Napa River Watershed Profile:
Past and Present Characteristics with Implications for Future Management of the Changing Napa River Valley




by
San Francisco Estuary Institute

March 2012 · Contribution No. 615

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by
Meredith Williams
Josh Collins
Sarah Pearce
Robin Grossinger
Michelle Lent
John Oram
Jonathan Koehler
and Rainer Hoenicke

Design
Joanne Cabling
Linda Wancyzk

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Gretchen E. Hayes
Jonathan Koehler
Sandy Elles

San Francisco Estuary Institute
4911 Central Avenue
Richmond, CA 94804
p: 510-746-SFEI, f: 510-746-7300
w: www.sfei.org

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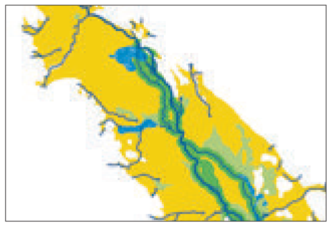
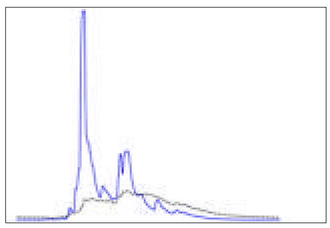
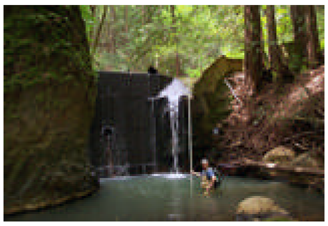
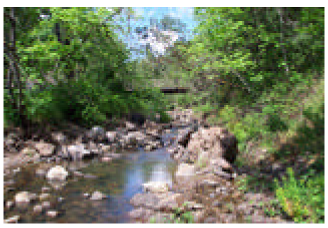








ACRONYMS

BAARI	Bay Area Aquatic Resource Inventory
BASMAA	Bay Area Stormwater Management Agencies Association
BMP	Best Management Practices
CDFG	California Department of Fish and Game
CIMIS	California Irrigation Management Information System
CRAM	California Rapid Assessment Method
DEM	Digital Elevation Model
DWR	California Department of Water Resources
ECP	Erosion Control Plan
FEMA	Federal Emergency Management Agency
FFF	Fish-Friendly Farming Certification Program
GIS	Geographical Information Systems
HSPF	Hydrological Simulation Program in FORTRAN
LID	Low Impact Development
NCRDC	Napa County Resource Conservation District
NCFWCD	Napa County Flood Control and Water
NRC	National Resource Council
NRCS	National Resource Conservation Service
NSWG	Napa Sustainable Winegrowing Group
PFC	Proper Functioning Condition
RAMs	Rapid Assessment Methods
RCD	Resource Conservation District
RWQCB	Regional Water Quality Control Board
SCC	State Coastal Conservancy
SCCWRP	Southern California Coastal Water Research Project
SCS	United States Soil Conservation Service
SCD	Soil Conservation District
SFEI	San Francisco Estuary Institute
SFBRWQCB	San Francisco Bay Regional Water Quality Control Board
SWAMP	Surface Water Ambient Monitoring Program
SWRCB	State Water Resources Control Board
TAT	Technical Advisory Team
THP	Timber Harvest Plan
TMDL	Total Maximum Daily Loads
USACE	United States Army Corps of Engineers
USDA	United States Department of Agriculture
USFS	United States Forest Services
USGS	United States Geological Survey
USEPA	U.S. Environmental Protection Agency
WARSSS	Watershed Assessment of River Stability and Sediment Supply
WICC	Watershed Information Center and Conservancy

ac	acres
ft	foot or feet
ft^3	cubed feet
ha	hectares
km	kilometers
m	meters
mi	miles
musym	multiple unit symbol
w:d	width to-depth

EXECUTIVE SUMMARY

Stag's Leap vineyard.
Photograph courtesy of Sandy Elles.

Overview

Ecological health and economic health are intimately interconnected in the Napa River Watershed. Napa Valley is the most recognized area within the best-known wine growing region in the United States. It yields wines that are enjoyed around the world. The community trades on the beauty and healthy life style that is emblematic of Napa Valley. The good health of the river ecosystem is essential to maintain this valuable reputation. The fish and wildlife that are endemic to the river ecosystem are primary aspects of its health. The habitat conditions for salmon and steelhead are especially important because they indicate not only the health of the river in the valley but also the health of its connection to tributaries and to San Francisco Bay.

Natural rivers adjust in width, depth, plan form, and slope to changes in sediment and water inputs. If the inputs are consistent enough in the long term, the ongoing natural processes of erosion and deposition within the river will stabilize its form. The stable form of a natural river usually includes pools and riffles, active bars and floodplains, meanders and straight reaches, and other elements that are predictably distributed along the river course. Seasonal and annual variability around the long term average inputs of water and sediment contribute to variations in river form that in turn increase the diversity of habitats for native plants and animals. Under natural conditions, rivers that are not confined by hillsides or canyon walls tend to migrate laterally. Napa Valley was formed over many thousands of years by the back-and-forth migration of the river.

The health of the Napa River ecosystem has significantly declined due to unnatural imbalances between inputs of water and sediment. In the Napa River watershed, a series of major land use changes beginning with Euro-American settlement increased the inputs of water relative to the inputs of coarse sediment, causing the river to erode its bed, abandon its floodplains, and become laden with fine sediment. Some reaches were artificially straightened and others were armored or revetted to prevent erosion of their banks. As a result of these land uses, the river system has become greatly simplified in physical form and unable to support healthy communities of aquatic and riparian plants and animals, including salmon and steelhead (Napolitano et al., 2009).

The Napa River is listed as impaired under Section 303(d) of the US Clean Water Act due to pathogens (RWQCB 2008), nutrients (RWQCB 2003), and excessive sedimentation (RWQCB 2007). The sediment problem is arguably most important because it significantly impacts the overall form and ecological complexity of the river ecosystem (Stillwater Sciences and W.E. Dietrich 2002), and because its solution is likely to involve adjustments in land and water management throughout the watershed (Pacific Watershed Associates 2003a,b,c; RWQCB 2007). A broad diagnosis of river health is warranted to outline possible solutions to the systemic imbalance between inputs of water and sediment that portends chronic river erosion and habitat loss.

This report recognizes that improvements in the health of the river ecosystem must also assure adequate flood control and water supplies. Studies of domestic and agricultural demands for water have recently been conducted (NCFWCD 2005, 2050 Napa Valley Water Resources Study). Almost none of the water used by agriculture in the Napa River Watershed is imported. Agriculture depends on precipitation that generates runoff and recharges groundwater aquifers within the watershed. Water shortages may become more widespread for agriculture outside of the groundwater-deficient areas due to its heavy reliance of the indigenous water supplies (2050 Napa Valley Water Resources Study). Agricultural growth, in combination with climate change, is likely to strain water supply further (Cooley et al., 2009, Lee et al., 2009, Lobell and Field 2009). Studies of flooding in Napa Valley and how to control it have also been conducted. A naturalistic approach to flood control is being implemented in parts of the river system and is likely to improve its health http://www.countyofnapa.org/pages/departmentcontent.aspx?id=4294971816.

This report builds on these studies with a broad recommendation for the agricultural community to decrease water consumption through conservative irrigation and frost control practices, water re-use, conjunctive water use, and a variety of ways of increasing the overall retention of water within the watershed. In essence, drainage to the river needs to be slowed and more evenly distributed through the seasons. This will require more water storage and cooperative management of innovative storage and drainage systems. Supplies of coarse sediment may have to be added and the river given room to widen for its health to be most fully restored. Some reaches of the river will be better suited for restoration than others. Every effort to improve the ecological health of the river must be planned in the context of the hydrological and ecological functions of the watershed as a whole.

Monitoring is essential to track the progress of efforts to improve river health, to assess the threats against progress, and to know when the desired improvements have been achieved. A program to monitor local salmon and steelhead populations has been initiated (Koehler 2008) and should be continued. Efforts to expand and coordinate groundwater monitoring have been explored (Center for Collaborative Policy 2010), and the resulting recommendations will need to be implemented. The existing efforts to monitor flows in the river will need to be expanded and augmented with a program to assess changes in river form and structure, with a focus on aquatic and riparian habitat conditions. To the extent appropriate, the monitoring data should be made available to the public through online information systems, such as the Watershed Information Center & Conservancy (WICC) for Napa County.

The historical form and structure of the Napa River ecosystem cannot be completely restored. There is no way to reach the past. But as is, the river ecosystem has large potential to provide higher levels of primary ecological services that are compatible with all other watershed management objectives. Realizing most of this potential will require setting realistic goals for water management that integrate across flood control, water quality improvement, and consumptive demands for each major tributary and for the watershed as a whole, then designing and implementing new watershed management policies and systems to achieve the goals. Without a doubt, all efforts to manage the sediment-water problems in the watershed need to be planned together in the context of an overall vision of watershed health that is shared among all the stakeholders. Restoring the health of the river ecosystem will require an explicit vision of success.

Report Objectives

The San Francisco Estuary Institute (SFEI), in partnership with the Napa County Resource Conservation District (Napa RCD) and the Napa County Farm Bureau, was funded through a California State Proposition 40 grant from the State Water Resources Control Board (SWRCB or State Water Board) to present a watershed-based framework for addressing agricultural challenges related to improving the health of the Napa River ecosystem. In particular, the project sought to identify possible adaptive management measures whose implementation could allow the State Water Board to declare the Napa River unimpaired under section 303(d) of the US Clean Water Act. The project objectives can be summarized as follows.

- Compare and contrast the historical and current aquatic and riparian habitats of the Napa River ecosystem, with a focus on the Napa River in its valley, since it is has been identified as impaired, is the centerpiece of the local aesthetic, and its condition is symptomatic of the overall health of its watershed.
- Identify how land use changes have contributed to current undesirable conditions in the river ecosystem.
- Describe relationships between agricultural practices and the major attributes of a highly functioning, healthy river ecosystem.
- Identify management approaches or practices that could help improve the health of the river ecosystem.
- Increase understanding within the agricultural community about the relationships between past and present agricultural practices and river health.

Approach

Our approach was designed to help land owners and managers understand how climate, geology, and land use influence inputs of water and sediment to the river, and how imbalances between these inputs reduce the ability of the river ecosystem to provide the full range of its desired functions, including groundwater recharge, irrigation, delivery of beneficial sediments and nutrients to the valley and San Francisco Bay, and the support of native aquatic and riparian plants and animals. We sought to elucidate how the sediment-water problem evolved and how it might be solved through coordinated adjustments in land and water management. We expected that the corrective actions might differ from place to place based on land use constraints and based on the natural relationships between water and sediment inputs and their locations within the watershed. The diagnostic framework called for comparing pre-settlement and existing conditions of the river as a physical system in terms of ten well-established attributes of a healthy river (after Trush et al., 2000):

1. the sequence of alternating river bars is intact as the primary geomorphic and ecological unit of the river ecosystem;
2. each component of the annual hydrograph provides specific, expected geomorphic and ecological functions;
3. the surface layer of sediment on the channel bed is frequently mobilized;
4. the alternating river bars are periodically scoured deeper than their coarse surface layers;
5. the inputs of fine and coarse sediments are balanced with the inputs of water;
6. the river channel is free to migrate laterally;
7. floodplains that are frequently flooded adjoin most of the river channel;
8. the river channel and its floodplains are complex in form and structure due to infrequent large floods;
9. the annual hydrograph sustains diverse riparian plant communities; and
10. groundwater in the valley is naturally connected to the river channel.

Not all attributes are present in every reach of a healthy river, but the existence of these attributes for the system as a whole indicates its overall integrity and good health. In this context, good health is assumed to be the capacity of a watershed to provide high levels of the beneficial uses as defined by the San Francisco Bay Regional Water Quality Control Board (RWQCB). Our assessment is that the ten attributes listed above support these uses. This approach enabled us to assess the relative contributions of nature and people to the current condition of the river ecosystem, and to explicitly link watershed science to watershed management for the purpose of adjusting inputs of water and sediment to realize, to the extent feasible, the healthy river attributes.

In the modern world, rivers provide many social services that are not necessarily compatible with all ten of these attributes. For example, there are usually necessary tradeoffs between the natural benefits of flooding and the need for flood control. However, consideration of the healthy river attributes can help guide an analysis of large-scale human impacts and future management options.

In general, the overall diversity and levels of functions and services of an ecosystem increase with its physical complexity (Holling et al., 1995, Jørgensen and Müller 2000). The more complex an ecosystem is, the more ways it has to process material and energy, and the more it can resist or rebound from stress and disturbance. Ecosystem resiliency is especially important in the face of the disturbances that are likely to result from local climate change. River systems that have the ten attributes listed above tend to be very complex, and therefore tend to have many functions and services, both physical (e.g., pollution filtration, groundwater recharge, flood stage desynchronization) and ecological (e.g., support of native riparian and aquatic species and communities). They also tend to be resilient to natural and unnatural disturbance.

There is abundant local interest in recovering sustainable populations of salmon and steelhead (salmonids). The health of salmonid populations is strongly correlated to the healthy river attributes. For example, diverse riparian vegetation that provides shade and large woody debris is imperative for maintaining suitable habitat for salmonid spawning, egg incubation, and rearing. The functional relationship between healthy salmonid populations and healthy river attributes is so strong that throughout the Northwest, the health status of salmonid populations is used to assess that status of river health. This is part of the rationale for the intense local focus on salmonid recovery, in addition to the State and Federal mandates to that effect. The healthy river attributes serve as a framework to analyze relationships between the physical form and structure of a river ecosystem and its desirable functions.

Historical Conditions

The historical Napa River Watershed was not wilderness. Indigenous people inhabited the watershed for thousands of years and expertly managed selected ecological processes to achieve desired outcomes. Their management was persistent and not inconsequential, but did not fully interrupt or eliminate natural processes. Fire was used to adjust plant communities, but there is little evidence that the overall species composition of the plant communities or the perviousness of the land or its ability to retain water were altered. There is no evidence of prehistoric artificial irrigation or extensive agriculture. Except when noted, the historical conditions largely represent natural processes. Our detailed reconstruction of the historical form and structure of the river ecosystem suggests that it abundantly expressed all ten attributes of good river health, except for river migration (Grossinger 2012). There is no evidence of extensive channel movements at the time of Euro-American settlement. The analysis of historical conditions helped to validate the healthy river attributes as a diagnostic framework.

The Napa River watershed was not unlike many other watersheds in the Central Coast Range. Variable geology, topography, rainfall patterns, plus a connection to ocean waters created a complex mosaic of aquatic habitats. There were no natural deepwater lakes and few ponds, but ephemeral and perennial streams connected the steeper reaches of the watershed to a verdant valley. Broad tidal marshes bordered the estuarine reaches of the river, where seasonal mixtures of ocean and river water created variable salinity gradients. The complex habitat mosaic supported diverse communities of plants, fish, and other wildlife.

The area commonly called Napa Valley consists of distinct geomorphic elements termed alluvial fans, river terraces, and floodplains. The fans were created by the major tributaries as they deposited sediment along the valley margins. The western fans are larger than the eastern fans, indicating that the western tributaries have tended to yield more sediment. This stems from differences in lithology and precipitation on the different sides of the watershed. With some exceptions, the western side is wetter and consists of more friable sedimentary geology prone to landslides. The eastern side largely consists of volcanic geology that is less friable. Terraces are abandoned river floodplains that are never or rarely flooded. Floodplains are flat areas of the valley that flood. Lower lying floodplains are flooded more frequently. The historical floodplains widened upstream and downstream of the large alluvial fans created by the major tributaries. The floodplains were narrowest where the valley is pinched between large opposing fans. Early settlements were built upon the larger fans, safely above major floods.

Aside from overland flow during major storms, some tributaries did not reach the river. Rather, they recharged local aquifers through their fans. Aquifers were high all year and emerged onto the valley floor during the wet season, at the base of fans and elsewhere, creating abundant wetlands. Some of the broader areas of the valley had a variety of side channels that carried flood flows. Much of the valley immediately bordering the river served as its active, low-lying floodplain that accommodated storm flows and trapped fine sediment. Riparian forests covered natural levees and low terraces along the river, shading it and supplying it with woody debris. In general, prior to Euro-American settlement, the watershed had great capacity to intercept and store rainwater and floodwaters in aquifers and wetlands. The high aquifers slowly drained to the river throughout the summer. As a result, the peak river flows during major storms were lower than they are today, and the summer base flows were cooler, more persistent, and more extensive.

Although the river was free to migrate, there is no historical evidence of rapid alterations in the river course, suggesting that inputs and outputs of sediment and water were more or less balanced for the system as a whole, and that the abundant floodplains and wetlands mitigated the effects of major floods on river form, structure, and location. Little is known about the actual nature of the historical river bed in the valley. There are no comprehensive historical descriptions of it, and it has been eroded away.

The coarseness of the river bed matters greatly to salmonids. Their successful spawning requires cool flows of well-aerated water through moderately coarse sediment that is relatively free of silts and clays. It seems likely that most of the historical inputs of coarse sediment originated in a few major tributaries, and that the coarseness of the bed decreased with distance downstream from these sediment sources.

These general descriptions of the historical presence and natural variability in the healthy river attributes are supported by reach-specific case studies. The current status of the attributes is explored in depth in this report.

Modern Conditions

The river in today's valley might appear natural, but it is actually a skeletal remnant of the much more complex historical river ecosystem. There are some exceptional areas with appreciable complexity, but overall the channel is greatly simplified. The healthy river attributes are absent or weakly evident in most reaches.

The simplified river system is a result of more than two centuries of intensifying and changing land uses. In essence, ranchers, farmers, loggers, dam builders, grape-growers, and urban developers altered the surface and sub-surface water storage and drainage systems to increase their reliability and efficiency. These changes were purposeful, popular, and supported by public policy. Their impacts upon the river ecosystem were seldom anticipated and only recently have they become a serious concern to responsible agencies and the public. Nevertheless, the changes and their negative impacts have been substantial. Not counting any sub-surface drains, about 450 kilometers (km) or 280 miles (mi) of surface channels currently drain the valley. Almost half of the channels have been artificially constructed to drain seasonally flooded areas and extend formerly discontinuous tributaries down their alluvial fans, through low-lying areas of the valley, and directly into the river. The total length of the surface drainage network in the valley has increased by almost 25%. Ditches comprise more than 10% of the entire drainage network for the watershed. As a result of both surface and sub-surface modifications of the natural hydrology, the drainage density (the ratio between the length and area of the drainage network), even in this relatively rural watershed, may now be comparable to more urbanized watersheds. It is primarily the increased drainage density that has contributed most to the considerable degradation of healthy river attributes described above.

People living and working in Napa Valley rely extensively on reservoirs to meet their water needs. Hennessey, Rector, Bell, Kimball, and Milliken Reservoirs supply municipal water. But these are only a few among the hundreds of smaller reservoirs that intercept runoff and sediment from about 30% of the watershed. Almost all of these impoundments are less than 2 hectares (ha) or 5 acres (ac) in area, and were designed as stock ponds or storage components of local irrigation systems. They tend to fill and spill each wet season. Both large and small reservoirs trap large amounts of sediment and contribute to the deficit of coarse sediment in the river. The type and amount of sediment trapped is dependent on geology, slope, upstream drainage area, and upstream drainage density, as well as reservoir size. For example, the Sonoma volcanics yield large amounts of coarse sediment that are trapped by Kimball Reservoir. In addition to these on-stream reservoirs, many impoundments, mostly located on the valley floor, are fed by groundwater or subsurface drainage and primarily serve dry-season irrigation needs and frost control purposes. The more than 1,200 on- and off-stream reservoirs probably equal or exceed evaporative losses of water compared to the wetlands, ponds, and oxbow lakes that were present historically. These evaporative losses from reservoirs can contribute to downstream water shortages.

No one knows the full extent of sub-surface drains. Most hillside vineyards have been fitted with drains that shunt runoff into fill-and-spill reservoirs or directly into tributary channels. Much of the valley has been fitted with sub-surface drains to dewater the root zone of vineyards in early spring. During winter, water is pumped from some of these drains into reservoirs built on the valley floor to be used later for irrigation and frost control. After the reservoirs are filled, groundwater flows through the sub-surface drains and surface ditches to the river. This accelerates drawdown of the groundwater near the river and contributes to the lack of cool summertime base flows, which in turn reduces the quality of the river as habitat for salmonids and other aquatic wildlife.

While much has been done in recent decades to reduce surface erosion and soil loss in the watershed, little has been done to reduce runoff. The volumes and rates of runoff that reach the river have been increasing ever since Euro-American settlement.

The modern hydrograph rises and falls more quickly and has a much higher peak than the historical hydrograph. This is due to the increased volumes and rates of runoff plus the accelerated groundwater discharge. The decrease in coarse sediment inputs, increase in flows, and channel simplification have occurred together, such that the river has had more energy than needed to carry and deposit sediment. The river has therefore been eroding its bed. Without inputs of sediment to balance the outputs, the bed has been lowered relative to the valley floor. As a result, the river has been gaining capacity to contain larger flows between its banks. As the depth of flows has increased, their power to erode the river bed has also increased. The positive feedback between the depth of peak flows and channel incision has caused the river to continue to incise, except where it has encountered bedrock or other resistant natural material, or where the bed has been dammed or artificially armored. Incision has been arrested in a few reaches by the collapse of the river banks, which widens the channel, broadens the flows, and lessens their erosive power. This is the natural way that channels stabilize following episodes of incision.

The rate of channel incision has waxed and waned depending on changes in water and sediment inputs, as affected by climate and land use. The effects of short term variations in climate, such as the various droughts of the last century, are masked by the greater effects of land use change. Since Euro-American colonization, net incision has been at least 2-3 meters (m) or 6 – 9 feet (ft) for much of the river in the valley, with greater and lesser rates locally evident. Incision has been so severe that most of the river in the valley is entrenched, meaning that most flows that historically would have inundated the floodplain no longer overtop the river banks.

The river in the valley probably receives much larger loads of fine sediment now than it did historically. Despite the implementation of erosion control measures on agricultural lands, there are inputs of fine sediment from hundreds of miles of dirt roads and roadside ditches. There is also greater erosion of the river bed and banks that are replete with fine sediment. Since chronic incision has caused the river to abandon its historical floodplains, there is much less area along the river to trap and store fine sediment. Valley wetlands, now ditched, also no longer trap fine sediment.

Starting in the mid-nineteenth century, artificial levees, channel incision, the obliteration of side channels, and land use encroachment into the historical riparian zone have created a relatively straight, entrenched, homogenous, single-thread channel with a narrow riparian corridor throughout most of the valley. Broad floodplains are almost nonexistent. The existing riparian forest is not structurally complex.

The tendency of the river to scour frequently, plus a lack of large woody debris, causes the river bed to be rather planar in many reaches, with long pools of unnaturally uniform depth.

Management Alternatives

Opportunities exist to restore the overall ecological health of the river ecosystem. Based on the findings of our work we propose that the following actions warrant consideration. These actions are possible but complex. They could impact many stakeholders and would involve the oversight of multiple governance agencies. Their feasibility and suitability vary among the river reaches. Selected appropriate actions would ideally be implemented in a coordinated way to ensure their useful synergies and maximize their cumulative benefits. The following list of possible actions belies the technical and political challenges that they would entail. We emphasize that the actions need not be implemented everywhere, but instead be considered for the most suitable reaches of the river.

- Release water from major reservoirs during the dry season to augment base flows as needed to improve salmonid rearing habitat and other aquatic and riparian resources.
- Release water from reservoirs or from subsurface drains during late spring to flush fine sediments as required to improve salmonid spawning habitat later in the year.
- Release water from reservoirs during springtime high flows to promote rejuvenation of river bars and to discourage their colonization by woody vegetation.
- Augment inputs of coarse sediment to improve salmonid spawning habitat. In this regard, consider dredging coarse sediment from major reservoirs, which would also increase their capacity to store water.
- Restrict bank revetment to allow the river to gradually widen and develop active floodplains.
- Construct multiple floodplains at different elevations to restore fine sediment entrapment processes, off channel salmonid habitat, and riparian functions. The uppermost plains might also be used for agriculture.
- Construct reservoirs with injection wells at the tops of alluvial fans to increase arable lands and groundwater resources, while eliminating ditches that cause excessive runoff by artificially connecting tributaries to the river.
- Remove selected dams on tributaries to release stored coarse sediment and reduce evaporative water losses.
- Remove fish barriers along tributaries.
- Redesign ditches and replace culverts and other engineered crossings to increase the inputs of coarse sediment and its transport while reducing inputs of fine sediment.
- Restore beaver population for building low dams that trap fine sediment, to restore riparian communities, and to increase overall river ecosystem complexity.
- Reduce agricultural water demands by promoting drought-resistant grape rootstock and by implementing conservative irrigation and frost control practices.
- Dedicate selected low-lying areas of historical wetlands for conjunctive use as aquatic habitat and surface water treatment and storage.

- Adopt additional urban water management strategies, beyond those already in place, that incentivize urban infill, and encourage Low Impact Development (LID) to reduce runoff.

- Add storage capacity on the valley floor as part of a coordinated system of conjunctive use of sub-drains and reservoirs to facilitate the careful targeted management of river flows as recommended above. This might be achieved via net reduction of current cumulative reservoir surface area and increase in arable acreage.

- Consider including wetlands and off-channel aquatic habitats as design elements of valley reservoirs.

Many of the individual actions identified above can be combined into synergistic management scenarios to increase the health of river reaches and selected subwatersheds. This will require more coordination among the water users than exists now. An irrigation district or other form of self-governance may be needed at the watershed scale to achieve the coordination necessary to improve overall river ecosystem health while providing adequate flood control and water supplies in the context of climate change. It may be helpful to develop map-based illustrations of alternative locations for habitat restoration projects and management actions that can be implemented to achieve various river health objectives.

All evidence to date indicates that water supplies are adequate to improve river health and sustain a vital agricultural community, if the community is willing to explore, develop, and adopt some of the actions outlined here. Detailed studies of the feasibility of these actions still will be needed. The feasibility studies should begin with a realistic water budget for each major tributary and for the Napa River Watershed as a whole. Realistic water budgets are essential for understanding how different actions or sets of actions are likely to affect downstream flows and sediment regimes. The studies should continue with numerical modeling of the relationships between flow and the attributes of river health. These relationships will vary among reaches. The water budget can then be used to help identify which actions are most likely to significantly improve the health of the river ecosystem while meeting goals for flood control and secure water supplies. Direct measures of flow and river conditions can, in turn, serve to calibrate the models and to assess the performance of management actions.

Proposed changes in public policy support the watershed approach to aquatic resource restoration and protection. The revised guidelines for aquatic habitat mitigation under Section 404 of the US Clean Water Act (http://www.epa.gov/wetlandsmitigation), the proposed California Wetlands and Riparian Area Protection Policy (http://www.swrcb.ca.gov/water_issues/programs/cwa401/wrapp.shtml), and the proposed Stream and Wetland Systems Protection Policy of the Bay Area Water Board (http://www.waterboards.ca.gov/sanfranciscobay/water_issues/programs/streamandwetlands.shtml) all emphasize a watershed approach to planning local management actions.

Monitoring

Important but limited monitoring of the Napa River ecosystem is ongoing. The Napa Creek Salmon Monitoring Project, initiated by the Napa Resource Conservation District (RCD) in 2006, can provide essential information about the effects of management actions on salmonid conservation. But, there is little information about many of the attributes of overall river ecosystem health. The monitoring plan for the Rutherford Dust Society's Rutherford Reach Restoration Project will generate a comprehensive dataset for channel conditions in this reach. It is unlikely, however, to shed light on the response of the restoration reach to upstream actions, or on the effects of the restoration on downstream conditions, since these areas are not being comparably monitored. Napa County is currently supporting an effort to coordinate the monitoring approaches among large restoration projects on the Napa River so that datasets can be shared, compared, and expanded throughout the watershed. Such coordinated and standardized monitoring is essential to compare one project to another, track each project over time, and to assess their cumulative effects on one or more of the ten attributes of river health described above.

All monitoring should be driven by clear and thoroughly vetted management questions and goals. For the Napa watershed, the monitoring program will need to answer questions about the success or performance of restoration, mitigation, and Best Management Practices (BMP), as well as track progress toward the goals for Total Maximum Daily Loads (TMDL), Low Impact Development (LID), wastewater reuse, salmonid recovery, flood control, etc. To meet these needs, a monitoring program will have to include both ambient monitoring and project-specific or targeted monitoring.

Ambient monitoring should have four basic elements: a comprehensive base map of aquatic and riparian habitats and related infrastructure, periodic comprehensive measurement of land use and land cover, continuous fixed-station monitoring of rainfall and in-channel flow, and probabilistic surveys of field conditions. A base map is a map of all channels, wetlands, lakes and other surface waters and their associated riparian areas that together comprise the places and pathways of water and sediment transport and storage within the watershed. The base map is as detailed and accurate as necessary to support numerical modeling of hydrological and ecological processes for informing local land management. Furthermore, the base map serves as the spatial framework for probabilistic sampling of ambient conditions of habitats and wildlife support.

Targeted monitoring is site-specific and has two components: projects and reference sites. Projects might include any efforts on the ground that alter the physical form or structure of the river ecosystem, including the channel, floodplains, and riparian areas, or that affect a change in water and sediment inputs to the ecosystem. The concept of targeted monitoring also pertains to sites that are not part of any project but must be repeatedly monitored to address a particular management concern. For example, some of the reaches that salmonids favor for spawning need to be regularly monitored to assess spawning success.

To the extent possible, the targeted monitoring should include the same methods that are used in the ambient monitoring. This is the only way to compare one project to another, to track change from an individual project over time, assess how projects perform relative to ambient condition, and re-evaluate management approaches that do not appear to yield the desired benefits. The response of the river ecosystem to climate change or to large-scale management actions may take place over decadal or longer periods. This increases the need to standardize methods for projects and ambient surveys that represent different timeframes.

A major component of successful monitoring is public access to monitoring results. Napa County's Watershed Information Center & Conservancy (WICC; www.napawatersheds.org) might serve as a local portal for the needed database. At the state level, the California Wetland Portal (www.californiawetlands.net) and proposed Watershed Portal should be explored as public domain systems for managing and sharing monitoring data and information. These portals use interactive, standardized base maps as called for above to enable the public to visualize and access information about aquatic and riparian resources and related projects.

