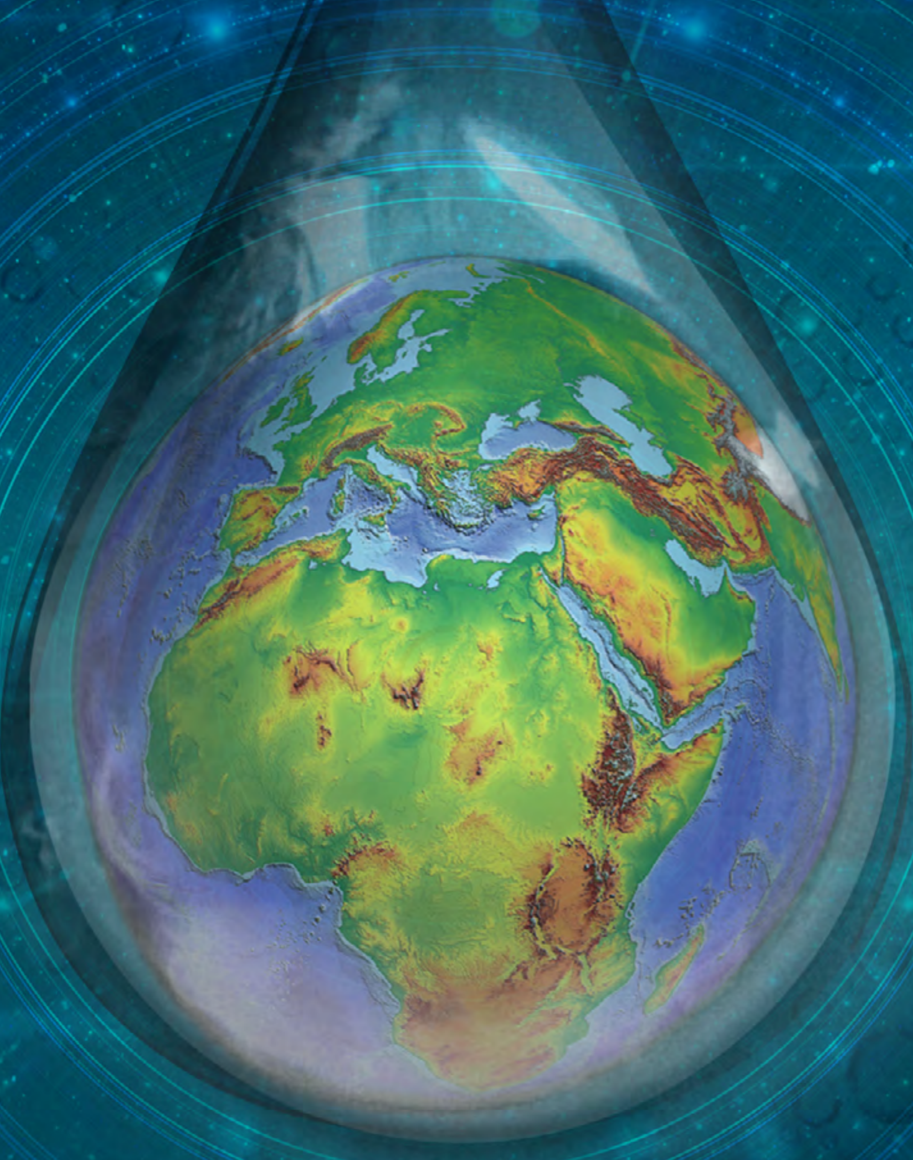
HYDROSPACE-GEOGLOWS 2021

SUMMARY AND RECOMMENDATIONS



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SUMMARY AND RECOMMENDATIONS

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ABSTRACT

This report summarises the main results, conclusions and recommendations of the "HYDROSPACE-GEOGLOWS 2021" Workshop organised by the European Space Agency (ESA), in collaboration with the French Space Agency (CNES) and the GEO Global Water Sustainability Initiative (GEOGloWS) (Fig. 1). This Workshop is a sequel to the ones held in Toulouse (F) in 2003, in Geneva (CH) in 2007 and in Frascati (I) in 2015. Nearly 300 scientists, engineers and managers registered to this virtual event from 41 countries, submitting 123 papers with more than 500 co-authors. The inclusion in the programme of large time slots for discussion and the advance preparation of "Seed Questions" offered the opportunity to have a community discussion focused on the future challenges of Inland Water monitoring and prediction and the future observational requirements. A "Manifesto" was drawn up from the discussion nourished by the participants. This report presents this "Manifesto", highlights the state of the art presented in the sessions, summarises the discussions and provides recommendations and guidance for future mission design, research activities for enhancing processing algorithms and developing new ones, calibration and validation, sustainable data exploitation, dissemination, outreach, capacity building and co-designing applications and operational services.

Figure 1
The "HYDROSPACE-GEOGloWS 2021" Workshop was held on-line from 7 to 11 June 2021, hosted by ESA-ESRIN.
Within the framework of this Workshop, three Sessions were scheduled over 8 half- days: **1**) Space techniques to measure hydrological surface variables, **2**) Modelling and Assimilation, **3**) From products to applications.

1. OBJECTIVES OF HYDROSPACE

Water on Earth's continents is continuously recycled through precipitation, evapotranspiration, discharge and runoff, vertical and horizontal diffusion and transfer in soils. An improved description of the global water cycle, especially the continental branch, is of significant importance for inventory and better management of water resources available for human consumption and activities (agriculture, urbanisation, hydroelectric energy resources, tourism, domestic use), as well as for biodiversity preservation and predictions to address disaster risk reduction. Both satellite and in situ observations are vital for understanding and creating solutions to the issues related to hydrology. HYDROSPACE2021 focused on inland water storage and runoff using in situ and remote sensing data, and modelling.

Satellites are an essential component of the observational network, providing an understanding of the relations among the regional, continental, and global scales. For instance, the monitoring of water level of lakes, reservoirs, rivers, and floodplains has been made possible thanks to the constant efforts and dedicated programs set up by several space agencies. The current and future generations of higher resolution radar-altimetry instruments, such as along-track Delay-Doppler (synthetic aperture radar) altimetry (CryoSat, Sentinel-3&6) and interferometric altimetry (SWOT, CRISTAL), are transforming the monitoring of surface hydrological parameters. With a new generation of instruments, images of higher resolution are obtained, requiring the development of new algorithms and the training of a new generation of scientists. It is also imperative to work towards analysis-ready satellite and in situ data and develop the technical skills needed to integrate and interpret the data and translate them into meaningful information that conforms to essential requirements of accuracy and utility to support policies and programs.

The Hydrospace conferences (2003 in Toulouse, 2007 in Geneva, and 2015 in Frascati) have traditionally focused on continental water monitoring using satellite techniques (altimetry, radar and optical imaging sensors, variable gravimetry) and hydrologic or hydrodynamic models. Since the last Hydrospace conference in 2015, some products, such as water level in lakes, reservoirs and rivers, flood extent and volume, river discharge, floodplain deltas, and estuaries have been promoted to operational delivery; others need further development, and some are just emerging as new products.

The Group on Earth Observations Global Water Sustainability (GEOGloWS) Initiative (www.geoglows.org) works to provide relevant, actionable water information to promote the use of earth observations in the decision-making process. Through partnerships, GEOGloWS leverages organisations' capabilities for projects that complement national efforts and provide information where little or none exists to achieve its mission. One of these collaborations includes ECMWF, NASA, NOAA, Brigham Young University, Esri, Aquaveo, the World Bank, and many National water organisations that have fuelled the streamflow forecasting services' technological development. These activities facilitate scientists' collaboration across disciplines to promote resource and project sharing while responding to user requirements in operational environments.

Considering the complementarity of GEOGloWS and the Hydrospace activities, this joint conference represents an opportunity to explore co-designed solutions with a broader view, and to address key issues including:

- What are the new key science questions? What are the new challenges and how should we address them?
- What are the new algorithms and the new advancements allowing the use of satellite data with the most advanced models, in particular for ungauged basin? How can we benefit from the new processing solutions offered by online super-computers?
- What aspects of surface water observations and modelling are sufficiently mature for use in operational services?
- Do we need new types of instruments? How can we extract new knowledge from the new missions ahead (Sentinel-6A, SWOT, Sentinel-3C/-3D, Sentinel-3 Next Generation Topography Mission [S3NG-T], CRISTAL, etc.)? How do we take advantage of all available data and give access for hydrologists to develop useful products?
- Could we improve the spatial and temporal coverage by altering scanning strategies (i.e., wider swaths of data) or by employing the satellite constellation concept rather than live with long repeat intervals?
- How do we fill the gap between Research and Development and Operational Use of remote sensing information in hydrological applications, forecasting operational system, and water resources management?
- How do we strengthen the collaboration between the four critical water communities: in situ, modelling, space observations and “non-scientist” users? Who the “non-scientist” users are and what they need is still an issue only partially addressed. Can we collectively do better? What are the new capabilities of space-based data for the application community?

The planned outcome of the workshop is to define an action plan for the future and converge on recommendations from the scientific, engineering and management communities. Several round table discussions were planned to cover the aforementioned seed-questions, detailed in **https://hydrospace2021.org/seed-questions**.

