidance provided by NOAA.

In a 1990 amendment to the Coastal Zone Management Act, Congress found that climate change requires coastal states to anticipate and plan for the "serious adverse effects" of sea level rise.[40] The same amendment also declared it a policy of the United States for states to manage coastal development in areas vulnerable to sea level rise.[41] These findings and policies notwithstanding, by 2017 only three of the twenty-three oceanfront states - Maryland, Massachusetts, and Rhode Island - have enacted state statutes or regulations that require the consideration of sea level rise when making most or all of the decisions required under their state coastal management programs. Only four other oceanfront states - California, Florida, Maine and New York - have state statutes or regulations that require the consideration of sea level rise when making at least a few of these types of decisions. That leaves fifteen oceanfront states without statutes or regulations that require the consideration of sea level rise when making decisions under the authority of their coastal management programs.

Some oceanfront states that do not have a statutory or regulatory requirement to consider sea level rise when making coastal management decisions nevertheless require such consideration during planning processes. The states of Connecticut, New Hampshire, Texas, and Virginia all have statutes or regulations that require consideration of sea level rise during specified planning activities.

V. State-By-State Summary of Oceanfront State Coastal Management Programs

This section, arranged in alphabetical order by state name, summarizes the coastal management program in each oceanfront state, with information on state and local jurisdiction, responsible state agencies, and the means by which sea level rise is addressed by state statute or regulation. These summaries reflect the status of oceanfront state coastal management programs as of May 31, 2017.

Alabama

The Alabama Coastal Area includes the lands and waters from the continuous ten-foot contour line in Alabama's two coastal counties to the seaward limit of the state's territorial sea.[42] The Alabama Department of Conservation and Natural Resources – State Land Division is the lead policy and planning agency for the Alabama Coastal Program.[43] The Alabama Department of Environmental Management (ADEM) is responsible for promulgating coastal management regulations and for coastal permitting, management and enforcement activities.[44] Permitting authority may be delegated to local governments with approval of ADEM.[45]

Sea Level Rise: There are no state statutes or regulations that require ADEM or any other state or local agencies to consider sea level rise when making decisions under the Alabama Coastal Program.

Alaska

The Alaska Coastal Management Program expired on July 1, 2011.[46] A ballot measure to establish a new coastal management measure failed 62.09% to 37.91% on August 28, 2012.[47]

Sea Level Rise: There are no state statutes or regulations that require state agencies or local authorities to consider sea level rise when considering coastal management issues.

California

The California coastal zone is a mapped area that includes the lands and waters from the seaward limit of the state's territorial sea and inland, generally 1,000 yards from the mean high tide line. [48] The inland reach of this coastal zone is less in developed urban areas and more in significant coastal estuarine, habitat and recreational areas.[49] The California coastal zone does not include areas under the jurisdiction of the San Francisco Bay Conservation and Development Commission.[50]

The California Coastal Commission (CCC) has coastal zone management jurisdiction,[51] but may delegate development review authority over inland coastal zones (other than public trust areas and state colleges and universities) to county or municipal governments.[52] County and municipal Local Coastal Programs (LCPs) now exercise development review jurisdiction over about 87% of the geographic area of the California coastal zone.[53]

Sea Level Rise: There are no state statutes or regulations that require the CCC, counties or municipalities to consider sea level rise when making coastal management permit decisions, but an executive order directs state agencies to consider sea level rise when planning state construction projects in areas vulnerable to sea level rise.[54] Furthermore, a comprehensive - but non-mandatory - CCC guidance document[55] strongly encourages counties and municipalities to incorporate sea level rise into their LCPs, and some have done so.[56]

Connecticut

The Connecticut coastal area includes the lands and waters from the seaward limit of the state's territorial sea, all towns on Long Island Sound, and specified inland towns subject to tidal waters. Within this coastal area is an inland Coastal Boundary, which is a continuous line defined by the furthest inland of (1) The 100 year coastal flood zone, (2) 1,000 feet inland from the mean high water mark, or (3) 1,000 feet inland from the tidal wetlands boundary.[57] The Connecticut Department of Energy and Environmental Protection (DEEP) has coastal management jurisdiction seaward of the Coastal Jurisdiction Line (CJL), a statutory elevation roughly equivalent to the high tide line.[58] Coastal towns have coastal management jurisdiction between the CJL and the Coastal Boundary.[59] DEEP and coastal towns share jurisdiction between the mean high water mark and the CJL.[60]

Sea Level Rise: There are no state statutes or regulations that require either the DEEP or the towns to consider sea level rise when making coastal management permit decisions. Nevertheless, sea level rise must be considered during the mandatory periodic revisions to state and town land use plans, and towns must consider sea level rise when preparing evacuation and hazard mitigation plans[61] The state is also required to consider sea level rise when establishing priorities for grants and loans to support water quality projects.[62]

Delaware

The Delaware Coastal Management Area includes all lands and waters of the state to the limit of the state's territorial sea.[63] Within the Coastal Management Area is a Coastal Strip that includes all land, water and subaqueous land between the territorial limits of Delaware in the Delaware River, Delaware Bay, and the Atlantic Ocean and a line formed by certain Delaware highways and roads.[64]

The Department of Natural Resources and Environmental Control (DNREC) is the primary planning, policy, administration and enforcement agency for the Delaware Coastal Management Program. DRNEC has jurisdiction and permit authority over development in coastal strip,[65] tidal wetlands,[66] submerged lands and tidelands,[67] and beach and dune areas seaward of the mapped coastal building line[68] Other state agencies enforce the goals, policies and objectives of the program within the scope of their statutory authority.[69]

<u>Sea Level Rise</u>: The Delaware Beach Preservation program recognizes "rising sea level" as a cause of beach erosion and shoreline migration,[70] but there are no state statutes or regulations that require state agencies, counties or municipalities to consider sea level rise when making decisions under the Delaware Coastal Management Program.

Florida

The Florida coastal zone includes the lands and waters within the seaward limit of the state's territorial sea and inland to the extent of marine influences.[71] Practically speaking, this encompasses all of Florida. However, for coastal resource protection and management purposes, coastal zone regulation is limited to the geographical area encompassed by the thirty five Florida coastal counties and the adjoining territorial sea.[72]

The Florida Coastal Office (FCO) in the Department of Environmental Protection (DEP) manages the Florida Coastal Management Program (FCMP). The program is implemented through a network of state agencies using twenty-four statutes that were combined create the FCMP. These "network agencies" have coastal zone management jurisdiction seaward of the mean high water mark[73] and fifty feet landward of either the mean high water mark or the erosion control line, whichever is more landward.[74] Network agencies also have coastal zone management jurisdiction landward from this fifty-foot line to the coastal construction line unless that authority has been delegated to a municipal or county government.[75] Municipal or county governments have coastal zone management jurisdiction landward of the coastal construction line.[76]

<u>Sea Level Rise:</u> Coastal county and municipal governments must consider sea level rise in the coastal management "redevelopment" portion of their comprehensive plans[77] and may consider sea level rise when deciding whether to include an "adaptation action area" in their comprehensive plans. However, the only state statute that requires consideration of sea level rise when making coastal management permit decisions applies to armoring permits issued by the DEP.[78]

Georgia

The Georgia coastal zone includes the lands and waters seaward to the limit of the state's territorial sea and landward to the entirety of all six of Georgia's coastal counties and all five inland counties with tidally-influenced waters.[79]

The Georgia Department of Natural Resources (DNR) administers the Georgia Coastal Management Program (GCMP) and is responsible for resource management, ecological monitoring, permitting, technical assistance, and federal consistency review.[80] DNR permits are required for all development in coastal marshlands[81] and in coastal waters, beaches and sand dunes.[82] Other state agencies implement the GCMP by managing coastal zone resources within the scope of their statutory authority.[83] Local governments assist in long-term planning, economic development, and natural resource protection through their comprehensive plans, local laws and zoning regulations, chambers of commerce and economic development authorities.[84]

Sea Level Rise: There are no state statutes or regulations that require state agencies, counties or municipalities to consider sea level rise when making decisions under the Georgia Coastal Management Program.

Hawaii

The Hawaii Coastal Zone Management Area includes all lands and waters of the state to the limit of the state's territorial sea with the exception of certain lands designated as State forest reserves.[85] Within the Coastal Zone Management Area are mapped Special Management Areas that extend inland from the shoreline as required to further the objectives and policies of the Coastal Zone Management Program.[86]

The State of Hawaii Office of Planning is the lead policy, planning and oversight agency for the Hawaii Coastal Zone Management Program.[87] Other state agencies implement the program on state lands and waters within the scope of their statutory authority.[88] County authorities have jurisdiction over, and permitting authority within, the Special Management Areas and are responsible for carrying out Coastal Zone Management Program objectives, policies and procedures within their Special Management Areas.[89]

Sea Level Rise: The Hawaii Interagency Climate Adaptation Committee is responsible for developing a sea level rise vulnerability and adaptation report by the end of 2017 and updating that report every five years.[90] However, there are no state statutes or regulations that require state agencies, counties or municipalities to consider sea level rise when making decisions under the Hawaii Coastal Zone Management Program.

Louisiana

The Louisiana Coastal Zone includes the lands and waters within the seaward limit of the state's territorial sea and the lands and waters in demarcated portions of the states twenty coastal parishes.[91] The Louisiana Coastal Management Program is administered by the Department of Natural Resources. [92]

The Department of Natural Resources exercises coastal management jurisdiction through coastal use permits.[93] Coastal use permits are required for a "use of state or local concern" that affect "coastal waters," which are waters within the coastal zone that have, over a period of years and under normal weather conditions, a measurable seawater content.[94] The Department may delegate permitting authority for uses of local concern to local governments that have an approved Local Coastal Program.[95] Eleven of the twenty coastal zone parishes have Local Coastal Programs.[96]

Sea Level Rise: Sea level rise was considered during the science-based evaluation that provided the basis for the 2012 legislation that refined and generally expanded the inland boundaries of Louisiana coastal zone.[97] However, there are no state statutes or regulations that require local governments, the Department of Natural Resources, or any other state agency to consider sea level rise when making decisions under the Louisiana Coastal Management Program.

Maine

The Maine Coastal Program applies to a coastal area that includes the lands and waters within the seaward limit of the state's territorial sea and all coastal municipalities and unorganized townships on tidal waters.[98] The program is administered by the Department of Agriculture, Conservation and Forestry[99] and operates as a partnership between local, regional, and state agencies.[100]

The Maine Department of Environmental Protection exercises coastal management jurisdiction over coastal wetlands,[101] which include sub-tidal lands, lands subject to tidal action during the highest tide of the year, and areas with vegetation primarily associated with a salt water or estuarine habitat.[102] Coastal management jurisdiction landward of coastal wetlands is exercised by the Maine Land Use Planning Commission or by municipalities that have been approved by the Maine Environmental Protection Board.[103] State statutes also require municipalities to exercise coastal management jurisdiction through zoning and land use controls that are based upon minimum standards established by the Environmental Protection Board.[104] By statute, this zoning and land use jurisdiction includes "shoreland areas" 250 feet upland from a coastal wetland and any structure built on, over or abutting a dock, wharf, pier or other structure extending or located below the normal high-water line or within a wetland.[105]

Sea Level Rise: It is a policy of the Maine legislature to "discourage growth and development in coastal areas where, because of coastal storms, flooding, landslides or sea-level rise, it is hazardous to health and safety."[106] In furtherance of this policy, the Maine Department of Environmental Protection anticipates that sea level will rise approximately two feet in the next 100 years and takes this rise into consideration when evaluating proposed developments on coastal sand dunes.[107] To this end, the flooding associated with a 100-year storm after a two-foot rise in sea level is included in the definition of an "erosion hazard area" and is identified as a disqualifying factor for projects proposed on coastal sand dunes if such flooding is likely to damage the project over the next 100 years.[108] There are no other state statutes or regulations that require local governments, the Department of Environmental Protection, or any other state agency to consider sea level rise when making decisions under the Maine Coastal Program.

Maryland

The Maryland Coastal Zone Management Program (CZMP) and its statutory authorities apply to the lands and waters within the seaward limit of the state's territorial sea, Baltimore City, and the sixteen counties that border the Atlantic Ocean, Chesapeake Bay and Potomac River.[109] For purposes other than federal consistency, statutory authority for coastal management is limited "critical areas" that include the land and waters of Chesapeake Bay and its tributaries, the land and waters of ocean bays and their tributaries, tidal wetlands, and the land and waters 1,000 feet beyond these areas.[110] Local jurisdictions may expand or exclude critical areas within their jurisdiction subject to approval by the state Critical Area Commission.[111]

The Department of Natural Resources is the lead agency for the Maryland CZMP, which includes the Chesapeake and Coastal Bays Critical Areas Protection Program.[112] Under the Critical Areas Program, local governments exercise coastal management jurisdiction above the mean high water mark in accordance with programs developed by the local governments and approved by the state Critical Area Commission.[113] The state Department of the Environment exercises coastal management jurisdiction below the mean high water mark. [114]

Sea Level Rise: The Maryland Board of Public Works and Department of the Environment must consider sea level rise when issuing licenses and permits for construction and fill activities in state and private tidal wetlands[115] and the Critical Area Commission must consider sea level rise when exercising approval authority for state development projects on state-owned land in critical areas[116] Furthermore, all capital projects planned and built by state agencies must comply with (or obtain a waiver from) Coast Smart Council siting and design criteria, which includes a statutory requirement for the lowest floor to be at least two feet above base flood elevation.[117] There are no state statutes or regulations that either require or prohibit local government consideration of sea level rise when making coastal management decisions.

Massachusetts

The Massachusetts coastal zone includes the lands and waters from the seaward limit of the state's territorial sea to generally 100 feet landward of the first specified major land transportation route and includes all of Cape Cod, Nantucket, Martha's Vineyard, and the Elizabeth Islands.[118] The Massachusetts Office of Coastal Zone Management (CZM) is the lead policy and planning agency for coastal zone issues, but administrative decisions on coastal zone issues within state jurisdiction are made by other state agencies.[119] These state "network agencies" are generally responsible for coastal zone administrative decisions seaward of the high water mark.[120] Municipal Conservation Commissions are generally responsible for coastal management administrative decisions landward of the high water mark and within 100 feet of coastal resources.[121]

Sea Level Rise: State agencies must consider sea level rise when considering and issuing coastal management permits.[122] There are no state statutes or regulations that require municipalities to consider sea level rise when considering or issuing coastal management permits.

New Hampshire

The New Hampshire coastal zone includes the lands and waters within the limits of the state's territorial sea and inland from the shorelines of the Atlantic Ocean and the Great and Little Bays either 1,000 feet or to the extent of Wetlands Board jurisdiction, whichever is further. The coastal zone also includes lands and waters along estuarine rivers within the limits of Wetland Board jurisdiction.[123]

The New Hampshire Coastal Program was developed using existing state laws and policies. The Office of State Planning is the lead agency for the program and coordinates local, state and federal involvement.[124] The state Wetlands Board has jurisdiction over dredging, fill, and the erection of structures within state coastal waters, submerged lands, and tidal wetlands up to three and a half feet above mean high tide,[125] and other state agencies are responsible for enforcing the program within the scope of their jurisdiction.[126] Local participation in the New Hampshire Coastal Program is voluntary.[127]

Sea Level Rise: At least once every five years the Commissioner of the Department of Environmental Service is required to update and distribute the 2014 report, "Sea Level Rise, Storm Surges, and Extreme Precipitation in Coastal New Hampshire: Analysis of Past and Projected Trends."[128] When scoring applications for coastal program grants, projects that promote climate change adaptation by planning and modeling sea level rise are identified as "high priority projects."[129] These requirements notwithstanding, there are no state statutes or regulations that require state or local agencies to consider sea level rise when making decisions under the New Hampshire Coastal Program.

New Jersey

The New Jersey Coastal Program applies to a coastal area that includes the lands and waters within the seaward limit of the state's territorial sea, the state waters of the Hudson and Delaware rivers, and the tidal portions of tributaries to these seas and rivers. [130] The Coastal Program extends inland to specified portions of municipalities and counties on tidal waters[131] and to the Hackensack Meadowlands District.[132]

The New Jersey Department of Environmental Protection (NJDEP) exercises coastal management jurisdiction through a permit system that applies to most coastal development.[133] NJDEP also exercises permit authority over regulated activities, such as the placement or removal of material and erection of structures, in coastal wetlands.[134]

Sea Level Rise: There are no state statutes or regulations that require the NJDEP or any other state or local agencies to consider sea level rise when making decisions under the New Jersey Coastal Program. However, sea level rise was identified in the rationale for development prohibitions in coastal overwash and erosion areas.[135]

New York

The New York State Coastal Management Program applies to a "coastal area" that includes the lands and waters within the seaward limit of the state's territorial sea and inland generally 500 feet or to the nearest roadway or railroad line in urban and developed areas and inland generally 1,000 feet from the shoreline in other areas.[136] The Coastal Management Program is administered by the Department of State and is implemented by various departments in accordance with their statutory authority.[137] The Long Island Sound Coastal Management Program is a sub-program of the Coastal Management Program that is tailored to the unique ecology and human development patterns in portions of the state that border Long Island Sound.[138]

The New York Department of Environmental Conservation (DEC) exercises state jurisdiction over tidal wetlands and areas immediately adjacent to tidal wetlands, and may share this jurisdiction with local governments.[139] Tidal wetlands include areas that border or lie beneath tidal waters and wetlands subject to tides that are populated with vegetation primarily associated with estuarine habitat.[140] Areas adjacent to tidal wetlands include areas from the landward boundary of the mapped tidal wetland to (1) 300 feet inland (150 feet in New York City), or (2) up to ten feet elevation above mean sea level, or (3) to the seaward edge of the closest lawfully existing functional and substantial structure.[141]

Sea Level Rise: The Long Island Sound Coastal Management Program, promulgated in 1999, requires consideration of sea level rise as a means to minimize loss of life and structures when siting and designing projects involving substantial expenditures of public funds.[142] More recently, the Community Risk and Resiliency Act of 2014 requires the DEC to adopt science-based projections of sea level rise that are updated every five years.[143] These projections are used to inform planning efforts and to incorporate the consideration of sea level rise into various state permit and funding programs.[144] This same act also requires the Department of State and the DEC to prepare model local laws that include consideration of the risk of sea level rise.[145] However, except as noted above for the Long Island Sound Coastal Management Program, sea level rise projections are not otherwise incorporated into the tidal wetlands permitting process or the Coastal Management Program.

North Carolina

The North Carolina coastal zone includes the lands and waters within the seaward limit of the state's territorial sea and the twenty coastal-area counties designated by the Governor.[146] The North Carolina Coastal Resources

Commission (CRC) has exclusive coastal zone management jurisdiction over "Areas of Environmental Concern" seaward of the mean high water mark and shares this jurisdiction landward of the mean high water mark with coastal municipalities and the state's twenty coastal-area counties.[147] Areas of Environmental Concern are designated by the CRC and include ocean and estuarine systems, oceanfront lands, inlets that connect the ocean to sounds, public water supply areas, and natural and cultural resource areas.[148]

The CRC implements the North Carolina Coastal Management Act though a permit system that regulates development activities that may affect an Area of Environmental Concern. The Coastal Management Division of the North Carolina Department of Environmental Quality serves as the staff to the CRC and is responsible for Major Permits and General Permits.[149] County and municipal governments are responsible for Minor Permits.[150]

Sea Level Rise: There are no state statutes or regulations that require the CRC, counties or municipalities to consider sea level rise when making coastal zone management permit decisions. State statutes allow local governments to define sea level change for regulatory purposes, but identify the CRC as the only state agency allowed to do so.[151] Legislation enacted in 2012 requires the CRC to commission a comprehensive assessment of peer-reviewed scientific literature on sea level change, to conduct an economic and environmental cost-benefit analysis of sea level change regulation, to report the results of these tasks to the legislature by March 1 of 2016, and to abstain from defining rates of sea level change for regulatory purposes until July 1, 2016.[152]

Oregon

The Oregon coastal zone includes the lands and waters from the seaward limit of the state's territorial sea to the crest of the coastal mountain range.[153] The coastal zone also includes the estuaries of the Umpqua, Rouge, and Columbia Rivers.[154]

The Oregon Coastal Management Program (CMP) aggregates a number of state land and water management laws into a coordinated coastal resource management program. The Oregon Department of Land Conservation and Development (DLCD) is the lead policy and planning agency for the CMP.[155] Other state agencies implement the CMP by managing coastal zone resources within the scope of their statutory authority.[156] Counties and municipalities implement the CMP through land use regulations that comply with mandatory statewide "planning goals" that include specific goals for estuarine resources, coastal shorelands, beaches and dunes, and ocean resources.[157]

Sea Level Rise: There are no state statutes or regulations that require state agencies, counties or municipalities to consider sea level rise when making decisions under the Oregon Coastal Management Program.

Rhode Island

The Rhode Island Coastal Resources Management Program encompasses a three tier coastal zone.[158] The first tier includes the lands and waters within the seaward limit of the state's territorial sea and 200 feet inland from shoreline features. [159] The Rhode Island Coastal Resources Management Council (CRMC) has exclusive coastal zone management jurisdiction in this first tier.[160] The second tier encompasses the entirety of all coastal municipalities, where all state activities, plans and projects must be consistent with the Rhode Island "State Guide Plan," which is the state's integrated long-range planning document.[161] The third tier is the entire state, where CRMC shares jurisdiction with other state agencies over inland activities that have coastal ramifications such as power plants, mines, chemical processing operations, sewage treatment plants, and solid waste disposal facilities.[162]

CRMC enforces the Rhode Island Coastal Resources Management Program in first tier areas through a process that requires CRMC "assent" for specified activities or alterations or any other activity or alteration which "(1) has a reasonable probability of conflicting with the Council's goals and its management plans or programs, and/or (2) has the potential to damage the environment of the coastal region."[163] For development above the mean high water mark, CRMC assent requires the applicant to demonstrate that local building permit has been issued or will be issued upon CRMC assent.[164]

Sea Level Rise: The CRMC is obligated to plan for sea level rise and to integrate sea level rise scenarios into its policies and programs.[165] The CRMC relies upon the most recent NOAA sea level rise data to address both short- and long-term planning horizons and the design life considerations for public and private infrastructure.[166]

South Carolina

The South Carolina coastal zone includes the lands and waters within the seaward limit of the state's territorial sea and the lands and waters in the all six of the state's coastal counties and in two inland counties subject to tidal waters. [167] The South Carolina Office of Ocean and Coastal Resource Management (OCRM) within the Department of Health and Environmental Control has exclusive coastal zone management jurisdiction seaward of the mean high water mark[168] and shares jurisdiction landward of the mean high water mark with counties and municipalities in all eight of the state's coastal zone counties.[169]

OCRM implements the South Carolina Coastal Tidelands and Wetlands Act (CTWA) through a permit system that regulates development activities in "Critical Areas" that include coastal waters, tidelands, beaches, and the beach/dune system from the mean high-water mark to the forty-year erosion setback line.[170] Counties and municipalities manage zoning and other day-to-day coastal issues in accordance "Local Comprehensive Beach Management Plans" that are developed by the local government and approved by OCRM.[171]

Sea Level Rise: There are no state statutes or regulations that require the OCRM, counties or municipalities to consider sea level rise when considering or issuing coastal management permits. However, an OCRM statement of regulatory policy acknowledges sea level rise as a factor that will ultimately require a retreat from the beachfront,[172] and some local governments have incorporated sea level rise into their local planning.[173]

Texas

The Texas coastal area includes the lands and waters within the seaward limit of the state's territorial sea and the lands and waters the eighteen Texas counties with tidewater shoreline.[174] Within this coastal area is a coastal zone established by the Commissioner of the General Land Office (GLO) in accordance with guidance set forth in Texas statutes.[175] The GLO is the lead policy and planning agency for the Texas Coastal Management Program (CMP),[176] but other state agencies and political subdivisions are responsible for enforcing the program within the scope of their jurisdiction.[177]

Texas state agencies and political subdivisions are obligated to affirm that they have taken into account the goals and policies of the CMP when taking actions that may adversely affect coastal natural resource areas within the coastal zone.[178] Under certain conditions such actions are subject to a GLO consistency review.[179] Actions deemed by the GLO to be inconsistent with the goals and policies of the CMP are remanded to the agency or political subdivision and forwarded to the Attorney General for an opinion if the action is not modified to comply with the remand.[180] The consistency review process also applies to certain rules adopted or amended by specified state agencies, which must be certified by the GLO.[181] Actions and rules subject to GLO consistency review are limited to those specifically identified by statute.[182]

Sea Level Rise: The GLO and the Parks and Wildlife Department are required to consider sea level rise when developing the State-Owned Wetlands Conservation Plan,[183] and sea level rise is identified as an "adverse effect" that could result in the physical destruction or detrimental alteration of a coastal natural resource area.[184] There are no state statutes or regulations that require the GLO or other state or local agencies to consider sea level rise when considering whether proposed actions or rules are consistent with the objectives of the CMP.

Virginia

For the purposes of the Virginia Coastal Zone Management Program, the "Coastal Area" includes the lands and waters within the seaward limit of the state's territorial sea and the lands and waters in "Tidewater Virginia," which includes designated counties and cities subject to tidal waters. [185] The Department of Environmental Quality (DEQ) is the lead agency of a networked program that is implemented by various departments in accordance with their statutory authority.[186]

The Virginia Marine Resources Commission has jurisdiction over territorial seas and exercises permit authority for development in submerged wetlands, tidal wetlands, and dunes and beaches.[187] Counties and municipalities may establish local wetlands boards and adopt local ordinances, consistent with statutory model ordinances, to regulate and permit development on wetlands and dunes above the mean low water line.[188] Wetlands board permits are subject to review by the Commissioner of Marine Resources and modification, remand, or reversal by the Marine Resources Commission.[189]

Sea Level Rise: There are no state statutes or regulations that require municipalities, counties, the Marine Resources Commission, or any other state agency to consider sea level rise when making decisions under the Virginia Coastal Zone Management Program. For planning purposes, a state statute requires localities in the Hampton Roads Planning District to incorporate sea level rise into comprehensive plan strategy reviews conduced after 2015 and directs certain state agencies and academic institutions to assist with those reviews when requested to do so.[190] To support this requirement, a state statute requires the Virginia Institute of Marine Sciences to develop comprehensive coastal resource management guidance for local governments and requires that guidance to consider sea level rise.[191]

Washington

The Washington Coastal Zone Management Program is a two-tier program encompasses all lands and waters in the fifteen Washington counties that front salt water.[192] The first tier of the program includes the "shorelines of the state," which include all marine waters of the state, reservoirs, lakes larger than twenty acres, streams with a mean annual flow of twenty cubic feet per second or more, the lands underlying them, and adjacent "shorelands."[193] Shorelands include land areas extending 200 feet inland from the ordinary high water mark, floodways and contiguous floodplains 200 feet from floodways, and wetlands and river deltas associated with shoreline streams, lakes and tidal waters, and local governments that implement the CZMP in the first tier may expand the scope of the program to include buffers for critical areas and the 100-year flood plains associated with shoreland floodways.[194] The second tier of the program encompasses lands and waters in the fifteen coastal counties that are not in the area covered by the first tier.

The Department of Ecology is the lead state agency for the Washington CZMP, but local governments have the primary responsibility for planning and administering a "shoreline master program" for first tier coastal management that complies with state statutory requirements.[195] Local governments exercise first tier coastal management jurisdiction through a permit system that applies to most coastal development activities.[196] The Department of Ecology acts in a supportive and review capacity to provide assistance to local governments and insure compliance with state statutes.[197] Development proposals in the second tier that may have a "direct and significant impact" on coastal waters are managed under other state programs invoke by the Washington CZMP.[198]

Sea Level Rise: There are no state statutes or regulations that require the Department of Ecology or any other state or local agency to consider sea level rise when making decisions under the Washington Coastal Zone Management Program. However, the Shoreline Master Program (SMP) Handbook published by the Department of Ecology encourages local governments to consider the impacts of sea level rise when developing and updating SMPs and provides guidance on how to do so.[199]

VI. Conclusion

More than 40 years ago the Federal Coastal Zone Management Act provided powerful incentives for states to develop formal coastal management programs. Today, twenty-two of the country's twenty-three oceanfront states have coastal management programs that protect and restore coastal resources, manage coastal development, prioritize water-dependent uses, and facilitate access to public trust beaches, waters, and submerged lands.

The twenty-first century will continue to challenge these programs with the traditional pressures for development and use. But this century will also challenge coastal management programs with climate change and sea level rise - issues that were not widely considered when these programs were adopted in the latter part of the previous century. To date, only eleven oceanfront states have statewide statutes or regulations that address sea level rise, and only three of those states require the consideration of sea level rise when making most or all coastal management decisions. It remains to be seen whether a system designed for local management of coastal resources can adapt to the global consequences of climate change and sea level rise.

Endnotes

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DISCLAIMER: *This white paper addresses issues of general interest and does not give any specific legal advice pertaining to any specific circumstance. Parties should obtain advice from a lawyer or other qualified professional before acting on the information in this paper.*

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[29] R.I. GEN. LAWS § 46-23-6.

[30] NAT'L OCEANIC & ATMOSPHERIC ADMIN., STATE OF RHODE ISLAND COASTAL ZONE MANAGEMENT PROGRAM AND FINAL ENVIRONMENTAL IMPACT STATEMENT (1978) (Appendix D Revised Spring 1986).

[31] Refer to the individual state summaries in Section Five for jurisdictional authority citations.

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[34] CONN. GEN. STAT. §§ 22a-102, 22a-103, 22a-104.

[35] INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE [IPCC], CLIMATE CHANGE 2013: THE PHYSICAL SCIENCE BASIS 6, fig.SPM.2 (Working Group I).

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[43] ALA. CODE §§ 9-7-15, 9-7-20 (2017).

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[54] Cal. Exec. Order No. S-13-08 (Nov. 14, 2008).

[55] CAL. COASTAL COMM'N, SEA LEVEL RISE POLICY GUIDANCE (2015).

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[58] CONN. GEN. STAT. § 22a-359 (2017).
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[60] *Id*.
[61] CONN. GEN. STAT. §§ 8-23 (Town Land Use Plans), 16a-27 (State Land Use Plans), 25-68o (Town Evacuation and Hazard Mitigation Plans).
[62] CONN. GEN. STAT. § 22a-478 (2017).
[63] DEL. CODE REGS. § 108-1.0 (LexisNexis 2010).
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[66] DEL. CODE. ANN. tit. 7 § 6604 (West 2017).
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[68] DEL. CODE. ANN. tit. 7 § 6805 (West 2017).
[69] Del. Exec. Order No. 61 (Aug. 24, 1978).
[70] DEL. CODE. ANN. tit. 7 § 6801 (West 2017).
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[72] *Id.*
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[80] NAT'L OCEANIC & ATMOSPHERIC ADMIN., COASTAL MANAGEMENT PROGRAM AND ENVIRONMENTAL STATEMENT II, 10–12 (1997) [Hereinafter GCMP II].
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[82] GA. CODE ANN. § 12-5-237 (West 2017).
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[85] HAW. REV. STAT. ANN. § 205A-22 (West 2017).
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[87] HAW. REV. STAT. ANN. § 205A-3 (West 2017).
[88] HAW. REV. STAT. ANN. § 205A-4 (West 2017).
[89] HAW. REV. STAT. ANN. § 205A-27 (West 2017).
[90] HAW. REV. STAT. ANN. § 225P-3 (West 2017).
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[92] LA. STAT. ANN. § 49:214.26 (2017).
[93] LA. STAT. ANN. § 49:214.30 (2017).
[94] LA. STAT. ANN. §§ 49:214.23, 49:214.30 (2017).
[95] LA. STAT. ANN. § 49:214.28 (2017).
[96] *Local Coastal Management Programs*, LA. DEPT. OF NAT. RES., http://www.dnr.louisiana.gov/index.cfm?md=pagebuilder&tmp=home&pid=111&pnid=192&nid=194 (Last Visited May 15, 2017).
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[99] ME. REV. STAT. tit. 12, § 541-A (2017).
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[101] ME. CODE R. § 06-096, Ch. 310, § 2 (2017).
[102] ME. REV. STAT. tit. 38, § 480-B (2017).
[103] ME. REV. STAT. tit. 38, §§ 480-E-1 and 480-F (2017).

[104] ME. REV. STAT. tit. 38, § 438-A (2017).
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[107] ME. CODE R. tit. 06-096, Ch. 355, § 1 d
[108] ME. CODE R. tit. 06-096, Ch. 355, §§ 3 and 5
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[113] MD. CODE, NAT. RES. § 8-1808 (2010).
[114] MD. CODE, ENVIR. § 5-203 (2018).
[115] MD. CODE REGS. 26.24.02.03 (2016).
[116] MD. CODE REGS. 27.02.05.02 (2016).
[117] MD. CODE, STATE FIN. & PROC. § 3-602.3 (2014).
[118] MASS. OFFICE OF COASTAL ZONE MGMT., POLICY GUIDE (2011).
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[121] MASS. GEN. LAWS ch.130 § 105; 310 MASS. CODE REGS. § 10
[122] MASS. GEN. LAWS ch.30 § 61 (applies to all state agency permitting and licensing decisions); 310 MASS. CODE REGS. § 9.37 (applies to state agency permitting decisions for nonwater-dependent buildings located within a flood zone and intended for human occupancy).
[123] NAT'L OCEANIC & ATMOSPHERIC ADMIN., NEW HAMPSHIRE COASTAL PROGRAM AND FINAL ENVIRONMENTAL IMPACT STATEMENT 2-1 (1988).
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[127] *Id.* at S-2.
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[135] N.J. ADMIN CODE §§ 7:7-9.17, 7:7-9.19 (2017).
[136] N.Y. EXEC. LAW § 914 (McKinney); NAT'L OCEANIC & ATMOSPHERIC ADMIN., STATE OF NEW YORK COASTAL MANAGEMENT PROGRAM AND FINAL IMPACT STATEMENT (1982).
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[138] N.Y. COMP. CODES R. & REGS. tit. 19 § 600.6; N.Y. DEP'T OF STATE, LONG ISLAND SOUND COASTAL MANAGEMENT PROGRAM (1999).
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[145] N.Y. ENVTL. CONSERV. LAW § 70-0117 (McKinney 2015).

[146] N.C. GEN. STAT. § 113A-103.
[147] *See* N.C. GEN. STAT. § 77-20 (identifying the seaward boundary of non-state property); *see also id.* § 113A-101 (describing the shared jurisdiction of state and local governments).
[148] N.C. GEN. STAT. § 113A-113.
[149] N.C. GEN. STAT. §§ 113A-118.1, 113A-119; 15A N.C. ADMIN. CODE 7J.0202.
[150] N.C. GEN. STAT. § 113A-121; 15A N.C. ADMIN. CODE 7J.0202 (2018).
[151] N.C. GEN. STAT. § 113A-107.1.
[152] 2011-2012 N.C. Sess. Laws 202
[153] OR. LAND CONSERVATION & DEV.T COMM'N, OREGON COASTAL MANAGEMENT PROGRAM 20 (1987).
[154] *Id.*
[155] OR. REV. STAT. ANN. § 196.435 (West 2003).
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[157] *Id.* at 7, 12–16.
[158] NAT'L OCEANIC & ATMOSPHERIC ADMIN., STATE OF RHODE ISLAND COASTAL ZONE MANAGEMENT PROGRAM AND FINAL ENVIRONMENTAL IMPACT STATEMENT (1978) (Appendix D Revised Spring 1986).
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[160] R.I. GEN. LAWS § 46-23-6.
[161] NAT'L OCEANIC & ATMOSPHERIC ADMIN., *supra* note 167.
[162] *Id.*; R.I. GEN. LAWS § 46-23-6.
[163] R.I. CODE R. § 100.1 (2000).
[164] R.I CODE R. § 100.2 (2000).
[165] R.I. CODE R. 16-2-1:145 (1956).
[166] *Id.*
[167] S.C. CODE ANN. § 48-39-10.
[168] State v. Pac. Guano Co., 22 S.C. 50 (S.C. 1884).
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[170] S.C. CODE ANN. §§ 48-39-10, 48-39-130.
[171] S.C. CODE ANN. § 48-39-350.
[172] S.C. CODE ANN. REGS. 30-1.
[173] *See e.g.*, CITY OF CHARLESTON, SEA LEVEL RISE STRATEGY (2015), http://www.charleston-sc.gov/DocumentCenter/View/10089.
[174] TEX. NAT. RES. CODE ANN. § 33.004 (West 2017).
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[176] TEX. NAT. RES. CODE ANN. § 33.204 (West 2017).
[177] TEX. NAT. RES. CODE ANN. § 33.208 (West 2017).
[178] TEX. NAT. RES. CODE ANN. §§ 33.205, 33.2051, 33.2053 (West 2017).
[179] TEX. NAT. RES. CODE ANN. § 33.205 (West 2017).
[180] TEX. NAT. RES. CODE ANN. § 33.206 (West 2017).
[181] TEX. NAT. RES. CODE ANN. § 33.2052 (West 2017); 31 TEX. ADMIN. CODE § 505.20 (West 2017).
[182] TEX. NAT. RES. CODE ANN. §§ 33.205, 33.2051, 33.2053 (West 2017).
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[184] 31 TEX. ADMIN. CODE § 501.3 (2017).
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[194] WASH. REV. CODE ANN. § 90.58.030 (West 2017).

195 WASH. REV. CODE ANN. § 90.58.050 (West 2017).
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Statutory Adoption of Updated Sea-Level Rise Scenarios

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Executive Summary

In the summer of 2013, the Connecticut General Assembly acknowledged the threat of rising seas with Public Act 13-179. Signed into law on June 21, this act requires state and municipal agencies to consider sea level rise when making critical plans for land use, hazard mitigation, and civil preparedness.

P.A. 13-179 will help Connecticut plan for rising seas, but the effectiveness of those plans may be limited by a dissonance within the act that involves the source of the sea level data to be used by the planners. Among other things, the act requires planners to use the sea level data in a specific 2012 NOAA report while simultaneously requiring the University of Connecticut to update the data in that report at least once every ten years. However, the act does not require - or even allow - the use of the UConn updates as they become available, nor does it specify a means by which the UConn updates are published. As a result, planners are obligated to consider the 2012 NOAA data even after newer, and presumably more accurate, updates are available from UConn.

This paper suggests the following legislative actions to assure that the latest UConn updates to the 2012 NOAA sea level data are used to implement the planning and emergency preparedness requirements of P.A. 12-179:

- modify the language of Connecticut General Statutes to include an imperative to use the UConn sea level updates, and
- modify the language of Connecticut General Statutes to specify a means by which the latest UConn updates are identified and published.

These relatively minor modifications will assure that planning agencies always have access to the latest UConn sea level data and eliminate any statutory ambiguity as to which sea level data should be used when conducting critical planning and emergency preparedness activities.

I. Introduction

Global sea levels are rising at an accelerating rate. In the past century, global median sea levels rose over seven inches.[1] While this rate is alarming, the National Oceanic and Atmospheric Administration (NOAA) anticipates the coming century will see an even greater rise of one to eight feet.[2] Furthermore, as the shoreline of Long Island Sound and the state's tidal rivers are increasingly inundated by rising waters, Connecticut's land is simultaneously sinking as the Earth's crust evens out from retreating glaciers.[3] This convergence of rising seas and sinking land is creating a disproportionate rise in sea levels, which will aggravate coastal and riverine flooding, which in turn will damage property and erode natural coastal barriers.[4] Such erosion will reduce stormwater resiliency as tropical storms grow stronger and winter storms more frequent.[5]

The Connecticut Department of Energy and Environmental Protection (DEEP) estimates that these changes will cause the effects of the current "100-year storm" to occur every seventeen to thirty-two years by 2100.[6] And the costs of these storms will be devastating. Federal Emergency Management Agency (FEMA) data from 2010 indicate that a statewide 100-year flood would result in property damage and business interruptions worth nearly $19 billion, with $13 billion of this devastation concentrated within Connecticut's shoreline communities.[7]

The Connecticut General Assembly responded to this threat with Public Act 13-179. Signed into law on June 21, 2013 and codified as Connecticut General Statutes sections 8-23, 16a-27, 25-68o, and 28-5, this act requires state and municipal agencies to consider sea level rise when making critical plans for land use, hazard mitigation, and civil preparedness.[8]

P.A. 13-179 represented Connecticut's second major legislative action designed to prepare the state for sea level rise. The first sea level rise action, P.A. 12-101, was signed into law just the year before. Among other things, P.A. 12-101 declared it a coastal management policy of the legislature to consider the potential impact of a rise during planning processes.[9] Because state agencies and towns are required by law to implement these legislative policies, the act effectively requires state agencies and towns to consider a rise in sea level during all coastal management planning activities.[10] P.A. 12-101 also included provisions for the Connecticut DEEP, the University of Connecticut (UConn), and the Connecticut State University System to study the effects of a rise in sea level and for the DEEP to establish a pilot program to encourage innovative and low impact approaches to shoreline protection and adaptation in the face of a rise in sea level.[11]

P.A. 13-179 picked up where P.A. 12-101 left off. While the planning requirements of P.A. 12-101 were implied, P.A. 13-179 made them explicit, with precise language that requires planners to consider sea level change when revising state and municipal plans of conservation and development, municipal evaluation and hazard mitigation plans, and the state civil preparedness plan and program.[12] P.A. 13-179 also requires the use of the forward-looking sea level change scenarios published in NOAA Technical Report OAR CPO-1 (2012) (hereinafter "the NOAA Report").[13] This is an important change from the requirements of P.A. 12-101, which defined "a rise in sea level" in terms of the backward-looking historical sea level rise based on tide gauges in Bridgeport and New London.[14]

The NOAA Report represented state of the art sea level rise predictions when published in 2012, but was quick to acknowledge the global nature of its predictions and the need to tailor those predictions to local conditions.[15] Recognizing this need as well as the rapid advances in the field of climate science, the legislature included in P.A. 13-179 a requirement for UConn to update the 2012 NOAA sea level rise scenarios at least once every ten years.[16] The draft executive summary of the first of these updates was promulgated on the website of the Connecticut Institute for Resilience and Climate Adaptation (CIRCA) website in September of 2017.[17]

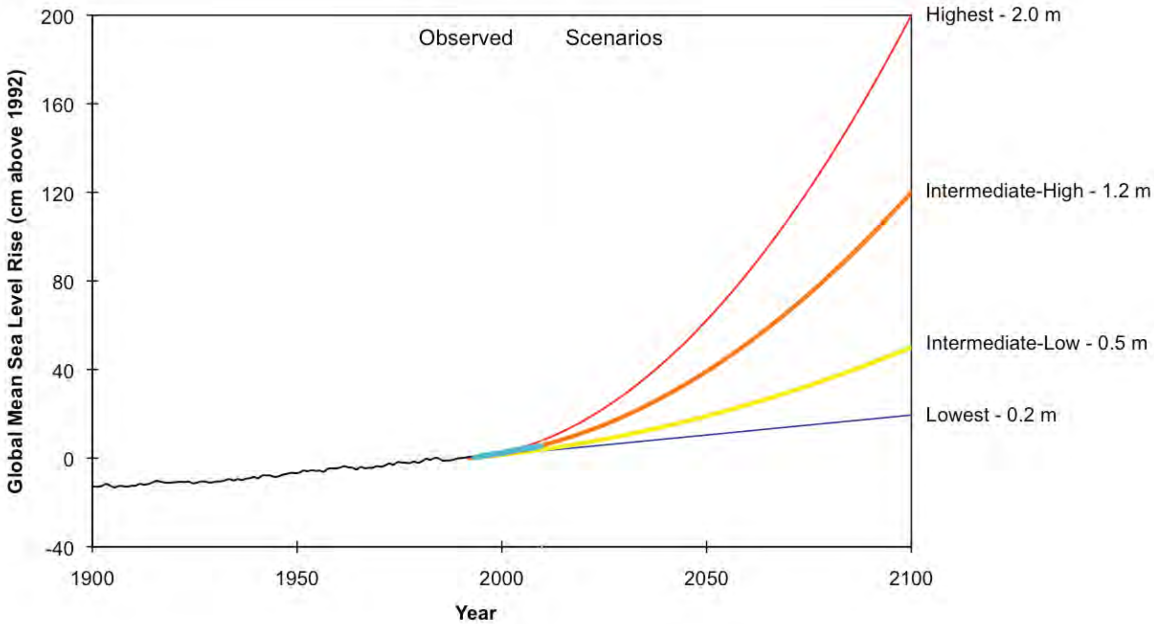
Even though P.A. 13-179 requires UConn to update the NOAA sea level rise scenarios, it does not mandate the use of these updated scenarios, nor does it specify a means by which the UConn updates are promulgated. The result of this dissonance is that Connecticut state and municipal agencies may be required to prepare for rising seas with increasingly outdated data that are not particularly applicable to the Connecticut shoreline or Long Island Sound.

