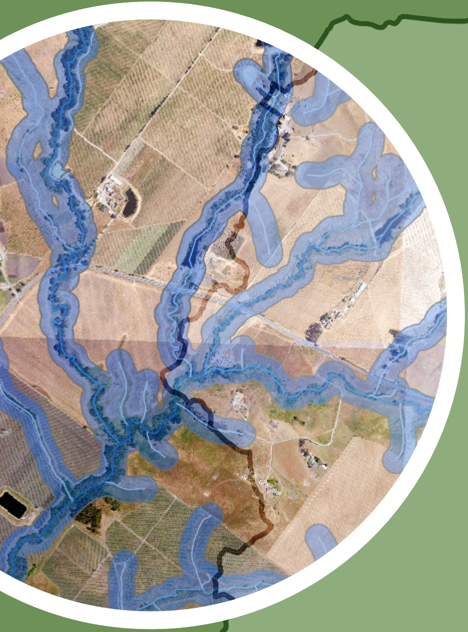
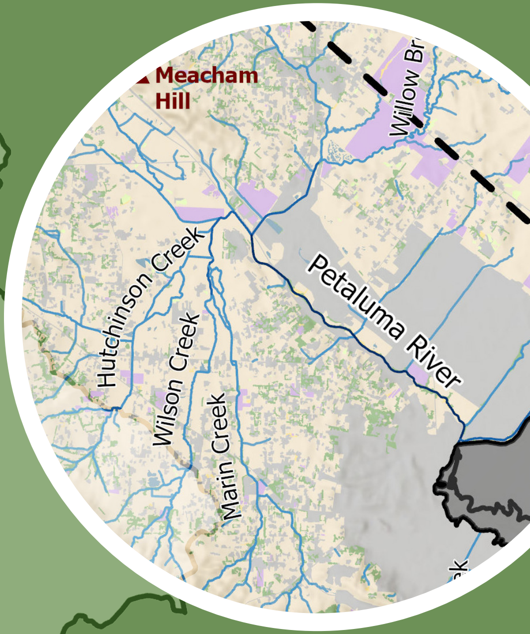
PETALUMA RIVER WATERSHED

CONTEMPORARY RIPARIAN CONDITION ASSESSMENT





SFEI San Francisco Estuary Institute

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CONTEMPORARY RIPARIAN CONDITION ASSESSMENT

January 2024

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IMAGE PERMISSION

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Contents

1. Introduction

Riparian habitats are defined as the physical and biotic components of ecosystems adjacent to waterbodies (Naiman et al., 1998; National Research Council, 2002). The riparian habitats of focus here are those adjacent to rivers and streams. Riparian habitats are important ecosystems on the landscape that provide unique habitat and functions at the intersection of upland and aquatic ecosystems. Riparian habitat is the most biodiverse and structurally diverse terrestrial ecosystem of the Pacific Coastal Region (Naiman et al., 1998). Forest, shrubland, grassland, and wetland vegetation communities all exist within the “riparian zone,” defined as the area that encompasses both the river channel and its adjacent habitats. For this assessment the riparian zone is identified primarily by the presence of riparian forest vegetation. Because of the significant role the riparian ecosystem plays in overall watershed biodiversity, exchange of materials, in-stream conditions, and other components of ecosystem health, it is important to characterize it and understand how its present condition relates to key drivers and ecosystem functions.

The objective of this technical memo is to describe the current channel and riparian condition and its drivers in the Petaluma River Watershed (Figure 1) and to describe the functions and stressors of riparian vegetation in the watershed by synthesizing the scientific literature. We combine spatial analysis of current riparian zone characteristics with a discussion of the historical context, the key drivers that define current conditions, and the ecological and hydrogeomorphic functions of the riparian zone in the watershed. This assessment draws from scientific literature, existing reports, and regional datasets, as described in Section 2 (Study Area and Methods). This document synthesizes existing information to describe the broader-scale regional drivers of channel and riparian characteristics (Section 3.1), provides a general description of current channel and riparian areas across the watershed, with a focus on riparian vegetation patterns (Section 3.2), provides a conceptual overview of the ecological functions supported by riparian areas across the watershed (Section 3.3), and details the key local drivers and riparian characteristics of the three major subwatersheds in the study area (Section 4). A summary of the current riparian assessment and further conclusions are provided in Section 5.

The full riparian assessment effort for the Petaluma River Watershed includes an examination of current conditions presented here and an overview of expected future conditions, which will be presented in a subsequent technical memo. This work is being done in coordination with an assessment of future watershed flow and sediment dynamics within the EPA-funded Sediment Solutions project. Ultimately, the work presented here will be expanded and incorporated into a synthesis report that describes present and future riparian, flow, and sediment dynamics in the Petaluma River Watershed and management actions to achieve desired dynamics and ecosystem functions under a changing climate.

2. Study Area and Methods

The Petaluma River Watershed is located roughly 18 miles north of San Francisco, California. The majority (13 mi) of the Petaluma River's 19 mi mainstem length is part of a tidal estuary system that drains into San Pablo Bay; this study focuses on the Petaluma River and its tributary streams above the head of tide (Figure 1). Above the tidal influence, the upper Petaluma River and its tributaries drain a watershed area of 123 mi^2. The channel network consists of 826 mi of streams (SFEI-ASC, 2017). Most (52%) are Strahler first order streams; second, third, fourth, fifth, and sixth order streams respectively make up 22, 12, 10, 2, and 2% of the total channel length. The Petaluma River above the head of tide is a sixth order stream. Typical geologic units, moving from east to west, include: the Sonoma Volcanics, Quaternary alluvial deposits, Franciscian Melange, and metamorphic Schists. Average annual precipitation in the watershed is 33.4 in, with wide ranges that generally follow changes in elevation. Most rainfall occurs in the winter months, which is typical for the area's Mediterranean climate.

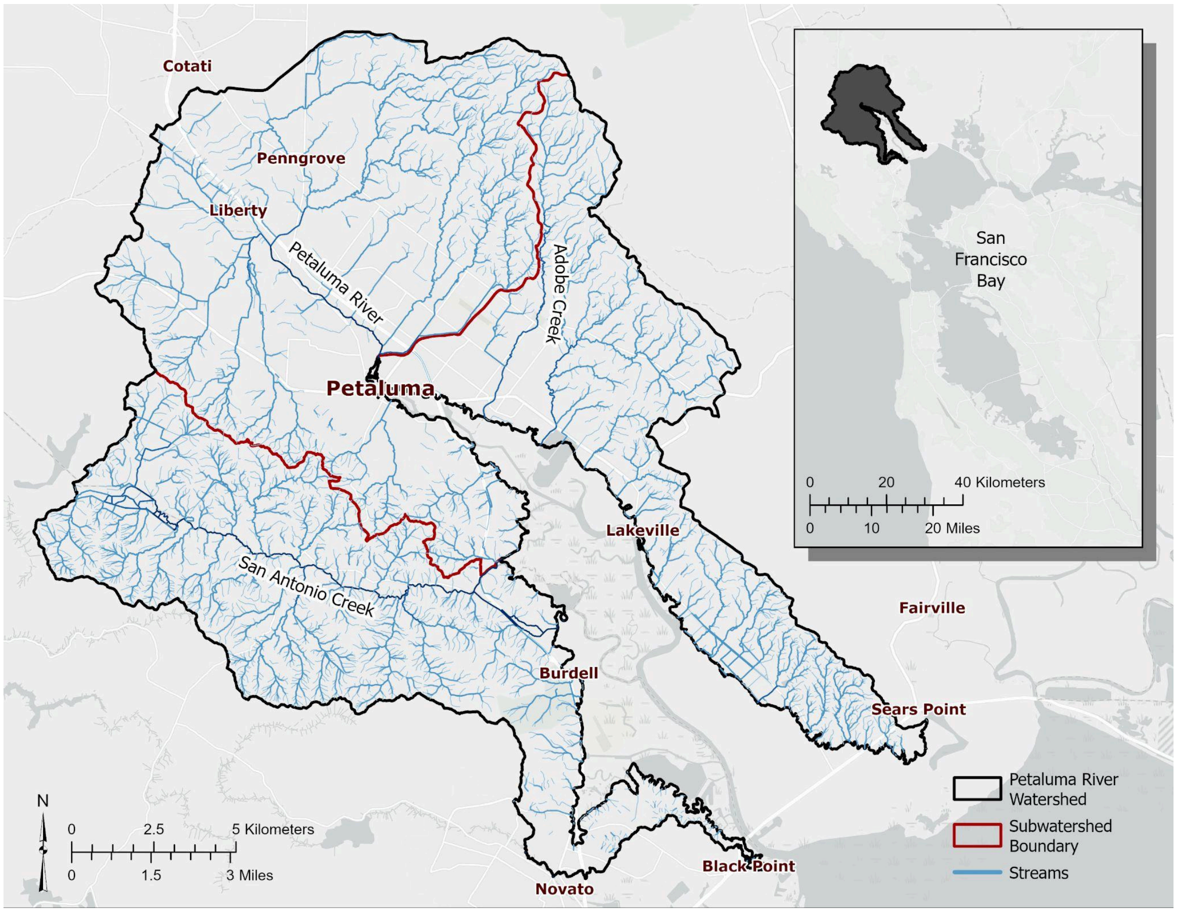
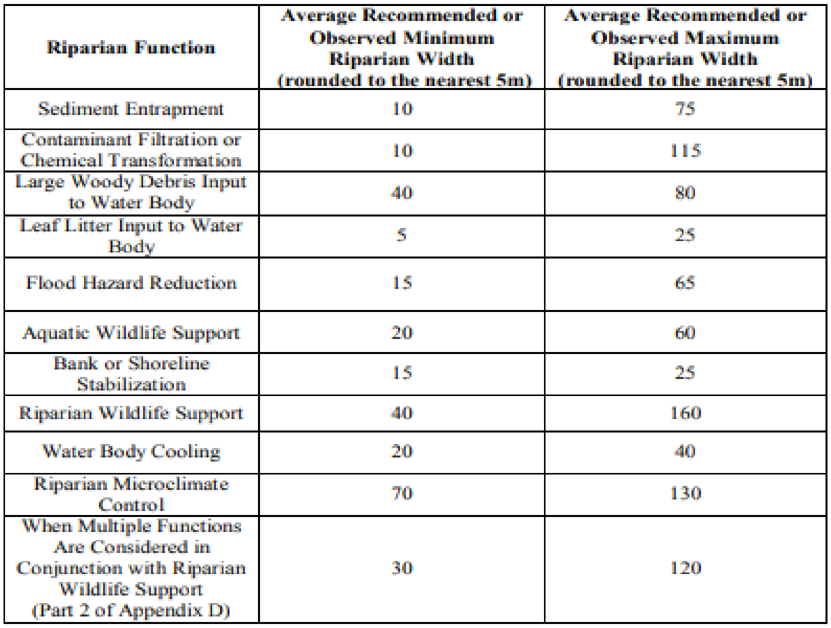


Figure 1. The Petaluma River Watershed study area is located north of the San Francisco Bay. The three primary drainages in the watershed (Petaluma River, San Antonio Creek, and Adobe Creek) are shown along with their subwatershed boundaries. Streams include those mapped in the Bay Area Aquatic Resource Inventory (SFEI-ASC, 2017).

The Petaluma River Watershed is within the Petaluma Operational Landscape Unit (OLU), which is a practical way to identify, manage, and interpret complex natural and anthropogenic processes using physical landscape boundaries (SFEI, 2023). OLUs are important for management because they provide distinct areas over which direct management action may take place. SFEI's Adaptation Atlas and Creek-to-Baylands Reconnection Opportunities memo (SFEI, 2023; SFEI & SPUR, 2019) identified thirty OLUs, each of which is defined as a physically-connected geographic area with common physical characteristics which would benefit from holistic management. The Petaluma OLU encompasses the Petaluma River Watershed and its estuary as it drains into San Pablo Bay.