2. THE HYDROSPACE MANIFESTO

On-line to Frascati (I), 11 June 2021 - We, the *"Inland Water Storage and Runoff: Modelling, In Situ Data and Remote Sensing"* community (Fig. 1 and 2), are proud to celebrate the astounding progress in this domain since the beginning of the space era. Although there is no spaceborne mission currently dedicated to open surface water on Earth's continents, yet, the community has been working ardently, assiduously, enthusiastically and with forethought on exploiting space missions and in situ networks, and blending them in hydrologic and hydrodynamic models, developing dedicated products and applications. This happened also thanks to the visionary initiatives of space agencies and national and international funding organisations to further exploit Earth observation measurements through the now famous and fulfilling "secondary" mission objectives.

Continental waters have a crucial impact on terrestrial life and human needs, and play a major role in climate variability. Without taking into account the ice caps, fresh continental waters are stored in various reservoirs: the snow pack, underground reservoirs, the root zone (first few meters of the soil) and vegetation, and surface waters (rivers, lakes, man-made reservoirs, wetlands and inundated areas).

An improved description of the global water cycle, especially in the continental domain, is of major importance for improved assessment and better management of water resources available for human consumption and other water uses, as well as for short-term predictions and climate projections. Global monitoring of inland waters requires data products for Essential Water Variables (EWVs, i.e., in the context of this workshop, lake, reservoir, wetland water levels and volume variations, river levels and discharge, groundwater, etc.) that may be derived from satellite datasets, as well as river basin and floodplain water dynamic models. Satellites now provide an essential component for the observation of continental water from local to regional to global scales. Indeed, since the launch of Topex/Poseidon, ERS-1 and other radar and optical imaging sensors in the early nineties, long term monitoring of water level and extent on lakes, reservoirs, rivers, wetlands, and floodplains has been made possible thanks to the constant efforts and dedicated programmes set up by several space agencies and national and international funding organisations. It is evident that the next generation of inland water observing systems will continue to depend upon in situ networks together with satellite missions or constellation of missions.

The current generation of high-resolution radar altimetry instruments exploiting new techniques such as along-track Delay-Doppler, also known as Synthetic Aperture Radar Altimetry (as in the CryoSat, Sentinel-3 and Sentinel-6 missions), interferometric altimetry (as in the CryoSat mission, enhanced for the future SWOT and CRISTAL missions) and laser altimetry (as is ICESat and ICESat-2 missions) leads to a breakthrough in the monitoring of surface hydrological parameters. With nearly three decades of exploitation of Radar and Laser Altimetry missions (ERS-1/2, Topex/Poseidon, Envisat, ICESat, Jason-1/2/3, CryoSat-2, SARAL/AltiKa, Sentinel-3A/B, ICESat-2, Sentinel-6 Michael Freilich) the development and validation of river and lake level measurements has matured and will be further supported by a future generation of sensors (SWOT, CRISTAL, S3NG-T), for which the community is preparing, along with the systematic of use of optical, radar

Figure 2
The audience in the virtual conference room of the HYDROSPACE-GEOGloWS 2021 Workshop

and microwave passive imagers data for volume variation, river width and river discharge, in conjunction with in situ observations, assimilation in models and the exploitation of variable gravity missions (GRACE, GRACE-FO) and the future Next Generation Gravity Mission - Mass-change and Geosciences International Constellation (NGGM-MAGIC), to improve our understanding of hydrological processes that affect river basins in response to climate variability and the management of water resources.

To meet the science, application and societal benefit objectives, the next challenges are to significantly improve modelling and forecasting skills through assimilation of observations, as well as operational production. Additionally, the new generation of instruments allows higher spatio-temporal resolutions that will require new and improved processing algorithms, designing new products and services, training a new generation of scientists and augmenting the user base for societal benefits, such as the GEO Societal Benefit Areas.

The HYDROSPACE Workshop series was initiated under the leadership of Anny Cazenave (CNES-LEGOS) in September 2003 in Toulouse, France (http://gos.legos.free.fr/HydroSpa2003.htm). The summary and recommendations, published in AGU's EOS, insisted on the organisation of a sequel meeting, which was sponsored by ESA and CNES and held in Geneva, Switzerland, in November 2007 (https://earth.esa.int/workshops/hydrospace07). A third workshop was held from 15 to 17 September 2015, convened at ESA-ESRIN, Frascati (Rome), Italy (http://altimetry.esa.int/hydrospace2015). It was again urgent to gather the community around this workshop-style brainstorming event, so we scheduled it in June 2021, even if with the less optimal physically distant format. Despite being a virtual gathering, a typical feedback comment from participants is "I found this workshop dynamic with very good discussions, great presentations and informative feedback". Obviously, the success of HYDROSPACE-GEOGloWS-2021 is due to the participants, with 277 registered from 41 countries, although not all connected simultaneously due to the different time zones. Inland water storage and runoff monitoring contributes to a large number of societal needs, from climate monitoring to weather forecasting, with subsequent applications in a range of activities of socioeconomic importance, including water management. The nearly thirty years of progress cannot mask the fact that this complex Earth observation system is fragile and at risk of observational gaps, particularly due to the diminishing in situ networks. This situation must be considered seriously in view of the dramatic and costly impact that flooding and associated extreme events will have on many worldwide floodplain, hinterland coastal, estuary and delta areas and their inhabitants.

We, the *"Inland Water Storage and Runoff: Modelling, In Situ Data and Remote Sensing"* community gathered on-line in the HYDROSPACE-GEOGloWS 2021 Workshop hosted virtually by ESA-ESRIN in Frascati (I) on 7 to 11 June 2021, wish to express our collective will to ensure the continuity of the historical Inland Water Storage and Runoff long-term monitoring and prepare for the next generation of missions dedicated to or exploitable for hydrology, which will continue the success and expansion of inland water monitoring and prediction.

The purpose of this Manifesto is to express the following recommendations that are addressed to the relevant scientific and application communities, to space agencies and to intergovernmental entities, national governments and the European Union.

The "Inland Water Storage and Runoff: Modelling, In Situ Data and Remote Sensing" community commits itself to:

uncertainty

- Working to reduce the present uncertainties affecting the monitoring of Inland Water Storage and Runoff and its interannual, seasonal, global, regional and local variability;
- Investigating means to alleviate the spatiotemporal and accuracy limitations of remote sensing to extract the most information from satellites and improve the return on investment from space agencies;
- Including discussions on data quality and algorithms in scientific workshops such as the HYDROSPACE series;

services

- Developing Earth observation products and services for use by a large fraction of the inland water science, application and management communities;

- Accelerating workflows from data to knowledge and information, with the use of interoperability standards (e.g., OGC, WaterML);
- Participating in public outreach, capacity building and providing information to decision and policy makers highlighting the societal importance of Inland Water monitoring;
- Supporting the development of global inland water storage and runoff systems that leverage remote sensing, in situ data, and models;

data

- Calling for globally coordinated actions in new data acquisition and integration approaches between satellite and in situ communities;
- Carrying out detailed measurement requirement studies in support of justifying satellite missions for hydrology that quantify data needs in terms of latency, spatial resolution, and temporal frequency;
- Working towards satellite and in situ "analysis ready data", and developing the technical skills needed to integrate and interpret the data and translate it into meaningful information that conforms to essential requirements of accuracy and utility to support policies and programmes;

community

- Striving to openly share our knowledge and methods for the advancement of science and the benefit of society, including open science practices and increased interdisciplinary interactions with societal stakeholders;
- Gathering the HYDROSPACE community in a workshop at regular intervals, e.g., every two years.

We encourage and urge all space agencies, whether R&D or operational, and national and international funding agencies, intergovernmental bodies and the European Union to:

extending the data record

- Maintain a long-term archive of all necessary raw and processed data, and ensure regular reprocessing of EWVs;
- Devote a substantial effort to cross-calibration and extensive validation campaigns for products derived from Earth Observation satellite missions all throughout their operational lifetime, as a key element of the success of exploiting EWVs, particularly calibrated river discharge, lake/reservoirs level, lake/reservoirs area and water volume variation;
- Consolidate the use of existing EO data, to improve hydrological forecast, to create Climate Data Records (CDRs), to gain expertise for the development of future missions, in parallel to the development of future missions;
- Ensure that consistency between satellite-derived water products is checked and that the water budget closure is preserved, before using the data. An 'integration layer' is suggested in the processing to optimise and harmonise the water related products before their distribution;

extending the data record - planning

- Encourage further discussion on the EWVs that can be derived from remote sensing between the end-users and remote sensing community; some variables have been under-considered so far (e.g., surface water extent, necessary with water height to calculate a volume) and need to be highlighted;
- Maintain the continuity of the Earth Observation record of EWVs by ensuring an uninterrupted time series of global, high-accuracy space data and designing future space missions dedicated to inland water monitoring;
- Plan a tandem phase for all new missions, to accurately link successive EWV monitoring missions' time series;
- Include inland EWVs in future observational requirements to cope with increasing impacts due to climate change on river basin discharge to the coastal ocean, inland flooding and coastal hazards, and launch initiatives to produce long inter-calibrated time series of river discharge, an Essential Climate Variable (ECV);