This white paper describes the sea level rise scenarios in the NOAA Report, identifies the statutes that invoke the NOAA Report, explains the need to periodically update sea level change scenarios, and proposes statutes that (1) require the use of the UConn updates in lieu of the scenarios in the 2012 version of the NOAA Report, and (2) specify the means by which the UConn updates are promulgated.

II. NOAA Technical Report OAR CPO-1 (2012)

Public Act 13-179 invokes a 2012 NOAA report entitled "Global Sea Level Rise Scenarios for the United States National Climate Assessment, Technical Report OAR CPO-1" (hereinafter "the NOAA Report").[18] This report was published under the authority of the Global Change Research Act of 1990, which requires a National Climate Assessment every four years.[19] The NOAA Report was prepared as a contribution to the 2014 version of that quadrennial National Climate Assessment.[20]

The NOAA Report is a technical report that synthesizes the scientific literature on global sea level rise. One product of this synthesis is a set of sea level rise scenarios prepared "for the purpose of assessing potential vulnerabilities and impacts."[21] These sea level rise scenarios, shown on the graph and table below, are the scenarios invoked by Connecticut P.A. 13-179.



"Figure 10" from "Global Sea Level Rise Scenarios for the United States National Climate Assessment, Technical Report OAR CPO-1" (2012)

Scenario	SLR by 2100 (m)*	SLR by 2100 (ft)*
Highest	2.0	6.6
Intermediate-High	1.2	3.9
Intermediate-Low	0.5	1.6
Lowest	0.2	0.7

* Using mean sea level in 1992 as a starting point.

Reproduced from "Table 2" from "Global Sea Level Rise Scenarios for the United States National Climate Assessment, Technical Report OAR CPO-1"

As indicated on the graph and table, the NOAA Report provides four different scenarios for global sea level rise. The "Lowest" projected rise, 0.2 meters by 2100, is a simple linear extrapolation of the historical rise based upon tide gauge data dating back to 1900. The remaining projections are based on various estimates of ocean warming and ice sheet loss from Greenland and Antarctica, with ice sheet loss accounting for the greatest difference between the projections. The "Highest" projected rise of 2.0 meters by 2100 is based upon an estimate of the greatest possible ice sheet loss. The "Intermediate-High" projection of 1.2 meters by 2100 considers limited ice sheet loss and the "Intermediate-Low" projection of 0.5 meters is based primarily upon ocean warming with little ice sheet loss.[22]

The NOAA Report leaves the selection of a particular sea level rise scenario to the user, but recommends that "the choice of scenarios involve interdisciplinary scientific experts, as well as coastal managers and planners who understand relevant decision factors."[23] The NOAA Report amplifies this guidance by identifying those decision factors as "location, time horizon, and risk tolerance."[24] For instance, municipal planners in a coastal town considering a new sewage treatment plant may decide to use the "Highest" sea level rise scenario after considering the site of the plant (location), the long design life (time horizon), and the consequences of losing the plant to sea level rise (risk tolerance).

The NOAA Report is also careful to note that its sea level rise projections are global in nature and that regional and local conditions should be considered when using these projections to conduct risk analysis. Conditions to be considered include, "regional mean sea level variability, local and regional vertical land movement, coastal environmental processes (geological, ecological, biological, and socio-economic), and the effect of extreme weather and climate on relative sea level."[25]

Finally, it should be noted that the scenarios in the NOAA Report are not the last word on sea level rise projections. Quite the contrary, the need to periodically update sea level rise scenarios is illustrated by the fact that NOAA has already released the successor publication to the 2012 NOAA Report, a report entitled, "Global and Regional Sea Level Rise Scenarios for the United States, Technical Report NOS CO-OPS 083."[26] Unsurprisingly, even though this report is only four years newer than the 2012 NOAA Report, it nevertheless indicates global sea level rise projections that are different than those set forth in the 2012 report.[27]

III. Statutes that Invoke NOAA Technical Report OAR CPO-1 (2012)

Public Act 13-179 incorporated the NOAA Report sea level rise projections into four state and municipal planning statutes. Two of these statues deal with plans of conservation development prepared by municipalities and the state, while the other two deal with emergency planning activities. One of these statutes also requires the UConn update to the NOAA Report sea level rise scenarios. The following sections describe how the sea level provisions of P.A. 13-179 were codified into each of these four statutes.

A. CGS § 8-23 - Preparation, Amendment or Adoption of a Plan of Conservation and Development

Connecticut General Statutes section 8-23 requires municipalities to prepare and adopt a Plan of Conservation and Development (POCD) at least once every ten years.[28] The overall purpose of the POCD is to be a statement of the policies, goals, and standards for the physical and economic development of the community. Subsection (d) of section 8-23 identifies the factors that must be considered when developing a POCD, and P.A. 13-179 added the NOAA Report sea level change scenarios to the list of these factors as shown below (words added by P.A. 13-179 are in ***bold italics***)

> (d) In preparing such plan, the commission or any special committee shall consider the following: (1) The community development action plan of the municipality, if any, (2) the need for affordable housing, (3) the need for protection of existing and potential public surface and ground drinking water supplies, (4) the use of cluster development and other development patterns to the extent consistent with soil types, terrain and infrastructure capacity within the municipality, (5) the state plan of conservation and development adopted pursuant to chapter 297, (6) the regional plan of conservation and development adopted pursuant to section 8-35a, (7) physical, social, economic and governmental conditions and trends, (8) the needs of the municipality including, but not limited to, human resources, education, health, housing, recreation, social services, public utilities, public protection, transportation and circulation and cultural and interpersonal communications,

> (9) the objectives of energy-efficient patterns of development, the use of solar and other renewable forms of energy and energy conservation, (10) protection and preservation of agriculture, and (11) ***sea level change scenarios published by the National Oceanic and Atmospheric Administration in Technical Report OAR CPO-1.***[29]

B. CGS §16a-27 - Revision of Existing Plan

Connecticut General Statutes section 16a-27 requires the Connecticut Office of Policy and Management to revise the state POCD at least once every five years.[30] The overall purpose of the state POCD is to provide an official policy for the executive department, subject to the approval of the General Assembly, for physical development and for conservation of state land and water resources. As shown below, P.A. 13-179 added the NOAA Report sea level change scenarios to subsection (h) as the determining factor when considering the risks of coastal erosion (words added by P.A. 13-179 are in ***bold italics***):

> (h) Any revision made after October 1, 2013, shall (1) take into consideration risks associated with increased coastal erosion, depending on site topography, ***as anticipated in sea level change scenarios published by the National Oceanic and Atmospheric Administration in Technical Report OAR CPO-1,*** (2) identify the impacts of such increased erosion on infrastructure and natural resources, and (3) make recommendations for the siting of future infrastructure and property development to minimize the use of areas prone to such erosion.[31]

C. CGS § 25-68o - Consideration of Sea Level Change Scenarios re Municipal Evacuation and Hazard Mitigation plans. Update of Sea Level Change Scenarios.

Connecticut General Statutes section 25-68o is a component of the flood management chapter of the Connecticut General Statutes.[32] All of section 25-68o was created by P.A. 13-179, and includes two subsections, (a) and (b), related to the NOAA Report sea level rise scenarios. Subsection (a) requires consideration of the NOAA Report sea level change scenarios when preparing municipal evacuation and hazard mitigation plans as shown below (words added by P.A. 13-179 are in ***bold italics***):

> ***(a) On and after October 1, 2013, in the preparation of any municipal evacuation plan or hazard mitigation plan, such municipality shall consider sea level change published by the National Oceanic and Atmospheric Administration in Technical Report OAR CPO-1***.[33]

P.A. 13-179 also created an all-new subsection (b), which includes the requirement for the UConn to update the NOAA Report sea level change scenarios as shown below(words added by P.A. 13-179 are in ***bold italics***):

> ***(b) Within available resources and not less than once every ten years, the Marine Sciences Division of The University of Connecticut shall update the sea level change scenarios published by the National Oceanic and Atmospheric Administration in Technical Report OAR CPO-1. Within available resources and not less than ninety days prior to any update of such sea level change scenarios by said Marine Sciences Division, the division shall conduct not less than one public hearing concerning such update***.[34]

D. CGS § 28-5 - Preparation for civil preparedness, etc.

Connecticut General Statutes section 16a-27 deals with state civil preparedness issues.[35] As shown below, P.A. 13-179 added an entirely new subsection (g) to include the NOAA Report sea level change scenarios as a factor to be considered by the state civil preparedness plan and program (words added by P.A. 13-179 are in ***bold italics***):

> ***(g) On and after October 1, 2013, the state civil preparedness plan and program established pursuant to subsection (b) of this section shall consider sea level change published by the National Oceanic and Atmospheric Administration in Technical Report OAR CPO-1.***[36]

IV. University of Connecticut Updates to Sea Level Rise Scenarios

As described above, Connecticut General Statutes section 25-68o requires UConn to update the NOAA Report sea level change scenarios at least once every ten years. This requirement is important because the climate science on which sea level rise is based is a dynamic and evolving field that is continually collecting new data and developing improved means to interpret those data. The fundamental need to keep up with changes in climate science was recognized by the federal government in the Global Change Research Act of 1990, which requires the U.S. Global Change Research Program (USGCRP) to update the National Climate Assessment every four years.[37] More recently, the USGCRP has implemented a "sustained assessment" process that allows new climate information and insights to be synthesized into the climate assessment as they emerge.[38] Furthermore, even NOAA has demonstrated the temporal nature of the sea level rise scenarios in the NOAA Report with the 2017 release of its successor publication, Global and Regional Sea Level Rise Scenarios for the United States, Technical Report NOS CO-OPS 083.[39] Clearly, climate science is advancing, so the sea level rise information used for critical planning decisions must advance as well.

While it is important to use the latest climate science for critical planning activities, it is equally important to use science that is based upon the unique conditions of Long Island Sound and the Connecticut Coast. The NOAA Report itself indicates the need for the local adaptation of the global scenarios:

> Additional information should be combined with the global scenarios to incorporate regional and local conditions when conducting risk analysis. These factors include regional mean sea level variability, local and regional vertical land movement, coastal environmental processes (geological, ecological, biological, and socio-economic), and the effect of extreme weather and climate on [relative sea level].[40]

The UConn updates to the NOAA global sea level rise scenarios will incorporate additional local and regional information as well as the latest advances in global climate science. The draft executive summary of the first of these updates was promulgated on the website of the Connecticut Institute for Resilience and Climate Adaptation (CIRCA) website in September of 2017.[41]

The legislative requirement for UConn to periodically update the NOAA sea level rise scenarios reflects the legislature's understanding of the dynamic nature of climate science and the need to use updated sea level rise scenarios when making critical plans for land use, hazard mitigation, and civil preparedness. However, the statutory invocation of "NOAA Technical Report OAR CPO-1" leaves the science behind these plans frozen in 2012. This dissonance can be resolved by specifying the use of the latest UConn sea level change scenarios in the statutes that currently invoke the scenarios in the 2012 NOAA Report.

V. Promulgation of the University of Connecticut Updates

P.A. 13-179 does not specify a means by which the UConn updates to the NOAA Report are promulgated. This is problematic because the affected agencies need ready access to a controlled copy of the latest update, particularly if future use of the UConn updates is mandated by legislation. Without a controlled copy, it could be difficult for an agency to determine whether a publication from "the Marine Sciences Division of The University of Connecticut" is the latest update required by Connecticut General Statutes section 25-68o or simply an academic paper on the same topic. Similarly, even if a Marine Sciences Division document is specifically identified as an update to the NOAA Report, there could be questions as to whether the document is the latest update. This issue can be resolved by revising the statute that requires the UConn update to include the means by which this update is published.

VI. Suggested Legislation

In order to assure that the best scientific data on sea level change are used for land use, hazard mitigation, and civil preparedness planning, the Connecticut General Assembly could enact legislation that mandates the use of the latest UConn update to the NOAA Report and specify a means by which the update is published. Suggestions for this legislation are detailed below:

A. Suggested Legislation to Specify How the UConn Updates Will Be Promulgated

This paper suggests legislation that requires the latest UConn update to the NOAA Report to be posted on the internet website of the Department of Energy and Environmental Protection (DEEP). The DEEP website is suggested as the best venue for the UConn updates because state and municipal agencies have historically looked to DEEP for information on matters related to coastal management, floodplain management, and Long Island Sound. Putting the UConn updates on the DEEP website also provides a means to assure that only the latest version of the update is in the designated location. Furthermore, this is not an unusual process for the DEEP as there are many examples of statutes that require the DEEP Commissioner to post important information on the department's web site.[42]

The following change to Connecticut General Statutes section 25-60o (b) is suggested as an effective means of publishing the UConn updates to the NOAA Report. (New words are identified by ***bold italics.***)

> **Subsection (b) of Connecticut General Statutes Section 25-68o**
>
> (b) Within available resources and not less than once every ten years, the Marine Sciences Division of The University of Connecticut shall update the sea level change scenarios published by the National Oceanic and Atmospheric Administration in Technical Report OAR CPO-1. Within available resources and not less than ninety days prior to any update of such sea level change scenarios by said Marine Sciences Division, the division shall conduct not less than one public hearing concerning such update. ***Within sixty (60) days after the last public hearing on any such update by said Marine Sciences Division, the Commissioner of Energy and Environmental Protection shall post the update on the department's internet web site and remove any previous updates from department's internet web site.***

B. Suggested Legislation that Mandates the Use of UConn Updates in Lieu of the NOAA Report

The requirements to use the NOAA Report sea level rise scenarios are set forth in Connecticut General Statutes sections 8-23, 16a-27, 25-68o, and 28-5. The current phrase that invokes the NOAA Report in these statutes was carefully crafted so that is identical in all four of the statutes:

> "sea level change scenarios published by the National Oceanic and Atmospheric Administration in Technical Report OAR CPO-1"

The suggested language to mandate the use of the UConn updates in lieu of the NOAA Report is similarly crafted so the exact same phrase can once again be used in all four statutes:

> "sea level change scenarios published on the Department of Energy and Environmental Protection website in accordance with the provisions of section 25-68o"

Note that the effectiveness of this phrase depends upon the changes suggested for section 25-68o that require the latest version of the UConn update to be posted on the DEEP website. However, if the suggested changes to section 25-68o are adopted, this phrase contains all of the information required to identify the exact sea level rise scenarios to be used for the purposes specified by statute. It is not necessary to specify that the scenarios are UConn updates to the NOAA Report because that information is provided in section 25-68o and section 25-68o is invoked by the suggested phrase. It is also unnecessary to specify a revision of the UConn update because section 25-68o requires the Commissioner of the DEEP to remove previous versions of the update when new versions are posted.

The following changes to Connecticut General Statutes sections 8-23, 16a-27, 25-68o, and 28-5 include the suggested phrase and are proposed as an effective means to specify the use of the UConn updates in lieu of the sea level rise scenarios in the NOAA Report. (New words are identified by ***bold italics.*** Deletions are identified by ~~strikethroughs~~.)

Subsection (d) of Connecticut General Statutes Section 8-23

(d) In preparing such plan, the commission or any special committee shall consider the following: (1) The community development action plan of the municipality, if any, (2) the need for affordable housing, (3) the need for protection of existing and potential public surface and ground drinking water supplies, (4) the use of cluster development and other development patterns to the extent consistent with soil types, terrain and infrastructure capacity within the municipality, (5) the state plan of conservation and development adopted pursuant to chapter 297, (6) the regional plan of conservation and development adopted pursuant to section 8-35a, (7) physical, social, economic and governmental conditions and trends, (8) the needs of the municipality including, but not limited to, human resources, education, health, housing, recreation, social services, public utilities, public protection, transportation and circulation and cultural and interpersonal communications, (9) the objectives of energy-efficient patterns of development, the use of solar and other renewable forms of energy and energy conservation, (10) protection and preservation of agriculture, and (11) sea level change scenarios published ~~by the National Oceanic and Atmospheric Administration in Technical Report OAR CPO-1~~ ***on the Department of Energy and Environmental Protection website in accordance with the provisions of section 25-68o.***

Subsection (h) of Connecticut General Statutes Section 16a-27

(h) Any revision made after ~~October 1, 2013~~ ***(insert effective date),*** shall (1) take into consideration risks associated with increased coastal erosion, depending on site topography, as anticipated in sea level change scenarios published ~~by the National Oceanic and Atmospheric Administration in Technical Report OAR CPO-1~~ ***on the Department of Energy and Environmental Protection website in accordance with the provisions of section 25-68o***, (2) identify the impacts of such increased erosion on infrastructure and natural resources, and (3) make recommendations for the siting of future infrastructure and property development to minimize the use of areas prone to such erosion.

Subsection (a) of Connecticut General Statutes Section 25-68o

(a) On and after ~~October 1, 2013~~ ***(insert effective date),*** in the preparation of any municipal evacuation plan or hazard mitigation plan, such municipality shall consider sea level change scenarios published ~~by the National Oceanic and Atmospheric Administration in Technical Report OAR CPO-1~~ ***on the Department of Energy and Environmental Protection website in accordance with the provisions of section 25-68o.***

Subsection (g) of Connecticut General Statutes Section 28-5

(g) On and after ~~October 1, 2013~~ ***(insert effective date),*** the state civil preparedness plan and program established pursuant to subsection (b) of this section shall consider sea level change scenarios published ~~by the National Oceanic and Atmospheric Administration in Technical Report OAR CPO-1~~ ***on the Department of Energy and Environmental Protection website in accordance with the provisions of section 25-68o.***

VII. Conclusion

Connecticut statutes invoke the sea level change scenarios published in the 2012 NOAA Report Technical Report OAR CPO-1 to improve state and municipal planning for land use, hazard mitigation, and civil preparedness. To assure that these scenarios stay relevant in the face of changing climate conditions and advances in scientific knowledge, Connecticut statutes require the UConn to update these sea level change scenarios at least once every ten years. A statutory requirement to publish and use these UConn updates to the NOAA Report scenarios will assure that state and local planners use up-to-date scientific data when making important decisions about land use, hazard mitigation, and civil preparedness.

Endnotes

This White Paper is sponsored by CIRCA, the Connecticut Institute for Resilience and Climate Adaptation. This work is made possible through a grant from the State of Connecticut Department of Housing Community Development Block Grant Disaster Recovery Program and the US Department of Housing and Urban Development.

DISCLAIMER: *This white paper addresses issues of general interest and does not give any specific legal advice pertaining to any specific circumstance. Parties should obtain advice from a lawyer or other qualified professional before acting on the information in this paper.*

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1 *Climate Change Primer – Sea Level Rise and Coastal Storms*, DEP'T OF ENERGY & ENVTL. PROT. [hereinafter *DEEP*], http://www.ct.gov/Deep/cwp/view.asp?a=2705&q=475764&deepNav_GID=2022 (last visited July 12, 2017).
2 NAT'L OCEANIC ATMOSPHERIC ADMIN., TECHNICAL REPORT NOS CO-OPS 083, GLOBAL AND REGIONAL SEA LEVEL RISE SCENARIOS FOR THE UNITED STATES 22 (2017) [hereinafter *CO-OPS 83*].
3 *DEEP*, *supra* note 1.
4 *Id*.
5 *Id*.
6 *Id*.
7 ADAPTATION SUBCOMM. TO THE GOVERNOR'S STEERING COMM. ON CLIMATE CHANGE, THE IMPACTS OF CLIMATE CHANGE ON CONNECTICUT AGRICULTURE, INFRASTRUCTURE, NATURAL RESOURCES AND PUBLIC HEALTH 88 (2010).
8 2013 Conn. Pub. Acts 233 (Spec. Sess.) [hereinafter *P.A. 13-179*].
9 2012 Conn Pub. Acts 92 (Spec. Sess.) [hereinafter *P.A. 12-101*].
10 CONN. GEN. STAT. § 22a-100 (2015) (for state activities); CONN. GEN. STAT. § 22a-102 (2015) (for municipal activities).
11 *P.A. 12-101*, *supra* note 9.
12 *P.A. 13-179*, *supra* note 8.
13 *Id.*
14 *P.A. 12-101*, *supra* note 9.
15 NAT'L OCEANIC ATMOSPHERIC ADMIN., TECHNICAL REPORT OAR CPO-1, GLOBAL SEA LEVEL RISE SCENARIOS FOR THE UNITED STATES NATIONAL CLIMATE ASSESSMENT 1 15 (2012) [hereinafter *CPO-1*].
16 *P.A. 13-179*, *supra* note 8.
17 James O'Donnell, Sea Level Rise and Coastal Flood Risk in Connecticut: An Overview (Sept. 2017) (unpublished) [Hereinafter *O'Donnell Sea Level Rise*], https://circa.uconn.edu/wp-content/uploads/sites/1618/2017/09/ExecSummarySeaLevelRise_J_ODonnell_Sept-2017-1.pdf.
18 *P.A. 13-179*, *supra* note 8.
19 *CPO-1*, *supra* note 15, at 1.
20 *Id*.
21 *Id*.
22 *CPO-1*, *supra* note 15, at 12–13.
23 *Id*. at 15.
24 *Id*.
25 *Id*.
26 *CO-OPS 83*, *supra* note 2
27 *Id*.
28 CONN. GEN. STAT. § 8-23 (2015).
29 *Id*.
30 CONN. GEN. STAT. § 16a-27 (2015).
31 *Id*.
32 CONN. GEN. STAT. § 25-68o (2015).
33 *Id*.
34 *Id*.

Endnotes

[35] CONN. GEN. STAT. § 28-5 (2015).
[36] *Id*.
[37] *CPO-1*, *supra* note 15, at 15.
[38] U.S. GLOB. CHANGE RESEARCH PROGRAM, http://www.globalchange.gov/what-we-do/assessment/sustained-assessment (last visited Aug. 8, 2017).
[39] *CO-OPS 83*, *supra* note 2.
[40] *CPO-1*, *supra* note 15, at 15.
[41] *O'Donnell Sea Level Rise, supra* note 17.
[42] *See, e.g.*, CONN. GEN. STAT. §§ 22a-06, 22a-6a, 22a-6p, 22a-6cc, 22a-200b, 22a-209f, 22a-424a. 22a-625a, 22a-634, 22a-639, 22a-904a, 22a-905a, 22a-905g (2017).

APPENDIX G2 - SECTION 2

COMMUNITY OUTREACH EVENTS
BY THE
CENTER FOR ENERGY & ENVIRONMENTAL LAW
(CEEL)

Abstract and Speaker Biography

Tabulation of Community Outreach Events

Example Community Outreach Event PowerPoint Presentations

- Typical CEEL Presentation When a CIRCA Scientist Presents Sea Level Rise Research Results

- Typical CEEL Presentation When CEEL Presents Sea Level Rise Research Results

Abstract and Speaker Biography
CIRCA Municipal Resilience Planning Assistance Project

Title

CIRCA Municipal Resilience Planning Assistance Project

Duration

As Preferred by the Organization
- 15 - 30 Minute Presentation
- 5 - 15 Minute Question and Answer

Abstract

In the wake of super-storm Sandy, the Connecticut Institute for Resilience and Climate Adaptation (CIRCA) secured a HUD grant to develop tools and techniques that shoreline communities can use to assess flood vulnerabilities in the face of climate change and rising seas. This presentation by the UConn Law Center for Energy & Environmental Law will introduce new sea-level rise projections that are specific for Long Island Sound, describe the likely ramifications of this rise, then focus on the legal issues associated with policy and regulatory decisions based upon forward-looking climate science rather than backward-looking historical floods. The legal issues explored during this presentation will be those not adequately covered by previous works, and will include the results of a national survey of oceanfront state coastal management programs, an evaluation of Connecticut sea-level rise statutes, a survey of local regulatory structures related to floodplain elevation requirements, an evaluation of floodplain zoning height restrictions, a discussion of the unintentional exemption of “shoreline flood and erosion control structures” from coastal site plan review, and guidance on how sea level rise can be incorporated into local coastal and floodplain management programs under existing legal authorities.

Speaker Bio

William R. Rath, Esq.

Bill Rath is a Legal Research Fellow at the University of Connecticut Center for Energy & Environmental Law. Bill earned his law degree in May of 2015 and was admitted to the Connecticut bar in November of that year. Prior to law school, he was a partner with an environmental health and safety consulting firm and a consulting engineer with a major Boston engineering firm. Bill holds a bachelor’s degree in nuclear engineering technology, is a veteran of the United States Navy submarine service, and is continuing his legal education at UConn with a master of laws in energy & environmental law.

Contact

William R. Rath, Esq.
Legal Research Fellow
Center for Energy & Environmental Law
University of Connecticut School of Law
Knight Hall, Room 101
35 Elizabeth Street
Hartford, CT 06105
(203) 430-9886
William.Rath@Uconn.edu

Municipal Resilience Planning Assistance Project (MRPAP)
Summary of Task 9 Community Outreach Events

<table>
<tr><th>Event
Date & Description</th><th>Topics</th><th>Attending</th></tr>
<tr><td>03/28/17

UConn Law
Climate Law Class

Chase 110
55 Elizabeth St.
Hartford, CT

45 Minutes
(Includes Q&A)

<u>Introduced By</u>
Joe MacDougald

<u>Presented By</u>
Bill Rath</td><td>

Coastal Management Issues

Coastal Resources
Coastal Jurisdiction - Connecticut & Nationwide
Coastal Management Programs
Floodplain Management Programs
Connecticut Coastal Regulatory Structures
Coastal & Floodplain Construction Requirements
Shoreline Flood & Erosion Control Structures
Living Shorelines
Case Study Dowling v CT DEEP (Administrative Adjudication)
Coastal Management in Other States

Municipal Resilience Planning Assistance Project

Tasks of the Center for Energy & Environmental Law
Resilience Concepts
Resilience Toolbox
Takings

Case Study: Lucas v. South Carolina Coastal Council
Case Study: Stop the Beach Renourishment v Florida Department of Environmental Protection
Case Study: Dooley v. (Fairfield) Town Plan & Zoning Commission
Case Study: Bartlett v. (Old Lyme) Zoning Commission,

</td><td>15 Second and Third Year Law Students</td></tr>
</table>

Municipal Resilience Planning Assistance Project (MRPAP)
Summary of Task 9 Community Outreach Events

Event Date & Description	Topics	Attending

08/01/17
 	
Coastal Resilience Experts
 	
UConn Avery Point
1084 Shennecossett
Groton, CT
 	
45 Minutes
(Plus Q&A)
 	
Introduced By
Joe MacDougald
 	
Presented By
Bill Rath
	• Introduction of the Municipal Resilience Planning Assistance Project
	• The Center for Energy & Environmental Law Role in the Municipal Resilience Planning Assistance Project
	• Sea level rise statutes and regulations in other states
	• Non-statutory sea level rise programs in other states (California & Washington)
	• Coastal Jurisdiction in Connecticut and other oceanfront states
	• Connecticut sea-level rise statutes and regulations
	  • Statutory inconsistencies and conflicts
	  • CEEL guidance to resolve statutory inconsistencies and conflicts
	• Local regulatory structures
	  • Implications of disparate flood return rates between east and west shoreline communities
	  • Floodplain elevation requirements, CEEL guidance & recommended statutory language
	  • Floodplain zoning height restrictions & CEEL guidance
	  • Unintentional exemption of "shoreline flood and erosion control structures" from coastal site plan review & CEEL guidance
	• State authority required and desired to support local coastal and floodplain management activities.
	
	(Note: This was an interactive event intended to gather input from coastal resilience experts on the effectiveness of the presentations. The CEEL presentation on law and policy was followed by a 45-minute presentation by James O'Donnell, Ph.D. of CIRCA. Dr. O'Donnell introduced his projections of Long Island Sound sea level rise, explained the scientific basis of those projections, and identified the likely effects of this sea level rise on Connecticut shoreline communities. A 45-minute Q&A and feedback session followed the presentations.)
		• C. Amento (SCRCOG)
		• W. Cobleigh (GZA)
		• R. French (CIRCA)
		• R. Kaliszewski (CT Dept. of Energy & Env. Prot.)
		• D. Kooris (CT Dept. of Housing)
		• K. Lund (CIRCA)
		• J. O'Donnell (CIRCA)
		• N. Slovin (Malone & McBroom)
		• D. Sutherland (The nature Conservancy)
		• D. Ullman (Univ. of Rhode Island)
		• Approximately 3 Others (UConn Students)

Municipal Resilience Planning Assistance Project (MRPAP)
Summary of Task 9 Community Outreach Events

<table>
<tr><th>Event
Date & Description</th><th>Topics</th><th>Attending</th></tr>
<tr><td>09/06/17

Connecticut Legislators

Capitol Building
210 Capitol Ave.
Hartford, CT

15 Minutes
(Plus Q&A)

<u>Introduced By</u>
Joe MacDougald

<u>Presented By</u>
Bill Rath</td><td>• The Center for Energy & Environmental Law role in the Municipal Resilience Planning Assistance Project
• Observations from the Coastal State Survey
  ◦ Coastal jurisdiction
  ◦ Sea level rise statutes and regulations
  ◦ Policy Examples (California & Washington State)
• Connecticut sea-level rise statutes and regulations
  ◦ Statutory inconsistencies and conflicts
  ◦ CEEL guidance to resolve statutory inconsistencies and conflicts
• Local regulatory structures
  ◦ Implications of disparate flood return rates between east and west shoreline communities
• State authority required and desired to support local coastal and floodplain management activities.

(Note: This presentation followed a 15-minute presentation by James O'Donnell, Ph.D. of CIRCA. Dr. O'Donnell introduced his projections of Long Island Sound sea level rise, explained the scientific basis of those projections, and identified the likely effects of this sea level rise on Connecticut shoreline communities. A 15 minute Q&A session followed both presentations.)</td><td>• L. Fasano (Senate Republican President Pro Tempore)
• J. Albas (State Representative)
• Senate Staffer Representing E. Kennedy (Senate Democrat Co-Chair of the Environment Committee)
• R. Klee (DEEP Commissioner)
• R. Kaliszewski (DEEP Deputy Commissioner)
• B. Thompson (DEEP Director of Land and Water Resources)
• R. LaFrance (DEEP Director - Office of Law and Policy for Environmental Conservation
• J. Lombardo (UConn Govt. Relations)
• J. O'Donnell (CIRCA)
• R. French (CIRCA)
• K. Lund (CIRCA)
• Two Other Legislative Staffers</td></tr>
</table>

Municipal Resilience Planning Assistance Project (MRPAP)
Summary of Task 9 Community Outreach Events

Event Date & Description	Topics	Attending

09/27/17
 	
South Central Regional Council of Governments
 	
127 Washington Ave
4th Floor West
North Haven, CT
 	
15 Minutes
(Plus Q&A)
 	
<u>Introduced By</u>
Joe MacDougald
 	
<u>Presented By</u>
Bill Rath
	• Introduction of the Municipal Resilience Planning Assistance Project
	• The Center for Energy & Environmental Law Role in the Municipal Resilience Planning Assistance Project
	• Connecticut sea-level rise statutes and regulations
	• CIRCA Long Island Sound sea-level rise projections
	• Inconsistencies and conflicts among Connecticut sea-level rise statutes
	  • CEEL guidance to resolve statutory inconsistencies and conflicts
	• Sea level rise statutes and regulations in other oceanfront states
	• Coastal Jurisdiction in Connecticut and other oceanfront states
	• Local regulatory structures
	  • Implications of disparate flood return rates between east and west shoreline communities
	  • Floodplain elevation requirements & CEEL guidance
	  • Floodplain zoning height restrictions & CEEL guidance
	  • Unintentional exemption of "shoreline flood and erosion control structures" from coastal site plan review & CEEL guidance
	• Guidance on how sea level rise can be incorporated into local coastal and floodplain management programs under existing legal authorities
	
	Attending (Continued)
	• M. Brody (Hamden-North Haven League of Women Voters)
	• G. Kozlowski (REX Development
	• M. Bigelow & J. Lecar (New Haven Transit District
	• M. Muszynski (CT Conference of Municipalities)
	• M. Piscitelli (City of New Haven)
	• L. Mangini & A. Tennanbaum (Office of U.S. Representative Rosa DeLauro)
	• E. Johnson (Office of U.S. Senator Christopher Murphy)
	
	Attending (Continued)
	• E. Graham (Office of U.S. Senator Richard Blumenthal)
	• N. Birdwhistall (MurthaCullina)
	• J. Wardzala (The Kennedy Center)
	• K. Shooshan-Stoller & D. Nardone (FHWA)
	• Carolyn Soltis, SCRCOG Regional Election Monitor;
	• Mark Zaretsky, New Haven Register
		<u>Chief Elected Officials</u>
		• D. Gorski (Bethany First Selectwoman)
		• J. Cosgrove (Branford First Selectman)
		• S. Brancati (Proxy for East Haven Mayor)
		• J. Mazza (Guilford First Selectman)
		• T. Banisch (Madison First Selectman)
		• B. Blake, Milford Mayor)
		• T. Harp (New Haven Mayor)
		• M. Paulhus(Proxy for North Haven Mayor)
		• M. Freda (North Haven First Selectman)
		• E. O'Brien (West Haven Mayor)
		• S. McCreven (Proxy for Woodbridge First Selectwoman)
		
		<u>SCRCOG Staff</u>
		• C. Amento
		• J. Rode
		• E. Livshits
		• C. Rappa
		• R. Andreucc

Municipal Resilience Planning Assistance Project (MRPAP)
Summary of Task 9 Community Outreach Events

Event Date & Description	**Topics**	**Attending**

10/16/17
 	
Connecticut Department of Energy & Environmental Protection
 	
79 Elm St.
Hartford, CT
 	
20 Minutes
(Plus Q&A)
 	
<u>Introduced By</u>
Joe MacDougald
 	
<u>Presented By</u>
Bill Rath
	• The Center for Energy & Environmental Law role in the Municipal Resilience Planning Assistance Project
	• Connecticut sea-level rise statutes and regulations
	  • Statutory inconsistencies and conflicts
	  • CEEL guidance to resolve statutory inconsistencies and conflicts
	• Sea level rise statutes and regulations in other states
	• Local regulatory structures
	  • Implications of disparate flood return rates between east and west shoreline communities
	  • Floodplain elevation requirements & CEEL guidance
	  • Floodplain zoning height restrictions & CEEL guidance
	  • Unintentional exemption of "shoreline flood and erosion control structures" from coastal site plan review & CEEL guidance
	• Guidance on how sea level rise can be incorporated into local coastal and floodplain management programs under existing legal authorities
	
	(Note: This presentation followed a 20-minute presentation by James O'Donnell, Ph.D. of CIRCA. Dr. O'Donnell introduced his projections of Long Island Sound sea level rise, explained the scientific basis of those projections, and identified the likely effects of this sea level rise on Connecticut shoreline communities. A 20 minute Q&A session followed both presentations.)
		• R. Klee (Commissioner)
		• R. Kaliszewski (Deputy Commissioner)
		• B. Thompson (Director of Land and Water Resources)
		• R. LaFrance (Director - Office of Law and Policy for Environmental Conservation
		• Dennis Schain (Director of Communications)
		• J. O'Donnell (CIRCA)
		• R. French (CIRCA)
		• K. Lund (CIRCA)
		• Approximately 120 Others (Predominantly DEEP Personnel)

Municipal Resilience Planning Assistance Project (MRPAP)
Summary of Task 9 Community Outreach Events

<table>
<tr><th>Event
Date & Description</th><th colspan="2">Topics</th><th>Attending</th></tr>
<tr><td rowspan="2">10/18/17

Southeastern Connecticut Council of Governments

5 Connecticut Ave. | Norwich, CT

10 Minutes
(Plus Q&A)

<u>Presented By</u>
Bill Rath</td><td colspan="2">• Introduction of the Municipal Resilience Planning Assistance Project
• The Center for Energy & Environmental Law Role in the Municipal Resilience Planning Assistance Project
• Connecticut sea-level rise statutes and regulations
• CIRCA Long Island Sound sea-level rise projections
• Inconsistencies and conflicts among Connecticut sea-level rise statutes
  • CEEL guidance to resolve statutory inconsistencies and conflicts
• Local regulatory structures
  • Implications of disparate flood return rates between east and west shoreline communities
  • Floodplain elevation requirements & CEEL guidance
• Guidance on how sea level rise can be incorporated into local coastal and floodplain management programs under existing legal authorities</td><td rowspan="2"><u>Chief Elected Officials</u>
• A. Shilosky (Colchester)
• M. Nickerson (East Lyme)
• K. Skulczyck (Griswold)
• B. Flax (Town of Groton)
• F. Allyn (Ledyard)
• T. Sparkman (Lisbon)
• R. McDaniel (Montville)
• M. Passero (New London)
• S. Murphy (N. Stonington)
• D. Hinchey (Norwich)
• Bob Congdon (Preston)
• C. Osten (Sprague)
• J. Callahan (Borough of Stonington)
• R. Simmons (Town of Stonington
• D. Steward (Waterford)
• J. Burt (Proxy for Town of Groton)
• ; Jim Rivers (Proxy for Windham.)