Definitions of riparian ecosystems vary and can be quite broad. For instance, Collins et al. (2006) distills the commonly referenced National Research Council's (NRC) riparian definition as such: "*Simply stated, the NRC definition indicates that every length of every lakeshore, stream or river channels, estuarine or marine shoreline, and wetland margin is riparian to some degree.*" This poses a challenge when deciding which areas along waterbodies to evaluate as the "riparian zone" for management purposes. Defining the extent of the riparian zone is complicated, as the width or area varies depending on both geomorphic conditions and which riparian ecosystem function is being evaluated. Channel shading, for example, is limited to vegetation that directly provides shade to a stream (Naiman et al., 2005), whereas flood attenuation is provided by much wider areas (Collins et al., 2006). The summary of literature by Collins et al. (2006) in Table 1 demonstrates this variability. It also shows that a single width could be used when multiple functions are considered.

Table 1. Average recommended minimum and maximum riparian zone widths (in meters) for various riparian functions, as summarized by Collins et al. (2006). This table is published as Table 1 in the 2006 report.



Riparian Function	Average Recommended or Observed Minimum Riparian Width (rounded to the nearest 5m)	Average Recommended or Observed Maximum Riparian Width (rounded to the nearest 5m)
Sediment Entrapment	10	75
Contaminant Filtration or Chemical Transformation	10	115
Large Woody Debris Input to Water Body	40	80
Leaf Litter Input to Water Body	5	25
Flood Hazard Reduction	15	65
Aquatic Wildlife Support	20	60
Bank or Shoreline Stabilization	15	25
Riparian Wildlife Support	40	160
Water Body Cooling	20	40
Riparian Microclimate Control	70	130
When Multiple Functions Are Considered in Conjunction with Riparian Wildlife Support (Part 2 of Appendix D)	30	120

The riparian zone assessed in this document was defined as a standard 100 ft width on either side of mapped streamlines (Figure 2). Based on measurements taken from aerial photography, this width captures the majority of riparian forest vegetation in this watershed. As Table 1 suggests, a single riparian width can be chosen when evaluating multiple functions, and because our evaluation of riparian functions relies primarily on vegetation mapping (as discussed below), we chose to use riparian forest width as a guide; along streams in much of the watershed, riparian forest was easily distinguishable by a distinct shift from forest to grassland vegetation, usually within 100 ft of the stream (Figure 2b). This 100 ft buffer area also encompasses many riparian functions related to flooding, bank stability, and runoff filtration, which are present even in the non-forested, open, grassland areas of the watershed. In some headwater areas, forests are wider than the riparian zone, but with a brief evaluation of a digital elevation model hillshade and local knowledge of the study area, we assume that beyond 100 ft, the forest transitions to upland ecosystems, more reliant on hillslope drainage than streamflow (Figure 2a). In the Petaluma Valley, riparian ecosystems may have historically been much wider, however the 100 ft buffer captures current riparian width in urban areas fairly well (Figure 2c). The buffer was applied to all mapped streams in the watershed.

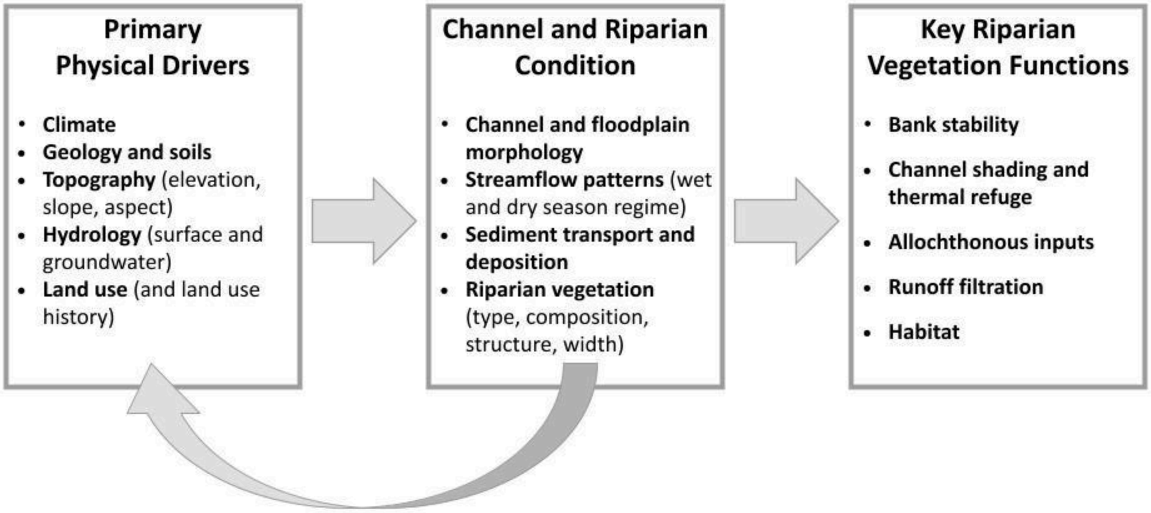
Several datasets were used in the assessment of the riparian zone, drawing from existing research and analyses in the region (e.g., Collins et al., 2001). We conducted a literature review of documents specific to the study area, including: Baumgarten et al., (2018); Langenheim et al., (2010); SFEI, (2021); Sonoma RCD, (2008), (2015); Traum et al., (2022). These reports provided current and historical context of riparian conditions and functions. Collins et al., (2000) is an example of a field-based geomorphological assessment of the area and analogous areas within the region. Quantification of current riparian condition was based on fine-scale vegetation mapping for Sonoma and Marin counties (One Tam & Tukman Geospatial, 2021; Tukman Geospatial & Kass Green & Associates, 2019) and aerial photography from the National Agriculture Imagery Program (NAIP; (U.S. Geological Survey, 2022). We crosswalked the fine scale vegetation mapping classes into seven land cover classes (cropland, developed, forest, grassland, other, shrub, and wetland), and conducted our analysis on this land cover within the riparian zone. Other landscape-scale digital products allowed for evaluation of regional differences within the study area. These included precipitation and temperature data from PRISM Climate Group (2014), geologic maps (Blake et al., 2000; Wagner & Gutierrez, 2017), elevation-derived products (Quantum Spatial, 2019; Watershed Sciences, Inc, 2013), land use mapping (ABAG, 2005), a recent groundwater report of the watershed from the U.S. Geological Survey (Traum et al., 2022), and soil descriptions (NRCS, 2005). Brief field visits by the authors helped contextualize the above reports and datasets, but no detailed surveys were conducted.

Channel and riparian conditions and functions can be evaluated at many spatial and temporal scales. This report is oriented toward the watershed and subwatershed scales. In order to describe current conditions, climate, land use and other drivers were evaluated at the decadal scale. Historical context has been taken into account to acknowledge the shifts in land use and vegetation patterns since European settlement in the early 19th century.

Figure 2. Aerial imagery (U.S. Geological Survey, 2022) showing examples of the riparian zone (dashed white lines) from various locations across the watershed. The riparian zone is 100 ft wide on either side of mapped streams (blue lines; SFEI-ASC, 2017). Images are A) forested headwaters of San Antonio Creek, B) the main stem San Antonio Creek, indicated by the darker blue streamline, C) East Washington Creek in the City of Petaluma, and D) gullied streams dominated by grassland vegetation in the southeast part of the watershed.

3. Overview of Riparian Zone Characteristics

The channel and riparian condition within the riparian zone reflects the relationship between state factors, interactive controls, and ecological processes (Chapin et al., 2002). Channel and riparian structure in the Petaluma River Watershed is driven by five main elements: climate, geology, topography, hydrology, and land use. The first four are considered state factors, or external drivers, and combine to provide conditions that define the ecological potential for the riparian area (Chapin et al., 2002). Land use is an interactive control that can drive patterns within that potential space (Chapin et al., 2002; Naiman et al., 2005). It is important to acknowledge the interplay between these drivers, as none operate in isolation; for example, the hydrology of the system is a result of climate, geology, topography, and land use. To add to this complexity, riparian vegetation–a characteristic of riparian condition–also influences physical drivers such as hydrology and geomorphology and other processes such as sediment transport and deposition. Figure 3 summarizes this understanding of the drivers and responses of channel and riparian condition, and provides a framework for how they are discussed in this document.



Primary Physical Drivers

- **Climate**
- **Geology and soils**
- **Topography** (elevation, slope, aspect)
- **Hydrology** (surface and groundwater)
- **Land use** (and land use history)

Channel and Riparian Condition

- **Channel and floodplain morphology**
- **Streamflow patterns** (wet and dry season regime)
- **Sediment transport and deposition**
- **Riparian vegetation** (type, composition, structure, width)

Key Riparian Vegetation Functions

- **Bank stability**
- **Channel shading and thermal refuge**
- **Allochthonous inputs**
- **Runoff filtration**
- **Habitat**

Figure 3. Conceptual diagram of the relationship between physical drivers, channel and riparian condition, and riparian vegetation functions. The five primary physical drivers determine channel and riparian condition, which includes riparian vegetation type, composition, structure, and width. Vegetation can influence both the physical drivers and channel and riparian condition, a complex feedback mechanism simplified here. Ecological functions of riparian vegetation are determined by the channel and riparian condition.

3.1 Drivers of Riparian Condition

Climate

The Petaluma River Watershed, like the rest of the San Francisco Bay Area, has a Mediterranean climate characterized by mild, wet winters and warm, dry summers. Average annual precipitation in the watershed is 33.4 in, ranging from 51.2 in at higher elevations to just 25.6 in on the valley floor (Figure 4; data are based on 30-year normals from 1991-2020; PRISM Climate Group, 2014). The region's rainfall predominantly occurs between November and April, often in episodic bursts. Summers are warm and arid, with an average daily maximum temperature of 81.7°F (PRISM Climate Group, 2014). The watershed is in close proximity to the Pacific Ocean, which provides some moisture from fog during the summer months. In recent years, periods of hot, dry, and windy weather have occurred in the fall, when vulnerability to fire is greatest. An important factor of the Mediterranean climate in this region is its high inter-annual variability, where shifts between wet and dry years can have extreme effects on hydrology (Kondolf et al., 2013) and other processes.

Regional climate is a dominant driver of channel and riparian structure and function on the landscape. Climate directly influences the vegetation community, and also influences factors of streamflow, erosion patterns, soil properties, and fire regimes that control the riparian zone. Precipitation and water availability drive which plant species can grow and where. The location, duration, intensity, and quantity of streamflow are all influenced by climate patterns. Soil production and shorter term hillslope and channel erosion are influenced as well. Months without rain are conducive to fires in this region, exacerbated or subdued at times by decadal droughts or wet periods. Climate also influences land and water use through the types of agriculture practiced and the need for groundwater pumping during dry periods.

Geology and Soils

Various underlying geologic units directly control the morphology of landforms and channels within a watershed, as well as the observed soil types and structures. Soil moisture and groundwater availability for plants are functions of geology as well. This provides the foundation for ecological expression across the landscape (Naiman et al., 1998). Riparian vegetation in turn influences channel morphology, a process discussed below.