As monitoring moves forward and data accumulate, they could be interpreted in terms of the ten attributes of a healthy river ecosystem (Trush et al., 2000) used to frame this study. The monitoring data could thus be used to assess the efficacy of watershed management in terms of the overall health status of the Napa River ecosystem. The monitoring program should consider the following specific recommendations.

- Once developed, the base map should serve to locate and track projects and environmental conditions. It will need to be updated periodically.

- Land use can be monitored by maintaining standardized maps of land cover types, and by annotating the maps with information about land use practices. These might include irrigation and other water management practices, erosion control practices, etc.

- The storm hydrograph and annual hydrograph of the river can be regarded as performance curves for assessing the effects of upstream land use on aquatic resources. This means the hydrographs will need to be monitored above and below projects expected or designed to modify river flows. To assess the cumulative effects of projects, the hydrographs might have to be monitored above and below tributaries.

- To understand management effectiveness, the relative cumulative effects of management actions and climate on the hydrographs and sediment regime will need to be assessed. This will require adding enough rain gauges to characterize rainfall for individual major tributaries.

- With regard to sediment, the main objectives for the Napa River ecosystem are to eliminate excessive scour and incision of the riverbed, and to increase the coarseness of the bed for selected reaches. Tracking progress toward these objectives will require a standardized set of field methods to assess conditions of the river bed as the net results of changes in sediment inputs and sediment transport by the river.

- Rapid assessment methods (RAMs) can yield cost-effective, field-based assessments of overall health that cannot be provided by more intensive, narrowly focused monitoring methods. RAMs typically involve standardized indicators of visible condition to answer a set list of questions relating to the ability of a site to provide a broad range of ecological functions or services. Many rapid assessment methods have been developed for streams and riparian corridors (NRCS 2001). In California, the two most often used RAMs are Proper Functioning Condition (PFC) (http://el.erdc.usace.army.mil/emrrp/emris/emrishelp6/process_for_assessing_proper_functioning_condition_tools.htm) and the California Rapid Assessment Method (CRAM) (www.cramwetlands.org). RAMs could easily be integrated into a monitoring program.

- Additional methods can be added to a program as needed to address particular management concerns or answer specific management questions. For example, as mentioned above, concerns about the river bed as spawning habitat for salmon and steelhead might warrant monitoring bed permeability where spawning is likely. Concerns about aquatic pathogens might warrant including standardized measures of them along with other routine water quality monitoring.

- Ambient surveys can also be conducted to assess changes in the distribution and abundance of selected habitats by re-mapping selected “status and trends” plots. This is the approach being used by the USEPA and other federal agencies to track net change in wetland acreages nationwide (http://www.epa.gov/owow/wetlands/survey/), and is being recommended as part of the California Wetland and Riparian Area Monitoring Program.

The State Water Resources Control Board (SWRCB) is working with United States Environmental Protection Agency (USEPA) to develop State policy for planning and monitoring restoration and mitigation actions in the context of ambient watershed condition (www.swrcb.ca.gov/water_issues/programs/cwa401/wrapp.shtml). The policy lays the foundation for developing and implementing standardized water quality monitoring methods as called for by the California Water Quality Monitoring Council (http://www.waterboards.ca.gov/mywaterquality/monitoring_council/index.shtml). While project-specific monitoring will continue to be an integral part of the regulatory process, new emphasis will be placed on understanding monitoring results in the context of ambient condition at the watershed scale.

INTRODUCTION

Juvenile steelhead and chinook salmon.
Photograph courtesy of Jonathan Koehler.

Napa Valley is the most recognized area within the best-known wine growing region in the United States. It yields wines that are enjoyed around the world. Much of this success is due to the expert understanding that wine-makers have about the geology, climate, soils of the Napa River Watershed, a 1,036 kilometers^2 (km^2) 400 miles^2 (mi^2) area of the Inner Coast Range draining southward into San Pablo Bay, the northernmost and largest of the bays that together with the Sacramen-to-San Joaquin Delta form the San Francisco Estuary (FIGURE 1). The Napa River Watershed supports about 17,348 ha (42,870 ac) of irrigated vineyards (Napa County Crop Report 2008).

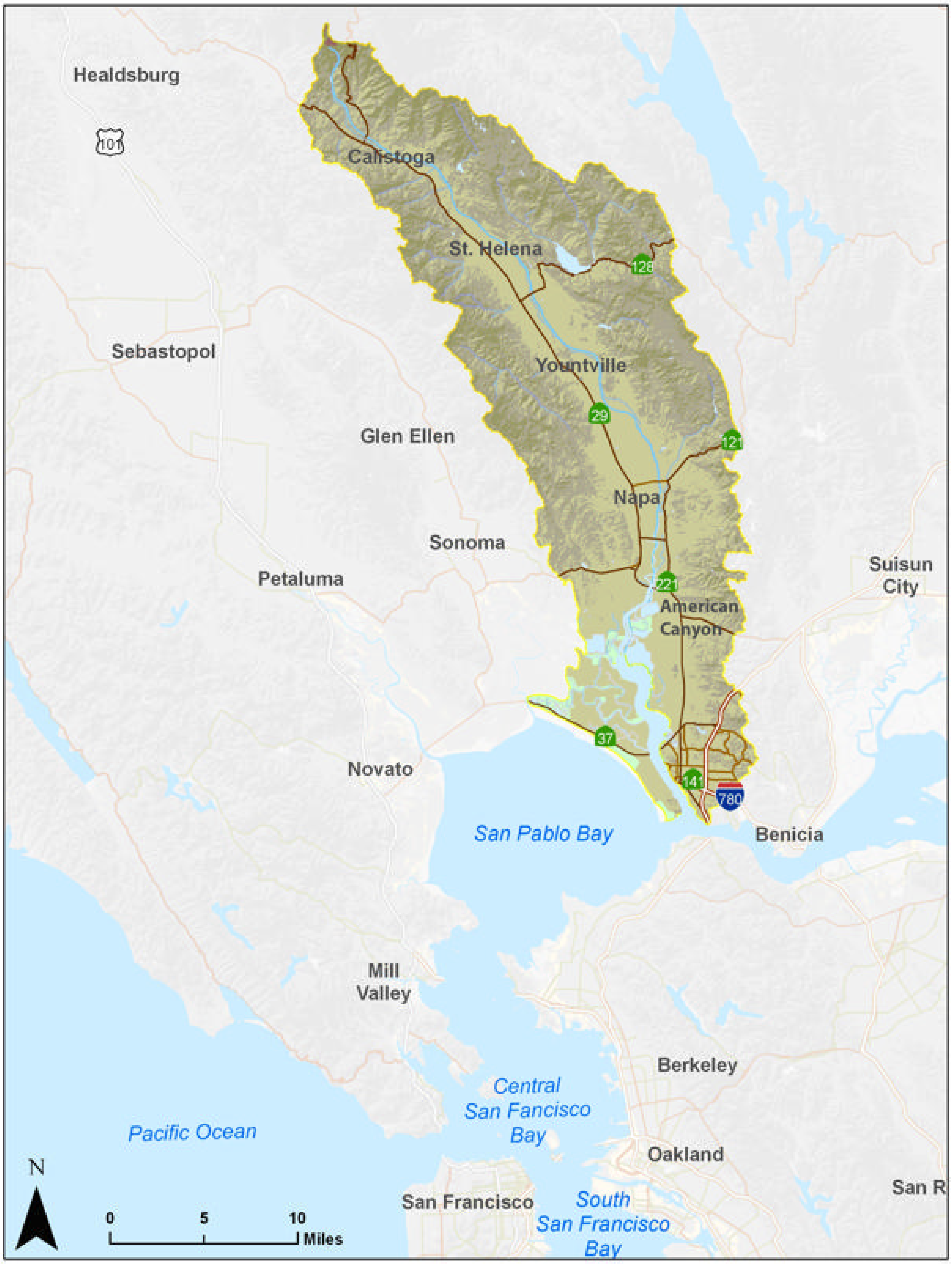
This report is mainly about the relationship between grape growing and the health of the Napa River ecosystem. To better understand this relationship, we examine how grape growing and other land uses have, over the centuries, influenced a set of universal parameters of river health. These parameters are presented in the section entitled "Conceptual Framework" near the end of this Introduction. We have focused on the river in its valley because its condition reflects the cumulative influences of local and upstream events and processes, both natural and caused by people. Much of this report is about delineating the effects of people and natural processes on conditions of the river in the valley. A fundamental tenet of this report is that people can adjust what they do in the watershed, especially with regard to water use, to improve the health of the river.

Napa Valley actually consists of distinct geomorphic elements termed alluvial fans, river terraces, and floodplains. The fans were created over thousands of years by the major tributaries moving sediment to the valley margins from the Mayacamas Mountains on the west and the Vaca Mountains on the east (FIGURE 2). The western fans are larger than the eastern fans, indicating that the western tributaries have tended to yield more sediment. This is due to differences in geology and climate on the different sides of the watershed. FIGURE 7 is a map of the dominant geology for the subwatersheds in Napa. With some exceptions, the western side is wetter (FIGURE 3) and consists of more friable sedimentary bedrock prone to landslides. The eastern side largely consists of volcanic bedrock that is less friable. Terraces are abandoned river floodplains that are never or rarely flooded. Floodplains are flat areas of the valley that still flood. Lower lying floodplains are flooded more frequently. The valley is 43 km (27 mi) long, with the cities of Napa and Calistoga occupying its lower (southern) and upper (northern) ends, respectively. It is about 8 km (5 mi) wide at its southern end and narrows northward to less than 1.6 km (1 mi) at Calistoga. The floodplain widens upstream and downstream of the large alluvial fans created by the major tributaries. The floodplain is narrowest between large opposing fans. A minor pass along the western shoulder of Mt. St. Helena leads to Knight's Valley, which links the northern end of Napa Valley to the Alexander Valley north of Healdsburg.

The climate of the valley is generally controlled by its position relative to the Pacific winter storm track and its location within the Central Coast Range. The Napa Watershed incorporates a number of mesoclimates. These range from more moderate, fog-influenced, lower rainfall areas near San Pablo Bay to higher rainfall areas in the upper reaches of the watershed, especially to the west (FIGURE 3). The Mayacamas and Vaca ranges, with an average ridge line elevation of about 600 m (2000 ft) are effective barriers to the prevailing northwesterly winds. The upper (northern) end of the valley reaches the base of 1,324 m (4,344 ft) Mount Saint Helena, one of a few mountains in the greater San Francisco Bay Area that ever receives snowfall.

The Napa River ecosystem is similar in overall physiography to other river systems of the Central Coast Range. The variable geology, topography, and rainfall patterns, plus a connection to ocean waters create a complex physical template for aquatic, wetland, riparian, and upland habitats. Ephemeral and perennial streams connect the Mayacamas and Vaca Mountains to the valley, where water tables naturally tend to be very high. Tidal flats and wetlands border the estuarine reaches of the river, where seasonal mixtures of ocean and river water create variable salinity gradients. The complex habitat mosaic tends to support diverse communities of fish and other wildlife. Although the abundance and distribution of several fish and wildlife species appear to be substantially diminished in the Napa River ecosystem, with one species of salmon (Coho) believed to have been

FIGURE 1. Napa Valley Watershed, located north of San Pablo Bay.



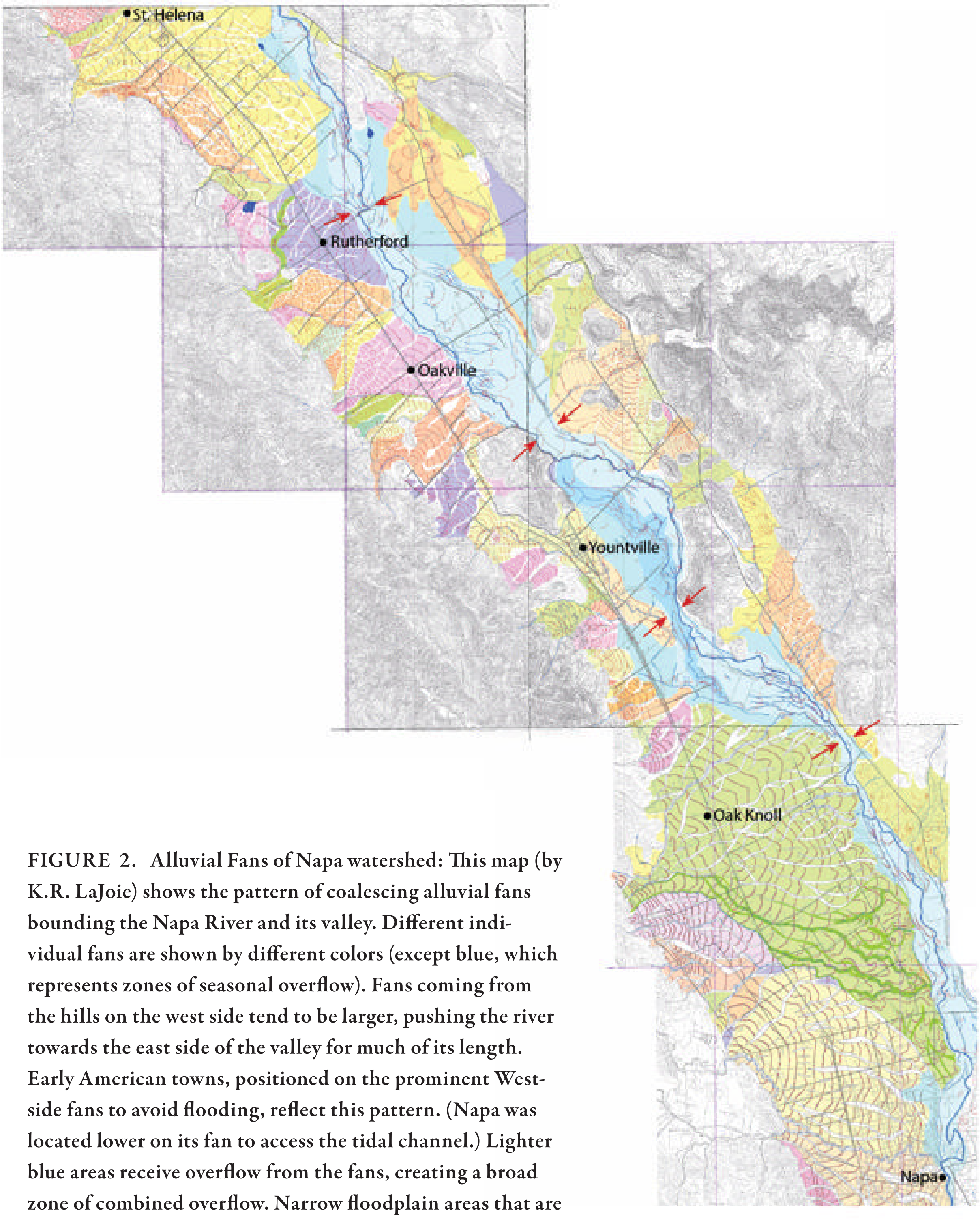
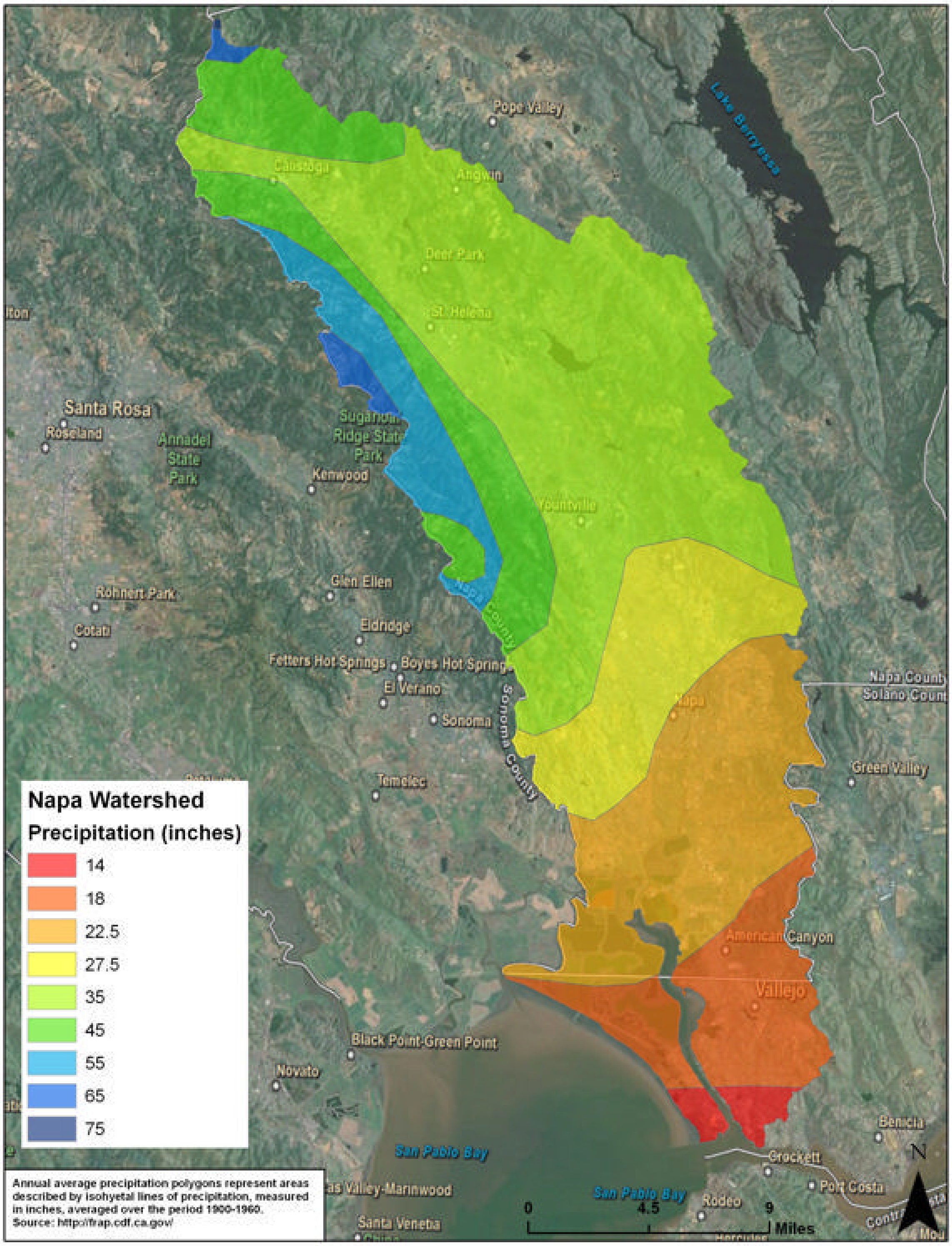


FIGURE 2. Alluvial Fans of Napa watershed: This map (by K.R. LaJoie) shows the pattern of coalescing alluvial fans bounding the Napa River and its valley. Different individual fans are shown by different colors (except blue, which represents zones of seasonal overflow). Fans coming from the hills on the west side tend to be larger, pushing the river towards the east side of the valley for much of its length. Early American towns, positioned on the prominent West-side fans to avoid flooding, reflect this pattern. (Napa was located lower on its fan to access the tidal channel.) Lighter blue areas receive overflow from the fans, creating a broad zone of combined overflow. Narrow floodplain areas that are constricted between opposing fans and/or bedrock hills can be seen in several places (red arrows).

FIGURE 3. Precipitation in the Napa watershed based on Rantz 1969, 1972 data. Note the higher rainfall levels on the western side of the upper watershed.



extirpated (Leidy 2007), the watershed continues to support sixteen native fish species including steelhead, Chinook salmon, Pacific and river lamprey, hardhead, hitch, tule perch, and Sacramento splittail (Leidy 1997). Although the Napa River ecosystem is physiographically similar to other river systems in the region, its diversity of native fish species is uncommonly high (Leidy 2000). The Napa River and some of its tributaries also support the endangered red-legged frog, yellow-legged frog, and California freshwater shrimp.

The biological diversity of the Napa River ecosystem has declined significantly over the past 200 years. The system is plagued by unnatural imbalances between water and sediment inputs that have caused chronic channel incision in the middle and upper reaches of the valley, and increased flood risks further downstream. Incision has been so severe that most of the river in the valley is entrenched, meaning that most flows that historically would have inundated the floodplain no longer overtop the river banks. As will be explained, while this condition can benefit local flood control, it can greatly diminish river health. The river is listed as impaired under Section 303(d) of the US Clean Water Act due to pathogens, excessive nutrients, and excessive sediment. A high value has been placed on ecologically sensitive management of the river, as evidenced by the continued significant investments in river health by Napa County residents and businesses. Some of the major efforts to help improve the health of the Napa River Ecosystem are listed below.

- Measure A sales tax. Napa County residents passed Measure A (Flood Protection and Watershed Improvement Sales Tax Ordinance) in 1998 to generate revenue to improve flood protection, water supply and the health of the watershed. Measure A funds helped implement the award-winning Napa River-Napa Creek Flood Protection Project based on "living river" principles. http://www.countyofnapa.org/pages/departmentcontent.aspx?id=4294971816

- Rutherford Reach Restoration. The Rutherford Dust Society's Rutherford Reach Restoration Project will restore about 7 km (4.5 mi) of the Napa River ranging from Zinfandel Lane Bridge to Oakville Cross Road.

- Removal of Dry Creek and York Creek dams. A seasonal dam on Dry Creek was removed in 2007 through a cooperative effort of Hall Winery, the Napa County Resource Conservation District (NCRCD), USDA-Natural Resources Conservation Service (NRCS), the California Department of Fish and Game (CDFG), Fish Friendly Farming, and other partnering agencies. The dam removal opened 27.2 km (16.9 mi) of steelhead habitat to spawning, rearing, and out-migration. A dam on Upper York Creek above St. Helena was approved in 2008 for removal by the United States Army Corps of Engineers. This dam has experienced high levels of siltation, and the reservoir was no longer in use. The removal will restore 3.2 km (2.0 mi) of steelhead habitat and 0.8 ha (2.0 ac) of riparian habitat.

- Napa River tidal wetland restoration projects. Approximately 3,600 ha (9,000 ac) of tidal wetlands are being restored that have direct hydrological connections to the Napa River. This includes about 590 ha (1,460 ac) of recently restored tide lands at the Napa Plant Site northwest of American Canyon. The State Coastal Conservancy (SCC) and CDFG are overseeing the restoration of more than 2,800 ha (7,000 ac) of tidal wetlands between the tidal reaches of the Napa River and Sonoma Creek.

- Green Certification programs. The Fish Friendly Farming certification program (http://www.fishfriendlyfarming.org/) has been created to improve vineyard/orchard management practices for water and soil conservation, creek and river riparian corridor management and restoration.

- Status and trend analyses. Analyses have been planned and conducted regarding the status and trends of salmon and steelhead populations, and of factors limiting their size and distribution (Koehler, Napa RCD 2008).

- Watershed Information Center and Conservancy. The Watershed Information Center & Conservancy (WICC) has been established to guide, coordinate, and support community efforts to maintain and improve the health of Napa County's watersheds.

Most of the river's health problems are due to more than 200 years of incrementally small, but cumulatively large changes in land and water management throughout the watershed, most of which happened before the environmental movement and the advent of watershed science. The lands and waters were historically used productively, but with little concern for long term environmental impacts. The restoration of healthy conditions will likely require collaborative, broad-based approaches involving many interests, especially if the health of the river ecosystem is to be improved faster than it has declined.

One hallmark of existing watershed science and management of the Napa River Watershed is erosion control on farmlands. The farming community has a long-term relationship with soil science and erosion control. The relationship was boosted after the dust-bowl era with formation of the US Soil Conservation Service (SCS), which developed many proven methods to prevent farmland erosion. Local counterparts of the SCS, called Soil Conservation Districts (SCDs), were set up under California law to help the SCS define and meet local needs. SCDs were originally empowered to manage soil and water resources for conservation, but these powers were expanded in the early 1970s to include "related resources," including fish and wildlife habitat. This expansion of powers was reflected in the change of name from Soil Conservation Districts to Resource Conservation Districts in 1971. The SCS became the Natural Resources Conservation Service (NRCS) in 1994, ostensibly to reflect the fact the agency's conservation mission encompassed water, air, plants, and animals in addition to soil. The NRCS and RCDs continue to benefit each other through shared strategies and strong partnerships. Both emphasize erosion control for whole watersheds, the upland areas as well as the channels and their floodplains. The work of the NRCS and RCD forms the foundation of any serious study of land use effects on environmental conditions in the Napa River Watershed.

Erosion control in the Napa River watershed has focused on reducing soil loss and inputs of fine sediment into the river ecosystem. The control mechanisms include many Best Management Practices (BMPs) to prevent erosion on farmlands, especially on hillsides with slopes greater than 5%. Appendix 1 provides a more detailed discussion of implementation of BMPs in the sub-watersheds in the Napa Watershed. In response to scientific studies relating to the determination of river impairment, the focus for erosion control has been broadened to include erosion of channel banks and beds. Channel erosion is now broadly recognized as a major source, if not the biggest single source, of excess fine sediment in the Napa River ecosystem. The examination of river erosion led to concerns about other aspects of river health, including the quantity and quality of associated wetlands and riparian habitats. It became apparent that the excess fine sediment, which warranted listing the river under Section 303(d) of the US Clean Water Act, was symptomatic of major declines in other aspects of river health, and that meaningful analyses of these declines and their reversal would require a more holistic analysis of the relative, cumulative effects of natural processes and land use for the watershed as a whole.

Report Goal

This profile of the Napa River Watershed is meant to improve the understanding of how the river's ecological health has declined and what might be done in the future to improve its health, while protecting its economic values, maintaining adequate flood control, and meeting future water demands. This profile should help residents in the watershed envision large-scale solutions to the systemic problems of channel erosion, poor water quality, habitat loss, and flooding, while beginning to address the emerging challenges of climate change. The wine industry of the

Napa Valley is strongly identified with the beauty and healthy lifestyle that is endemic and emblematic of the region. The good health of the river ecosystem is essential to maintain this valuable reputation. Ecological health and economic health are intimately interconnected in the Napa River Watershed.

Report Objectives

The San Francisco Estuary Institute (SFEI), in partnership with the Napa County Resource Conservation District (RCD) and the Napa County Farm Bureau, was funded through a Proposition 40 grant from the State Water Resources Control Board (SWRCB or State Water Board) to develop a watershed-based framework for addressing agricultural management challenges related to improving the health of the Napa River ecosystem. In particular, the project sought to identify possible adaptive management measures whose implementation could allow the State Water Board to remove the Napa River from the list of impaired waters under section 303(d) of the US Clean Water Act. The project objectives can be summarized as follows.

- Compare and contrast the historical and current aquatic and riparian habitats of the Napa River ecosystem, with a focus on the Napa River in its valley, since it is has been identified as impaired, is a centerpiece of the local aesthetic, and its health status is symptomatic of overall watershed conditions.
- Identify how land use changes have contributed to current undesirable conditions in the river ecosystem.
- Describe the relationship between agricultural practices and the major attributes of a highly functioning, healthy river ecosystem.
- Identify management approaches or practices that could help improve the health of the river ecosystem.
- Increase understanding within the agricultural community of the Napa River Watershed about the relationships between past and present agricultural practices and river health.

The San Francisco Bay Regional Water Quality Control Board (SFBRWQCB or Regional Board) has determined that the Napa River is impaired based on significant declines in condition for salmon and steelhead habitats (henceforth referred to collectively as salmonid habitat). More specifically, the Regional Board has found that the river ecosystem is impaired due to an excess of fine sediment that limits salmonid support. Previous studies of Napa River impairment have included the 2002 Napa River Basin Limiting Factors Analysis, and the subsequent Sediment TMDL Staff Report by the Regional Board (Napolitano et al., 2009). In its report, the Regional Board recognizes that its focus on sediment in relation to salmonid habitat does not address all aspects of salmon ecology and de-emphasizes other aspects of river health. Over the course of this project SFEI was encouraged to regard river health in broad terms. The operating assumption has been that any increase in the general health of the ecosystem increases its physical and ecological complexity, thus benefiting salmon populations as well as many other aspects of the river ecosystem.

Conceptual Framework

A broader view of the river's health must consider the channel, its floodplain, and adjoining wetlands and riparian areas as integral components of the river ecosystem (Leopold 1994). Any analysis of changes in the river's health must be based on an understanding of the hydrological, geomorphologic, and ecological processes that create and maintain these integral components. Complex systems, however, are more easily examined by their major components. While separate consideration of these components might de-emphasize their inter-relations, the approach taken in this report has been chosen to more clearly elucidate the responses of the river ecosystem to changes in runoff and sediment inputs, as affected by climate, geology, and land use change.

These concepts are well represented by the ten attributes of river health described by Trush et al., (2000). In this work, the authors describe a series of attributes for a highly functional river ecosystem. One of the objectives for developing the attributes was "to help river managers identify desired processes, and then help prescribe necessary impetuses based on useful empirical relationships and thresholds developed by river geomorphologists and ecologists." The ten attributes constitute an appropriate framework for this report because they span the full breadth of health conditions for the river ecosystem and explicitly link watershed science to watershed management. Other frameworks could be applied to an analysis of the Napa River ecosystem; however, the strength of the chosen approach lies in its specific considerations of the linkages between science and management. For instance, Napa River flood protection and restoration efforts are guided by "Living River" principles (Community Coalition for a Napa River Flood Management Plan 1996). A Living River approach seeks to balance a broad array of ecological and societal needs such as flood protection, dynamic natural function, and ecosystem protection (van der Velde et al., 2006). The underlying concepts of Living Rivers could be applied here, but they are less specific and therefore less practicable than the healthy river attributes put forth by Trush et al., as listed below.

Attribute No. 1. The primary geomorphic and ecological unit of an alluvial river is the alternate bar sequence. Dynamic alternating bar sequences are the basic structural underpinnings for aquatic and riparian communities in healthy alluvial river ecosystems.

Attribute No. 2. Each annual hydrograph component accomplishes specific geomorphic and ecological functions. Annual hydrograph components (including winter storm events, baseflows, snowmelt peaks, and snowmelt recession limbs) collectively provide the impetus for processes that shape and sustain alluvial river ecosystems. These components are uniquely characterized by year-to-year variation in flow magnitude, duration, frequency, and timing.

Attribute No. 3. The channelbed surface is frequently mobilized. Coarse alluvial channelbed surfaces are significantly mobilized by bankfull or greater floods that generally occur every 1–2 years.