<u>Other Council Members</u>
• R. Hayward (Mashantucket Pequot Tribal Liaison)
• Capt. P . Whitescarver, US Naval SUBASE Liaison)</td></tr>
<tr><td>Attending (Continued)
<u>SCCOG Staff</u>
• J. Butler
• A.Kennedy
• K. Rattan

<u>Others</u>
• C. Young (CT Airport Authority)
• N. Cowser (seCTer)
• M. Gerber (Preston)
• D. Monahan (TVCCA)
• Jen Granger (UCFS)
• M. Carroll & A. Fritzsche (SEAT)</td><td>Attending (Continued)
<u>Others</u>
• J. Pizunski (Amalgamated Transit Union)
• John Rayman (WRTD)
• T. Daugherty (New London)
• E. Monahan (SCWA)
• A. Grant (Congressman Courtney's office)
• E. Graham (Senator Blumenthal's office)
• R. Collins (CCM)
• Erik Shortell (FHWA)
• Randall Benson (Colchester)
• M. Schultz, US Naval SUBASE)
• One reporter</td></tr>
</table>

Municipal Resilience Planning Assistance Project (MRPAP)
Summary of Task 9 Community Outreach Events

<table>
<tr><th>Event
Date & Description</th><th>Topics</th><th>Attending</th></tr>
<tr>
<td>10/19/17

General Public

UConn Avery Point
1084 Shennecossett
Groton, CT
<u>and</u>
Webinar Access

25 Minutes
(Plus Q&A)

<u>Introduced By</u>
Joe MacDougald

<u>Presented By</u>
Bill Rath</td>
<td>• The Center for Energy & Environmental Law role in the Municipal Resilience Planning Assistance Project
• Connecticut sea-level rise statutes and regulations
  • Statutory inconsistencies and conflicts
  • CEEL guidance to resolve statutory inconsistencies and conflicts
• Sea level rise statutes and regulations in other oceanfront states
• Coastal Jurisdiction in Connecticut and other oceanfront states
• Local regulatory structures
  • Implications of disparate flood return rates between east and west shoreline communities
  • Floodplain elevation requirements & CEEL guidance
  • Floodplain zoning height restrictions & CEEL guidance
  • Unintentional exemption of “shoreline flood and erosion control structures” from coastal site plan review & CEEL guidance
• Guidance on how sea level rise can be incorporated into local coastal and floodplain management programs under existing legal authorities

(Note: This presentation followed a 25-minute presentation by James O'Donnell, Ph.D. of CIRCA. Dr. O'Donnell introduced his projections of Long Island Sound sea level rise, explained the scientific basis of those projections, and identified the likely effects of this sea level rise on Connecticut shoreline communities. A 20 minute Q&A session followed both presentations.)</td>
<td>• 27 In Person
• 55 via Webinar</td>
</tr>
</table>

Municipal Resilience Planning Assistance Project (MRPAP)
Summary of Task 9 Community Outreach Events

Event Date & Description	Topics	Attending

10/25/17
 	
Connecticut Association of Flood Managers
 	
Four Points Hotel
275 Research Parkway
Meriden, CT
 	
12 Minutes
(Plus Q&A)
 	
<u>Presented By</u>
Bill Rath
	• Introduction of the Municipal Resilience Planning Assistance Project
	• The Center for Energy & Environmental Law Role in the Municipal Resilience Planning Assistance Project
	• Connecticut sea-level rise statutes and regulations
	  • CIRCA Long Island Sound sea-level rise projections
	  • Statutory inconsistencies and conflicts
	  • CEEL guidance to resolve statutory inconsistencies and conflicts
	• Sea level rise statutes and regulations in other oceanfront states
	• Coastal Jurisdiction in Connecticut and other oceanfront states
	• Local regulatory structures
	  • Implications of steady sea level rise on shoreline communities
	  • Implications of disparate flood return rates between east and west shoreline communities
	  • Floodplain elevation requirements & CEEL guidance
	  • Floodplain zoning height restrictions & CEEL guidance
	  • Unintentional exemption of "shoreline flood and erosion control structures" from coastal site plan review & CEEL guidance
	• Guidance on how sea level rise can be incorporated into local coastal and floodplain management programs under existing legal authorities
	
	(Note: This presentation was one of three presentations on a "legal issues" panel. Each presenter was allowed 12 minutes and the three presentations were followed by nine minutes o Q&A. The CEEL presentation was the last of the three presentations and was preceded by Attorney Dwight Merriam presenting "Is Intentional Flooding by the Government a Taking?" and by Attorney Marjorie Shansky presenting "Case Law Update - Variances, Non-conformity, FEMA.")
		• 86 People (See CAFM Attendance List on the Following page)

2017 CAFM ANNUAL CONFERENCE ATTENDEES					
First Name	Last Name	Firm	First Name	Last Name	Firm
Elizabeth	Ahearn	USGS	Ken	Kittredge	BL Companies
Dan	Albrecht	Chittenden County RPA	Eugene	Kohls	ISO
Peter	Allen	Smart Vent	David	Kooris	State of CT, Department of Housing
Karl	Anderson	FEMA	Krystyna	Krudysz	DEEP
Nathaniel	Arai	GZA	Ann	KuzYk	DEEP
Sean	Arruda	Fuss & O'Neill	Thomas	Lane	Town of Waterford
Kristine	Baker	Fuss & O'Neill	Katie	Lund	CIRCA
Marcy	Balint	DEEP	Matt	Lundsted	Comprehensive Environmental Inc.
Bob	Bass	City of Meridan	Thomas	Makowicki	Town of Old Saybrook
Cynthia	Baumann	CDM	William	Maurer	Town of Trumbull
Gardner	Bent	USGS	John	McGrane	GEI
Scott	Bighinatti	Milone & MacBroom	Dwight	Merriam	Robinson & Cole
Julie	Bjorkman	JKB Consulting	Thomas	Metcalf	Metcalf Engineering and Surveying
Gina	Bourque	Fuss & O"Neill	Karen	Michaels	DEEP
Victoria	Brudz	CIRCA	Keith	Mikolinski	Fuss & O'Neill
Margot	Burns	River COG	Phil	Moreschi	Fuss & O'Neill
Jeff	Caiola	DEEP	Dave	Murphy	Milone & MacBroom
Joe	Canas	Tighe & Bond	Ronald	Nault	Luchs
P Branford	Cheney	CME Engineers	Rick	Nicklas	FEMA
Scott	Choquette	Dewberry	Michael	Ott	Summer Hill Civil Engineers and Land Surveyors
Colin	Clark	DEEP	Eileen	Pannetier	CEI Engineers
Doug	Colter	City of West Haven	Stacy	Pappano	DEEP
Christine	Costa	Town of Old Saybrook	Gregory	Pidluski	City of Milford
Scott	Deledala	Town of Stonington	Janice	Plaziak	Town of Branford
Bob	Desaulniers	FEMA	Arde	Ramthun	USDA
Jule	Dybdahl	USDA	Deanna	Rhodes	City of Norwich
Paula	Fernald		Frank	Ricciardi	Weston & Sampson
Carla	Feroni	DEEP	Jonathan	Richer	Tighe & Bond
Phil	Forzley	Fuss & O'Neill	Andrea	Sangrey	Town of Westport
Peter	Francis	DEEP	Robert	Santella	City of West Haven
Rebecca	French	UCONN	Jenabay	Sezen	Milone & MacBroom
Terrance	Gallagher	Luchs	Rob	Sibley	Town of Newtown
Michael	Glidden	Town of Simsbury	Frank	Smeriglio	Town of Trumbull
Tom	Gormley	TP Gormley Consultant	Joseph	Smith	Town of East Lyme
Janice	Greenwood	Woodward & Curran	Ben	Smith	USDA
Sarah	Hamm	Dewberry	Daniel	Stapleton	GZA
Emmeline	Harrigan	Town of Fairfield	Christien	Suhonen	GZA
Ted	Hart	Milone & MacBroom	Lesley	Sweeny	USDA
John	Hoefferle	Town of Branford	Scott	Tardif	UCONN
Kathleen	Holland	Town of New Canaan	Raju	Vasamsetti	Weston & Sampson
Diane	Ifkovic	DEEP	Kristin	Walker	USDA
Susan	Jacobson	DEEP	Don	Watson	Earthrise
Kenneth	Johnson	GZA	Cary	White	The Nature Conservancy

Municipal Resilience Planning Assistance Project (MRPAP)
Summary of Task 9 Community Outreach Events

Event Date & Description	Topics	Attending

11/07/17
 	
UConn Law Environmental Law Class
 	
Chase 110
55 Elizabeth St.
Hartford, CT
 	
45 Minutes
(Includes Q&A)
 	
Introduced By
Joe MacDougald
 	
Presented By
Bill Rath
	• The Center for Energy & Environmental Law role in the Municipal Resilience Planning Assistance Project
	• Connecticut sea-level rise statutes and regulations
	  • Statutory inconsistencies and conflicts
	  • CEEL guidance to resolve statutory inconsistencies and conflicts
	• Sea level rise statutes and regulations in other oceanfront states
	• Coastal Jurisdiction in Connecticut and other oceanfront states
	• Local regulatory structures
	  • Implications of disparate flood return rates between east and west shoreline communities
	  • Floodplain elevation requirements & CEEL guidance
	  • Floodplain zoning height restrictions & CEEL guidance
	  • Unintentional exemption of "shoreline flood and erosion control structures" from coastal site plan review & CEEL guidance
	• Incorporating sea level rise into local coastal and floodplain management programs under existing legal authorities
	
	(Note: This presentation followed a 25-minute presentation by James O'Donnell, Ph.D. of CIRCA. Dr. O'Donnell introduced his projections of Long Island Sound sea level rise, explained the scientific basis of those projections, and identified the likely effects of this sea level rise on Connecticut shoreline communities. A 20 minute Q&A session followed both presentations.)
		• 1 Member of the CT Judiciary
		• 1 Member of the UConn Law Faculty
		• 18 Second and Third Year Law Students

Municipal Resilience Planning Assistance Project (MRPAP)
Summary of Task 9 Community Outreach Events

Event Date & Description	Topics	Attending

12/07/17
 	
Madison Connecticut Planning & Zoning Commission
 	
Meeting Room A
Madison Town Campus
8 Campus Drive
Madison, CT
 	
60 Minutes
(Includes Q&A)
 	
Introduced By
Joe MacDougald
 	
Presented By
Bill Rath
	• Introduction of the Municipal Resilience Planning Assistance Project
	• The Center for Energy & Environmental Law Role in the Municipal Resilience Planning Assistance Project
	• Connecticut sea-level rise statutes and regulations
	  • Statutory inconsistencies and conflicts
	  • CIRCA Long Island Sound sea-level rise projections
	  • CIRCA Sea Level Rise Planning Recommendation: 50 Centimeters by 2050
	  • CEEL guidance to resolve statutory inconsistencies and conflicts
	• Sea Level Rise Statutes And Regulations In Other Oceanfront States
	• Coastal Jurisdiction In Connecticut and Other Oceanfront States
	• Effects of Sea Level Rise
	  • Implications of steady sea level rise on shoreline communities
	  • Implications of disparate flood return rates between east and west shoreline communities
	• Shoreline Regulatory Environment
	  • Coastal Management Programs
	  • Floodplain Management Programs
	  • Flood Insurance Rate Maps
	• Local regulatory structures
	  • Floodplain elevation requirements & CEEL guidance
	  • Madison floodplain elevation requirements & CEEL guidance
	  • Floodplain zoning height restrictions & CEEL guidance
	• Guidance on how sea level rise can be incorporated into local coastal and floodplain management programs under existing legal authorities
		P&Z Commissioners
		• R. Clark (Chairman)
		• F. Larson (Vice Chairman)
		• J. Miller
		• B. Richardson
		• J. Matteson
		• J. Mathers
		• A. Mitchell
		• E. Hitchcock (Alternate)
		
		Others
		• D. Anderson (Madison Director of Planning and Economic Development)
		• T. Banisch (First Selectman)
		• J. Ferris (Selectwoman)
		• A. Goldberg (Selectman)
		• H. Crawford (Conservation Commission Chairwoman)
		
		Broadcast
		• Madison Public Television Channel 20 (Live and Seven Re-Broadcasts)

<table>
<tr><th>Event
Date & Description</th><th colspan="2">Topics</th><th>Attending</th></tr>
<tr>
<td rowspan="2">12/14/17

American Institute of Architects (Connecticut Section)

AIA CT Conference Room
370 James Street
Suite 402
New Haven, CT

35 Minutes
(Includes Q&A)

<u>Introduced By</u>
Joe MacDougald

<u>Presented By</u>
Bill Rath</td>
<td colspan="2">• Introduction of the Municipal Resilience Planning Assistance Project
• The Center for Energy & Environmental Law Role in the Municipal Resilience Planning Assistance Project
• Connecticut sea-level rise statutes and regulations
  • Tide Gauge Statutes
  • NOAA OAR CPO-1 Statutes
  • UConn Projections
  • CIRCA Planning Recommendations: 50 Centimeters by 2050
  • CEEL guidance to resolve statutory inconsistencies and conflicts
• Sea Level Rise Statutes And Regulations In Other Oceanfront States
• Implications of Sea Level Rise
  • Implications of steady sea level rise on shoreline communities
  • Implications of disparate flood return rates between east and west shoreline communities
• Shoreline Regulatory Environment
  • Coastal management
  • Floodplain management
• Flood Insurance rate maps
• Local Regulatory Programs
  • Floodplain elevation requirements & CEEL guidance
  • Floodplain zoning height restrictions & CEEL guidance
• Guidance on good design practices in the face of Sea Level Change
• Guidance on how sea level rise can be incorporated into local coastal and floodplain management programs under existing legal authorities

(Note: This presentation was one segment of an all-day AIA workshop entitled, "Resilient Connecticut: Helping Communities to Prepare for Weather and Climate Changes.")</td>
<td rowspan="2">• Paul Antinozzi III, AIA
• Kojo Asiedu, AIA
• Illyn Azaroff, AIA
• Rodger Braley, AIA
• Tracey Brown, AIA
• George Buchanan, AIA
• Walker Burns III, AIA
• Philippe Campus, AIA
• Dan Conlon, AIA
• Kathleen Dorgan, FAIA
• George Fellner, AIA
• Phil Forzley
• Robert Frew, AIA
• Sabrina Foulke, AIA
• Laura Ghorbi, P.E.
• Emmeline Harrigan, AICP
• Thomas Hood, Assoc. AIA
• Diane Ifkovic, CT DEEP
• Liz Jahn, AIA
• Craig Lapinski
• Ann Lathrop, AIA
• Howard Lathrop, AIA
• Bernard Lombardi, AIA
• Meg Lyons, AIA
• Bob Mocarsky, AIA
• Robert Orr, FAIA
• Bob Parisot, AIA
• Kenneth Pilon, AIA
• Laura Pirie, AIA
• Joel Raphael, AIA
• Paul Reslink, AIA</td>
</tr>
<tr>
<td><u>Attending (Cont.)</u>
• Robert Sanders, Jr., AIA
• Tim Shea, AIA
• Rick Staub, AIA
• Lindsay Suter, AIA</td>
<td><u>Attending (Cont.)</u>
• Jennifer Tate, AIA
• Don Watson, FAIA
• Adam Whelchel, PhD
• Ron Zocher, AIA</td>
</tr>
</table>

Municipal Resilience Planning Assistance Project (MRPAP)
Summary of Task 9 Community Outreach Events

Event Date & Description	Topics	Attending

01/09/18
 	
Western Connecticut Council of Governments (WestCOG)
 	
Comstock Community Center
180 School Road
Wilton, CT
.
30 Minutes
(Includes Q&A)
 	
<u>Presented By</u>
Bill Rath
	• Introduction of the Municipal Resilience Planning Assistance Project
	• The Center for Energy & Environmental Law Role in the Municipal Resilience Planning Assistance Project
	• WestCOG Regional Flood Mitigation Rating System
	• Connecticut sea-level rise statutes and regulations
	• Tide Gauge sea-level rise projections
	• NOAA OAR CPO-1 global sea-level rise projections
	• CIRCA Long Island Sound sea-level rise projections
	• Inconsistencies and conflicts among Connecticut sea-level rise statutes
	    • CEEL guidance to resolve statutory inconsistencies and conflicts
	• Sea Level Rise Statutes and Regulations in Other Oceanfront States
	• Effects of Sea Level Rise
	    • Increased Flood Levels
	    • Increased Flood Return Rates
	• Local regulatory structures
	    • Shoreline Community Floodplain Elevation Requirements
	    • Height Restrictions on Elevated Buildings
	    • Seawalls Landward of the Coastal Jurisdiction Line
	• Good Practices in the Face of Sea Level Change
	• Incorporating sea level rise into local coastal and floodplain management programs under existing legal authorities
		• Betsy Paynter, Brookfield; Economic Development
		• Marcia Wilkins, Brookfield Energy Commission
		• Evan White, New Fairfield Zoning Enforcement Officer
		• Jeremy Ginsberg, Darien Director of Planning and Zoning
		• Christal Prezler, Newtown Deputy Director Planning Department Economic and Community Development
		• Pat LaRow, Greenwich Deputy Planner
		• Tracy Kuilkowski, Weston Land Use Director
		• Adam Schnell, Ridgefield Assistant Planner
		• Robert Nerney, Wilton Director of Planning
		• Alyssa Norwood, Sustainable CT Energy Technical Specialist
		• Elizabeth Esposito, Associate Planner, Western Connecticut Council of Governments
		• 12 Members of the General Public

Municipal Resilience Planning Assistance Project (MRPAP)
Summary of Task 9 Community Outreach Events

Event Date & Description	Topics	Attending

01/24/18
 	
City of New Haven Planning Department Technical Team
 	
5th Floor
Conference Room
New Haven City Hall
165 Church Street
New Haven, CT
 	
25 Minutes
(Plus Q&A)
 	
<u>Introduced By</u>
Joe MacDougald
 	
<u>Presented By</u>
Bill Rath
	• The Center for Energy & Environmental Law role in the Municipal Resilience Planning Assistance Project
	• Connecticut sea-level rise statutes and regulations
	    • Statutory inconsistencies and conflicts
	    • CEEL guidance to resolve statutory inconsistencies and conflicts
	• Sea level rise statutes and regulations in other oceanfront states
	• Coastal Jurisdiction in Connecticut and other oceanfront states
	• Local regulatory structures
	    • Implications of disparate flood return rates between east and west shoreline communities
	    • Floodplain elevation requirements & CEEL guidance
	        ○ Elevation Requirements in New Haven
	    • Floodplain zoning height restrictions & CEEL guidance
	    • Unintentional exemption of “shoreline flood and erosion control structures” from coastal site plan review & CEEL guidance
	• Good Practices in the Face of Sea Level Change
	• Guidance on how sea level rise can be incorporated into local coastal and floodplain management programs under existing legal authorities
	
	(Note: This presentation followed a 25-minute presentation by Rebecca French, Ph.D. of CIRCA. Dr. Dr. French introduced the CIRCA projections of Long Island Sound sea level rise, explained the scientific basis of those projections, and identified the likely effects of this sea level rise on Connecticut shoreline communities. A 40 minute Q&A session followed both presentations.)
		<u>New Haven Planning Dept.</u>
		• D. Hall
		• N. Mougrand
		• S. Davis
		
		<u>Other New Haven Officials</u>
		• M. Piscitelli (Deputy Economic Development Administrator)
		• R. Williams (Office of Corporation Counsel)
		• G. Zinn (Engineering Dept).
		• D. O’Neill
		• J. Turico
		• A. Hartjen
		
		<u>Others</u>
		
		• S. Bronin, UConn Law CEEL
		• R. Cane, UConn Law Gallivan Research

Municipal Resilience Planning Assistance Project (MRPAP)
Summary of Task 9 Community Outreach Events

<table>
<tr><th>Event
Date & Description</th><th>Topics</th><th>Attending</th></tr>
<tr><td>02/06/18

UConn Law
Climate Law Class

Knight 215

35 Elizabeth St.
Hartford, CT

25 Minutes
(Includes Q&A)

<u>Introduced By</u>
Joe MacDougald

<u>Presented By</u>
Bill Rath</td><td>• The Center for Energy & Environmental Law role in the Municipal Resilience Planning Assistance Project
• Connecticut sea-level rise statutes and regulations
  • Statutory inconsistencies and conflicts
  • CEEL guidance to resolve statutory inconsistencies and conflicts
• Sea level rise statutes and regulations in other oceanfront states
• Coastal Jurisdiction in Connecticut and other oceanfront states
• Local regulatory structures
  • Implications of disparate flood return rates between east and west shoreline communities
  • Floodplain elevation requirements & CEEL guidance
    ○ Elevation Requirements in New Haven
  • Floodplain zoning height restrictions & CEEL guidance
  • Unintentional exemption of "shoreline flood and erosion control structures" from coastal site plan review & CEEL guidance
• Good Practices in the Face of Sea Level Change
• Guidance on how sea level rise can be incorporated into local coastal and floodplain management programs under existing legal authorities

(Note: This presentation followed a 25-minute presentation by James O'Donnell, Ph.D. of CIRCA. Dr. O'Donnell introduced his projections of Long Island Sound sea level rise, explained the scientific basis of those projections, and identified the likely effects of this sea level rise on Connecticut shoreline communities.)</td><td>• 8 Second and Third Year Law Students</td></tr>
</table>

Municipal Resilience Planning Assistance Project (MRPAP)
Summary of Task 9 Community Outreach Events

Event Date & Description	Topics	Attending

02/20/18
 	
Stratford Planning Commission
 	
Council Chambers
Stratford Town Hall
2725 Main Street
Stratford, CT
 	
.
50 Minutes
(Includes Q&A)
 	
<u>Presented By</u>
Bill Rath
	• Introduction of the Municipal Resilience Planning Assistance Project
	• The Center for Energy & Environmental Law Role in the Municipal Resilience Planning Assistance Project
	• Southern Connecticut Regional Framework for Coastal Resilience
	• Connecticut sea-level rise statutes and regulations
	• Tide Gauge sea-level rise projections
	• NOAA OAR CPO-1 global sea-level rise projections
	• CIRCA Long Island Sound sea-level rise projections
	• Inconsistencies and conflicts among Connecticut sea-level rise statutes
	  ◦ CEEL guidance to resolve statutory inconsistencies and conflicts
	• Sea Level Rise Statutes and Regulations in Other Oceanfront States
	• Effects of Sea Level Rise
	  ◦ Increased Flood Levels
	  ◦ Increased Flood Return Rates
	• Local regulatory structures
	  ◦ Shoreline Community Floodplain Elevation Requirements
	  ◦ Height Restrictions on Elevated Buildings
	  ◦ Seawalls Landward of the Coastal Jurisdiction Line
	• Good Practices in the Face of Sea Level Change
	• Incorporating sea level rise into local coastal and floodplain management programs under existing legal authorities
		Planning Commissioners
		• P. Patusky
		• J. Vigliotti
		• H. Watson
		• D. Senft
		• J. Staley
		• J. Sturmer
		• J. Tremesani
		
		Others
		
		• J. Habansky (Planning & Zoning Administrator)
		• 2 Members of the General Public

Municipal Resilience Planning Assistance Project (MRPAP)
Summary of Task 9 Community Outreach Events

Event Date & Description	Topics	Attending

06/06/18
 	
Connecticut Environmental Forum
 	
Keeney Memorial Cultural Center
200 Main Street
Wethersfield, CT
.
15 Minutes
(Plus Q&A)
 	
<u>Presented By</u>
Bill Rath
	• The Center for Energy & Environmental Law role in the Municipal Resilience Planning Assistance Project
	• Connecticut sea-level rise statutes and regulations
	  • Senate Bill No. 7
	  • Sea level rise statutes and regulations in other oceanfront states
	  • Coastal Jurisdiction in Connecticut and other oceanfront states
	• Effects of Sea Level Rise
	  • Increased Inundation
	  • Implications of disparate flood return rates between east and west shoreline communities
	  • Floodplain elevation requirements & CEEL guidance
	• Local regulatory structures
	  • Floodplain Building Elevation Requirements
	  • Floodplain zoning height restrictions
	  • Unintentional exemption of "shoreline flood and erosion control structures" from coastal site plan review & CEEL guidance
	• Good Practices in the Face of Sea Level Change
	
	• (Note: This presentation followed a 15-minute presentation by Katie Lund of CIRCA. Ms. Lund introduced the CIRCA projections of Long Island Sound sea level rise and explained the scientific basis of those projections.)
	
	-- 	
	
	Attending (Continued)
	
	• E. Tyler - Kaman Corp.
	• Y. Zhang - AECOM
	• D. Kooris, CT DECD
	• L. Hoffman - Pullman & Comley
	• K. Lund -UConn CIRCA
	P. McIntosh -UConn
		• M. Franson - Charter Oak Environmental Services
		• D. Pelham - Cohn, Burnbaum & Shea p.c.
		• K. Neville, CTR Industries
		• C. Weisner (??) - Ensafe, LLC.
		• S. Molofsky, CT EPOC
		• R. Standish - Terracon
		• J. Meyer - Terracon
		• J. Mastuangelo - Tighe & Bond
		• R. Calabrese - TRC
		• D. Defelice - - Ulbrich Specialty Strip mill
		• Yaynzl (??) - UConn
		• H. DelRosso - U.S. Ecology
		• W. Abrams - Yale Univ.
		• B. Armstrong - Yale Univ.
		• L. Chappel - Swift Textile Metalizing
		• J. Rydel - Swift textile Metalizing
		• K. Trella - CT DEEP
		• G. Wilkerson - Clean Earth LLC
		• M. Miller - Lourero Engineering
		• K. Wermter - REC Technologies
		• J. Pelczan - Atlas Environmental

APPENDIX G2 - SECTION 2

COMMUNITY OUTREACH PRESENTATION
EXAMPLE ONE

TYPICAL CEEL PRESENTATION WHEN A CIRCA SCIENTIST PRESENTS SEA LEVEL RISE RESEARCH RESULTS

MUNICIPAL RESILIENCE PLANNING ASSISTANCE PROJECT

William R. Rath, Esq.
Legal Research Fellow
Center for Energy & Environmental law
University of Connecticut School of Law
860-570-5058
William.Rath@ UConn.edu

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CIRCA

CEEL Tasks

- Survey sea level rise adaptation laws and policies in other oceanfront states
- Identify legal and policy issues that frustrate sea level rise adaptation efforts
- Prepare white papers on sea level rise law and policy issues not adequately addressed by others
- Conduct outreach events to communicate legal and policy recommendations.

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CIRCA

But Not . . .

Duplicating the work of others:

- DEEP
- CIRCA
- The Nature Conservancy
- CLEAR / Adapt CT
- COGs
- Georgetown Climate Center
- Marine Affairs Institute (RWU, URI)
- National Association of Floodplain Managers

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CIRCA

What is Sea Level Rise In Connecticut?

Rise in Sea Level
or
Sea Level Change
or
UConn Projections?

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CIRCA

P.A. 12-101 – Rise in Sea Level

"Rise in sea level" means the arithmetic mean of the most recent equivalent per decade rise in the surface level of the tidal and coastal waters of the state, as documented in the National Oceanic and Atmospheric Administration online or printed publications for said agency's Bridgeport and New London tide gauges.

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Rise in Sea Level (Tide Gauge)

22a-92	States that is a general policy and goal of the legislature to consider a rise in sea level in "the planning process"
22a-93	Defines "rise in sea level"
22a-363h	Authorizes DEEP studies and pilot programs and UConn support to improve coastal community resilience to a rise in sea level
22a-478	Requires DEEP to consider a rise in sea level when establishing priorities for eligible water quality projects. (P.A. 13-15)
25-157t	Requires a Blue Plan that adapts to a rise in sea level. (P.A. 15-66)

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CIRCA

P.A. 13-179 - Sea Level Change

Sea Level Change scenarios published by the National Oceanic and Atmospheric Administration in Technical Report OAR CPO-1.

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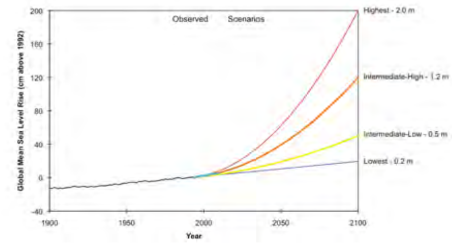
CIRCA



Scenario	SLR by 2100 (m)*	SLR by 2100 (ft)*
Highest	2.0	6.6
Intermediate-High	1.2	3.9
Intermediate-Low	0.5	1.6
Lowest	0.2	0.7

* Using mean sea level in 1992 as a starting point.

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CIRCA

Sea Level Change (NOAA Projections)

8-23 Municipal Plan of Conservation & Development

16a-27 State Plan of Conservation & Development

28-5 State civil preparedness plan and program

25-68o Municipal evacuation and hazard mitigation plans.

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CIRCA

Sea Level Change (NOAA Projections)

25-68o UConn must update the NOAA sea level change scenarios every 10 years.

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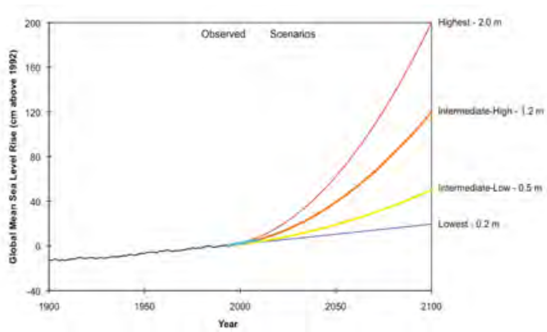
CENTER FOR ENERGY & ENVIRONMENTAL LAW
CIRCA



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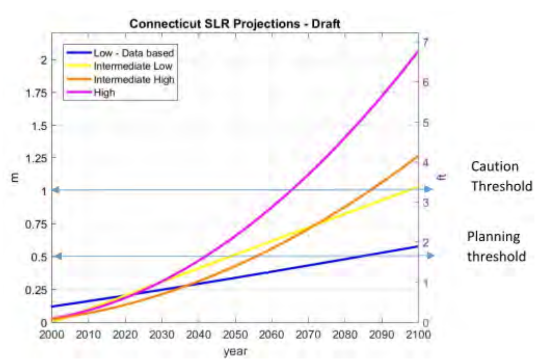
CENTER FOR ENERGY & ENVIRONMENTAL LAW
CIRCA



UCONN | SCHOOL OF LAW
CENTER FOR ENERGY & ENVIRONMENTAL LAW
CIRCA

Sea Level Change (NOAA Projections)

25-68o UConn must update the NOAA sea level change scenarios every 10 years.

But there is no statute that :

- Requires or allows the UConn updates to be used where the NOAA scenarios are specified
- Specifies a means of publication

CEEL Recommendations
Rise in Sea Level / Sea Level Change

- Adopt single standard for sea level rise
- Make that single standard the latest UConn Updates to the NOAA projections
- Require a formal peer review of the UConn Updates to validate the scientific method and improve acceptance (C.A.S.E.?)
- Publish the UConn Updates on the DEEP Web Page

So How Do Connecticut Sea Level Rise Statutes Compare to Other States?

Of the 23 Oceanfront States, Connecticut is . . .

- One of 11 with state SLR statutes
  - Three States Consider SLR in All Coastal Management Decisions
  - Four States Consider SLR In Some Coastal Management Decisions
  - Four States - Including Connecticut - Consider SLR Only During Planning Processes

Local Programs

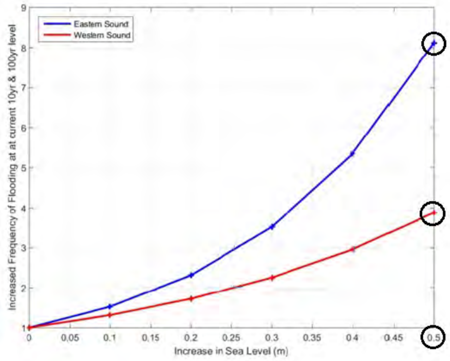
Local Programs

Coastal Management Programs

- Protect and restore coastal resources
- Manage coastal development, prioritize water-dependent uses
- Facilitate access to public trust beaches, waters and submerged lands.

Floodplain Management Programs

- Promote public health, safety and general welfare in floodplain areas.
- Minimize public and private losses from floods in floodplains areas.

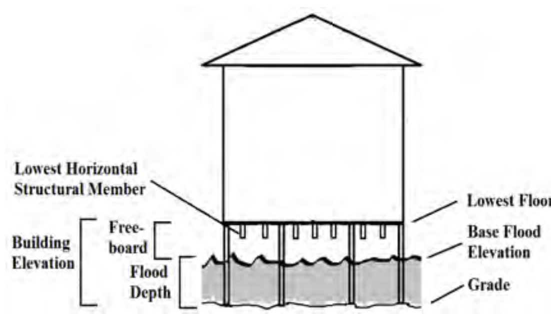


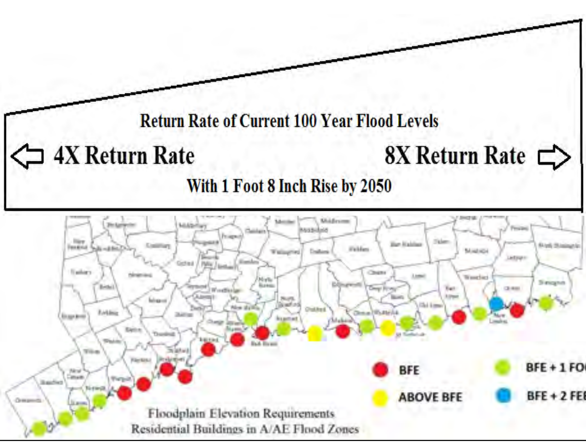
CEEL Analysis of Local Programs

- Floodplain Building Elevation Requirements in Connecticut Shoreline Municipalities
- Height Restrictions on Elevated Residential Buildings in Connecticut Coastal Floodplains
- Seawall Exemptions from Municipal Coastal Site Plan Review
- Incorporating Sea Level Rise into Existing Coastal and Floodplain Management Programs

Floodplain Building Elevation Requirements in Connecticut Shoreline Municipalities

Elevated Shoreline House





Shoreline Community Floodplain Elevation Requirements

- All 24 shoreline communities have floodplain ordinances that meet the elevation requirements of the National Flood Insurance Program
- 13 of the 24 shoreline communities have floodplain ordinances that do not meet the elevation requirements of the Connecticut State Building Code

Floodplain Elevation Recommendations

- Increase Building Elevation Requirements
  - Good: Meet State Building Code Requirements
  - Better: Adopt ASCE 24-14 for All Floodplain Structures

    (ASCE 24-14 = American Society of Civil Engineers consensus standard, "Flood Resistant Design and Construction")
  - Best: Add *at least* two feet of freeboard above ASCE 24-14 requirements

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Freeboard is Cheap!

According to FEMA:

- Initial elevation is expensive, but additional freeboard is not:
  - 4 feet of freeboard ≈ 1-2% more than the cost of elevating to BFE
- Insurance savings can pay for freeboard:
  - Six years in A Zones
  - Three years in VE zones

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More Floodplain Elevation Recommendations

- Establish a "Coastal A" Zone
  - Increased elevation (and other) standards for "A Zones" subject to 1½ to 3 Foot Waves
- Consider an ordinance to implement FEMA Publication P-804, "Wind Retrofit Guide for Residential Buildings."
- Participate in the NFIP Community Rating System
  - Get money back for doing the right thing!

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Height Restrictions on Elevated Residential Buildings

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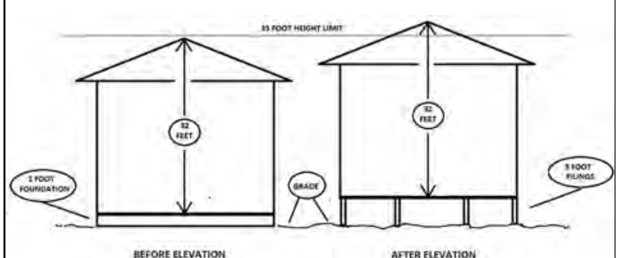
Height Restrictions on Elevated Residential Buildings



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Height Restrictions on Elevated Residential Buildings

- Eight shoreline communities have adopted floodplain ordinances that accommodate some height above the usual limits without a ZBA hearing
  - Bridgeport, Fairfield, Greenwich, Guilford, Norwalk, Stamford, Waterford, Westport
- Some just add height above grade, some allow extra height based on flood levels
- Recommendation: Consider this option

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Walls Landward of the Coastal Jurisdiction Line

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CIRCA

Of the 24 Shoreline Municipalities

- Two have incorporated the DEEP recommended language that exempts walls as long as they don't meet the definition of a "flood and erosion control structure"
- Two have eliminated "walls" from the list of on-premises structures exempt from the site plan review process
- Twenty retain the language that exempts "walls" from the site plan review process

CEEL Recommendation: Eliminate the "walls" from the exemption or incorporate the DEEP recommended language for "flood and erosion control structure"

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<u>Public Meeting</u>

October 19, 2017
9:30 – 11:00 a.m.

Updated SLR Projections

In Person at UConn Avery Point
or
Via Webinar

Google UConn CIRCA for Details

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MUNICIPAL RESILIENCE PLANNING ASSISTANCE PROJECT

William R. Rath, Esq.
Legal Research Fellow
Center for Energy & Environmental law
University of Connecticut School of Law
860-570-5058
William.Rath@ UConn.edu

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APPENDIX G2 - SECTION 2

COMMUNITY OUTREACH PRESENTATION
EXAMPLE TWO

TYPICAL CEEL PRESENTATION WHEN CEEL PRESENTS SEA LEVEL RISE RESEARCH RESULTS

MUNICIPAL RESILIENCE PLANNING ASSISTANCE PROJECT

William R. Rath, Esq.
Legal Research Fellow
Center for Energy & Environmental law
University of Connecticut School of Law
860-570-5058
William.Rath@ UConn.edu

Project Deliverables

- Projections of Long Island Sound sea level rise
- Models and maps of combined coastal storm surge and riverine flooding that consider sea level rise and climate change
- Methods and tools for municipal infrastructure flooding vulnerability assessments
- Legal and policy options for municipal resilience

CEEL Tasks

- Survey sea level rise adaptation laws and policies in other oceanfront states
- Identify legal and policy issues that frustrate sea level rise adaptation efforts
- Prepare white papers on sea level rise law and policy issues not adequately addressed by others
- Conduct outreach events to communicate legal and policy recommendations.

But Not . . .

Duplicating the work of others:

- DEEP
- CIRCA
- The Nature Conservancy
- CLEAR / Adapt CT
- COGs
- Georgetown Climate Center
- Marine Affairs Institute (RWU, URI)
- National Association of Floodplain Managers

UConn CLEAR
Climate Adaptation Legal Issues

Fact Sheets

- Takings and Coastal Management
- Property & Permitting Boundaries at the Shoreline
- Governmental Tort Liability for Disclosure of Flood Hazard Information
- Flood and Erosion Control Structures

UConn CLEAR
Legal Issues Workshop

December 15
8:30 a.m. – 3:30 p.m.

Mercy by the Sea Retreat
& Conference Center

Registration Closes Tomorrow at Noon!

Google Adapt CT for Details

Connecticut Statutory Requirements to Consider Sea Level Rise

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Sea Level Rise Must Be Considered . .

- By the State
  - During development of the state plan of conservation & development (CGS 16a-27)
  - During development of the state civil preparedness plan and program (CGS 28-5)
- By Municipalities
  - During the development of municipal plans of conservation & development (CGS 8-23)
  - During development of municipal evacuation and hazard mitigation plans (25-68o)

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Sea Level Rise Must Be Considered . .

- By the State and Municipalities
  - As a general policy and goal of the legislature during "the planning process" related to coastal management (CGS 22a-92)
- By the University of Connecticut
  - At least once every ten years when updating global sea level rise projections to reflect the unique conditions of Long Island Sound and the Connecticut shoreline (25-68o)

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What is Sea Level Rise?

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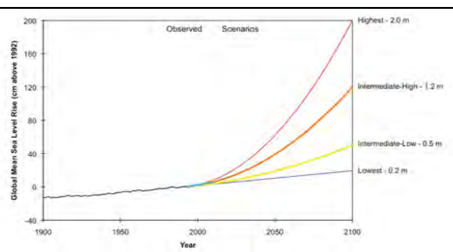

Scenario	SLR by 2100 (m)*	SLR by 2100 (ft)*
Highest	2.0	6.6
Intermediate-High	1.2	3.9
Intermediate-Low	0.5	1.6
Lowest	0.2	0.7

* Using mean sea level in 1992 as a starting point.

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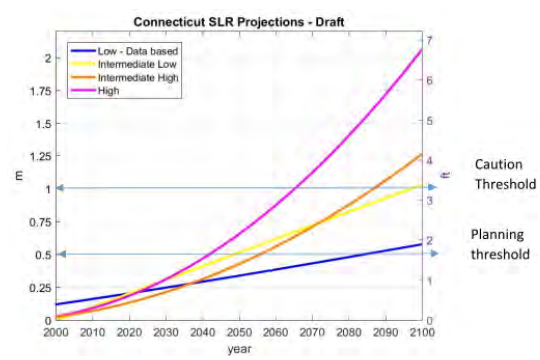

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CIRCA SLR Recommendation

- Plan for 50 Centimeter Sea Level Rise by 2050
  - 50 CM = 1 Foot 8 Inches
- 50 by 50!

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So How Do Connecticut Coastal Management Statutes Compare to Other States?

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Of the 23 Oceanfront States, Connecticut is . . .

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Of the 23 Oceanfront States, Connecticut is . . .

- One of 16 where state and local governments share coastal management jurisdiction
- One of one state where local coastal management programs are not subject to state approval

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Local Programs

Coastal Management Programs

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- Facilitate access to public trust beaches, waters and submerged lands.

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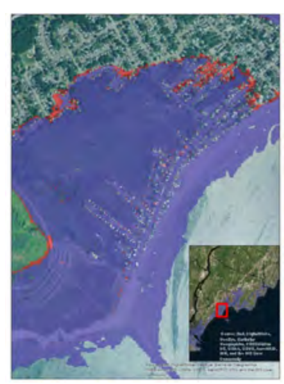

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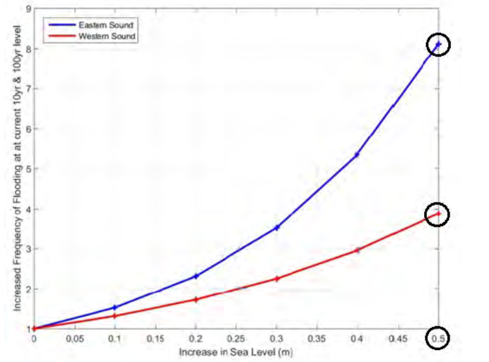

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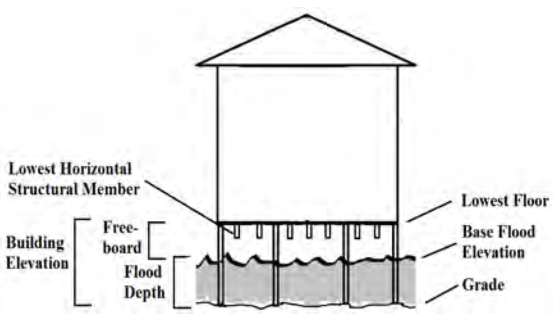
Elevated Shoreline House



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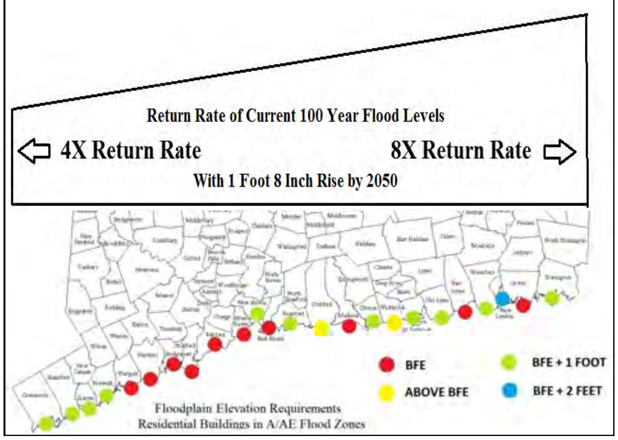

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ZONE	2016 STATE CODE FOR RESIDENTIAL	MADISON FLOODPLAIN MANAGEMENT ORDINANCE
A AE	Lowest Floor Elevated to Design Flood Elevation (DFE)	Lowest Floor Elevated to at least Base Flood Elevation (BFE)
V VE	Lowest Horizontal Structural Member Elevated to • DFE if Parallel to Wave Approach • BFE +1' or DFE (Whichever is Higher) if Perpendicular to Wave Approach	Lowest Supporting Horizontal Structural Member Elevated to no lower than BFE

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ZONE	2016 STATE CODE FOR NON-RESIDENTIAL	MADISON FLOODPLAIN MANAGEMENT ORDINANCE
A **AE**	**Lowest Floor** • **Elevated to BFE +1 or DFE , *OR*** • **Flood-proofed to BFE +1**	**Lowest Floor** • **Elevated to at least BFE, *OR*** • **Flood-proofed to at least BFE**
V **VE**	**Lowest Horizontal Structural Member Elevated to** • **DFE if Parallel to Wave Approach** • **BFE +1' or DFE (Whichever is Higher) if Perpendicular to Wave Approach**	**Lowest Supporting Horizontal Structural Member Elevated to no lower than BFE**

Floodplain Elevation Recommendations

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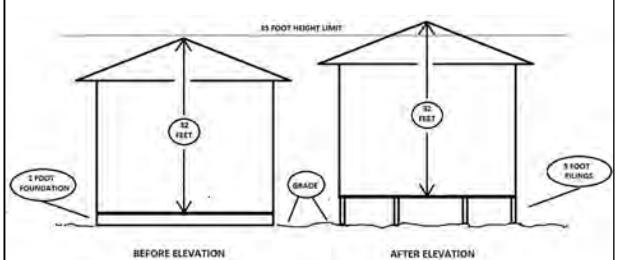

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- Recommendation: Consider this option

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Walls Landward of the Coastal Jurisdiction Line

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Walls Landward of the CJL

Of the 24 Shoreline Municipalities

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MUNICIPAL RESILIENCE PLANNING ASSISTANCE PROJECT

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APPENDIX G2 - SECTION 3

CAPSTONE CONFERENCE
CREATING A RESILIENT CONNECTICUT: A CIRCA FORUM ON SCIENCE, PLANNING, POLICY & LAW

Agenda

Program

Registrants

PowerPoint Presentation - Center for Energy & Environmental Law

UCONN
UNIVERSITY OF CONNECTICUT

Creating a Resilient Connecticut:
A CIRCA Forum on Science, Planning, Policy & Law

May 11, 2018
UConn School of Law – Hartford, CT
Reading Room, William F. Starr Hall

AGENDA:

8:15 **Registration** (continental breakfast provided)

8:45 **Welcome**
Tim Fisher, UConn School of Law Dean and Professor of Law
Joe MacDougald, UConn Professor in Residence, Exec. Director of Center for Energy & Environmental Law, and CIRCA Director of Applied Research

9:00 **Opening Remarks**
Rob Klee, Commissioner, Connecticut Department of Energy & Environmental Protection (CT DEEP)

9:15 **MUNICIPAL RESILIENCE PLANNING ASSISTANCE PROJECT**
Part 1 – Research Results (talks followed by 15 mins of Q &A)

- *Sea Level Rise in Long Island Sound (25 mins)*
  Jim O'Donnell, CIRCA Exec. Director and UConn Professor of Marine Sciences
- *Statewide Riverine Flood Vulnerability Assessment (25 mins)*
  Manos Anagnostou, UConn Professor of Engineering
- *Legal and Policy Analyses to Support Resilience Measures (25 mins)*
  Bill Rath, UConn Center for Energy & Environmental Law (CEEL)

10:45 **Break**

11:00 **Part 2 – Additional Research and Applications** (talks followed by 15 mins of Q &A)

- *Tracking Connecticut's Coast Using Aerial Photography (10 mins)*
  DeAva Lambert, Environmental Analyst, CT DEEP Land & Water Resources Div.
- *Resilience of Wastewater and Drinking Water Systems (25 mins)*
  Christine Kirchhoff, UConn Assistant Professor of Engineering
- *Vulnerability Assessment and Planning in New London (25 mins)*
  Peter Miniutti, UConn Associate Professor Landscape Architecture

12:15 **Lunch (provided)**

1:00 - 1:45 **Keynote Address: *Connecticut's Future in a Disaster-Prone World***
Harriet Tregoning, Strategic Policy Advisor and Former Deputy Assistant Secretary of the Office of Community Planning and Development at the U.S Department of Housing

1:45 – 2:30 **Audience Based Policy Discussion with Expert Panel**

- Harriet Tregoning
- George Bradner, Director, Connecticut Insurance Department
- Sara Bronin, UConn Professor of Law and Hartford Planning and Zoning Commission
- Mike Piscitelli, Director, New Haven City Plan Department and President, CT Chapter, American Planning Association

2:30 – 2:45 **Break**

2:45 – 4:15 **Climate Resilience Project Panel** (15 mins for each talk - followed by 15 mins of Q &A)

Coastal Council of Governments	**Amanda Kennedy**, Assistant Director - Southeastern CT COG: Critical Facilities Assessment
Inland Council of Governments	**Joanna Wozniak-Brown**, Regional Planner - Northwest Hills COG: Municipal LID Design and Enhancing Rural Resiliency in the Northwest Hills
Watershed Organization	**Mike Jastremski**, Watershed Conservation Director - Housatonic Valley Association: Planning for Flood Resilient and Fish-Friendly Road-Stream Crossings
Inland Municipality	**Shubhada Kambli**, Hartford Sustainability Coordinator: Climate Stewardship Initiative and Green Infrastructure Specialist
Coastal Municipality	**Jim O'Donnell**, CIRCA Executive Director and Professor of Marine Sciences: Road Flooding in Coastal Connecticut (Branford)

4:15 **Closing Remarks and Ice Cream Social**

POSTERS & TOOLS: Participants are invited throughout the day to view posters and online tools located around the venue, which highlight CIRCA funded projects & products related to this event

This event is the culmination of work undertaken over the past two years by DEEP/UCONN-CIRCA in ten focus areas to address the resilience of vulnerable communities along Connecticut's coast and inland waterways to the growing impacts of climate change. Important research is leading to the creation of products for assessing vulnerabilities and strategies to mitigate potential damage from climate change and storm impacts.