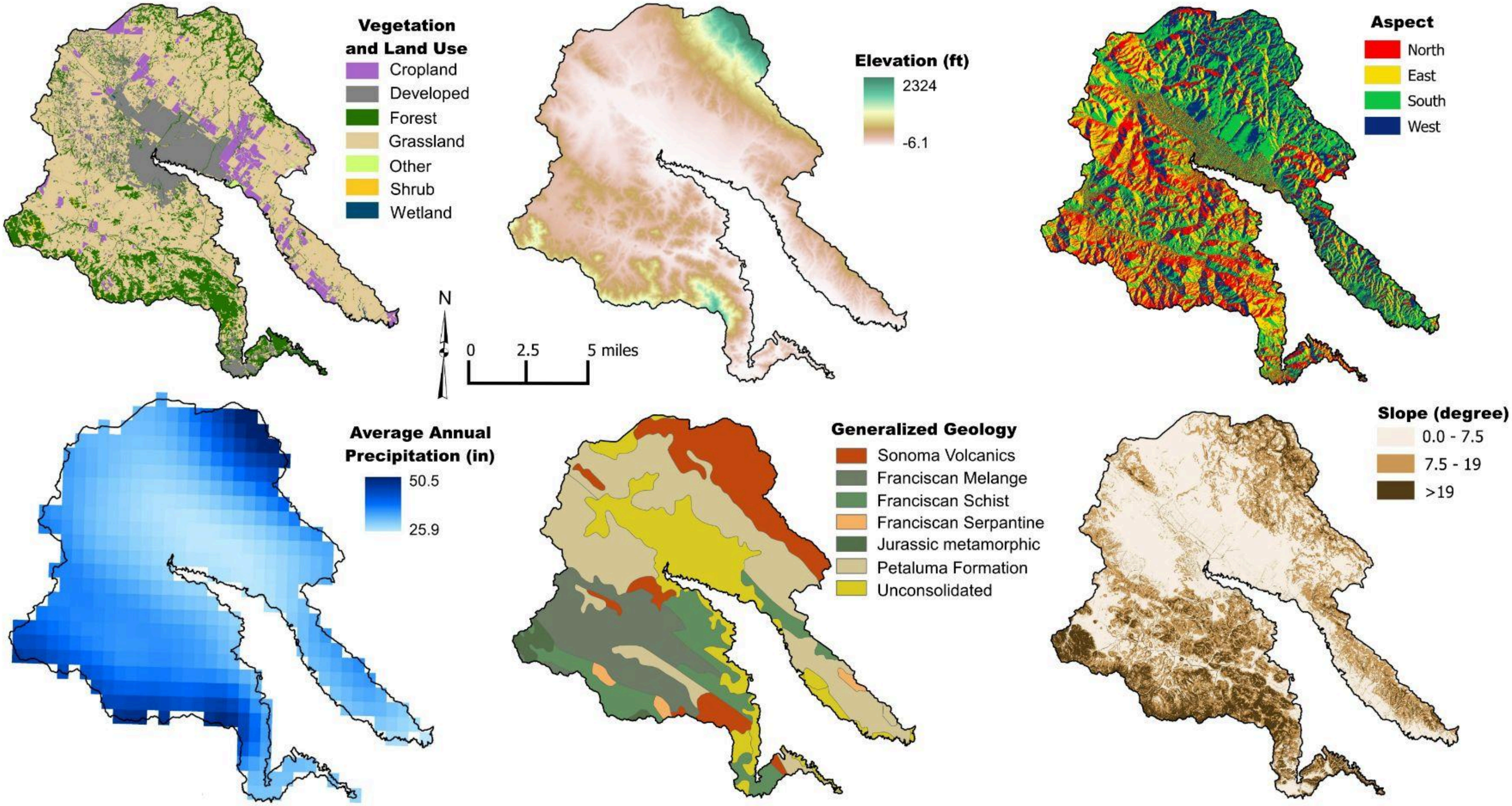


Figure 4. Key drivers of riparian structure within the Petaluma watershed. From top left: Crosswalked vegetation mapping (One Tam & Tukman Geospatial, 2021; Tukman Geospatial & Kass Green & Associates, 2019), LiDAR-derived elevation (Quantum Spatial, 2019; Watershed Sciences, Inc, 2013), slope aspect (derived from elevation data), 30 year annual precipitation averages (PRISM Climate Group, 2014), fine-scale geologic mapping (Blake et al., 2000; Wagner & Gutierrez, 2017), and slope (derived from elevation data).

Generally, the Petaluma Valley is bounded by two metamorphic and igneous formations. The northeast section of the watershed (Sonoma Mountain) is primarily underlain by Pliocene-age Sonoma Volcanics (Figure 4) and sedimentary rocks from the Miocene-age Petaluma Formation. On the other side of the valley, the southwestern mountainous boundary consists of highly erodible Franciscan Melange from the Jurassic-Cretaceous period. Quaternary unconsolidated alluvial deposits from the late Pleistocene to Holocene periods fill the basins and valley floor areas (Figure 4). An alluvial plain lies on the entire mountain front of the Sonoma Mountains, where historically streams likely spread across the landscape in constantly shifting braided channels, depositing coarse material and transporting finer material to the lowland valley. Today, streams follow a singular flow path, often incised, more efficiently flushing both coarse and fine sediment downstream.

The structural integrity and erodibility of geologic features vary, resulting in differences in topography, hydrology, and soil types across the watershed. Accordingly, geology is a primary distinction between the three major subwatersheds (see Section 4). A nearby 2019 study of Franciscan formation lithological controls on plant-available water via the critical zone found that the young, unweathered melange had low water storage capacity, resulting in flashy stream runoff and plant communities dominated by annual grasses and oaks (Hahm et al., 2019). Older, more deeply weathered lithologies may support more forest growth. This is an example of how geology can directly drive patterns in surface runoff and riparian vegetation community and condition in this watershed (Hahm et al., 2019).

Soil types are fairly homogeneous across the watershed. The Natural Resources Conservation Service (NRCS) soil database (NRCS, 2005) describes soils in the watershed as ranging from silty clay to sandy loam. These were detailed further in the Soil Survey of Sonoma County (Vernon, 1972). The major classified soil types east of Petaluma (Figure 1) of the watershed included Diablo clay, Goulding cobbly clay loams (high runoff and high erosion hazard), an erosive Gullied land class, and Clear Lake clay, which was associated with slow runoff characteristics and low erosion potential. In San Antonio Creek (Figure 1), the Soil Survey of Marin County (Kashiwagi, 1985) described similar soil characteristics. Specific soil types included Zamora silty loams, Clear Lake clay, Los Osos clay loam, Ballard gravelly loam, Blucher silt loam, Cole clay loam (characterized by a moderate erosion hazard).

Topography

Topography is the expression of elevational relief and landforms within the watershed, driven by the interaction of geologic units, tectonics, and erosional processes. The Sonoma Mountains form the eastern border of the watershed, and the southern and western boundaries are mountainous as well. These areas drain into the Petaluma Valley, an alluvial basin, and also directly into the Petaluma Marsh. The highest elevation in the watershed is 2,324 ft above sea level in the Sonoma Mountains. To the south, the highest elevation is 1,560 ft in the Burdell Mountain area. The broad Petaluma Valley in the center of the watershed has both low elevation, not exceeding 250 ft, and flat terrain. The San Antonio Creek area has the steepest hillslopes, where high slopes range from 18 to as high as 77 degrees. The Sonoma Mountains have steep terrain as well, especially in the upper Adobe Creek drainage, with slopes becoming more gradual as they transition into the Petaluma Valley.

The Petaluma River Watershed channel network is controlled by basin morphology, which directly reflects the geologic units, relief, and slope within the watershed. In addition, channel morphology across the network is affected by relief, with slope directly controlling the dominant channel pattern. Topography also influences climate on a local and regional scale. Regionally, greater precipitation is found at higher elevations. Locally, slope and aspect interact to create microclimates. Slope steepness is a factor, as steeper slopes see greater microclimate effects. The combined effects of climate and topography are reflected in the vegetation of the Petaluma River Watershed. Higher elevations generally have greater forest cover, but this varies based on aspect. South-facing slopes, such as the ones found in the Sonoma Mountain area, generally have more grassland than North-facing slopes, like the ones found in the San Antonio Creek headwaters. The reduced solar energy on North-facing slopes allows soils to retain moisture for longer periods, supporting higher forest coverage.

Hydrology

All tributaries to the Petaluma River (and occasionally reaches of the Petaluma River) have intermittent flow regimes, lacking surface flow in the summer months (Traum et al., 2022). Headwater and higher elevation streams are largely ephemeral and drain the landscape during storm events in the rainy winter and spring seasons. Due to the Mediterranean climate of the region, most fluvial processes occur during punctuated rain events. Sediment, nutrients, contaminants, and wood are transported in pulses during these events. These effects are subject to high variability in this climate (Kondolf et al., 2013).

While surface runoff is the primary source of streamflow in the Petaluma River, groundwater also plays a significant role in this watershed, historically providing baseflow in various perennial reaches throughout the watershed and providing hydraulic connectivity between them in dry summer months (Traum et al., 2022). Groundwater inputs contribute seasonally to gaining stream reaches along portions of the Petaluma River mainstem and other tributaries, and springs have been mapped at the base of alluvial fans as well as in the Sonoma Mountains and Burdell Mountain area (Traum et al., 2022). Modeling work conducted by Traum et al. (2022) has shown that gaining streams exist in the valley, while reaches on the alluvial fans lose flow to groundwater. There is little evidence that faults influence groundwater flow in this watershed, although faults do bound aquifers (Traum et al., 2022). Groundwater pumping both for irrigation of agricultural areas and for urban water supply caused a decline in water table levels in some parts of the watershed between the late 19th and early 20th centuries (Baumgarten et al., 2018). Overall, groundwater levels have not changed substantially since the 1950s, though levels fluctuate seasonally and groundwater pumping has resulted in local drawdown (Traum et al., 2022).

Drawdown of the water table reduces the amount of groundwater support provided to stream reaches, increases the extent and severity of intermittent flow, and stresses riparian vegetation through lack of water and nutrients. Channel incision and groundwater pumping for agriculture along tributaries to the Petaluma River, like San Antonio Creek, have increased the distance between ground surface and the water table, reducing the availability of shallow groundwater for riparian vegetation. As hillslope water and nutrient movement may help support vegetation along smaller streams (Naiman et al., 2005), this same level of support is not necessarily available to riparian forests along larger tributaries, which means that prolonged periods of drawdown may cause these riparian forests to become stressed. Signs of riparian forest stress are not evident based on land cover mapping used in this assessment, however understory vegetation may be a useful indicator to help evaluate stress (Geoff Wang, 2000).

Land Use

Land use changes that have occurred over the past two centuries have driven widespread changes in channel and riparian conditions within the watershed, both directly and indirectly. Current conditions are influenced both by present day land uses and the legacy of past land use and land use change.

The City of Petaluma is the largest urban zone in the watershed, with developed land occupying approximately 15% of the total watershed area (Figure 4). Forested bay laurel and oak assemblages make up 17% of the total watershed area, alongside shrub and wetland areas which cover just 1% each. The majority of the watershed (60%) is open space grasslands, with 44% of this area used as pasture, and 22% used as rangeland (ABAG, 2005). 6% of the watershed is dedicated to cropland agriculture, consisting primarily of managed hayfields and vineyards (Tukman Geospatial & Kass Green & Associates, 2019).

Agriculture has been the primary land use throughout much of the watershed, beginning in the early to mid-19th century (Baumgarten et al., 2018). The focus of agriculture has historically shifted from grain production to poultry to dairy, and pasture and rangeland currently occupy the majority of land in the watershed. The watershed’s grasslands are dominated by multiple non-native and invasive grass species (e.g., *Avena sp.*, *Bromus sp.*, *Hordeum sp.* and *Phalaris sp.*), which arrived with European settlement, often in association with cattle grazing. This change from native perennial grasses to non-native annuals has reduced soil stability and infiltration rates (Stromberg & Kephart, 1996), potentially causing greater runoff and erosion rates. As noted above, groundwater pumping for hay production and other agricultural uses, as well as for water supply has contributed to drawdown of the water table.

The impacts of livestock grazing on riparian conditions depend on the timing, intensity, and duration of activity. Livestock impact riparian systems in a few ways. Livestock can alter channel morphology by trampling the bed and banks and widening channels, contributing direct sediment inputs (Kauffman & Krueger, 1984). By reducing forest and understory growth along streams via grazing and trampling (Kauffman & Krueger, 1984), grazing pressure can narrow riparian forest width, and heavy, continuous grazing can prevent forest regeneration. The widespread extent of rangeland and pasture on the watershed's grasslands indicates that grazing may be the most influential land use-related driver of current riparian characteristics in non-urbanized areas across the Petaluma River Watershed.

Urban and suburban development accelerated in the mid to late 20th century, particularly on the eastern side of the Petaluma River Valley. The increase in impervious surface cover has likely resulted in flashier flows and increased peak flow volumes downstream of urban areas. When floods occur, the reduced extent of the riparian area can concentrate more water in a smaller area and increase the available shear forces to initiate channel incision. Infrastructure associated with major transportation corridors, such as Highway 37 and Highway 101, directly altered the hydrography of the Petaluma River, San Antonio Creek, and other stream channels. In the valley floor in particular, these anthropogenic land use changes have been a dominant driver of riparian conditions, overriding much of the imprint from other physical drivers.

Channelization and other direct changes in channel alignment and morphology have impacted many streams throughout the watershed. The most notable of these changes is at the mouth of San Antonio Creek, whose outlet to the Petaluma Marsh was relocated. Numerous tributaries throughout the watershed have been ditched and straightened to increase drainage efficiency and control flooding. This includes portions of Thompson, Hutchinson, Marin, Washington, and Adobe Creeks, among others. Historically, the downstream portions of many tributaries spread out through distributary networks, which helped to sustain non-tidal freshwater wetlands and replenish groundwater. The lower portions of many of these creeks, including Adobe, East Washington, Washington, Lynch, Marin, Hutchinson, and Wilson, have been channelized and connected to downstream systems to convey flows and sediment more rapidly downstream. Channelization is usually associated with partial or full destruction of riparian habitat and can significantly alter the functions of riparian areas that have been affected (U.S. EPA, 2017).