- Invest in the development of satellite constellations that enable more frequent temporal sampling and capture faster hydrologic variability than allowed by single or double-spacecraft approaches, further facilitating adoption of remote sensing for decision making;

community

- Strengthen the relationships between space, in situ networks and modelling funding agencies, which has led to the successful merging of individual space mission data sets, in situ data and assimilation in hydrodynamical models;
- Strengthen relations with GEO, in particular, leveraging activities of the Water Initiatives (e.g., GEOGloWS, Aquawatch, BluePlanet) and the activities of the regional GEOs (e.g., AmeriGEO, AfriGEO, EuroGEO etc) to ensure continued feedback from the user community, and advance capacity building and advanced training of the new generation of inland water hydrology scientists;
- Ensure continued capacity building and advanced training of the new generation of Inland water hydrology scientists, both in situ and remote sensing hydrologists;
- Maintain the international scientific framework of User Consultation Workshops such as HYDROSPACE and expand it to new partners and additional EWVs to help define the observables that need to be monitored through time to inform Water Cycle Indicators for water managers and policy-makers;
- Recognize the value and importance of the expertise needed to accomplish a transition between research and applications, together with end-users and beneficiaries, such as transboundary river basin organisations.

community - funding

- Sustain and strengthen the funding necessary to accomplish the scientific research and development to extract maximum knowledge from all space missions and in situ networks, whether research or operational;
- Secure the funding necessary to pursue the invaluable long-term time series of inland water monitoring data, bearing in mind that the costs involved are a fraction of the cost of damages that could be avoided or mitigated and the benefits that will be harvested;

services

- Ensure good and permanent cooperation between R&D and operational agencies to share expertise and to co-design the application tools and services necessary for water managers and policy-makers;
- Ensure production and dissemination of altimetry, extent and temperature products, served by interoperable databases, for use by the inland water community, including those who are not remote sensing scientists;
- Support the move from data to applications (through hydroinformatics, WebGIS), with lessons learned in the ocean and atmospheric communities.

services – open science

- Distribute value-added science and application products on a global free, timely and open access basis;
- Continue support for the Data Democracy initiative which aims to build the capacity, particularly in developing countries for accessing satellite data sets free of charge, enhanced data dissemination capabilities, the sharing of software tools, increased training, and the transfer of technology to end users;
- Encourage and support open science practices (open software, open data, open papers, and open methods) to accelerate development and facilitate broader adoption of remote sensing methods;

3. HYDROSPACE-GEOGLOWS 2021

Workshop Themes

The themes covered by the Workshop are: -

1. Space techniques to measure hydrological surface variables.

1.1 Status of space techniques (improvements, requirements): Gravimetry, altimeters (SAR and SARIn modes and laser), radar and optical imagers

1.2 Hydrological surfaces variables and their spatio-temporal monitoring: water surfaces, water elevations, wetlands, floodplain, groundwater variations, Digital elevation Models for hydrology, etc.

1.3 Blending/fusion of large and diverse datasets. How can we take advantage of the in situ network and satellite-based product to better understand the amount of water available in rivers and lakes?

1.4 From large-scale hydrology to small-scale hydrology: Do hydrology requirements depend on scale? How can space techniques answer these challenges? Downscaling? Precision vs. resolution?

1.5 Retrieval methods for other applications of space observations in large river basins (e.g., sediments transport, systematic mapping of wet areas, flood monitoring, use of altimetry for vertical referencing)

2. Modelling and Assimilation

2.1 River discharge, lake water balance, basin-scale water cycle.

2.2 Global and regional hydrological modelling: objectives, state of the art, improvement and data requirements (accuracy and space-time resolution).

2.3 Expected potential of space and ground data in hydraulic and hydrodynamic modelling: calibration, parameterisation, assimilation, validation and forecasting.

2.4 Specific modelling of estuaries.

2.5 Lake/reservoir modelling for meteorological and climate issues, for exchanges with rivers and volume variations.

3. From products to applications

This part is linked with different initiatives, such as AquaWatch, GEOFAST, AfriGEOSS and SWOT downstream programs which aim is to leverage the use of satellite

data for end-user's needs. It includes the theme of "Fitness for use".

3.1 Applications to water resources management.

3.2 Monitoring and forecasting the extremes floods/droughts.

3.3 Applications to climate research

3.3.1 long-term data records for climate: Essential Water variables.

3.3.2 dedicated session on ESA Climate Change Initiative.

Concerning "Fitness for use", the user community focuses on the degree to which the products conform to essential requirements and meet the user needs for which they are intended. How are the product developers addressing the following requirements?

3.4 Data metrics (precision and accuracy).

3.5 Error variation as a function of: scene, geography, climate zone etc.

3.6 Dataset characteristics: latency, grid interval in space/time and length of record.

3.7 Protocols for applications-ready end-user products: observations and modelling research to applications to end-user/decision making information products.

3.8 End-User applications products.

4. SESSION SUMMARIES

4.1. Space techniques to measure hydrological surface variables
Co-chairs: *Peter Bauer-Gottwein, Jérôme Benveniste, Philippa Berry, Jean-Francois Crétaux, Karina Nielsen, Fabrice Papa, Rodrigo Paiva, Christian Schwatke, Angelica Tarpanelli and Mohammad Tourian*

4.1.1. Block 1 - Space techniques to measure hydrological surface variables
Chairs: *Jean-François Cretaux, Angelica Tarpanelli*

This session block provided an overview of the use of remote sensing for the estimation of river discharge, river bathymetry and water storage over watershed.

Rodrigo Paiva presented a comprehensive study on the hydrology of the Amazon River in which the satellite remote sensing plays a major role in supporting research and findings. Particularly, the Amazon basin is considered as a remote sensing laboratory in which the variables of the water cycle (precipitation, evapotranspiration, surface water elevation and extent, water quality, water storage, modelling the water cycle, aquatic ecosystems, environmental changes) derived by space are extensively reviewed focusing on scientific advances and future challenges. Specifically, the benefits of the lessons learnt in the Amazon is useful to i) understand the hydrology of other large tropical river basins (Congo, Niger, Ganges, Brahmaputra, Mekong), ii) to provide recommendations for observations, models algorithms and their integration, iii) for the characterization of hydrological processes with the support of the remote sensing and finally iv) to understand the changing due to anthropogenic effects and support the sustainable science.

Discussion on: 1) the different initiatives from geological survey of Brazil and research groups to forecast floods (as the recent inundations in Manaus); 2) the orographic issues of the satellite precipitation product, especially in Amazon in which a few ground rainfall observations are available and satellite measurements are highly variable in space.

Luciana Fenoglio showed river discharge estimation by the satellite altimetry over the Rhine River, Germany. As a first step, the comparison of different products of water level from Sentinel-3 is presented: the Copernicus Land Product (OCEAN and OCOG retrackers) and the ESA product (SAMOSA+ retracker on the GPOD/SARvatore processor). This latter outperforms the other products, if compared to the in situ measurements. The second step concerns the estimation of river discharge by three different methods: empirical rating curve, Bjerklie formula and traditional Manning formulas. Errors against the in situ measurements of river discharge are around 3-7% with the empirical rating curve, 22-23% with the Bjerklie formula and 15% for the physically-based algorithm. By using the slope, the elevation and top width from 1D-hydrodynamic Sobek/Deltares model runs, the error is about 6%. Further studies are planned with the observations of the next SWOT mission, through the simulator and further work will be addressed for the ungauged river site.

Benjamin Kitambo presented the joint use of in situ and earth observation datasets (radar altimetry water surface elevation, WSE, and Global Inundation Extent from Multi-Satellite, GIEMS-2) to improve our understanding of how waters flow in the Congo River Basin. Specifically, the study focused on the use of the radar altimetry WSE time series from several missions (ERS-2, ENVISAT, SARAL-AltiKa, JASON 2&3 and SENTINEL 3A) with in situ water level from gauges to observe the annual amplitude of the basin. The GIEMS-2 monthly time series underlying agreements over five major sub-basins, and low correlation over Lualaba sub-basin due to the presence of lakes and their connections with floodplains. At the basin scale, GIEMS reveals the flood propagation dynamics and water residence time in flooded areas. Globally, both the satellite datasets, WSE and GIEMS, showed their suitability for monitoring the flows into the Congo River Basin, potentially bridging the gap between past in situ databases and current and future monitoring. Perspective and discussion on: 1) the water level amplitude higher over the tributaries and lower in the main river that is due to the topography of the basin; 2) the effect of the delay in the flood wave due to the main river floodplains (similar to the effect over the Amazon basin).

Nicolas Le Moine showed how to combine in situ measurements and spectral ratios of high-resolution airborne imagery for an improved representation of river bathymetry. Differently from the standard practices based on the interpolation of in situ depth measurements from differential GPS, total station survey, LiDAR or echo sounding, here, the high-resolution (20 to 50 cm) airborne imagery in 4 bands - red, green, blue and NIR – is used to estimate the bathymetry of the river, using spectral ratios between adjacent bands. This passive method is already used in coastal applications and it is extended at river applications. The method is applied in a 40-km reach of the Garonne River with encouraging results.