Attribute No. 4. Alternate bars must be periodically scoured deeper than their coarse surface layers. Floods that exceed the threshold for scouring bed material are needed to mobilize and rejuvenate alternate bars. Alternate bars are periodically scoured deeper than their coarse surface layer, typically by floods exceeding 5- to 10-year annual maximum flood recurrences. Scour is generally followed by redeposition, often with minimal net change in the alternating bar topography

Attribute No. 5. Fine and coarse sediment budgets are balanced. River reaches export fine and coarse sediment at rates approximately equal to sediment input rates.

Attribute No. 6. Alluvial channels are free to migrate. During lateral migration, the channel erodes older floodplain and terrace deposits on the outside bend whereas it deposits sediment on the bar and floodplain of the inside bend. Although outer and inner bend processes may be caused by different hydrograph components, the long-term result is maintenance of channel width.

Attribute No. 7. Floodplains are frequently inundated. Floodplain inundation typically occurs every 1–2 years. Floodplain inundation attenuates flood peaks, moderates alternate bar scour, and promotes nutrient cycling.

Attribute No. 8. Large floods create and sustain a complex main stem and floodplain morphology. Large floods—those exceeding 10- to 20-year recurrence events—reshape and/or redirect entire meander sequences, avulse main stem channels, rejuvenate mature riparian stands to early successional stages, form and maintain side channels, scour floodplains, and perpetuate off-channel wetlands, including oxbows.

Attribute No. 9. Diverse riparian plant communities are sustained by the natural occurrence of annual hydrograph components. Natural, interannual variability of hydrograph components is necessary for woody riparian plant life history strategies to perpetuate early and late successional stand structures.

Attribute No. 10. Groundwater in the valley bottomlands is hydraulically connected to the main stem channel. When floodplains are inundated, a portion of surface runoff from the watershed is retained as groundwater recharge in the valley bottomlands.

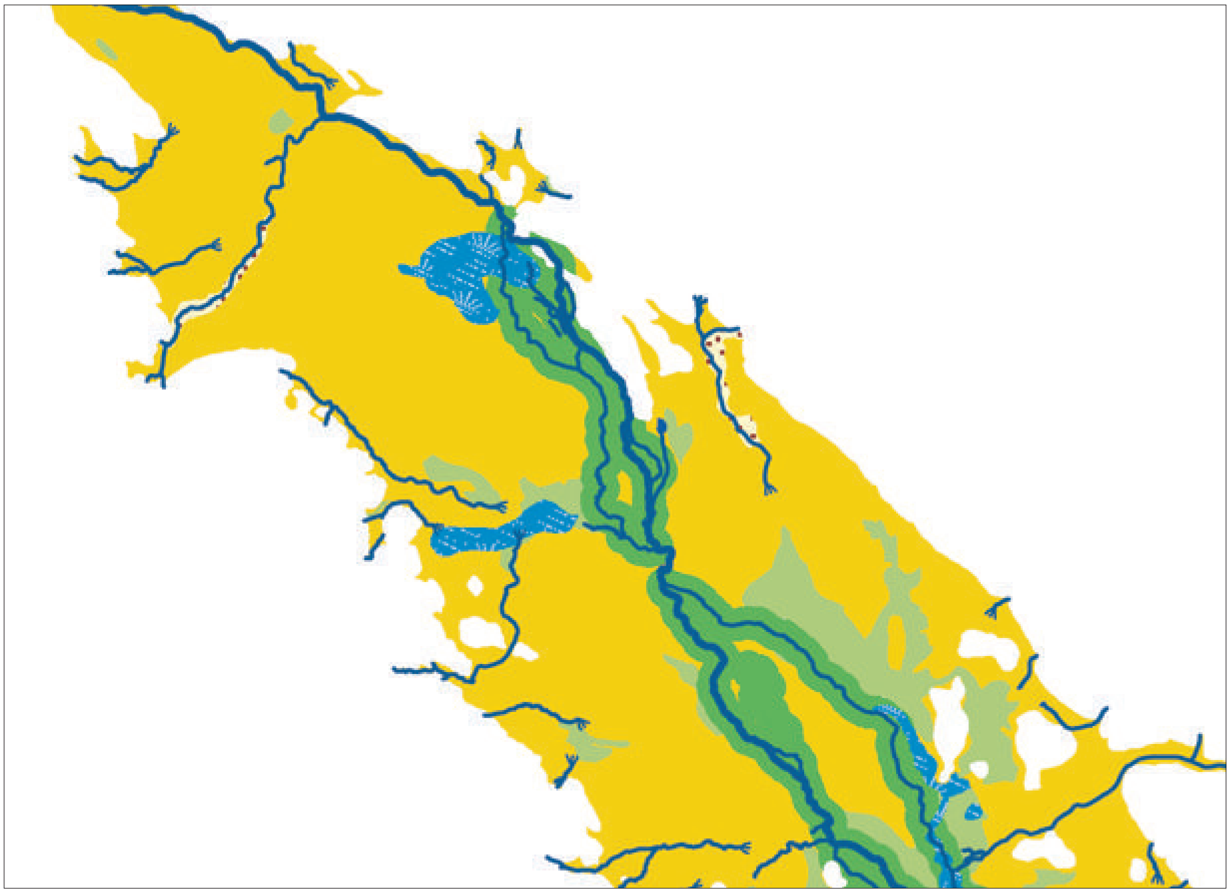
While these attributes can be extended with some caveats to the tidal reaches of rivers, they mostly pertain to fluvial reaches above any tidal influences. This report, therefore, gives limited attention to the tidal reaches of Napa River ecosystem, focusing instead on the areas to which the healthy river attributes most clearly pertain. It should be understood, however, that the Bay, in many ways, is an extension of its watersheds. The watersheds discharge treated and untreated effluents and runoff that the Bay receives and dilutes. The fine sediments yielded by the watersheds help the tidal wetlands around the Bay build upward as sea level rises. As well, the watersheds are extensions of the Bay. For example, salmon and steelhead must pass through the Bay on their way to spawning habitats in the Napa River and its tributaries. Thus, the gradients of salinity and turbidity that form between the watersheds and the Bay enrich the diversity of the region’s plant and animal communities.

The health of salmonid populations correlates closely with the state of the healthy river attributes. Salmon and steelhead reproduction depends on sufficient flows of cool, clean, aerated water through interstitial spaces in gravelly river beds where the fish prefer to spawn (Attributes 1, 3, 4). Excess fine sediment can fill interstitial spaces, thus suffocating the fish eggs (Nawa and Frissell 1993), physically prevent egg hatching and fish emergence (Koski 1966, Tappel and Bjornn 1983), and eliminate predation refuges for very young fish (alevin and fry) (Cordone and Kelly 1961). Inputs and outputs of sediment need to be balanced (Attributes 4 and 5) or fine sediments can become overly abundant. Fine sediments can retard fish growth by inhibiting feeding and increasing water temperatures above preferred thresholds, and, in extreme cases, interfere with breathing (Sigler et al., 1984, Newcombe and MacDonald 1991, Higgins 2002). Particularly during periods of low flow, excess fine sediment can become trapped in depressions (redds) in the riverbed created by spawning fish and inhibit the spawning process. (Kondolf 2000). Juvenile salmonids rely on a well-developed array of pools along the river bed with adequate shade and woody debris to prevent high water temperatures and provide food and refuge (Attributes 1, 4, 7-9). Riparian forests provide large woody debris that is essential to form debris jams, which in turn create plunge pools that serve as high quality pool habitat (Attributes 7-9). The tailing end of the receding limb of the annual hydrograph (Attributes 2 and 10) represents summertime base flows that can enhance hydrological connectivity between pools, expand the foraging habitat for juvenile fish (parr and smolt), and facilitate their outmigration (Marchetti and Moyle 2001, Lake 2003).

In general, the overall diversity and levels of function of an ecosystem increase with its complexity. The physical complexity of an ecosystem, meaning its variety of form and structure at many scales of time and space, has significant influence on its capacity to transform material and energy, to support biodiversity, and to provide the many ecosystem services expected by society. The more complex the habitat mosaic, and the more structurally complex each patch of the mosaic, the more life forms the ecosystem can support, and the more it can resist or rebound from stress and disturbance. In these ways, complexity increases ecosystem resilience (Campbell et al., 2009). A river ecosystem with all of the attributes listed above would have a high degree of natural complexity, and would, therefore, be expected to have high levels of most, if not all, of the natural functions endemic to it.

Not all of the healthy river attributes are consistent with the needs of society. For example, many important land uses are not well-suited for a river that migrates, or floods, or harbors pests or vectors of disease. Watershed residents and managers are challenged to minimize costly conflicts between the natural and social functions of river ecosystems. This report was constructed with an eye on the attributes of river health (especially since they determine the health of salmon and steelhead populations), and describes how land use might be adjusted to meet the challenges in the Napa River Watershed.

HISTORICAL LANDSCAPE ANALYSIS



Historical wetlands complexes of Napa Valley.

Climate and Setting

The analysis of landscape changes in the Napa Valley is somewhat complicated by the fact that the advent of Euro-American land use was coincident with a regional shift in long term climate. Euro-Americans settled the Napa Valley and introduced cattle and other livestock during the early 1800s. This was approximately when a 400-year cool-wet climatic period called the Little Ice Age ended (FIGURE 4). Although local landscape responses to the shift in climate are not known, studies of the southern Colorado plateau provide some clues. The Little Ice Age was characterized by infrequent large floods and frequent small floods that caused many valleys on the plateau to aggrade (gain elevation). After the end of the Little Ice Age, channels in at least some of these valleys began to incise (Hereford 2002, Leopold 1976)

One might infer from the studies mentioned above that the Napa River also began to incise after the Little Ice Age, however, most of the channel incision occurred later (see Section titled *System response and current configuration* below). Rainfall patterns that have apparently not changed much over the period of channel incision are an additional factor (FIGURE 5). The regional drought of the 1930s is noteworthy. Clearly evident in the rainfall records is a slight trend toward less annual rainfall, at least until the last few decades. In addition, there are patterns in rainfall variability at multiple time scales, i.e., from seasons and years to decades. On average, however, the annual amount of rainfall varies little over the historical record. For these reasons, the assumption is made that land use rather than climate change accounts for the observed incision.

Historical Reach Attributes

The contemporary Napa River is a relatively homogenous channel bordered by a narrow riparian forest. Without the context of history, the river might appear natural. Compared to conditions prior to local Euro-American settlement, however, the river is highly altered from the much more complex historical river ecosystem (FIGURE 6). There are some exceptional areas with appreciable complexity, but overall the channel is highly simplified. In general, the entrenched channel is dominated by long glides or pools lacking woody debris and other structural elements indicative of healthy stream ecosystems of the Coast Ranges. In contrast, when the various reaches of the historical river from Calistoga to the Bay are considered together, all of the attributes of a healthy river are evident. Not every historical reach exhibited every attribute to the same degree, but all the expected natural functional relationships between the river and its valley were evident for the historical ecosystem as a whole. In-depth information about the Historical Ecology analytical methods and findings used to inform this work are published in the Napa Valley Historical Ecology Atlas (Grossinger 2012)

In the absence of modern land cover, the shapes and sizes of the alluvial fans and low-lying floodplains on either side of the river are easily visualized. Where large fans oppose each other, the floodplains become pinched and very narrow (FIGURE 7 and FIGURE 8). Alternatively, upstream and downstream of major tributary confluences where there are no large opposing fans, the floodplains are wider. Note that the early settlements in the valley were built upon the larger alluvial fans, at elevations high enough to escape the major floods.

The spatial variations in floodplain width created by the tributary fans had major effects on the distribution of the healthy river attributes. In general, since the historical river was not entrenched, its slope paralleled that of the valley. The river was probably steeper and faster in the narrow areas downstream of major tributaries. These were presumably relatively high energy reaches with narrower floodplains and coarser beds and bars, due in part to the supplies of coarse sediment from the nearby tributaries.

Where the floodplains were narrow, the effects of infrequent large floods on riparian community structure were laterally less extensive, i.e., they were more confined to the river banks. Groundwater inputs from adjacent fans would have been more direct, and bank erosion was probably more prominent. Floodplain features, such as side channels, wetlands, and broad

FIGURE 4. 15,000-yr summary of North American climate. Red-shaded areas represent periods of relative warmer and drier climates in the West. Blue-shaded areas represent a cooler/wetter period.

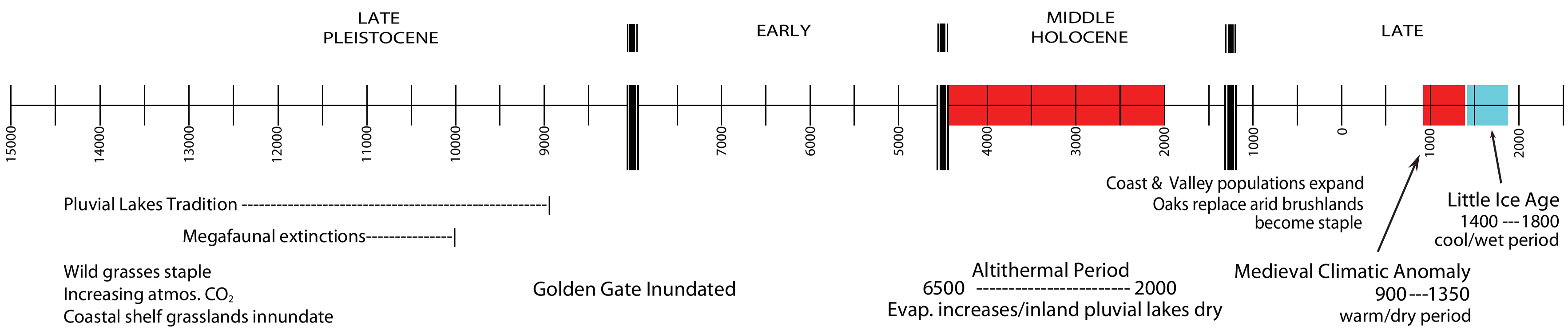


FIGURE 5. 10-yr running mean rainfall (inches) at Napa State Hospital and St. Helena.

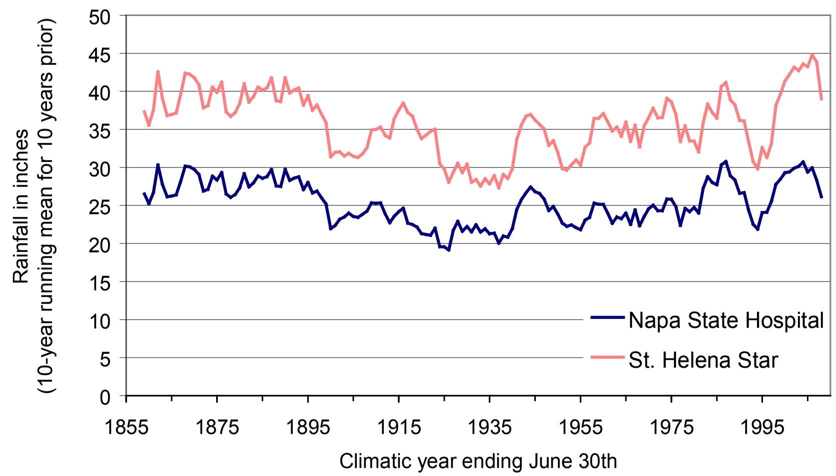


FIGURE 6. Napa Valley floor historical habitat types (Grossinger 2012).

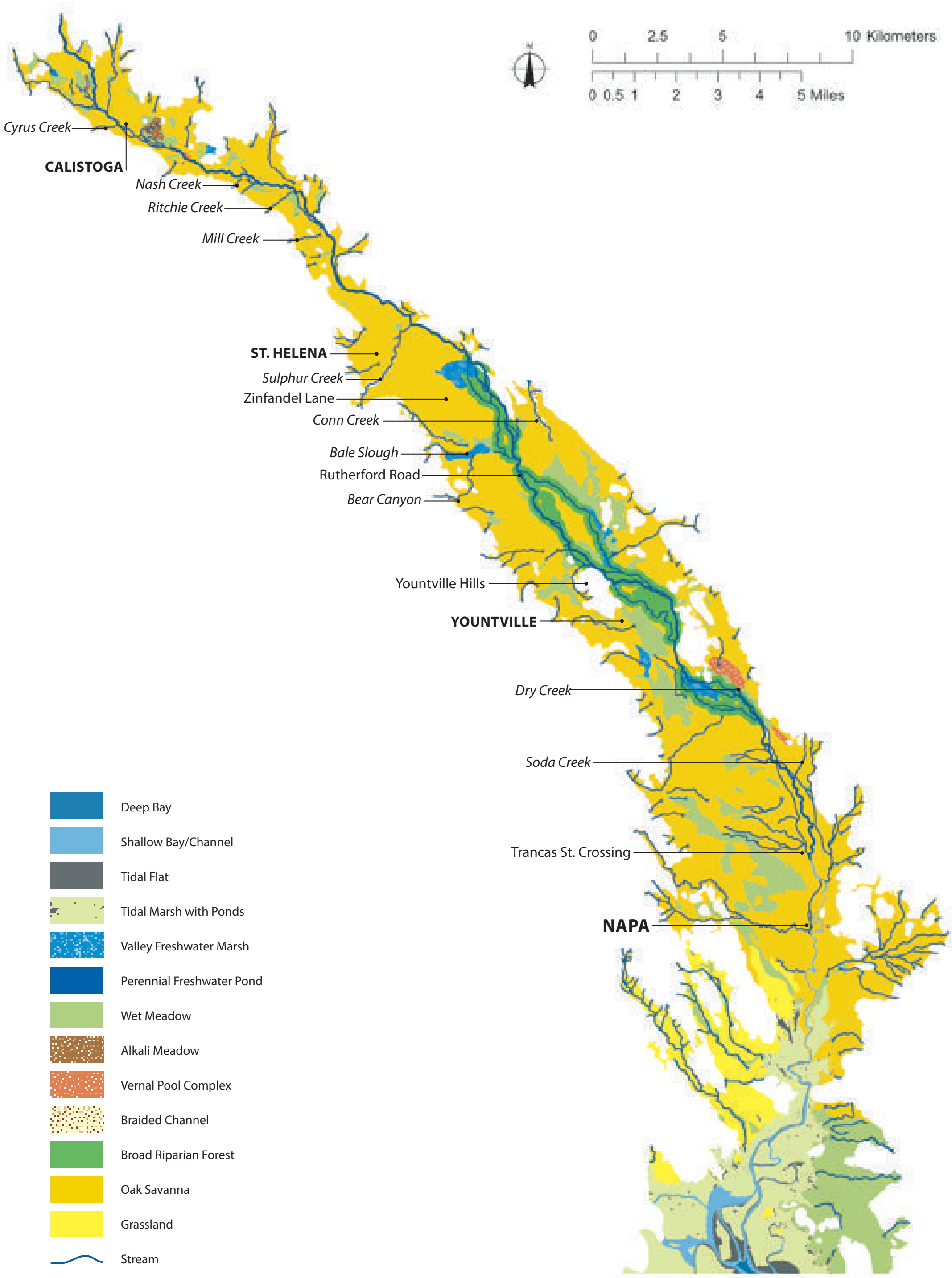


FIGURE 7. Dominant geologic type for each sub-watershed and pinch points in Napa Valley.

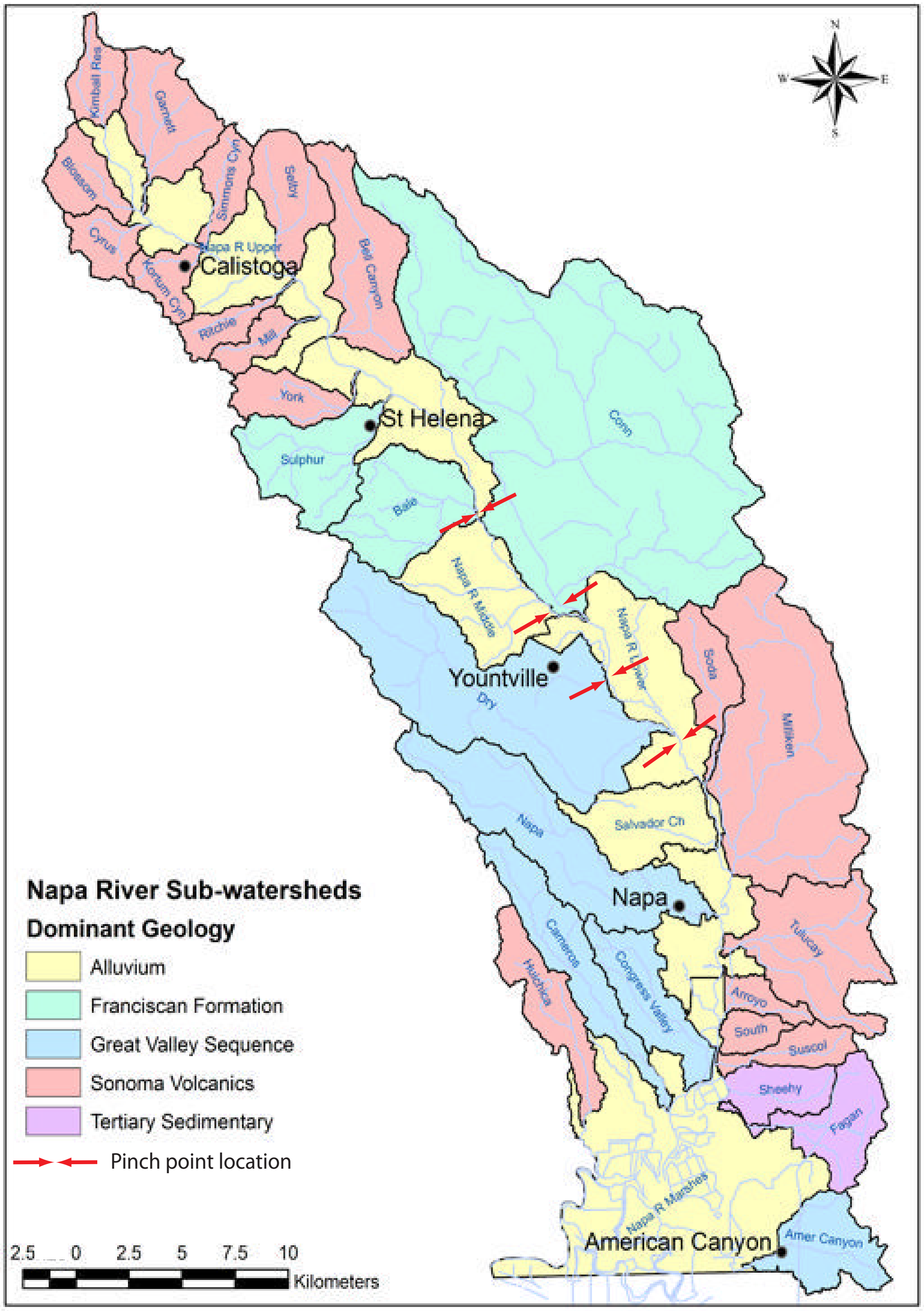
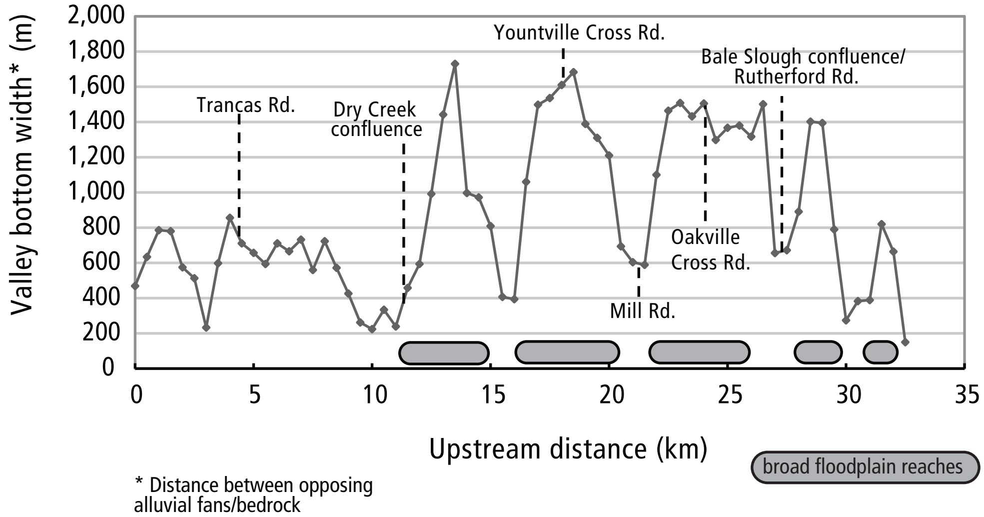


FIGURE 8. Key landscape features of the Napa Valley. This graph illustrates spatial relationships between width of valley floor, location of major tributary confluences, valley bottom wetlands, and broad floodplain reaches with sloughs and islands along the Napa River.



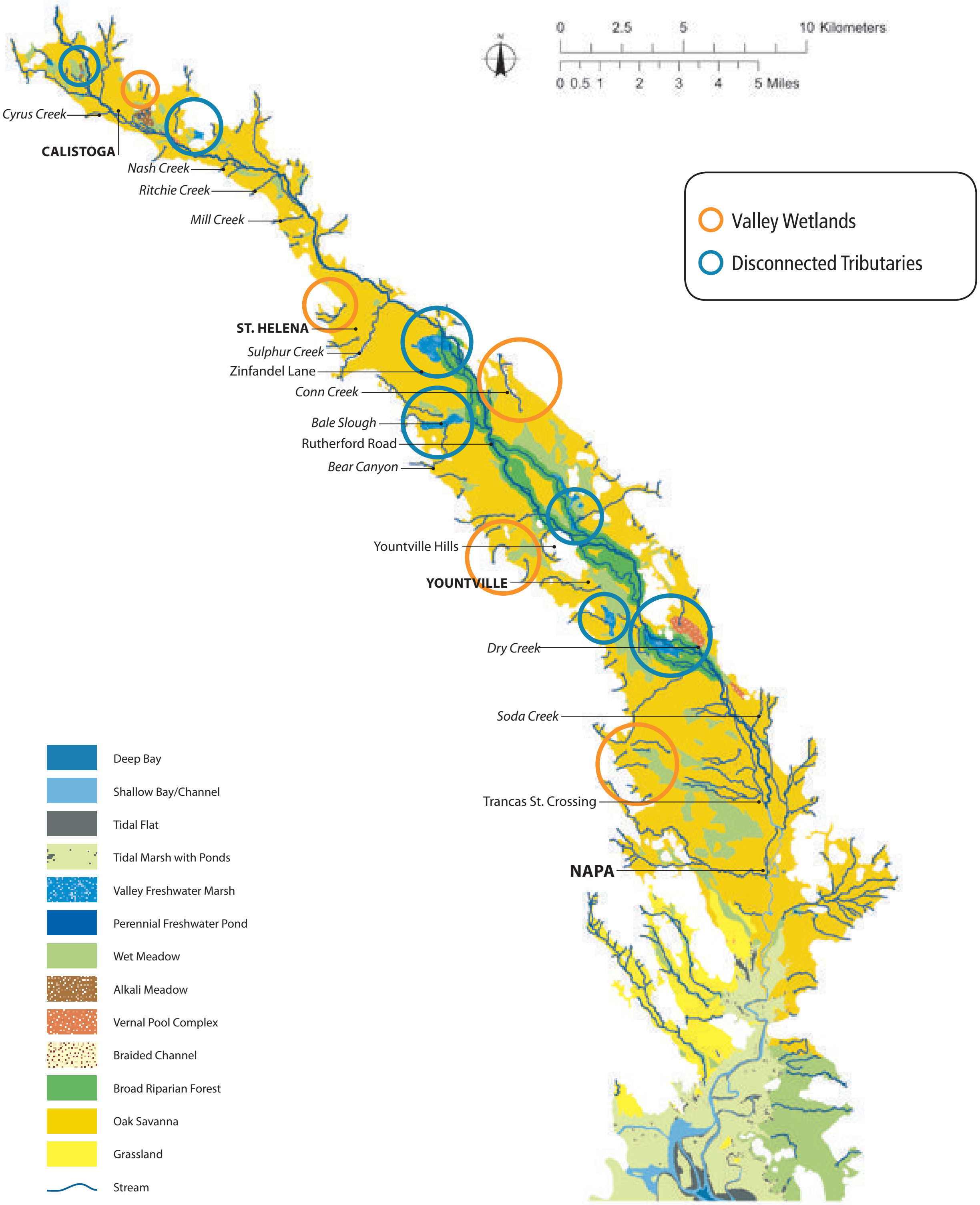
riparian forests tended to become more prevalent as the slope of the river flattened and the floodplains expanded. Large floods became more extensive, as were their effects on riparian ecology. Whereas groundwater discharged directly from the fans to the channel in narrow areas, it emerged onto the valley floor as wetlands in the broader areas.

In some of the broad areas, the river channel divided into multiple secondary channels, each fairly fixed in location, dissecting the floodplain and lower terraces into sizeable islands. These areas were complex mosaics of uplands, secondary channels large and small (some of which were likely perennial), plus wetlands of various sizes, shapes, and degrees of persistence from season to season and year to year. Inputs of large woody debris from the riparian forest would have accumulated in some of these channels during the periods between major floods, increasing the ability of the channels to trap fine sediment. Historical evidence suggests that beavers were present in the valley (Work 1833, in Maloney 1943, Skinner 1962). Although the abundance of beavers is unknown, their presence would have helped create shallow ponds and wetlands along the floodplains and in the channels in the broader areas of the valley.

As the river approached the Bay, the valley widened to its maximum extent, and transitioned into the tidal marshes and flats. The transition was gradual due to the varying heights of the tides and the gentle slopes of the valley and the river. The broad area of tidal marshland was shared to some extent by neighboring watersheds, including the watersheds of Carneros Creek, Huichica Creek, and Sonoma Creek. The tidal marshes depend on the sediment from these watersheds to build upwards apace with sea level rise (Malamud-Roam 2006, Sonoma Ecology Center et al., 2006)

Little is known about the actual nature of the historical river bed. There are no comprehensive historical descriptions of it, and it cannot be observed today. In every reach examined, the historical bed had been eroded away. There are no known reaches where the historical bed has been buried and might be exhumed for inspection. However, it seems likely that most of the coarse sediment moving along the channel was supplied by some major tributaries, and that the coarseness of the bed therefore varied with distance downstream from these sediment sources.