Because of the significant negative effects of land use changes on riparian areas, several local ordinances have been implemented to protect riparian ecosystems in the area. In Sonoma County, Sec. 26-65 of the municipal code was adopted in 2014 (Sonoma County, 2014). This section establishes Riparian Corridor Combining Zones to protect these areas for their habitat and environmental value. Generally, this ordinance protects a minimum buffer of 50 ft surrounding designated streams within the county. Exceptions exist (see Sec. 26-65-030 of the municipal code), and can include some forms of agriculture. Larger buffers of 200 ft are mandated in Streamside Conservation Areas in agricultural zones (Ordinance

Number 6089 amendment to Chapter 26 of the Sonoma County Code). Marin County (which covers much of the San Antonio Creek subwatershed) has adopted similar goals of preserving riparian areas, but does not have specific ordinances surrounding specific streams.

Riparian preservation and restoration efforts have also begun. EcoAtlas (SFEI, 2017) documents restoration efforts within the watershed, including a Capri Creek Flood Reduction and Habitat Enhancement Project. The Petaluma Watershed Enhancement Plan also describes opportunities for future restoration of riparian areas; it recommends revegetating high and medium priority riparian sites, managing livestock access to the creeks, especially during the wet season, conducting community outreach, and providing technical assistance to landowners to help manage and protect riparian areas, among other recommendations (Sonoma RCD, 2015).

3.2 Channel and Riparian Condition

The climate, geology, topography, hydrology, and land use drivers discussed above combine to create current channel and riparian conditions in the Petaluma River Watershed.

The steep mountains on either side of Petaluma Valley create a pinnate dendritic drainage pattern, where tributaries have relatively short, straight flow paths to the Petaluma River that flows along the axis of the valley. The only tributary with a large bend is Lichau Creek which flows west from the Sonoma Mountains, meets the Petaluma Valley Fault, and turns south at a 90 degree angle where it is joined by Willow Brook Creek before draining into the Petaluma River. Due to the short, steep flow paths, there are few floodplains outside of the Petaluma Valley along tributaries of the Petaluma River (FEMA, 2020). As channels have incised, floodplains, like those seen on San Antonio Creek, have formed into terraces. The functions provided by floodplain ecosystems are now only available during large, less frequent flood events.

Historical data suggest riparian oaks (*Quercus sp.*), California bay laurel (*Umbellularia californica*), buckeyes (*Aesculus californica*), and willows (*Salix sp.*) dominated riparian forests along San Antonio Creek (Collins et al., 2000), and similar conditions existed on the Petaluma River mainstem and its tributaries (Baumgarten et al., 2018). Where modern land uses permit, a similar assemblage of riparian tree species exists today (Figure 5). In urban and suburban areas the riparian zone is heavily managed for aesthetic and flood control purposes. Non-native species such as eucalyptus (*Eucalyptus sp.*), walnuts (*Juglans sp.*), elm (*Ulmus sp.*), and acacia (*Acacia sp.*) have been introduced. Eucalyptus is problematic in that it prevents other species from growing, and poses increased fire risk. Riparian understory across the watershed has experienced widespread invasion by Himalayan blackberry (*Rubus armeniacus*), which also dominates structure and prevents other species from growing. Other understory species include poison oak (*Toxicodendron diversilobum*), elderberries (*Sambucus sp.*) and gooseberries (*Ribes sp.*). Multiple grass species are present across the watershed including *Avena sp.*, *Bromus sp.*, *Phalaris sp., Cynodon dactylon, Ehrharta sp., Paspalum sp.,* and *Hordeum murinum*, which are non-native.

Within the riparian zone across the watershed, land cover consists of 60% grassland, 30% forest, 4% developed, 3% cropland, 1% shrub, 1% wetland, and 1% other categories (Table 2). The riparian zone generally has higher tree cover than the rest of the watershed; 41% of all forested areas in the watershed are found within the 100 ft riparian zone buffer, despite this area accounting for only 11.5% of total land area. Within the riparian zone, trees generally grow directly adjacent to streams. Although grassland comprises a majority of the riparian zone, a significant portion of the grassland within the 100 ft buffer is not stream-adjacent, seen on the Figure 5 inset and Figure 2b. Grassland is, however, directly adjacent to 52% of streams, most commonly in arid, south-facing drainages in the southeastern part of the watershed and north side of the San Antonio Creek drainage where little to no tree cover exists (Figure 2d).

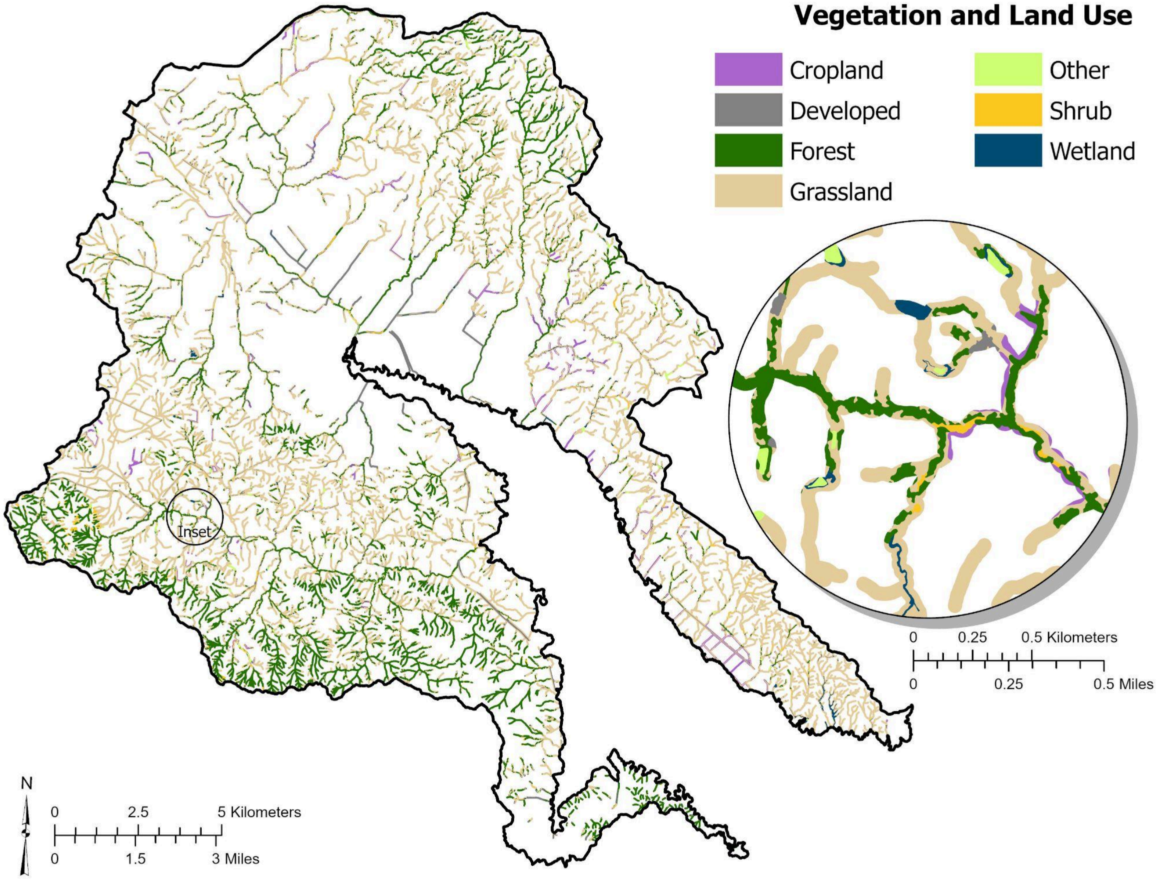


Figure 5. Vegetation and land use within the riparian zone, identified as a 100 ft buffer around mapped streams. The inset map provides a more detailed view of a portion of San Antonio Creek and its tributaries. Land cover classes are adapted from One Tam & Tukman Geospatial (2021) and Tukman Geospatial & Kass Green & Associates (2019).

Vegetation communities shift longitudinally along the stream network from headwaters to mouth. High rainfall in the Sonoma Mountains and the northern aspect in San Antonio Creek headwaters allow for greater coverage of forested areas, dominated by bay laurel stands (Figure 5). In mid elevations, channels transition into reaches lined with oaks or open grassy banks. Channels in the urbanized Petaluma Valley are sparsely forested by hardwoods such as bigleaf maple (*Acer macrophyllum*), California buckeye (*Aesculus californica*), and oaks (*Quercus sp.*).

The majority of the watershed's grasslands are used to graze livestock, with 44% of the grassland area classified as pasture and 22% classified as rangeland (ABAG, 2005). While grazing impacts were not explicitly quantified in this assessment, aerial photography, site visits, and the Draft Petaluma Watershed Enhancement Plan (Sonoma RCD, 2015) provide general information. Impacts include widening and shallowing of some channels, soil compaction within the riparian zone, and reduction of woody vegetation. Grazing management varies across the watershed, with some allotments having been intensely grazed, nearly to bare soil. Channels in such intensely grazed areas are susceptible to increased bank erosion and incision. Sonoma RCD (2015) has recommended reducing livestock access to the riparian zone, especially during the wet season when negative impacts from bank trampling and wallowing are increased, and to develop grazing plans to reduce overall impacts.

Table 2. Land cover of the Petaluma River Watershed and within the Riparian Zone

	Full Watershed		**Riparian Zone**	
Class	Acres	Percent of watershed	Acres	Percent of riparian zone
Cropland	4,865	6%	482	3%
Developed	11,798	15%	811	4%
Forest	13,521	17%	5,482	30%
Grassland	47,139	60%	11,283	60%
Other	455	0.5%	170	1%
Shrub	527	1%	256	1%
Wetland	381	0.5%	231	1%
Total	**78,686**	**100%**	**18,715**	**100%**

3.3 Riparian Vegetation Functions

Stream channels and riparian zones in the Petaluma River Watershed provide numerous ecological functions, both affecting and affected by hydrogeomorphic and biotic systems. This section provides a conceptual overview of the importance of key ecological functions and their relationship with physical drivers of channel and riparian condition, based primarily on the scientific literature. We focus on the key functions of riparian vegetation identified by Naiman et al., (2005), which include bank stability, channel shading and thermal refuge, allochthonous inputs, runoff filtration, and habitat for a variety of species.

A comprehensive, spatially explicit assessment of riparian function in the Petaluma River Watershed was not possible given data limitations. Overall, we assume that the highest degree of riparian function can be found where greater cover of native riparian forest exists, observed erosion and incision rates are minimal, channel straightening or other direct modifications have not occurred, and management practices limit impacts to the riparian zone.

Bank stability

Bank stabilization by riparian vegetation is particularly important in the Petaluma River Watershed, given the high rates of bank erosion, especially along San Antonio Creek (Collins et al., 2000). Much of the riparian zone is covered by non-native annual grasses that tend to have shallower root systems than their native counterparts that dominated the landscape prior to European settlement. These non-native grasslands may provide less bank stability and protection against erosion than historical native-dominated grasslands. However, stream banks vegetated by grasses and other herbaceous plants do provide enough stability to influence the morphology of channels. The influence of grassland vegetation on bank stability depends in part on the topographic and land use context. In low gradient stream reaches (<3%), the root systems of vegetated grassland stream banks tend to maintain narrower and deeper streams (compared to unvegetated banks), which benefits fish and aquatic organisms (Wohl, 2014). Vegetated banks contribute to healthy sediment dynamics, overall channel stability, and hydrologic function. Grass generally does not provide the same functions in steeper reaches, where hydrogeologic controls are likely more influential (Wohl, 2014). The effect of grassy, vegetated banks on bank stability is further influenced by grazing management practices. Heavy grazing diminishes the ability of grasses to stabilize banks, and cattle access to streams negatively impacts channel morphology (Kauffman & Krueger, 1984).