Fabrice Papa addressed the scientific questions about the spatial-temporal variation of the fluxes and storage of continental freshwater and about their interactions with the climate and the anthropogenic pressure by presenting a study over continental waters specially over the tropics, and for the Amazon and Congo basin, often subject to large climate variability and prolonged extensive drought/floods. The study showed how to decompose the total water storage from GRACE into its components: surface water storage, soil moisture root zone storage and ground water storage by the use of multi-mission satellite observations. The combination of Global Inundation Extent from Multi-Satellites, GIEMS and ENVISAT radar altimetry water elevation variations at hundreds of virtual stations is used to estimate the surface water storage variations, demonstrating that the relative contribution of the surface water storage to the total water storage of the main rivers (Amazon, Congo and others, i.e., Ganges, Brahmaputra, Mekong) is found highly variable among the various basins and sub-basins in link with climatic and geological features. Removing from the total water storage measured by GRACE, the surface water storage and the soil moisture water storage derived by satellite observations or models (WGHM, ISBA, GLDAS) the ground water storage is estimated and compared with a few in situ well observations over the Negro and the Madeira basins with fair agreement demonstrating that the method is robust. For the first time, maps of variability of the groundwater storage variations over the Amazon basin are showed in regards to their link to regional climate variability and the 2005 extreme drought. Some satellite perspectives of the work: 1) improve the spatial resolution of the maps (90 m); 2) merge the dataset to better understand flood dynamics and hydrological processes of SW and GE exchanges and the drivers during extreme events; 3) extent the temporal series; 4) apply the methodology to other basins; 5) support to the SWOT mission with a global inventory of surface water and rivers and direct estimates of global surface water storage variability.

Discussion included: 1) leakage effects in GRACE products; 2) the increasing of soil moisture storage occurring ahead of surface water storage at basin scale.

Mohammad Tourian showed how to estimate river discharge using a mass-conserved Kalman filter approach relying on simulated SWOT observations over the Po River, Italy. The method is based on the Manning equation, in which the flow law parameters (roughness parameter and the minimum flow area). are obtained by the definition of a priori discharges estimated by the combination of SWOT observations (simulated using Landsat-derived river width by the SWOT-CNES simulator) and the in situ historical data. For each reach and month, the prior discharge is obtained by a Kalman filter estimation with a spatial-temporal process model and mass conservation condition as the observation equation. Using the obtained prior discharge, flow law parameters are estimated through interior-point optimization with inequality constraints. Posterior discharge estimates are obtained by adding discharge observations derived from simulated measurements and estimated flow law parameters. The validation against in situ data do not show satisfactory results mainly due to non-representative simulated measurements. Improvements are expected adding height variation from altimetry as inputs to the simulation.

Discussion included: 1) the possibility of adapting the methodology at ungauged areas by the use of global hydrological model; 2) how precipitation, evapotranspiration and runoff affect the mass conservation assumption; 3) the flow law parameters are considered constant in order to not introduce bias and random errors.

4.1.2. Block 2 - Space techniques to measure hydrological surface variables

Chairs: *Karina Nielsen, Fabrice Papa*

Jean-Francois Crétaux presented the recent advances on estimations and databases regarding lake water levels, the various evolutions from Topex/Poseidon to Sentinel-3 and how the discipline went from R&D to operational products. Lakes are important component of the regional and global water cycle and a proxy and a sentinel of climate change. There is now a solid international framework around the science and management of lakes world-wide. There are many databases that provide now estimate of lake surface area, level and volume, especially from remote sensing. Jean-Francois Crétaux presented the activities at LEGOS, France, and databases such as Hydroweb, the international Lakes_cci project and the Global Land Service. These databases and projects have 3 main objectives regarding the estimates of variable of lake: 1) provide multi-decadal intercalibrated estimates 2) with an error budget 3) and improved data processing. For instance, currently on Hydroweb, there are 166 operational virtual stations for 166 and 124 classified as re-search (much less than rivers where >11000 VS are now available). Lake water levels are also combined to satellite imagery to monitor lake volume (hypsometry technique). New missions but also past missions will ensure long term time series to survey lakes and reservoirs water levels and volumes

Gennadii Donchyts presented an upcoming platform "Global water watch" that will contain worldwide, high-resolution, near-real-time, water data. In the presentation, several examples demonstrating the benefits of having a global real-time reservoir monitoring system for various applications spanning agriculture, disaster management, and water diplomacy was shown. Multiple methods of monitoring surface water changes in reservoirs using a fusion of multispectral optical and SAR sensors were shown as well as challenges when building an automated monitoring system to quantify water dynamics in tens of thousands and, potentially, millions of reservoirs globally.

Mathilde De Fleury et al., presented a study regarding the use of altimetry and optical imagery to monitor small water bodies in Sahel in Africa to better understand their hydrological regime. They found that available algorithms for water detection missed many lakes due to vegetation. By fixing a MNDWI threshold in Sentinel-2 images for each lake and not with respect to time they were able to detect more lakes in the different seasons. To extract water level variables from Sentinel-3 they used the ALTIS V1.5 (LEGOS-CNRS) software. To identify measurement related to the water surface a backscatter threshold of 40dB was selected. From time series of surface water extent and water level relation between these variables could be formed. This was exploited to densify the water level time series.

Jean Francois Crétaux presented recent results on the hydrology of the Lake Chad under current climate change. Lake Chad is located at the southern edge of the Sahara and was ranked as the world's sixth largest inland water body with an open water area of 25,000 km2 in the 1960s. Since then, it has shrunk dramatically and reached less than 2000 km2 during the 1980s, decreasing by more 90% in area. Using a multi-satellite approach combined with ground-based observations, the study asses the current status of the lake. It shows that Lake Chad extent has remained stable during the last two decades, even slightly increasing. Combining several observations (GRACE, models, MODIS, altimetry) results show that since the 2000s, groundwater which contributes to 70% of Lake Chad's annual water storage, is increasing due to water supply provide by its two main tributaries of the Lake. The results indicate that in tandem with groundwater and tropical origin of water supply, over the last two decades, Lake Chad is not shrinking and that in the last two decades it recovers seasonally its surface water extent and volume.

Claude Duguay presented a study investigating the impact of ice and snow when estimating lake ice thickness (LIT) from satellite altimetry. Lake ice thickness is an important cli-mate indicator and is listed as an ECV (essential climate variable). In situ observations of LIT are sparse and expensive to collect so satellite observations are an important supplement. The object of the study was to examine the backscatter and brightness temperature under different snow and ice properties. Through several simulation experiment of backscatter and brightness temperature if was found that snow and ice properties may affect the quality of the LIT.

Manon Delhoume presented a study where simulated SWOT data was used to estimate water volume of Canadian lakes. In the study the large scale CNES simulator was used. One of the objectives was to develop methods to test the SWOT performances on water storage changes on lakes. Examples from 3 Canadian lakes were shown where both area and water levels were simulated. The RMSE of the simulated level and area were, respectively, 9 cm and ranged from 0.4 to 2 km2.

The discussions and questions dealt with how water under vegetation will be processed in the "Global Water Watch" database and how the results over the Lake Chad could be used to predict how many years it would take for the lake to fully recover.

4.1.3. Block 3 - Space techniques to measure hydrological surface variables

Chairs: *Rodrigo Paiva, Philippa Berry*

This section block focused on surface water and soil moisture measurements, including techniques and applications.

Chi-hung Chang presented methods for forecasting inundation extents using Rotated Empirical Orthogonal Function analysis (FIER). It was used to forecast inundation over the Lower Mekong River. RS is useful in this is a transboundary basin where upstream countries regulate discharge on hydropower reservoirs and there is no data sharing transparency. FIER is used based on SAR Sentinel 1 imagery, and in situ water levels to predict spatial and temporal patterns. Inundation maps present high accuracy in validation. VIC model was forced with GPM near real time satellite precipitation to forecast discharge and water levels in lower Mekong. Discussion with the audience include: possible errors coming from poor hydraulic connectivity in the studies domain, comparison of flood forecasts from GLOFAS, next steps applying FIER using finer resolution cloud-based imagery from Google Earth Engine.

Simon Boitard presented New Upgrades of Open-Loop Tracking Command (OLTC) Tables of Nadir Altimeters. OLTC tables are used to center the reception window of the radar altimetry sensor. Upgrades were performed in 2020 based on input data from users (e.g., LEGOS) over rivers and lakes. Validation shows that the acquisition performance is now high (>95%). The OLTC Web Portal is open to users to contribute. Questions from the audience include discussions on the difficulties over wetland regions and highly dynamic water surfaces, e.g., new or highly managed reservoirs.

Fernando Jaramillo presented InSAR analyses to study Connectivity, and Barriers in Wetland Systems Worldwide. Using InSAR applied to Sentinel-1 data, several examples were presented over different types of wetlands. Coherence is used to detect flooded areas and the water elevation change signal is used to interpret on connectivity and barriers over wetlands. Discussion with the audience included the challenges to make the InSAR approach operational to estimate water level changes for dozens of wetlands, e.g., all Ramsar sites in South America, where for example a multi sensor could be necessary for dense forest over the amazon, for example.

Ayan Fleischmann presented the contrasting behaviour of South American wetlands using multiple Remote Sensing data. These wetlands are 14% of south America and fluvial and interfluvial wetlands may have different sensitivities to human impacts. Fluvial wetlands store more river water and shape river hydrographs. Interfluvial wetlands presented lower precipitation flooding delay (< 2 months). Water level amplitude is lower <2 m over interfluvial wetlands. ET is more influence by wetlands over temperate regions. Questions from the audience include to use InSAR to study the internal connectivity of these wetlands and that the ET and Budyko analyses are still performed at large scale for each wetland.