FIGURE 9. Historical wetlands on Napa Valley floor. In addition to these year-round wetlands, seasonal wetlands ("Wet Meadow" in green) were extensive.



The river banks were probably not important sources of coarse sediment. They mostly consisted of the fine-grain sediments of floodplain wetlands and the lowermost margins of alluvial fans. There may have been some coarsening of the bed downstream from broad floodplains due to their entrapment of fine sediment carried by flood flows, but the historical magnitude and extent of such an effect is unknown.

There is no historical evidence of rapid changes in the position of the river within its valley. Its migration was apparently very slow. Channel aggradation (raising of the bed) and avulsions (sudden large scale changes in river course) due to excessive loads of coarse sediment are not evident. Inputs and outputs of sediment appear to have been more or less balanced for the system as a whole. Migration in the narrow valley areas was naturally inhibited by the opposing alluvial fans and outcrops of bedrock. Migration was inhibited in the broader areas by natural levees and the distribution of flows among multiple secondary channels.

The general descriptions above of the physical condition and behavior of the river in the valley are supported by reach-specific case studies. The character of selected reaches along the river's course from Calistoga to Trancas Street in Napa are considered below and assigned appropriate attributes from the Trush list (Trush et al., 2000). Note that the historical record suggests that the healthy river attributes vary in their prevalence among these reaches.

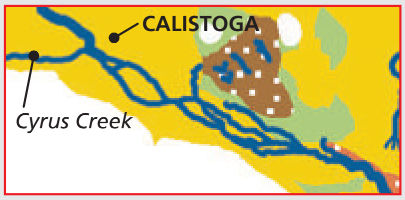
Trush Attributes

1. Alternate bar sequence
2. Annual hydrograph components affect functions
3. Channelbed surface frequently mobilized
4. Alternate bars periodically scoured
5. Fine and coarse sediment budgets balanced
6. Alluvial channels free to migrate
7. Flood plains frequently unindated
8. Large floods create complex morphology
9. Diverse riparian plant communities
10. Groundwater connected

Legend

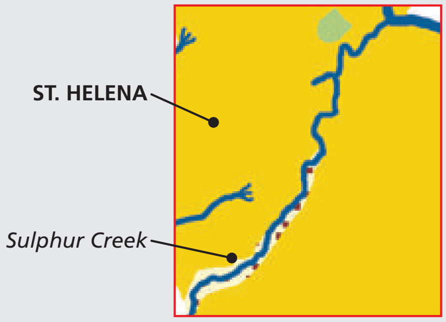
- Deep Bay
- Shallow Bay/Channel
- Tidal Flat
- Tidal Marsh with Ponds
- Valley Freshwater Marsh
- Perennial Freshwater Pond
- Wet Meadow
- Alkali Meadow
- Vernal Pool Complex
- Braided Channel
- Broad Riparian Forest
- Oak Savanna
- Grassland
- Stream

8 Large floods create complex morphology



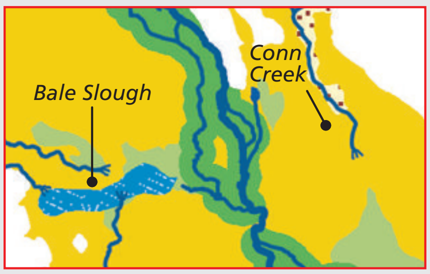
In Calistoga, just downstream from the Cyrus Creek confluence, the flows of the river spread into a complex network of secondary channels that meandered among broad wetlands supported by groundwater return flow for at least 1.6 km (1 mile) downstream. These channels were apparently stable and fixed in place (Attributes 2, 5-10).

1 Alternate bar sequence
4 Alternate bars periodically scoured
7 Flood plains frequently unindated



Sulphur Creek's fan – one of the valley's largest – exerted a strong control on Napa River in the vicinity of modern-day St. Helena, confining it to the base of the eastside hills. The morphology of the river changed downstream of the Sulphur Creek confluence to a wide channel with large, non-vegetated gravel bars. This change would be expected given the large coarse sediment load carried by Sulphur Creek from its erodible sedimentary headwaters (Attributes 1-5, 7-9).

7 Flood plains frequently unindated
8 Large floods create complex morphology

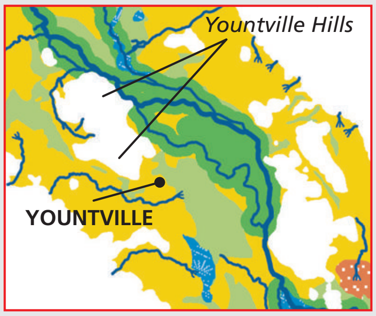


Once the river passed the Sulphur Creek fan, it spread into one of its largest areas of floodplain wetlands. A mosaic of willow groves and tule marshes dominated the reach from the present-day location of Zinfandel Lane to the vicinity of Bale Slough. In this area, the main channel was relatively indistinct even after substantial reclamation efforts. 1940 aerial photography shows a narrow, poorly defined channel with few trees where the river is today. The adjacent wetland complexes around Bale Slough and the Zinfandel wetland area extended widely across the valley (Attributes 2, 5-10).

5 Fine and coarse sediment budgets balanced

At the present-day location of Rutherford Road, the valley was constricted by the opposing alluvial fans of Conn Creek and Bear Canyon Creek. Accordingly, the river flowed through a single thread channel. Further downstream, where the valley broadens, the river was subdivided into an array of secondary channels crossing the broad floodplain shared by the river and Conn Creek. (Attributes for the steep-narrow reach: 1, 3-5, 7; Attributes for the adjoining less steep reach: 2, 5-10)

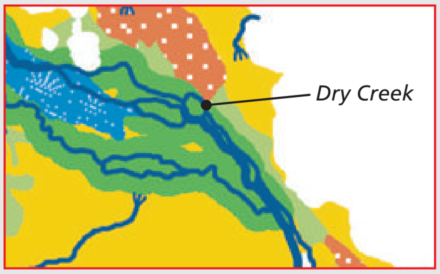
7 Flood plains frequently unindated



The floodplain again constricted at the Yountville Hills before spreading into another array of secondary channels adjacent to present-day Yountville. These widely branching sloughs or channels created effective "islands" as much as 1,000 m (3,280 ft) wide. The Yountville Hills still direct the river southward. The floodplain narrowed between the local bedrock knoll and the alluvial fan of Hopper Creek, upon which Yountville was built. Immediately downstream, the river spread into another floodplain wetland mosaic with tule marshes and willow groves, north of the large Dry Creek fan. (Attributes 2, 5-10).

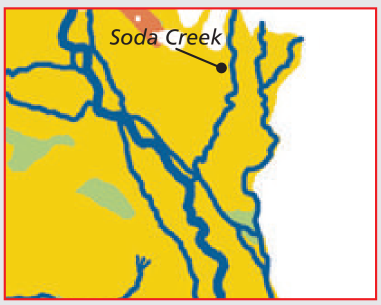
2 Annual hydrograph components affect functions

9 Diverse riparian plant communities



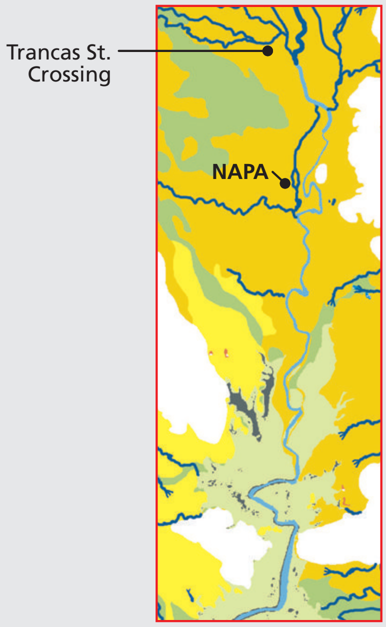
The fans of Dry Creek and Napa Creek keep the river pressed against the east side of the valley. Despite the narrowness of the valley in this area, there is evidence of a broad, closed-canopy riparian forest and secondary channels along the floodplain. This might be attributed to the summer base flow provided by the slow release of water from the valley bottom wetlands immediately upstream. (A similar situation has been documented for the Tulare Lake wetlands on the San Joaquin River, Katibah 1984). (Attributes for the steep-narrow reach: 1, 3-5, 7; Attributes for the adjoining less steep reach: 2, 5-10)

1 Alternate bar sequence



The reach immediately downstream of the Soda Creek confluence had broad, non-vegetated gravel bars with little adjacent riparian forest. Secondary channels parallel the river, but there is no evidence of an especially extensive riparian forest. A secondary channel continued as far south as Napa Creek; in fact, its remnant mouth can still be seen in downtown Napa (Attributes 1-8).

6 Alluvial channels free to migrate



Downstream from the current location of Trancas Street, the river intercepted the tides, and its effective slope flattened; as a result, the channel became more sinuous. "The Oxbow" is an historical place name reflecting the very sinuous tidal reach of the river. The historical transition from fluvial-terrestrial to tidal-estuarine conditions was gradual, producing broad gradients in flooding regimes and salinity. The transition was especially broad in the east, where the valley sloped gradually to the Bay. To the west, where the Napa Creek fan restricted the inland extent of tidal marshland, the transition was more abrupt (Attributes 2, 3, 5-10). A natural levee extended more than 300 m (1000 ft) along the west side of the tidal reach of the river, separating it from the adjacent tidal marshland. Downstream from this natural levee, the river became part of a vast network of tidal channels that extended southeast to Mare Island and west to Sears Point.

Historical Riparian Corridor

For the purposes of this report, the riparian corridor is defined by the distribution of forest trees indicative of exchanges of surface water and groundwater between the river and its adjacent active floodplains and low terraces. This is a restrictive definition of the riparian zone relative to the definition that is recommended by the National Research Council (NRC 2002), and being considered by the State Water Board and RWQCB as their standard riparian definition (http://www.swrcb.ca.gov/water_issues/programs/cwa401/docs/wrapp/tatmemo3_061610.pdf). The NRC definition indicates that all boundaries between aquatic or wetland areas and uplands are riparian, regardless of the nature of the associated vegetation. The species composition and morphometry of the vegetation affects riparian width but not its extent along the aquatic or wetland boundary.

Direct early evidence of the nature of the historical riparian zone is limited. The riparian forest was rarely mapped explicitly although several lines of evidence indicate that the river historically supported a much wider riparian forest, at least on some reaches, than it does today. In the upper valley, early maps and aerial imagery document reaches with broad forest segments, 60-120 m (200 to 400 ft) wide (Dewoody 1873, Grossinger 2012).

On lower Napa River, an 1866 survey near Zinfandel documents even wider, willow-dominated riparian forests associated with side channels of the river. The survey recorded "willow thickets" more than a 100m (several hundred feet) wide, i.e., 220 m (726 ft) wide at an oblique angle on the northeast side of the river. On the other side of the river, the survey indicates a nearly continuous forest extending over 530 m (one third of a mile) away from the river bank (Dewoody 1866).

These are the best-documented broad riparian forests along the river, but it is likely that there were other comparable areas in the valley, as lands covered in riparian willows were particularly valuable for agriculture and often subject to early clearing (Belden 1887; Beller 2008). For example, the Coomb property near Trubody

Lane encompassed side channels along the river and was called "The Willows." A portion of Salvador Vallejo's lands on the east side of the river was known as Sausal (willow grove) Rancho (Smith and Elliott 1878:3; Gregory 1912; Weber 1998:123-24; Winfrey 1953; Stone 2003). George Yount's granddaughter also described a "willow copse" that was likely located along the sloughs near Yount's Mill (Mary Bucknall 1917). An 1871 article suggested that willow lands covered broad areas along the river: "I cannot help thinking how much better it would be for all parties if land-holders would sell these waste lands ... to such of those as would make a thorough business of clearing out the useless willows and covering the broad and fertile acres with blackberries, gooseberries, currents, or other fruits..." (Pacific Rural Press 1871). It is likely that expansive willow forests or thickets like those evidenced by historical data were commonly associated with the complexes of sloughs and side channels along the Napa River.

Historical Hydrological Function

A graph of water flow (discharge or volume) past a point along a river over time is called a hydrograph. A storm hydrograph shows how flow responds to a rainfall event over hours or days. An annual hydrograph shows how flow varies throughout a year, usually in monthly or seasonal increments. An average annual hydrograph shows how flow tends to vary throughout a year for a period of multiple years.

Hydrographs are influenced by many factors, including inputs of water (runoff or groundwater return flow), Anything that influences inputs of water or sediment, such as rainfall, topography, vegetation, groundwater height, and land use, also influences the river's hydrograph. Changes in an average annual hydrograph indicate changes in flow regimes to which the form of channel that carries the flow will tend to adjust. Hydrographs are, therefore, fundamental to the assessment of the effects of watershed management and climate change on flow, flooding, channel form, and the healthy river attributes.

The shape of a hydrograph depends on the shapes of its primary components, which reflect conditions in the channel and its watershed. The four primary components are (1) base flow, which is the relatively constant flow that is sustained between inputs of water; (2) the rising limb, during which flow increases in response to water inputs; (3) the crest or peak, when flow is maximized; and (4) the falling limb that represents a decrease in flow between inputs of water. The area under the graph represents the volume of flow. For any given climate, larger rivers with greater drainage areas have larger hydrographs. Rapid runoff causes a steep rising limb. Channels that are not complex in form and therefore drain very efficiently tend to have steep falling limbs. For complex channels that receive water slowly, the rising and falling limbs are not steep, and the crests tend to be broad. For perennial reaches of channels (where there is flow year-round), the falling limb of the annual hydrograph ends with a resumption of base flow. For ephemeral or intermittent reaches that lack base flow, the falling limb of an annual hydrograph ends when all surface flow in the channel ceases.

The historical record does not contain explicit information about components of the historical hydrograph., The degree of complexity of the historical river ecosystem indicates, however, that the associated hydrograph had all the diverse components necessary to support a full complement of ecological processes and functions expected for a system of this size and location.

This supposition was explored by reconstructing the historical average annual hydrograph for the Napa River based on a model of the hydrology of the historical watershed. HSPF (Hydrological Simulation Program in FORTRAN) was chosen for this exercise because it is a comprehensive and robust model sensitive to overall watershed conditions. HSPF is public-domain software jointly supported and maintained by the USEPA and the USGS, and is widely used across the United States for watershed modeling. HSPF has been successively used to model flow regimes for Bay Area watersheds (Bay Area Hydrological Model; http://www.bayareahydrologymodel.org/), and to estimate amounts of copper in urban runoff (Donigian and Bicknell 2007).

Hydrological Model Setup

The model was set up to generate a spatially averaged, time-variant annual hydrograph for the non-tidal portion of the Napa River in Napa Valley (APPENDIX 2). The model requires watershed geometry (size, overall slope), land use, and soil characteristics as basic setup parameters. Watershed geometry was determined from the SFEI detailed watershed map. Soils data were provided by the National Resource Conservation Service (NRCS). Land use data were obtained from the USEPA Spatial Data Library. The model requires a time series of rainfall and evaporation as inputs. Rainfall data were acquired for the National Climatic Data Center (NCDC) weather stations at St. Helena (NCDC #7643) and Napa State Hospital (NCDC #6074), for the period of 1987 to 2006. Coincident evaporation records were obtained from the California Irrigated Management Information System (CIMIS). The model also requires representation of all water sources and sinks. For an undeveloped watershed, specifically those with unmodified drainage systems such as the Napa River Watershed before Euro-American contact, precipitation (source) and evaporation (sink) data drive the model results.

To model the historical hydrograph of the Napa River, the acreages of selected land use types were adjusted to represent historical conditions (TABLE 1). Under more natural conditions, the soils would have been less compacted, especially in areas that were subsequently subject to development, farming, grazing, timber harvest, etc. Soil moisture storage capacity, infiltration rates, and soil hydraulic conductivity would therefore have been greater. Since the soils would have held more moisture, the groundwater recession rates would have been greater. Taller and denser vegetation would have been more extensive, which would have caused greater rates of rainfall interception and evapotranspiration. The coefficient of friction for surface runoff (Manning's) would have been greater for the more undisturbed, rough surfaces of hillsides, valleys, and floodplains. Over the course of a year, less rainfall would be needed to recharge the aquifers because their levels were perennially higher. Historical precipitation and evaporation patterns were assumed to be similar to current conditions.

TABLE 1. Estimated historic land use/land cover for the Napa non-tidal portions of the watershed. Data reflect historical ecology habitat analysis of valley floor and known extent of forested land cover throughout the remainder of the watershed.

Land Use/Cover	Est. Historical Acreage	Est. Historical %
Urban/Built-up	0	0
Agriculture	0	0
Grass/Rangeland	24,000	17%
Forest	109,600	79%
Wetland/Water	5,500	4%

Hydrological Model Calibration

The model was calibrated by comparing the **simulated** average daily flow to the **actual** average daily flow for the USGS stream gauge for Napa River near Napa (USGS gauge #11458000) for the period 1987 to 2006. This is the same time period covered by the rainfall data. Calibration was achieved by adjusting storage volumes, rates of water runoff and transfer between the ground surface, sub-surface, and atmosphere until the model *reasonably* simulated the actual average daily flow patterns. Defining what constituted a *reasonable* simulation required knowledge of anticipated uses of the simulation. For this project, simulated flow was used to compare the historical and modern hydrographs in terms of the general shapes of their components. The required level of certainty needed for these simulations determined their *reasonableness*.

Reconstructing an historical hydrograph has intrinsic uncertainties, many of which are greater than the uncertainties of any given hydrological model. For example, it is difficult to know for certain what the historical landscape and weather patterns were like: Where were the main channel and its tributaries? What was the channel geometry? Where were the most erodible soils? What was the vegetation cover and what was the infiltration capacity of the soils? What were the prevailing precipitation patterns? Given these unknowns, the simplest approach to reconstruct a hydrograph was to calibrate a hydrological model to current conditions and then change the model parameters to reflect some of the conceptualized landscape differences mentioned above, based on the detailed analysis of historical conditions conducted. The reconstructed hydrograph is specific to these conceptualized conditions and should not be extended to other conceptualizations. The hydrological model should be updated as the conceptual understanding of pre-settlement conditions evolves.

It is difficult to assess the accuracy of the resulting reconstructed hydrograph, and it is certainly unreasonable to expect that it captures the day-to-day variability of the historical system. It is, however, reasonable to expect that the model generates the overall shape of the historical average annual hydrograph, and the general shapes of its components. Thus, for the purpose of historical hydrograph reconstruction, a reasonable calibration of the hydrological model is one that captures the observed hydrograph variability on the scale of weeks to months. Note that the model tends to overestimate peak flows. As explained below, this means that the model conservatively estimates how much the average annual hydrograph has changed (see System Response and Current Configuration section, Modern Hydrograph discussion).

Model Results

To generate the historical average annual hydrograph, the rainfall and evaporation data used to simulate the actual average annual hydrograph were applied to the historical watershed conditions as described above. In essence, the model simulates the average annual hydrograph that would have occurred for the period 1987 to 2006 if the historical watershed existed during that period.

The model output is striking but not surprising (FIGURE 10). The very gradual slopes of the rising and falling limbs suggest that the historical watershed tended to absorb and retain rainfall, releasing it slowly to the river. The broad crest of the hydrograph suggests that the channel was very complex, with abundant active floodplains, complex riparian plant communities, and in-channel debris jams that spread and slowed the storm flows. The model results also suggest that the historical watershed sustained perennial base flow, at least in the lower reaches of the river. It seems likely that wintertime recharge of the valley's aquifers through the alluvial fans and wetlands on the valley floor maintained high water tables that discharged gradually to the river throughout the summertime. These interpretations are consistent with our detailed reconstruction of the historical landscape.

Groundwater

Groundwater data are not abundantly available for the Napa River Watershed. The major groundwater basins have been identified as mapped in FIGURE 11. General conditions for the 20th century have been summarized based on data available from the California Department of Water Resources (California Dept. of Water Resources 1995). These data suggest that historical groundwater levels approached the ground surface for most of the valley during the wet season, and dropped less than 2m below the surface during the dry season (FIGURE 17).

Under historical conditions, the relatively narrow valley was bounded by substantial tributary watershed with moderate amounts of precipitation. These watersheds had a high capacity for groundwater recharge. In many cases, the tributaries terminated on permeable alluvial fans that served as recharge areas and do so to this day in areas where they have not been converted to impervious surfaces. In addition, the river had access to broad floodplains that also served to recharge the shallow aquifers of the valley floor adjacent to the river. As a result, groundwater probably remained high enough to sustain cool base flows through much of the valley. Historical textual evidence supports this interpretation. (Grossinger 2012)

"Napa River itself is not an important direct contributor to groundwater and acts rather as a drain of the alluvial fill" (Bryan 1932). This and other previous groundwater studies for Napa Valley have consistently concluded that more water flowed from the ground into the river than from the river into the ground (e.g., Bryan 1932, Faye 1973). The construction of dams and the draining of the high groundwater likely reduced groundwater recharge in the lower reaches by the mid-20th century. This would explain why Kunkel and Upson (1960) referred to only the most downstream reaches of the river as perennial, stating that the river was "intermittent throughout most of its course." However, Faye (1973) considered the river to be "perennial except during years of less than normal rainfall." But he noted that much of the Napa River base flow was water discharged from municipal sewage treatment plants at Calistoga and St. Helena, as well as controlled releases of water from the Conn Creek Reservoir. It is possible that, as in many other watersheds, the introduction of new discharges to the river in recent decades have actually increased base flow in some reaches.

FIGURE 10. Average annual hydrographs for the historical watershed (dashed line) and existing watershed (blue line) for Napa River near Napa. Each daily flow value for either hydrograph represent the average flow calculated for that day of the year using daily rainfall data for the period 1987 to 2006.

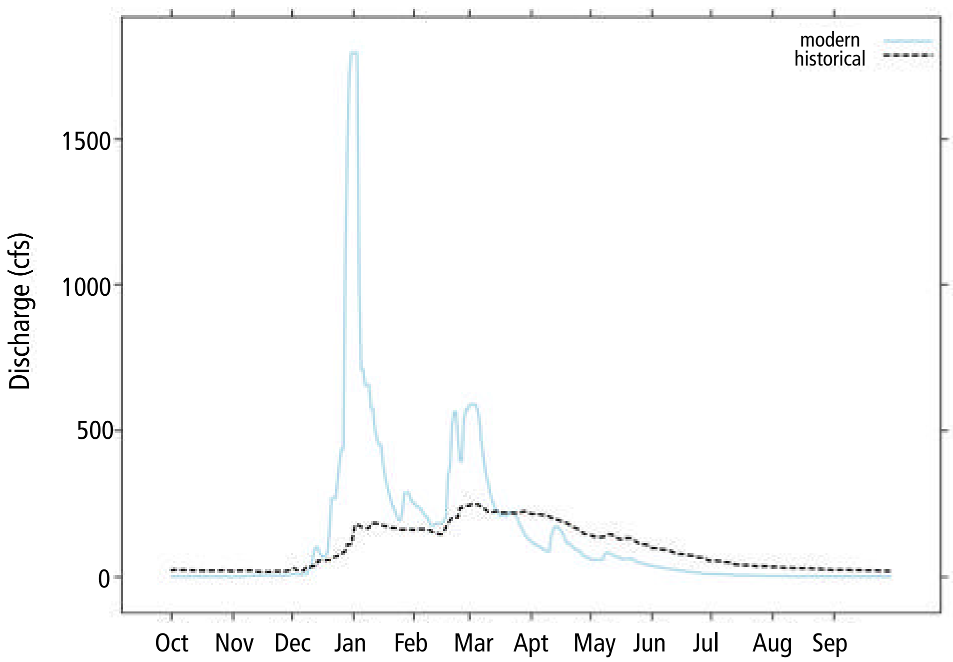
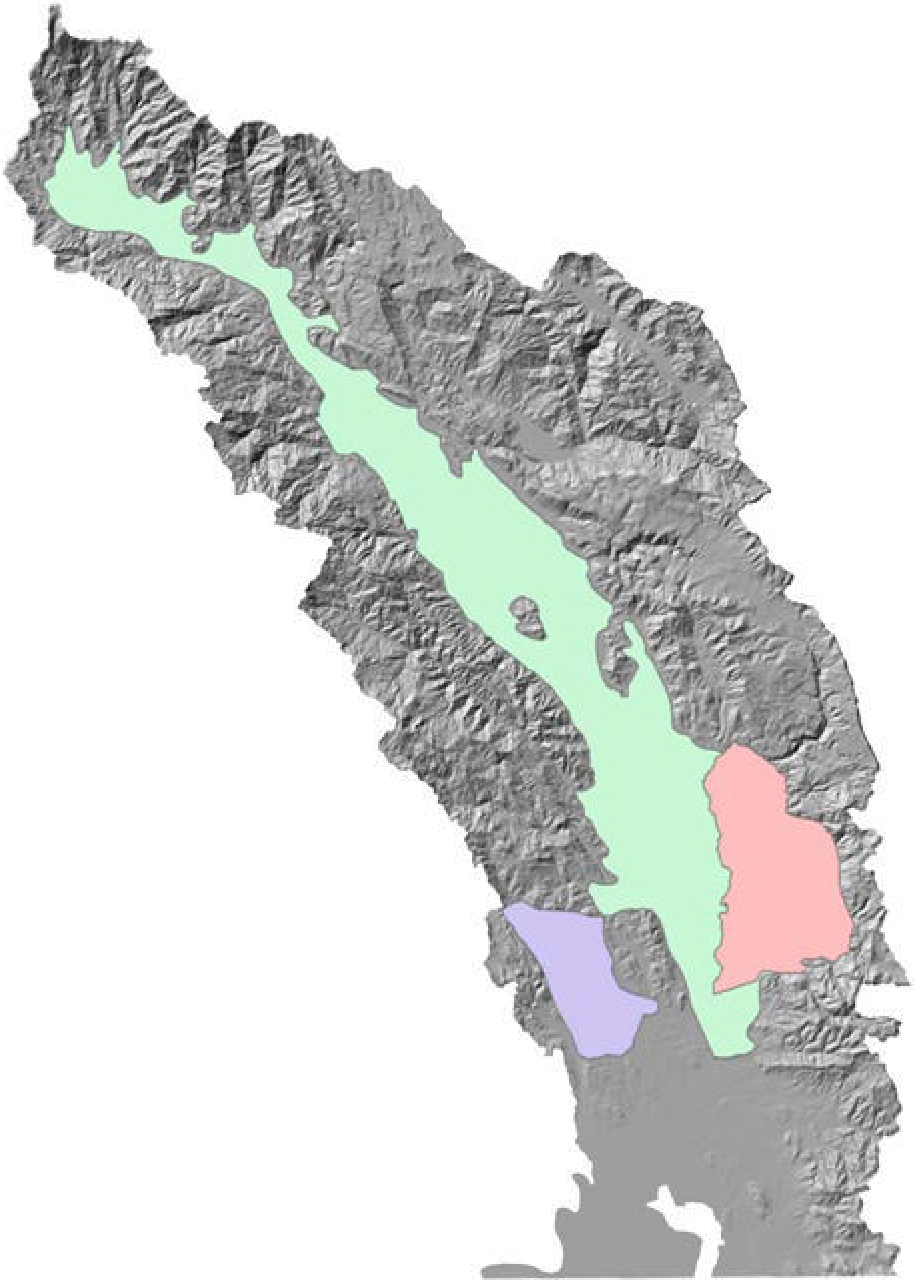
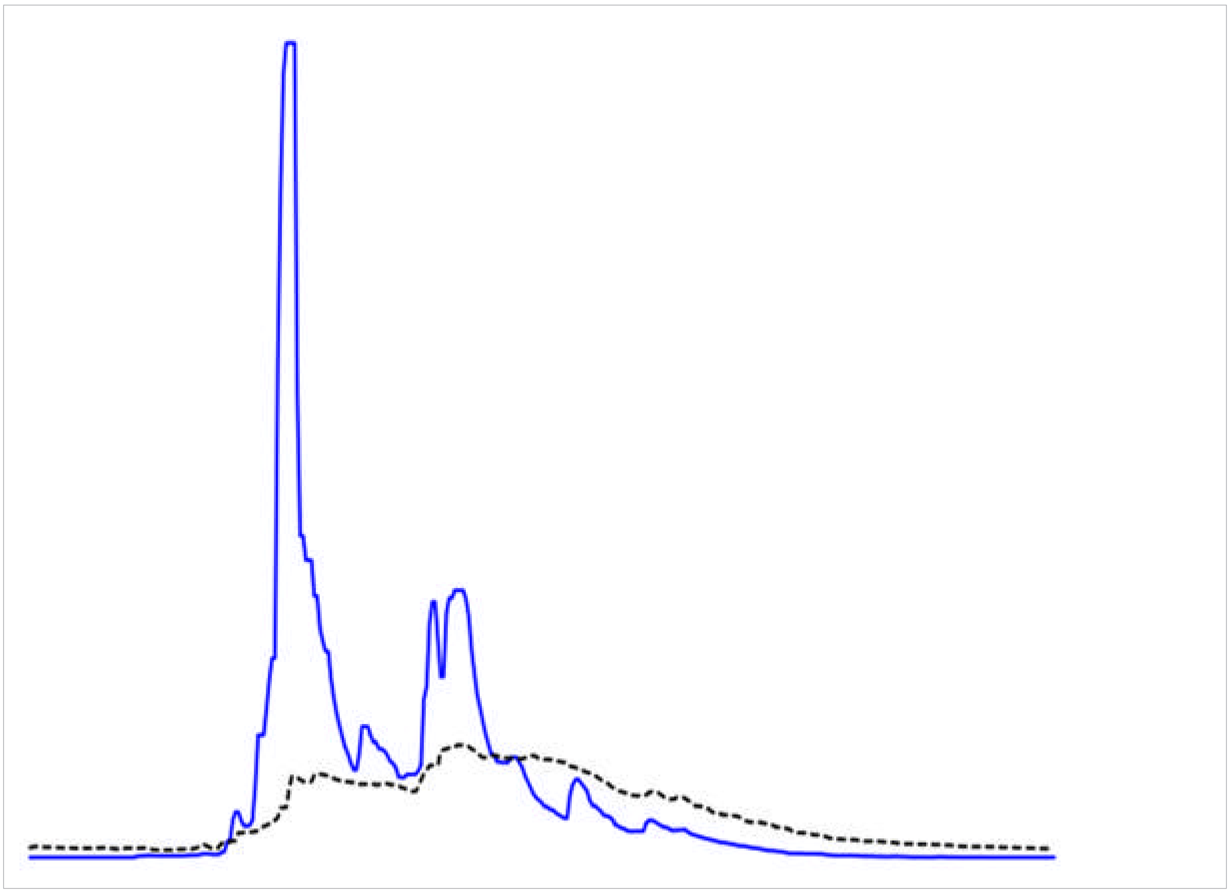


FIGURE 11. Groundwater basins of Napa watershed as depicted in the Napa County Baseline Data Report: Groundwater Hydrology (2005); based on CDWR (2004), Farrar and Metzger (2003), and NFCWCD (1991).