Work is made possible through a grant from the State of Connecticut Department of Housing CDBG-Disaster Recovery Program and the US Department of Housing and Urban Development.

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CIRCA
CONNECTICUT
Department of Housing

CREATING A RESILIENT CONNECTICUT:

A CIRCA Forum on Science, Planning, Policy & Law

University of Connecticut School of Law
Hartford, CT
May 11, 2018

Table of Contents

This event is the culmination of work undertaken over the past two years by the Connecticut Institute of Resilience and Climate Adaptation (CIRCA) and the Connecticut Department of Energy & Environmental Protection (CT DEEP). A grant from the Connecticut Department of Housing CDBG-Disaster Recovery Program included ten focus areas to address the resilience of vulnerable communities along the state's coast and inland waterways to the growing impacts of climate change. Important research is leading to the creation of products for assessing vulnerabilities and strategies to mitigate potential damage from climate change and storm impacts. Products will be available in December 2018 on CIRCA's website: http://circa.uconn.edu

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Joseph MacDougald, UConn Professor in Residence, Exec. Director of UConn Center for Energy & Environmental Law, and CIRCA Director of Applied Research

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- *Vulnerability Assessment and Planning in New London*
  Peter Miniutti, UConn Associate Professor Landscape Architecture

12:15 **Lunch** (provided)

1:00 - 1:45 **KEYNOTE ADDRESS**

Introduction by Evonne Klein, Commissioner, Connecticut Department of Housing

Connecticut's Future in a Disaster-Prone World:
Harriet Tregoning, Strategic Policy Advisor and Former Deputy Assistant Secretary of the Office of Community Planning and Development at the U.S Department of Housing

1:45 – 2:30 **Audience Based Policy Discussion with Expert Panel**

- Harriet Tregoning
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- Michael Piscitelli, AICP, Deputy Economic Development Administrator, City of New Haven and President, CT Chapter, American Planning Association

2:30 – 2:45 **Break**

2:45 – 4:15 **Climate Resilience Project Panel**

Moderated by Katie Lund, CIRCA Project Coordinator

- *Southeastern Connecticut Critical Facilities Assessment*
  Amanda Kennedy, Assistant Director, Southeastern CT COG
- *Municipal LID Design and Enhancing Rural Resiliency in the Northwest Hills*
  Joanna Wozniak-Brown, Regional Planner, Northwest Hills COG:
- *Planning for Flood Resilient and Fish-Friendly Road-Stream Crossings*
  Mike Jastremski, Watershed Director, Housatonic Valley Association
- *Hartford Climate Stewardship Initiative and Green Infrastructure Specialist*
  Shubhada Kambli, Hartford Sustainability Coordinator
- *Coastal Road Flooding Study in Branford*
  James O'Donnell, CIRCA Executive Director, Professor of Marine Sciences

4:15 **Closing Remarks and Ice Cream Social**

POSTERS & TOOLS

Participants are invited throughout the day to view information located around the venue, which highlight CIRCA funded projects and products related to this event. Posters include overviews of the work being done by CRCOG, New Haven, RiverCOG, SCROG, WestCOG, and UConn researchers.

SPONSORS

This event is co-sponsored by CIRCA, CT DEEP, and the UConn Center for Energy & Environmental Law. Funding is made possible through a grant from the State of Connecticut Department of Housing CDBG-Disaster Recovery Program and the US Department of Housing and Urban Development.

Keynote Speaker

Harriet Tregoning
Strategic Advisor and Previous Principal Deputy Assistant Secretary of the Office of Community Planning and Development at the U.S Department of Housing and Urban Development

At HUD, Harriet Tregoning**'s** work addressed homelessness, but also helped communities from the state to the local level plan for resilience in the face of changing economic, social, and climate factors. Tregoning was Director of the District of Columbia Office of Planning, where she oversaw the re-writing of the city's zoning code and pushed for smart-growth and a pedestrian and bike friendly city. She was formerly the Secretary of Planning in Maryland and Director of the Governors' Institute on Community Design. Tregoning also served as the Director of Development, Community and Environment at the United States Environmental Protection Agency where she launched the Smart Growth Network. In 2004, she was a Loeb Fellow at the Harvard Graduate School of Design.

In Order of Appearance

Timothy Fisher
Dean and Professor of Law, University of Connecticut, School of Law

Tim Fisher became the 17th dean of University of Connecticut School of Law on July 1, 2013, following thirty-five years in private practice. Prior to becoming dean he was a partner at a major regional law firm with a long history of public service. During his career prior to becoming dean, he taught at UConn School of Law as an adjunct instructor and participated in the life of the school through moot court judging, a faculty workshop presentation, and numerous activities with students and faculty.

A graduate of Yale University and Columbia Law School, Dean Fisher has served in numerous public service and private sector leadership roles. He recently chaired the state Commission on Judicial Compensation and co-chaired the Legislature's Task Force on Access to Legal Counsel in Civil Matters. He previously served on the Governor's Commission on Judicial Reform, as well as various commissions of the Connecticut Judicial Branch, and was recently president of the Connecticut Bar Foundation. He served as president of a social service agency and has held leadership positions in Greater Hartford Legal Aid and the Connecticut Bar Association. Dean Fisher conceived and undertook the organizational and fundraising effort to create the Connecticut Innocence Fund, a first-in-the-nation program to assist exonerees to re-enter society when released from prison after proof of their innocence. He brings a deep belief in public service to his role as dean of UConn School of Law.

Joseph MacDougald
Professor in Residence, University of Connecticut, School of Law
Executive Director, Center for Energy & Environmental Law
Director of Applied Research, CIRCA

Joe MacDougald was appointed professor-in-residence and the executive director of UConn Law's Center for Energy and Environmental Law (CEEL) in 2011, after serving as an adjunct professor for several years and as a visiting scholar in the fall of 2009. He regularly teaches Land Use, Climate Law, and Renewable Energy Law, as well as instructs and oversees the work of students in CEEL's externship clinic.

Professor MacDougald, a 1996 graduate of UConn Law, holds a B.A. from Brown University, an M.B.A. from NYU, and a master's degree in environmental management from Yale University's School of Forestry & Environmental Studies, where he divided his coursework between policy classes in the forestry program and environmental law offerings at Yale Law School. Prior to pursuing a fulltime teaching career Professor MacDougald spent twenty years in private industry, serving as general counsel, CEO, president, board member, and ownership group representative of an international biomaterials company that, under his direction, was sold to a Fortune 500 company in 2009.

A longtime resident of Madison, CT, Professor MacDougald, who researches, writes and lectures in the fields of environmental law, energy law, constitutional law and land use law, served for more than ten years on Madison's Planning and Zoning Commission, including six years as its chairman. Currently, he serves as a town selectman and a member of the board of the Madison Land Conservation Trust. Professor MacDougald also has served as a board member or volunteer for numerous other non-profit institutions. Most recently, he was appointed to the board of the Connecticut Resources Recovery Authority.

Rob Klee
Commissioner, Connecticut Department of Energy & Environmental Protection

Commissioner Klee was appointed by Governor Dannel P. Malloy in January 2014. Commissioner Klee joined DEEP in April 2011 as Chief of Staff. Prior to joining state service, Commissioner Klee was an attorney with Wiggin and Dana LLP, in New Haven, where he specialized in appellate work and energy and environmental law. Commissioner Klee holds a Ph.D. from Yale's School of Forestry & Environmental Studies in industrial ecology, a law degree from Yale, and an undergraduate degree from Princeton in geology and environmental science.

James O'Donnell
Executive Director, Connecticut Institute for Resilience and Climate Adaptation
Professor of Marine Sciences, University of Connecticut

Before Jim O'Donnell's appointment to Executive Director of CIRCA, Dr. O'Donnell, earned a BSc. (Hons) in Applied Physics from Strathclyde University in Scotland, and a M.S. and Ph.D. in Oceanography from the University of Delaware. After serving as Postdoctoral Research Associate at Cambridge University, he joined the faculty of the University of Connecticut in 1987. In 1999 he was promoted to the rank of Professor and served as interim Head of the Department of Marine Sciences and Director of the Marine Science and Technology Center from 2002 to 2005. He was elected to the Connecticut Academy of Science and Engineering in 2009.

Emmanouil Anagnostou
Professor of Engineering, University of Connecticut
Director of Applied Research, CIRCA

Manos Anagnostou holds a Ph.D. and MSc. Degrees in Hydrometeorology from the University of Iowa and a diploma in Civil and Environmental Engineering from the National Technical University of Athens. Dr. Anagnostou's internationally recognized expertise is in remote sensing applications in water resources. He collaborates in the planning of the Global Precipitation Measurement mission and international research on precipitation and floods. Dr. Anagnostou has been recognized with several prestigious awards and medals including the Plinius Medal from the European Geophysical Union and he was inducted into the Connecticut Academy of Science and Engineering in 2010.

William Rath
Legal Research Fellow, UConn Center for Energy & Environmental Law (CEEL)

Bill Rath earned his law degree in May of 2015 and was admitted to the Connecticut bar in November of that year. Prior to law school, he was a partner with an environmental health and safety consulting firm and a consulting engineer with a major Boston engineering firm. Bill holds a bachelor's degree in nuclear engineering technology, is a veteran of the United States Navy submarine service, and is continuing his legal education at UConn with a master of laws in energy & environmental law.

DeAva Lambert
Environmental Analyst, CT DEEP Land & Water Resources Division

DeAva Lambert has been with CT DEEP since January 2007, where she has worked in regulatory permitting and enforcement for Connecticut's Coastal Management Program and currently works on geospatial projects analyzing aspects of Connecticut's coastal resources. DeAva earned her M.S. in Environmental Science & Policy from Johns Hopkins University as well as a Graduate Certificate in Sustainable Environmental Planning and Management from the University of Connecticut, where her research focused on developing climate change policy and coastal resilience in Connecticut. DeAva obtained her undergraduate degree in Biology with a focus in Coastal Ecology from the University of Massachusetts (Amherst).

Christine Kirchhoff
Assistant Professor of Engineering, University of Connecticut

Christine Kirchoff is an Assistant Professor in the Civil & Environmental Engineering Department at the University of Connecticut. Dr. Kirchhoff's research on water, climate and society encompasses the following areas: (1) understanding and improving water policy, management and governance under uncertainty and change; (2) understanding and improving the ways in which we collaborative produce more usable science and the application of that science, particularly of climate science, to inform decision making; (3) determining the factors that enhance sustainability, adaptive capacity and resilience in the governance and management of water resources.

Peter Miniutti
Associate Professor of Landscape Architecture, University of Connecticut
Director, UConn's Community Research & Design Collaborative (CRDC)

As the Director of UConn's CRDC, Peter oversees CRDC's mission to be a regional leader in sustainable planning and design. We help Connecticut municipalities plan and design affordable, equitable, and ecologically healthy environments. Since 2000 he holds the Directorship of UConn's Community Research & Design Collaborative. He holds a Masters of Landscape Architecture from Harvard's Graduate School of Design and a Bachelor's degree from University of Massachusetts (Amherst) in Environmental Design.

Evonne Klein
Commissioner, Connecticut Department of Housing

Appointed by Governor Dannel P. Malloy in 2013, Evonne M. Klein is the first Commissioner of the newly created Connecticut Department of Housing, the lead state agency on housing matters. The department provides a wide array of funding programs and services aimed at ending homelessness, increasing the supply of affordable housing, and creating new homeownership opportunities for Connecticut residents.

Prior to her appointment as Commissioner of Housing, Klein served from 2001 to 2009 on the Board of Selectmen in the town of Darien, including three terms as First Selectman. During her tenure she also served as Vice Chair of the South Western Region Metropolitan Planning Organization and as Co-Vice Chair on the Alliance for Sensible Airspace Planning.

Klein is a graduate of Fairfield University in Fairfield, Connecticut, receiving a Masters in Corporate and Political Communications as well as her Bachelor's degree. She also completed coursework in Economics and Comparative Government at Oxford University, the London School of Economics, and the University of London.

George Bradner
Director of the Property and Casualty Division, Connecticut Insurance Department,
State of Connecticut

The Property and Casualty division regulates insurance through statutory standards and reviews all rate, rule, and form filings made by property and casualty insurers in the state. In addition, the division evaluates competitive prices and availability and affordability of insurance for consumers.

Sara Bronin
Professor of Law, University of Connecticut
Planning and Zoning Commission, City of Hartford

Sara Bronin is the Thomas F. Gallivan chair in Real Property Law and a Faculty Director of the Center for Energy and Environmental Law at the University Of Connecticut School Of Law. Her research focuses on land use, property, historic preservation, renewable energy law, and green building. She is chair of the City of Hartford's Planning and Zoning Commission and oversaw the award-winning re-write of the city's zoning regulations. In addition, she served as chair of the city's Climate Stewardship Council which collaboratively drafted and adopted an innovative Climate Action Plan. Professor Bronin chairs Hartford's Energy Improvement District Board and is a member of the Connecticut Trust for Historic Preservation.

Mike Piscitelli
Deputy Economic Development Administrator, City of New Haven
President, CT Chapter, American Planning Association

Mike Piscitelli is the Interim Director of the City of New Haven City Plan where he also serves as Deputy Economic Development Administrator coordinating seven city departments. He previously served as Director of Transportation, Traffic and Parking, and as the Comprehensive Planner in the City Plan Department. Mike is a member of the Elm City Innovation Collaborative, a multi-party consortium developed to apply for an Implementation grant from CTNext's Innovation Places program fostering entrepreneurs and leaders by developing places that attract needed talent. Mike has worked extensively to strengthen the relationship between the City of New Haven and Yale University and received the Yale University Seton Elm-Ivy Award in 2014. Mike also serves as the President of the American Planning Association CT Chapter.

Katie Lund
Project Coordinator, CIRCA

Katie Lund supports and tracks the Institute's grant projects that are intended to increase resilience and sustainability of Connecticut's vulnerable coastal communities to the growing impacts of climate change. Katie has worked for over 15 years on a variety of coastal management topics. Most recently with the Northeast Regional Ocean Council to support New England's ocean planning effort. In addition to managing projects that lay a foundation for the Northeast Ocean Plan, she worked with federal, state, and tribal members to support their planning activities and communications. Katie also worked at Massachusetts Office of Coastal Zone Management (CZM) from 1998-2006. In her role as stewardship coordinator, she partnered with agencies, municipalities, and conservation organizations to better manage and protect the state's designated coastal special areas. She also worked at a sustainability institute on the University of Michigan campus where she focused on climate, water resource, and urban sustainability assessments with faculty and student research teams. Katie holds an M.S. in Marine Resource Management from Oregon State University.

Amanda Kennedy
Assistant Director, Southeastern Connecticut Council of Governments

Amanda Kennedy is the Assistant Director/Director of Special Projects at the SCCOG in Norwich. Previous positions include Connecticut Director at the Regional Plan Association in Stamford and Development Coordinator for West Hartford-based Konover Properties (now the Simon Konover Company). She holds a Master of City and Regional Planning Degree from the Edward J. Bloustein School of Planning and Public Policy at Rutgers University and a bachelor's degree in anthropology from Yale University. Amanda was the recipient of the Bloustein School's 2008 AICP Outstanding Student Award as well as the Connecticut Association of Community Transportation's 2014 Friend of Public Transportation Award. Amanda also serves as Government Relations Co-Chair of the American Planning Association, CT Chapter.

Joanna Wozniak-Brown
Regional Planner, Northwest Hills Council of Governments

At the NHCOG, Joanna Wozniak-Brown is responsible for environmental, emergency, and transportation planning. Prior to working at NHCOG, she worked as an environmental consultant on brownfields, as an outreach consultant to the Department of Housing on Phase I of the National Disaster Resilience Competition, and a coordinator of pilot testing of NOAA's Climate Resilience Toolkit. Dr. Wozniak-Brown completed her PhD at Antioch University New England. Her dissertation focused on socio-ecological approaches to climate change adaptation, the meaning of rural character, and effective methods of local municipal adaptations to climate change. She is parlaying that work into a Rural Resiliency Vision & Toolkit through a Municipal Resilience Grant from UConn CIRCA. She also holds a Masters of Science in Environmental Planning from Johns Hopkins University and a Bachelor of Arts from Drew University in Political Science.

Michael Jastremski
Watershed Director, Housatonic Valley Association

Mike Jastremski joined HVA in March 2013. He coordinates the Stream Team program, organizes cleanups and educates the community on river issues. Mike comes from New York's Delaware County Planning Department where he has served as the Environmental Planner since 2010 (before that serving as their Stream Management Planner). Mike's on-the-ground experience includes extensive work with communities on such things as stream corridor management, water quality protection and planning, environmental regulation, natural hazard mitigation, habitat restoration, storm water management and site plan review.

Shubhada Kambli
Sustainability Coordinator, City of Hartford

Shubhada Kambli has more than ten years of experience building environmental programs at the local, state and national levels. She specializes in creating strong educational outreach and conservation training programs for diverse audiences, and worked with teams across the country to build multiple successful, data-driven initiatives in New England, the Midwest and the South. Educated at Wesleyan, Tufts, and Harvard, Shubhada has advanced academic training in environmental health and policy.

The mission of the **Connecticut Institute for Resilience and Climate Adaptation** (CIRCA) is to increase the resilience and sustainability of vulnerable communities along Connecticut's coast and inland waterways to the growing impacts of climate change on the natural, built, and human environment.

CIRCA is a multi-disciplinary, center of excellence that brings together experts in the natural sciences, engineering, economics, political science, finance, and law to provide practical solutions to problems arising as a result of a changing climate. The Institute will help coastal and inland floodplain communities in Connecticut and throughout the Northeast better adapt to changes in climate and also make their human-built infrastructure more resilient while protecting valuable ecosystems and the services they offer to human society (food, clean air and water, and energy). The Institute will combine the world-class research capabilities of UConn and the progressive policies and practical regulatory experience of the Connecticut Department of Energy and Environmental Protection (CTDEEP) to translate sound scientific research to actions that can ensure the resilience and sustainability of both the built and natural environments of the coast and watersheds of Connecticut.

While Connecticut and the Northeast are particularly susceptible to the impacts of climate change and associated severe weather events, the problem exists at the national and international scales, with droughts and flooding worldwide. Severe storms in the United States cause 110 deaths per year in flood-related accidents and an average of $3.8 billion annually in property damage. In addition to floods, droughts, pollution of water resources and coastal areas, ocean currents and severe weather (ice/snow/hail storms, hurricanes, etc.) are the most costly and deadly of all natural disasters. Climate change affects the water cycle increasing the frequency of abnormal weather, including heavy rains and droughts, around the world with particularly severe impacts in developing countries. While its immediate attention will be in Connecticut and the Northeast, the Institute will develop comprehensive approaches to climate change research and its impacts at the national and international scales.

The **Connecticut Department of Energy and Environmental Protection** (DEEP) is charged with conserving, improving and protecting the natural resources and the environment of the state of Connecticut as well as making cheaper, cleaner and more reliable energy available for the people and businesses of the state. The agency is also committed to playing a positive role in rebuilding Connecticut's economy and creating jobs – and to fostering a sustainable and prosperous economic future for the state.

DEEP was established on July 1, 2011 with the consolidation of the Department of Environmental Protection, the Department of Public Utility Control, and energy policy staff from other areas of state government. The environmental protection agency had been established in 1971 at the dawn of the environmental movement, while the public utilities regulatory authority traces its roots back more than 150 years to the state's Railroad Commission.

The overarching goals of the agency are to:

- Integrate energy and environmental policies and programs in a more systematic, proactive and coherent manner to provide a better structure for decision-making and to build a sustainable and prosperous economic future.

- Bring down the cost of electricity to make Connecticut more competitive, promote energy efficiency, and encourage the development and use of clean energy technologies.

- Unleash a renewed spirit of innovation for pollution control, conservation of natural resources, and management of Connecticut's parks and forests.

Symposium Partners

UCONN | SCHOOL OF LAW
CENTER FOR ENERGY & ENVIRONMENTAL LAW

CIRCA

CONNECTICUT
Department of Housing

UCONN | SCHOOL OF LAW

CENTER FOR ENERGY & ENVIRONMENTAL LAW

APPENDIX G2 - SECTION 3

CAPSTONE CONFERENCE REGISTRANTS

First Name	Last Name	Organization	Title
David	Kozak	CT DEEP	Coastal Planner
Joanna	Wozniak-Brown, PhI	NHCOG	Regional Planner
Pamela	Soto	Trust for Public Land	Program Manager
Karen	Stackpole	GEI Consultants, Inc.	Sr. Consultant, Natural Resources
Brian	Carey	Town of Fairfield	Conservation Director
marcy	balint	ct deep LWRD	Sr. Environmental Planner
Kathleen	Schomaker	Town of Hamden	Energy Efficiency Coordinator/Sustainable CT in Hamden Coordinator
Emily	Hall	CT DEEP	NOAA Coastal Management Fellow
MARTIN	CONNOR	CITY OF TORRINGTON	CITY PLANNER
Richard	Dmochowski	Fairfield, Flood & Erosion Control Board	Chairman
Mark	Kasinskas	Burns & McDonnell	Sr. Environmental Scientist
Max	Tanguay-Colucci	Naugatuck Valley Council of Governments	Regional Planner
Edith	Pestana	CTDEEP	Administrator EJ Program
rebecca	bunnell	Fairfield Ct Flood and Erosion Control board	member
Kimberly	Bradley	CIRCA	Project Specialist
Hermia	Delaire	Department of Housing	Disaster Recovery Program Director
Tracey Arne	Brown, AIA	Tracey Arne Brown Architect	Principal
Krishnan	Raman	Solar Energy Association of Connecticut	Co-President
Donald	Lamberty	Flood & Erosion Board, Town of Fairfield	Mr Donald Lmberty
Kirby	Williams	Stonington Garden Club	Chairperson, Conservation
Joseph	Williams	Stonington Harbor Yacht Club	Vice Commodore
Meg	Parulis	Town of Westbrook	Town Planner
Lynne	Pike DiSanto	CRCOG	Principal Planner and Policy Analyst
David	Murphy	Milone & MacBroom, Inc.	Manager of Water Resources Planning
Christine	Goupil	Town of Clinton	First Selectman
Todd	Berman	Fuss & O'Neill	Senior Project Manager
Meghan	Sloan	MetroCOG	Planning Director
Carl	Amento	South Central Regional Council of Governments	Executive Director
Matthew	Hoey	Town of Guilford	FIrst Selectman
Brooke	Mercaldi	Werth Center for Coastal and Marine Studies, SCSU	Miss

James	Tait	Werth Center for Coastal and Marine Studies, SCSU	Professor of Marine and Environmental Sciences
Kevn	Magee	Town of Guilford	Environmental Planner
Alfred	Kovalik	Tipping Point Resources Group, LLC	President
Lauren	Brideau	Werth Center for Coastal and Marine Studies, SCSU	Ms.
Colleen	DeBenedetto	Cronin Management	Principal
Margot	Burns	Lower Connecticut River Valley Council of Governments	Environmental Planner
Gillian	Carroll	Town of Old Saybrook	Environmental Planner
Glenn	Chalder	Planimetrics, Inc.	President
Catie	LeMontangue	University of Connecticut	Student
Gary	Goeschel	Town of East Lyme	Director of Planning
Brian	Lampert	UConn Law	Student
Jade	Serrano	The Werth Center for Coastal and Marine Studies, SCSU	Research Assistant
Colleen	Dollard	CIRCA	Intern
Carolyn	Carlson	Connecticut Resident	Interested Citizen
Edwin	Williams	Connecticut Resident	Planner
Douglas	Royalty	State Historic Preservation Office	National Register specialist/Hurricane Sandy grant administrator
Alicia	Mozian	Town of Westport, CT	Conservation Director
Peter	Francis	CT DEEP	Supervising Environmental Analyst
Sarah	Fonts	The University of Connecticut Foundation	Assistant Director of Development, CLAS
Lori	Mathieu	State of CT - Dept. of Public Health	Section Chief
Patrick	Carleton	Connecticut Metropolitan Council of Governments	Deputy Director
Don	Swinton	The University of Connecticut Foundation	Director of Development, School of Engineering
Anastasia	Roy	APTIM	Resiliency Client Program Manager
Don	Watson	EarthRise design	prin cipal
Angela	Rath	None	None
Laura	Pulie	Town of Fairfield	Senior Civil Engineer
Jared	Grise	Dennis Group	Counsel
Christopher	Kelly	UConn Law	Student

Danielle	Bergmann	Self	Quality Assurance Analyst
Laura	Tessier	Woodard & Curran	Senior Planner
Katie	Lund	CIRCA	Project Coordinator
Jeff	Howard	CT DEEP, Office of Climate Change	Environmental Analyst
Evan	Ward	UConn - Marine Sciences	Professor and Head
DeAva	Lambert	Connecticut Department of Energy and Environmental Protection	Environmental Analyst
Frank	Morse	Garg Consulting Services, Inc.	Vice President
Emmeline	Harrigan	Town of Fairfield	Assistant Planning Director
Genevieve	Nuttall	Audubon Connecticut	Bird Conservation Program Associate
Kristen	Coperine	Green Thread Consulting	Founding Consultant
Michael	Sahm	Energy Analytics	Principal
Debra	Hall	New Ecology Inc.	CT Regional Manager and Director of New Markets
Genevieve	Halloran	The Halloran Group	Principal
Victoria	Brudz	CIRCA	Project Specialist
Dawn	Henry	Westport Green Task Force member, Climate Reality Leader, Connecticut Fund for the Environment Board Member	Member
Suzanne	Huminski	Southern CT State University	Sustainability Coordinator
David	Steuber	CT Senate Democrats	Policy Analyst
Tayler	Thorpe	Connecticut State Democratic Caucus	Policy Analyst
Bruce	Wittchen	CT OPM	Environmental Analyst
Laura	Morse	Orsted , US Wind Power	Environmental Manager
Grace	Yi	City of Hartford	Green Infrastructure Assistant
Mia	Forgione	Southern Connecticut State University	Student
Lauren	Yaworsky	CIRCA	staff
Rob	Klee	CT DEEP	Comissinor
Joe	MacDougald	UConn School of Law	Professor in Residence, Exec. Dir., Center for Energy & Env. Law, CIRCA Dir. of Applied Research
James	O'Donnell	CIRCA	Executive Director
Manos	Anagnostou	UConn Engineering	Professor
Tim	Fisher	UConn School of Law	Dean and Professor
Bill	Rath	UConn CEEL	Legal Research Fellow
Christine	Kirchoff	UConn Civil and Environmental Engineering	Assistant Professor

Peter	Miniutti	UConn College of Ag, Health & Natural Resources, Plant Science and Landscape Architecture	Associate Professor
Evonne	Klein	CT Dept. of Housing	Commissioner
Harriet	Tregoning	Keynote	Speaker
George	Bradner	CT Insurance Dept.	Director
Sarah	Bronin	UConn School of Law Hartford Planning and Zoning Commission	Professor
Michael	Piscitelli	City of New Haven	Deputy Economic Dev. Administrator
Amanda	Kennedy	SCCOG	Assistant Director
Mike	Jastremski	Housatonic Valley Association	Watershed Director
Shubhada	Kambli	City of Hartford	Sustainability Coordinator
Wayne	Cobleigh	GZA	Vice President
Azamat	Tashev	Department of Civil and Environmental Engineering, University of Connecticut	Graduate Research Assistant
Miriam	Theroux	DEEP/PURA	Principal Attorney
antonio	santoro	state of connecticut	staff attorney
Jennifer	O'Donnell	UConn, Dept. of Marine Sciences	Dr.
Elizabeth	Santovasi	UConn Law; CEEL	Student; CEEL Research Assistant
Louanne	Cooley	UConn Law; CEEL	Student; CEEL Research Assistant
Robert	Kaliszewski	CT DEEP	Deputy Commissioner - Environmental Quality Branch
Lilia	Hrekul	UConn Law School	Student
Po	Cheng	Eversource Energy	Investment and Business Development
David	Blatt	DEEP Land and Water Resources Division	Supervising Environmental Analyst
Linda	Ferraro	CT Dept. of Public Health	Public Health Services Manager
Galen	Treuer	University of Connecticut	Postdoctoral Researcher
Alex	Felson	Yale University	Associate Professor
Francis	Brady	Town of Madison	Conservation Commissioner
Diane	Lauricella	CT Roundtable on Climate and Jobs	Board Member
Larry	Levesque	Department of Energy and Environmental Protection	Attorney
Jessica	Panella	UConn School of Law Library	Head of Access & Administrative Services
Louise	Nadeau	Legislative Commissioners' Office	Director
John	Rosenthal	CT DOH	Development Agent

Julie	Bjorkman	JKB Consulting, LLC	Principal
Mary	Pelletier	Park Watershed	Founding Director
Charles	Towe	University of Connecticut	Associate Professor
Francis	Brady	Town of Madison	Conservation Commissioner
Marguerite	Purnell	Cornwall Conservation Commission	Consultant
Max	Tanguay-Colucci	Naugatuck Valley Council of Governments	Regional Planner
Dan	Ciarcia	Two Willows Consulting	Founder
Lisa	Chase	Two Willows Consulting	Communications/Business Development
Zhenshan	Chen	UCONN	Graduate Student
Dawn	Henning	City of New Haven	Project Manager
Krista	Romero	DEEP	Environmental Analyst

APPENDIX G2 - SECTION 4

AN ACT CONCERNING CLIMATE CHANGE PLANNING AND RESILIENCY

Governor's Bill S.B. No. 7

- Deletions to existing statutory language are [enclosed within brackets].
- Additions to existing statutory language are underlined.
- Changes inspired by the Task 9 white paper entitled "Statutory Adoption of Updated Sea-Level Rise Scenarios" are highlighted in yellow.

Connecticut Public Act 18-82

- Deletions to existing statutory language are [enclosed within brackets].
- Additions to existing statutory language are underlined.
- Changes inspired by the Task 9 white paper entitled "Statutory Adoption of Updated Sea-Level Rise Scenarios" are highlighted in yellow.

Public Hearing Testimony by the Center for Energy & Environmental Law before the Connecticut General Assembly Environment Committee

- Joseph A. MacDougald, Executive Director
- William R. Rath, Legal Research Fellow

General Assembly

February Session, 2018

Governor's Bill No. 7

LCO No. **235**

Referred to Committee on ENVIRONMENT

Introduced by:
SEN. LOONEY, 11th Dist.
SEN. DUFF, 25th Dist.
REP. ARESIMOWICZ, 30th Dist.
REP. RITTER M., 1st Dist.

AN ACT CONCERNING CLIMATE CHANGE PLANNING AND RESILIENCY.

Be it enacted by the Senate and House of Representatives in General Assembly convened:

Section 1. Subsection (d) of section 8-23 of the 2018 supplement to the general statutes is repealed and the following is substituted in lieu thereof (*Effective from passage*):

(d) In preparing such plan, the commission or any special committee shall consider the following: (1) The community development action plan of the municipality, if any, (2) the need for affordable housing, (3) the need for protection of existing and potential public surface and ground drinking water supplies, (4) the use of cluster development and other development patterns to the extent consistent with soil types, terrain and infrastructure capacity within the municipality, (5) the state plan of conservation and development adopted pursuant to chapter 297, (6) the regional plan of conservation and development adopted pursuant to section 8-35a, (7) physical, social, economic and governmental conditions and trends, (8) the needs of the municipality including, but not limited to, human resources, education, health, housing, recreation, social services, public utilities, public protection, transportation and circulation and cultural and interpersonal communications, (9) the objectives of energy-efficient patterns of development, the use of solar and other renewable forms of energy and energy conservation, (10) protection and preservation of agriculture, (11) **[**sea level change scenarios published by the National Oceanic and Atmospheric Administration in Technical Report OAR CPO-1**]** the most recent sea level change scenario updated pursuant to subsection (b) of section 25-68o, as amended by this act, and (12) the need for technology infrastructure in the municipality.

Sec. 2. Subsection (a) of section 16a-3a of the general statutes is repealed and the following is substituted in lieu thereof (*Effective from passage*):

(a) The Commissioner of Energy and Environmental Protection, in consultation with the electric distribution companies, shall review the state's energy and capacity resource assessment and approve the Integrated Resources Plan for the procurement of energy resources, including, but not limited to, conventional and renewable generating facilities, energy efficiency, load management, demand response, combined heat and power facilities, distributed generation and other emerging energy technologies to meet the projected requirements of customers in a manner that minimizes the cost of all energy resources to customers over time and maximizes consumer benefits consistent with the state's environmental goals and standards, including, but not limited to, the state's greenhouse gas reduction goals established in section 22a-200a, as amended by this act. The Integrated Resources Plan shall seek to lower the cost of electricity while meeting such environmental goals and standards in the most cost-effective manner.

Sec. 3. Section 16a-3d of the general statutes is repealed and the following is substituted in lieu thereof (*Effective from passage*):

(a) On or before October 1, **[**2016**]** 2020, and every **[**three**]** four years thereafter, the Commissioner of Energy and Environmental Protection shall prepare a Comprehensive Climate and Energy Strategy. Said strategy shall reflect the legislative findings and policy stated in section 16a-35k, **[**and shall**]** provide any analysis and recommendations necessary to guide the state's energy policy to meet greenhouse gas emission reduction requirements, as established in section 22a-200a, as amended by this act, in the most cost-effective manner and incorporate (1) an assessment and plan for all energy needs in the state, including, but not limited to, electricity, heating, cooling, and transportation, (2) the findings of the Integrated Resources Plan, (3) the findings of the plan for energy efficiency adopted pursuant to section 16-245m, (4) the findings of the plan for renewable energy adopted pursuant to section 16-245n, **[**and**]** (5) the Energy Assurance Plan developed for the state of Connecticut pursuant to the American Recovery and Reinvestment Act of 2009, P.L. 111-5, or any successor Energy Assurance Plan developed within a reasonable time prior to the preparation of any Comprehensive Climate and Energy Strategy, and (6) the findings of any report prepared pursuant to section 22a-200a, as amended by this act. Said strategy shall further include, but not be limited to, (A) an assessment of current energy supplies, demand and costs, (B) identification and evaluation of the factors likely to affect future energy supplies, demand and costs, (C) a statement of progress made toward achieving the goals and milestones set in the preceding Comprehensive Climate and Energy Strategy, (D) a statement of energy policies and long-range energy planning objectives and strategies appropriate to achieve, **[**among other things**]** the state's greenhouse gas reduction goals established in section 22a-200a, as amended by this act, a sound economy, the least-cost mix of energy supply sources to meet said goals and measures that reduce demand for energy, giving due regard to such factors as consumer price impacts, security and diversity of fuel supplies and energy generating methods, protection of public health and safety, environmental goals and standards, conservation of energy and energy resources and the ability of the state to compete economically, (E) recommendations for administrative and legislative actions to implement such policies, objectives and strategies, (F) an assessment of the potential costs savings and benefits to ratepayers, including, but not limited to, carbon dioxide emissions reductions or voluntary joint ventures to repower some or all of the state's coal-fired and oil-fired generation facilities built before 1990, **[**and**]** (G) the benefits, costs, obstacles and solutions related to the expansion and use and availability of natural gas in Connecticut, and (H) a strategy for ensuring the state's energy efficiency goals are met. **[**If the department finds that such expansion is in the public interest, it shall develop a plan to increase the use and availability of natural gas.**]**

(b) In adopting the Comprehensive Climate and Energy Strategy, the Commissioner of Energy and Environmental Protection shall conduct a proceeding that shall not be considered a contested case under chapter 54, but shall include not less than one public meeting and one technical meeting at which technical personnel shall be available to answer questions. Such meetings shall be transcribed and posted on the department's Internet web site. Said commissioner shall give not less than fifteen days' notice of such proceeding by electronic publication on the department's Internet web site. Not later than fifteen days prior to any such public meeting and not less than thirty days prior to any such technical meeting, the commissioner shall publish notice of either such meeting and post the text of the proposed Comprehensive Climate and Energy Strategy on the department's Internet web site. Notice of such public meeting or technical meeting may also be published in one or more newspapers having state-wide circulation if deemed necessary by the commissioner. Such notice shall state the date, time, and place of the meeting, the subject matter of the meeting, the manner and time period during which comments may be submitted to said commissioner, the statutory authority for the proposed strategy and the location where a copy of the proposed strategy may be obtained or examined in addition to posting the proposed strategy on the department's Internet web site. Said commissioner shall provide a time period of not less than sixty days from the date the notice is published on the department's Internet web site for public review and comment. During such time period, any person may provide comments concerning the proposed strategy to said commissioner. Said commissioner shall consider fully all written and oral comments concerning the proposed strategy after all public meetings and technical meetings and before approving the final strategy. Said commissioner shall (1) notify by electronic mail each person who requests such notice, and (2) post on the department's Internet web site the electronic text of the final strategy and a report summarizing all public comments and the changes made to the final strategy in response to such comments and the reasons therefor. The Public Utilities Regulatory Authority shall comment on the strategy's impact on natural gas and electric rates.

(c) The Commissioner of Energy and Environmental Protection shall submit the final Comprehensive Climate and Energy Strategy electronically to the joint standing committees of the General Assembly having cognizance of matters relating to energy and the environment.

(d) The Commissioner of Energy and Environmental Protection may modify the Comprehensive Climate and Energy Strategy in accordance with the procedures outlined in subsections (b) and (c) of this section.

Sec. 4. Section 16a-3e of the general statutes is repealed and the following is substituted in lieu thereof (*Effective from passage*):

The Integrated Resources Plan, as described in section 16a-3a, as amended by this act, shall (1) indicate specific options to reduce electric rates and costs while achieving the state's greenhouse gas emission reduction requirements established in section 22a-200a, as amended by this act. Such options may include the procurement of new sources of generation. In the review of new sources of generation, the Integrated Resources Plan shall indicate whether the private wholesale market can supply such additional sources or whether state financial assistance, long-term purchasing of electricity contracts or other interventions are needed to achieve the goal; (2) analyze in-state renewable sources of electricity in comparison to transmission line upgrades or new projects and out-of-state renewable energy sources, provided such analysis also considers the benefits of additional jobs and other economic impacts and how they are created and subsidized; (3) include an examination of average consumption and other states' best practices to determine why electricity rates are lower elsewhere in the region; (4) assess and compare the cost of transmission line projects, new power sources, renewable sources of electricity, conservation and distributed generation projects to ensure the state pursues only the least-cost alternative projects; (5) analyze the potential for electric vehicles, as defined in section 16-19eee, to provide energy storage and other services to the electric grid and identify strategies to ensure that the grid is prepared to support increased electric vehicle charging, based on projections of sales of electric vehicles; (6) continually monitor supply and distribution systems to identify potential need for transmission line projects early enough to identify alternatives; and (7) assess the least-cost alternative to address reliability concerns, including, but not limited to, lowering electricity demand through conservation and distributed generation projects before an electric distribution company submits a proposal for transmission lines or transmission line upgrades to the independent system operator or the Federal Energy Regulatory Commission, provided no provision of such plan shall be deemed to prohibit an electric distribution company from making any filing required by law or regulation.