Qianqian Han developed a High Resolution (1km) Global Soil Moisture Product Based on Google Earth Engine. Several high-resolution maps were used as an input for a random forest regression model, including antecedent precipitation, land surface temperature, NDVI, EVI, Soil grids, and topographic index. The model was calibrated and validates using in situ soil moisture from the global network. It was also compared to the ESA CCI SSM product. Discussion with the audience include the fact that the comparison with CCI SM can be biased due to its coarser spatial resolution. It was suggested the use of other 1 km SM products as the ones derived from Sentinel-1. It was also discussed that most of the in situ calibration/validation observations locates at specific regions (e.g. US) while others are poorly covered, where there are still questions on the performance of the statistical model.

Vahid Freeman demonstrates the Surface water detection and soil moisture monitoring using Spire's GNSS-R bistatic radar measurements. It was discussed the potential of using several GNSS data, including spire constellation. It was show examples of surface water mapping over the Congo and the Amazon, where it was possible to detect flooding below the forest. Soil moisture estimates were compared to SMAP estimates, showing promising results. Discussion included issues on how level 1 data is freely available, how GNSS signal how does the GNSS signal distinguish soil moisture and vegetation and suggestions for further validation of surface water detection using other estimates (e.g., SAR based products over Amazon and Congo).

Overall, several themes recurred in these papers:

1. A focus on the interconnectivity of rivers, wetlands, floodplains and taking a holistic approach to inland water monitoring including soil moisture;
2. The vital importance of multi-sensor synergy; this is shown to be a rapidly advancing field, pushing the boundaries of both sensors and models;
3. Novel uses of a range of existing sensors, and new techniques being developed.

4.1.4. Block 4 - Space techniques to measure hydrological surface variables

Chairs: *Mohammad Tourian, Peter Bauer-Gottwein*

This section block focused on surface water level and storage and river discharge with a focus on methodology improvements.

Fernando Nino presented a Deep Learning-based method for tracking altimeter waveforms. The approach is to interpret a sequence of consecutive altimeter waveforms (a radargram) as an image. Thus, the problem can be reformulated as the problem of implementing a neural network to automatically compute water surface elevation from radargrams. Neural networks were trained with supervised learning algorithms on simulated Jason-3 waveforms. Validation was performed with other simulated radargrams, as well as with real Jason-3 radargrams. The validation against the in situ water level data shows correlation coefficients of 0.88-0.95. They did not compare the performance of this method to standard racking methods, which remains as future work.

Maxime Vayre presented results of Fully Focused SAR altimeter processing and the obtained inland water level time series. SAR-mode altimetry brought significant improvements when comparing with to conventional altimetry including inland waters areas. In the operational ground segments, the current SAR-mode processing is based on the so-called unfocused SAR altimeter (UF-SAR) processing. As part of ESA and CNES project a so-called SMAP open-source software (FF-SAR Standalone Multi-Mission Altimetry Processor) has been developed. He presented the FF-SAR results over different water bodies (French rivers, the Amazon, the Congo, the Niger …) using Sentinel-3 and Sentinel-6 measurements acquired in Open-Loop mode. The results showed significant improvement in comparison to UF-SAR. A focus was given on the issues of "Replicas" their implications for the FF-SAR processing will also be discussed regarding Sentinel-3 and Sentinel-6.

Nicolas Gasnier presented a method for water detection in SWOT HR interferometric SAR images. The baseline SWOT water detection method uses an iterative approach that iteratively detects water on the SWOT image using a parameter map and re-evaluates it based on the detected water grid. The detection is done using a Markov random field approach that combines a data term based on the image and parameter map and a regularization term that mitigates the effect of noise by favoring a regular water map. He presented that the base method is suboptimal for narrow rivers (less than 100m) because they are likely to be cancelled out by the regularization term. He proposed a new three-step process using an existing exogenous database (Global Rivers Widths from Landsat) as input along with SWOT imagery. He showed that in addition to the SWOT classification map (Pixel Cloud) of the processing chain, a priori masks are needed to define which pixels can and cannot contain water. Such masks are used to identify areas to be included in the product and to set flags ("dark water", "light land", "overlay", etc.).

Christian Schwatke presented DAHITI – Satellite-derived Hydrological Products for Monitoring the Global Water Cycle. He introduced the "Database for Hydrological Time Series of Inland Waters" (DAHITI, https://dahiti.dgfi.tum.de) and its products. The main product of DAHITI is water level. Additionally, surface area time series and water occurrence masks derived from optical imagery are available for almost 200 lakes and reservoirs. Moreover, the combination of water levels and surface areas allows to derive further products such as time series of volume variations for lakes and reservoirs as well as discharge time series for rivers. Besides time series, also bathymetry and hypsometry models for lakes and rivers are available. Nicolas Taburet talked about operational lakes and rivers water level monitoring using satellite altimetry data and highlighted the contributions of HydroWeb and Copernicus Global Land Services. He described both the processes yielding the definition of new targets and their qualification for operation as well as the regular quality assessment of the produced water level timeseries. Finally, planned evolutions of the services were also presented, in particular the integration of the Sentinel6-MF mission and its benefits.

Catherine Prigent presented satellite-derived global surface water extent and dynamics over the Last 25 Years (GIEMS-2). She presented a new methodology, based on which GIEMS-2 provides monthly estimates of surface water extent, including open water, wetlands, or rice paddies. It has been applied to the Special Sensor Microwave/Imager and the Special Sensor Microwave Imager Sounder intercalibrated observations to produce a global data record of surface water extent from 1992, on an equal area grid of 0.25° × 0.25° at the equator (25 km). Their comparisons with precipitation estimates show good agreement, displaying expected patterns related to surface conditions and precipitation regimes. The temporal variability of basin-averaged estimates has also been compared with altimeter river height, showing a reasonable agreement.

4.1.5. Block 5 - Space techniques to measure hydrological surface variables

Chairs: Jérôme Benveniste, Christian Schwatke

This session block focused on the driving of hydrological variables (Talk 1-4) and future missions (Talk 5-6) for a better monitoring on inland waters.

Omid Elmi presented a new approach for estimating global dynamic river masks from Landsat imagery to derive channel characteristics such as width and depth. As input data was the Global Surface Water Dataset (GSWD, Pekel et al, 2016) used. Because of existing data gaps in monthly masks caused by clouds or SLC failure of Landsat-7, a new region-based classification algorithm for correcting the dynamic rivers masks is applied. This algorithm considers temporal and spatial corrections between pixels. The resulting water masks were finally used to estimate river discharge and were validate with in situ discharge stations.

The second presentation of this block was given by Huilin Gao about the new NASA´s MODIS/VIIRS Global Water Reservoir product suite. It is based on data from Moderate Resolution Imaging Spectroradiometer (MODIS), and the Visible Infrared Imaging Radiometer Suite (VIIRS). The presented product contains 8-day and monthly measurements for 164 large lakes. In the 8-day product are area, elevation and volume included which are then aggregated to monthly products including evaporation rate. The validation of these products shows high correlations between 0.71 and 0.96 for elevation and water storage. It was noted also that the evaporation model can be applied to other larger water bodies.

Sarah Cooley presented the potential of using ICESat-2 for monitoring water level time series of inland waters. It was shown that ICESat-2 has the capability to quantify global variability in water level over 227,386 water bodies from October 2018 to July 2020. The derived water levels are very precise with a high accuracy. By using ICESat-2 water levels, the potential to monitor seasonal changes in reservoirs especially in human-managed areas was demonstrated. Additionally, it was also shown that ICESat-2 has the potential to derive area information of reservoirs. The availability of the dataset has been raised and is not yet decided. It was also mentioned that this dataset could help to update the OLTC for nadir altimeters in the future.

In the talk of Eva Boergens, a new web portal "Gravity Information Service" (GravIS, http://gravis.gfz-potsdam.de) has been introduced. It provides terrestrial water storage (TWS) variations and uncertainties derived from GRACE (Gravity Recovery and Climate Experiment, 2002-2017) and GRACE-FO (GRACE-Follow-On, since 2018) for river basins or climatically similar regions on Earth. This data set is essential for hydrological applications since this is the only one which can measure the total water column.

This approach is not well suitable for smaller inland water bodies because of the coarse resolution of GRACE/ GRACE-FO.

The fifth presentation of this block was given by Denis Blumstein who presented the future mission SMASH (SMall Altimetry Satellites for Hydrology) which is dedicated to monitor inland water bodies and estuaries. The development of this new mission was led by CNES with Thales Alenia Space (TAS) with the objective to design a satellite constellation with a daily revisit. The resulting SMASH mission is a constellation of ten small satellites flying on a Sun Synchronous Orbit in a single plane. They are equipped with a nadir altimeter satellite which should provide an accuracy of about 10 cm, which is sufficient for inland water applications but not for ocean applications. There is a strong synergy between SMASH and swath altimetry missions such as SWOT.

Discussion: It was mentioned that today's altimeter missions are "oversized" for inland applications since they are mainly developed for Ocean applications which require higher accuracies. Therefore, SMASH could provide also good altimeter measurements for inland waters using less expensive small CubeSats.

The last presentation was given by Craig Donlon about the hydrology component of the Sentinel-3 Next Generation Topography Mission (S3NG-T). This mission is dedicated to ensure the continuity of the existing Sentinel-3 constellation after 2030. The current status of the expert group was presented which results in three potential scenarios (nadir altimeters, swath altimeter or hybrid approach).