SYSTEM RESPONSE AND CONDITIONS



Historical and modern annual hydrographs.

The historical changes in land use have significantly altered surface water storage, hydrological connectivity, imperviousness, seasonal groundwater levels, sediment inputs, water inputs, patterns of river flow, and the overall physical form of the river in the valley in ways that significantly reduce the overall health of the river ecosystem.

Surface Water Storage

At the time of Euro-American contact, almost all the surface storage occurred in natural channels and wetlands. A subsequent section on Channel Form provides evidence that the channel network is absolutely longer now than it was historically. This represents a negligible increase in surface water storage, however, because the added channel length consists of small ditches and other ephemeral channels. Furthermore, there has been a decrease in base flow in the larger channels, including the river in the valley, thus decreasing the amount of water stored in these channels. The total acreage of non-reservoir wetlands that stores surface water has been reduced by 94% while fully 97% of the current wetlands in the watershed are attributable to artificial lakes and ponds[1] (TABLE 2) (BAARI 2011).

Most surface water storage is currently provided by five publicly owned reservoirs built before 1950 to meet the growing water demands of agriculture, industry, and municipalities. Since about 1975, many private reservoirs have been constructed above grade on the valley floor to support irrigation and frost control. Their sources of water are not always public knowledge, but the available sources are rainwater, deep groundwater, shallow groundwater (including sub-surface agricultural drains), or the river and its tributaries. Many hundreds of small private reservoirs have been built on small tributaries throughout the watershed. Some of these were built to support ranching, but most were built to support viticulture. All of the reservoirs on tributaries are designed to fill and spill while most of the reservoirs on the valley floor are designed to hold water without spilling.

Analysis of the current distribution of reservoir surface area within the Napa River Watershed reveals that nearly 1,000 ha (2,500 ac) of surface water is distributed among a total of 1,278 reservoirs (APPENDIX 3). Altogether, reservoirs intercept runoff from about 30% of the watershed. The capacity of these reservoirs is unknown, but has certainly been reduced by the entrapment of sediment eroded from their catchments. A reservoir's capacity is considered proportional to its surface area reservoir size. The size distribution and cumulative area of the reservoirs are shown in FIGURE 12 and FIGURE 13. Lake Hennesey is the largest reservoir in the watershed, accounting for 300 ha (741 ac) of surface area. If the five public reservoirs are discounted, the other reservoirs represent about 630 ha (1,570 ac) of surface area. Discounting the ten largest reservoirs leaves a total of 528 ha (1,438 ac) of surface area. The majority of reservoirs falls below 2.5 ha (6.4 ac) in surface area (FIGURE 13).

TABLE 2. Change in wetland surface storage on the Napa Valley floor. Historical changes in acreage of some common classes of wetlands. This comparison between historical and current wetland areas is restricted to Napa Valley upstream of tidal influences, and only involves the classes of wetlands that could be comparably mapped for both periods

Wetland Feature Type	Number of distinct areas		Total area (acres)		Natural areas (acres)		Unnatural areas (acres)	
	past	present	past	present	past	present	past	present
Slope Wetlands	427	10	11,868.9	15.0	11,868.9	11.3	N/A	3.8
Vernal Pools	12	14	836.9	0.7	836.9	0.7	N/A	-
Freshwater Marsh	23	167	830.6	110.4	830.6	12.2	N/A	98.2
Ponds and Lakes	9	542	12.7	694.0	12.7	0.1	N/A	693.9
Totals	471	733	13,549.1	820.2	13,549.1	24.3		795.9

1 One class of wetland, termed "slope wetlands", only forms where groundwater rises into the root zone but seldom or never emerges onto the land surface.

FIGURE 12. Cumulative reservoir storage acreage.

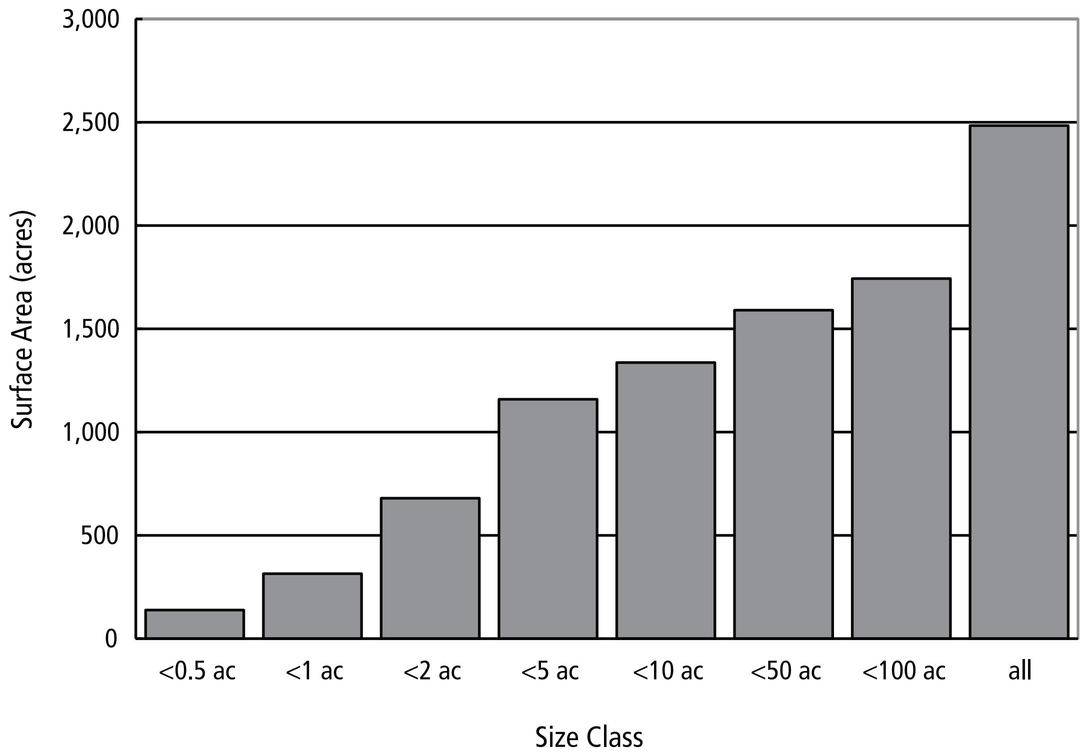
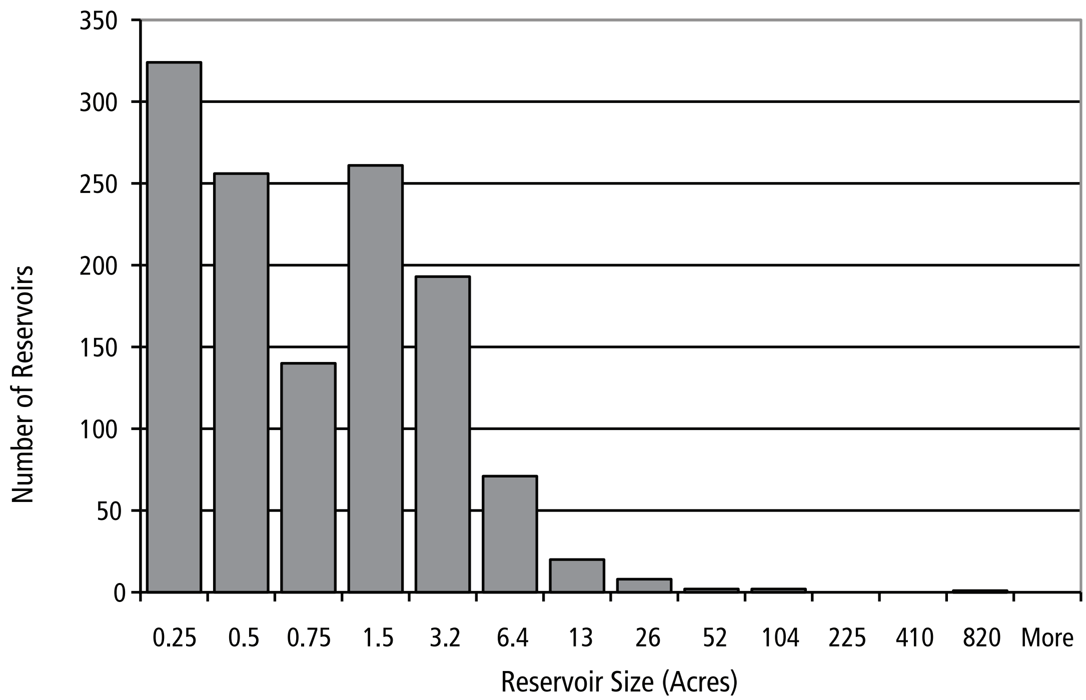


FIGURE 13. Reservoir size distribution. The vast number of reservoirs is less than 6.4 acres in size.



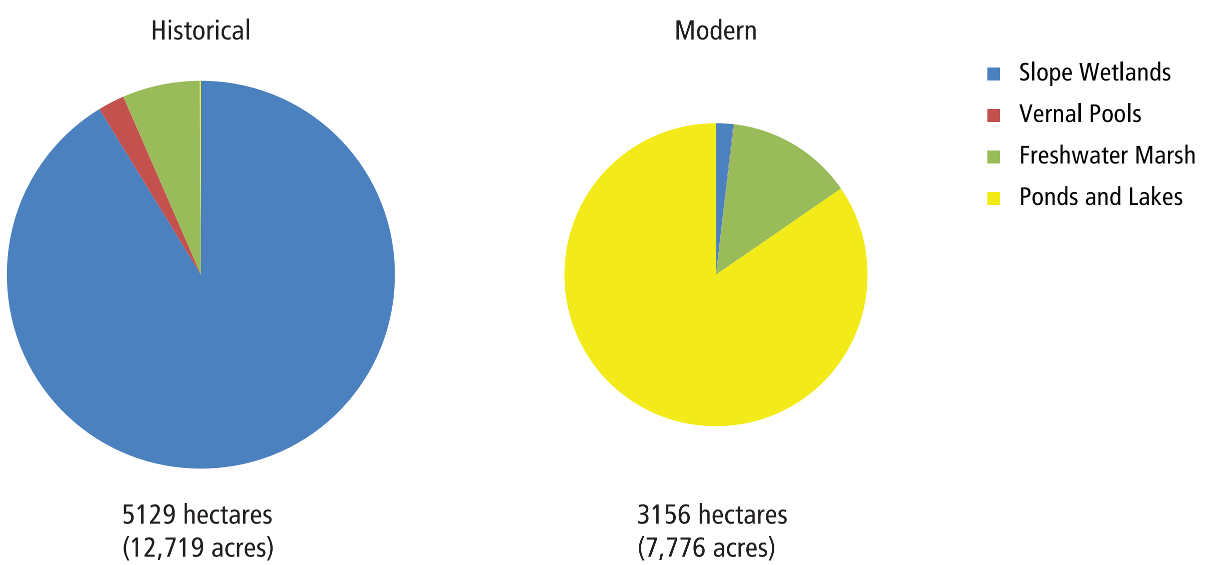
The reservoirs do not function the same as the historical, natural places of surface water storage. The dramatic change in wetland storage is illustrated in FIGURE 14. Reservoirs can have dramatic environmental upstream and downstream effects (Wetzel 2001). Effects of most concern are those downstream, since the focus on the river in the valley is downstream of most reservoirs. The magnitude of these effects is usually directly related to the size of the dam. The flow below reservoirs tends to have a reduced hydrograph with steeper rising and falling limbs and lower crests. This can have significant effects on downstream channel form and ecology, as discussed below in the sections on Channel Form and Riparian Area. In cases where the entire flow has been diverted, there may seldom be any flow immediately downstream. In the Napa River watershed, the fill-and-spill reservoirs lack facilities for deepwater (hypolimnetic) releases that could be used to reduce downstream water temperatures. Surface waters exiting the reservoirs during their spill could have elevated amounts of nutrients and dissolved salts, and lower amounts of dissolved oxygen depending on factors including reservoir size, water chemistry, and vertical mixing. Water losses due to evaporation can be greatly increased by reservoirs, especially for large reservoirs that lack vegetative or other cover in arid and semi-arid environments. Perhaps the greatest downstream effects of the reservoirs in the Napa River watershed relate to the entrapment of sediment.

According to the Napa River Sediment TMDL and Habitat Enhancement Plan (Napolitano et al., 2009), sediment entrapment by the major reservoirs represents about 40% of the total sediment inputs to the drainage network for Napa River watershed. At the current rate of sediment input to the reservoirs, they are not likely to fill enough with sediment to release significantly more sediment downstream for at least a few hundred years. The capacities of some reservoirs to hold water, however, such as Rector and Hennessey, might be reduced by 10% within the next 50 years

Hydrological Connectivity

For the purposes of this report, hydrological connectivity refers to the continuity of a drainage network. A drainage network consists of the channels, lakes, reservoirs, and wetlands that together comprise the pathways and places for transporting and storing surface waters and the sediments and other materials that the waters transport downstream within a watershed. The focus of this report centers upon the channels, referred to as the channel network.

FIGURE 14. Change in wetland type and extent.



There has been an overall increase in the total length of the drainage network in the valley, and an increase in its connectivity to the river (FIGURE 16). Drainage ditches are now commonplace and have resulted in a much higher degree of hydrological connectivity between the hillsides, fans, valley floor, and the river. Of the 453 km (280 mi) of channels currently draining the valley (not including sub-surface drains and many of the smaller roadside ditches), almost half (47%) are artificial. Only about 50% (241 km or 150 mi) of the existing channels follow their historical alignment. About 34% (125 km or 78 mi) of the historical natural channels has been filled or buried. Most (78%) of the current drainage network was created to drain seasonally flooded areas, rather than straighten or re-route existing channels. About 45% of the current network drains areas that formerly had no surface drainage, 33% extends formerly discontinuous natural channels directly into the river, and 22% of the network results from straightening or re-routing historical channels. Ditches now comprise at least 10% of the channel network in the valley. This is a conservative estimate, given that it is based on interpretations of aerial imagery that do not clearly reveal all ditches. In fact, the estimate ignores roof drains, small roadside ditches, storm drains, and sub-surface agricultural drains that are common elements of channel networks in the valley's current urban, sub-urban, and agricultural landscapes.

Imperviousness

In the context of watershed hydrology, imperviousness refers to the tendency of a type of land cover to shed rainfall as runoff. Imperviousness can significantly reduce the threshold intensity or amount of rainfall that alters flow within the river, especially the onset of the rising limb of the storm hydrograph, the height of its crest, and the overall volume of storm-related flow (Huang-ii et al., 2007). Imperviousness integrates two primary factors of runoff: the degree to which the land cover is impenetrable to rain, and the rapidity or ease with which the rain as runoff can reach a channel. These factors can be measured or estimated and combined into

FIGURE 15. Historical change in the total length (km) of tributary channels confluent with the Napa River in Napa Valley. Overall connectivity between the river and its valley and tributaries has been artificially increased, mainly by ditching.

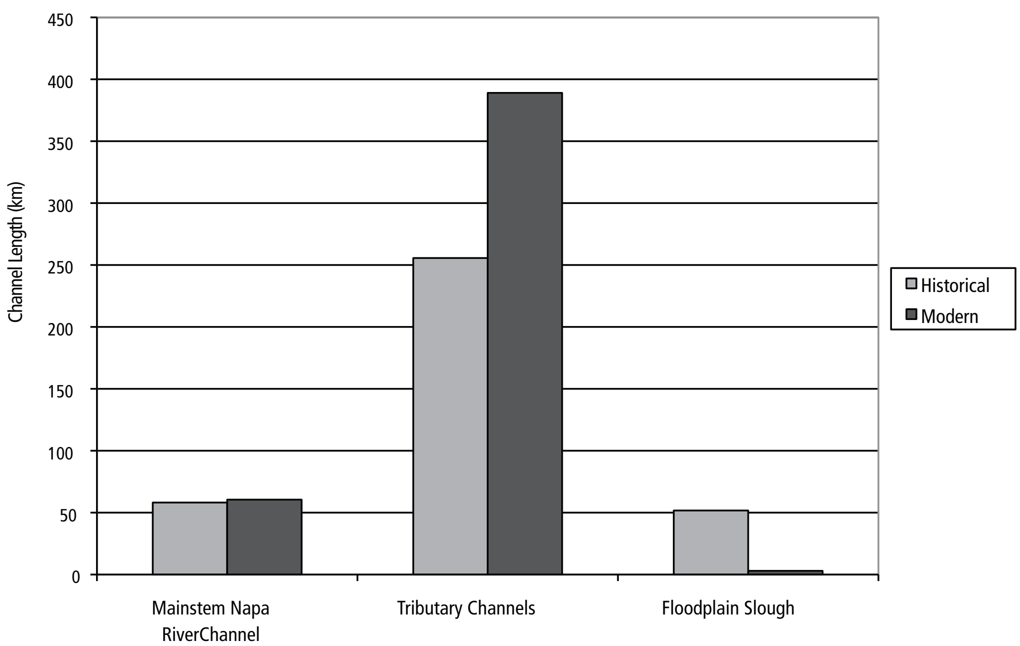
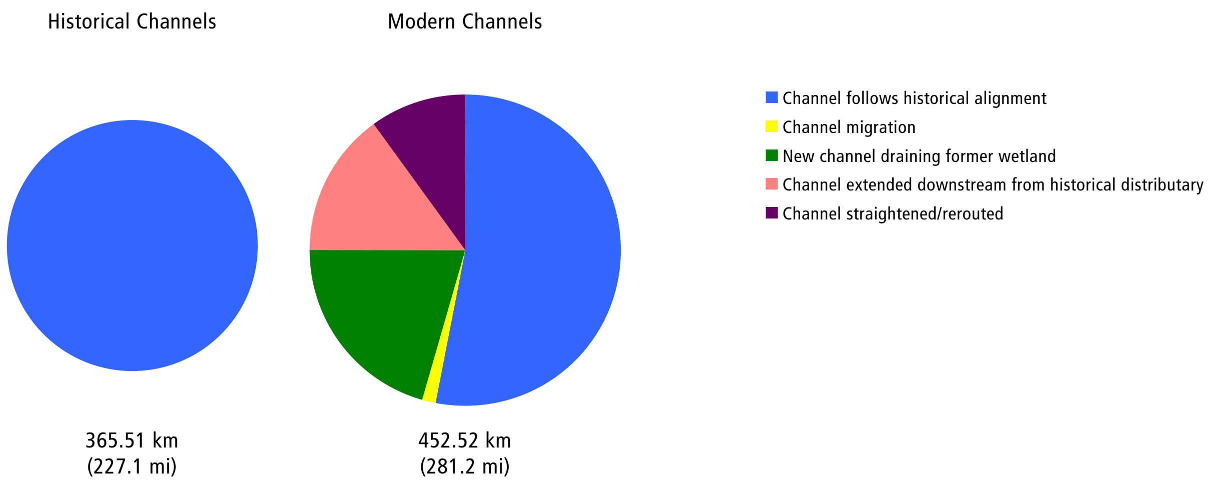


FIGURE 16. Historical changes in the channel network within Napa Valley. Total channel length has increased 24% resulting in more channel-per-unit area of the valley (greater channel density) and greater overall hydrological connectivity and drainage efficiency.



a runoff coefficient for any type of land cover. (See for example, National Land Cover Institute, http://landcover.usgs.gov/index.php) Pavement and roofs in urban areas tend to have very high coefficients because they are impenetrable and drain directly to ditches, storm drains, or natural channels. Unpaved urban areas are less impervious. Runoff coefficients vary for agricultural lands depending on management practices and topography. Management practices designed to improve the penetrability of agricultural lands or their ability to retain water can reduce runoff for a broad range of land steepness. But, in general, runoff tends to increase with topographic slope for any land cover type. It also increases when natural lands with dense vegetation and intact soils are converted to agriculture or urban land uses (Brabec et al., 2002, Allan 2004). Urban landscapes of the Bay Area have runoff coefficients of about 35%, while industrial areas and transportation corridors areas have coefficients of 70%, whereas more natural open space areas and forested lands have coefficients of about 10% (BASMAA 1996).

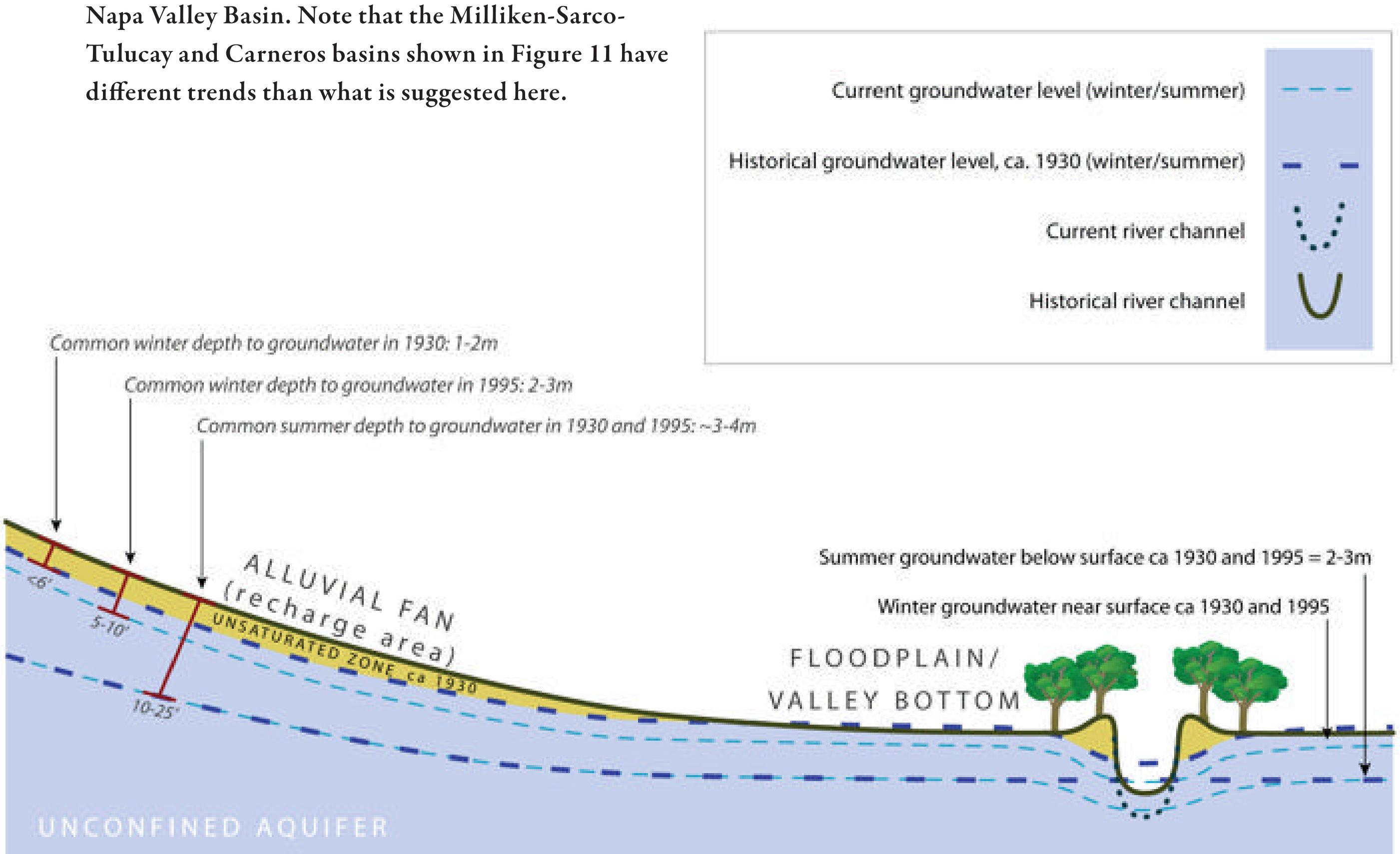
Much of the Napa River watershed consists of land covers that are not regarded as very impervious. The urban areas are not large compared to the watershed as a whole. Any reservoir that is overflowing is considered impervious, but the larger reservoirs do not often overflow, and all the smaller reservoirs together only represent a small fraction of the total areas of the watershed. Paved and compacted dirt roads comprise a larger portion of the watershed, and are a significant source of runoff because they are relatively impenetrable and usually drain directly into ditches or natural channels. Vineyards include a variety of roadways that can effectively increase the total area of roadways per unit area of land (i.e., road density). For example, the vineyards in the Carneros Creek watershed have increased the total area of roadways by about 130% (PWA 2003) compared to the days when the Carneros was primarily used for grazing cattle.

Groundwater

Except for the distinct Milliken-Tulocay-Sarco aquifer and the Carneros area, the Napa Valley aquifers are generally unconfined and have not experienced significant long-term declines (California Dept. of Water Resources 1995, NCFWCD 2005). In the 1930s, when almost all crops were dry-farmed, winter groundwater came within a few feet of the surface throughout most of the valley, limiting the rooting depth of crop plants (Carpenter and Cosby 1938). Substantial increases in groundwater withdrawals, plus the ditching of alluvial fans and other recharge areas roughly doubled winter depths to groundwater. This has increased the acreage of arable croplands (Carpenter and Cosby 1938, California Dept. of Water Resources 1995). Such extraction, however, may have reduced base flows in some reaches of the river (Jackson 2010).

Sometime during the 1970s, or perhaps earlier, vineyards began to be planted over sub-surface drains designed to keep the root zone from becoming saturated during early spring. The systems are variously referred to as sub-surface drains, agricultural drains, agricultural tiles, tile drains, and infiltration galleries. They consist of a network of perforated pipes that capture groundwater within the root zone and shunt it to the channel network or to above-ground reservoirs for later use in irrigation or frost control. Pumps are used to lift the water from the drains into the reservoirs. Where these drains exist, they typically keep the groundwater level 1 – 2 m (3 - 7 ft) below the ground surface. In most areas of the valley, the volume of drain water exceeds the dedicated above-ground storage capacity. During the wet season and in some years, the early part of the dry season, these sub-surface drains may contribute significant amounts of water to surface ditches, natural tributaries, and the Napa River. More sub-surface drains are being added as vineyards on the valley floor are replaced, and new vineyards are added to hillsides. They are now important components of the drainage network for the watershed. Their possible influence on the hydrology of the Napa River is further discussed below (see section on River Flow).

FIGURE 17. Conceptual model of changes in Napa Valley near-surface groundwater heights for the North Napa Valley Basin. Note that the Milliken-Sarco-Tulucay and Carneros basins shown in Figure 11 have different trends than what is suggested here.



Coarse sediment

For the purposes of this report, coarse sediment is considered to include particles that are larger than sand-sized (2 mm). This includes gravels, cobbles, and boulders. The coarse sediment that enters the river comprises its bedload, meaning that it is moved by the flow along the bed of the river and is not usually suspended in the flow.

The large alluvial fans naturally built by some tributaries indicate that they can yield large amounts of sediment. As a channel enters its fan, the flow spreads and slows, causing the sediments to be deposited on the fan surface. Since the coarser sediments are heavier, they are deposited nearer the fan apex. Sediment size, therefore, tends to decrease with distance downhill from the apex of a fan to its base. During the Holocene period, the general decrease in rainfall and runoff would have caused a decrease in sediment yield. This would have caused some of the larger tributaries to stop building their fans and incise them instead. The channels would have tended to become fixed in their positions, rather than migrating or avulsing across their fans. Historical maps of some natural tributary channels that extended through their fans and across the valley floor provide evidence of this tendency. Having incised their fans, the larger channels would have had the power during times of high flow to move coarse sediment through their fans and into the river. Historical gravel mining on some of these tributaries is evidence of their substantial coarse sediment loads. Sulphur Creek, for example, was mined for gravel until 2002. Because of the large sediment supply provided by this watershed, and because gravel mining only removed the top few feet of bed material, the channel has since aggraded to its historical elevation, indicating that Sulphur Creek Watershed will be a continuing source of coarse sediment.

On-stream reservoirs throughout the watershed act as filters, retaining coarse sediment relative to fine sediment (APPENDIX 4). The trapping efficiency of a reservoir is defined as the difference between the annual amount of sediment coming into the reservoir from its catchment and the annual amount going out through diversion, managed releases, or spills. It largely depends on the amount of time water is resident in the reservoir. For reservoirs in the Napa River watershed, residence time mainly depends on reservoir capacity and inflow volumes. Empirical measurements of trapping efficiencies reported in the literature suggest that for large reservoirs (typically with a capacity greater than 106 m^3 (3536 ft^3) (106 m^3), trapping efficiency is typically greater than 70% (Kummu 2007, Maneux et al., 2001, Vorosmarty et al., 2003). Smaller reservoirs have a much more variable trapping efficiency, however, ranging from 10 % up to 100%, primarily dependent on their capacity (Dendy and Cooper 1984).

Most of the published literature does not differentiate between the trapping efficiency for coarse and fine sediment. It is widely accepted, however, that trapping efficiency is greater for coarser sediments since they tend to be deposited at the head of the reservoir. Some portion of the fine sediment tends to remain suspended in the reservoir, and can be transported downstream. The Napa River Sediment TMDL and Habitat Enhancement Plan contains some estimates of sediment entrapment efficiency for large reservoirs in the Napa River watershed, and reductions in sediment loads below dams (Napolitano et al., 2009). The trapping efficiency for coarse sediment is assumed to be 100%. The estimates of fine sediment trapping efficiency for large reservoirs range from 90% to about 67%. Kimball Dam, for instance, has a fine sediment trapping efficiency of 90% due to its large capacity and long residence time, while the fine sediment trapping capacity of Upper York Creek Dam is about 67% due to its historical sedimentation, greatly reduced capacity, and short residence time. Estimates show that 75% of the coarse load and 50% of the fine load is trapped behind reservoirs in the Milliken Creek watershed. Approximately 20% of the total sediment load is trapped in the Carneros Creek watershed. Approximately 45% of the coarse load and 33% of the fine load is trapped upstream of the confluence of the Napa River and Conn Creek. Based upon the literature for other reservoirs, plus the estimates cited above, nearly 100% of the coarse load and perhaps 10-60% of the fine load is expected to be trapped in the numerous small stock ponds and irrigation ponds distributed throughout the watershed that are directly connected to the drainage network. The net effect of all the entrapment is an increase in the proportion of fine sediment entering the river in the valley.