Sec. 5. Subsection (h) of section 16a-27 of the general statutes is repealed and the following is substituted in lieu thereof (*Effective from* *passage*):

(h) Any revision made after October 1, **[**2013**]** 2019, shall (1) take into consideration risks associated with increased coastal flooding and erosion, depending on site topography, as anticipated in **[**sea level change scenarios published by the National Oceanic and Atmospheric Administration in Technical Report OAR CPO-1**]** the most recent sea level change scenario updated pursuant to subsection (b) of section 25-68o, as amended by this act, (2) identify the impacts of such increased flooding and erosion on infrastructure and natural resources, **[**and**]** (3) make recommendations for the siting of future infrastructure and property development to minimize the use of areas prone to such flooding and erosion, and (4) take into consideration the state's greenhouse gas reduction goals established pursuant to section 22a-200a, as amended by this act.

Sec. 6. Subsection (a) of section 22a-92 of the general statutes is repealed and the following is substituted in lieu thereof (*Effective from passage*):

(a) The following general goals and policies are established by this chapter:

(1) To ensure that the development, preservation or use of the land and water resources of the coastal area proceeds in a manner consistent with the rights of private property owners and the capability of the land and water resources to support development, preservation or use without significantly disrupting either the natural environment or sound economic growth;

(2) To preserve and enhance coastal resources in accordance with the policies established by chapters 439, 440, 446i, 446k, 447, 474 and 477;

(3) To give high priority and preference to uses and facilities which are dependent upon proximity to the water or the shorelands

immediately adjacent to marine and tidal waters;

(4) To resolve conflicts between competing uses on the shorelands adjacent to marine and tidal waters by giving preference to uses that minimize adverse impacts on natural coastal resources while providing long term and stable economic benefits;

(5) To consider **[**in the planning process**]** the potential impact of a rise in sea level, coastal flooding and erosion patterns on coastal development so as to minimize damage to and destruction of life and property and minimize the necessity of public expenditure and shoreline armoring to protect future new development from such hazards;

(6) To encourage public access to the waters of Long Island Sound by expansion, development and effective utilization of state-owned recreational facilities within the coastal area that are consistent with sound resource conservation procedures and constitutionally protected rights of private property owners;

(7) To conduct, sponsor and assist research in coastal matters to improve the data base upon which coastal land and water use decisions are made;

(8) To coordinate the activities of public agencies to ensure that state expenditures enhance development while affording maximum protection to natural coastal resources and processes in a manner consistent with the state plan for conservation and development adopted pursuant to part I of chapter 297;

(9) To coordinate planning and regulatory activities of public agencies at all levels of government to ensure maximum protection of coastal resources while minimizing conflicts and disruption of economic development; and

(10) To ensure that the state and the coastal municipalities provide

adequate planning for facilities and resources which are in the national interest as defined in section 22a-93, as amended by this act, and to ensure that any restrictions or exclusions of such facilities or uses are reasonable. Reasonable grounds for the restriction or exclusion of a facility or use in the national interest shall include a finding that such a facility or use: (A) May reasonably be sited outside the coastal boundary; (B) fails to meet any applicable federal and state environmental, health or safety standard; or (C) unreasonably restricts physical or visual access to coastal waters. This policy does not exempt any nonfederal facility in use from any applicable state or local regulatory or permit program nor does it exempt any federal facility or use from the federal consistency requirements of Section 307 of the federal Coastal Zone Management Act.

Sec. 7. Subdivision (7) of section 22a-93 of the general statutes is repealed and the following is substituted in lieu thereof (*Effective from passage*):

(7) "Coastal resources" means the coastal waters of the state, their natural resources, related marine and wildlife habitat and adjacent shorelands, both developed and undeveloped, that together form an integrated terrestrial and estuarine ecosystem; coastal resources include the following: (A) "Coastal bluffs and escarpments" means naturally eroding shorelands marked by dynamic escarpments or sea cliffs which have slope angles that constitute an intricate adjustment between erosion, substrate, drainage and degree of plant cover; (B) "rocky shorefronts" means shorefront composed of bedrock, boulders and cobbles that are highly erosion-resistant and are an insignificant source of sediments for other coastal landforms; (C) "beaches and dunes" means beach systems including barrier beach spits and tombolos, barrier beaches, pocket beaches, land contact beaches and related dunes and sandflats; (D) "intertidal flats" means very gently sloping or flat areas located between high and low tides composed of muddy, silty and fine sandy sediments and generally devoid of vegetation; (E) "tidal wetlands" means "wetland" as defined by section

22a-29; (F) "freshwater wetlands and watercourses" means "wetlands" and "watercourses" as defined by section 22a-38; (G) "estuarine embayments" means a protected coastal body of water with an open connection to the sea in which saline sea water is measurably diluted by fresh water including tidal rivers, bays, lagoons and coves; (H) "coastal hazard areas" means those land areas inundated during coastal storm events or subject to erosion induced by such events, including flood hazard areas as defined and determined by the National Flood Insurance Act, as amended (USC 42 Section 4101, P.L. 93-234), all areas subject to inundation as determined by the most recent sea level change scenario updated pursuant to subsection (b) of section 25-68o, as amended by this act, and all erosion hazard areas as determined by the commissioner; (I) "developed shorefront" means those harbor areas which have been highly engineered and developed resulting in the functional impairment or substantial alteration of their natural physiographic features or systems; (J) "island" means land surrounded on all sides by water; (K) "nearshore waters" means the area comprised of those waters and their substrates lying between mean high water and a depth approximated by the ten meter contour; (L) "offshore waters" means the area comprised of those waters and their substrates lying seaward of a depth approximated by the ten meter contour; (M) "shorelands" means those land areas within the coastal boundary exclusive of coastal hazard areas, which are not subject to dynamic coastal processes and which are comprised of typical upland features such as bedrock hills, till hills and drumlins; (N) "shellfish concentration areas" means actual, potential or historic areas in coastal waters, in which one or more species of shellfish aggregate;

Sec. 8. Subdivision (19) of section 22a-93 of the general statutes is repealed and the following is substituted in lieu thereof (*Effective from passage*):

(19) "Rise in sea level" means the [arithmetic mean of the most recent equivalent per decade rise in the surface level of the tidal and

coastal waters of the state, as documented in National Oceanic and Atmospheric Administration online or printed publications for said agency's Bridgeport and New London tide gauges] most recent sea level change scenario updated pursuant to subsection (b) of section 25-68o, as amended by this act.

Sec. 9. Section 22a-94 of the general statutes is repealed and the following is substituted in lieu thereof (*Effective from passage*):

(a) The Connecticut coastal area shall include the land and water within the area delineated by the following: The westerly, southerly and easterly limits of the state's jurisdiction in Long Island Sound; the towns of Greenwich, Stamford, Darien, Norwalk, Westport, Fairfield, Bridgeport, Stratford, Shelton, Milford, Orange, West Haven, New Haven, Hamden, North Haven, East Haven, Branford, Guilford, Madison, Clinton, Westbrook, Deep River, Chester, Essex, Old Saybrook, Lyme, Old Lyme, East Lyme, Waterford, New London, Montville, Norwich, Preston, Ledyard, Groton and Stonington.

(b) Within the coastal area, there shall be a coastal boundary which shall be a continuous line delineated on the landward side by the interior contour elevation of the one hundred year frequency coastal flood zone, as defined and determined by the National Flood Insurance Act, as amended (USC 42 Section 4101, P.L. 93-234), plus the elevation of the most recent sea level change scenario updated pursuant to subsection (b) of section 25-68o, as amended by this act, or a one thousand foot linear setback measured from the mean high water mark in coastal waters that shall be determined from the elevation of the most recent sea level change scenario updated pursuant to subsection (b) of section 25-68o, as amended by this act, or a one thousand foot linear setback measured from the inland boundary of tidal wetlands, [mapped under section 22a-20,] whichever is farthest inland; and shall be delineated on the seaward side by the seaward extent of the jurisdiction of the state.

(c) The coastal boundary as defined in subsection (b) of this section shall be shown on maps or photographs prepared by the commissioner which supplement flood hazard rate maps prepared by the United States Department of Housing and Urban Development under the National Flood Insurance Act. Such maps shall be sufficiently precise to demonstrate whether the holdings of a property owner, or portions thereof, lie within the coastal boundary. Copies of such maps or photographs shall be filed with the commissioner and with the clerk of each coastal municipality.

(d) The maps described in subsection (c) of this section shall be promulgated not later than July 1, 1980. Prior to final adoption of any map, the commissioner shall hold a public hearing in accordance with the provisions of chapter 54 within the applicable coastal town. The commissioner may use interim maps prepared on United States Geological Survey Topographic base at a scale of one to twenty-four thousand or their metric equivalent. In preparing such interim maps, the commissioner may use any man-made structure, natural feature, property line, preliminary flood hazard boundary maps as prepared by the United States Department of Housing and Urban Development, or a combination thereof which most closely approximates the landward side of the boundary. Further, the commissioner may use city or town property tax maps or aerial photographs, state tidal wetlands photographs, or similar maps of property delineation as they are available.

(e) The commissioner may, from time to time, amend such maps described in subsection (c) of this section. Prior to the adoption of an amendment to any map, the commissioner shall hold a public hearing in the affected municipality in accordance with the provisions of chapter 54. The commissioner shall consider for amendment changes in the boundary petitioned by the coastal municipality, by any person owning real property within the boundary, or by twenty-five residents of such municipality. The commissioner shall approve, deny or modify such petition within sixty days of receipt and shall state, in writing, the reasons for his action. All amendments to the boundary shall be consistent with subsection (b) of this section.

(f) A municipal coastal boundary may be adopted or amended by the municipal planning commission of each coastal municipality in accordance with the notice, hearing and other procedural requirements of section 8-24. Not later than one year after the most recent sea level change scenario updated pursuant to subsection (b) of section 25-68o, as amended by this act, the municipal planning commission of each coastal municipality shall adopt or amend a municipal coastal boundary, in accordance with the notice, hearing and other procedural requirements of section 8-24, to reflect the landward extent of the interior contour elevation of the coastal boundary established in accordance with subsection (b) of this section. Such boundary may be delineated by roads, property lines or other identifiable natural or man-made features, provided such boundary shall approximate and in no event diminish the area within the coastal boundary as **[**defined**]** established in accordance with subsection (b) of this section and as mapped under subsection (d) of this section. Such boundary shall be sufficiently precise to demonstrate whether the holdings of a property owner, or portions thereof, lie within the boundary. Upon adoption, such boundary shall be submitted to the commissioner, **[**for mapping in accordance with subsection (c) of this section**]** in electronic and paper form, as specified by the commissioner, for the commissioner's review and approval and shall be effective upon receipt of the commissioner's written approval. The municipal planning commission may, at its own discretion or upon request of a property owner, amend the coastal boundary in accordance with the procedures and criteria of this subsection.

(g) All property lying within the coastal boundary shall be subject to the regulatory, development and planning requirements of this chapter.

Sec. 10. Subsection (a) of section 22a-200a of the general statutes is repealed and the following is substituted in lieu thereof (*Effective from passage*):

(a) The state shall reduce the level of emissions of greenhouse gas:

(1) Not later than January 1, 2020, to a level at least ten per cent below the level emitted in 1990; **[**and**]**

<u>(2) Not later than January 1, 2030, to a level at least forty-five per cent below the level emitted in 2001; and</u>

[(2)**]** <u>(3)</u> Not later than January 1, 2050, to a level at least eighty per cent below the level emitted in 2001.

[(3)**]** <u>(4)</u> All of the levels referenced in this subsection shall be determined by the Commissioner of Energy and Environmental Protection.

Sec. 11. Subsection (a) of section 22a-478 of the general statutes is repealed and the following is substituted in lieu thereof (*Effective from passage*):

(a) The commissioner shall maintain a priority list of eligible water quality projects and shall establish a system setting the priority for making project grants, grant account loans and project loans. In establishing such priority list and ranking system, the commissioner shall consider all factors he deems relevant, including but not limited to the following: (1) The public health and safety; (2) protection of environmental resources; (3) population affected; (4) attainment of state water quality goals and standards; (5) consistency with the state plan of conservation and development; (6) state and federal regulations; (7) the formation in municipalities of local housing partnerships pursuant to the provisions of section 8-336f; and (8) the necessity and feasibility of implementing measures designed to mitigate the impact of a rise in sea level<u>, as defined in section 22a-93, as amended by this act,</u> over the projected life span of such project. The priority list of eligible water quality projects shall include a description of each project and its purpose, impact, cost and construction schedule, and an explanation of the manner in which priorities were established. The commissioner shall adopt an interim priority list of eligible water quality projects for the purpose of making project grants, grant account loans and project loans prior to adoption of final regulations, which priority list shall be the priority list currently in effect under subsection (c) of section 22a-439.

Sec. 12. Section 25-68b of the general statutes is repealed and the following is substituted in lieu thereof (*Effective from passage*):

As used in sections 25-68b to 25-68h, inclusive:

(1) "Activity" means any proposed state action in a floodplain or any proposed state action that impacts natural or man-made storm drainage facilities that are located on property that the commissioner determines to be controlled by the state;

(2) "Base flood" means that flood which has a one per cent chance of being equaled or exceeded in any year, as defined in regulations of the National Flood Insurance Program (44 CFR 59 et seq.), or that flood designated by the commissioner pursuant to section 25-68c. Any flood so designated by the commissioner shall have at least a one per cent chance of being equaled or exceeded in any year. Such flood may be designated as the A or V zones on maps published by the National Flood Insurance Program. The "base flood for a critical activity" means the flood that has at least a .2 per cent chance of being equaled or exceeded in any year. Such flood may be designated as the B zone on maps published for the National Flood Insurance Program;

(3) "Commissioner" means the Commissioner of Energy and Environmental Protection;

(4) "Critical activity" means any activity, including, but not limited to, the treatment, storage and disposal of hazardous waste and the

siting of hospitals, housing for the elderly, schools or residences, in the .2 per cent floodplain in which the commissioner determines that a slight chance of flooding is too great;

(5) "Floodplain" means that area located within the real or theoretical limits of the base flood or base flood for a critical activity;

(6) "Flood-proofing" means any combination of structural or nonstructural additions, changes or adjustments which reduce or eliminate flood damage to real estate or improved real property, to water and sanitary facilities, and to structures and their contents, including, but not limited to, for properties within the coastal boundary, as established pursuant to subsection (b) of section 22a-94, as amended by this act, not less than an additional two feet of freeboard above base flood and any additional freeboard necessary to account for the most recent sea level change scenario updated pursuant to subsection (b) of section 25-68o, as amended by this act;

(7) "Freeboard" means a safety factor, expressed in feet above a calculated flood level, that compensates for unknown factors contributing to flood heights greater than the calculated height, including, but not limited to, ice jams, debris accumulations, wave actions, obstructions of bridge openings and floodways, the effects of urbanization on the hydrology of a watershed, loss of flood storage due to development and sedimentation of a watercourse bed;

(8) "Proposed state action" means individual activities or a sequence of planned activities proposed to be undertaken by a state department, institution or agency, any state or federal grant or loan proposed to be used to fund a project that affects land use, or proposed transfer of real property belonging to the state.

Sec. 13. Subsection (h) of section 25-68d of the 2018 supplement to the general statutes is repealed and the following is substituted in lieu thereof (*Effective from passage*):

(h) The provisions of subsections (a) to (d), inclusive, and (f) and (g) of this section shall not apply to the following critical activities above [the one-hundred-year flood elevation] base flood that involve state funded housing reconstruction, rehabilitation or renovation, provided the state agency that provides funding for such activity certifies that it complies with the provisions of the National Flood Insurance Program and the requirements of this subsection: (1) Projects involving the renovation or rehabilitation of existing housing on the Department of Housing's most recent affordable housing appeals list; (2) construction of minor structures to an existing building for the purpose of providing accessibility to persons with disabilities pursuant to the State Building Code; (3) construction of open decks attached to residential structures, properly anchored in accordance with the State Building Code; (4) the demolition and reconstruction of existing housing for persons and families of low and moderate income, provided there is no increase in the number of dwelling units and (A) such reconstruction is limited to the footprint of the existing foundation of the building or buildings used for such purpose, or which could be used for such purpose subsequent to reconstruction, or (B) such reconstruction is on a parcel of land where the elevation of such land is above the one-hundred-year flood elevation, provided there is no placement of fill within an adopted Federal Emergency Management Agency flood zone.

Sec. 14. Section 25-68o of the general statutes is repealed and the following is substituted in lieu thereof (*Effective from passage*):

(a) On and after October 1, [2013] 2019, in the preparation of any municipal evacuation plan or hazard mitigation plan, such municipality shall consider [sea level change scenarios published by the National Oceanic and Atmospheric Administration in Technical Report OAR CPO-1] the most recent sea level change scenario updated pursuant to subsection (b) of this section.

(b) Within available resources and not less than once every ten years, the Marine Sciences Division of The University of Connecticut shall update the sea level change scenarios published by the National Oceanic and Atmospheric Administration in Technical Report OAR CPO-1. Within available resources and not less than ninety days prior to any update of such sea level change scenarios by said Marine Sciences Division, the division shall conduct not less than one public hearing concerning such update. <u>Not later than sixty days after the last public hearing conducted by the Marine Sciences Division on any such update, the Commissioner of Energy and Environmental Protection shall post such update on the Internet web site of the Department of Energy and Environmental Protection along with a notice that any previous updates are superseded.</u>

Sec. 15. Subsection (g) of section 28-5 of the general statutes is repealed and the following is substituted in lieu thereof (*Effective from passage*):

(g) On and after October 1, **[**2013**]** <u>2019</u>, the state civil preparedness plan and program established pursuant to subsection (b) of this section shall consider **[**sea level change scenarios published by the National Oceanic and Atmospheric Administration in Technical Report OAR CPO-1**]** <u>the most recent sea level change scenario updated pursuant to subsection (b) of section 25-68o, as amended by this act</u>.

Sec. 16. (NEW) (*Effective from passage*) (a) There is established a Connecticut Council on Climate Change that shall facilitate and coordinate efforts among state agencies, businesses, municipalities and nongovernmental organizations to reduce greenhouse gas emissions and make Connecticut more resilient to the effects of climate change.

(b) The Connecticut Council on Climate Change shall:

(1) Meet not less than biannually;

(2) Monitor climate change science and the state's progress in meeting the greenhouse gas reduction requirements established in

section 22a-200a of the general statutes, as amended by this act;

(3) Review existing state and municipal policies, statutes, ordinances and regulations, as applicable, and recommend emission reduction measures to meet state-wide greenhouse gas reduction requirements established in section 22a-200a of the general statutes, as amended by this act, in a manner that minimizes costs and maximizes benefits for Connecticut's economy, improves and modernizes Connecticut's energy infrastructure, maintains electric system reliability and complements the state's efforts to improve air quality;

(4) For each agency that is represented on the Connecticut Council on Climate Change:

(A) Include in any agency planning strategies, measures to support the greenhouse gas reduction requirements established in section 22a-200a of the general statutes, as amended by this act; and

(B) Report annually to the Connecticut Council on Climate Change on its progress in implementing measures to support the greenhouse gas reduction requirements established in section 22a-200a of the general statutes, as amended by this act; and

(5) Report any findings and recommendations made pursuant to this section to the Governor and the joint standing committees of the General Assembly having cognizance of matters relating to the environment, energy and technology and transportation not later than October 1, 2020, and biennially thereafter.

(c) The Department of Energy and Environmental Protection and the Office of Policy and Management shall coordinate the Connecticut Council on Climate Change, which shall consist of the following members: (1) The Secretary of the Office of Policy and Management, or the secretary's designee, who shall serve as cochairperson, (2) the Commissioner of Energy and Environmental Protection, or the commissioner's designee, who shall serve as cochairperson, (3) the chairperson of the Public Utilities Regulatory Authority, or the chairperson's designee, (4) the Commissioner of Economic and Community Development, or the commissioner's designee, (5) the Commissioner of Administrative Services, or the commissioner's designee, (6) the Insurance Commissioner, or the commissioner's designee, (7) the Commissioner of Housing, or the commissioner's designee, (8) the Commissioner of Transportation, or the commissioner's designee, (9) the commissioner of any other state agency, as appointed by the Governor, (10) the president of the Connecticut Green Bank, (11) the Executive Director of the Connecticut Institute for Resilience and Climate Adaptation, (12) the Executive Director of the Connecticut Conference of Municipalities, (13) the Executive Director of the Connecticut Council of Small Towns, and (14) any other individual who represents business and industry, a nongovernmental organization, or a local government, as appointed by the Governor.

(d) All appointed members of the Connecticut Council on Climate Change shall serve a two-year term from May first in the year in which such members are appointed or until a successor is appointed. All appointed members shall serve at the pleasure of the Governor.

Sec. 17. Subsection (m) of section 16-2 of the general statutes is repealed and the following is substituted in lieu thereof (*Effective from passage*):

(m) Notwithstanding any provision of the general statutes, the decisions of the Public Utilities Regulatory Authority, including, but not limited to, decisions relating to rate amendments arising from the Comprehensive <u>Climate and</u> Energy Strategy, the Integrated Resources Plan, the Conservation and Load Management Plan and policies established by the Department of Energy and Environmental Protection, shall be guided by said strategy and plans and such policies.

Sec. 18. Subsections (b) and (c) of section 16-19e of the general statutes are repealed and the following is substituted in lieu thereof (*Effective from passage*):

(b) The Public Utilities Regulatory Authority shall promptly undertake a separate, general investigation of, and shall hold at least one public hearing on new pricing principles and rate structures for electric distribution companies and for gas companies to consider, without limitation, long run incremental cost of marginal cost pricing, peak load or time of day pricing and proposals for optimizing the utilization of energy and restraining its wasteful use and encouraging energy conservation, and any other matter with respect to pricing principles and rate structures as the authority shall deem appropriate. The authority shall determine whether existing or future rate structures place an undue burden upon those persons of poverty status and shall make such adjustment in the rate structure as is necessary or desirable to take account of their indigency. The authority shall require the utilization of such new principles and structures to the extent that the authority determines that their implementation is in the public interest, as identified by the Department of Energy and Environmental Protection in the Integrated Resources Plan and the Comprehensive <u>Climate and</u> Energy Strategy, and necessary or desirable to accomplish the purposes of this provision without being unfair or discriminatory or unduly burdensome or disruptive to any group or class of customers, and determines that such principles and structures are capable of yielding required revenues. In reviewing the rates and rate structures of electric and gas companies, the authority shall be guided by the goals of the Department of Energy and Environmental Protection, as described in section 22a-2d, the Comprehensive <u>Climate and</u> Energy Strategy, the Integrated Resources Plan and the Conservation and Load Management Plan. The authority shall issue its initial findings on such investigation by December 1, 1976, and its final findings and order by June 1, 1977; provided that after such final findings and order are issued, the authority shall at least once every two years undertake such further investigations as it deems appropriate with respect to new developments or desirable modifications in pricing principles and rate structures and, after holding at least one public hearing thereon, shall issue its findings and order thereon.

(c) The Department of Energy and Environmental Protection shall coordinate and integrate its actions, decisions and policies pertaining to gas and electric distribution companies, so far as possible, with the actions, decisions and policies of other agencies and instrumentalities in order to further the development and optimum use of the state's energy resources and conform to the greatest practicable extent with the state energy policy as stated in section 16a-35k, the Comprehensive <u>Climate and</u> Energy Strategy and the Integrated Resources Plan taking into account prudent management of the natural environment and continued promotion of economic development within the state. The department shall defer, as appropriate, to any actions taken by other agencies and instrumentalities on matters within their respective jurisdictions.

Sec. 19. Subsection (a) of section 16-19ff of the general statutes is repealed and the following is substituted in lieu thereof (*Effective from passage*):

(a) Notwithstanding any provisions of the general statutes to the contrary, each electric distribution company shall allow the installation of submeters at (1) a recreational campground, (2) individual slips at marinas for metering the electric use by individual boat owners, (3) commercial, industrial, multifamily residential or multiuse buildings where the electric power or thermal energy is provided by a Class I renewable energy source, as defined in section 16-1, or a combined heat and power system, as defined in section 16-1, or (4) in any other location as approved by the authority where submetering promotes the state's energy goals, as described in the Comprehensive <u>Climate and</u> Energy Strategy, while protecting consumers against termination of residential utility service or other related issues. Each entity approved to submeter by the Public Utilities Regulatory Authority, pursuant to subsection (c) of this section, shall provide electricity to any allowed facility, as described in this subsection, at a rate no greater than the rate charged to that customer class for the service territory in which such allowed facility is located, provided nothing in this section shall permit such entity to charge a submetered account for (A) usage for any common areas of a commercial, industrial or multifamily residential building, or (B) other usage not solely for use by such account.

Sec. 20. Section 16-244y of the 2018 supplement to the general statutes is repealed and the following is substituted in lieu thereof (*Effective from passage*):

An electric distribution company may submit to the Public Utilities Regulatory Authority for approval one or more plans to acquire new fuel cell electricity generation that began operation on or after July 1, 2017. Any such plan shall utilize a competitive process for the purpose of providing distribution system benefits, including, but not limited to, avoiding or deferring distribution capacity upgrades, and enhancing distribution system reliability, including, but not limited to, voltage or frequency improvements. Any such plan shall give preference to proposals that make efficient use of existing sites and supply infrastructure. In the event that the authority approves such plan, an electric distribution company may submit to the authority (1) one or more proposals to build, own and operate new fuel cell generation, (2) proposed power purchase agreements negotiated with persons to build, own and operate new fuel cell generation, or (3) proposals to provide financial incentives for the installation of combined heat and power systems powered by fuel cells, provided any such incentives shall be consistent with the Comprehensive Climate and Energy Strategy pursuant to section 16a-3d, as amended by this act. The facilities acquired, built pursuant to said power purchase agreements and that receive said financial incentives under this section shall not exceed a total nameplate capacity rating of thirty megawatts in the aggregate. Any proposal submitted by an electric distribution company to build, own and operate a fuel cell shall include the electric distribution company's full projected costs and shall demonstrate to the authority that such facility is not supported in any form of cross subsidization by affiliated entities. The authority shall evaluate any proposal submitted pursuant to this section in a manner that is consistent with the principles of sections 16-19 and 16-19e<u>, as amended by this act,</u> and may approve one or more proposals if it finds that such proposal (A) was developed in a manner that is consistent with the acquisition plan approved by the authority, (B) serves the long-term interests of ratepayers, and (C) cost-effectively avoids or defers distribution system costs. The costs incurred by an electric distribution company under this section shall be recovered from all customers of the electric distribution company through a fully reconciling component of electric rates for all customers of the electric distribution company, until the electric distribution company's next rate case, at which time any costs and investments for new fuel cell generation owned by the electric distribution company pursuant to subdivision (1) of this section shall be recoverable through base distribution rates. Nothing in this section shall preclude the resale or other disposition of any energy products, capacity and associated environmental attributes purchased by the electric distribution company, provided the electric distribution company shall net the cost of payments made to projects under any long-term contracts entered into pursuant to subdivision (2) of this section against the proceeds of the sale of any energy products, capacity and environmental attributes and the difference thereof plus any net costs incurred pursuant to subdivision (3) of this section shall be credited or charged to distribution customers through a reconciling component of electric rates, as determined by the authority, that is nonbypassable when switching electric suppliers. The electric distribution company may use any energy products, capacity and environmental attributes produced by such facility to meet the needs of customers served pursuant to section 16-244c. Notwithstanding the provisions of subdivision (1) of subsection (h) of section 16-244c, certificates issued by the New England Power Pool Generation Information System for any Class I renewable energy source acquired pursuant to this section may be retained by the electric distribution company to meet the requirements of section 16-245a.

Sec. 21. Subsection (a) of section 16-258e of the 2018 supplement to the general statutes is repealed and the following is substituted in lieu thereof (*Effective from passage*):

(a) In furtherance of the Comprehensive Climate and Energy Strategy established pursuant to section 16a-3d, as amended by this act, relating to the evaluation of district heating and thermal loops in high-density areas, on or before January 1, 2018, an electric distribution company serving customers located in a distressed municipality, as defined in section 32-9p, that has a population in excess of one hundred twenty-seven thousand, shall conduct a procurement for electricity and renewable energy credits from a combined heat and power system located in such municipality that (1) has a nameplate capacity of not more than ten megawatts, (2) is in a configuration that is compatible for use with a district heating system, as defined in section 16-258, (3) is owned by a thermal energy transportation company, and (4) may include fuel cells. Such combined heat and power system shall be (A) procured by a thermal energy transportation company through a competitive bidding process, (B) in a configuration compatible for use with a district heating system, and (C) installed at a location that will maximize the efficient use of the thermal energy from the combined heat and power system by a thermal energy transportation company. The thermal energy produced by such combined heat and power system shall be subject to firm customer commitments to subscribe to thermal energy services from such thermal energy transportation company, as demonstrated by such thermal energy transportation company, for the term of the power purchase agreement entered into pursuant to this section. After reviewing any proposals submitted in response to such procurement, the electric distribution company may enter into a power purchase agreement with a thermal energy distribution company for the purchase of electricity and renewable energy credits for a period of not more than twenty years.

Sec. 22. Section 16a-3f of the general statutes is repealed and the following is substituted in lieu thereof (*Effective from passage*):

On or after January 1, 2013, the Commissioner of Energy and Environmental Protection, in consultation with the procurement manager identified in subsection (l) of section 16-2, the Office of Consumer Counsel and the Attorney General, shall, in coordination with other states in the region of the regional independent system operator, as defined in section 16-1, or on the commissioner's own, solicit proposals, in one solicitation or multiple solicitations, from providers of Class I renewable energy sources, as defined in section 16-1, constructed on or after January 1, 2013. If the commissioner finds such proposals to be in the interest of ratepayers including, but not limited to, the delivered price of such sources, and consistent with the requirements to reduce greenhouse gas emissions in accordance with section 22a-200a, as amended by this act, and in accordance with the policy goals outlined in the Comprehensive Climate and Energy Strategy, adopted pursuant to section 16a-3d, as amended by this act, the commissioner may select proposals from such resources to meet up to four per cent of the load distributed by the state's electric distribution companies. The commissioner may direct the electric distribution companies to enter into power purchase agreements for energy, capacity and environmental attributes, or any combination thereof, for periods of not more than twenty years. Certificates issued by the New England Power Pool Generation Information System for any Class I renewable energy sources procured under this section shall be sold in the New England Power Pool Generation Information System renewable energy credit market to be used by any electric supplier or electric distribution company to meet the requirements of section 16-245a. Any such agreement shall be subject to review and approval by the Public Utilities Regulatory Authority, which review shall commence upon the filing of the signed power purchase agreement with the authority. The authority shall issue a decision on such agreement not later than thirty days after such filing. In the event the authority does not issue a decision within thirty days after such agreement is filed with the authority, the agreement shall be deemed approved. The net costs of any such agreement, including costs incurred by the electric distribution companies under the agreement and reasonable costs incurred by the electric distribution companies in connection with the agreement, shall be recovered through a fully reconciling component of electric rates for all customers of electric distribution companies.

Sec. 23. Section 16a-3g of the general statutes is repealed and the following is substituted in lieu thereof (*Effective from passage*):

On or after July 1, 2013, the Commissioner of Energy and Environmental Protection, in consultation with the procurement manager identified in subsection (l) of section 16-2, the Office of Consumer Counsel and the Attorney General, may, in coordination with other states in the region of the regional independent system operator, as defined in section 16-1, or on the commissioner's own, solicit proposals, in one solicitation or multiple solicitations, from providers of Class I renewable energy sources, as defined in section 16-1, or verifiable large-scale hydropower, as defined in section 16-1. If the commissioner finds such proposals to be in the interest of ratepayers, including, but not limited to, the delivered price of such sources, and consistent with the requirements to reduce greenhouse gas emissions in accordance with section 22a-200a, as amended by this act, and in accordance with the policy goals outlined in the Comprehensive Climate and Energy Strategy, adopted pursuant to section 16a-3d, as amended by this act, and section 129 of public act 11-80, including, but not limited to, base load capacity, peak load shaving and promotion of wind, solar and other renewable and low carbon energy technologies, the commissioner may select proposals from such resources to meet up to five per cent of the load distributed by the state's electric distribution companies. The commissioner may on behalf of all customers of electric distribution companies, direct the electric distribution companies to enter into power purchase agreements for energy, capacity and any environmental attributes, or any combination thereof, for periods of not more than (1) fifteen years, if any such agreement is with a provider of verifiable large-scale hydropower, or (2) twenty years, if any such agreement is with a provider of a Class I renewable energy source. Certificates issued by the New England Power Pool Generation Information System for any Class I renewable energy sources procured under this section shall be sold in the New England Power Pool Generation Information System renewable energy credit market to be used by any electric supplier or electric distribution company to meet the requirements of section 16-245a. Any such agreement shall be subject to review and approval by the Public Utilities Regulatory Authority, which review shall (A) include a public hearing, and (B) be completed not later than sixty days after the date on which such agreement is filed with the authority. The net costs of any such agreement, including costs incurred by the electric distribution companies under the agreement and reasonable costs incurred by the electric distribution companies in connection with the agreement, shall be recovered through a fully reconciling component of electric rates for all customers of electric distribution companies.

Sec. 24. Section 16a-3h of the 2018 supplement to the general statutes is repealed and the following is substituted in lieu thereof (*Effective from passage*):

On or after October 1, 2013, the Commissioner of Energy and Environmental Protection, in consultation with the procurement manager identified in subsection (l) of section 16-2, the Office of Consumer Counsel and the Attorney General, may solicit proposals, in one solicitation or multiple solicitations, from providers of the following resources or any combination of the following resources:

Run-of-the-river hydropower, landfill methane gas, biomass, fuel cell, offshore wind or anaerobic digestion, provided such source meets the definition of a Class I renewable energy source pursuant to section 16-1, or energy storage systems. In making any selection of such proposals, the commissioner shall consider factors, including, but not limited to (1) whether the proposal is in the interest of ratepayers, including, but not limited to, the delivered price of such sources, (2) the emissions profile of a relevant facility, (3) any investments made by a relevant facility to improve the emissions profile of such facility, (4) the length of time a relevant facility has received renewable energy credits, (5) any positive impacts on the state's economic development, (6) whether the proposal is consistent with requirements to reduce greenhouse gas emissions in accordance with section 22a-200a, as amended by this act, including, but not limited to, the development of combined heat and power systems, (7) whether the proposal is consistent with the policy goals outlined in the Comprehensive Climate and Energy Strategy adopted pursuant to section 16a-3d, as amended by this act, (8) whether the proposal promotes electric distribution system reliability and other electric distribution system benefits, including, but not limited to, microgrids, (9) whether the proposal promotes the policy goals outlined in the state-wide solid waste management plan developed pursuant to section 22a-241a, and (10) the positive reuse of sites with limited development opportunities, including, but not limited to, brownfields or landfills, as identified by the commissioner in any solicitation issued pursuant to this section. The commissioner may select proposals from such resources to meet up to four per cent of the load distributed by the state's electric distribution companies, provided the commissioner shall not select proposals for more than three per cent of the load distributed by the state's electric distribution companies from offshore wind resources. The commissioner may direct the electric distribution companies to enter into power purchase agreements for energy, capacity and environmental attributes, or any combination thereof, for periods of not more than twenty years on behalf of all customers of the state's electric distribution companies. Certificates issued by the New England Power Pool Generation Information System for any Class I renewable energy sources procured under this section may be: (A) Sold in the New England Power Pool Generation Information System renewable energy credit market to be used by any electric supplier or electric distribution company to meet the requirements of section 16-245a, provided the revenues from such sale are credited to all customers of the contracting electric distribution company; or (B) retained by the electric distribution company to meet the requirements of section 16-245a. In considering whether to sell or retain such certificates, the company shall select the option that is in the best interest of such company's ratepayers. Any such agreement shall be subject to review and approval by the Public Utilities Regulatory Authority, which review shall be completed not later than sixty days after the date on which such agreement is filed with the authority. The net costs of any such agreement, including costs incurred by the electric distribution companies under the agreement and reasonable costs incurred by the electric distribution companies in connection with the agreement, shall be recovered through a fully reconciling component of electric rates for all customers of electric distribution companies. All reasonable costs incurred by the Department of Energy and Environmental Protection associated with the commissioner's solicitation and review of proposals pursuant to this section shall be recoverable through the nonbypassable federally mandated congestion charges, as defined in section 16-1.

Sec. 25. Subsection (d) of section 16a-3i of the general statutes is repealed and the following is substituted in lieu thereof (*Effective from passage*):

(d) In the event there is such a presumption pursuant to subsection (a) of this section and the commissioner finds a material shortage of Class I renewable energy sources pursuant to subsection (b) of this section, and in addition to determining the adequacy pursuant to subsection (c) of this section, the commissioner shall, in consultation with the procurement manager identified in subsection (l) of section 16-2, the Office of Consumer Counsel and the Attorney General, solicit proposals from providers of Class I renewable energy sources, as defined in section 16-1, operational as of the date that such solicitation is issued. If the commissioner, in consultation with the procurement manager identified in subsection (l) of section 16-2, finds such proposals to be in the interest of ratepayers including, but not limited to, the delivered price of such sources, and consistent with the requirements to reduce greenhouse gas emissions in accordance with section 22a-200a, <u>as amended by this act,</u> and in accordance with the policy goals outlined in the Comprehensive <u>Climate and</u> Energy Strategy, adopted pursuant to section 16a-3d, <u>as amended by this act,</u> the commissioner, in consultation with the procurement manager identified in subsection (l) of section 16-2, may select proposals from such sources to meet up to the amount necessary to ensure an adequate incremental supply of Class I renewable energy sources to rectify any projected shortage of Class I renewable energy supply identified pursuant to subsection (c) of this section. The commissioner shall direct the electric distribution companies to enter into power purchase agreements for energy, capacity and environmental attributes, or any combination thereof, from such selected proposals for periods of not more than ten years. Certificates issued by the New England Power Pool Generation Information System for any Class I renewable energy sources procured under this section shall be sold in the New England Power Pool Generation Information System renewable energy credit market to be used by any electric supplier or electric distribution company to meet the requirements of section 16-245a. Any such agreement shall be subject to review and approval by the Public Utilities Regulatory Authority, which review shall commence upon the filing of the signed power purchase agreement with the authority. The authority shall issue a decision on such agreement not later than thirty days after such filing. In the event the authority does not issue a decision within thirty days after such agreement is filed with the authority, the agreement shall be deemed approved. The net costs of any such agreement, including costs incurred by the electric distribution companies under the agreement and reasonable costs incurred by the electric distribution companies in connection with the agreement, shall be recovered through a fully reconciling component of electric rates for all customers of electric distribution companies.

Sec. 26. Subsection (a) of section 16a-3j of the general statutes is repealed and the following is substituted in lieu thereof (*Effective from passage*):

(a) In order to secure cost-effective resources to provide more reliable electric service for the benefit of the state's electric ratepayers and to meet the state's energy and environmental goals and policies established in the Integrated Resources Plan, pursuant to section 16a-3a, as amended by this act, and the Comprehensive Climate and Energy Strategy, pursuant to section 16a-3d, as amended by this act, the Commissioner of Energy and Environmental Protection, in consultation with the procurement manager identified in subsection (l) of section 16-2, the Office of Consumer Counsel and the Attorney General, may, in coordination with other states in the control area of the regional independent system operator, as defined in section 16-1, or on behalf of Connecticut alone, issue multiple solicitations for long-term contracts from providers of resources described in subsections (b), (c) and (d) of this section.

Sec. 27. Subsection (e) of section 16a-3j of the general statutes is repealed and the following is substituted in lieu thereof (*Effective from passage*):

(e) The Commissioner of Energy and Environmental Protection, in consultation with the procurement manager identified in subsection (l) of section 16-2, the Office of Consumer Counsel and the Attorney General, shall evaluate project proposals received under any solicitation issued pursuant to subsection (b), (c) or (d) of this section, based on factors including, but not limited to, (1) improvements to the reliability of the electric system, including during winter peak demand; (2) whether the benefits of the proposal outweigh the costs to ratepayers; (3) fuel diversity; (4) the extent to which the proposal contributes to meeting the requirements to reduce greenhouse gas emissions and improve air quality in accordance with sections 16-245a, 22a-174 **[**,**]** and 22a-200a, as amended by this act; (5) whether the proposal is in the best interest of ratepayers; and (6) whether the proposal is aligned with the policy goals outlined in the Integrated Resources Plan, pursuant to section 16a-3a, as amended by this act, and the Comprehensive Climate and Energy Strategy, pursuant to section 16a-3d, as amended by this act, including, but not limited to, environmental impacts. In conducting such evaluation, the commissioner may also consider the extent to which project proposals provide economic benefits for the state. In evaluating project proposals received under any solicitation issued pursuant to subsection (b), (c) or (d) of this section, the commissioner shall compare the costs and benefits of such proposals relative to the expected or actual costs and benefits of other resources eligible to respond to the other procurements authorized pursuant to this section.

Sec. 28. Subsection (a) of section 16a-3m of the 2018 supplement to the general statutes is repealed and the following is substituted in lieu thereof (*Effective from passage*):

(a) For the purposes of this section:

(1) "Best interest of ratepayers" means the benefits of a contract or proposal outweigh the costs to electric ratepayers, based on whether the delivered prices of sources included in such contract or proposal are less than the forecasted price of energy and capacity, as determined by the commissioner or the commissioner's designee, and based on a consideration of the following factors, as determined by the commissioner or the commissioner's designee: (A) Impacts on electric system operations and reliability; (B) the extent to which such contract

or proposal will contribute to (i) the local sourcing requirement set by the regional independent system operator, as defined in section 16-1, and (ii) meeting the requirements to reduce greenhouse gas emissions and improve air quality in accordance with sections 16-245a, 22a-174 and 22a-200a, as amended by this act; (C) fuel diversity; and (D) whether the proposal is aligned with the policy goals outlined in the Integrated Resources Plan developed pursuant to section 16a-3a, as amended by this act, and the Comprehensive Climate and Energy Strategy developed pursuant to section 16a-3d, as amended by this act, including, but not limited to, environmental impacts; and

(2) "Eligible nuclear power generating facility" means a nuclear power generating facility that is located in the control area of the regional independent system operator, as defined in section 16-1, and is licensed to operate through January 1, 2030, or later.