4.2. Modelling and Assimilation

Co-chairs: *Alice Andral, Ayan Fleischmann, Angelica Gutierrez and Catherine Prigent.*

4.2.1. Block 1 - Modelling and Assimilation

Chairs: *Ayan Fleischmann, Catherine Prigent*

This session block focused on river modelling at large (Adrien Paris) and reach scales (Monica Frias), use of satellite altimetry to estimate real-time water levels and discharges (Adrien Paris) and input/validation data for model (ICESat-2 by Monica Frias, and roughness coefficients for the SWOT discharge algorithm by Charlotte Emery), assimilation of EO data to improve flood estimates (Renaud Hostache), and new approaches to quantify the water cycle components (SAWC by Victor Pellet and DTE by Luca Brocca), with a focus on precipitation input data in the case of Luca Brocca.

Adrien Paris presented the monitoring of Congo River Basin river discharge from altimetry in near-real-time. He used more than 700 satellite altimetry virtual stations (S3 & J3) in the Congo Basin to complement in situ network. The calibration of rating curves is first made by combining altimetry, MGB model discharges, and in situ measurements. The rating curves are then used in near-real time to provide discharges to end users. The method is applicable to other ungauged basins. Questions were related to the bathymetry information provided by the method, to the use of the methodology for prediction of discharge and flooding.

Monica Frias presented the intensive use of ICESat-2 data to provide input and validation data for the hydrodynamic modelling of a complex river reach in Yellow River, where high spatial resolution is required and is not provided by the altimeter. The goal is to provide the required model parameters (including the rating curves) for this reach. The question of the atmospheric correction on the lidar signal has been raised.

Victor Pellet presented a new approach to estimate river discharges across the Amazon Basin, combining multiple RS-based evapotranspiration precipitation and TWS (GRACE), and in situ river discharges along with flow accumulation information in a consistent way. The method showed satisfactory validation with in situ river discharge. It stresses the capability to obtain pure observation-based estimate for the river discharge in the framework of the water budget closure. In addition, the method can help calibration the models and infer pixel scale river parameter such as river height and river width. The model ability to perform forecasts was discussed, considering the latency of GRACE-FO data.

Renaud Hostache showed synthetic tests to assimilate frequent soil moisture (SMOS) and flood extent (Sentinel-1 SAR) into a distributed conceptual hydrologic model in order to improve the estimation of flooding in ungauged rivers. The next step will be to perform real world case studies.

Questions were related to the consistency between the SMOS and the SAR variables and to which soil moisture product to assimilate (surface or root zone).

Luca Brocca presented a high-resolution precipitation field for the Digital Twin Earth (DTE) Hydrology experiment. The author presented the DTE hydrology system with focus on water cycle representation, insisting on the precipitation input to be used in the DTE system. The study concentrated on the Po River valley, where a DTE 1km hourly precipitation product has been developed. It has been compared to other products (IMERG-LR, SM2RAIN-ASC, IMERG+SM2RAIN) and provided satisfactory results. The possibility of using AI method for the downscaling of the rainfall field has been questioned.

Charlotte Emery presented the estimation of hydrogeomorphological parameters in the context of the SWOT discharge algorithm. Case studies were Upper Garonne and Po rivers. Manning (for floodplain and channel) roughness maps were obtained from Cowan formula based on soil types, land use classification and other data as obstructions, meandering ratio and cross-sectional irregularities.

4.2.2. Block 2 - Modelling and Assimilation
Chairs: *Alice Andral, Angelica Gutierrez*

This second block of presentations focused on modelling and the application of Earth System approach for Streamflow forecasting.

The first presentation was by Calum Baugh from the ECMWF presented the use of Earth Observations for Operational Hydrological Forecasting at ECMWF. The land surface model HTESSEL is now coupled with the global hydrodynamic CaMa-flood model which allows to have a better water budget. Hydrological modelling is a key component of the Earth System model.

GloFAS, as part of the Copernicus emergency service, gives access to an operational hydrological forecasting, especially suitable for flood forecasting. Earth Observation data can be integrated into initial conditions of an operational forecast through the Land Data Assimilation (LDAS) scheme. Snow depth and cover and soil moisture are already assimilated. However, there is some issues in snow dominated catchment and also on systematic errors in irrigated regions. Further work is ongoing to compare EO derived irrigation against what it is observed in the model. He concluded on the potential benefits of Sentinel data and SWOT missions which could enable the assimilation of data regarding lake storage and river discharge but there are still challenges on latency, repeat time and spatial coverage.

The next two presentations were dedicated to the GEOGloWS ECMWF Streamflow service.

Riley Hales from the Brigham Young University presented the GEOGloWS ECMWF Streamflow, a Global Hydrology Model Service that Provides a Sustainable Source of Water Information. This streamflow system uses the gridded surface runoff results calculated by ECMWF using the HTESSEL model before the resampled and performs an area-weighted grid-to-vector downscaling for the runoff. The Routing Application for Parallel computation of Discharge (RAPID) model is then used to route these inputs through the stream network. One other peculiarity of this GEOGLOWS streamflow is that more than 40 years of worldwide historical simulation are freely available, in addition to 15-days discharge forecast refreshed daily.

This system has been made to ease the use of data and decision making: a python package to automate retrieving and plotting data from the data service is available, data can be retrieved with an API.

Publications relevant to the modelling described by Riley Hales and validations are available here with more of this work in review currently and will be added: https://geoglows.ecmwf.int/publications

Jorge Sanchez Lozano from the Brigham Young University presented then the Streamflow Bias Correction for GEOGloWS ECMWF Streamflow Services. He showed how well it works for flood event. He compared the forecasted discharge on reaches where observed streamflow data were available. Depending on the sites, there can be a difference in moment of the maximum discharge or in the magnitude of the flood event. Some events are also not captured. One of the reasons of those discrepancies is the presence of hydraulic infrastructures that modify the discharge and are not considered in the models and routing system.

Kévin Larnier from C-S Group – France presented a hybrid data-driven and physically-based algorithm to estimate river discharge from SWOT-like. Three unknowns have to be inferred: bathymetry, discharge, and roughness. The HiVDI algorithm is thus based on three steps. First, a purely data-driven estimation of discharge and bathymetry is obtained using an Artificial Neural Network; then, a physically consistent discharge estimation is obtained using a flow model dedicated to spatial and temporal scales of the satellite observations. It allows an estimate of the bathymetry and the effective friction parameter. So, it is now possible to estimate discharge in "NRT" with the simulated SWOT water level, slope, and surface data.

Stefania Camici from the National Research Council gave the last talk of the session. She presented the STREAMRIDE project aiming at estimating river discharge by using satellite observations. It benefits from two prior projects:

- The STREAM (SaTellite based Runoff Evaluation And Mapping), which used satellite observations of precipitation and soil moisture for quick flow and terrestrial water storage for slow flow. These data are integrated into a conceptual hydrological model whose outputs are daily river discharge and runoff at the basin scale.
- The RIDESAT project (River flow monitoring and discharge estimation by integrating multiple SATellite data) used altimetry and NIR wavebands of MODIS and Sentinel 3 to retrieve the flow velocity used to provide 3-day river discharge estimates at specific river cross-sections. Vegetated areas and dams, human infrastructures remain problematic.

Discussion on Modelling and Assimilation:

A diverse range of hydrological variables is available for modelling and assimilation. The consistency of the water-related data has been widely discussed. Indeed, there are biases in EO-derived parameters, with spatial, and temporal patterns. Using the water budget closure is one way to preserve the water balance while optimizing the data. Optimal interpolation methods are capable of merging diverse sets of water-related parameters, in a consistent way, with specific constraints, primarily the closure of the water budget.

Providing an error estimate with each single product is required.

It is suggested to add an 'integration layer' to the processing of the water-related variables, to optimize and harmonize the hydrological variables and to ensure their consistency, before using them, possibly jointly, for modelling or assimilation.

All agree on the benefits of having a diversity of products, data. Data fusion algorithms should help also to optimize the coherence and consistency of data. The use of artificial intelligence could also provide new patterns that have not been explored till now. However, caution should be exercised to wisely use the AI methodologies.

The EO products are sometimes considered to 'break' the models. Strategies have to be developed to avoid it, and a careful estimation of the product accuracy and precision, along with the consistency checking of the parameters to be assimilated will likely help in this direction.

The question of the model selection is raised. The ECMWF develops a global hydrological model (H-TESSEL / Cama-Flood). Having a global hydrological model that can be applicable locally, with engaged users is judged interesting. Local application can generate exchanges of expertise and in situ data, between local actors and global modelers. It is mentioned that NASA has its own hydrological model.

Besides water level and river discharges, the surface water extent has been mentioned as an important hydrological variable (an Essential Water Variable). Today, very large differences can be observed between available surface water extent products (over the Amazon basin for instance). It is expected that work could be done to consolidate these estimates, improving and merging some of them in a coherent way. The role of the flood extent should be reconsidered in the EO community, as required by end users (disaster monitoring, insurance company). Associated with water level, it can provide flood water storage. This need has been indicated by ECMWF, as well as the need for lake water storage. The interest for reliable EO evapotranspiration products was also indicated. This is a critical parameter in the hydrological equation, and its reliability is still questionable.

There were also discussions about the end-user requirement (although this question will be raised in depth in session 3). End-users require practical tools to use satellite observations, and we need to move from data to applications. The need for standardized products has also been raised. The ocean and atmospheric community are more mature in the use of EO products. Their example should be followed for the hydrology community.