Some have suggested that a few of the older and smaller reservoirs have filled with sediment and no longer have any trapping capacity (pers comm, Napa Farm Bureau, April 1 2009). Many of the older, smaller reservoirs probably represent locally significant pools of sediment that could be released if their dams fail or are removed. Additionally, many reservoirs have caused increased downstream incision (further increasing the proportion of fines delivered to the network) due to the release of "hungry water".

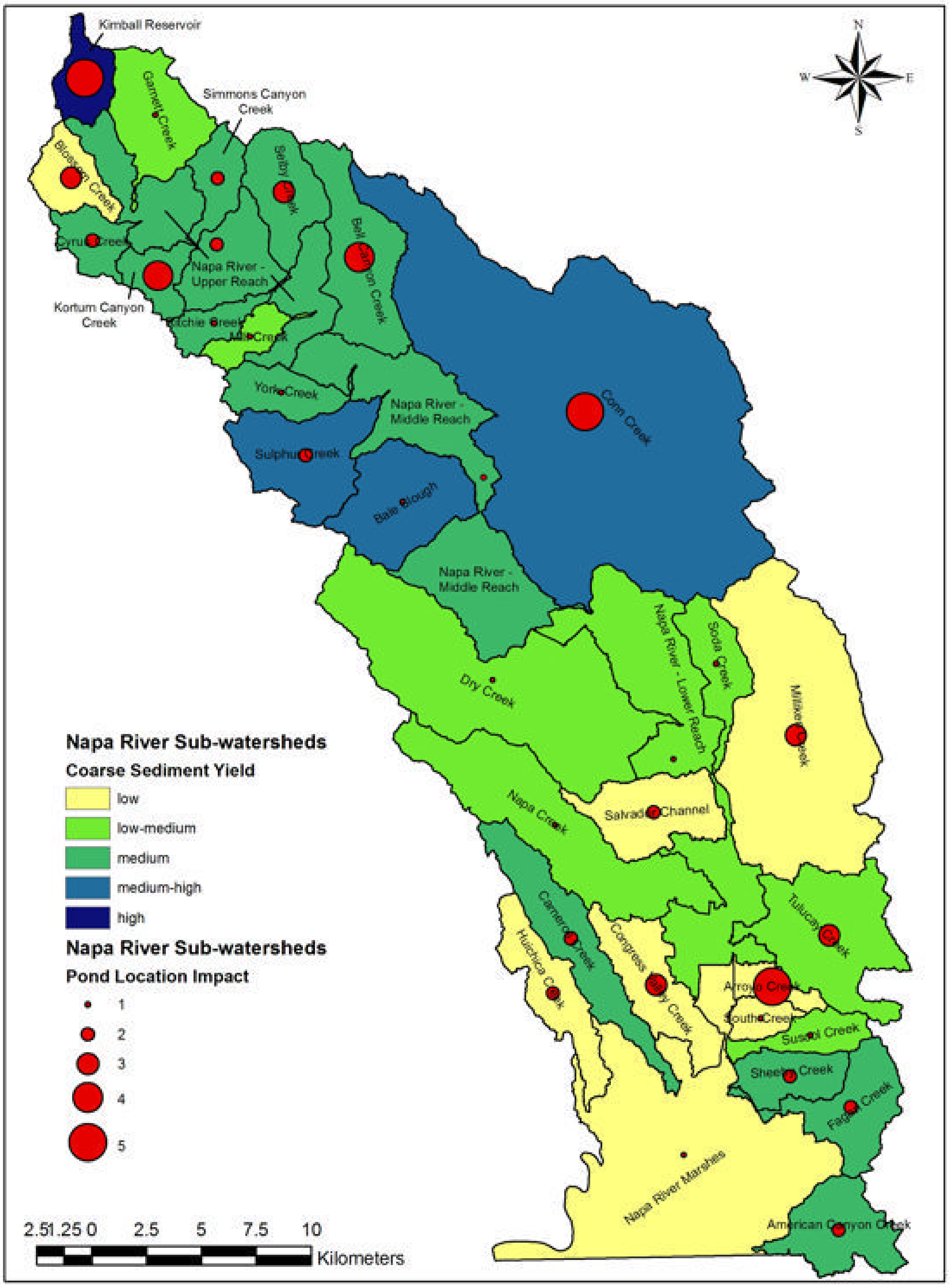
In this report, attempts are made to identify which on-stream reservoirs in the Napa River watershed trap the greatest amounts of coarse sediment (FIGURE 18, based on a conceptual model of the various factors controlling trapping efficiency (APPENDIX 4). According to the model, the primary factors are upstream geology (the tendency of the bedrock to generate coarse sediment), topography and upstream channel density (the likelihood that coarse sediment will enter the channel network and be transported downstream), reservoir size (the capacity of the reservoir to store sediment), and upstream drainage area or catchment (the total area contributing sediment to the reservoir). For any given reservoir, the model allowed answers to key questions, including:

- Is the local bedrock likely to generate coarse sediment?
- Is the channel network likely to deliver sediment to the reservoir?
- Is the reservoir large enough to trap much sediment?
- Is it located far enough downstream to intercept most of the sediment yielded from its catchment?

Based on answers to these questions, the tributaries with the greatest potential per unit area to yield coarse sediment to the river are Kimball Creek, Sulphur Creek, Bale Slough, and Conn Creek. This assessment agrees closely with the estimates of erosion risk prepared by the Napa County RCD (APPENDIX 1).

According to the Napa River Sediment TMDL and Habitat Enhancement Plan (Napolitano et al., 2009), the current rate of coarse sediment input to the middle reach of the valley upstream of Conn Creek approximates the natural input rate. Further upstream, the current rate might exceed the natural rate. Such coarse sediment entrapment by the numerous reservoirs on tributaries that drain to the middle and upper reaches of the valley suggests that channel erosion downstream of these reservoirs is not enough compensation to effect a net reduction in coarse sediment inputs to the river in the valley. Kimball Reservoir could be especially important as a coarse sediment filter because it is located near the head of the valley in a sub-watershed that is known to yield large amounts of coarse sediment. In the absence of this reservoir, the historical supply of coarse sediment to the upper half of the valley was probably much greater than it is today. In fact, most of the reservoirs with at least medium potential to trap coarse sediment drain to the upstream third of the valley.

FIGURE 18. General classification of Napa River sub-watersheds in terms of their coarse sediment loads, and classification of major reservoirs in terms of their impacts (reductions) in coarse sediment inputs to the Napa River in the valley. Ranges extend from low impact (small red circle with value of 1) to high impact (large red circle with value of 5).



Fine Sediment

For this report, fine sediment includes particles that are less than or equal to sand-sized (2 mm) including all of the sediment that is typically transported in suspension (suspended load usually consists of sediment ≤0.25 mm). The overall input of fine sediment to the river in the valley has increased in part because of a reduction in course sediment inputs (see section on Coarse Sediment immediately above), and because there has been an increase in the input of fine sediment. Information about the sources of fine sediment is summarized below.

The Napa River Sediment TMDL and Habitat Enhancement Plan (Napolitano et al., 2009) suggests that land use practices associated with viticulture, grazing, roads, and urbanization are major sources of fine sediment in the Napa River Watershed. Vineyards comprise most of the landcover in the valley and are becoming more extensive on hillsides in numerous tributary watersheds. Vineyards can yield fine sediment due to erosion of exposed soil in rows and vineyard avenues, disturbed soil, and small, artificial drainage channels that tend to erode. Although many BMPs are being implemented to conserve soil, such as settling basins, standpipes in reservoirs, and cover crops, the increased runoff, especially from rainfall, is not as well conserved. Fine sediment from disturbed soils and eroding ditches moves more efficiently through the ditches and other artificial channels to the river.

Re-planting practices may in some cases greatly increase the amount of disturbed soil and the risk of it becoming a source of fine sediment. Vines are replaced for three main reasons: they can become too old to produce adequate amounts of grapes; they can become too diseased to be successfully treated; or they can be exchanged for different grape varietals. Planting is usually done in the spring but can continue into summer. Some amount of replanting happens in the Napa River watershed every year. Rapid and large scale replanting occurred throughout the Napa Valley during the late 1800s and again in the 1990s to combat phylloxera infestations. The initial planting of a vineyard is usually regulated to prevent harmful discharges of sediment and other materials into aquatic habitats (Ziblatt 2001). Replanting is generally less regulated, but has the potential to yield significant amounts of fine sediment to the river. The relative importance of replanting as a sediment source is not known.

Fine sediment from grazing is primarily due to hillslope effects, including soil compaction, reduction of vegetation cover, and conversion of the plant community to species that are less able to intercept and take up water. These effects tend to increase surface erosion due to raindrop impacts, and to increase runoff. The increased runoff can cause gullying and headward erosion of small channels, which can weaken side slopes and trigger landslides. Surface erosion from grazing has historically been a problem, but it has been reduced by improved range management plus a conversion of range lands to non-grazed open space or vineyards. However, historical dirt roads, gullies, and cattle trails that have captured surface runoff have become effective components of the drainage network that provide abundant fine sediment and help transport it downstream.

The road network, including both paved roads and unpaved roads (e.g., vineyard roads and alleys, residential roads, ranch roads, and active and inactive timber roads) deserves special consideration. They contribute fine sediment via direct erosion of the roadbed surface and inboard ditches. Surface erosion of the roadbed, caused by wind erosion, or formation of rills and gullies on the surface is widely observed in the Napa River watershed. The runoff from roads is also important. Since roads are either impervious (paved) or highly compacted, they tend to generate large volumes of runoff. This runoff can cause erosion of the inboard ditches that convey the runoff, and erosion of hillsides and channels into which the runoff is directed. The Napa River Sediment TMDL and Habitat Enhancement Plan (Napolitano et al., 2009) includes an estimate that 50% of the total road system in the Napa River Watershed is connected hydrologically to the channel network that drains to the river. Bridges and culverts can also be sources of sediment. If they are undersized or become blocked with sediment or debris, the backflow can cause bank erosion.

Storm drains are artificial drainage systems for urban environments and other areas with abundant impervious land cover. They convey runoff from paved roofs, sidewalks, parking lots, and roads, including highways and freeways. Runoff from these areas tends to have large suspended loads of fine and ultrafine sediments and other pollutants (Guy 1972, Leopold 1968, Barrett et al., 1995, Adachi and Tainosho 2005). Prior to the 1930s, storm drains were usually combined with sewage collection systems. Runoff from major rainstorms can exceed the capacity of such combined systems, causing overflows. Modern storm drains are separate from sewerage. All the municipal and industrial storm drains in Napa Valley are now separate from sewerage and drain to the Napa River (Napa County Stormwater Pollution Prevention Program FAQs http://www.countyofnapa.org/Pages/DepartmentContent.aspx?id=4294969023). The agricultural sub-surface drains used to dewater the root zone of vineyards and to manage hillside runoff also function as storm drains. Their overall extent is unknown, but they might be more extensive then the municipal and industrial storm drains. Many of them incorporate soil conservation BMPs that help filter and entrap their sediment loads before they get to the river. According to the Napa River Sediment TMDL and Habitat Enhancement Plan (Napolitano et al., 2009), the sediment loads from storm drains are much smaller than the loads from other sources in the Napa River watershed.

During recent decades, most of the fine sediment load in the Napa River has probably resulted from erosion of the bed and banks of the river and its major tributaries. Furthermore, channel incision is a local source of fine sediment that directly reduces habitat quality for salmonids and other wildlife by significantly simplifying the overall physical complexity of the river ecosystem.

River erosion is discussed more thoroughly in the following section on Channel Form. Simply stated, historical and ongoing reductions in coarse sediment inputs, plus the overall increase in runoff and peak annual flows (see following section on Flow) have caused the river and most of its tributaries to erode their beds and banks. These adjustments proceed upstream in a process called headward erosion. It can progress all the way upstream through the channel network, unless it intercepts a dam, bedrock, or other obstruction. In the uppermost reaches of the channel network, increased runoff can cause headward erosion that proceeds upslope from the channel head, thus elongating the channel network. Hillside gullies are a manifestation of this kind of headward erosion. As the channel beds degrade and erode headward, the channel banks become unstable and more susceptible to failure. In the upper reaches of the channel network, where the channels drain steep hillsides, degradation and headward erosion can trigger landslides. The river in the valley has undergone multiple periods of chronic incision with net degradation since the time of Euro-American contact (see following Timeline of land use effects). Some reaches are still incising.

The Napa River Sediment TMDL and Habitat Enhancement Plan (Napolitano et al., 2009), reports that the total average rate of sediment input to the channel network below the major dams is about 159,000 tonnes per year. This is estimated to be about twice the historical rate. The modern rate is attributed to roadway-related processes (55,000 tonnes/yr), surface erosion in vineyards and range lands (37,000 tonnes/yr), gullies and landslides (30,000 tonnes per year), and channel incision plus bank erosion (37,000 tonnes/yr). The estimates for channel erosion (channel incision and bank erosion) noted in this report are conservative, based on the review of historical evidence (see following section on Channel Form). The proportions of fine and coarse sediment inputs due to channel erosion depend largely on the nature of the sediment sources. The proportion of fines is likely to be greater where channels pass through areas of friable sedimentary bedrock, the toes of alluvial fans, or the valley floor. The valley is described as consisting of poorly consolidated and non-cohesive gravels, sands, silts, and clays (Knudsen et al., 2000). The areas of historical wetlands along the valley floor are likely to consist of very fine silts and clays. Bank and bed erosion in these areas can deliver large quantities of fine sediment directly to the channel network.

The excess fine sediment in the river is affected by the historical reduction in active floodplain areas, as well as the absolute increase in fine sediment inputs and the decrease in coarse sediment inputs. Prior to its degradation, the river was bounded by broad vegetated floodplains, across which floodwaters would spread and slow, depositing much of their suspended load. The degraded channel in the valley has abandoned most of its historical floodplains, and replacement floodplains have yet to evolve.

River Flow

The historical version of the average annual hydrograph that was simulated for Napa River at Napa City (see section above on Historical Conditions) is remarkably different than the modern version hydrograph (**FIGURE 19**). The historical version is much broader and flatter. This is probably due to the overall retentive nature of the extensive historical watershed relative to current conditions. As explained above, historical changes in land cover have significantly increased runoff, reduced the number of groundwater recharge areas (especially alluvial fans and wetlands), while concurrently causing the river to abandon its historical floodplains and greatly increasing the overall efficiency of the channel network. Despite the increase in surface water storage (large and small reservoirs), there is more runoff and it reaches the river faster, especially after reservoir capacity has been reached and additional storms result in discharges over the spillway. Early in the wet season and during droughts, the unfilled reservoirs attenuate downstream peak flows by withholding runoff. But, once they have reached their capacity, they release essentially the same volumes of water that they receive, minus evaporation (which is minor during storms). These land use changes explain the steeper rising and falling limbs of the current hydrograph, its higher and sharper peaks, and the overall increase in flow volume. Reduced infiltration, artificial sub-surface drainage, and a lower groundwater recession rate no longer allow for extended summer base flow.

It should be noted that the model used to simulate the average annual hydrograph probably overestimates the peak flows because it does not account for flows spreading onto floodplains. This means that, with regard to peak flows, the actual difference between the historical and current hydrographs are probably greater than portrayed here. It should also be pointed out that although the peak flows were historically lower, the historical river bed was higher, such that the valley floor probably flooded more often. As discussed further in the following section on Management Actions, dedicating more valley land to natural flooding is one way to reduce overall flood hazards while greatly improving the health of the river ecosystem.

The historical watershed was much more retentive, due to the more complex drainage system that minimized runoff and slowed its movement through the river to the Bay. The natural system served as a dynamic physical template for complex mosaics of habitats that supported very diverse plant and animal communities. The current watershed with its artificially efficient drainage network, including rapid groundwater drainage to the river, has short-circuited the historical hydrological processes and compromised the associated ecological functions.

TABLE 3. Current and [estimated] historic land use/land cover for the non-tidal portions of the Napa watershed. Current acreage based on ABAG 2000 reported land use. Although more recent land use data are available, the year 2000 data are included in the ten year rainfall record used for this modeling (1987-2006).

Land Use/Cover	Est. Historic Acreage	Est. Historic %	Current Acreage	Current%	% Change
Urban/Built-up	0	0	11,900	9%	-
Agriculture	0	0	49,200	35%	-
Grassland/Range	24,000	17%	21,400	15%	-11%
Forest	109,600	79%	55,100	40%	-50%
Wetland/Water	5,500	4%	1,400	1%	-75%

FIGURE 19. Historical and modern average annual hydrographs. The modern graph (blue line) is based on mean daily flows calculated for the USGS gauging station at Napa (USGS gage #11458000). The historical graph (dashed black line) represents a model of mean daily flows based on precipitation records for the Napa State Hospital weather station (#046074) for the same period as the flow record (1987 to 2006).

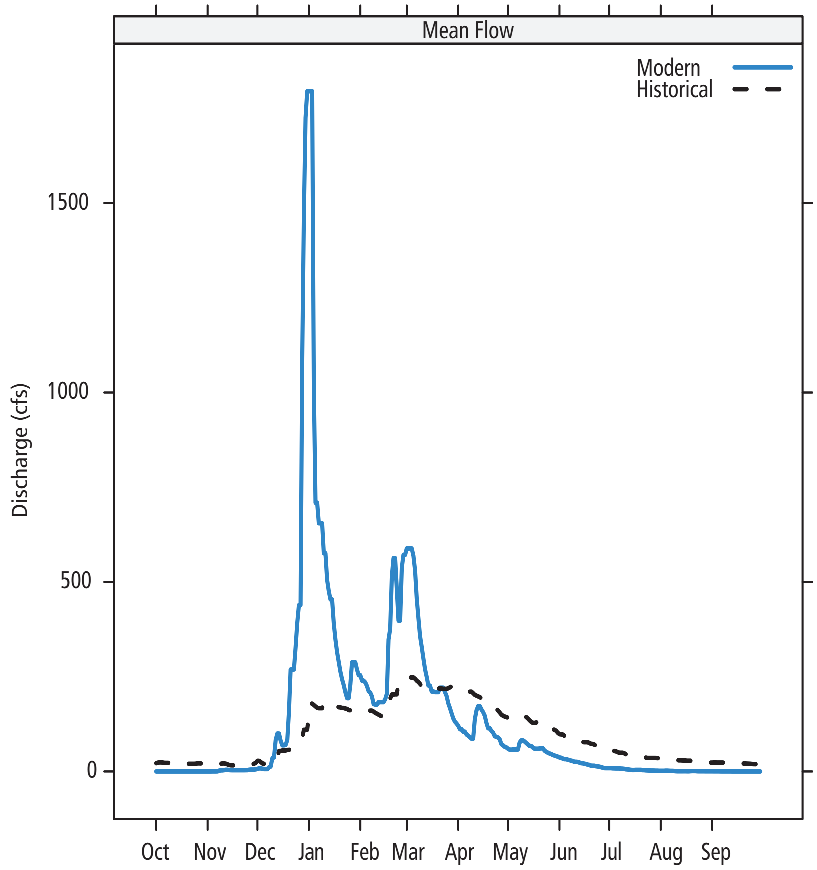
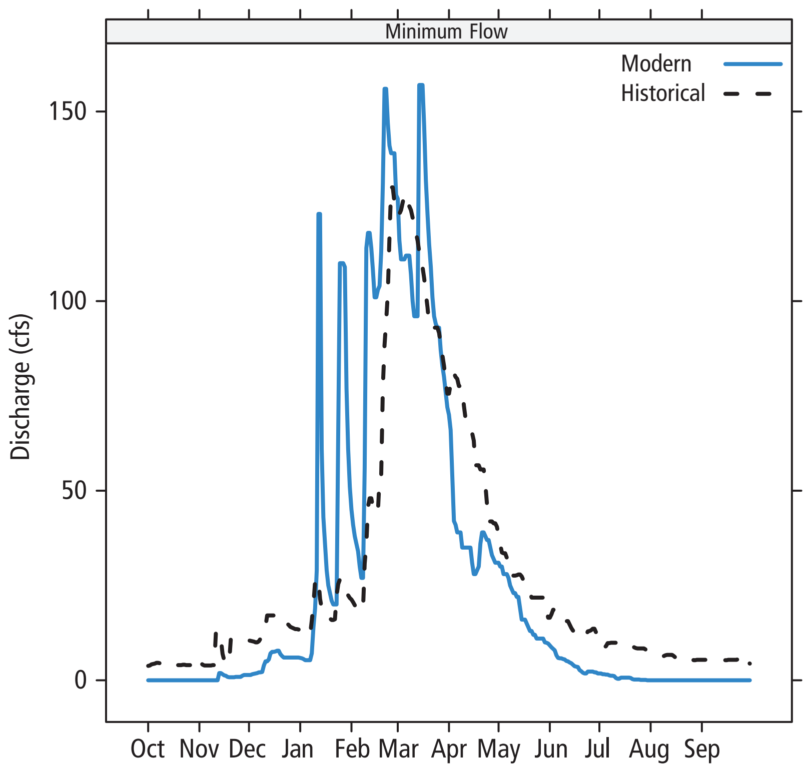


FIGURE 20. Reconstructed average minimum annual hydrograph for Napa River at Napa City based on historical conditions (dashed black line) and current conditions (blue line). Discharge values for the historical hydrograph are average daily minima for the period 1987 to 2006. Note that the peaks in daily minimum flow in the historical hydrograph are attenuated relative to the peaks in the current hydrograph, while the minimum historical base flow extends throughout the dry season.



Channel Form

The form of a channel is its shape in cross-section, longitudinal profile, and plan view. The form of a natural channel is not static. It is constantly adjusting to changes in the timing, frequency, duration, and amounts of inputs of water and sediment. If the inputs are persistent (i.e., if they vary around long-term averages that do not effectively change), channel form will change little. In other words, channels can reach a dynamic equilibrium with the prevailing water and sediment regimes. However, if the regimes change enough, the channel form will adjust to a new dynamic equilibrium. The adjustments can be small and localized or large and pervasive, depending on the sizes of the changes in water and sediment regimes.

Under historical conditions, only a few river reaches in the valley were characterized by a single-thread channel. Most of the reaches were characterized by active floodplains and side channels with perennial and seasonal wetlands that varied in extend along the river course but generally spread and slowed the river flows (see previous section of Historical Landscape Condition). Since the early 1800s, the construction of artificial levees and channels, wetland reclamation, increased hydrological connectivity, increases runoff, and decreased proportion of coarse sediment inputs has effectively turned most of the river into a relatively straight, single- thread channel with a narrow riparian corridor. The simplification of the channel network in plan view and the increase in drainage efficiency has led to significant losses in aquatic, wetland, and riparian habitats, as indicated by the loss or diminishment of the healthy river attributes. All of these changes simplify the channel and diminish or eliminate healthy river attributes (FIGURE 21- FIGURE 22).

Preceding sections discuss the major changes in water and sediment inputs to the Napa River. In general, changes in land use (e.g., urbanization, wetland reclamation, intensive agriculture, the construction of major reservoirs, etc.) and modifications to the channel network as previously described have cumulatively contributed to increases in the amount of runoff and decreases in its travel time. The watershed below the major dams drains to the river more quickly and yields larger volumes of runoff than it did historically.

The same land use changes have created an ongoing imbalance between the inputs of water to the river and the inputs of sediment, with a deficit in coarse sediment. This imbalance, coupled with artificial levees and bank revetment, has caused an increase in the volumes of flows that can be contained between the river banks. This in turn has increased the shear stress against the channel bed, causing it to erode. Bed erosion without compensatory deposition is termed channel incision. Chronic incision can lower the elevation of the bed. This is called channel degradation.

For the river in the valley, the inputs of sediment have not always been adequate to compensate for bed incision. The bed has therefore degraded. This further increased the volume of flows that could be contained within the channel, which promoted further incision of the channel bed. The positive feedback between channel degradation, depth of flow, and degradation has caused the channel to become entrenched, meaning that few flows exceed the heights of channel banks.

Evidence was gathered to evaluate long-term net bed degradation for the river in the valley. Data from repeated channel cross sections at fixed locations comprise the most direct and precise measures of local degradation. Such data are rare for the Napa River. Using a combination of historical cross sections, current channel cross sections (Napa RCD 1996 and 2006 data), historical photos (FIGURE 27), and other accounts of channel bed elevation, net amounts of channel degradation for various locations were documented. TABLE 4 is a summary table of the estimates of net degradation based on the difference between bed height (relative to bank top) for 2006 and the earliest available records. An assessment of confidence level is also provided for each comparison. Confidence levels represent the amount of uncertainty in the historical values for channel bed height, and not in the modern field measurements. These data in aggregate confirm a general degradation of the Napa River from Calistoga

FIGURE 21. Evolution of select Napa River reaches (Part 1). Most, if not all these reaches are now entrenched, resulting in the loss of, or diminishment of many healthy river attributes.

An 1871 map shows multiple channels in a probable floodplain wetland reach (the channels have been highlighted in blue). Current images shows only a single channel and no active floodplain.

Remnants of a broad riparian forest are common north of St. Helena circa 1940 but are no longer evident by 2005.

Naturally confined reaches have relatively narrow stream habitat zones in both historical and modern aerial photography. This pair of images shows the effect of Sulphur Creek alluvial fan at Pratt Avenue. The 2005 image shows encroachment of riparian forest onto the once-exposed gravel bars.

Large, unvegetated gravel bars are prominent immediately downstream of the Sulphur Creek confluence in historical but not modern imagery. The bar and flood plain topography are less accessible now.

FIGURE 22. Evolution of select Napa River reaches (Part 2).

Mid 19th century records for the present-day location of Zinfandel Lane describe a broad reach with side channels, willow groves, and tule marshes. By 1940, the wetlands have been drained, willows are absent, and the river has abandoned the floodplain, but side channels persist. The river system is further simplified by 2005.

Interconnected sloughs and side channels carved the floodplain and low terraces in large islands. The large side channel visible in 1940 is absent in 2005.

The reach downstream of the Dry Creek confluence remains characterized by relatively wide areas of riparian forest with closely spaced side channels, although the channel has abandoned its floodplain.

Large gravel bars evident in 1940 have been colonized by riparian trees. The prominent side channel has mostly been removed.

FIGURE 23. Historic channels at Bale Slough dissipated on the valley bottom or lower alluvial fans. High flows temporarily linked valley floor wetlands, intermittent streams and the Napa River. In the dry season, these features were mostly disconnected.

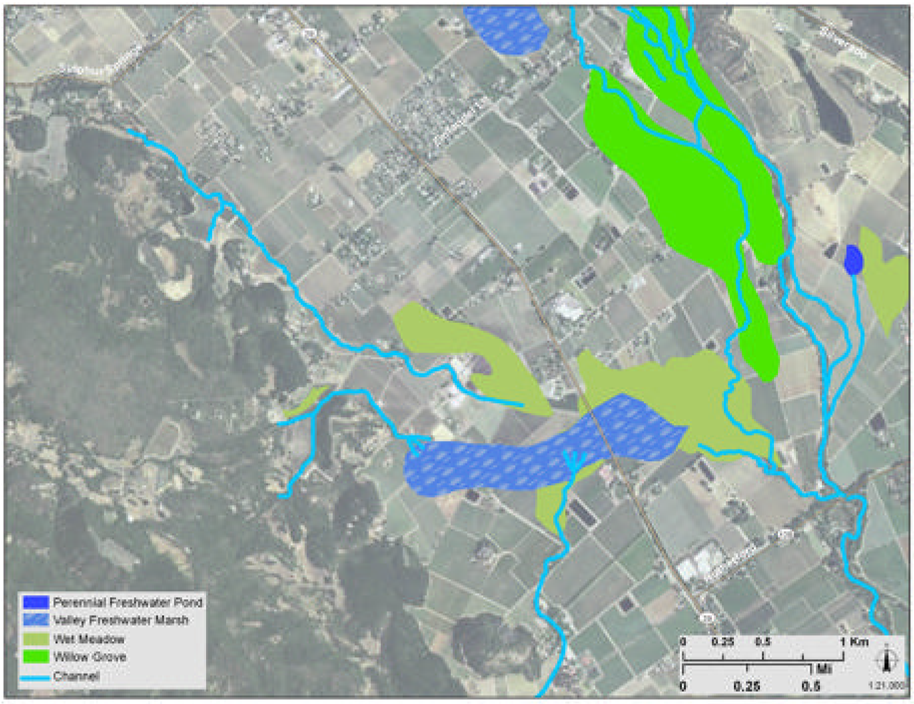


FIGURE 24. Current day channel network associated with the confluence of Napa River and Bale Slough near Rutherford Rd shows numerous agricultural drainage ditches (lost or diminished attributes 1-10).