To a greater degree than grasses, trees and shrubs stabilize stream banks and influence channel morphology. Forests offer greater stabilization compared to annual grasses, especially in steeper-gradient reaches, as their deeper and more extensive root systems can armor banks more effectively. Undercut banks, which provide cover for fish, can form under extensive tree root systems. Robust riparian forests help increase channel sinuosity and contribute to floodplain development. In the channel, exposed tree roots and large wood inputs also provide hydraulic resistance, which can slow sediment transport downstream.

In urban areas, riparian vegetation helps stabilize banks, and active channel maintenance and bank armoring are widespread. In agricultural or cropland settings, bank stability depends on the management of riparian vegetation; grasses, shrubs and trees provide stability, but are often removed to maximize cropland area. Riprap or other bank armoring features may be installed to remedy the loss of this function by the riparian zone.

Channel shading and thermal refuge

Riparian forests shade the riparian zone and the channels that they grow beside, creating important microclimates that influence many ecological processes (Naiman et al., 1998, 2005). By blocking solar radiation, canopy cover can cool the riparian zone, and both streamflow and canopy cover can cool the air through evaporation and transpiration (Naiman et al., 1998). This creates thermal refugia in both aquatic and terrestrial habitats, critical for many species who rely on thermal refugia to survive the hot summer months or complete their life cycles.

The effect of tree canopy on water temperatures depends on the width of the stream and how much coverage trees can provide (Naiman et al., 2005). The need for shading is more pronounced on south facing aspects, because steep, north-facing aspects also provide protection from solar radiation. Riparian trees can also contribute to thermal refugia for fish, macroinvertebrates, and amphibians by encouraging the formation of local scour pools around exposed root balls or fallen trees. Several large in-channel pools existed historically within the Petaluma River mainstem, and may have provided cold-water refugia for salmonids and other native fish during the dry season (Baumgarten et al. 2018). Small pools continue to hold water in many of the major tributaries of the watershed even into the late summer months. Channel morphology in medium and low gradient streams (<5%) that have consistent pool-riffle sequences support these types of refugia. Together riparian forests and consistent pool-riffle channel morphology are key to providing habitat through the summer months.

Allochthonous inputs

A key function of riparian vegetation is its role as a consistent source of allochthonous material to the aquatic ecosystem (Naiman et al., 2005). Wood and leaf litter inputs create a steady supply of carbon and other nutrients, supporting aquatic food webs and contributing to nutrient cycling (Richardson et al., 2005). Alder (*Alnus sp.*) are an important nitrogen-fixing species occasionally found along streams in this watershed. Riparian vegetation contributes both primary and secondary production to aquatic ecosystems, supporting detrital food webs and providing food resources (e.g., invertebrate subsidies) for higher consumers (Baxter et al., 2005). Large wood inputs from riparian forests, such as fallen trees or limbs, create fish habitat and refuge from predators, and can initiate and maintain the formation of pools. Riparian vegetation is crucial for providing hydraulic roughness for flood flows, potentially lessening the impact of large floods. Wide floodplains are not common in this watershed on most of the tributary streams, and incision has disconnected many floodplains from the channel. However, when floods inundate the riparian zone, an exchange of sediment, litter, and nutrients occurs.

Riparian forests are particularly important sources of allochthonous materials to streams due to their high production of woody debris, litter, and food subsidies. However, grasslands also provide organic matter and invertebrate inputs. The management of riparian grasslands is important, as studies have found that invertebrate inputs to streams are greater for natural grassland compared to pasture (Edwards & Huryn, 1996) and for high density, short duration grazing compared to season-long grazing (Saunders & Fausch, 2007). The supplementary food sources from forests and grasslands can be a significant factor in supporting the growth of federally threatened steelhead and chinook salmon (Doucett et al., 1996).

Runoff filtration

Riparian ecosystems facilitate chemical transformations at the transition of upland and riverine systems, supporting aquatic ecosystem health through runoff filtration and biogeochemical cycling (Naiman et al., 2005). Development in the watershed can negatively impact aquatic water quality in several ways. Excess mineral nitrogen from agricultural practices and wastewater treatment may degrade water quality, leading to algal blooms and low-oxygen events. The Petaluma River is listed as impaired for eutrophication under the Clean Water Act. In addition, a Total Maximum Daily Load (TMDL) for bacteria has been established due to elevated bacterial concentrations in the Petaluma River and tributaries (SFBRWQCB, 2020). These elevated levels are associated with municipal wastewater treatment plants, sanitary sewer collection systems, private sewer laterals, grazing lands/operations, and municipal and California Department of Transportation stormwater runoff. These elevated bacterial concentrations may have negative effects on various riparian systems and have been associated with adverse effects in human populations. The Sonoma RCD (2015) has recommended creating livestock management plans to reduce direct manure inputs to streams.

Riparian forests aid in runoff filtration by providing hydraulic resistance to hillslope runoff, slowing transport to streams and allowing infiltration into the soils. Functioning riparian areas are able to slow the downstream transport of surface runoff, thus reducing peak flows in the channel network. Just as forested floodplains provide allochthonous inputs during flood events, the hydraulic resistance created by riparian forests also allows for groundwater recharge, ultimately contributing to maintenance of summertime base flow, and allows for fine sediment deposition. Both processes are important for nutrient cycling. Forested assemblages with robust root systems and wildlife burrows create larger subsurface flow paths for rainfall and flood flows to seep into the water table quickly, which also aids in subsurface nutrient cycling.

Habitat

Riparian areas are highly biodiverse and are often the area on the landscape most utilized by wildlife due to their unique position at the interface between aquatic and upland habitats (Naiman et al., 1993). Riparian habitat is especially important as a refuge during periods of drought (Naiman et al., 2005). Riparian forests also provide important connectivity between habitat patches, supporting biodiversity across the landscape. Throughout the Petaluma

River Watershed, the riparian zone supports high plant and animal species diversity, with species assemblages varying from high to low elevations. Higher elevations have greater forest coverage and are dominated by California bay laurels (*Umbellularia californica*), whereas lower elevations tend to have oak-dominated riparian forests with more limited coverage. Locally unique combinations of topography, microclimate, and hydrology create small-scale heterogeneity in the riparian structure, also supporting biodiversity (Naiman et al., 2005). Listed below are examples of bird, mammal, reptile, amphibian, fish, and macroinvertebrate species that utilize the riparian zone in the Petaluma River Watershed.

Birds that utilize riparian zone are numerous, but include the Traill's (willow) flycatcher (*Empidonax taillii*), yellow warbler (*Setophaga petechia*), Lincoln's sparrow (*Melospiza lincolnii*), Nuttail's woodpecker (*Picoides nuttallii*), Bullock's oriole (*Icterus bullockii*), and Lazuli bunting (*Passerina amoena*) (Baumgarten et al., 2018). Mammals include the black-tailed deer (*Odocoileus hemionus hemiounus*), red fox (*Vulpus vulpus*), coyote (*Canis latrans*), skunk (*Mephitidae mephitis*), racoon (*Procyon lotor*), black-tailed jackrabbit (*Lepus californicus*), long-tailed weasel (*Mustela frenata*), and California vole (*Microtus californicus*) (Petaluma Wetlands Alliance, 2023a). Reptiles found in the watershed include garter snakes like the California red-sided garter (*Thamnophis sirtalis*) and coast garter (*Thamnophis atratus*), the California king snake (*Lampropeltis getula californiae*), turtles like the red-eared slider (*Trachemys scripta elegans*) and western pond turtle§ (*Actinemys marmorata*), and various lizards (Petaluma Wetlands Alliance, 2023b). The California red-legged frog†§ (*Rana aurora draytonii*), California tiger salamander†* (*Ambystoma californiense*), and foothill yellow-legged frog§ (*Rana boylii*), are amphibians that rely upon riparian habitats in this watershed (CDFW, 2023). The California tiger salamander mostly rely on vernal pools, but can be found in riparian habitats. Historically, vernal pool complexes were more extensive in the watershed and supported these species, even outside of riparian corridors. As streams dry, pools remaining in channel beds provide refuge for these species into the dry season.

Two anadromous salmonid species, the Central California Coast steelhead† (*Oncorhynchus mykiss*) and Chinook salmon†* (*Oncorhynchus tshawytscha*), spawn in this watershed. These fish take advantage of the extended stream network during the wet winter season, and juveniles may rely on pools and thermal refuges as creeks dry. Many other fish species thrive in the Petaluma River Watershed, including the Sacramento splittail§ (*Pogonichthys macrolepidotus*). Robust riparian vegetation supports healthy macroinvertebrate populations (e.g., *Trichoptera sp.*, *Plecoptera sp.*, and *Ephemeroptera sp.*) that fish rely on. The riparian zone acts as a source of shade, protection, food, and habitat structure for these fish. Additionally, riparian trees that fall into the stream channel play an important role in creating diverse aquatic habitats and by sorting and selectively trapping coarse sediment that supports salmonid spawning and benthic macroinvertebrate production.

Symbols indicate species listed as federally threatened (†) or federally endangered (‡) under the Endangered Species Act, as well as those listed by the State of California as threatened (*), endangered (**) or species of special concern (§).

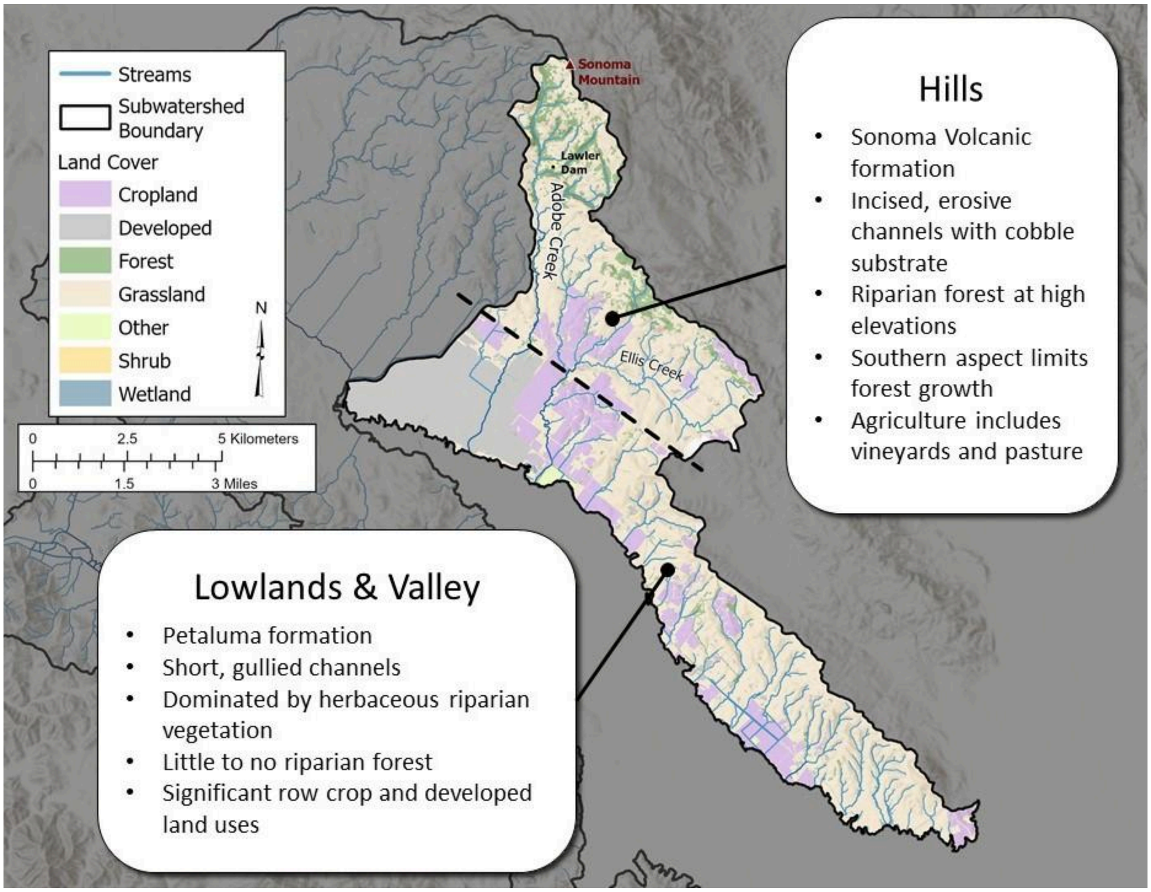
4. Channel and Riparian Assessment by Subwatershed

Within the Petaluma River Watershed, variations in topographic, geologic, hydrologic, and land-use controls have led to local differences in riparian characteristics. To describe these differences, we have divided the watershed into three subwatersheds: the Petaluma (53 mi^2), Adobe (31 mi^2), and San Antonio (39 mi^2) subwatersheds. Subwatershed delineations are based on the four Hydrologic Unit Code 12 (HUC12) subwatersheds within the study area, with the small Burdell Mountain-Frontal San Pablo Bay Estuaries subwatershed split at the mouth of San Antonio Creek and incorporated into the Petaluma and San Antonio subwatersheds (Figure 1). We consider these subwatersheds because they are primarily defined by topographic boundaries, and only slightly altered from the HUC12 boundaries. The Petaluma and Adobe subwatersheds have further distinctions between the valley and hills (Figures 6 and 7), a general separation used for discussion. Key spatial differences in subwatershed riparian characteristics are summarized in Figures 6-8.