Sec. 29. Subsections (b) and (c) of section 22a-200a of the general statutes are repealed and the following is substituted in lieu thereof (*Effective from passage*):

(b) On or before January 1, 2010, and biannually thereafter, the state agencies that are members of the **[**Governor's Steering Committee**]** Connecticut Council on Climate Change shall submit a report to the Secretary of the Office of Policy and Management and the Commissioner of Energy and Environmental Protection. The report shall identify existing and proposed activities and improvements to the facilities of such agencies that are designed to meet state agency energy savings goals established by the Governor. The report shall also identify policies and regulations that could be adopted in the near future by such agencies to reduce greenhouse gas emissions in accordance with subsection (a) of this section.

(c) Not later than January 1, 2012, and every three years thereafter, the Commissioner of Energy and Environmental Protection shall, in consultation with the Secretary of the Office of Policy and

Management and the **[**Governor's Steering Committee**]** Connecticut Council on Climate Change, report, in accordance with the provisions of section 11-4a, to the joint standing committees of the General Assembly having cognizance of matters relating to the environment, energy and transportation on the quantifiable emissions reductions achieved pursuant to subsection (a) of this section. The report shall include a schedule of proposed regulations, policies and strategies designed to achieve the limits of greenhouse gas emissions imposed by said subsection, an assessment of the latest scientific information and relevant data regarding global climate change and the status of greenhouse gas emission reduction efforts in other states and countries.

Sec. 30. Section 22a-200e of the general statutes is repealed. (*Effective from passage*)

This act shall take effect as follows and shall amend the following sections:		
Section 1	*from passage*	8-23(d)
Sec. 2	*from passage*	16a-3a(a)
Sec. 3	*from passage*	16a-3d
Sec. 4	*from passage*	16a-3e
Sec. 5	*from passage*	16a-27(h)
Sec. 6	*from passage*	22a-92(a)
Sec. 7	*from passage*	22a-93(7)
Sec. 8	*from passage*	22a-93(19)
Sec. 9	*from passage*	22a-94
Sec. 10	*from passage*	22a-200a(a)
Sec. 11	*from passage*	22a-478(a)
Sec. 12	*from passage*	25-68b
Sec. 13	*from passage*	25-68d(h)
Sec. 14	*from passage*	25-68o
Sec. 15	*from passage*	28-5(g)
Sec. 16	*from passage*	New section
Sec. 17	*from passage*	16-2(m)
Sec. 18	*from passage*	16-19e(b) and (c)
Sec. 19	*from passage*	16-19ff(a)

Sec. 20	*from passage*	16-244y
Sec. 21	*from passage*	16-258e(a)
Sec. 22	*from passage*	16a-3f
Sec. 23	*from passage*	16a-3g
Sec. 24	*from passage*	16a-3h
Sec. 25	*from passage*	16a-3i(d)
Sec. 26	*from passage*	16a-3j(a)
Sec. 27	*from passage*	16a-3j(e)
Sec. 28	*from passage*	16a-3m(a)
Sec. 29	*from passage*	22a-200a(b) and (c)
Sec. 30	*from passage*	Repealer section

Statement of Purpose:
To implement the Governor's budget recommendations.

[Proposed deletions are enclosed in brackets. Proposed additions are indicated by underline, except that when the entire text of a bill or resolution or a section of a bill or resolution is new, it is not underlined.]

Senate Bill No. 7

Public Act No. 18-82

AN ACT CONCERNING CLIMATE CHANGE PLANNING AND RESILIENCY.

Be it enacted by the Senate and House of Representatives in General Assembly convened:

Section 1. Subsection (d) of section 8-23 of the 2018 supplement to the general statutes is repealed and the following is substituted in lieu thereof (*Effective from passage*):

(d) In preparing such plan, the commission or any special committee shall consider the following: (1) The community development action plan of the municipality, if any, (2) the need for affordable housing, (3) the need for protection of existing and potential public surface and ground drinking water supplies, (4) the use of cluster development and other development patterns to the extent consistent with soil types, terrain and infrastructure capacity within the municipality, (5) the state plan of conservation and development adopted pursuant to chapter 297, (6) the regional plan of conservation and development adopted pursuant to section 8-35a, (7) physical, social, economic and governmental conditions and trends, (8) the needs of the municipality including, but not limited to, human resources, education, health, housing, recreation, social services, public utilities, public protection, transportation and circulation and cultural and interpersonal communications, (9) the objectives of energy-efficient patterns of development, the use of solar and other renewable forms of energy and energy conservation, (10) protection and preservation of agriculture, (11) **[**sea level change scenarios published by the National Oceanic and Atmospheric Administration in Technical Report OAR CPO-1**]** the most recent sea level change scenario updated pursuant to subsection (b) of section 25-68o, as amended by this act, and (12) the need for technology infrastructure in the municipality.

Sec. 2. Subsection (a) of section 16a-3a of the general statutes is repealed and the following is substituted in lieu thereof (*Effective from passage*):

(a) The Commissioner of Energy and Environmental Protection, in consultation with the electric distribution companies, shall review the state's energy and capacity resource assessment and approve the Integrated Resources Plan for the procurement of energy resources, including, but not limited to, conventional and renewable generating facilities, energy efficiency, load management, demand response, combined heat and power facilities, distributed generation and other emerging energy technologies to meet the projected requirements of customers in a manner that minimizes the cost of all energy resources to customers over time and maximizes consumer benefits consistent with the state's environmental goals and standards, including, but not limited to, the state's greenhouse gas reduction goals established in section 22a-200a, as amended by this act. The Integrated Resources Plan shall seek to lower the cost of electricity while meeting such environmental goals and standards in the most cost-effective manner.

Sec. 3. Subsection (a) of section 16a-3d of the general statutes is repealed and the following is substituted in lieu thereof (*Effective from passage*):

(a) On or before October 1, **[**2016**]** 2020, and every **[**three**]** four years thereafter, the Commissioner of Energy and Environmental Protection shall prepare a Comprehensive Energy Strategy. Said strategy shall reflect the legislative findings and policy stated in section 16a-35k, [and shall] provide any analysis and recommendations necessary to guide the state's energy policy to meet greenhouse gas emission reduction requirements, as established in section 22a-200a, as amended by this act, in the most cost-effective manner and incorporate (1) an assessment and plan for all energy needs in the state, including, but not limited to, electricity, heating, cooling, and transportation, (2) the findings of the Integrated Resources Plan, (3) the findings of the plan for energy efficiency adopted pursuant to section 16-245m, (4) the findings of the plan for renewable energy adopted pursuant to section 16-245n, and (5) the Energy Assurance Plan developed for the state of Connecticut pursuant to the American Recovery and Reinvestment Act of 2009, P.L. 111-5, or any successor Energy Assurance Plan developed within a reasonable time prior to the preparation of any Comprehensive Energy Strategy. Said strategy shall further include, but not be limited to, (A) an assessment of current energy supplies, demand and costs, (B) identification and evaluation of the factors likely to affect future energy supplies, demand and costs, (C) a statement of progress made toward achieving the goals and milestones set in the preceding Comprehensive Energy Strategy, (D) a statement of energy policies and long-range energy planning objectives and strategies appropriate to achieve, [among other things] the state's greenhouse gas reduction goals established in section 22a-200a, as amended by this act, a sound economy, the least-cost mix of energy supply sources to meet said goals and measures that reduce demand for energy, giving due regard to such factors as consumer price impacts, security and diversity of fuel supplies and energy generating methods, protection of public health and safety, environmental goals and standards, conservation of energy and energy resources and the ability of the state to compete economically, (E) recommendations for administrative and legislative actions to implement such policies, objectives and strategies, (F) an assessment of the potential costs savings and benefits to ratepayers, including, but not limited to, carbon dioxide emissions reductions or voluntary joint ventures to repower some or all of the state's coal-fired and oil-fired generation facilities built before 1990, **[**and**]** (G) the benefits, costs, obstacles and solutions related to the expansion and use and availability of natural gas in Connecticut, and (H) a strategy for ensuring the state's energy efficiency goals are met. **[**If the department finds that such expansion is in the public interest, it shall develop a plan to increase the use and availability of natural gas.**]**

Sec. 4. Section 16a-3e of the general statutes is repealed and the following is substituted in lieu thereof (*Effective from passage*):

The Integrated Resources Plan, as described in section 16a-3a, as amended by this act, shall (1) indicate specific options to reduce electric rates and costs while achieving the state's greenhouse gas emission reduction requirements established in section 22a-200a, as amended by this act. Such options may include the procurement of new sources of generation. In the review of new sources of generation, the Integrated Resources Plan shall indicate whether the private wholesale market can supply such additional sources or whether state financial assistance, long-term purchasing of electricity contracts or other interventions are needed to achieve the goal; (2) analyze in-state renewable sources of electricity in comparison to transmission line upgrades or new projects and out-of-state renewable energy sources, provided such analysis also considers the benefits of additional jobs and other economic impacts and how they are created and subsidized; (3) include an examination of average consumption and other states' best practices to determine why electricity rates are lower elsewhere in the region; (4) assess and compare the cost of transmission line projects, new power sources, renewable sources of electricity, conservation and distributed generation projects to ensure the state pursues only the least-cost alternative projects; (5) analyze the potential for electric vehicles, as defined in section 16-19eee, to provide energy storage and other services to the electric grid and identify strategies to ensure that the grid is prepared to support increased electric vehicle charging, based on projections of sales of electric vehicles; (6) continually monitor supply and distribution systems to identify potential need for transmission line projects early enough to identify alternatives; and (7) assess the least-cost alternative to address reliability concerns, including, but not limited to, lowering electricity demand through conservation and distributed generation projects before an electric distribution company submits a proposal for transmission lines or transmission line upgrades to the independent system operator or the Federal Energy Regulatory Commission, provided no provision of such plan shall be deemed to prohibit an electric distribution company from making any filing required by law or regulation.

Sec. 5. Subsection (h) of section 16a-27 of the general statutes is repealed and the following is substituted in lieu thereof (*Effective from passage*):

(h) Any revision made after October 1, **[**2013**]** 2019, shall (1) take into consideration risks associated with increased coastal flooding and erosion, depending on site topography, as anticipated in **[**sea level change scenarios published by the National Oceanic and Atmospheric Administration in Technical Report OAR CPO-1**]** the most recent sea level change scenario updated pursuant to subsection (b) of section 25-68o, as amended by this act, (2) identify the impacts of such increased flooding and erosion on infrastructure and natural resources, **[**and**]** (3) make recommendations for the siting of future infrastructure and property development to minimize the use of areas prone to such flooding and erosion, and (4) take into consideration the state's greenhouse gas reduction goals established pursuant to section 22a-200a, as amended by this act.

Sec. 6. Subdivision (19) of section 22a-93 of the general statutes is repealed and the following is substituted in lieu thereof (*Effective from passage*):

(19) "Rise in sea level" means the **[**arithmetic mean of the most recent equivalent per decade rise in the surface level of the tidal and coastal waters of the state, as documented in National Oceanic and Atmospheric Administration online or printed publications for said agency's Bridgeport and New London tide gauges**]** most recent sea level change scenario updated pursuant to subsection (b) of section 25-68o, as amended by this act.

Sec. 7. Subsection (a) of section 22a-200a of the general statutes is repealed and the following is substituted in lieu thereof (*Effective from passage*):

(a) The state shall reduce the level of emissions of greenhouse gas:

(1) Not later than January 1, 2020, to a level at least ten per cent below the level emitted in 1990; **[**and**]**

(2) Not later than January 1, 2030, to a level at least forty-five per cent below the level emitted in 2001; and

[(2)**]** (3) Not later than January 1, 2050, to a level at least eighty per cent below the level emitted in 2001.

[(3)**]** (4) All of the levels referenced in this subsection shall be determined by the Commissioner of Energy and Environmental Protection.

Sec. 8. Section 25-68b of the general statutes is repealed and the following is substituted in lieu thereof (*Effective from passage*):

As used in sections 25-68b to 25-68h, inclusive:

(1) "Activity" means any proposed state action in a floodplain or any proposed state action that impacts natural or man-made storm drainage facilities that are located on property that the commissioner determines to be controlled by the state;

(2) "Base flood" means that flood which has a one per cent chance of being equaled or exceeded in any year, as defined in regulations of the National Flood Insurance Program (44 CFR 59 et seq.), or that flood designated by the commissioner pursuant to section 25-68c. Any flood so designated by the commissioner shall have at least a one per cent chance of being equaled or exceeded in any year. Such flood may be designated as the A or V zones on maps published by the National Flood Insurance Program. The "base flood for a critical activity" means the flood that has at least a .2 per cent chance of being equaled or exceeded in any year. Such flood may be designated as the B zone on maps published for the National Flood Insurance Program;

(3) "Commissioner" means the Commissioner of Energy and Environmental Protection;

(4) "Critical activity" means any activity, including, but not limited to, the treatment, storage and disposal of hazardous waste and the siting of hospitals, housing for the elderly, schools or residences, in the .2 per cent floodplain in which the commissioner determines that a slight chance of flooding is too great;

(5) "Floodplain" means that area located within the real or theoretical limits of the base flood or base flood for a critical activity;

(6) "Flood-proofing" means any combination of structural or nonstructural additions, changes or adjustments which reduce or eliminate flood damage to real estate or improved real property, to water and sanitary facilities, and to structures and their contents, including, but not limited to, for properties within the coastal

boundary, as established pursuant to subsection (b) of section 22a-94, not less than an additional two feet of freeboard above base flood and any additional freeboard necessary to account for the most recent sea level change scenario updated pursuant to subsection (b) of section 25-68o, as amended by this act;

(7) "Freeboard" means a safety factor, expressed in feet above a calculated flood level, that compensates for unknown factors contributing to flood heights greater than the calculated height, including, but not limited to, ice jams, debris accumulations, wave actions, obstructions of bridge openings and floodways, the effects of urbanization on the hydrology of a watershed, loss of flood storage due to development and sedimentation of a watercourse bed;

(8) "Proposed state action" means individual activities or a sequence of planned activities proposed to be undertaken by a state department, institution or agency, any state or federal grant or loan proposed to be used to fund a project that affects land use, or proposed transfer of real property belonging to the state.

Sec. 9. Section 25-68o of the general statutes is repealed and the following is substituted in lieu thereof (*Effective from passage*):

(a) On and after October 1, **[**2013**]** 2019, in the preparation of any municipal evacuation plan or hazard mitigation plan, such municipality shall consider **[**sea level change scenarios published by the National Oceanic and Atmospheric Administration in Technical Report OAR CPO-1**]** the most recent sea level change scenario updated pursuant to subsection (b) of this section.

(b) Within available resources and not less than once every ten years, the Marine Sciences Division of The University of Connecticut shall **[**update**]** publish a sea level change scenario for the state based upon the sea level change scenarios published by the National Oceanic and Atmospheric Administration in Technical Report OAR CPO-1 and other available scientific data necessary to create a scenario applicable to the state coastline. Within available resources and not less than ninety days prior to **[**any update of**]** publishing such sea level change **[**scenarios**]** scenario by said Marine Sciences Division, the division and the Department of Energy and Environmental Protection shall conduct not less than one public hearing concerning such update. Not later than sixty days after the last public hearing, the Commissioner of Energy and Environmental Protection shall publish the sea level change scenario for the state on the Internet web site of the Department of Energy and Environmental Protection along with a notice that any previous updates are superseded.

Sec. 10. Subsection (g) of section 28-5 of the general statutes is repealed and the following is substituted in lieu thereof (*Effective from passage*):

(g) On and after October 1, **[**2013**]** 2019, the state civil preparedness plan and program established pursuant to subsection (b) of this section shall consider **[**sea level change scenarios published by the National Oceanic and Atmospheric Administration in Technical Report OAR CPO-1**]** the most recent sea level change scenario updated pursuant to subsection (b) of section 25-68o, as amended by this act.

Approved June 6, 2018

Testimony on 2018 Senate Bill Number 7

Joseph A. MacDougald
Executive Director
University of Connecticut Center for Energy & Environmental Law

Hello. My name is Joe MacDougald from the faculty of the University of Connecticut School of Law where I am Professor in Residence and the Executive Director for the Center for Energy & Environmental. It is my great privilege to come before you to support the Sea Level Rise legislation in S. B. 7.

For the last 18 months, our center, through our legal fellow Bill Rath , CIRCA Executive Director, Professor James O'Donnell and others, have worked to unpack some of the complex policy problems associated with the increased storm and flood risk that will impact Connecticut.

While I may be speaking to you, today, in my role as law professor, my experience is also colored by my nearly 20 years as an elected and appointed municipal official in Madison, a town seriously damaged by both Irene and Sandy.

Based on this and conversations CEEL and others have had over the last year I want to tell you a few things, which I believe should drive policy and argue for this bill's passage.

First – Our towns have enormous planning and legal authority – but they need help. Having a single, common definition of Sea Level Rise is critical. Your constituents are looking for specific guidance. They understand that different types of structures, power plants versus homes versus parks, will require different timeframes – but they are truly looking for a planning number as a starting point.

Second – The Federal Government's guidance is insufficient. So many towns are using the "FEMA line" or 100 year flood line as planning guidance. Yet this does not reflect the real world storm and flood experiences that will be affecting Connecticut. We actually see town's trying to adjust to the Connecticut risk on their own, but it is haphazard without state guidance.

Third – One of the most shocking policy implications of the CIRCA analysis is that the real world storm experience is going to change up and down our coast. The "100 year or 1%" storm will become a 4 times more likely near Greenwich but 8X more likely in near the Rhode Island line. Our law's are not set up for different threats. All towns have the same tools whether they are Stamford or Groton but they are about to get different realities. The CIRCA work provides guidance on this point to alert our towns that the risks are changing.

For too long our towns have been guessing at the threat. They need help.

I support SB 7 with one suggestion – 10 years is too long. The updates need to be more frequent.

But SB 7 is a great first step. It delivers a Connecticut specific, scientifically informed planning benchmark to be endorsed by statute. SB 7 will not solve our climate change based problems, but it is the beginning toward developing policies to preserve our coast, our towns, and our state.

Thank you.

Testimony on 2018 Senate Bill Number 7

William R. Rath
Legal Research Fellow
University of Connecticut Center for Energy & Environmental Law

My Name is Bill Rath. I am a Legal Research Fellow at the University of Connecticut School of Law Center for Energy & Environmental Law.. For the past 18 months I have studied and analyzed the legal and policy aspects of resilience planning in the face of sea level rise. Today I offer testimony on three issues associated with the sea level change provisions of S.B. 7.

Issue One: The Center for Energy & Environmental Law fully supports S.B. 7's intent to use the University of Connecticut sea level projections whenever sea level change is invoked by Connecticut Statutes.

Current Connecticut statutes invoke either historical tide gauge data or the 2012 NOAA global sea level change projections. Historical tide gauge data do not account for the effects of climate change, and the 2012 NOAA projections are global means that are not specific for any one location. In stark contrast, the UConn projections are specific to Long Island Sound. They reflect the unique geology, geography and bathymetry of the sound. They are informed by recent climate science. And, by statute, they are updated at least every ten years. For these reasons, the UConn projections provide the best available information on which to make important coastal management decisions, and it is wise for S.B. 7 to specify their use.

Issue Two: The Center for Energy & Environmental Law fully supports) S.B. 7's intent to require the consideration of sea level rise during coastal management decision-making and jurisdictional activities

Current Connecticut statutes require the consideration of sea level change during planning activities like the preparation of municipal plans of conservation and development. S,B. 7 expands the consideration of sea level rise to include coastal management decision activities, like approving coastal site plans, and to coastal management jurisdictional activities, like delineating coastal hazard areas. Considering sea level rise during these types of activities is an excellent coastal management practice, and brings Connecticut coastal management practices more in line with those used in our neighboring states of New York, Rhode Island and Massachusetts.

Issue Three: The Center for Energy & Environmental Law fully supports S.B. 7's intent to use a single, specific, time-referenced number whenever sea level change is invoked by Connecticut Statutes.

To be useful for decision-making and jurisdictional activities, the "sea level change scenario" invoked by S.B. 7 must be a single, specific, time-referenced value such as the "50 centimeters by 2050" planning value offered by Dr. James O'Donnell of CIRCA. But the 2012 NOAA scenarios upon which the UConn projections are based offer a near infinite number of values from four different scenarios that project out to the year 2100. For this reason, Section 14 of S.B. 7 must be carefully crafted to assure that there is statutory authority for the development and deployment of a single, specific, and time-referenced value to be invoked by statutes that address sea level change.

Thank you.

APPENDIX G2 - SECTION 5

TABULATION OF OCEANFRONT STATE COASTAL AND FLOODPLAIN MANAGEMENT DECISION AUTHORITY

Important: These are draft documents that describe coastal and floodplain management programs in place in seven states on May 31, 2017. This in an incomplete work that is included here to provide a template for future work of this nature. Refer to the body of the Task 9 report for additional information on this work.

CALIFORNIA COASTAL AND FLOODPLAIN MANAGEMENT DECISION AUTHORITY

(DRAFT - MAY 31, 2017)

Decision Item	Floodplain Management or Coastal Management	Legislative Decision Maker	Administrative Decision Maker	Admin. Decision Considers Sea Level Rise?[1]
Consistency with State Coastal Resource Policies	Coastal	Legislature, CCC, County, Municipality[2]	CCC, County, Municipality[3]	NAS[4]
Impact on Coastal Resources	Coastal	Legislature, CCC, County Municipality[2]	CCC, County Municipality[3]	NAS[4]
Impact on Future Water-Dependent Activities	Coastal	Legislature, CCC, County Municipality[2]	CCC, County Municipality[3]	NAS[4]
Public Access to Coastal Waters and Resources	Coastal	Legislature, CCC, County Municipality[2]	CCC, County Municipality[3]	NAS[4]
Armor	Coastal	Legislature, CCC, County Municipality[2]	CCC, County Municipality[3]	NAS[4]
Buildings, Structures	Coastal	Legislature, CCC, County Municipality[2]	CCC, County Municipality[3]	NAS[4]
Material Removal	Coastal	Legislature, CCC, County Municipality[2]	CCC, County Municipality[3]	NAS[4]
Material Deposition	Coastal	Legislature, CCC, County Municipality[2]	CCC, County Municipality[3]	NAS[4]
Dredging	Coastal	Legislature, CCC	CCC	NAS[4]
Change in Use	Coastal	Legislature, CCC, County Municipality[2]	CCC, County Municipality[3]	NAS[4]
Living Shoreline	Coastal	County, Municipality[5]	County, Municipality[5]	
Site Plans	Coastal	Legislature, CCC, County Municipality[2]	CCC, County Municipality[3]	NAS[4]
Site Plan Exemptions Variances	Coastal	Legislature, CCC, County Municipality[2]	CCC, County Municipality[3]	NAS[4]
Setback from Coastal Resources	Coastal	County, Municipality[5]	County, Municipality[5]	NAS[4]
Rolling Easements	Coastal	County, Municipality[5]	County, Municipality[5]	NAS[4]
Tidal Waters Construction Standards	Coastal	Legislature, CCC	CCC	NAS[4]
Floodplain Construction Standards[6]	Floodplain	Legislature, County, Municipality[7]	County, Municipality	NAS[4]
Floodplain Encroachment	Floodplain	Municipality	Municipality	NAS[4]
Floodway Encroachment	Floodplain	Municipality	Municipality	NAS[4]
Coastal Boundary Zoning Regulations	Coastal	Municipality	Municipality	NAS[4]

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[1] Consideration of sea level rise is "Required," "Allowed," or "NAS" (not addressed by the enabling state statute).

[2] Legislative decisions for coastal management of the public trust, state colleges and universities, and areas seaward of the mean high tide line take the form of statutes by the legislature or regulations by the California Coastal Commission (CCC). Legislative decisions for coastal management of other areas landward of the mean high tide line take the form of statutes by the legislature, regulations by the CCC, or, where a Local Coastal Program (LCP) has been approved by the CCC, a county or municipality. (Cal. Pub. Res. Code § 30519)

[3] The CCC makes coastal management administrative decisions for the public trust, state colleges and universities, and areas seaward of the mean high tide. Coastal management administrative decisions for other areas landward of the mean high tide line are made by the CCC, or, where a Local Coastal Program (LCP) has been approved by the CCC, a county or municipality. (Cal. Pub. Res. Code § 30519)

[4] There is no state statute or regulation that requires consideration of sea level rise. However, California Executive Order S-13-08 directs state agencies to consider sea level rise as part of planning projects and the California Coastal Commission Sea Level Rise Policy Guidance document (April 12, 2015) strongly encourages counties and municipalities to incorporate seal level rise into their LCPs.

[5] There is no state statute or regulation that either requires or prohibits counties or municipalities from considering this decision item when making decisions within the scope of their jurisdiction. CCC guidelines encourage incorporation of this decision item into county and municipal Local Coastal Programs and some have done so.

[6] Includes standards for materials, elevation, setbacks anchoring, hydraulic force resistance, breakaway walls, construction methods and certification by architects and engineers.

[7] California statutes require compliance with the California State Building Standards Code, which specifies the minimum standards for floodplain construction. Municipalities may impose more stringent requirements where allowed by the State Code.

Feasible Alternatives	Coastal	Legislature, CCC, County Municipality[2]	CCC, County Municipality[3]	NAS[4]
Adopted Local Comprehensive Plans	Coastal	Regional District, County, Municipality	N/A	NAS[4]
Adopted State Comprehensive Plan	Coastal	(None)[8]	- - - -	- - - -

[8] California does not have a comprehensive, state-wide land use plan.

CONNECTICUT COASTAL AND FLOODPLAIN MANAGEMENT DECISION AUTHORITY

(DRAFT - MAY 31, 2017)

Decision Item	Floodplain Management or Coastal Management	Legislative Decision Maker	Administrative Decision Maker	Admin. Decision Considers Sea Level Rise?[1]
Consistency with State Coastal Resource Policies	Coastal	CT Legislature, DEEP, Municipality[2]	DEEP, Municipality[3]	NAS
Impact on Coastal Resources[4]	Coastal	CT Legislature, DEEP, Municipality[2]	DEEP, Municipality[3]	NAS
Impact on Future Water-Dependent Activities[4]	Coastal	CT Legislature, DEEP, Municipality[2]	DEEP, Municipality[3]	NAS
Public Access to Coastal Waters and Resources	Coastal	CT Legislature, DEEP, Municipality[2]	DEEP, Municipality[3]	NAS
Armor	Coastal	CT Legislature, DEEP, Municipality[2]	DEEP, Municipality[3]	NAS
Buildings, Structures	Coastal	CT Legislature, DEEP, Municipality[2]	DEEP, Municipality[3]	NAS
Material Removal	Coastal	CT Legislature, DEEP, Municipality[2]	DEEP, Municipality[3]	NAS
Material Deposition	Coastal	CT Legislature, DEEP, Municipality[2]	DEEP, Municipality[3]	NAS
Dredging	Coastal	CT Legislature, DEEP	DEEP	NAS
Change in Use	Coastal	CT Legislature, DEEP, Municipality[2]	DEEP, Municipality[3]	NAS
Living Shoreline	Coastal	CT Legislature, DEEP, Municipality[2]	DEEP, Municipality[3]	NAS
Site Plans	Coastal	CT Legislature	Municipality[5]	NAS
Site Plan Exemptions	Coastal	Municipality[6]	Municipality	NAS
Setback from Coastal Resources	Coastal	Municipality	Municipality	NAS
Rolling Easements	Coastal	(None)[7]	- - -	- - -
Tidal Waters Construction Standards	Coastal	CT Legislature, DEEP[2]	DEEP	NAS
Floodplain Construction Standards[8]	Floodplain	CT Legislature, Municipality[9]	Municipality	NAS
Floodplain Encroachment	Floodplain	Municipality	Municipality	NAS
Floodway Encroachment	Floodplain	Municipality	Municipality	NAS
Coastal Boundary Zoning Regulations	Coastal	Municipality[6]	Municipality	NAS
Feasible Alternatives	Coastal	CT Legislature, DEEP, Municipality[2]	DEEP, Municipality[3]	NAS

[1] Consideration of sea level rise is "Required," "Allowed," or "NAS" (NAS = not addressed by the enabling state statute).

[2] Legislative decisions for coastal management of areas seaward of the Coastal Jurisdiction Line take the form of statutes by the legislature and regulations by the Department of Energy & Environmental Protection (DEEP). Legislative decisions for coastal management of areas landward of the mean high water mark take the form of statutes by the legislature and ordinances by shoreline municipalities. Municipal coastal management ordinances must effectuate the policies of the state Coastal Management Act and must be reviewed by the DEEP, but they are not subject to DEEP or state legislature approval (Conn. Gen. Stat. §§ 22a-101, 22a-102, 22a-103).

[3] DEEP is responsible for coastal management administrative decisions waterward of the Coastal Jurisdiction Line in accordance with Connecticut General Statutes Chapter 440, "Wetlands and Watercourses." (Conn. Gen. Stat. § 22a-359) Municipalities are responsible for administrative decisions landward of the Mean High Water Mark in accordance with Connecticut General Statutes Chapter 444, "Coastal Management Act." (Conn. Gen. Stat. § 22a-101) Note the overlapping DEEP and municipal jurisdiction for administrative decisions between the Mean High Water Mark and the more landward Coastal Jurisdiction Line.

[4] The administrative decision maker must determine if the adverse impacts are acceptable and whether the applicant has incorporated all reasonable measures to mitigate adverse impacts. (Conn. Gen. Stat. §§ 22a-106, 22a-33)

[5] A non-binding DEEP review is mandatory for municipal-jurisdiction site plans that involve Flood and Erosion Control Structures or changes to zoning maps or coastal zone regulations. A non-binding DEEP review is at the municipality's option for other municipal-jurisdiction site plans. (Conn. Gen. Stat. §§ 22a-109, 22a-95)

[6] Within the limits set by the Connecticut state legislature.

[7] There are no legislative mandates regarding rolling easements.

[8] Floodplain construction standards include standards for materials, elevation, setbacks anchoring, hydraulic force resistance, breakaway walls, construction methods and certification by architects and engineers.

[9] CT statutes require compliance with the Connecticut State Building Code, which specifies by reference the minimum standards for floodplain construction. Municipalities may impose more stringent requirements where allowed by the state code.

Decision Item	Floodplain Management or Coastal Management	Legislative Decision Maker	Administrative Decision Maker	Admin. Decision Considers Sea Level Rise?[10]
Adopted Local Comprehensive Plans	Coastal	Municipality	Municipality	Required (For Plans Adopted After 10/01/13)
Adopted State Comprehensive Plan	Coastal	CT Legislature	State Executive Departments	Required (For Plans Adopted After 10/01/13)

[10] Consideration of sea level rise is "Required," "Allowed," or "NAS" (NAS = not addressed by the enabling state statute).

FLORIDA COASTAL AND FLOODPLAIN MANAGEMENT DECISION AUTHORITY

(DRAFT - MAY 31, 2017)

Decision Item	Floodplain Management or Coastal Management	Legislative Decision Maker	Administrative Decision Maker	Admin. Decision Considers Sea Level Rise?[1,]
Consistency with State Coastal Resource Policies	Coastal	Legislature, Agencies, Municipality, County[2]	Agencies, Municipality, County[3]	NAS
Impact on Coastal Resources	Coastal	Legislature, Agencies, Municipality, County[2]	Agencies, Municipality, County[3]	NAS
Impact on Future Water-Dependent Activities	Coastal	Legislature, Agencies, Municipality, County[2]	Agencies, Municipality, County[3]	NAS
Public Access to Coastal Waters and Resources	Coastal	Legislature, Agencies, Municipality, County[2]	Agencies, Municipality, County[3]	NAS
Armor	Coastal	Legislature, Agencies, Municipality, County[2]	Agencies, Municipality, County[3]	Required[4], NAS[5]
Buildings, Structures	Coastal	Legislature, Agencies, Municipality, County[2]	Agencies, Municipality, County[3]	NAS[6]
Material Removal	Coastal	Legislature, Agencies, Municipality, County[2]	Agencies, Municipality, County[3]	NAS
Material Deposition				
Dredging				
Change in Use	Coastal	(None)[7]	- - -	- - -
Living Shoreline				
Site Plans	Coastal	Legislature, Agencies, Municipality, County[2]	Agencies, Municipality, County[3]	NAS
Site Plan Exemptions Variances	Coastal	Legislature, Agencies, Municipality, County[2]	Agencies, Municipality, County[3]	NAS
Setback from Coastal Resources	Coastal	Legislature, Agencies, Municipality, County[2]	Agencies, Municipality, County[3]	NAS
Rolling Easements	Coastal	Legislature, Agencies, Municipality, County[2]	Agencies, Municipality, County[3]	NAS[6]
Tidal Waters Construction Standards	Coastal	Legislature	Agencies	Required[4]
Floodplain Construction Standards[8]	Floodplain	County, Municipality	County, Municipality	NAS[9]
Floodplain Encroachment	Floodplain	County, Municipality	County, Municipality	NAS[9]
Floodway Encroachment	Floodplain	County, Municipality	County, Municipality	NAS[9]

[1] Consideration of sea level rise is "Required," "Allowed," or "NAS" (not addressed by the enabling state statute).

[2] Legislative decisions for coastal management seaward of the mean high water mark take the form of statutes by the legislature or regulations by State Agencies (primarily the Department of Environmental Protection, or DEP) (Fla. Stat. § 161.053). Legislative decisions for coastal management between the mean high water mark and the coastal construction control line take the form of statutes by the legislature, regulations by State Agencies, or municipal or county zoning and building codes when such codes have been approved by the DEP. (Fla. Stat. § 161.053)

[3] Network Agencies (primarily the DEP) make coastal management administrative decisions for activities seaward of the mean high water mark (Fla. Stat. § 161.041) and 50 feet landward of either the mean high water mark or the erosion control line, whichever is more landward (Fla. Stat. § 161.052). Network agencies are also responsible for coastal management administrative decisions from 50 feet landward of either the mean high water mark or the erosion control line, whichever is more landward, to the coastal construction line unless that authority has been delegated to a municipal or county government (Fla. Stat. § 161.053). Municipal and county governments make coastal management administrative decisions for activities landward of the coastal construction line (Fla. Stat. § 161.156).

[4] DEP is required to consider sea level rise when considering armoring permits (Fla. Admin. Code 62B-41.005).

[5] For municipalities and counties.

[6] Consideration of sea level rise is not required *per se*, but no permitting authority (DEP, county, or municipal) may issue a permit for a structure seaward of the coastal construction line that in 30 years will be seaward of the seasonal high water line based on DEP erosion projections (minor structures, coastal or shore protection structures, piers, and certain intake and discharge structures are excepted from this prohibition) (Fla. Stat. § 161.053).

[7] There are no state legislative mandates regarding this decision item.

[8] Floodplain construction standards include standards for materials, elevation, setbacks anchoring, hydraulic force resistance, breakaway walls, construction methods and certification by architects and engineers.

[9] There are no state statutory or regulatory requirements for municipalities to consider sea level rise when considering or issuing floodplain management permits.

FLORIDA COASTAL AND FLOODPLAIN MANAGEMENT DECISION AUTHORITY

(DRAFT - MAY 31, 2017)

Decision Item	Floodplain Management or Coastal Management	Legislative Decision Maker	Administrative Decision Maker	Admin. Decision Considers Sea Level Rise?[10,]
Coastal Boundary Zoning Regulations	Coastal	(None)[11]	- - -	- - -
Feasible Alternatives	Coastal	(None)[12]	- - -	- - -
Adopted Local Comprehensive Plans	Coastal	County, Municipality	County, Municipality	Required[13]
Adopted State Comprehensive Plan	Coastal	(None)[14]	- - - -	- - - -

[10] Consideration of sea level rise is "Required," "Allowed," or "NAS" (not addressed by the enabling state statute).
[11] There are no state legislative mandates regarding this decision item.
[12] There are no state legislative mandates regarding this decision item.
[13] Coastal counties and municipalities governments must consider sea level rise in the coastal management "redevelopment" portion of their comprehensive plans (Fla. Stat. § 163.3178) and may consider sea level rise when deciding whether to include an "adaptation action area" in their comprehensive plans (Fla. Stat. § 163.3177).
[14] Florida does not have a comprehensive, state-wide land use plan.

MASSACHUSETTS COASTAL AND FLOODPLAIN MANAGEMENT DECISION AUTHORITY

(DRAFT - MAY 31, 2017)

Decision Item	Floodplain Management or Coastal Management	Legislative Decision Maker	Administrative Decision Maker	Admin. Decision Considers Sea Level Rise?[1]
Consistency with State Coastal Resource Policies	Coastal	Legislature, DEP[2 3]	Agencies[4], Municipality[5]	Required[6], NAS.[7]
Impact on Coastal Resources	Coastal	Legislature, DEP[3]	Agencies[4], Municipality[5]	Required[6], NAS[7]
Impact on Future Water-Dependent Activities	Coastal	Legislature, DEP[3]	Agencies[8]	Required[6]
Public Access to Coastal Waters and Resources	Coastal	Legislature, DEP[3]	Agencies[8]	Required[6]
Armor	Coastal	Legislature, DEP[3]	Agencies[4], Municipality[5]	Required[6], NAS[7]
Buildings, Structures	Coastal	Legislature, DEP[3]	Agencies[4], Municipality[5]	Required[6,9], NAS[7]
Material Removal	Coastal	Legislature, DEP[3]	Agencies[4], Municipality[5]	Required[6], NAS[7]
Material Deposition	Coastal	Legislature, DEP[3]	Agencies[4], Municipality[5]	Required[6], NAS[7]
Dredging	Coastal	Legislature, DEP[3]	Agencies[4], Municipality[5]	Required[6], NAS[7]
Change in Use	Coastal	Legislature, DEP[3]	Agencies[4], Municipality[5]	Required[6], NAS[7]
Living Shoreline	Coastal	(None)[8]	(None)[8]	
Site Plans	Coastal	DEP[3]	Agencies[4], Municipality[5]	Required[6,9], NAS[7]
Site Plan Exemptions Variances	Coastal	DEP[3]	Agencies[4], Municipality[5]	Required[6], NAS[7]
Setback from Coastal Resources	Coastal	DEP[3] 310 § 10.3, 10.5	Agencies[4], Municipality[5]	Required[6], NAS[7]
Rolling Easements	Coastal	(None)[8]	- - - -	- - - -
Tidal Waters Construction Standards	Coastal	Legislature	Agencies	Required[6]
Floodplain Construction Standards[10]	Floodplain	Municipality	Municipality	NAS[7]
Floodplain Encroachment	Floodplain	Municipality	Municipality	NAS[7]
Floodway Encroachment	Floodplain	Municipality	Municipality	NAS[7]
Coastal Boundary Zoning Regulations	Coastal	Municipality	Municipality	NAS[7]
Feasible Alternatives	Coastal	DEP[3]	Agencies[4], Municipality[5]	Required[6], NAS[7]
Adopted Local Comprehensive Plans	Coastal	(None)[8]	- - - -	- - - -
Adopted State Comprehensive Plan	Coastal	(None)[11]	- - - -	- - - -

[1] Consideration of sea level rise is "Required," "Allowed," or "NAS" (not addressed by the enabling state statute).

[2] DEP = Massachusetts Department of Environmental Protection.

[3] DEP promulgates Coastal Management regulations in accordance with MGL Chapter 91, "Waterways" and MGL Chapter 130 § 105, "Protection of Coastal Wetlands."

[4] The Massachusetts Office of Coastal Zone Management (CZM) is the lead policy and planning agency for coastal issues, but administrative decisions on coastal issues are made by other state agencies (most frequently the DEP). State agencies are generally responsible for coastal management administrative decisions waterward of the High Water Mark in accordance with MGL Chapter 91, "Waterways" and 310 CMR 9.00 "Waterways."

[5] Municipal Conservation Commissions are generally responsible for coastal management administrative decisions landward of the High Water Mark in accordance with MGL Chapter 130 § 105, "Protection of Coastal Wetlands" and 310 CMR 10.0, "Wetlands Protection."

[6] MGL Ch. 30 § 61 requires state agencies to consider sea level rise when considering and issuing permits.

[7] There are no state statutory or regulatory requirements for municipalities to consider sea level rise when considering or issuing permits.

[8] There is no state statute or regulation that either requires or prohibits municipalities from considering this decision item when making decisions within the scope of their jurisdiction.

[9] 310 CMR 9.37, "Engineering and Construction Standards," requires state agencies to consider sea level rise when considering or issuing permits for nonwater-dependent buildings located within a flood zone and intended for human occupancy.

[10] Floodplain construction standards include standards for materials, elevation, setbacks anchoring, hydraulic force resistance, breakaway walls, construction methods and certification by architects and engineers.

[11] Massachusetts does not have a comprehensive, state-wide land use plan.

NORTH CAROLINA COASTAL AND FLOODPLAIN MANAGEMENT DECISION AUTHORITY

(DRAFT - MAY 31, 2017)

Decision Item	Floodplain Management or Coastal Management	Legislative Decision Maker	Administrative Decision Maker	Admin. Decision Considers Sea Level Rise?[1]
Consistency with State Coastal Resource Policies	Coastal	Legislature, CRC, Municipality, County[2,]	CRC, Municipality, County[3]	Allowed[4]
Impact on Coastal Resources	Coastal	Legislature, CRC, Municipality, County[2]	CRC, Municipality, County[3]	Allowed[4]
Impact on Future Water-Dependent Activities	Coastal	Legislature, CRC, Municipality, County[2]	CRC, Municipality, County[3]	Allowed[4]
Public Access to Coastal Waters and Resources	Coastal	Legislature, CRC, Municipality, County[2]	CRC, Municipality, County[3]	Allowed[4]
Armor	Coastal	Legislature, CRC[5]	CRC[5]	Allowed[4]
Buildings, Structures	Coastal	Legislature, CRC, Municipality, County[2]	CRC, Municipality, County[3]	Allowed[4]
Material Removal	Coastal	Legislature, CRC, Municipality, County[2]	CRC, Municipality, County[3]	Allowed[4]
Material Deposition	Coastal	Legislature, CRC, Municipality, County[2]	CRC, Municipality, County[3]	Allowed[4]
Dredging	Coastal	Legislature, CRC[2]	CRC	Allowed[4]
Change in Use	Coastal	Legislature, CRC, Municipality, County[2]	CRC, Municipality, County[3]	Allowed[4]
Living Shoreline	Coastal	(None)[6]	- - -	- - -
Site Plans	Coastal	Legislature, CRC, Municipality, County[2]	CRC, Municipality, County[3]	Allowed[4]
Site Plan Exemptions	Coastal	Legislature, CRC, Municipality, County[2]	CRC, Municipality, County[3]	Allowed[4]
Setback from Coastal Resources	Coastal	Legislature, CRC, Municipality, County[2]	CRC, Municipality, County[3]	
Rolling Easements	Coastal	CRC[7]	CRC, Municipality, County[3]	Allowed[4]
Tidal Waters Construction Standards	Coastal	CRC[2]	CRC	Allowed[4]
Floodplain Construction Standards[8]	Floodplain	Legislature, Municipality, County[9]	Municipality, County	Allowed[4]

[1] Consideration of sea level rise is “Required,” “Allowed,” or “NAS” (not addressed by the enabling state statute).