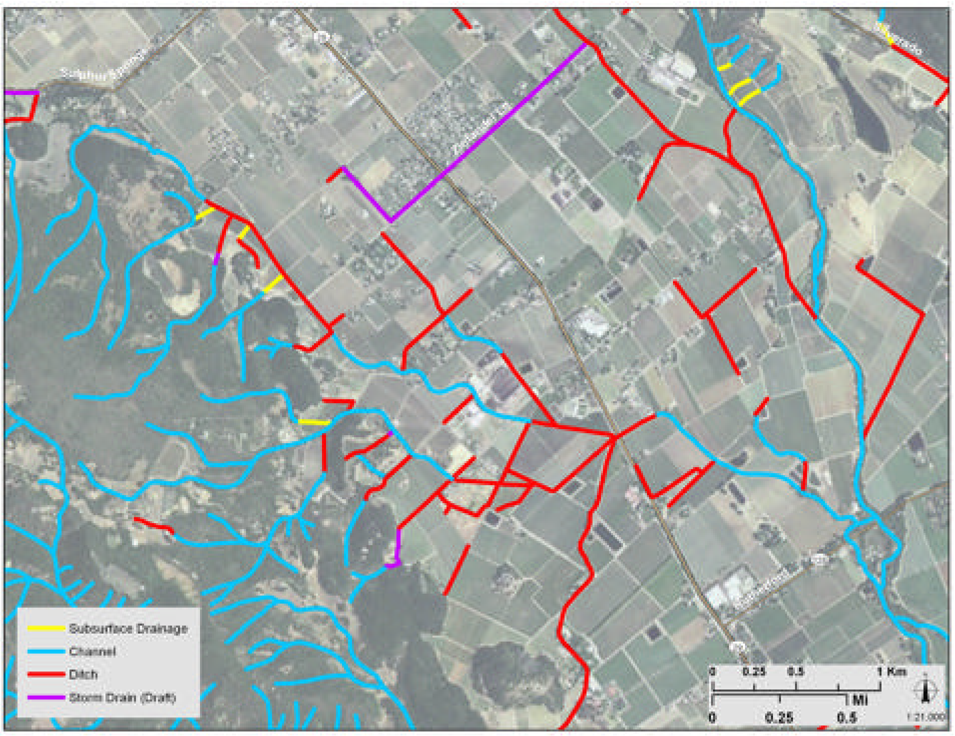


FIGURE 25. Historical channels at Bale Slough dissipated on the valley bottom or lower alluvial fans. High flows temporarily linked valley floor wetlands, intermittent streams and the Napa River. In the dry season, these features were hydrologically less interconnected.

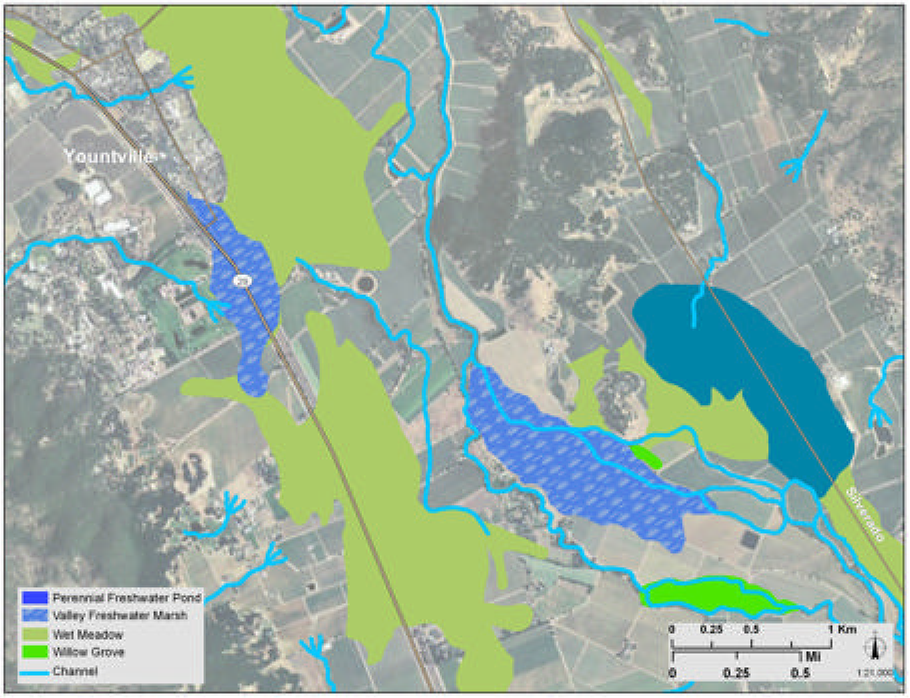
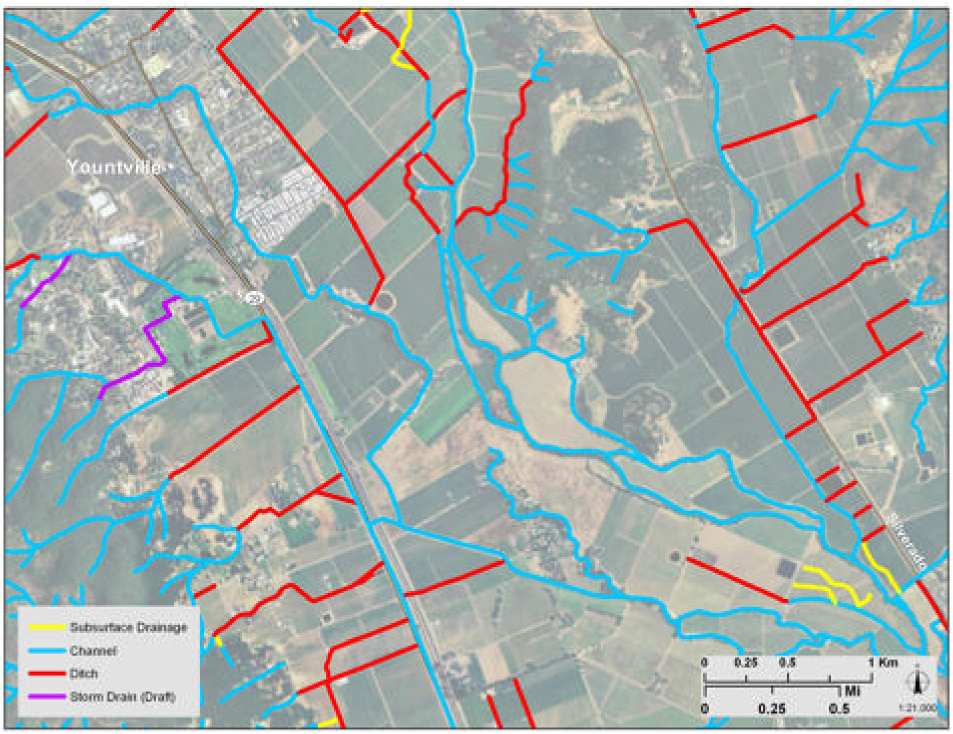


FIGURE 26. Many of the historical channels just south of Yountville are still evident but they have been artificially interconnected by numerous agricultural ditches, some of which are old enough to have become naturalized (lost or diminished attributes 1-10).



to Napa during the 20th century. Over the last 40-100 years, net degradation evidently ranged from about 2-3 m (6.5-10 ft), with larger and smaller values also observed. These results are very similar to the upper range of incision values reported by previous studies. The Napa River Sediment TMDL and Habitat Enhancement Plan (Napolitano et al., 2009) reported long-term net degradation of 3 m (10 ft); the Napa River Basin Limiting Factors Analysis (Stillwater and Dietrich 2002) reported a range of 1.8 to 2.0 m (6 to 6.5 ft). Qualitative descriptions dating from the 19th-century, such as diversions of river flow to irrigate agriculture on the valley floor and to power gristmills without pumps or siphons, as well as the historical evidence of abundant off-channel aquatic habitat supported by river flooding, also suggest that the channel bed was historically not as far below the valley floor as it is today.

Degradation of the river was assessed in the valley by comparing longitudinal profiles of the river's thalweg (the deepest continuous line along the riverbed). The thalweg profile that SFEI and the Napa RCD constructed between St. Helena and Napa City in 1996 was compared to one constructed for the same reach based on the 1950 USGS 1:24,000 scale topographic quadrangle. The results indicate 3-4 m (10-13 ft) of degradation during the last 50-60 years. Lesser amounts of incision were observed upstream of St. Helena. The RCD and Tessera Sciences completed a detailed thalweg profile from Zinfandel Lane to Rutherford Cross Road in 2009. A comparison of this profile to the one derived from 1972 FEMA data indicates as much as 4.5 m (15 ft) of degradation in this reach during that 27-yr period. The variability in these estimates of degradation reflects differences in methodology, accuracy, and temporal and spatial variability of channel processes. Any given cross-section represents a moment during ongoing adjustments to previous and/or continuing upstream changes in flow and sediment load. The instantaneous measures of bed elevation could represent various stages of channel response to pulses of sediment coming from upstream erosion of banks and beds, and to headward erosion of the bed as it moves upstream. No effort has been made to account for these sources of variability within or among cross-sections (APPENDIX 5).

There is some evidence, however, that the data from some locations may be biased toward conservative estimates of channel degradation. Some of the cross-sections and photographs upon which historical estimates of bed height are based pertain to the construction of bridges, most of which are located at relatively stable channel reaches. Some bridges involve cement aprons that cross the bed and prevent incision (e.g., Zinfandel Lane). It should also be noted that some degradation may have taken place after Euro-American contact but prior to any of the historical cross-sectional or longitudinal data. This degradation is not accounted for in our estimates of long term net degradation.

In some reaches, incision has been arrested by encountering resistant natural material (bedrock or layers of still clay), or the bed has been dammed or cemented. In other reaches, incision is likely to continue unless peak flows are adequately decreased, the channel is adequately widened to lessen flow depths, or the inputs of coarse sediment are adequately increased. Entrenched channels tend to widen on their own as their banks erode. This can lead to repetitive failure and repair of bank revetments.

The cross-sectional data has been explored for evidence that the river channel in the valley is widening. A general widening would indicate that bed incision and degradation is at least slowing. An ideal measurement would be the ratio between channel width and channel depth at the height of the water surface during the effective or channel-forming flow. This is the flow to which the channel tends to adjust over time, given that the sediment inputs do not significantly change (Copeland et al., 2000). A common estimate of the channel forming flow is termed bankfull stage (e.g., Rosgen 1994). None of the cross sections available for this study, however, include a determination of bankfull stage or any other estimate of the height of effective flow. As a result, changes were estimated in the maximum width-to-depth (w:d) ratio of the channel, defined here as banktop-to-banktop width divided by thalweg depth relative to bank top (TABLE 4). This ratio was calculated for the Oak Knoll to Oakville based on the 1996 and 2006 cross section surveys provided by the Napa RCD, and for bridge locations with reliable as-built cross section data that we re-occupied in 2006. For the Oak Knoll to Oakville reach, the maximum w:d ratio has generally increased from 1996 to 2006, suggesting that the channel is widening. For the cross-sections at the bridge locations, the maximum w:d ratio has decreased. Although there is some uncertainty about these data (due to uncertainty about the historical measurements), they should reflect the fact that relatively stable reaches are selected for bridges, and that bank erosion near bridges is inhibited by the bridge footings and related revetments.

In general, channel depth has increased much more than channel width. Many reaches of the river in the valley are deeply entrenched. This can benefit flood control, since fewer flows overtop the channel banks, but it wreaks havoc on the river ecosystem. The channel is essentially a sediment chute, with a highly mobile bed subject to scour during rain storms, and with little evidence of the natural flooding and the related ecological connectivity that historically existed between the river and its valley. The resulting homogeneous bed with long pools favors native and introduced fishes that prey upon juvenile salmonids and has likely reduced Chinook populations (Stillwater Sciences and Dietrich 2002). Restoration of natural bars, plunge pools, and floodplain connectivity may also be needed to protect other rare or threatened species, including the red-legged frog, riparian birds, and the California freshwater shrimp that were once much more abundant in the Napa River. Vineyards and other land uses are also threatened by bank erosion related to channel degradation. Addressing the problem of historical degradation and ongoing incision of the Napa River in the valley and the lower reaches of its tributaries will be the primary focus of the Napa River sediment TMDL (Napolitano et al., 2009).

Riparian Areas

Riparian areas have traditionally been defined as areas along channels with vegetation that is strongly influenced by surface or subsurface exchanges of water between the channels and the riparian area. The riparian definition recommended by the National Research Council (NRC 2002) and the Technical Advisory Team for the California Wetland and Riparian Area Protection Policy (TAT 2009)) is much more inclusive. It indicates that the entire perimeter of any aquatic landscape feature, such as a lake, channel, estuary or wetland, is riparian, whether it is vegetated or not. The width of a riparian area varies, however, with riparian function. It is wider for functions that extend relatively far from the boundary, such as floodwater retention or

TABLE 4. Napa River mainstem width-to-depth ratios

Section number and location (RCD river station)	Historic Cross Section w:d	2006 Cross Section w:d	Change
Part 1: Oak Knoll to Oakville reach (1996 represents the “historical” condition)			
#13 (33770) DS of Oakville Cross Rd	6.2	8.0	+1.8
#19 (34670) DS of Oakville Cross Rd	3.3	6.0	+2.7
#40 (37260) Immed. DS of Yountville Cross Rd	4.4	4.8	+0.4
#56 (39430) DS of Yountville Cross Rd	5.6	5.6	+0.0
# 68 (40780) DS of Yountville Cross Rd	3.6	4.1	+0.5
Part 2: Bridges			
Oak Knoll	(1922) 4.9	4.7	-0.2
Pratt Ave	(1921) 8.6	6.0	-2.6
Lodi Lane	(1919-1950) 8.7	7.9	-0.8

riparian wildlife support, and narrower for functions that do not extend far from the boundary, such as bank stability or allochthonous input (deposition of organic material into the aquatic area or wetland from outside sources such as riparian trees). Riparian areas can extend into uplands.

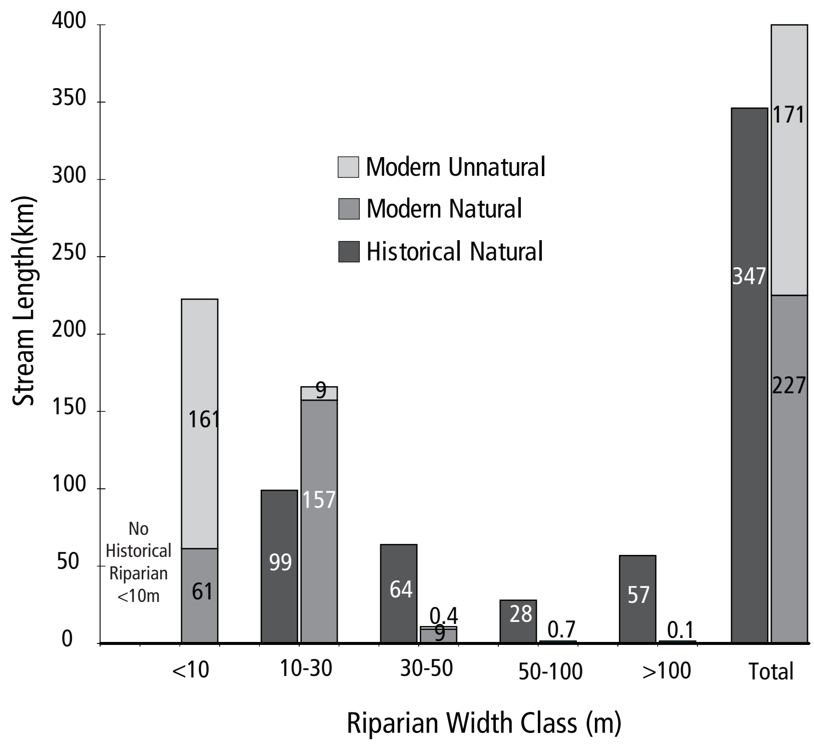
As a way to map the recommended definition, a tool has been developed for estimating riparian width for a variety of riparian functions based on topography, plant community composition, and land use (Collins et al., 2006). The tool was developed through a related project that uses the Napa River Watershed for testing and refinement. Once the tool was developed through an advisory group, it was applied to the historical and current drainage networks of the Napa Valley. The riparian areas were then classified into width classes that correspond to groups of riparian functions, based on a broad literature review of the relationship between riparian function and riparian width (Collins et al., 2006). In general, wider areas have higher levels of more functions, up to a maximum width of perhaps 300 m (about 1,000 ft). The widest riparian areas are defined by support for motile wildlife species, such as amphibians and birds that are endemic to the ecotone between aquatic areas (and wetlands) and their neighboring uplands. As riparian width increases, more functions are provided. The areas defined by riparian wildlife support tend to also provide many other riparian functions.

FIGURE 27. Historical photographs were used to assist our estimate of incision. The historical photograph (left, courtesy of Al Edmister) and current photograph (right) looking downstream at the Zinfandel Lane bridge shows the channel condition in relation to the fixed elevation of the bridge deck or roadway. Photos show the historic bridge pillar at grade, and the now-exposed bridge pillar and concrete apron. Although the exact date of the historical photograph is not known, it clearly shows that the historical elevation of the channel bed generally corresponded to the base of the bridge abutment. After the historical photo was taken, the channel bed incised, requiring the pouring of a concrete slab underneath the abutment. An estimate of the amount of incision at this site since the time of the older photo is provided as the difference between the height of the base of the concrete slap and the height of the original base of the abutment.

As evident in many images of the Napa River in the valley (FIGURE 21 - FIGURE 22) most of the current riparian areas are significantly narrower than they were historically. Nearly all of the historical areas of riparian wider than 200 ft (60 m) have been converted to agriculture or other land uses. At the same time, riparian vegetation has encroached upon formerly exposed gravel bars and become established adjacent to narrow artificial channels, including some agricultural ditches that cannot support broad riparian areas. In fact, the actual extent of riparian habitat as measured in linear feet has increased by more than 10%, due to the addition of unnatural channels, but the riparian areas of these channels are very narrow, and therefore have very limited riparian functions (FIGURE 28).

The overall decline in riparian width plus changes in channel form have caused a significant reduction in riparian ecological functions. In some areas, the narrowed riparian area still provides shade and some allochthonous inputs (including large woody debris), but the high flows in the entrenched river channel remove woody debris and prevent the formation of debris jams that would otherwise trap coarse sediment, create plunge pools, and increase the overall complexity of the river ecosystem. As a result, although there has been an increase in the overall length of riparian area, there has been a decrease in its functional capacity.

FIGURE 28. Historical change in riparian width. Riparian width was estimated for the entire historical and current channel networks within the valley, with regard to a combination of riparian functions, namely bank stability, allochthonous input, shading, adjacent hillslope processes (not relevant for most of the valley), and general wildlife support. Width was measured from the river centerline to the outermost riparian boundary for one side of the river. Width would be doubled if both sides of the river were considered. The increase in total riparian length represents narrow areas (0-10 m or 0-30 ft) along unnatural channels, especially agricultural and roadside ditches. There has been a conversion of wide areas (>30 m or 100 ft) to moderately wide area (10-30 m or 30-100 ft) due mainly to encroachment of agriculture into the historical wide areas. As a result, although there has been an increase in overall length of riparian area, there has been a decrease in functional capacity.



System Response Timeline

The general effects of land use on the form of the river in the valley can be separated into five main periods (APPENDIX 6). The period of indigenous management spanned thousands of years, but there is no evidence of any major impacts on natural hydrological processes. No evidence of river diversion or impoundment has been found, although the river undoubtedly adjusted to alterations of runoff caused by the indigenous use of fire to manage vegetation. The remaining four periods have each lasted less than a century, although the current period is, of course, ongoing.

The Mission period begins with the cessation of indigenous management and the advent of Euro-American settlement. It is characterized by the introduction of ranching, and other non-indigenous land use practices. These practices may have had some impact on watershed processes, but this period was relatively brief in Napa Valley.

The Agricultural period begins in the mid 1800's, after the California gold rush. It is characterized by a sudden increase in the extent and intensity of most Euro-American land uses, due to increased settlement in the valley. Ranching gave way to farming, with major shifts in dominant crops from grains to vineyards and orchards. A multitude of small reservoirs were built in the hills surrounding the valley to provide water for local ranches, farms, and vineyards. Significant increases in overall channel density, channel degradation, bankfull width, and peak flow began during this period, as did decreases in dry season base flow.

The urbanization period began after WWII. It is characterized by rapid growth in local urban centers, especially Napa and Calistoga, plus the construction of major dams to meet growing water demands. Both the large dams and urbanization contributed to channel incision by entrapping coarse sediment and increasing urban runoff, respectively. The river became sufficiently entrenched to contain high storm flows that further exacerbated the incision problem. Large woody debris that might have been entrained by flood flows was routinely removed from the river to reduce flood hazards.

The major tributaries and the river were probably still adjusting to urbanization when the current Modern period began, around 1970. This period has been characterized by an expansion and intensification of viticulture designed to meet a rapid increase in the worldwide demand for wine. New irrigation practices, especially drip irrigation, have helped meet this demand. Ditching has continued, reservoirs have been built on the valley floor to meet the increased need for frost control and irrigation, and the practice of sub-surface drainage has been extended throughout most of the valley. Vineyards have been planted on hillsides and fitted with their own storm drain systems. The resulting increases in the rate and volume of runoff have been unprecedented for the watershed. Channel incision and bank erosion have continued, with concomitant increases in the supply of fine sediment, declines in salmonid populations, and reductions in riparian resources. The river ecosystem has become greatly simplified overall, with narrow riparian zones, narrower floodplains, and a lack of in-stream habitat complexity.

Public understanding of the negative environmental impacts of historical land use practices in the Napa Watershed increased markedly during the 1990s. Local agencies translated this understanding into new practices intended to minimize or eliminate the negative impacts. The focus has been on the control of agricultural land erosion through cover crops, retention basins, minimized planting on steep slopes, and other proven practices. One unintended effect of these modern practices has been an increase in runoff without a compensating increase in coarse sediment supply. The next phase in the relationship between channel morphology and land use could emphasize a watershed approach to comprehensive river management.

The following schematics illustrate a broad set of changes in the hydrology, morphology, and sediment regime of the river. Given the scope and purpose of this report, the schematics focus on the effects of agriculture rather than urban land use. They serve as a visual summary of the effects of land use change on river form and function that are discussed in more detail elsewhere in this report.

FIGURE 29. Conceptual diagram of hydrological response to land use changes. Starting in the mid-19th century, channel density (i.e., the total length of drainage channel per unit area of the watershed) increased (see Figure 25 above), resulting in greater runoff over shorter periods as evidenced by decreases in base flow and increases in peak flow. Drought and flood events would have caused short term (less than decadal) perturbations to the general trends in base flow and peak flow.

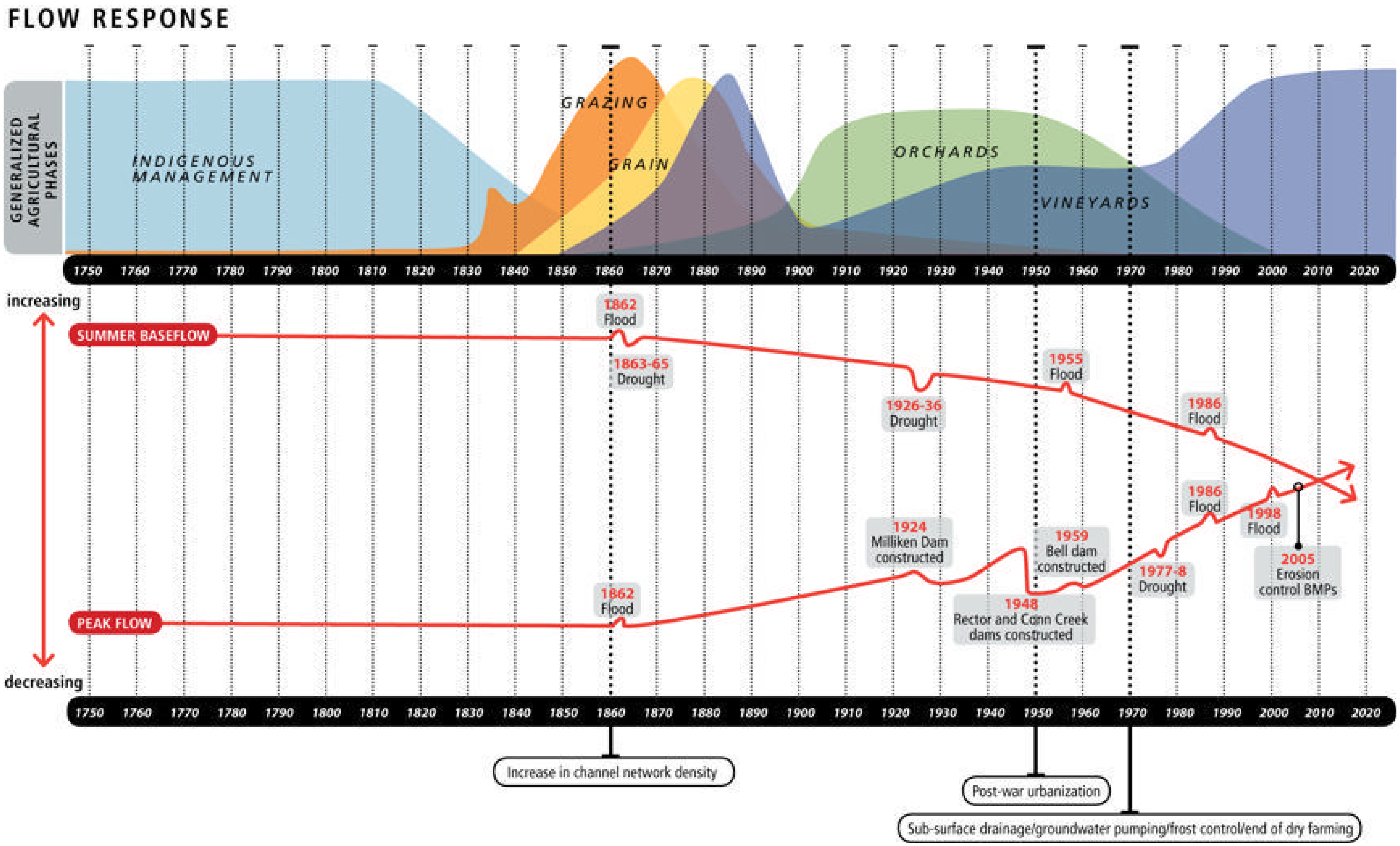


FIGURE 30. Conceptual diagram of channel morphological response to land use changes. Prior to Euro-American settlement, the channel network was in dynamic equilibrium with runoff and inputs of sediment. Broad floodplains were inundated at least once every few years. The riparian forest provided large woody debris that created debris jams in the channel, with pools that served as salmonid refugia and rearing habitat. By ditching the wetlands and alluvial fans, settlers increased runoff, which likely caused channel degradation beginning in the second half of the 19th century (Stillwater, 2002). Degradation accelerated in the 1930s, following shifts in agriculture and the beginning of increased urbanization. Large storm flows with entrained debris that could not escape the incised channels threatened bridges and other infrastructure along the river banks. Bank revetment and the removal of large woody debris became standard practices of river management in the 1950s.

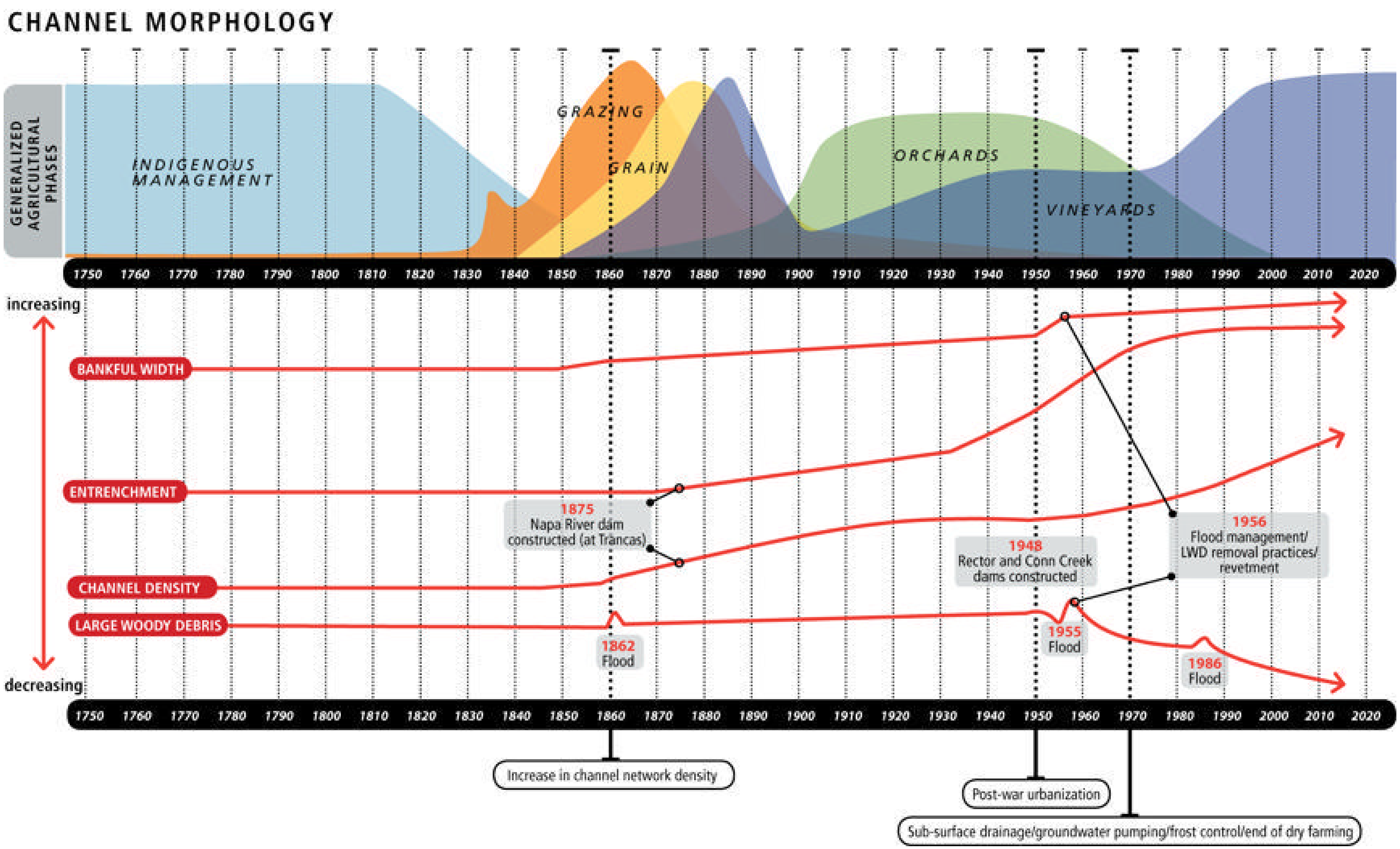
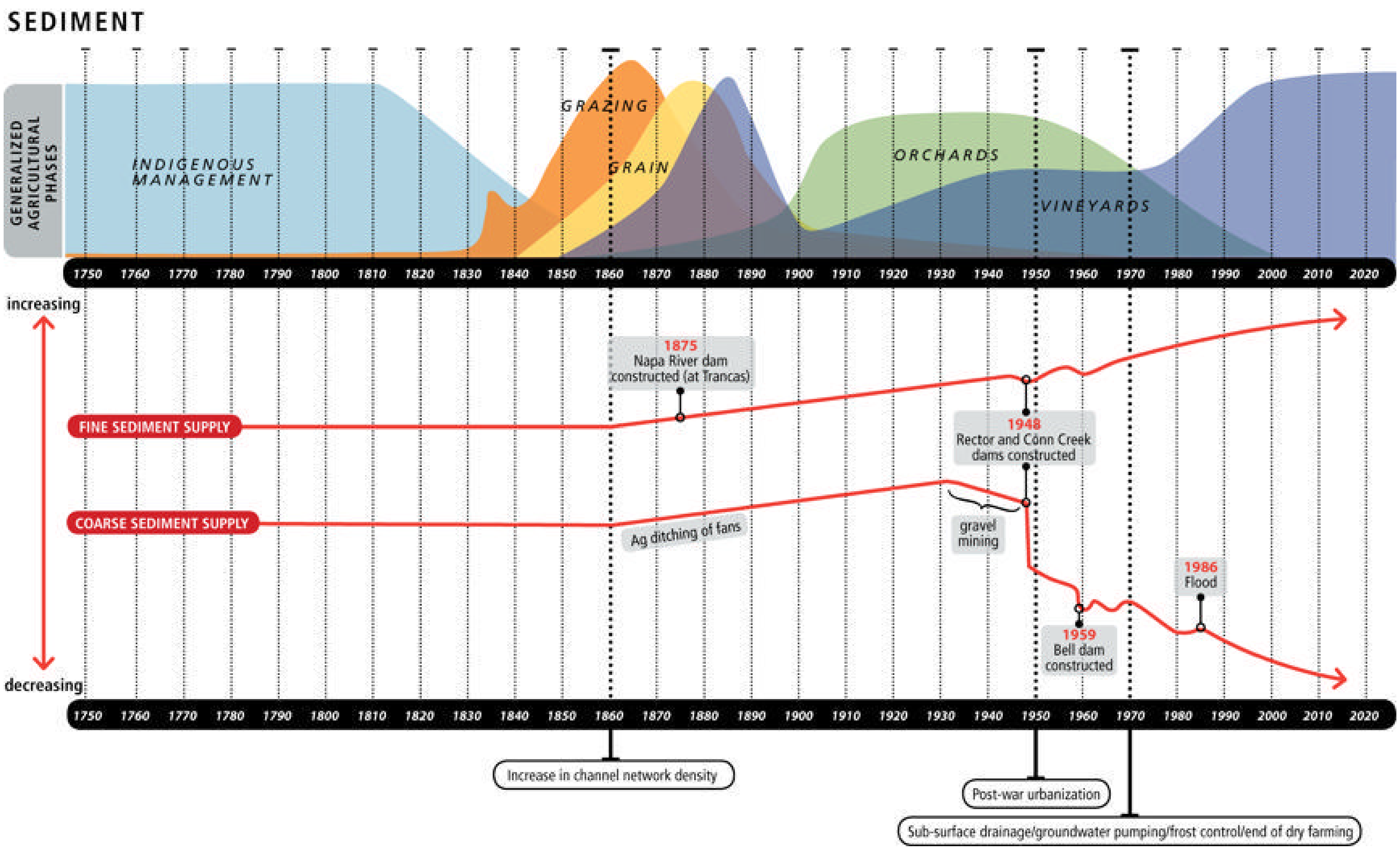


FIGURE 31. Changes in sediment supply in relation to agricultural land use changes. The total amounts and proportions of coarse and fine sediment delivered to the river in the valley have changed dramatically over the last 150 years in contrast to the assumption that the sediment supply changed little over long periods of time prior to Euro-American settlement. Early ranching and farming probably increased the total inputs of both fine and coarse sediment due to ground compaction, ditching, and increased runoff that caused gullies on steep hillsides and initiated channel incision. With the advent of gravel mining in the 1930s, and the entrapment of coarse sediment behind under-sized culverts, within low-gradient ditches, and behind large dams constructed on major tributaries after WWII, coarse sediment supply decreased markedly.