Our evaluation of these subwatersheds is an attempt to highlight unique and important elements of channel and riparian drivers, condition, and functions across the watershed. While the riparian functions listed above in Section 3.3 are important across the watershed, key functions in each subwatershed were identified based on the authors' best professional judgment, using the synthesis of information compiled in this assessment.

4.1 Adobe Subwatershed

Adobe Creek is the main tributary draining the western slope of Sonoma Mountain in the Adobe Subwatershed, along with Ellis Creek and numerous smaller tributary streams to the southeast (Figure 6). Riparian areas in the subwatershed are dominated by grassland vegetation (72%; the highest proportion of the three subwatersheds). This area also has the highest proportion (81%) of grassland dedicated to livestock, with 66% pasture and 15% rangeland (ABAG, 2005). Moreover, this subwatershed has the lowest proportion of riparian forest (14%) of the subwatersheds and cropland (6% of the riparian zone, but 15% of the entire subwatershed; Table 3). Two distinct regions exist in the subwatershed: the upper, south-facing hills and lower valley urban areas. The predominantly south and southwest-facing aspects of hillslopes lead to higher rates of evapotranspiration and generally drier conditions despite the high rates of rainfall in the upper hills of the watershed. Areas of riparian forest exist primarily along the mainstem of Adobe Creek and larger tributaries and are dominated by California bay laurel (*Umbellularia californica*), oaks (e.g., *Quercus lobata*, *Quercus garryana*), maple (*Acer sp.*) and alder (*Alnus sp.*) (Tukman Geospatial & Kass Green & Associates, 2019). In riparian forest areas, understory vegetation varies from less managed areas dominated by dense willows (*Salix sp.*) and Himalayan blackberry (*Rubus armeniacus*) to heavily managed areas where vegetation is cleared.



Hills

- Sonoma Volcanic formation
- Incised, erosive channels with cobble substrate
- Riparian forest at high elevations
- Southern aspect limits forest growth
- Agriculture includes vineyards and pasture

Lowlands & Valley

- Petaluma formation
- Short, gullied channels
- Dominated by herbaceous riparian vegetation
- Little to no riparian forest
- Significant row crop and developed land uses

Figure 6. Adobe Subwatershed of the Petaluma River Watershed with stream lines and general land cover and land use. Note that grassland land cover is typically livestock pasture or rangeland. A dotted line following Adobe Creek Road roughly divides the hills and lowlands/valley portion of the subwatershed.

Table 3. Land cover of the Adobe Subwatershed and the riparian zone within the subwatershed.

	Adobe Subwatershed		**Adobe Riparian Zone**	
Class	Acres	Percent of subwatershed	Acres	Percent of riparian zone
Cropland	2,974	15%	271	6%
Developed	2,741	14%	145	3%
Forest	1,515	8%	665	14%
Grassland	12,047	61%	3,398	72%
Other	181	0.9%	54	1%
Shrub	76	0.3%	58	1%
Wetland	156	0.8%	105	2%
Total	**19,690**	**100%**	**4,696**	**100%**

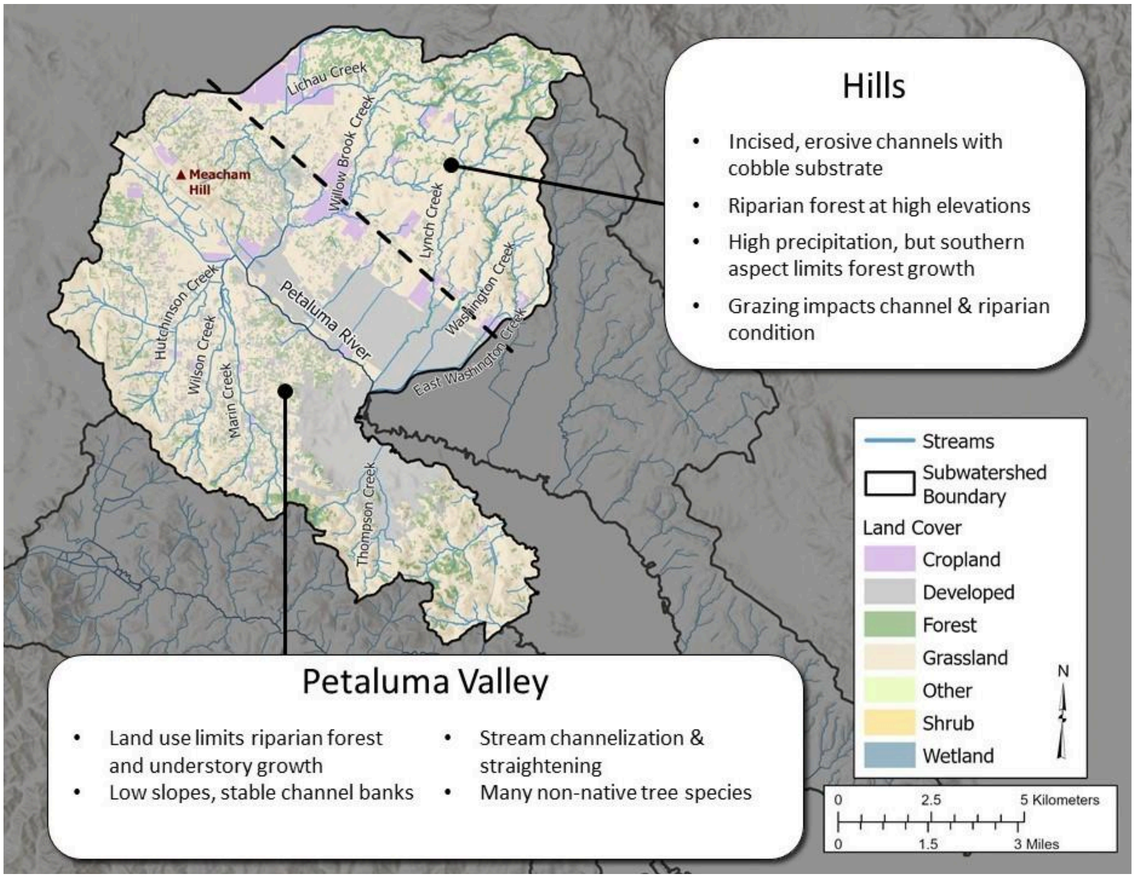
At 2,463 ft, Sonoma Mountain is the highest point in the Petaluma River Watershed. Precipitation increases with elevation on Sonoma Mountain, to an maximum average rainfall of ~50 in/yr near the summit (the highest precipitation total in the watershed - PRISM Climate Group, 2014). Surficial geology is dominated by Sonoma Volcanics at higher elevations and sedimentary rocks in the Petaluma Formation at lower elevations (Blake et al., 2000; Wagner & Gutierrez, 2017). Most of this subwatershed has moderate landslide susceptibility (Sonoma RCD, 2015). Average slopes in the valley portions of the subwatershed are <7 degrees, with moderate slopes (~7-19 degrees) in the hills portions of the subwatershed. Land uses are primarily rural, with large areas devoted to livestock grazing. The lower reaches of Adobe Creek flow through low-density urban development (ABAG, 2005).

Historically, the upper reaches of Adobe Creek reportedly supported perennial streamflow, while lower reaches were seasonally dry (Baumgarten et al., 2018), a pattern also seen today. Lawler Dam was constructed in 1910 on the headwaters of Adobe Creek to provide water supply to the City of Petaluma, and was decommissioned in the early 1990s. Adobe Creek historically terminated in a distributary channel that spread flows and sediment on the alluvial plain east of Petaluma Baylands. Lower portions of Adobe Creek were characterized by a sparsely vegetated braided channel, likely maintained by naturally high sediment loads and substantial flow variability (Baumgarten et al., 2018). The lower reach of Adobe Creek has been straightened and channelized, and as a result water and sediment are now conveyed further downstream than historically, and the channel has become highly incised (Sonoma RCD, 2015).

The riparian zone provides many important functions in the Adobe subwatershed. Thermal refuge, large wood inputs, and stream habitat support are important for steelhead and Chinook salmon spawning and rearing in this subwatershed. Adobe Creek is a highly erosive channel, and riparian vegetation and floodplain connectivity provide much-needed bank stability. In addition, due to the large amount of cropland agriculture and grazing activities in this subwatershed, runoff filtration provided by riparian forest is another key ecological function needed in this area. These benefits are, however, constrained in many areas through a combination of land use drivers such as agriculture and development, and natural drivers such as precipitation and aspect.

4.2 Petaluma Subwatershed

The Petaluma Subwatershed (Figure 7) encompasses the mainstem Petaluma River, several tributaries draining the western slope of Sonoma Mountain (Lichau, Willow Brook, and Lynch and Washington creeks), and tributaries to the west (Hutchinson, Wilson, Marin and Thompson creeks). The dominant land cover types within the riparian zone include grassland (62%), forest (25%), and developed (8%; the highest of the three subwatersheds; Table 4). Livestock pasture makes up 41% of the grassland area and rangeland makes up 10% of grassland in this subwatershed (ABAG, 2005). Forested riparian areas are concentrated in the higher elevation portions of the subwatershed as well as the Petaluma River mainstem. Riparian forests on Sonoma Mountain are dominated by oaks (*Quercus agrifolia*, *Q. garryana*, *Q. lobata*) and California bay laurel (*Umbellularia californica*), while forested headwater reaches of Marin, Wilson, and Hutchinson creeks also include substantial cover of non-native eucalyptus (*Eucalyptus sp.*). Similar to the Adobe Subwatershed, understory vegetation varies in this area from less managed areas dominated by dense willows (*Salix sp.*) and Himalayan blackberry (*Rubus armeniacus*) to heavily managed areas where vegetation is cleared.



Hills

- Incised, erosive channels with cobble substrate
- Riparian forest at high elevations
- High precipitation, but southern aspect limits forest growth
- Grazing impacts channel & riparian condition

Petaluma Valley

- Land use limits riparian forest and understory growth
- Low slopes, stable channel banks
- Stream channelization & straightening
- Many non-native tree species

Figure 7. Petaluma Subwatershed with stream lines and general land cover and land use. Note that grassland land cover is typically livestock pasture or rangeland. A dotted line following Adobe Creek Road roughly divides the hills and lowlands/valley portion of the subwatershed.

Table 4. Land cover of the Petaluma Subwatershed and the riparian zone within the subwatershed.

	Petaluma Subwatershed		Petaluma Riparian Zone	
Class	Acres	Percent of subwatershed	Acres	Percent of riparian zone
Cropland	1,456	4%	139	2%
Developed	7,741	23%	487	8%
Forest	3,905	11%	1,573	25%
Grassland	20,593	61%	3,912	62%
Other	135	0.3%	44	1%
Shrub	143	0.3%	91	1%
Wetland	129	0.3%	69	1%
Total	**34,102**	**100%**	**6,315**	**100%**

Geology on the western side of the subwatershed (to the west of Meacham Hill) is dominated by the Wilson Grove Formation (marine sandstone) while the east section of the subwatershed is dominated by the Petaluma Formation (non-marine conglomerate) (Blake et al., 2000; Wagner & Gutierrez, 2017). The most upstream reaches of the Petaluma River (the drainage historically referred to as Liberty Creek) are seasonally intermittent. Average slopes in the valley portions of the subwatershed are <7 degrees, while slopes in the hills portions of the subwatershed are moderate (>7 degrees), particularly in the headwaters of the Sonoma Mountain channels. Channel morphology, hydrology, and sediment dynamics in the hills of this subwatershed are similar to that of the Adobe Subwatershed. The Petaluma River gains flow downstream of the confluence with Wiggins Creek, while the reach below the confluence with Lynch Creek experiences tidal influence (Sweetkind and Teague 2022). Land uses in this subwatershed are divided between dense urban areas within the City of Petaluma, and rural, suburban, and agricultural land uses outside of the city center (ABAG, 2005). In these urban areas, channels have been straightened and floodplains disconnected, resulting in narrow and disconnected riparian areas.