It is time also to move on forecasting instead of just monitoring river discharge and also to have user-oriented products. Having an estimate of discharge is not enough because the values themselves are not understood by end-users. They need flood extent and other map/dashboards on the impact on people, infrastructures, etc.

There is already a large range of satellite observations that can capture elements of the water cycle. There is still significant room for improvement in the current use of these satellite data to produce accurate and precise water-related variables. Working on new satellite missions is certainly appealing, but consolidating the use of the existing data is also critical, to make sure 1) the end users fully benefit from the currently available EO data, especially to improve hydrological forecast, 2) climate data records are produced with the existing observations, and 3) the best possible new missions and their related algorithms are designed, based on the expertise gained with the analysis of the existing EO data.

4.3. From Products to Applications

Co-chairs: *Christophe Brachet, Cédric David, Huilin Gao, Andreas Güntner, and Hyongki Lee, Arjumand Zaidi.*

4.3.1. Block 1 - From Products to Applications

Chairs: *Hyongki Lee, Christophe Brachet*

This section block focused on different initiatives about spatial hydrology in relation with quantitative management. It enhanced specific applications and collaboration with different stakeholders and communities.

Richard Lawford made a Status Report on the Global Earth Observation System of Systems (GEOSS) Water Strategy implementation: EWVs, research and product development, system interoperability, and capacity development. It guides activities related to the acquisition, archival, processing, dissemination, and use of water observations and data products.

Chris Bremmer presented the Future Perspectives for Earth Observation in Quantitative Water Management. Current demands regarding information on the variables for water and coastal management has been mapped on current and near future capabilities in earth observation. The spatio-temporal specifications of in situ monitoring and earth observation have been compared with a classification of hydrological processes according to typical length and time scales. Flood protection and drought warning are areas where earth observation has potentially large socio-economic benefits.

Margaret Srinivasan presented the Promotion of Societal Benefits From SWOT, and the Applications developed for Early Adopters and User Communities. SWOT mission, to be launched in 2022, will provide measurements with unprecedented resolution and accuracy on global surface water parameters. The SWOT Applications Working Group has been engaging members of broad user communities including water managers, altimetry experts, the private sector, modelers and others in order to prepare them for use of SWOT data after launch.

Nina Kickinger presented The Space4Water Portal, and Lessons learnt in building a community of practice. The web portal serves as a multi-stakeholder platform for interdisciplinary knowledge exchange on space technologies and water-related topics. Organizations and actors use the Portal to share information on projects, initiatives, satellite missions, software, data and community portals, APIs, models, capacity building & training material, conferences, workshops, and publications. The Space4Water Portal aims to invite actors and stakeholders at all skill levels and representing the various sectors into a common discourse on the use of space technology for a sustainable water future

Blaise Dhont went From altitudes to actions, using Space hydrology for transboundary river basin Management. After a few reminders about SWOT downstream program, he presented the "French Working group on spatial hydrology" and its activities. The Group has specific projects on several transboundary River basins, with the concerned transboundary organizations: Congo River Commission (CICOS), Niger Basin Authority, Senegal River Commission (OMVS), and two Guiana basins, Oyapock and Maroni. Some questions came about the validation of altimetry data.

Tien Du presented CERES – A Citizen Science Approach Monitoring Reservoir Operation from Space for Poorly Gauged Reservoirs. The cloud-based interactive web app, with freely available remote sensing datasets including Sentinel-1 SAR imagery, global DEM datasets, and JRC Global Surface Water Mapping Layers, for the purpose of monitoring reservoir operation has been developed to employ a citizen science approach. The app is designed for end users to email back the developer the performance metrics for further improvement. Comments about including outflow from reservoirs were made.

4.3.2. Block 2 - From Products to Applications

Chairs: *Andreas Güntner, Huilin Gao*

Vanessa Pedinotti presented a demonstrator of a real-time river discharge forecasting system that assimilates water level information from altimetry after conversion to discharge using rating curves. The system has been set up for the example of the Niger basin in a geo-portal that also allows for real-time visualization of output time series and maps. The audience asked about the approach for developing rating curves.

Jorge Sanchez Lozano described a bias correction method for streamflow simulations of the GEOGloWS ECMWF Streamflow Services. The method is based on the flow duration curves of the observed and simulated data and demonstrated improvements for both historical and forecasted data. The speaker discussed with the audience about the options to further improve the results and better informing the users (e.g., providing QC information).

Andreas Güntner laid out the approach taken towards developing a global-scale Copernicus service product of groundwater storage variations (G3P). It is based on reducing total water storage variations derived from satellite gravimetry with storage variations of other compartments such as surface water provided by already operational Copernicus services. The speaker addressed the audience's questions about the future plan for validating the product and potential applications by the modelling community.

Flavien Gouillon introduced the Hysope II (The THEIA Hydrology Data Access and SWOT HR Distribution System) data portal, with a focus on the Hydroweb-NG web interface. Hysope II provides access to hydrological data collected from in situ observations, remote sensing, and modelling. It is intended to serve broad communities of scientists, agencies, and stakeholders. The server handles a very large amount data (7Tb) every day. The users have the flexibility to choose the programming language for processing the data (e.g., R, QGIS, Matlab, Python). The portal is user centered. The users can fill out surveys to provide inputs. The audience was impressed by the iterative user engagement, and asked what types of users in terms of their professional job have been engaged, and plans to further the engagements.

Santiago Pena Luque presented a framework for monitoring dam water storage at near-real-time using satellite remote sensing. The algorithm estimates reservoir storage by combining satellite image classifications (from Sentinel-1 and Sentinel-2 at 10 m resolution) and bathymetry (from DEM). The algorithm makes a priority of using satellite data only. The current reservoirs studies are the small reservoirs in France, at weekly interval. The data product has been developed for 2019 and 2020, with an error less than 15%. The product is suitable for drought monitoring. Future plans include expanding the spatial coverage to Europe, using better quality DEM data, integrating with Hydroweb-NG, improving calibration/validation, and synergy with SWOT mission (when available). Discussions with the audience focused on the possible alternatives for the occurrence map (e.g., Global Surface Water by JRC) and rating curves (e.g., from surveys for reservoir operating agencies).

Christophe Fatras presented the FloodDAM Space Climate Observatory project which automatically monitors flood from space. The project involves five steps: water level measurement, water height anomaly detection, flood rapid mapping from EO imagery, risk mapping and CFD modelling, and result visualization. Comparisons between TerraSAR-X and Sentinel-1 results suggest that the former has a promise for generating high quality flood maps. Compared to the previous FloodML algorithm, FloodDAM is much more computationally efficient. Other highlights for the project include: automatic alert when an anomaly is detected, capability of monitoring ongoing events and/or on-demand, post-processing, automatic report generation, and adoption of user feedback. The speaker and audience discussed the time it takes for automatically generating the results.

4.3.3. Block 3 - From Products to Applications

***Chairs:** Zaidi Arjumand, Cédric David*

Suxia Liu presented on the estimation of hydrological variables with the combined VIP model and remote sensing observations. Two notable examples were the estimation of human-induced evapotranspiration from the difference between a GRACE-based mass balance with natural evapotranspiration from a model, and the comparison of river surface water elevation computed from the LISFLOOD-PRO model with Sentinel 3 estimates.