[2] Legislative decisions for coastal management seaward of the mean high water mark take the form of statutes by the legislature or regulations by the Coastal Resources Council (CRC). (N.C. Gen. Stat. § 77-20) Legislative decisions for coastal management landward of the mean high water mark take the form of statutes by the legislature, regulations by State Agencies, or municipal or county zoning codes. (N.C. Gen. Stat. § 113A-101) County and municipal coastal management ordinances are based on local coastal management implementation and enforcement plans, which must be approved by the CRC. (N.C. Gen. Stat. § 113A-117)

[3] The Coastal Management Division of the North Carolina Department of Environmental Quality is responsible for administrative decisions associated with major and general permits. (N.C. Gen. Stat. § 113A-118) County and municipal governments are responsible for administrative decisions associated with minor permits issued for projects that don't require a major or general permit when the authority to make these decisions has been delegated by the CRC. (N.C. Gen. Stat. § 113A-121)

[4] Counties and municipalities are allowed to define “sea level change” for regulatory purposes. (N.C. Gen. Stat. § 113A-107.1) CRC is allowed to define “sea level change” for regulatory purposes after July 1, 2016. (2011 N.C. H.B. No. 819, N.C. 2011 Gen. Assemb. - 2012 Reg. Sess.)

[5] Most coastal armoring is prohibited by North Carolina statute (N.C. Gen. Stat. § 113A-115.1)

[6] There are no state legislative mandates regarding this decision item.

[7] Permits for development in Ocean Hazard Areas of Environmental Concern are issued under the condition that the structure shall be relocated or dismantled when it becomes imminently threatened by erosion. Any such structure must be relocated or dismantled within two years or immediately upon collapse or subsidence. (15A N.C. Admin. Code 7H.0306)

[8] North Carolina statutes require compliance with the State Building Codes, which specify the minimum standards for floodplain construction. Municipalities may impose more stringent requirements where allowed by the State Codes. (N.C. Gen. Stat. § 143-138)

[9] Coastal counties and municipalities have exclusive jurisdiction over floodplain management programs, but these programs must comply with the requirements of the state floodplain statutes. (N.C. Gen. Stat §§ 143-215.51 - 143-215.61)

Decision Item	Floodplain Management or Coastal Management	Legislative Decision Maker	Administrative Decision Maker	Admin. Decision Considers Sea Level Rise?[10]
Floodplain Encroachment	Floodplain	Legislature, Municipality, County[9]	Municipality, County	Allowed[4]
Floodway Encroachment	Floodplain	Legislature, Municipality, County[9]	Municipality, County	Allowed[4]
Coastal Boundary Zoning Regulations	Coastal	Municipality, County[11]	Municipality, County	Allowed[4]
Feasible Alternatives	Coastal	Legislature, CRC, Municipality, County [12,]	CRC, Municipality, County[13]	Allowed[14]
Adopted Local Comprehensive Plans	Coastal	Municipality, County[15]	Municipality, County	Allowed[14]
Adopted State Comprehensive Plan	Coastal	(None)[16]	- - -	---

[10] Consideration of sea level rise is "Required," "Allowed," or "NAS" (not addressed by the enabling state statute).
[11] County and municipal coastal management zoning ordinances are based on local coastal management implementation and enforcement plans, which must be approved by the CRC. (N.C. Gen. Stat. § 113A-117)
[12] Legislative decisions for coastal management seaward of the mean high water mark take the form of statutes by the legislature or regulations by the Coastal Resources Council (CRC). (N.C. Gen. Stat. § 77-20) Legislative decisions for coastal management landward of the mean high water mark take the form of statutes by the legislature, regulations by State Agencies, or municipal or county zoning codes. (N.C. Gen. Stat. § 113A-101) County and municipal ordinances are based on local coastal management implementation and enforcement plans, which must be approved by the CRC. (N.C. Gen. Stat. § 113A-117)
[13] The Coastal Management Division of the North Carolina Department of Environmental Quality is responsible for administrative decisions associated with major and general permits. (N.C. Gen. Stat. § 113A-118) County and municipal governments are responsible for administrative decisions associated with minor permits issued for projects that don't require a major or general permit when the authority to make these decisions has been delegated by the CRC. (N.C. Gen. Stat. § 113A-121)
[14] Counties and municipalities are allowed to define "sea level change" for regulatory purposes. (N.C. Gen. Stat. § 113A-107.1) CRC is allowed to define "sea level change" for regulatory purposes after July 1, 2016. (2011 N.C. H.B. No. 819, N.C. 2011 Gen. Assemb. - 2012 Reg. Sess.)
[15] County and municipal comprehensive land use plans must consider local coastal management implementation and enforcement plans, which must be approved by the CRC. (N.C. Gen. Stat. § 113A-117)
[16] North Carolina does not have a comprehensive, state-wide land use plan.

RHODE ISLAND COASTAL AND FLOODPLAIN MANAGEMENT DECISION AUTHORITY

(DRAFT - MAY 31, 2017)

Decision Item	Floodplain Management or Coastal Management	Legislative Decision Maker	Administrative Decision Maker	Admin. Decision Considers Sea Level Rise?[1]
Consistency with State Coastal Resource Policies	Coastal	CRMC[2, 3]	CRMC[4]	Required[5]
Impact on Coastal Resources	Coastal	CRMC[3]	CRMC[4]	Required[5]
Impact on Future Water-Dependent Activities	Coastal	CRMC[3]	CRMC[4]	Required[5]
Public Access to Coastal Waters and Resources	Coastal	CRMC[3]	CRMC[4]	Required[5]
Armor	Coastal	CRMC[3]	CRMC[4]	Required[5]
Buildings, Structures	Coastal	CRMC[3]	CRMC[4]	Required[5]
Material Removal	Coastal	CRMC[3]	CRMC[4]	Required[5]
Material Deposition	Coastal	CRMC[3]	CRMC[4]	Required[5]
Dredging	Coastal	CRMC[3]	CRMC[4]	Required[5]
Change in Use	Coastal	CRMC[3]	CRMC[4]	Required[5]
Living Shoreline	Coastal			
Site Plans	Coastal	CRMC[3]	CRMC[4]	Required[5]
Site Plan Exemptions	Coastal	CRMC[3]	CRMC[4]	Required[5]
Setback from Coastal Resources	Coastal	CRMC[3]	CRMC[4]	Required[5]
Rolling Easements	Coastal	CRMC[6]	CRMC	Required[5]
Tidal Waters Construction Standards	Coastal	CRMC[3]	CRMC[4]	Required[5]
Floodplain Construction Standards[7]	Floodplain	CRMC[8], Municipality[9]	CRMC[8], Municipality[9]	Required § 23-27.3-100.1.5.5
Floodplain Encroachment	Floodplain	Municipality	Municipality	NAS ??
Floodway Encroachment	Floodplain	Municipality	Municipality	NAS ??
Coastal Boundary Zoning Regulations	Coastal	Municipality	Municipality	NAS ??
Feasible Alternatives	Coastal	CRMC[3]	CRMC[4]	Required[5]
Adopted Local Comprehensive Plans	Coastal	Municipality § 45-22.2-5	Municipality § 45-22.2-13	Required § 45-22.2-6
Adopted State Comprehensive Plan	Coastal	RI Legislature	State Planning Council, Municipality § 45-22.2-10	Required § 45-22.2-6

[1] Consideration of sea level rise is "Required," "Allowed," or "NAS" (not addressed by the enabling state statute).
[2] CRMC = Coastal Management Resource Council, an agency of the State of Rhode Island. CRMC jurisdiction is exclusive and comprehensive below mean high water, shared and limited from mean high water to 200 feet inland of the most inland "shoreline feature," and shared and limited statewide for specified inland activities that could affect the coastal environment (large power plants, sewage treatment facilities, etc.). 46-23-6 (2)
[3] CRMC promulgates regulations for waters and lands within its jurisdiction as authorized by Rhode Island General Laws Title 46, Chapter 23, "Waters and Navigation."
[4] Municipalities may establish a coastal zone and exercise concurrent coastal management decision authority with CRMC (as does Narragansett), or defer all coastal management decision authority to CRMC (as does Westerly).
[5] The CRMC relies upon the most recent NOAA sea level rise data to address both short- and long term planning horizons and the design life considerations for public and private infrastructure. R.I. Code R. 16-2-1:145
[6] Reconstruction of structures destroyed 50 percent or more by storm-induced flooding, wave or wind damage must comply with current CRMC requirements, which may prohibit reconstruction altogether. Such reconstruction is completely prohibited on certain barrier islands and spits for residential and non-water-dependent recreational, commercial, and industrial structures.
[7] CRMC and municipalities invoke the Rhode Island State Building Code, which in turn invokes ASCE-24, "Flood Resistant Design and Construction." ASCE 24 includes standards for materials, elevation, setbacks, anchoring, hydraulic force resistance, breakaway walls, siting and construction methods.
[8] CRMS is responsible for decisions within its jurisdiction.
[9] Municipalities are responsible for decisions landward of the mean high water mark.

SOUTH CAROLINA COASTAL AND FLOODPLAIN MANAGEMENT DECISION AUTHORITY

(DRAFT - MAY 31, 2017)

Decision Item	Floodplain Management or Coastal Management	Legislative Decision Maker	Administrative Decision Maker	Admin. Decision Considers Sea Level Rise?[1]
Consistency with State Coastal Resource Policies	Coastal	Legislature, OCRM, Municipality, County[2],	OCRM, Municipality, County[3]	NAS[4]
Impact on Coastal Resources	Coastal	Legislature, OCRM, Municipality, County[2]	OCRM, Municipality, County[3]	NAS[4]
Impact on Future Water-Dependent Activities	Coastal	Legislature, OCRM, Municipality, County[2]	OCRM, Municipality, County[3]	NAS[4]
Public Access to Coastal Waters and Resources	Coastal	Legislature, OCRM, Municipality, County[2]	OCRM, Municipality, County[3]	NAS[4]
Armor	Coastal	Legislature, OCRM	OCRM	NAS[4]
Buildings, Structures	Coastal	Legislature, OCRM, Municipality, County[2]	OCRM, Municipality, County[3]	NAS[4]
Material Removal	Coastal	Legislature, OCRM, Municipality, County[2]	OCRM, Municipality, County[3]	NAS[4]
Material Deposition	Coastal	Legislature, OCRM, Municipality, County[2]	OCRM, Municipality, County[3]	NAS[4]
Dredging	Coastal	Legislature, OCRM	OCRM	NAS[4]
Change in Use	Coastal	Legislature, OCRM, Municipality, County[2]	OCRM, Municipality, County[3]	NAS[4]
Living Shoreline	Coastal	(None)[5]	- - -	- - -
Site Plans	Coastal	Legislature, OCRM, Municipality, County[2]	OCRM, Municipality, County[3]	NAS[4]
Site Plan Exemptions	Coastal	Legislature, OCRM, Municipality, County[2]	OCRM, Municipality, County[3]	NAS[4]
Setback from Coastal Resources	Coastal	Legislature, OCRM, Municipality, County[2]	OCRM, Municipality, County[3]	NAS[4]
Rolling Easements	Coastal	OCRM[6]	OCRM	NAS[4]
Tidal Waters Construction Standards	Coastal	OCRM[2]	OCRM	NAS[4]

[1] Consideration of sea level rise is "Required," "Allowed," or "NAS" (not addressed by the enabling state statute).

[2] Legislative decisions for coastal management seaward of the mean high water mark take the form of statutes by the legislature or regulations by the Coastal Resources Council (OCRM). (State v. Pac. Guano Co., 22 S.C. 50, 1884) Legislative decisions for coastal management landward of the mean high water mark take the form of statutes by the legislature, regulations by State Agencies, or municipal or county coastal management ordinances. (S.C. Code § 48-39-100) County and municipal coastal management ordinances are based on "Local Comprehensive Beach Management Plans" that are developed by the local government and approved by OCRM.. (*Id.*) In practice, the vast majority of coastal management legislative decisions are made at the state level.

[3] OCRM implements the South Carolina Coastal Tidelands and Wetlands Act (CTWA) through a permit system that regulates development activities in "Critical Areas" that include coastal waters, tidelands, beaches, and the beach/dune system from the mean high-water mark to the forty-year erosion setback line. (S.C. Code §§ 48-39-10, 48-39-130) Counties and municipalities manage zoning and other day-to-day coastal issues in accordance "Local Comprehensive Beach Management Plans." S.C. Code (§ 48-39-350). In practice, the vast majority of coastal management administrative decisions are made at the state level.

[4] There are no state statutes or regulations that require the OCRM to consider sea level rise when considering or issuing coastal management permits. But an OCRM statement of regulatory policy acknowledges sea level rise as a factor that will ultimately require a retreat from the beachfront, and some local governments have incorporated sea level rise into their local planning. (S.C. Code Regs. 30-1)

[5] There are no state legislative mandates regarding this decision item.

[6] South Carolina has a "forty year retreat policy" that is implemented via a "baseline" and a "setback line." The baseline is set at the crest of the primary oceanfront sand dune or other equivalent location when a dune is not present. The setback line is landward of the baseline at a distance equal to forty times the average annual erosion rate. The baseline and setback lines must be revised every seven to ten years to account for changing shoreline conditions, except that the baseline can never be moved seaward. Construction or reconstruction of habitable structures is not allowed seaward of the baseline. Strict limitations are placed on the type, size, and location of habitable and other structures erected between the baseline and the setback line. (S.C. Code §§ 48-39-280, 48-39-290)

Floodplain Construction Standards[7]	Floodplain	Legislature, Municipality, County	Municipality, County	NAS[4]
Floodplain Encroachment	Floodplain	Legislature, Municipality, County	Municipality, County	NAS[4]
Floodway Encroachment	Floodplain	Legislature, Municipality, County	Municipality, County	NAS[4]
Coastal Boundary Zoning Regulations	Coastal	Municipality, County[8]	Municipality, County	NAS[4]
Feasible Alternatives	Coastal	Legislature, OCRM, Municipality, County [2]	OCRM, Municipality, County[3]	NAS[4]
Adopted Local Comprehensive Plans	Coastal	Municipality, County[9]	Municipality, County	NAS[4]
Adopted State Comprehensive Plan	Coastal	(None)[10]	- - -	---

[7] Floodplain construction standards include standards for materials, elevation, setbacks anchoring, hydraulic force resistance, breakaway walls, construction methods and certification by architects and engineers. Construction standards must comply the NFIP and the nationally recognized codes adopted and amended by the South Carolina Building Codes Council. (S.C. Code § 6-9-10) Counties and municipalities may not impose more stringent requirements without approval of the Council. (S.C. Code § 6-9-105, S.C. Code Regs. 8-240)

[8] County and municipal coastal management zoning ordinances are based on “Local Comprehensive Beach Management Plans” that are developed by the local government and approved by OCRM (S.C. Code § 48-39-350)

[9] County and municipal comprehensive land use plans must consider “Local Comprehensive Beach Management Plans” that are developed by the local government and approved by OCRM (S.C. Code § 48-39-350)

[10] South Carolina does not have a comprehensive, state-wide land use plan. The Department of Health and Environmental Control has been tasked with creating a "State Comprehensive Beach Management Plan" (S.C. Code § 48-39-350), but as of April 30, 2017, this plan has not been consolidated into a single, comprehensive planning document.

APPENDIX G2 - SECTION 6

SUMMARY OF TASK 9 PROJECT MEETINGS

Municipal Resilience Planning Assistance Project (MRPAP)
Summary of Task 9 Project Meetings

Task 9: Legal and Policy Analyses that Support State and Municipal Efforts to Implement Resiliency Measures

Implementing Tasks:

- Survey sea level rise adaptation laws and regulations in other oceanfront states
- Identify legal and policy issues that frustrate sea level rise adaptation efforts
- Prepare white papers on sea level rise law and policy issues not adequately addressed by others
- Conduct outreach events to communicate legal and policy recommendations.

ORGANIZATION ABBREVIATIONS

AIA CT	Connecticut Chapter of the American Institute of Architects
CASE	Connecticut Association of Scientists and Engineers
CAFM	Connecticut Association of Flood Managers
CEEL	UConn Law Center for Energy & Environmental Law
CIRCA	Connecticut Institute for Resilience and Climate Adaptation
CLEAR	UConn Center for Land Use Education and Research
DEEP	Connecticut Department of Energy & Environmental Protection
FEMA	Federal Emergency Management Agency
TNC	The Nature Conservancy
UConn	University of Connecticut

Date Location	Organiza- tions	Purpose	Topics	Attending
09/20/16 Teleconference	• CEEL • CIRCA • UConn	MRPAP Coordination Meeting	• Updates on tasks 1, 2,3,4,5,7, 8 & 9 • Planning and Scheduling	CEEL • J. MacDougald (Executive Director) • W. Rath (Legal Research Fellow) CIRCA • J. O'Donnell (Executive Director) • R. French (Director of Community Engagement) • K. Lund (Project Coordinator) UCONN • Manos Anagnostou (Professor of Engineering) • Christine Kirchhoff, (Professor of Engineering)
10/19/16 UConn Law Hosmer 120 55 Elizabeth St. Hartford, CT	• CEEL • CIRCA	• Introductions • Identify MRPAP Priorities	• MRPAP Participants & Responsibilities • Project Status • Towns with Progressive Coastal and Floodplain Management Programs • Engineering Consultants to Coastal Towns • CIRCA Coastal and Floodplain Management Grantees	CEEL • J. MacDougald (Director) • W. Rath (Legal Research Fellow) CIRCA • R. French (Director of Community Engagement)

Municipal Resilience Planning Assistance Project (MRPAP)
Summary of Task 9 Project Meetings

Date Location	Organiza-tions	Purpose	Topics	Attending
10/24/16 DEEP 79 Elm St. Hartford, CT	• CEEL • DEEP	• Introductions • Identify DEEP Priorities	• Background on MRPAP and CEEL Task 9 • Organization of New DEEP Land and Water Resources Division • Municipal Authority for Coastal and Floodplain Management • Living Shorelines • Permitting • Floodplain Management Beyond FEMA Minimums ("CIRCA LINE") • Emergency Powers • Programs in Other States • Coordination Between CEEL and DEEP for Task 9 Activities	<u>CEEL</u> • J. MacDougald (Executive Director) • W. Rath (Legal Research Fellow) <u>DEEP</u> • B. Thompson (Director of Land and Water Resources) • D. Blatt (Supervising Environmental Analyst) • P. Francis (Supervising Environmental Analyst)

11/01/16
 	
UConn Avery Point
1084 Shennecossett
Groton, CT
	• CEEL
	• CLEAR
		• Introductions
		• Task Coordination
			• Task 10
			  ◦ Scope
			  ◦ Work To Date
			  ◦ Questionnaire for Municipalities
			  ◦ Anticipated Output
			• Coastal Management Issues (Flood Levels with SLR, Living Shorelines, Tidal Wetlands, ZBA Variances, Marshes, Land Use Planning and Regulation)
			• Municipal Priorities (Based on Preliminary Results)
			• Possible Issues with Municipal Acceptance of New SLR Data
			• Coordination of Task 8 With Task 9
				<u>CEEL</u>
				• J. MacDougald (Executive Director)
				• W. Rath (Legal Research Fellow)
				<u>CLEAR</u>
				• J. Barrett (Assistant Educator, CT Sea Grant)
				• B. Hyde (Land Use Academy Director)

Municipal Resilience Planning Assistance Project (MRPAP)
Summary of Task 9 Project Meetings

Date Location	Organiza-tions	Purpose	Topics	Attending
11/01/16 UConn Avery Point 1084 Shennecossett Groton, CT	• CEEL • CIRCA	• Introductions • Project Coordination	• Task 2 Sea Level Rise Preliminary Results and Ramifications • Coastal Management Issues (Flood Levels with SLR, Living Shorelines, Tidal Wetlands, ZBA Variances, Marshes, Land Use Planning and Regulation) • Coordination of Task 9 with Other MRPAP Tasks • Task 9 Output	CEEL • J. MacDougald (Executive Director) • W. Rath (Legal Research Fellow) CIRCA • J. O'Donnell (Executive Director) • R. French (Director of Community Engagement)
12/14/16 Town Hall 8 Campus Drive Madison, CT	• CEEL • Town of Madis-on CT	• Research	• Coastal and Floodplain Management Concerns of Shoreline Town Planners • Financial Ramifications of Shoreline Retreat • Task 9 Output That Would Be of Value to Shoreline Town Planners, Engineers, Floodplain Managers, and Zoning Enforcement Officers	CEEL • J. MacDougald (Executive Director) • W. Rath (Legal Research Fellow) Town of Madison • David Anderson (Town Planner)
12/15/16 UConn Law Hosmer CR 1 55 Elizabeth St. Hartford, CT	• CEEL • CIRCA	• Project Coordination	• Coordination of Task 9 with Other MRPAP Tasks • Task 9 Outreach Opportunities • Task 9 White Paper Opportunities	CEEL • J. MacDougald (Executive Director) • W. Rath (Legal Research Fellow) CIRCA • J. O'Donnell (Executive Director)
01/05/17 Town Hall 108 Pennsylvania Niantic, CT	• CEEL • Town of East Lyme CT	• Research • CIRCA Grant	• Coastal and Floodplain Management Concerns of Shoreline Town Planners and Building Officials • Task 9 Output That Would Be of Value to Shoreline Town Planners, Engineers, Floodplain Managers, and Zoning Enforcement Officers • East Lyme Plans for Recently Awarded CIRCA Grant	CEEL • W. Rath (Legal Research Fellow) Town of East Lyme • G. Goeschel (Town Planner) • J. Smith (Chief Building Official)

Municipal Resilience Planning Assistance Project (MRPAP)
Summary of Task 9 Project Meetings

Date Location	Organiza-tions	Purpose	Topics	Attending
01/06/17 Yale Univ. 370 Prospect St. New Haven, CT	• CEEL • Yale Univ.	• Introductions • Research	• Holistic Approaches to Coastal and Floodplain Management • Proposals for Resilience Improvements to Fairfield CT Coastal Areas • Coastal Resilience Plan for Guilford, CT • General Opportunities for Resilience Improvements in CT Shoreline Towns • Task 9 Output That Would Be of Value to Improve Shoreline Town Resilience	<u>CEEL</u> • J. MacDougald (Executive Director) • W. Rath (Legal Research Fellow) <u>Yale University</u> • A. Felson (Associate Professor, Yale School of Architecture)

02/16/17
 	
UConn Avery Point
1084 Shennecossett
Groton, CT
	• CEEL
	• CIRCA
		• Project Coordination	• Task 2 - Sea Level Rise Projections
			  • Science
			  • Ramifications
			  • Practical Use
			• Tasks 3 & 4 - Coupled Model for Riverine & Coastal Surge Flooding
			• Task 5 - SLR and Storm Surge Mapping Tool
			• Task 6 - Floodplain Mapping
				<u>CEEL</u>
				• J. MacDougald (Executive Director)
				• W. Rath (Legal Research Fellow)
				<u>CIRCA</u>
				• J. O'Donnell (Executive Director)
				• R. French (Director of Community Engagement)

03/09/17
 	
UConn Avery Point
1084 Shennecossett
Groton, CT
	• CEEL
	• CLEAR
		Task Coordination	• Task 10
			  • Work To Date
			  • Preliminary Results
			• Incorporating Task 10 results into Task 9
				<u>CEEL</u>
				• W. Rath (Legal Research Fellow)
				<u>CLEAR</u>
				• J. Barrett (Assistant Educator, CT Sea Grant)
				• B. Hyde (Land Use Academy Director)

04/3/17 Teleconference	• CEEL • CLEAR	Task Coordination	• Task 10 Update • Task 10 Influence on Task 9 Work • Opportunities to incorporate Task 10 Results into Task 9 Deliverables	<u>CEEL</u> • W. Rath (Legal Research Fellow) <u>CLEAR</u> • B. Hyde (Land Use Academy Director)

Municipal Resilience Planning Assistance Project (MRPAP)
Summary of Task 9 Project Meetings

Date Location	Organiza- tions	Purpose	Topics	Attending
04/11/17 UConn Storrs Castleman 306 261 Glenbrook Road Storrs CT	• CEEL • CIRCA • UConn	MRPAP Coordination Meeting	• Updates on tasks 2,3,4,5,6, 7, 8, & 9 • Planning and Scheduling	CEEL • J. MacDougald (Executive Director) • W. Rath (Legal Research Fellow) CIRCA • J. O'Donnell (Executive Director) • R. French (Director of Community Engagement) • K. Lund (Project Coordinator) UCONN • Manos Anagnostou (Professor of Engineering) • Christine Kirchhoff, (Professor of Engineering) • Xinyi Shen (Postdoctoral Engineering Fellow)
04/12/17 DEEP 79 Elm St. Hartford, CT	• CEEL • CIRCA • DEEP • OPM	Introduce Preliminary Long Island Sound Sea Level Rise results	• Preliminary Long Island Sound Sea Level Rise Results • Introduced by Dr. Jim O'Donnell, UConn, CIRCA • Opportunities to Use New SLR Projections • Problems with using New SLR Projections	CEEL • W. Rath (Legal Research Fellow) CIRCA • J. O'Donnell (Executive Director) • R. French (Director of Community Engagement) • K. Lund (Project Coordinator) DEEP • R. Klee (Commissioner) • R. Kaliszewski (Deputy Commissioner) • B. Thompson (Director of Land and Water Resources) • R. LaFrance (Director - Office of Law and Policy for Environmental Conservation) • D. Blatt (Supervising Environmental Analyst) • Approximately Four Others

04/27/17
 	
Teleconference
	• CEEL
	• CLEAR
		Task Coordination	• Task 10 Update
			  • Legal Issues Faced by Municipalities
			  • Scheduling
			  • Standards of Authority for SLR Data
				CEEL
				• W. Rath (Legal Research Fellow)
				CLEAR
				• B. Hyde (Land Use Academy Director)

Municipal Resilience Planning Assistance Project (MRPAP)
Summary of Task 9 Project Meetings

Date Location	Organiza- tions	Purpose	Topics	Attending
05/10/17 DEEP 79 Elm St. Hartford, CT	• CEEL • DEEP	Legislative Regulation Review Committee	• Regulation Approval Process • Examples of Unintended Outcomes as a Result of Partial Approvals by the Legislative Regulation Review Committee	CEEL • W. Rath (Legal Research Fellow) DEEP • Melinda Decker (Agency Legal Director)

05/18/17
 	
DEEP
79 Elm St.
Hartford, CT
	• CEEL
	• DEEP
		DEEP Coordination Per Task 9 Mandate	• CEEL Deliverables for Task 9
			  • White Papers
			  • Draft Rules, Regulations, Ordinances Statutes
			  • Outreach Activities
			• Preliminary Long Island Sound Sea Level Rise Results
				CEEL
				• J. MacDougald (Executive Director)
				• W. Rath (Legal Research Fellow)
				DEEP
				• R. Klee (Commissioner)
				• R. Kaliszewski (Deputy Commissioner)
				• B. Thompson (Director of Land and Water Resources)
				• R. LaFrance (Director - Office of Law and Policy for Environmental Conservation)
				• Melinda Decker (Agency Legal Director)
				• Ken Collette (Staff Attorney)

05/22/17 WebEx	• CEEL • CIRCA • UConn	MRPAP Coordination Meeting	• Updates on tasks 2,3,4,5, 6 & 9 • Planning and Scheduling	CEEL • J. MacDougald (Executive Director) • W. Rath (Legal Research Fellow) CIRCA • J. O'Donnell (Executive Director) • R. French (Director of Community Engagement) • K. Lund (Project Coordinator) • Todd Fake (Research Support) UCONN • Manos Anagnostou (Professor of Engineering) • Christine Kirchhoff, (Professor of Engineering) • Xinyi Shen (Postdoctoral Engineering Fellow) • Alejandro Cifuentes-Lorenzen, (Postdoctoral Marine Sciences Fellow)

Municipal Resilience Planning Assistance Project (MRPAP)
Summary of Task 9 Project Meetings

Date Location	Organiza- tions	Purpose	Topics	Attending

05/25/17
 	
UConn Law
Knight 110
35 Elizabeth St,
Hartford, CT
	• CEEL
	• CLEAR
		Task Coordination	• Task 10
			  • Specific Results from Municipal Interviews
			  • Standards of Authority Required for Acceptance of New SLR Data
			  • Anticipated Completion Date
			• CLEAR Input on Proposed Task 9 Deliverables:
			  • White Papers
			  • Draft Rules, Regulations, Ordinances Statutes
			  • Outreach Activities
			• CLEAR Participation in Capstone Conference / Workshop
				<u>CEEL</u>
				• J. MacDougald (Executive Director)
				• W. Rath (Legal Research Fellow)
				• C. Kelly (Legal Writing Fellow)
				<u>CLEAR</u>
				• J. Barrett (Assistant Educator, CT Sea Grant)
				• B. Hyde (Land Use Academy Director)

06/07/17
 	
Teleconference
	• CEEL
	• UConn
		Research	• Groton Climate Change Workshops
			  • Process
			  • Output
			  • Implementation of Recommendations
				<u>CEEL</u>
				• W. Rath (Legal Research Fellow)
				<u>UCONN</u>
				• S. Ebbins (Sea Grant Research Coordinator))

06/27/17 DEEP 79 Elm St. Hartford, CT	• CEEL • DEEP	Review CEEL Legislative Proposals	• Review Legislation Proposed by CEEL • Requirements for Statutory Construction & Language • Key Players for Legislative initiatives • Means to Promulgate CIRCA Sea Level Rise Data • DEEP Contacts for Specific Legislative Issues • DEEP Desires for Legislative Initiatives	<u>CEEL</u> • W. Rath (Legal Research Fellow) <u>DEEP</u> • R. LaFrance (Director - Office of Law and Policy for Environmental Conservation) • D. Blatt (Supervising Environmental Analyst)
07/05/17 Teleconference	• CEEL • CIRCA	Task 2 and 9 Presentations	• Coordinate Presentations of task 2 SLR Data and Task 9 Law & Policy Options • Schedule and Venues for Capstone Conference / Workshop	<u>CEEL</u> • W. Rath (Legal Research Fellow) <u>CIRCA</u> • J. O'Donnell (Executive Director) • R. French (Director of Community Engagement)

Municipal Resilience Planning Assistance Project (MRPAP)
Summary of Task 9 Project Meetings

Date Location	Organiza- tions	Purpose	Topics	Attending
07/07/17 Teleconference	• CEEL • DEEP	Legislative History (For OAR-CPO-1 White Paper)	• Evolution of PA 12-101 and PA 13-179	CEEL • W. Rath (Legal Research Fellow) DEEP • R. LaFrance (Director - Office of Law and Policy for Environmental Conservation)
07/10/17 Teleconference	• CEEL • TNC	Legislative History (For OAR-CPO-1 White Paper)	• Evolution of PA 12-101 and PA 13-179	CEEL • W. Rath (Legal Research Fellow) The Nature Conservancy • D. Sutherland (Director of Government Relations)
07/10/17 Teleconference	• CEEL • DEEP	Legislative History (For OAR-CPO-1 White Paper)	• Evolution of PA 12-101 and PA 13-179	CEEL • W. Rath (Legal Research Fellow) DEEP • D. Blatt (Supervising Environmental Analyst)
07/17/17 Teleconference	• CEEL • FEMA	Flood Plain Expansion	• Opportunities and Limitations of Floodplain Expansion by Local Authorities. • FEMA Enforcement of 44 CFR 60.2(h) • Limitations on Data that can be Used by FEMA to Develop Flood Insurance Rate Maps.	CEEL • W. Rath (Legal Research Fellow) FEMA • K. Bogdan (FEMA Region I Senior Engineer/Program Manager)
07/19/17 Teleconference	• CEEL • CIRCA	Coordination and Integration of Tasks 2 & 9	• SLR Effects on Flood Return Rates • Reasons for Different Flood Return Rates in East and West Sound	CEEL • W. Rath (Legal Research Fellow) CIRCA • J. O'Donnell (Executive Director)
07/19/17 Teleconference	• CEEL • CIRCA	Flood Plain Expansion	• Means and Methods of Expanding Floodplains Beyond That Shown on FEMA FIRMs • Legal & Practical Ramifications • Executive Order 13690	CEEL • W. Rath (Legal Research Fellow) CIRCA • R. French (Director of Community Engagement)
08/02/17 Teleconference	• CEEL • CIRCA	SLR Peer Review	• Evaluate Options for Peer Review of CIRCA SLR Projections	CEEL • W. Rath (Legal Research Fellow) CIRCA • J. O'Donnell (Executive Director)

Municipal Resilience Planning Assistance Project (MRPAP)
Summary of Task 9 Project Meetings

Date Location	Organiza- tions	Purpose	Topics	Attending

08/07/17
 	
Teleconference
	• CEEL
	• CIRCA
		Task 9 Outreach Activities	• Outreach Opportunities
			  • Target Groups
			  • Interested Groups
			  • Underserved Groups
			• Outreach Strategies
			• Opportunities for a "Capstone" Workshop / Conference to Encompass Entire MRPAP
				CEEL
				• W. Rath (Legal Research Fellow)
				CIRCA
				• R. French (Director of Community Engagement)

08/14/17 DEEP 79 Elm St. Hartford, CT	• CEEL • DEEP	Review CEEL Legislative Proposals	• Ramifications of Incorporating Sea Level Rise into State Planning Processes • Interaction Between DEEP and Municipalities on Coastal and Floodplain Management Issues • Legislative History of PA 12-101 • Use of FEMA Flood Insurance Ratee Maps for Other Purposes • Retreat Strategies	CEEL • W. Rath (Legal Research Fellow) DEEP • R. Kaliszewski (Deputy Commissioner)
08/17/17 Teleconference	• CEEL • CIRCA	SLR Public Rollout	• Time, Place and Format of Public Roll-Out of Task 2 SLR Projections	CEEL • W. Rath (Legal Research Fellow) CIRCA • R. French (Director of Community Engagement)
08/23/17 Teleconference	• CEEL • CIRCA	Prepare for Presentation to Legislative Leaders	• Identification of Likely Attendees • Content of Task 2 and Task 9 Presentations • Coordination of Task 2 and Task 9 Presentations • CEEL Legislation Recommendations	CEEL • J. MacDougald (Executive Director) • W. Rath (Legal Research Fellow) CIRCA • J. O'Donnell (Executive Director) • R. French (Director of Community Engagement)
08/23/17 Teleconference	• CEEL • CASE	SLR Peer Review	• CASE Availability for Peer Review of UConn SLR Projections	CEEL • W. Rath (Legal Research Fellow) CASE • R. Strauss (Executive Director)

Municipal Resilience Planning Assistance Project (MRPAP)
Summary of Task 9 Project Meetings

Date Location	Organiza-tions	Purpose	Topics	Attending

08/28/17
 	
OPM
450 Capitol Avenue
Hartford, CT
	• CEEL
	• OPM
		Identify the Ramifications of the Requirement to incorporate SLR into the State POCD	• Introductions
			• Legislative Nature of the POCD
			• OPM State Project Approval
			  • Limitations of Authority
			  • Approval Process
			• Legal Challenges to OPM Decisions
			• Origin and Operation of Councils of Governments
			• Task 9 Outreach Opportunities
				CEEL
				• W. Rath (Legal Research Fellow)
				OPM
				• D. Morely (Assistant Director, Division of Transportation, Conservation & Development, and Policy & Planning)
				• Eric Lindquist (OPM)

08/29/17 Teleconference	• CEEL • UConn	Task Coordination	• Task 3 & 4 Outputs • Incorporating Tasks 3 & 4 Outputs into Task 9	CEEL • W. Rath (Legal Research Fellow) UCONN • Manos Anagnostou (Professor of Engineering)
08/31/17 Teleconference	• CEEL • DEEP	Prepare for Presentation with Legislative Leaders	• CEEL Legislation Recommendations	CEEL • J. MacDougald (Executive Director • W. Rath (Legal Research Fellow) DEEP • R. LaFrance (Director - Office of Law and Policy for Environmental Conservation)
09/07/17 Teleconference	• CEEL • AIA CT	Outreach	• CEEL/ CIRCA Participation at AIA / CAFM "Resilient Connecticut Workshop"	CEEL • J. MacDougald (Executive Director • W. Rath (Legal Research Fellow) CT AIA • D. Watson (Architect)

10/02/17
 	
Teleconference
	• CEEL
	• CIRCA
		MRPAP Coordination Meeting	• Updates on tasks 2 & 9
			• Planning and Scheduling
			• Outreach Opportunities
			  • COGs
			  • Professional Groups
			  • "Capstone" Event
				CEEL
				• J. MacDougald (Executive Director)
				• W. Rath (Legal Research Fellow)
				CIRCA
				• J. O'Donnell (Executive Director)
				• R. French (Director of Community Engagement)
				• K. Lund (Project Coordinator)

Municipal Resilience Planning Assistance Project (MRPAP)
Summary of Task 9 Project Meetings

Date Location	Organiza- tions	Purpose	Topics	Attending
10/18/17 Teleconference	• CEEL • Lawyers	Outreach	• Coordinate Panel at CAFM Annual Meeting • Merriam, Rath & Shansky	CEEL) • W. Rath (Legal Research Fellow) Lawyers • D. Merriam (Robinson & Cole) • M. Shansky (Marjorie Shansky = Attorney at Law)

11/08/17
 	
CAFM & CIRCA
333 Ferry Street
Old Lyme, CT
	CEEL
	CIRCA
	CAFM
		Coordinate Spring 2018 Outreach Events	• CAFM Flood Symposium 03/14/18
			  • Target audience
			  • Content
			• CEEL MRPAP Forum (Tentatively 03/09/18)
			  • Target audience
			  • Content
			• Opportunities to maximize utility of each event without detracting from the other
				CEEL
				• W. Rath (Legal Research Fellow)
				CIRCA
				• R. French (Director of Community Engagement)
				• K. Lund (Project Coordinator)
				CAFM
				• E. Harrigan (President)
				• J. McGrane (Secretary)
				• D. Murphy (Treasurer)
				• J. Smith
				• S. Bighinatti
				• J. Canas
				DEEP
				• .D. Ikovic

11/13/17 Teleconference	• CEEL • CIRCA	Coordinate Spring 2018 Outreach Events	• Review of 11/08/17 Meeting with CAFM • Goals of CAFM and CEEL Conferences • Likely Attendance at CAFM and CEEL Conferences • Alternative Dates for the CEEL/CIRCA Conference	CEEL • J. MacDougald (Executive Director) • W. Rath (Legal Research Fellow) CIRCA • J. O'Donnell (Executive Director) • R. French (Director of Community Engagement) • K. Lund (Project Coordinator)
12/12/17 Teleconference	• CEEL • DEEP	Legislative Initiatives	• Appropriate parties to introduce legislative initiatives resulting from the MRPAP • Process and procedure for introducing legislative initiatives • DEEP / CEEL collaboration on legislative initiatives	CEEL • W. Rath (Legal Research Fellow) DEEP • R. LaFrance (Director - Office of Law and Policy for Environmental Conservation)

Municipal Resilience Planning Assistance Project (MRPAP)
Summary of Task 9 Project Meetings

Date Location	Organiza-tions	Purpose	Topics	Attending
01/12/18 Teleconference	• CEEL • CIRCA	Outreach Coordination & Final Conference Planning	• New Haven Planning Department Presentation • Coordinating Final Conference with CAFM March Conference • Likely Scope and Audience of Final Conference	<u>CEEL</u> • W. Rath (Legal Research Fellow) <u>CIRCA</u> • R. French (Director of Community Engagement)
01/17/18 Teleconference	• CEEL • CIRCA	Final Conference Planning	• Speaker Options • Poster Sessions • Logistics	<u>CEEL</u> • W. Rath (Legal Research Fellow) <u>CIRCA</u> • K. Lund (Project Coordinator)
01/23/18 Teleconference	• CEEL • CIRCA	Outreach Coordination	• New Haven Planning Department Presentation	<u>CEEL</u> • W. Rath (Legal Research Fellow) <u>CIRCA</u> • R. French (Director of Community Engagement)
01/29/18 Teleconference	• CEEL • CIRCA	Final Conference Planning	• Consolidate Conference Ideas • Preliminary Planning & Scheduling	<u>CEEL</u> • J. MacDougald (Executive Director) • W. Rath (Legal Research Fellow) <u>CIRCA</u> • K. Lund (Project Coordinator)
02/07/18 Teleconference	• CEEL • CIRCA	Final Conference Planning	• Coordinate Speakers	<u>CEEL</u> • W. Rath (Legal Research Fellow) <u>CIRCA</u> • K. Lund (Project Coordinator)
02/13/18 Teleconference	• CEEL • CIRCA • UConn Law	Final Conference Planning	• Coordinate Facilities	<u>CEEL</u> • W. Rath (Legal Research Fellow) <u>CIRCA</u> • K. Lund (Project Coordinator) <u>UCONN LAW</u> • D. King (Events and Programs Manager)
02/14/18 Teleconference	• CEEL • CIRCA	S.B. No. 7	• Features of Senate Bill No. 7, An Act Concerning Climate Change Planning And Resilience	<u>CEEL</u> • W. Rath (Legal Research Fellow) <u>CIRCA</u> • J. O'Donnell (Executive Director)

Municipal Resilience Planning Assistance Project (MRPAP)
Summary of Task 9 Project Meetings