Flooding was historically common in the low-lying Denman Flat area west of the confluence of the Petaluma River and Lynch Creek, which supported a mosaic of seasonal wetland types (Baumgarten et al., 2018). These wetlands were supplied by seeps and springs as well as surface flow from Marin, Hutchinson, and Wilson creeks. Lower portions of numerous streams, which historically spread flows and sediment through distributary networks, have been channelized and lengthened to increase drainage efficiency around the highly urbanized areas.

This subwatershed has the greatest amount of developed land cover of the three. Although the riparian zone in this area is often confined, and connectivity is limited compared to more rural areas, a likely key ecological function of riparian vegetation here is habitat. In urban areas, wildlife tends to concentrate in riparian areas for both local habitat and for corridors connecting larger habitat patches (Ehrenfeld & Stander, 2015). The effectiveness of this function can be improved by managing for greater riparian forest habitat connectivity and for conditions that are generally understood to benefit wildlife such as habitat complexity and the presence of native vegetation. Bank stability and floodplain connectivity are also important functions in the hills where streams drain the Sonoma Mountains. Channel shading is important for rearing juvenile Chinook and steelhead that reside in this subwatershed.

4.3 San Antonio Subwatershed

San Antonio Creek is the largest tributary to the Petaluma Baylands, and is the main tributary draining this subwatershed (Figure 8). Overall, forests comprise 42% of the riparian zone along stream channels in the San Antonio Subwatershed, while grasslands comprise 52% (Table 5). Of the three subwatersheds, San Antonio thus has the highest density of riparian forest, dominated by species such as California bay laurel (*Umbellularia californica*), valley oak (*Quercus lobata*), coast live oak (*Quercus agrifolia*), and willow (*Salix sp.*). This subwatershed has the greatest bay laurel coverage of the three zones. 58% of the subwatershed is grassland (Table 5); of this, 46% is rangeland and 31% is pasture (ABAG, 2005), therefore livestock grazing is the dominant land use.

The San Antonio Subwatershed is distinguished by its geology, dominated by mechanically weak Franciscan melange and Franciscan schist (Blake et al., 2000; Shobe et al., 2021; Wagner & Gutierrez, 2017). Aspect is a key driver of riparian vegetation in this subwatershed (Figure 4). San Antonio Creek generally flows west to east, and the entire southern side of the creek shares a north-facing aspect. This, coupled with steep slopes, provides significant protection from solar radiation. The southern side of San Antonio Creek also sits at a higher elevation, capturing more annual rainfall than other areas in the watershed. Adding to the effects of aspect, slope, and elevation, this subwateshed's proximity to the Pacific Ocean may allow for greater moisture inputs from fog formed in the marine layer. These microclimate effects support densely forested riparian zones in the southern portion of the subwatershed. Additionally, while not evaluated in this assessment, first order streams on these north facing slopes may support riparian forest as well. When defining riparian zones across the watershed and the broader region, aspect may be a useful factor to include in zone delineations.

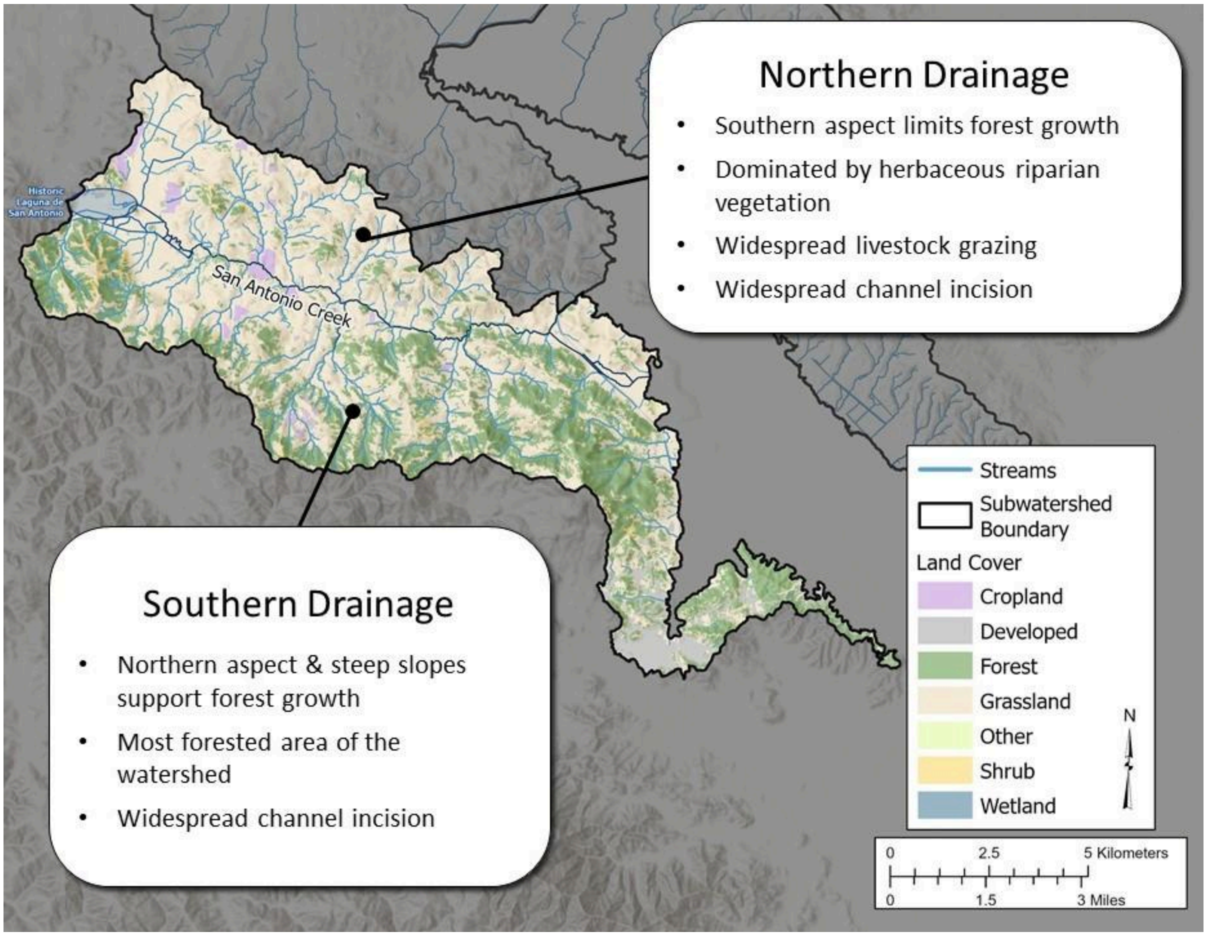


Figure 8. San Antonio Creek Subwatershed with stream lines and general land cover and land use. Note that grassland land cover is typically livestock pasture or rangeland.

Table 5. Land cover of the San Antonio Subwatershed and the riparian zone within the subwatershed.

	San Antonio Subwatershed		**San Antonio Riparian Zone**	
Class	Acres	Percent of subwatershed	Acres	Percent of riparian zone
Cropland	435	2%	73	1%
Developed	1,316	5%	178	2%
Forest	8,103	33%	3,244	42%
Grassland	14,501	58%	3,973	52%
Other	139	0.5%	73	1%
Shrub	308	1%	107	1%
Wetland	97	0.5%	57	1%
Total	**24,899**	**100%**	**7,704**	**100%**

The combination of geology, aspect, slope, and climate in the San Antonio Subwatershed lead to high erosion potential. This has been greatly exacerbated by the draining of the historical Laguna de San Antonio, which fundamentally altered the hydrology of San Antonio Creek. Situated at the head of the valley, the Laguna historically functioned as a natural reservoir, reducing peak flows during the wet season and supplying base flows during the dry season (Baumgarten et al., 2018; Collins et al., 2000). Due to ditching and draining for agricultural purposes, the Laguna de San Antonio no longer provides this function, and no remnant wetlands are apparent. Additionally, groundwater pumping has significantly lowered the water table throughout the watershed (Baumgarten et al., 2018; Collins et al., 2000). These changes to the hydrologic system have caused channel incision and increased flow intermittency throughout the drainage network.

Figure 9. Riparian Valley Oak (*Quercus lobata*) at a large bank erosion feature in an incised reach of San Antonio Creek.

Erosion and incision impact the riparian area in a few ways. First, accelerated erosion of cutbanks and encroachment on historical riparian forests are causing long-established trees to fall into the channel. In a 2023 field visit, we observed estimated 100+-year-old valley oaks and coast live oaks being lost to bank erosion (Figure 9). Lowered baseflow and water table elevations stress the existing riparian vegetation along the mainstem of San Antonio Creek and hinder the reestablishment of riparian forests along incised reaches. Although smaller tributaries of San Antonio Creek are also incised, riparian vegetation along these streams typically have access to water and nutrients from hillslopes. According to a preliminary study conducted in 2000, increased rates of bank erosion and stream incision along San Antonio Creek, coupled with drawdown of the adjacent water table, have led to the loss of riparian vegetation along terrace banks (Collins et al., 2000). These factors, alongside channel straightening, have sped up the erosion process significantly. Human activities in the watershed have increased sediment production by estimates greater than 50%, and have sharply reduced base flow and increased peak flows (Collins et al., 2000).

Anthropogenic changes to the creek network have markedly altered sediment dynamics in lower San Antonio Creek. The creek was redirected to the north in the 1930s or early 1940s, and today flows into a constructed slough, which connects with the Petaluma River approximately 8 km further upstream from its original outlet. The altered alignment reduced the gradient of lower San Antonio Creek, which, in combination with increased rates of erosion upstream, has resulted in increased sediment accumulation and bed aggradation in this part of the channel (Baumgarten et al., 2018).

Grazing pressure, steep slopes, and the aforementioned anthropogenic changes create a need for bank stabilization in this subwatershed. Robust riparian forest in much of this subwatershed creates abundant riparian habitat and provides bank stability. However, these and other riparian functions and conditions depend on the intensity of grazing and livestock access to the riparian zone. Many of the ecological functions tied to riparian forest vegetation may further be hindered by the channel incision seen across the subwatershed.

5. Summary and Conclusions

Through review of existing datasets, reports, and scientific literature, we provided an assessment of current channel and riparian condition, drivers, and functions in the Petaluma River Watershed, and highlighted key characteristics in its three subwatersheds that influence riparian condition and function. Climate, geology, topography, hydrology, and land use constitute the primary controls driving current channel and riparian conditions and functions, and within the watershed, variations in riparian vegetation are particularly pronounced among areas with differing microclimates. Nearly twice as much annual precipitation is observed in the higher elevation regions like Sonoma Mountain than in the valley, and most of this precipitation occurs during the winter and spring months. Most streams in the watershed support intermittent streamflow driven by seasonal rainfall and groundwater inputs. Aspect, particularly on steep slopes, controls moisture availability through its effects on solar incidence and shading. As a result, north-facing slopes, like those in the San Antonio Creek Subwatershed, retain more soil moisture and support more extensive riparian forests than south-facing slopes like those in the Sonoma Mountain region. Riparian areas on drier stream reaches are characterized by grassland and shrubland. Riparian forests are characterized by trees such as oaks (*Quercus sp.*), California bay laurel (*Umbellularia californica*), maple (*Acer sp.*), willows (*Salix sp.*), and occasionally non-native eucalyptus (*Eucalyptus sp.*), while grasslands are dominated by non-native annual grasses.