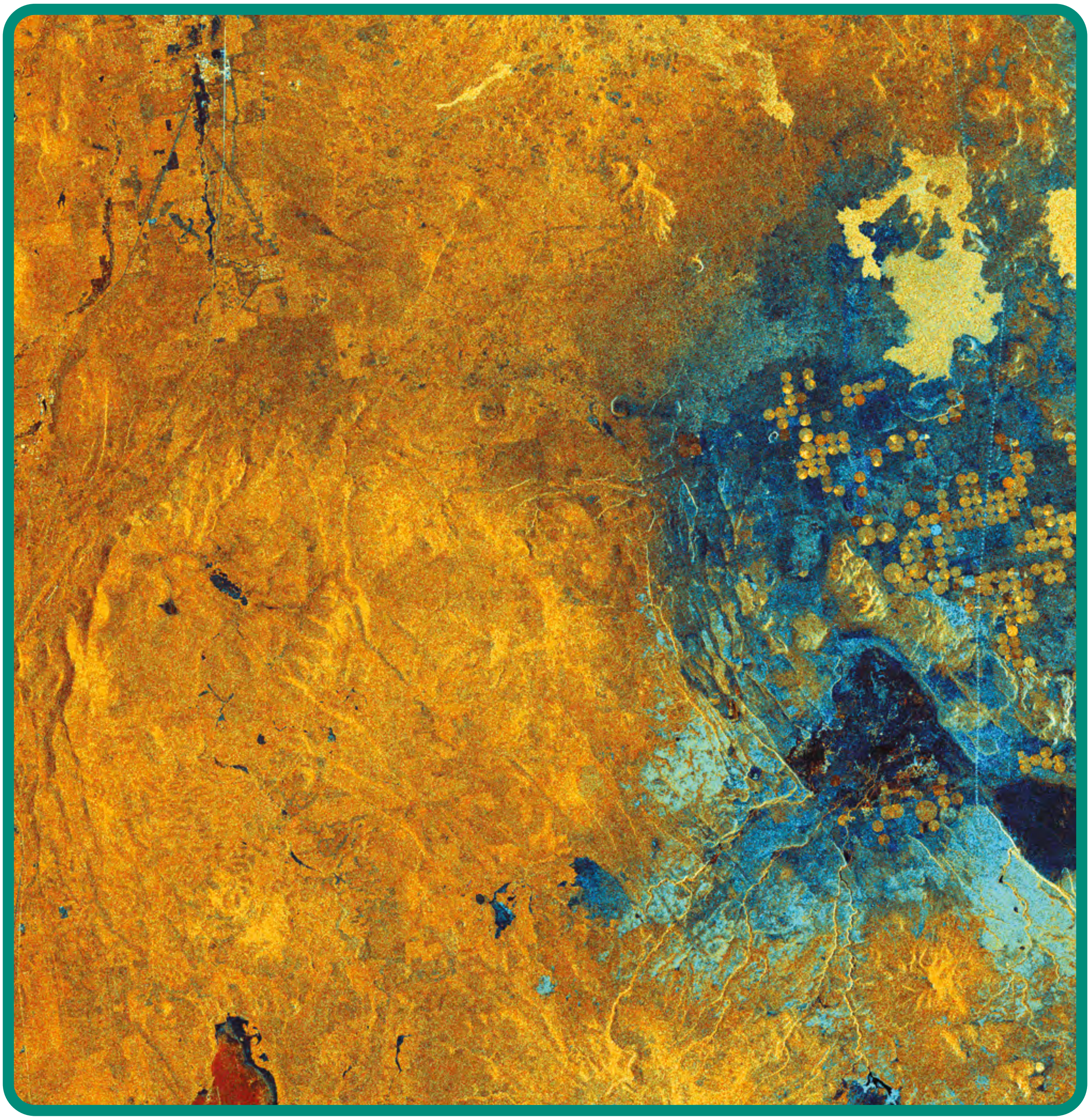
Angelica Tarpanelli showed her work on using surface reflectance data from MODIS to estimate discharge in rivers of width greater than 500 m. The approach was based on the ratio of reflectance at the river/bank interface and reflectance on land, serving as a proxy for river discharge to be used in probability mapping. The wider rivers led to better results than narrower rivers, and peak flow estimates suffered challenges, perhaps due to cloud covers impacting distributions at peak flows, or to the presence of sediments at peak discharge.

Paoli Filippucci adapted the aforementioned MODIS reflectance approach to account for increased sediment concentration at high peaks which tends to decrease the contrast between land and rivers and limit sensing capabilities. The modified methodology accounted for a new river pixel at the centre of the river channel – in addition to a pixel at the boundary between the river and its banks and to a land pixel – and improved high peak detection with MODIS.

Jessica Fontoura presented an analysis of water quality in Brazilian rivers, specifically a Google Earth Engine Approach to evaluate the colour of river water in Brazil. A ten-year analysis of predominant colour in rivers was shown to be characteristic of well-known features in Brazilian rivers such as clear rivers or those with strong sediment or organic matter concentrations.

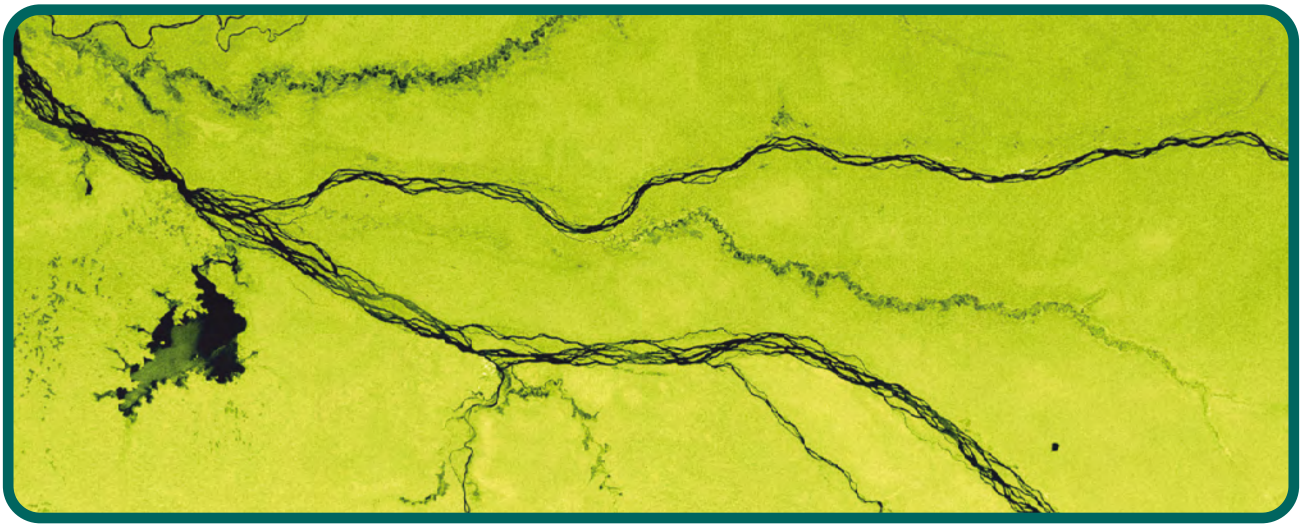
Thomas Ledauphin shared work on the joint variations of water level and inundated area in a French lake using remote sensing from Jason 3 and Sentinel-2, respectively. These joint measurements allow for an estimate of changes in water storage in the lake of interest, and informed a pre-SWOT analysis through their use in an instrument simulator.

Arjen Haag presented on an open-source application using optical measurements from Sentinel 2 and Landsat 8 as well radar measurements from Sentinel-1 to determine surface water inundation. The use of multi-mission data allowed alleviating for the sparse temporal sampling of any individual mission and offered new opportunities for data fusion methods.



5. ACRONYMS

CNES	French Space Agency
CFD	Computational fluid dynamics (modelling)
CRISTAL	Copernicus Polar Ice and Snow Topography Altimeter Mission
DAHITI	Database for Hydrological Time Series of Inland Waters
DEM	Digital Elevation Model
DTE	Digital Twin Earth
ECMWF	European Centre for Medium-Range Weather Forecasts
ECV	Essential Climate Variable
ENVISAT	Environment Satellite (ESA)
ERS1/2	European Remote Sensing missions
ESA	European Space Agency
FF-SAR	Fully-Focused SAR Altimetry
GEO	Group on Earth Observations
GEOGloWS	Group on Earth Observations Global Water Sustainability
GEOSS	Global Earth Observation System of Systems
GIEMS	Global Inundation Extent from Multi-Satellites
GRACE	Gravity Recovery And Climate Experiment
GravIS	Gravity Information Service
GloFAS	Global Flood Awareness System
GSWD	Global Surface Water Dataset
GNSS-R	Reflected Global Navigation Satellite System
HydroWeb	River and lake level database
ICESat/-2	Ice, Cloud, and land Elevation Satellite
LDAS	Land Data Assimilation
LISFLOOD	hydrological rainfall-runoff model
LIT	Lake Ice Thickness
NASA	National Aeronautics and Space Administration
NGGM-MAGIC	Next Generation Gravity Mission - Mass-change and Geosciences International Constellation
MODIS	Moderate Resolution Imaging Spectroradiometer
QC	Quality Control
SAMOSA	SAR Altimetry Mode Studies and Applications over Ocean, Coastal Zones and Inland Water - SAR altimeter ocean waveform retracker
S3NG-T	Sentinel-3 Next Generation Topography Mission
SARAL	Satellite with ARGOS and AltiKa Altimeter
SAR	Synthetic Aperture Radar Altimetry
SARvatore	SAR altimetry versatile application toolkit for research and exploitation
SM	Soil Moisture
SMASH	SMall Altimetry Satellites for Hydrology
SSM	remotely-sensed surface soil moisture
SWOT	Surface Water and Ocean Topography Mission
VIIRS	Visible Infrared Imaging Radiometer Suite



6. URLs

1st HYDROSPACE Workshop 2003

http://gos.legos.free.fr/HydroSpa2003.htm

2nd HYDROSPACE Workshop 2007

https://earth.esa.int/workshops/hydrospace07

3rd HYDROSPACE Workshop 2015

http://altimetry.esa.int/hydrospace2015

4th HYDROSPACE-GEOGloWS 2021 Workshop

https://hydrospace2021.org

Copernicus Global Land Monitoring Service/Water

https://land.copernicus.eu/global/themes/water

DAHITI

https://dahiti.dgfi.tum.de/en

EO FOR WATER CYCLE SCIENCE 2020

https://eo4water2020.esa.int

GEO

https://www.earthobservations.org

GEOGloWS

https://www.geoglows.org

GEOGloWS ECMWF Streamflow Service

https://geoglows.apps.aquaveo.com/apps/geoglows-hydroviewer

GEOSS Geoportal

www.geoportal.org

HYDROWEB

http://hydroweb.theia-land.fr

Global Surface Water Explorer (Pekel et al., 2016)

https://global-surface-water.appspot.com

SPACE4WATER

http://space4water.org

7. ACKNOWLEDGEMENTS

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Figure 3
The Co-Chairs of the "HYDROSPACE-GEOGloWS 2021" Workshop, on behalf of all the participants, would like to extend their grateful thanks to the sponsors of this workshop whose contributions, alongside the organisational effort from ESA and CNES, made this event possible.

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