Date Location	Organiza-tions	Purpose	Topics	Attending
02/16/18 Teleconference	• CEEL • The Nature Conserv-ancy	S.B. No. 7	• Features of Senate Bill No. 7, An Act Concerning Climate Change Planning And Resilience	CEEL • W. Rath (Legal Research Fellow) TNC • D. Sutherland (Director of Government Relations)
02/27/18 Teleconference	• CEEL • CIRCA	Final Conference Planning	• Review / Revise Draft Agenda • Speaker Selection	CEEL • J. MacDougald (Executive Director) • S. Bronin (Faculty Director) • W. Rath (Legal Research Fellow) CIRCA • K. Lund (Project Coordinator)
02/28/18 Teleconference	• CEEL • CLEAR	White Papers	• CLEAR review of CEEL White papers	CEEL • W. Rath (Legal Research Fellow) CLEAR • B. Hyde (Land Use Academy Director)
03/05/18 Teleconference	• CEEL • CIRCA	Final Conference Planning	• Review / Revise Draft Agenda • Logistics • Speakers	CEEL • J. MacDougald (Executive Director) • W. Rath (Legal Research Fellow) • E. Santovasi (Research Assistant) CIRCA • K. Lund (Project Coordinator)
03/12/18 Teleconference	• CEEL • DEEP	Coordinate S.B. No. 7 Testimony for Connecticut General Assembly Environment Committee	• Testimony Topics	CEEL • J. MacDougald (Executive Director) • W. Rath (Legal Research Fellow) DEEP • B. Thompson (Director of Land and Water Resources)
03/12/18 Teleconference	• CEEL • CIRCA	Coordinate S.B. No. 7 Testimony for Connecticut General Assembly Environment Committee	• Testimony Topics	CEEL • J. MacDougald (Executive Director) • W. Rath (Legal Research Fellow) CIRCA • J. O'Donnell (Executive Director)

Municipal Resilience Planning Assistance Project (MRPAP)
Summary of Task 9 Project Meetings

Date Location	Organiza-tions	Purpose	Topics	Attending
03/12/18 Teleconference	• CEEL • CIRCA	Coordinate S.B. No. 7 Testimony for Connecticut General Assembly Environment Committee	• Testimony Topics	CEEL • J. MacDougald (Executive Director) • W. Rath (Legal Research Fellow) CIRCA • J. O'Donnell (Executive Director)
03/12/18 Teleconference	• CEEL • CIRCA	Coordinate S.B. No. 7 Testimony for Connecticut General Assembly Environment Committee	• Testimony Logistics	CEEL • W. Rath (Legal Research Fellow) The Nature Conservancy • D. Sutherland (Director of Government Relations)
03/14/18 Connecticut Legislative Office Building Room 2B	• CEEL • CIRCA • CT DEEP • Legis-lative Env. Cmte.	S.B. No. 7 Testimony for Connecticut General Assembly Environment Committee	• Senate Bill No. 7, An Act Concerning Climate Change Planning And Resilience	CEEL • J. MacDougald (Executive Director) • W. Rath (Legal Research Fellow) CIRCA • J. O'Donnell (Executive Director) DEEP • R. Klee (Commissioner) • R. Kaliszewski (Deputy Commissioner) • B. Thompson (Director of Land and Water Resources)
03/19/18 Teleconference	• CEEL • CIRCA	Final Conference Planning	• Review / Revise Draft Agenda • Logistics • Speakers	CEEL • J. MacDougald (Executive Director) • W. Rath (Legal Research Fellow) • E. Santovasi (Research Assistant) CIRCA • K. Lund (Project Coordinator)
03/26/18 Teleconference	• CEEL • CIRCA	Final Conference Planning	• Review / Revise Draft Agenda • Logistics • Speakers	CEEL • J. MacDougald (Executive Director) • W. Rath (Legal Research Fellow) • E. Santovasi (Research Assistant) CIRCA • K. Lund (Project Coordinator)

Municipal Resilience Planning Assistance Project (MRPAP)
Summary of Task 9 Project Meetings

Date Location	Organiza- tions	Purpose	Topics	Attending
04/02/18 Teleconference	• CEEL • CIRCA	Final Conference Planning	• Review / Revise Draft Agenda • Logistics • Speakers	CEEL • J. MacDougald (Executive Director) • W. Rath (Legal Research Fellow) • E. Santovasi (Research Assistant) CIRCA • K. Lund (Project Coordinator)
04/04/18 UConn Storrs Innovation Partnership Building Room 203	• CEEL • CIRCA • UConn	Planning Grant Meeting	• Review / Revise Draft Agenda • Discuss / Agree-Upon Outline for Final Reports • Review Presentations for May 11 Conference	CEEL • J. MacDougald (Executive Director) • W. Rath (Legal Research Fellow) CIRCA • J. O'Donnell (Executive Director) • E. Anagnostou, Director of Applied Research) • R. French (Director of Community Engagement) • K. Lund (Project Coordinator) UCONN • C. Kirchoff (Professor of Engineering) • P. Minutti (Professor of Architecture) • Three UConn Grad Studnets
04/09/18 Teleconference	• CEEL • CIRCA	Final Conference Planning	• Review / Revise Draft Agenda • Logistics • Promotion • White Paper Integration	CEEL • J. MacDougald (Executive Director) • W. Rath (Legal Research Fellow) • E. Santovasi (Research Assistant) CIRCA • K. Lund (Project Coordinator)
04/18/18 DEEP 79 Elm St. Hartford, CT	• CEEL • DEEP	Legislative Agenda	• Senate Bill No. 7	CEEL • J. MacDougald (Executive Director) • W. Rath (Legal Research Fellow) DEEP • R. Kaliszewski (Deputy Commissioner) • B. Thompson (Director of Land and Water Resources) • L. Sawyer (Director of Legislative Affairs)
04/23/18	• CEEL • CIRCA	Final Conference Planning	• Review / Revise Draft Agenda • Logistics	CEEL • J. MacDougald (Executive Director)

Date Location	Organiza-tions	Purpose	Topics	Attending
Teleconference	• UConn Law		• Promotion	• W. Rath (Legal Research Fellow) • E. Santovasi (Research Assistant) • L. Cooley (Research Assistant) CIRCA • K. Lund (Project Coordinator) UCONN LAW • D. King (Events and Programs Manager)

04/25/18
 	
UConn Law
Starr Reading Room
	• CEEL
	• UConn
	• UConn Law
		Final Conference Planning	• P. Minutti Presentation
			  ○ Identify IT Requirements
			  ○ Identify Stage requirements
			  ○ Rehearse
				CEEL
				• J. MacDougald (Executive Director)
				• W. Rath (Legal Research Fellow)
				• E. Santovasi (Research Assistant)
				UCONN
				• P. Minutti (Professor of Architecture)
				UCONN LAW
				• D. King (Events and Programs Manager)
				• M. Linn (IT)

04/23/18 Teleconference	• CEEL • CIRCA	Final Conference Planning	• Programs • Promotion • Sponsorship	CEEL) • W. Rath (Legal Research Fellow) CIRCA • K. Lund (Project Coordinator)
04/30/18 Teleconference	• CEEL • CIRCA	Final Conference Planning	• Speakers • Logistics • Promotion	CEEL • J. MacDougald (Executive Director) • W. Rath (Legal Research Fellow) CIRCA • K. Lund (Project Coordinator)
05/07/18 UConn Law Starr Reading Room	• CEEL • UConn • UConn Law	Final Conference On-Site Planning	• Speakers • Logistics • Promotion	CEEL • J. MacDougald (Executive Director) • W. Rath (Legal Research Fellow) CIRCA • K. Lund (Project Coordinator) UCONN LAW • D. King (Events and Programs Manager) • M. Lynn (IT)

Municipal Resilience Planning Assistance Project (MRPAP)
Summary of Task 9 Project Meetings

Date Location	Organiza- tions	Purpose	Topics	Attending
05/22/18 Teleconference	• CEEL • CIRCA	Final Conference Review	• Post-Conference Review	<u>CEEL</u> • J. MacDougald (Executive Director) • W. Rath (Legal Research Fellow) <u>CIRCA</u> • K. Lund (Project Coordinator)

APPENDIX H

UCONN | COLLEGE OF AGRICULTURE, HEALTH AND NATURAL RESOURCES

September 2017

Municipal Issues & Needs for Addressing Climate Adaptation in Connecticut

Bruce Hyde, UConn Center for Land Use Education and Research and UConn Extension
Juliana Barrett, Connecticut Sea Grant College Program and UConn Extension

This report is a product sponsored by the Connecticut Institute for Resilience and Climate Adaptation (more information about CIRCA can be found at circa.uconn.edu). The work is made possible through a grant from the State of Connecticut Department of Housing CDBG-Disaster Recovery Program and the US Department of Housing and Urban Development.

Sea Grant Connecticut

CLEAR

About this Report

Coastal municipalities are facing a significant number of challenges in planning for, and adapting to, changing weather patterns and climate change. Lack of resources and staff expertise make it more important than ever that research and support designed to assist municipalities with resiliency planning and implementation be something they can truly use. This study, designed to collect information on what exactly coastal communities can "truly use," was one of ten tasks comprising the *Municipal Resilience Planning Assistance Project*, funded by the U.S. Department of Housing and Urban Development in 2015 and coordinated by the Connecticut Institute for Resilience and Climate Adaptation (CIRCA). All ten tasks were focused on the coastal counties impacted by Storm Sandy in 2012.

From June 2016 to February 2017, officials from twenty municipalities in Connecticut counties impacted by Superstorm Sandy were interviewed to develop a list of their most pressing concerns and needs with respect to climate resiliency. A second objective was to determine what standard of authority and data uncertainty associated with research on sea level rise and floodplain mapping municipal officials are willing to accept, with regard to including this information in their planning and regulatory documents. The information in this report can be used by researchers and state agencies so they can provide resources that municipalities find applicable to their needs and defensible when used.

Task 10: Determination of Municipal Issues and Policy and Research Needs

Scope

The purpose of this task is to understand the most pressing needs facing municipalities with respect to climate change and to develop a list of research questions that municipal officials need answered. These questions/issues will assist CIRCA directors, climate researchers and others to develop practical solutions to municipal climate challenges through applied research. In addition, interviews sought to determine what standard of authority and data uncertainty municipal officials are willing to accept, in terms of research results for sea level rise and floodplain mapping for inclusion in their planning and regulatory documents. This information will guide researchers and state agencies so that they can provide results that municipalities find applicable and defensible when they are used. This project also included coordination with a Legal Research Fellow from the UConn Law School Center for Energy and Environmental Law (Task 9) and appropriate CIRCA Directors on the information gathered. This task was implemented by the Connecticut Sea Grant College Program and the UConn Center for Land Use Education and Research (CLEAR).

Methodology

Municipalities are facing a significant number of challenges in planning for and adapting to changing weather patterns and climate change. Officials from thirteen municipalities in Connecticut counties impacted by Superstorm Sandy were interviewed between June 2016 and February 2017. Interview questions for municipal officials were reviewed by UConn's Institutional Review Board and shared with a CIRCA research director. Interviewees were a mix of municipal officials including elected officials and officials from town departments including public works, planning, conservation, emergency management and health. Also interviewed were engineers contracted by multiple towns to provide engineering services. All interviews were conducted in person. Interview questions are listed in Appendix A.

Presentations and confirmation interviews were conducted with an additional seven municipalities to ensure the findings were valid. A list of municipalities interviewed for each phase can be found in Appendix B. These interviews also consisted of a mix of municipal officials. They were provided with a summary of the findings (See Appendix C) and asked if they agreed, disagreed or had anything to add. The responses received from these interviews have been incorporated into the findings in this report. **To ensure an uninhibited flow of information, all interviewees were assured their responses would be kept confidential.** All participants will receive a copy of the final report.

Regular meetings and calls were conducted with the CEEL Legal Research Fellow and CIRCA Director for Applied Research working on Task 9. Information on municipal priorities was provided as interviews were conducted.

Executive Summary

Information from the interviews was grouped into 17 categories based on issue similarity. In addition, categories were ranked into high, medium and low priorities based on feedback from interviewees. In many areas, the issues overlap categories (and each other), illustrating the complexity of the climate adaptation challenges facing communities.

Categories and a brief discussion of issues follow. More detail is provided in the next section.

HIGH PRIORITY ISSUES

Flooding: Impacts on Infrastructure

- This is the biggest municipal concern based on the number of comments made during the interviews. Concerns with flooding ranged from the need to raise roads that flood during astronomical high tides to protecting wastewater treatment plants and pump stations from flooding during storm events.
- Planning and policy issues come into play when considering the best adaptation strategy to protect infrastructure from future vulnerability. Infrastructure impacts in a broad sense extend to whole neighborhoods as well as to those that are site specific.
- Tight municipal budgets are forcing communities to react to problems rather than address the issue proactively. Most municipalities need assistance determining what infrastructure assets are going to be vulnerable under what flood scenarios, how best to protect them and where to get funding to implement solutions.
- *Note*: While maps are helpful, many municipal officials draw on their years of experience in knowing which areas are most vulnerable to flooding. However, changes particularly in intense precipitation events are causing flooding in areas that previously never flooded before.

Flooding: Predicting Inundation Levels

- Municipal officials want to know what areas of their community are going to flood, when and how deep when a storm is forecast. They need to be able to accurately identify areas that will be impacted by a particular event. This information is used to determine when and where to issue evacuation orders, deploy emergency operations equipment like fire and ambulance, and protect vulnerable infrastructure.
- Some communities need maps that combine storm surge with riverine flooding, particularly during heavy precipitation events.

- Desirable areas for development may lie within areas that will be prone to flooding or be impacted by future sea level rise. Given the financial situation in Connecticut towns it is very difficult to not allow any development in these areas, so towns need to know what development alternatives they might have. (e.g. Should all structures be elevated?)
- This category also includes the increasing frequency of residents being isolated by higher tides not related to storm events ("sunny day flooding"). As this situation becomes more common, municipalities need help to address this issue.
- Towns are particularly concerned that retaining the character of their communities may become more and more difficult as homes and roads are elevated and other roads are abandoned due to flooding and (future) retreat.

Stormwater Management/Extreme Precipitation

- How to cope with increasing frequency of intense precipitation events also ranked high on the list of climate related concerns facing municipalities. Most municipal stormwater systems were developed 40-50 years ago and are straining to handle the new precipitation levels (in combination with, in most cases, the increase of impervious surfaces related to development). This has caused an increase in street flooding in urban areas.
- Municipalities need design and financial assistance to: 1) develop a comprehensive analysis of municipal stormwater systems; 2) determine priorities for replacement, and; 3) determine how to cost effectively retrofit existing stormwater infrastructure and how to better manage increased stormwater flows.

Coastal Erosion

- Municipalities are concerned about protection of private residents, commercial structures, beaches, dunes, and bluffs from erosion caused by coastal storms. The potential loss of town tax base if retreat becomes necessary was mentioned by several municipalities.
- Other issues include the most cost effective way to prevent erosion, restoration of breached dunes, and exposure of septic systems on coastal properties.

MEDIUM PRIORITY ISSUES

Emergency Operations and Storm Events

- Downed wires during storm events were one of the major issues for towns. How to better manage municipal response before, during and after a storm event was mentioned.

CT DEEP

- While DEEP personnel are well liked as individuals, there is a general perception that DEEP has not been helpful when it comes to assisting towns with climate related matters.
- One community mentioned that there were a lot of regulatory problems with DEEP not embracing resiliency projects that are in a coastal resource area, i.e. below the coastal jurisdiction line.
- Some communities feel DEEP is difficult to work with, needs to streamline the permitting process and has a credibility problem. Part of this may be related to the way DEEP is structured with enforcement and planning being within the same unit. Some communities mentioned that enforcement actions contributed to the overall negative view of DEEP.
- One community suggested looking to other states to see how they organize their “DEEP responsibilities” and how they assist municipal efforts aimed at addressing climate issues.
- Communities would like the State to be a leader with regard to climate.

Policy/Planning/Zoning

- Municipal policy, planning and regulatory efforts relative to climate adaptation are inconsistent from town to town. Some elected municipal officials are supporting efforts to incorporate climate adaptation actions into their municipal plans and policies and others are not.
- Municipal staff are the driving force behind moving these efforts forward and they must fit these efforts into existing responsibilities. Additional guidance and support is needed with the weight of the State behind it.
- Related to communications, municipal staff need an outside agency to provide public education about local (municipal level) climate change impacts.

Budget/Costs/Taxes

- Municipalities are concerned about the impacts of climate change on their tax base if retreat becomes necessary.
- In one community, the assessor is getting appeals of tax bills from some residents claiming that their property is worth less due to sea level rise or coastal erosion.
- Municipalities need to know what to do about vulnerable neighborhoods. The high cost of flood insurance may contribute to decreasing property values in the future.

Communications—Public

- Municipalities need assistance communicating climate challenges and adaptation actions to local boards and the public. For example, getting people to understand what

1 ft. of SLR really means and risks associated with sea level rise and extreme precipitation events is needed.
- As one municipality put it, “public outreach is tough, it takes money.” There is a need to strengthen emergency preparedness communications with residents.

Septic System Failure
- Storm surge, high water tables and heavy precipitation events are increasingly causing septic systems to fail.
- During storm events, coastal septic systems have been uncovered and in some cases, physically moved.
- Septic system failure on the coast can cause a reduction in water quality, environmental damage and potentially contaminate water supply systems. This is of concern not just during storm events, but as groundwater levels rise and with possible saltwater intrusion.

Low Priority Issues

FEMA
- Some communities expressed concern and frustration over FEMA storm damage reimbursement procedures and changes to these procedures between Storms Irene and Sandy.

Communications—Utilities/Amtrak
- Although it was generally felt that utility companies and Amtrak have done a better job communicating with local officials, there is still room for improvement. Communication problems are most apparent during storm events when both utilities and municipalities are working to manage their own storm responses.

Budget/Capital Improvement Plan
- With few exceptions, communities are not budgeting for climate adaptation in either their Capital Improvement Plan or annual budget.
- Climate is not really an “immediate” issue and so is not included in capital programs. Other capital needs are taking priority.
- Some municipalities are starting to look at their capital budgets in terms of climate change. One problem is that funding sources may not allow upgrading in consideration of climate change.
- Municipal officials are reluctant to support anything that increases the budget and raises taxes.

- Some municipalities are considering climate change impacts for site-specific projects like raising or replacement of bridges and roads.

Water Supply and Quality

- While some municipalities have had issues with saltwater intrusion into drinking water, most are on municipal water systems.
- One community mentioned having major issues with road salt in water systems. Although one municipality said that this was one of their five most pressing issues, there does not appear to be a significant problem at the present time.
- Shoreline agriculture, while small, is growing with numerous Community Supported Agriculture farms (CSA's) and legacy agriculture. There are growing concerns related to salt water intrusion and the water supply needed to maintain these farms, particularly during periods of drought.

Post Storm and Debris Management

- A number of municipalities mentioned dealing with debris resulting from a storm as a problem. Issues with finding a site to stockpile debris, what can be done with certain types of debris, permitting and the FEMA reimbursement process were raised.
- A priority for municipalities after a storm is to clear the roads to allow for emergency vehicle access and residents to return to their home. Sand is often pushed up onto roads and, in some cases, mixed with glass and other debris so cannot be put back on beaches.

Environment

- The impact of a changing climate on the environment received little mention. Impacts of salt on vegetation and salt water intrusion with regard to agriculture were raised.
- Concern was raised about impacts of SLR and storms on town beaches as well as impacts of warmer temperatures on the water quality of Long Island Sound, and consequences of this on tourism and swimming in the Sound.

Health

- Several climate change related health issues were raised by municipalities, particularly as many communities have an aging population. There was some concern expressed about vector borne diseases, prolonged heat waves, and the need to ensure that at-risk populations have needed medical supplies and appliances during storm events.
- Mold following flood events is of concern.
- Other concerns were associated with water quality in Long Island Sound and the ability to swim in public beaches.

Municipal Climate Adaptation Needs and Questions

A more detailed account of municipal adaptation needs and questions is provided below. This information can be used by researchers, engineers, regulators and others to focus their efforts on the areas of highest priority for municipalities, such that towns can better plan for and implement adaptation measures.

Flooding-Impacts on Infrastructure

1. Assistance determining what will be vulnerable and under what conditions. Municipalities need this to prepare for climate related impacts, and they must have an accurate assessment for inclusion in a municipal CIP and other budgets. Of particular concern is how to protect municipal wastewater systems—treatment plants, pump stations and collection systems—from flooding caused by storm surge and sea level rise. Wastewater systems that span multiple communities need a coordinated effort – not just resilience for the wastewater treatment plant itself.
2. Design assistance for site-specific projects and funding sources to build new infrastructure or solve an existing problem. How should a road through a wetland that floods be redesigned to account for climate related changes, have the least environmental impact and be most cost effective? How can flooding caused by rail line embankments be mitigated? What does a municipality need to do to its wastewater treatment system to protect it from the impacts of climate change? Wastewater treatment plants and pump stations on the shore are particularly vulnerable. Sewer lines are subject to infiltration during periods of heavy precipitation.
3. Updated design standards and procedures related to rebuilding stormwater systems, culverts and bridges after damage from storms or when replacing older infrastructure are needed. Municipalities would like to see updated design standards that take into account changes in precipitation patterns and frequency of events. They want to know if they should be designing for more extreme weather events. Until there is a new design standard adopted by the state or federal government, some municipalities are unlikely to change from the TP 40 standards. Some communities indicated that they do take into account new precipitation rates for site-specific projects such as increasing culvert size when replacing one.
4. Several municipalities mentioned that current FEMA regulations only allow for replacement in kind when reimbursing a municipality for repairs related to storm damage. This results in newly constructed infrastructure that may be as inadequate for current and future conditions as what was damaged. One community suggested allowing for a rebuild of 1.2 X the original size similar to what is done in Massachusetts.
5. Often times, an entire stormwater system does not need to be replaced, but rather, key locations. Modeling of stormwater systems is needed to determine the most cost

effective way to improve drainage to minimize flooding due to undersized systems given current/predicted precipitation levels.

Flooding-Predicting Inundation Levels

1. Information is needed to allow municipal officials to determine impacts from a particular storm. As far in advance as possible, they need to know what areas of their community are going to flood, when and how deep. This information is critical to municipal decision making in an emergency situation. They need to decide when and where to issue evacuation orders, deploy emergency operations equipment such as fire and ambulance, and protect vulnerable infrastructure.
2. Mapping to identify areas isolated by locally flooded roads that are vulnerable to sea level rise and planning assistance for how to best address the site-specific situations.
3. More accurate information about inundation probability to maintain credibility. There is a concern about ordering evacuations or taking some other action based on predictions and the storm intensity/inundation levels turn out to be significantly less than predicted. When this occurs more than once, residents tend to be skeptical of future warnings.
4. Accurate mapping and elevation data which show flood levels from all combined sources—precipitation, tides, storm surge, sea level rise, and river flooding.
5. Installation of high watermark signs to inform residents of the potential for flooding in a particular area. However, there are pros and cons to this: these signs may get taken down by people trying to sell homes.

Stormwater Management/Extreme Precipitation (some of these issues are related to infrastructure impacts)

1. Municipalities are experiencing an increase in flooding during periods of extreme rainfall. Guidance on how best to manage short duration, high intensity storms and their impacts on stormwater systems is needed. How can a municipality identify choke points in an existing stormwater system and design a solution in the most cost effective way? How to best assist municipalities to address stormwater management in their regulations?
2. Update, using the best source of data, the Connecticut Stormwater Quality Manual to reflect the new precipitation realities. Many municipalities are waiting for this to happen before they replace or build new infrastructure.
3. What authority do municipalities have to require maintenance of privately owned detention basins to ensure they are functioning as designed? Also there are concerns related to vector borne diseases in detention ponds.
4. What is the impact on septic systems and municipal infrastructure of supersaturated soils during major storm events?
5. Determine the relationship between SLR and groundwater levels and future impacts on groundwater.

Coastal Erosion

1. During recent storm events, many municipalities experienced dune blowouts. Research on the most cost effective methods of protecting dunes from erosion before it is too late to recover is needed.
2. Engineering design and financing options for protecting roads leading to residences that are subject to erosion during storm events.
3. As noted in the Issues/Septic System section, erosion from storm events has uncovered and, in some cases, washed away septic systems. Developing alternatives to placement of on-site systems in areas subject to erosion will help to reduce this vulnerability.

Emergency Operations and Storm Events

1. Develop best practices for better communications between utilities and municipalities before, during and after storm events.
2. Development of apps (and other technologies) to better manage emergency situations (e.g. real time feedback on clearing of downed trees and wires).
3. Best management practices for how to address Emergency Operations issues, such as firefighting, when residences are elevated.
4. Information on what to do about fire hydrants being impacted by sea level rise.
5. Assistance for vulnerable businesses with planning for storm events. Some large manufacturers in vulnerable areas need to have a plan in place for what to do when power goes out, evacuations, etc.
6. Need guidance on planning for emergency shelter operations during storm events. Need more guidance of how to fund shelters. Need planning for long-term shelters and pet accommodations.
7. Need to develop better communications to tell residents of available resources to help them prepare their home for storm events and possible evacuation.

CT DEEP

1. Need to develop more reasonable regulations re: removing rubble after it is deposited in the water after a storm. Provide clarification (better wording) when an Emergency Authorization is issued so people understand what they are authorized to do. Coordination needed between DEEP and ACOE when an EA is issued.
2. Need support from DEEP in enforcement when people repair their property after storms.
3. Need DEEP to embrace resiliency projects that are in a coastal resource area, i.e. below the coastal jurisdiction line, rather than establish regulatory hurdles. The permitting process needs to be streamlined for repairs.
4. Need for DEEP to better relate to municipalities and their needs to regain trust. Some of the comments received included DEEP “needs to be educated in a lot of areas” and DEEP “needs to understand the science.”

5. Dam safety is a concern in several municipalities. The DEEP Dam Safety Inspection Program is understaffed. A BMP guide for maintaining the safety of municipal and private dams, including recognizing indicators of dam failure, should be developed.
6. After major coastal storms, repairs to sea walls on neighboring properties were not always coordinated, so there were different types of solutions.
7. Municipalities have ideas for solutions to road flooding but DEEP regulations are a problem when resilience solutions go into tidal wetlands. There is a need to streamline or override the regulatory process and better balance resources and resilience solutions.
8. DEEP assistance is needed to help communities develop design solutions for sewer lines that go through sensitive areas like marshes.

Zoning/Planning/Policy

1. Municipalities that have not been fortunate enough to receive grant assistance to hire a consultant need assistance preparing municipal climate adaptation assessments and plans. This should include choices about what to rebuild or redesign infrastructure with limited resources.
2. Assistance with rewriting municipal plans and regulations that address climate adaptation actions. Before enacting regulations as a response to climate related threats, municipalities need to know about any conflicts between private property rights and regulatory controls.
3. Research to determine what the impact on municipalities would be if the Federal Government were to no longer subsidize the National Flood Insurance Program. How will the increase in premiums affect property values and tax bases?
4. Need to determine new building code standards so structures are more resistant to wind and wave damage.
5. Can a municipality adopt a policy that would allow the creation of special taxing districts in flood hazard zones where there is municipal infrastructure? Can they use funds for the protection of the district, like a TIP for climate adaptation?
6. Municipalities need guidance from state or federal government about what data to use in plans and regulations. Several communities mentioned the need for consistency of data in planning documents from one town to the next. Currently some climate action plans use data from one source and others from another. Other states benefit from a State Planning office to coordinate climate adaptation efforts.

Budget/Cost/Taxes

1. Municipalities need to understand the possible impacts of sea level rise on the municipal tax base when/if retreat becomes necessary.
2. Municipalities need financial resources to implement some of the known solutions to problems.

3. Municipalities need to address the question of what to do about vulnerable neighborhoods. There are many issues municipalities may be facing when considering the impacts of climate change related events on neighborhoods. How to address road flooding, septic tank failure, water supply, emergency services and possible loss of structures are already issues in some municipalities.
4. How does a municipality respond to a property owner who is appealing his/her tax assessment claiming that the property is worth less due to loss of property with sea level rise or coastal erosion?

Communications—Public

1. Municipalities need help communicating the climate adaptation challenges they are facing to the public, such as getting people to understand what 1 ft of SLR really means in terms of impacts. Often someone from the outside has a better opportunity to communicate this than municipal staff.
2. Resilience education is needed. Most people on the coast recognize the need to elevate homes. Riverine systems residents have less understanding of climate issues. They need information on what they need to do to protect themselves.

Septic System Failure

1. Septic system failure due to intense rainstorms or coastal flooding is becoming more common. Municipalities need information on impacts of SLR on ground water levels—septic tank failure and how to deal most economically address the problem.
2. During some storm events, coastal erosion results in the exposure of on-site systems. Design solutions to address this issue are needed as this problem will only get worse.

FEMA

1. Many communities would like FEMA to amend storm related reimbursement procedures to be clearer and so that infrastructure can be upgraded to take into account new precipitation standards.
2. Most municipalities are concerned over the accuracy of FEMA Flood Insurance Rate Maps. Recent revisions to the maps resulted in a number of residents needing to obtain flood insurance. Municipalities need more accurate maps that are approved by FEMA for the purposes of the National Flood Insurance Program.

Communications—Utilities/Amtrak

1. Better communication between Amtrak and local residents is needed. There is concern that projects Amtrak undertakes are not done in consultation with municipalities and do not consider local impacts.
2. Municipalities want to work with Eversource to establish a list of critical facilities to prioritize for restoration of electrical service.
3. Need better communication from utilities.

Budget/Capital Improvement Program

1. Many communities are not considering climate change impacts when budgeting for new infrastructure. They would like the State to take the lead in encouraging municipalities to use updated information when designing capital investments. Need a cost/benefit analysis taking climate adaptation into account when making capital investments. Funding sources are needed to help communities invest in climate adaptation.

Water Supply

1. While many communities have community water systems, salt water intrusion into drinking water supplied through individual or community wells is becoming more of a concern. Sea level rise, storm surge and road salt application are contributors to the problem. The issue also extends to salt water intrusion on water supply for agricultural interests. Research into the best method of protecting water supply from salt water intrusion is needed.

Post Storm and Debris Management

1. Municipalities need a standard set of procedures for how to deal with debris management, especially when it comes to environmental regulations and reimbursement procedures. Several municipalities felt that procedural changes need to be made well in advance of a storm so there is time to understand them. These standards should address securing debris during a storm event as well as disposal after it.
2. If the National Guard is called in during an emergency event, they will do things their way. Because their reporting structure is totally different from municipal ones, it can be difficult to work with them. How can this issue be addressed by municipalities?

Environment

1. Follow up on research that identifies the impact of sea level rise on marsh migration and flood storage capacity. Looking for innovative ways to duplicate marsh flood storage capacity when it is lost to sea level rise.

Health Issues

1. A few municipalities raised concerns about health issues in the future especially from vector borne diseases and extreme temperatures. During storm events there is a need to identify at risk populations that need power for medical appliances. Some municipalities need assistance with the logistics of establishing shelters for residents, particularly the elderly, during storm events and heat waves.
2. Need to address the issue of old sanitary lines and the backup of sewage into people's homes. There is also the need to address the issue of sewer lines in tidal wetlands.

Next Steps

It is clear that municipalities have many needs that could be addressed by researchers to help them address the impacts of climate change on municipal operations. Not funded as part of this task but a necessary next step is comparing municipal needs to existing research efforts. For each of the needs identified, what is the current status of research, if any, that addresses those needs? Has it been peered reviewed and published? What research being conducted at UConn is similar to research at other institutions or in the private sector? How does it compare to current research efforts?

For example, the Town of Stonington used consultants to prepare a resiliency plan. The consultants developed models that show inundation levels for the town taking into account sea level rise, storm surge and intense precipitation events. How does ongoing modeling research done at UConn compare to this modeling effort. It would be helpful if there was a standard model that was approved by the State and used in the future by all municipalities so there is consistency from municipality to municipality. A review of the status of research which meets identified municipal climate adaptation needs is necessary to gain an understanding of where future research should focus.

It should be noted that research needs to meet certain standards for municipalities to be comfortable using it in official documents. A discussion of those standards can be found in the next section of this report, *Standards of Authority for Data*.

Task 10 Standard of Authority for Data Sources

Summary

Municipalities were adamant about using data that had a state or federal stamp of approval in their regulatory documents. Every municipality except one stated that they need to have some form of official endorsement of data from the state or federal government for use in certain municipal documents. For planning documents the standard was less stringent: peer reviewed data from universities or information developed by NGO's was acceptable to some municipalities, while others would only use that which was approved by the state or federal government. Municipal officials are concerned about justifying data sources to both citizens and to town boards and commissions in the event the data are challenged. Chief elected officials, town councils, finance boards, etc. generally do not have the expertise to justify the use of specific data so they need to rely on a "higher authority" such as a state or federal agency.

The following list of comments made by municipal officials during the interviews is the best way to illustrate their concerns.

Comments made by municipal officials with respect to regulatory documents include:

1. Need to be able to point to something and say, "They made me do it" when it comes to using data. Even with using it for a plan, one will need backing of the town council and they will ask where the data came from.
2. Need to have official approval for data to be useful. Want to be absolved of responsibility for accuracy of data by passing the buck to the state.
3. Concerned about the potential for legal challenges for different sources of data in planning and regulatory documents.
4. Data needs to be defensible in court. Would be nervous about using anything other than FEMA data even in planning documents.
5. Need maps to be certified by federal agencies or state.
6. If data from a university professor is wrong, is he going to pay for the consequences?
7. Data that are peer reviewed are considered "good data."

There were a limited number of comments that showed more flexibility when it comes to planning documents:

1. Universities are a great source of science if it comes from more than one place and is peer reviewed. The question is how do you get it to be more generally accepted?
2. No concerns about using data from Universities, NGOs, etc. in planning documents.
3. If using other data (other than federally or state approved sources), the question of qualifications to do the modeling comes up and a host of issues can result afterwards.

Appendix A – Interview Questions for Municipal Officials

Climate Change in Connecticut's Coastal Communities – Municipal Assessment

Target Audience: Municipal Officials (both elected and staff)**,** Regional Planning Agency Officials

Identification of Needs: Questions will focus on community needs to respond to extreme weather events in the short term as a result of more intense precipitation and storm events, as well as adaptation efforts for the long term challenges of climate change.

Methods/Structure of Interviews

The pool of interviewees included chief elected officials, town planners, zoning officers, wetlands or conservation officers, environmental planners, engineers, public works and health officials and consultant engineers. It should be stressed that information collected in the interviews was limited to opinions of the individuals, and do not necessarily reflect the perception of all the towns' staff and/or officials.

Each interview ranged from approximately 1 to 2 hours in length. During these conversations, we used a "semi-structured" interview approach. Interviews were loosely structured conversations focused on the questions found below, along with impromptu follow-up questions based on individuals' responses. Verbal responses were categorized by question with hand written notes.

Current Climate Related Issues and Needs

1. Remembering the challenges your town went through during recent storms over the past 5 years, Sandy, Irene, October snowstorm and other heavy wind, rain and snow events. What were the biggest challenges you faced, how did you deal with those challenges and what information or resources would have helped you better meet those challenges?

   This question is designed to get the respondent thinking about a real event and give them a frame of reference rather than hitting them right away with something abstract (What do you think the effects of climate change will be on your community in the future?). Also it will help to raise addressing of short-term issues.

   <u>Prompts</u>*: permitting issues, infrastructure issues (what was damaged or vulnerable), street flooding, post storm clean-up, flooding predictions v. reality, stormwater management*

2. Thinking back to Irene, Sandy and the October Snowstorm, what impacts do you think a Category 2 or 3 hurricane (with major rain/wind inland) would have on your community?

   Prompt: what infrastructure or critical assets were damaged or in danger of being damaged that would be impacted more severely by a larger storm?
   For inland communities – think about power outages and stormwater flooding; potential for dams to give out.

3. If a storm was headed your way, what information do you need to make emergency management decisions?

   Prompts: evacuations, inundation levels (tide stage plus surge) and areas predicted to flood, when it will hit, what to protect.
4. FOR COASTAL COMMUNITIES---If NOAA predictions of SLR (approx. 3 ft by 2085) hold true, what impact in terms of erosion, flooding, damage, etc. would that have on (name of Community)? What information do you need to help prepare for SLR and reduce risk vulnerable assets?

Future Climate Change Issues

1. What do you feel will be the biggest municipal management challenges you will face from:
   a. Sea level rise
   b. Changes in precipitation events flooding, infrastructure vulnerability, stormwater management, etc.
   c. Erosion (coastal)
   d. Aging infrastructure (including dams)
   e. Drought conditions—reservoirs depleted, lack of water for irrigation
   f. Prolonged heat waves
   g. Vector born diseases (mosquitoes)

2. As part of the preparation of your municipal budget and capital improvements plan, have you started to consider the impacts of climate adaptation needs?
   a. *Prompts: need to increase culvert size or other stormwater considerations, use of Green Infrastructure*

Climate Adaptation Planning and Policy

The purpose of these questions is to explore what municipalities are doing to address climate adaptation on the planning/policy level.

1. What is the political environment in your town toward taking action to address climate change?
2. What do you need to help you move adaptation efforts along?
3. What do you feel are the 5 most pressing climate adaptation challenges that will be facing your town in the next 25 years? What information or data do you need to address those challenges?
4. What research projects would help you address climate adaptation challenges?
5. In general, what would be most helpful to you to address climate adaptation challenges that will be facing your community now and in the next 5, 10, 25 years?
6. Is there anything that we haven't discussed that you would like to bring up related to how your municipality is addressing climate adaptation issues?

<u>Prompts</u>: Do you address climate adaptation in your POCD or other land use documents? Has your town established policy or regulations to address climate adaptation issues? Would it help to have sample regulations and/or policies that you can modify to suit your needs?

Standard of Authority Questions for Climate Change in Connecticut's Coastal Communities

1. How concerned are you about the sources of the data you use in your planning documents?
2. How concerned are you about the sources of the data you use in regulatory documents?
3. Are you concerned about potential legal challenges to your official town documents or decisions based on the source of data used?
4. Do you require data, for example flood maps, sea level rise projections, used in your official documents to be accepted, certified or approved by a state or federal agency.

Appendix B– List of Municipalities Interviewed

Initial Interviews

Branford
City of Groton
East Lyme
Greenwich
Madison
Milford
North Branford
Old Lyme
Old Saybrook
Stratford
Waterford
Westbrook
Jacobson Engineering

Confirmation Interviews

Clinton
East Haven
Guilford
New London
Stonington
Town of Groton
Fairfield

Appendix C—Summary sheet provided to municipalities for the confirmation interviews

Municipal Needs to Address Climate Adaptation Issues

<u>**High Priority**</u>

Flooding-Impacts on Infrastructure

Most municipalities need assistance determining what infrastructure assets are going to be vulnerable, when they will be vulnerable, how best to protect them and where to get funding to implement the solution.

Flooding-Predicting Inundation Levels

Municipal officials want to know what areas of their community are going to flood, when and how deep when a storm is forecast. They need to be able to accurately identify impacted areas arising from a particular event.

Flooding—Isolate residents/businesses

Related to predicting inundation levels during storm events, this category also includes the increasing frequency of residents being isolated by higher tides not related to storm events.

Stormwater Management/Extreme Precipitation

Municipalities need design and financial assistance to determine how to cost effectively retrofit existing stormwater infrastructure and how to better manage increased stormwater flows.

Coastal Erosion

Municipalities are concerned about protection of private residents, commercial structures, beaches, dunes, and municipal facilities from erosion caused by coastal storms. Potential loss of tax base if retreat becomes necessary was mentioned by several municipalities. Other issues included the most cost effective way to prevent erosion, restoration of breached dunes, and exposure of septic systems.

<u>**Medium Priority**</u>

Emergency Operations and Evacuation Routes

How to better manage municipal response before, during and after storm events was mentioned. For example: need for more efficient emergency operations systems, shelter operations, and evacuation routes.

DEEP

There is a general perception that DEEP has not been helpful when it comes to assisting towns with climate related matters. One community mentioned that there were a lot of regulatory problems with DEEP not embracing resiliency projects that are in a coastal resource area, i.e. below the coastal jurisdiction line. While individual DEEP employees are well liked, some communities feel DEEP is difficult to work with, needs to streamline the permitting process and has a credibility problem.

Policy/Planning/Zoning

Municipal policy, planning and regulatory efforts relative to climate adaptation are inconsistent from town to town. Municipal staff is the driving force behind moving these efforts forward and they must fit these efforts into existing responsibilities. Additional guidance and support is needed with the weight of the state behind it.

Budget/Costs/Taxes

Municipalities are concerned about the impacts of climate change on their tax base if retreat becomes necessary. In one community the assessor is getting appeals of tax bills from some residents claiming that their property is worth less. Municipalities need to know what to do about vulnerable neighborhoods. The cost of flood insurance may contribute to decreasing property values in the future.

Communications—Public

Municipalities need assistance communicating climate challenges and adaptation actions to local boards and the public. Municipalities also need assistance communicating to residents what to do before, during and after a storm.

Septic System Failure

Municipalities need assistance to determine the most cost effective way to address on-site septic system failure. Storm surge, high water tables and heavy precipitation events are increasingly causing septic systems to fail. Septic system failure on the coast can cause a reduction in water quality, environmental damage and potentially contaminate water supply systems.

<u>Low Priority</u>

FEMA

Some communities expressed concern and frustration over FEMA storm damage reimbursement procedures. There is also dissatisfaction with the FIRMs.

Communications—Utilities/Amtrak

Although it was generally felt that utility companies and Amtrak have done a better job communicating with local officials there is still room for improvement. Communication problems are most apparent during storm events when both utilities and municipalities are working to manage their own storm response.

Budget/CIP

With a few exceptions, communities are not budgeting for climate adaptation in either their Capital Improvement Plan or annual budget. Other capital needs take priority. Some municipalities are considering climate change impacts for site-specific projects such as raising roads or replacement of bridges.

Water Supply

While some municipalities have had issues with saltwater intrusion into drinking water most are on municipal water systems. There does not appear to be a significant problem at the present time.

Environment

The impact of a changing climate on the environment received little mention. Impacts of salt on vegetation and agriculture were raised but d0 not appear to be of major concern at the present time.

Debris Management

A number of municipalities mentioned dealing with debris resulting from a storm as a problem. Issues with finding a site to stockpile debris, what can be done with certain types of debris, permitting and the FEMA reimbursement process were raised.

Health

Climate related health issues were not a pressing need for municipalities. There was some concern expressed about vector borne diseases and ensuring at risk populations had needed medical appliances during power outages.

Standard of Authority for Data Sources

Almost every municipality stated that it needs to have some form of official endorsement of data from the state or federal government for use in municipal documents; Less so for planning documents but municipalities (with one exception) were adamant about using only data that had a state or federal stamp of approval in their regulatory documents. However, there is concern about the potential for legal challenges for different sources of data in planning and regulatory documents. Municipal officials are concerned about justifying data sources to both citizens and to town boards and commissions in the event the data are challenged. Chief elected officials, town councils, finance boards, etc. generally do not have the expertise to justify the use of specific data so they need to rely on a "higher authority" such as a state or federal agency.