The composition and function of riparian areas have been dramatically altered by land and water use in some parts of the watershed. Widespread livestock grazing has exacerbated bank erosion and sediment input to channels, and has broadly degraded riparian conditions in a number of locations. Around the City of Petaluma, urban development has resulted in straightened channels and confined and altered riparian vegetation. Downstream portions of many channels have been extended to increase drainage efficiency. Channel incision and groundwater pumping have lowered water tables across the watershed, disconnecting floodplains, increasing bank erosion, and stressing riparian vegetation. The draining of the historical Laguna de San Antonio has substantially altered streamflow and sediment dynamics in San Antonio Creek. All of these factors have both impacted the riparian zone and increased the importance of the functions it still provides.

Riparian areas in the watershed provide a number of ecological functions. While we were not able to directly measure riparian functions in this effort, several metrics serve as useful indicators of function, including degree of riparian vegetation, degree and rate of erosion/incision, extent of channel modifications, and management context. Many areas that are less impacted by overgrazing, channelization, channel incision, or other modifications (e.g., some tributaries in the southern San Antonio Creek drainage, and forested reaches in the Sonoma Mountains) provide high quality habitat for a range of riparian wildlife, buffer streams from sediment and pollutants, and provide inputs of wood and leaf litter to aquatic ecosystems. These functions have been degraded in other stream reaches, particularly in the lower elevation portions of the watershed where urban development and high intensity grazing have encroached on the riparian zone and channels are confined to narrower flowpaths.

Looking forward, anthropogenic climate change may further alter riparian conditions in the watershed. According to the Climate Ready Sonoma County Climate Hazards and Vulnerabilities 2014 report, wetter, warmer spring weather could introduce new pests and other vectors for disease that threaten the stability of these riparian areas (Cornwall et al., 2014). Under a drier and hotter climate, these same riparian areas are under risk of a high climate water deficit. A subsequent technical memo will provide an overview of expected future riparian conditions for the Petaluma Watershed. Forward-thinking management should consider these future stressors and identify management actions that will help sustain high levels of riparian function.

References

Collins, L. M., Grossinger, R. M., McKee, L. J., Riley, A., & Collins, J. N. 2001. Wildcat Creek Watershed: A Scientific Study of Physical Processes and Land Use Effects. SFEI Contribution No. 363. San Francisco Estuary Institute: Richmond, CA.

Collins, J. N., Sutula, M., Stein, E. D., Odaya, M., Zhang, E., & Larned, K. 2006. Comparison of Methods to Map California Riparian Areas. Final Report Prepared for the California Riparian Habitat Joint Venture.

ABAG (Association of Bay Area Governments). 2005. Land Use GIS Dataset.

Baumgarten, S. A., Clark, E. E., Dusterhoff, S. R., Grossinger, R. M., & Askevold, R. A. 2018. Petaluma Valley Historical Hydrology and Ecology Study. Prepared for the Sonoma Resource Conservation District and U.S. Environmental Protection Agency. A report of SFEI-ASC's Resilient Landscapes Program, SFEI Publication #861, San Francisco Estuary Institute.

Baxter, C. V., Fausch, K. D., & Carl Saunders, W. 2005. Tangled webs: Reciprocal flows of invertebrate prey link streams and riparian zones. Freshwater Biology, 50(2), 201–220. https://doi.org/10.1111/j.1365-2427.2004.01328.x

Blake, M. C., Jones, D. L., Graymer, R. W., & digital database by Soule, A. 2000. Geologic map and map database of parts of Marin, San Francisco, Alameda, Contra Costa, and Sonoma counties, California (Report 2337; Version 1.0, Miscellaneous Field Studies Map). USGS Publications Warehouse. https://doi.org/10.3133/mf2337

CDFW (California Department of Fish and Wildlife). 2023. California Natural Diversity Database.

Chapin, F. S. I., Matson, P. A., & Mooney, H. A. 2002. Principles of Terrestrial Ecosystem Ecology. https://doi.org/10.1007/978-1-4419-9504-9

Collins, L., Amato, P., & Morton, D. 2000. SFEI Watershed Science Analysis of San Antonio Creek, Sonoma and Marin counties. (p. 8). SFEI.

Cornwall, C., Moore, S., DiPietro, D., Veloz, S., Micheli, L., & Mersich, M. 2014. Climate Ready Sonoma County: Climate Hazards and Vulnerabilities (1). North Bay Climate Adaptation Initiative.

Doucett, R. R., Power, G., Barton, D. R., Drimmie, R. J., & Cunjak, R. A. 1996. Stable isotope analysis of nutrient pathways leading to Atlantic salmon. 53.

Edwards, E. D., & Huryn, A. D. 1996. Effect of riparian land use on contributions of terrestrial invertebrates to streams. Hydrobiologia, 337(1–3), 151–159. https://doi.org/10.1007/BF00028516

Ehrenfeld, J. G., & Stander, E. K. 2015. Habitat Function in Urban Riparian Zones. In J. Aitkenhead-Peterson & A. Volder (Eds.), Agronomy Monographs (pp. 103–118). American Society of Agronomy, Crop Science Society of America, Soil Science Society of America. https://doi.org/10.2134/agronmonogr55.c6

FEMA (Federal Emergency Management Agency). 2020. National Flood Hazard Layer

(NFHL). https://gis-fema.hub.arcgis.com/maps/FEMA::national-flood-hazard-layer-2/about

Geoff Wang, G. 2000. Use of understory vegetation in classifying soil moisture and nutrient regimes. Forest Ecology and Management, 129(1–3), 93–100. https://doi.org/10.1016/S0378-1127(99)00142-5

Hahm, W. J., Rempe, D. M., Dralle, D. N., Dawson, T. E., Lovill, S. M., Bryk, A. B., Bish, D. L., Schieber, J., & Dietrich, W. E. 2019. Lithologically Controlled Subsurface Critical Zone Thickness and Water Storage Capacity Determine Regional Plant Community Composition. Water Resources Research, 55(4), 3028–3055. https://doi.org/10.1029/2018WR023760

Kashiwagi, J. 1985. Soil survey of Marin County, California. (38). NRCS.

Kauffman, J. B., & Krueger, W. C. 1984. Livestock Impacts on Riparian Ecosystems and Streamside Management Implications...A Review. Journal of Range Management, 37(5), 430–438.

Kondolf, G. M., Podolak, K., & Grantham, T. E. 2013. Restoring mediterranean-climate rivers. Hydrobiologia, 719(1), 527–545. https://doi.org/10.1007/s10750-012-1363-y

Langenheim, V. E., Graymer, R. W., Jachens, R. C., McLaughlin, R. J., Wagner, D. L., & Sweetkind, D. S. 2010. Geophysical framework of the northern San Francisco Bay region, California. Geosphere, 6(5), 594–620. https://doi.org/10.1130/GES00510.1

Petaluma Wetlands Alliance. 2023a. Mammals. https://petalumawetlands.org/wetlands-life/mammals/

Petaluma Wetlands Alliance. 2023b. Reptiles and Amphibians. https://petalumawetlands.org/wetlands-life/reptiles-and-amphibians/#!

Naiman, R. J., Décamps, H., & McClain, M. E. 2005. Riparia: Ecology, conservation, and management of streamside communities. Elsevier Academic.

Naiman, R. J., Decamps, H., & Pollock, M. 1993. The Role of Riparian Corridors in Maintaining Regional Biodiversity. Ecological Applications, 3(2), 209–212. https://doi.org/10.2307/1941822

Naiman, R. J., Fetherston, K. L., McKay, S. J., & Chen, J. 1998. Ecology and Management of Streams and Rivers in the Pacific Northwest Coastal Ecoregion. Chapter 12: Riparian Forests. 10.1007/978-1-4612-1652-0_12

National Research Council. 2002. Riparian Areas: Functions and Strategies for Management (p. 10327). National Academies Press. https://doi.org/10.17226/10327

NRCS (Natural Resources Conservation Service). 2005. Web Soil Survey. https://websoilsurvey.nrcs.usda.gov/

One Tam, & Tukman Geospatial. 2021. Marin Countywide Fine Scale Vegetation Map. https://tukmangeospatial.egnyte.com/dl/lh8BPnoMUK

PRISM Climate Group. 2014. PRISM Gridded Climate Data. https://prism.oregonstate.edu

Quantum Spatial. 2019. Marin County, California QL1 LiDAR. https://www.marinmap.org/dnn/DataServices/2019LIDAROrthos.aspx

Richardson, J. S., Bilby, R. E., & Bondar, C. A. 2005. Organic Matter Dynamics in Small Streams of the Pacific Northwest. Journal of the American Water Resources Association, 41(4), 921–934. https://doi.org/10.1111/j.1752-1688.2005.tb03777.x

Saunders, W. C., & Fausch, K. D. 2007. Improved Grazing Management Increases Terrestrial Invertebrate Inputs that Feed Trout in Wyoming Rangeland Streams. Transactions of the American Fisheries Society, 136(5), 1216–1230. https://doi.org/10.1577/T06-260.1

SFBRWQCB (San Francisco Bay Regional Water Quality Control Board). 2020. Total Maximum Daily Load for Bacteria in the Petaluma River Watershed.

SFEI. 2017. Bay Area EcoAtlas: Geographic information system of wetland habitats past and present. San Francisco Estuary Institute.

SFEI. 2021. Sonoma County Riparian Corridor Mapping Pilot Study Project. San Francisco Estuary Institute.

SFEI. 2023. Creek-to-Baylands Reconnection Opportunities in San Francisco Bay. San Francisco Estuary Institute.

SFEI, & SPUR. 2019. San Francisco Bay Shoreline Adaptation Atlas: Working with Nature to Plan for Sea Level Rise Using Operational Landscape Units (915). San Francisco Estuary Institute. https://trid.trb.org/view/1605924

SFEI-ASC (San Francisco Estuary Institute-Aquatic Science Center). 2017. Bay Area Aquatic Resource Inventory (BAARI) Version 2.1 GIS Data. (2.1).

Shobe, C. M., Bennett, G. L., Tucker, G. E., Roback, K., Miller, S. R., & Roering, J. J. 2021. Boulders as a lithologic control on river and landscape response to tectonic forcing at the Mendocino triple junction. GSA Bulletin, 133(3–4), 647–662. https://doi.org/10.1130/B35385.1

Sonoma County. 2014. Article 65. - RC Riparian Corridor Combining Zone, 26-65–005.

Sonoma RCD (Resource Conservation District). 2008. San Antonio Creek Watershed Plan.

Sonoma RCD (Resource Conservation District). 2015. Draft Petaluma Watershed Enhancement Plan (p. 129).

Strahler, A. N. 1952. Dynamic Basis of Geomorphology. GSA Bulletin, 63(9), 923–938. https://doi.org/10.1130/0016-7606(1952)63[923:DBOG]2.0.CO;2

Strahler, A. N. 1957. Quantitative analysis of watershed geomorphology. Eos, Transactions American Geophysical Union, 38(6), 913–920. https://doi.org/10.1029/TR038i006p00913

Stromberg, M. R., & Kephart, P. 1996. Restoring Native Grasses in California Old Fields. Ecological Restoration, 14(2), 102–111. https://doi.org/10.3368/er.14.2.102

Traum, J. A., Teague, N. F., Sweetkind, D. S., & Nishikawa, T. 2022. Hydrologic and geochemical characterization of the Petaluma River watershed, Sonoma County, California. In Scientific Investigations Report (2022–5009). U.S. Geological Survey. https://doi.org/10.3133/sir20225009

Tukman Geospatial, & Kass Green & Associates. 2019. Sonoma County Vegetation and Habitat Map. https://sonomaopenspace.maps.arcgis.com/home/item.html?id=fced9481d8224bc0ac53cdb3233de3b9

U.S. EPA (Environmental Protection Agency). 2017. Causal Analysis/Diagnosis Decision Information System (CADDIS): Urbanization—Riparian/Channel Alteration. https://www.epa.gov/caddis-vol2/urbanization-riparianchannel-alteration

U.S. Geological Survey. 2022. National Agriculture Imagery Program (NAIP). https://earthexplorer.usgs.gov/

Vernon, M. 1972. Soil Survey, Sonoma County, California. NRCS.

Wagner, D., & Gutierrez. 2017. Preliminary Geologic Map of the Napa and Bodega Bay 30’ x 60’ Quadrangles, California. California Geological Survey.

Watershed Sciences, Inc. 2013. Sonoma County, California QL1 LiDAR. https://sonomavegmap.org/data-downloads/

Wohl, E. 2014. Rivers in the Landscape, Science and Management.