River Health Summary

Based on the previous discussion of system response to landscape changes, the river's condition with respect to the health river attributes can now be summarized (**TABLE 5**).

TABLE 5. Current Attributes of the Napa River in Napa Valley.

Attribute Number	Attribute description	Current condition
1	Alternate bar sequence	Basic bar structure evident in most reaches; recent incision and scour have reduced bar size; larger historical bars have been colonized by perennial vegetation.
2	Annual hydrograph component function	Excessive peak flows and inadequate summer base flow in most reaches.
3	Channel bed surface mobilization	Excessive due to channel entrenchment, levees, bank revetment.
4	Periodic deep scouring of alternate bars	
5	Fine/coarse sediment balanced	Excess fine sediment in most reaches.
6	Alluvial channels migration	Channel naturally not very migratory; local meandering, natural widening, and migration inhibited by bank revetment.
7	Frequent floodplain inundation	Floodplain minimal or non-existent due to severe entrenchment in most reaches; natural widening that could create floodplains in entrenched setting inhibited by bank revetment and natural bank strength.
8	Large floods enable complex main stem and floodplain morphology.	Severe entrenchment in most reaches without adequate floodplain; seasonal scour reducing bed complexity; little woody debris in channel.
9	Annual hydrograph components sustain diverse riparian plant communities	Severe entrenchment in most reaches without adequate floodplain; hydrograph lacks base flow in some reaches; riparian area artificially narrow and simplified; little woody debris in channel.
10	Groundwater connection to main stem	Connectivity severely altered by loss of recharge on alluvial fans and shunting of groundwater to artificial above-ground storage or to the river via sub-surface agricultural drains; loss of dry season base flow in some reaches.

POTENTIAL MANAGEMENT ACTIONS

Severe incisions along Napa River.
Photography courtesy of Gretchen E. Hayes.

The condition of the system is a consequence of dynamic interactions between water and sediment supplies, as mediated by vegetation. Plants intercept the movements of water and sediment and influence their chemical and physical characteristics. The physical and ecological functions of each component of the system depend on its position along the elevation gradient between the upper watershed boundaries and San Pablo Bay. Every aspect of the drainage system, including the quantity and quality of water and sediment as well as the steepness and length of the elevation gradient along which they move, is ultimately controlled by geology (including hydrology), climate, and land use. Land use is an integral component of the watershed because it influences water and sediment supplies by altering the structure, form, and functions of the drainage network (**FIGURE 32**).

Relationship between attributes and management actions:

Opportunities exist to restore or improve most of the river health attributes and the associated ecological functions. The following actions are proposed for consideration to address the deterioration of the full range of functions of the Napa River ecosystem (**TABLE 6**). Feasibility and suitability of these actions is dependent on reach specifics. The implementation of any of these actions should fully consider their physical, ecological, and economic interactions to assure their compatibility in the watershed context.

FIGURE 32. Basic conceptual model of the condition of drainage systems as the consequence of dynamic interactions between sediment supplies and water supplies, as mediated by vegetation and ultimately controlled by climate, geology, and land use.

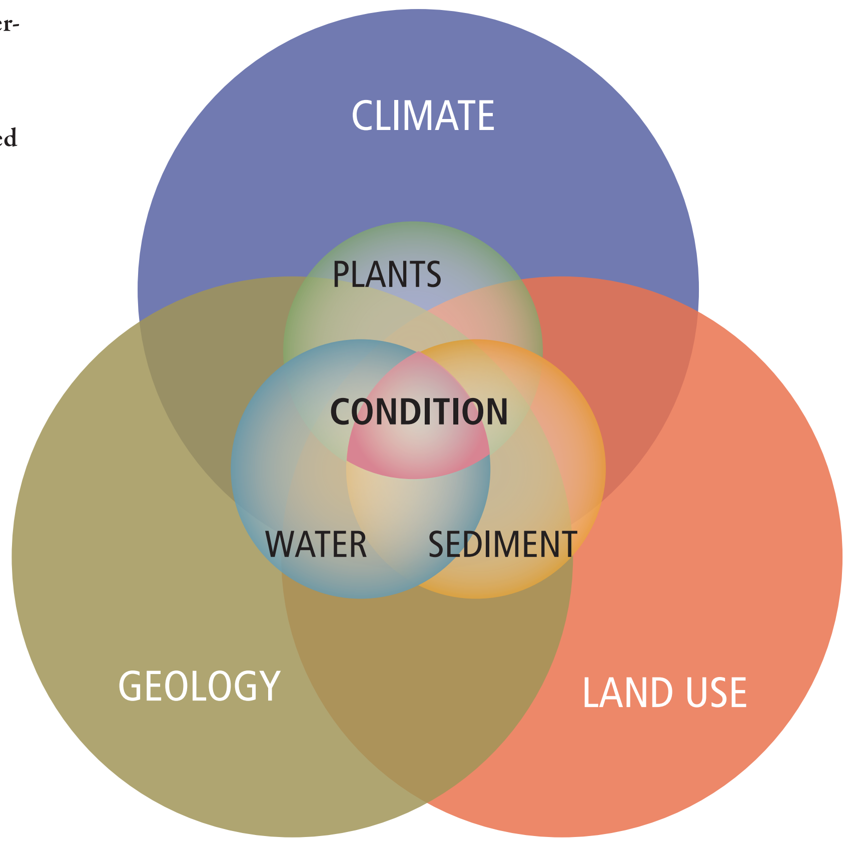


TABLE 6. Potential actions to address the deterioration of functioning of the Napa River system (pt. 1)

Primary Management Action	Mainstem Attribute Primarily Affected	Desired Effect on Water	Desired Effect on Sediment	Desired Effect on Channel profile
A. Dry season releases of water from major reservoirs to augment base flow in main-stem and tributaries	2, 5, 9	Increased dry season base flow	Winnowing of fine sediment from active bedload. Possible increased bed coarseness	Maintenance of low-flow channel; increased depth and duration of in-stream pools during dry season
B. Managed spring-time releases of water from reservoirs large or small or from sub-surface drains to extend storm hydrograph to flush fine sediments from main-stem bed to improve salmon spawning habitat in mainstem for subsequent spawning season	2, 5, 9	Extended falling limb of selected storm hydrographs	Winnowing of fine sediment from active bedload. Possible increase in bed coarseness	Maintenance of low-flow channel; increased depth and duration of in-stream pools during dry season
C. Releases of water from reservoirs during springtime high flow events to scour deep pools in mainstem	1, 2, 3, 4	Increased peak flows of late springtime storm hydrographs	Mobilization and sorting of bedload from pools and in alternate bars	Maintenance of deep pools and replacement of alternate bar materials
D. Coarse sediment augmentation/ artificial delivery of coarse material	1, 5		Increased coarse sediment fraction of active bedload	Maintenance of riffles. Also supports coarser alternate bars
E. Reduce amount of bank revetment to encourage main-stem widening. This may include planned retreat from some active bank erosion areas.	1, 5, 6, 7	Reduced stream power for most hydrographs to prevent chronic scour of bed	Increased storage of fine sediment on floodplains with possible increased bed coarseness. Increased residence time of coarse clasts.	Maintenance of alternate bars; natural formation of floodplains; formation of large woody debris jams, overall increase in ecosystem complexity. Allows channel to evolve to shape that is adjusted to sediment and water inputs.
F. Floodplain construction	1, 2, 5, 7, 8, 9	Reduced peak flow during storm events; reduced stream power for most hydrographs to prevent chronic scour of bed. Lengthens falling limb of storm hydrographs.	Increased storage of fine sediment on floodplains with possible increased bed coarseness. Increased residence time of coarse clasts.	Maintenance of alternate bars; natural formation of floodplains; formation of large woody debris jams , overall increase in ecosystem complexity.
G. Incorporation of multistage floodplain designs in restoration plans	1, 2, 5, 7, 8, 9	Reduced peak flow during storm events; reduced stream power for all hydrographs to prevent chronic scour of bed.	Increased storage of fine sediment on floodplains with possible increased bed coarseness.	Maintenance of alternate bars; maximum overall increase in ecosystem complexity.
H. Above ground valley-bottom reservoirs and conjunctive use of subdrains	1, 2, 3, 4, 5, 9, 10	Increased dry season base flow; extended falling limb of selected storm hydrographs; increased peak flows of late springtime storm hydrographs.	Winnowing of fine sediment from active bedload. Possible increased bed coarseness; mobilization and sorting of bedload from pools and in alternate bars.	Maintenance of low-flow channel; increased depth and duration of in-stream pools during dry season; maintenance of deep pools and replacement of alternate bar materials; overall increase in ecosystem complexity.

TABLE 6. Potential actions to address the deterioration of functioning of the Napa River system (pt. 1)

Primary Management Action	Mainstem Attribute Primarily Affected	Desired Effect on Water	Desired Effect on Sediment	Desired Effect on Channel profile
K. Removal of selected dams on tributaries to increase storm hydrograph variability and improve coarse sediment supply to mainstem	1, 2, 3, 4, 5, 7, 8, 9	Increased frequency of low to moderate flows; possibly increased dry season base flow and extended falling limb of selected storm hydrographs.	Increased natural provisions of coarse sediments and possibly increased bed coarseness.	Maintenance of low-flow channel; maintenance of alternate bars; formation and maintenance of bankfull floodplain; increased riparian ecosystem complexity.
L. Replacement of ditches, culverts, and other engineered crossings based on state-of-science designs to effciently convey flood flows and coarse sediment	5	Decreased backwater effects of undersized engineered crossings; decreased effects of hydraulically inefficient ditches on their stability and sediment transport capacity.	Decreased supply of fine sediment from channel bank erosion; posssible increased bed coarseness.	Increased channel stability; maintenance of bankfull floodplain.
M. Increased extent of dry farming, conservation, and use of new frost control BMPs to reduce water consumption and thus increase water avalaibility for all other needs	1, 2, 3, 4, 5, 6, 7, 8, 9, 10	Can affect desired conditions for all other actions.	Can affect desired conditions for all other actions.	Can affect desired conditions for all other actions.
N. Increased LID practices in urbanized areas to reduce runoff	2, 5	Decreased peak flow of storm hydrographs; reduced NPS pollution loads.	Decreased supply of fine sediment from developed areas.	Increased channel stability below urban stomwater inputs.

Management Action Considerations

A. ***Dry season cold-water releases from major reservoirs to augment base flow in the river and tributaries.*** This action can help support fish and aquatic wildlife during the dry season. An increase in summer flow can improve fish rearing habitat by ensuring the persistence of deep pools that serve as refugia. Many other habitat factors influence whether the flows will help improve habitat conditions for salmonids, however. For example, augmented baseflows might not be cold enough for salmonids unless there is adequate riparian shading. This action should be targeted at specific reaches rather than for the river in the valley as a whole. The influence of any given release on in-stream habitat conditions will decrease downstream; achieving desired effects on the river in the valley as a whole could require unacceptably large releases of stored water.

B. ***Managed springtime releases of stored water from reservoirs or from sub-surface drainage.*** These kinds of releases could be used to extend the falling limbs of the springtime storm hydrographs to help flush fine sediments from the riverbed and thus improve salmonid spawning habitat. Although those drains without sump pumps currently allow springtime flow, it is unregulated. Flushing flows might have to be repeated during the dry season to make sure the bed is properly prepared for fall runs of salmon or steelhead. In order to have the biggest benefit for salmonids, flushing flows should be targeted toward those reaches that have adequate upstream supplies of coarse sediment, either from natural tributary sources, artificial augmentation efforts, or both. Possible candidate target reaches in the valley include areas immediately downstream of the confluences with Kimball, Conn, Sulphur, and Soda Creeks.

C. ***Releases of water from reservoirs during springtime high flow events.*** This kind of release would help promote the periodic scour of deep pools and the renewal of channel bar materials along the river in the valley. High flows of this kind can also help maintain low flow channels and generally improve overall riverbed complexity. This action will mostly influence tributaries downstream of releases and perhaps the river immediately downstream of the confluences with those tributaries. These releases should target reaches that have deep pools. At elevations below the valley floor, this action might be postponed until affected reaches have stabilized and appreciable floodplains have reformed in the entrenched settings, so that the releases do not exacerbate current scour events or induce further incision.

D. ***Coarse sediment augmentation.*** This action involves harvesting coarse sediment, such as gravel, from one place along the drainage network of the watershed and adding it to another place. It could improve the availability of coarse sediment where natural sources are inadequate. This has to be regularly repeated since the added sediments tend to be transported downstream through the targeted reaches during high flow events. It could complement other actions designed to increase the coarseness of the riverbed (actions A-C, F-H). This action should probably be used to augment natural coarse sediment sources such as Kimball Creek, Conn Creek, and Sulphur Creek. The larger dams have trapped appreciable amounts of coarse sediment from the upper reaches of some major tributaries. These sediments could be dredged for use to augment coarse sediment supplies in selected river reaches in the valley or along the lower reaches of main tributaries. Such dredging would also increase the capacity of the reservoirs, an action that might help meet the challenge of climate change (see action H). The ongoing high costs to harvest and transport sediment could be prohibitive, however, and legacy concerns about negative impacts of local gravel mining would have to be addressed. Detailed studies of the dose effects and costs of augmentation should be conducted in the field based on modeled predictions.

E. ***Reduce amount of bank revetment.*** Revetment includes any action to strengthen or armor channel banks to prevent or inhibit their erosion. The erosion problem is usually caused by changes in flow, sediment supply, or bed elevation that originate upstream of the revetment site (changes in bed elevation can also start downstream). Revetments treat the effects of these upstream (or downstream) changes but not their causes. The revetments, therefore, tend to fail and need replacement or repair. Where revetment is discontinued, the channel will tend to widen naturally, the channel banks will become less steep, and new floodplains will evolve below the level of the valley floor. The channel will eventually evolve a stable configuration relative to the prevailing flows and sediment supplies. The rate of channel evolution will depend on many factors, including the materials that comprise the banks. Clayey banks are not easily eroded and will slow the evolutionary processes. Bank erosion, channel widening, and natural floodplain development are expected to be very slow in most reaches in the valley due to the clayey nature and natural strength of the river banks. With localized exceptions, the processes could transcend generations of people living and working on the adjacent land. To accommodate these processes, most landowners along the river might only suffer a few feet of bank erosion in most years. Identifying local areas of more rapid erosion that might warrant revetment will be important. As the channel widens to achieve a stable configuration, it might temporarily increase the supplies of large woody debris and fine sediment from the riparian zone along the eroding banks. This might also temporarily increase the need to manage woody debris. The stable channel that eventually evolves would be much more complex in form and structure, and the problem of ongoing bank erosion would be greatly diminished.

This action may not be appropriate for some of the most deeply entrenched reaches of the river in the valley. These reaches typically are not revetted because they have clayey banks that naturally resist erosion. This action should target reaches where bank erosion tends to be rapid, and revetment is common, but away from any engineered crossings that might be threatened by the natural processes of channel widening. Bridges and other crossings should be analyzed to determine if their designs are consistent with a stable channel configuration.

F. *Floodplain construction.*
Discontinuing revetment (action E above) can help the channel achieve a wider and more stable configuration within a reasonable time frame in reaches where banks tend to erode. In the absence of revetment, these reaches tend to be less entrenched. In other reaches with less erodible banks, entrenchment tends to be more severe, the channel is in greater need of widening to prevent further incision, but natural bank erosion is slow. These reaches are not likely to achieve a wider stable configuration in the foreseeable future without intervention. One possibility is to construct an active floodplain by grading the channel banks. This action should be considered in the context of comprehensive river ecosystem restoration that is designed to restore many of the attributes of a healthy river throughout the valley. The height, length, and width of the constructed floodplain must be carefully planned based on consideration of its intended functions and the prevailing flow regimes and sediment supplies. The Napa River Rutherford Reach Restoration Project (http://www.co.napa.ca.us/GOV/Departments/DeptPage.asp?DID=29000&LID=1836) is a local example of a river restoration design that incorporates floodplain processes and functions including side channels.

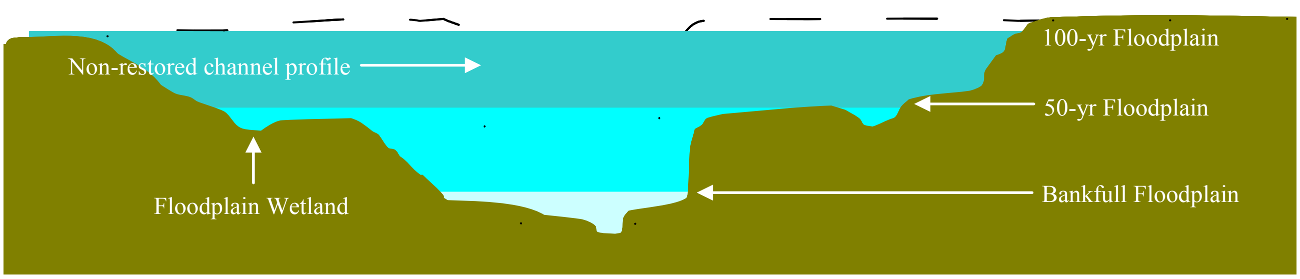
G. *Incorporation of multistage floodplain designs in restoration plans.*
This action is an elaboration of the fundamental approach to floodplain restoration described above as action F. In multistage floodplain design, multiple floodplains are constructed to coincide with differing water height or flood stages (Figure 33). The floodplain design works to minimize flood risks, store fine sediment, and maximize overall channel complexity (Herrick and Jenkins 1995, Rosgen 2007). It is applicable to reaches that have been artificially over-widened for prevailing flows, and to deeply entrenched reaches where adequate amounts of adjacent land can be dedicated to flood management. A two-stage design focuses on the low-flow channel and bankfull floodplain, and is intended to dissipate the energy of flood flows and to foster a balance in sediment transport, stor-

age, and supply (Sellin et al., 2007, NRCS 2007). Multistage design adds additional, higher floodplains to accommodate larger floods. It can help greatly to restore overall ecological complexity of the river ecosystem (McBain and Trush 1997, TRTAC 2000, Williams 2009). This approach is fundamental to restoration of the Trinity River in Texas where channel design accommodates multiple flow regimes through a series of floodplains at different elevations (http://trinitybasin.tamu.edu/). It is also being applied to the Trinity River in northwestern California.

Multistage designs can incorporate land uses that are compatible with frequent flooding and either tolerate or even benefit from infrequent flooding. For example, the historical natural primary productivity of the Napa Valley was due to flooding that renewed soil nutrients. Many crops including grapes can similarly benefit from floods if they are not accompanied by large amounts of debris that batters and otherwise damages fencing, above-ground irrigation, etc. In concept, multistage channel designs can include lower plains that are frequently flooded and dedicated to natural ecological functions, and higher plains that are infrequently flooded and can be productively farmed. The risk of large floods carrying destructive debris onto the farmed floodplains can be reduced by the filtering functions of the riparian vegetation of the lower plain(s), selective removal of hazardous debris, as well as the prevention of anthropogenic debris from entering the river from the built environment. Designs for the Rutherford Reach Restoration Project reflect careful consideration of the importance of accommodating frequent flooding within the channel system, but have not incorporated multiple floodplains.

H. ***Valley reservoirs and conjunctive use of sub-drains.*** This is a complex action involving the elaboration of existing agricultural water management practices to help meet environmental needs for water and future increases in agricultural water demands due to local climate warming. Models of climate change are improving but remain inexact at local scales, producing widely varying predictions of climate change effects. Some recent studies indicate that local mean annual air temperatures are likely to increase slightly, seasonal differences in mean temperature

FIGURE 33. Simple schematic diagram of the concept of multiple floodplains to accommodate floods of different size and frequency. The bankfull floodplain is designed to store fine sediment and thus increase the coarseness of the streambed. Other floodplains are designed to accommodate greater flood flows without causing excessive sheer stress on the bed, thus protecting it against scour and incision. Floodplains can include secondary channels and wetlands. The different plains and the sloping banks between them tend to support different communities of plants and animals. In time a diverse riparian community of trees and shrubs will develop, shading the river and providing large woody debris needed to create pools and other aquatic habitats. The optimal elevations and widths of the plains can be estimated from flow records, sediment regime data, and land use data.



will also increase, the wet season will be shorter, rain storms will intensify, and droughts may be more frequent and last longer (www.climatechange.ca.gov/research/index.html, Cayan et al. 2006, Dettinger http://www.agci.org/dB/PPTs/04S1_MDettinger_0313.pdf). One study suggests that climate change will have modest effects on grape quality in most regions over the next few decades (e.g., Cahill et al., 2008). However, another study suggests that, toward the end of the century, wine grapes could ripen as much as one to two months earlier, affecting grape quality in all but the coolest coastal locations (Lobell 2009). More severe deleterious impacts to grape growing have also been predicted (Stanford University 2009).

While predictions of climate change and its effects on wine grapes are variable, all suggest that significant effects will occur before the end of this century. While not considering the possible effects of climate change on grape growing, Napa County predicts an increase vineyard density (from 726 to 1815 vines per acre) and an expansion of vineyard acreage, perhaps 5,500 additional acres (NCFCWCD 2005). These predictions, as well as the expected new water demands due to a warmer climate, suggest that any approach to restore the ecological health of the Napa River and resolve its sediment-water problem should include greater and more flexible management of water supplies. Meeting the challenge of climate change will involve conservation actions (Low Impact Development, perhaps more dry-farming, conversion to drought-resistant grapevine root stock and varietals, etc.), and additional storage of wet season rainfall and runoff within the Napa watershed for its environmental and agricultural uses later in the water year. These uses could include frost control, irrigation, and seasonal flushing flows to scour the deep river pools and channel bars or to remove fine sediment from the channel bed and augment base flows (action A-C).

Groundwater is unlikely to be a long-term solution to any increase in water supply demand. While the Napa Valley aquifers are generally unconfined and have not experienced significant long-term declines with the exception of the smaller Carneros and Milliken-Sarco-Tulokay groundwater basins (DWR 1995, NCFWCD 2005), an ever increasing rate of groundwater pumping will eventually lower the aquifers, causing land subsidence, permanent loss of storage capacity, and increased pumping costs. The scenario is clearly evident in Central Valley and Santa Clara Valley (Poland and Ireland 1988, Wilson and Gorelick 1995). One consequence of subsidence would be a lowering of the base elevations of tributary channels that could cause another period of their incision (Jordan et al., 2010).

Increased use of reclaimed wastewater has been proposed as one way to meet future water demands. These waters might be injected into aquifers to maintain them, used to "top-off" existing private reservoirs as they are drawn down, or additional storage facilities might be required. It seems likely that additional local storage on the valley floor will be part of the long term solution.

It should be understood that increased diversions from the Napa River or the enlargement of local reservoirs by raising their dams may not be feasible in the current regulatory framework (NCFCWCD 2005). This report suggests, however, that all technically feasible options and approaches should be considered. Especially in the context of meeting the challenges relating to climate change, the changes suggested could influence how water resources are regulated. Important to note are the new federal guidelines for mitigation of unavoidable losses of waters of the US, including wetlands and streams protected under the federal Clean Water Act, that emphasize mitigation design in the context of comprehensive watershed plans (http://www.epa.gov/wetlandsmitigation/#regs). Also, the California Water Resources Control Board and its Bay Area Regional Water Board are developing separate but coordinated policies that are likely to encourage watershed planning to protect wetlands, streams, and riparian areas under the State's Porter Cologne Water Quality Control Act. (http://www.swrcb.ca.gov/board_decisions/adopted_orders/resolutions/2008/rs2008_0026.pdf,http://www.sfestuary.org/projects/detail.php?projectID=27). Alternatively, where feasible, the surface to depth ratios of existing reservoirs could be changed to increase their total volume by dredging accumulated sediments, while at the same time decreasing the evaporative surface area. This action would have the added benefit of increasing the arable acreage in the valley.

In concept, local above-ground storage to meet both environmental and consumptive water demands could be accomplished by augmenting the existing system of private reservoirs and sub-drains on the valley floor. Such a system would have to be carefully engineered and require ongoing management. The augmentation would involve adding reservoirs of similar size to those that now exist, into which reclaimed water and excess output from the drains could be transferred. Reservoir and drain management are variable: In general, after the drains have been tapped to fill the irrigation reservoirs (usually before February), the high groundwater is allowed to flow freely from the sub-surface drains and/or shallow ditches into the river. This flow is essentially an acceleration of the groundwater discharge that historically happened slowly throughout the spring and into the summer. This unnatural discharge of groundwater tends to increase during major storms and can contribute to peak river flows, thus increasing risks of river scour, incision, bank erosion, and perhaps flooding. Off-channel storage of this groundwater along the river in the valley could be achieved by increasing the existing storage capacity (without having to expand and possibly even decreasing the area required for this purpose). The off-channel storage could facilitate use of the river to restore critical hydrograph components – base flow between winter storms, extended spring recession flow, or summer base flow (Actions A-C), and to meet future increases in agricultural water demands. Reclaimed wastewater might also play a role in meeting the demands by making more of the groundwater available for environmental uses. Whether or not the reclaimed water can be used for environmental purposes or agriculture depends on its quality. Mixing it with groundwater may increase its usability. A system of interconnected local reservoirs filled with water from sub-surface drains and reclaimed wastewater, and cooperatively managed, should be considered as a way to meet existing and increasing water demands.

The design of any additional reservoirs should reflect the wetland habitat potential they could provide. For example, a reservoir might be designed in part as off-channel wetland habitat. This would require increasing the size of the reservoir relative to the size meeting only agricultural and in-stream environmental needs. Such multi-use reservoirs might be located in areas of historical wetlands where clayey wetland soils persist and growing conditions are less than optimal.

The evaporative losses from above-ground storage should be addressed. One creative solution has been taken by the Far Niente Winery to help wineries and local communities achieve energy independence. The winery has minimized evaporation on impoundments by covering a reservoir with solar panels[2].

I. *Selective restoration of beaver population to the valley.* Farming and flood control interests generally regard the North American beaver (Castor canadensis) as a nuisance species because of its tendency to forage in croplands and to increase flooding. For instance, beavers can increase the rate at which banks erode by burrowing into them. Beaver dams that are destroyed by high flows can add debris that increases the destructiveness of floods and the risk of clogging engineered river crossings. Beavers, however, can greatly improve river ecosystem health, (Pollock et al., 2004). Fine sediment can become entrapped behind beaver dams causing the bed downstream to coarsen. Large in-channel beaver ponds provide deep water areas and support complex pool systems. Studies indicate that Coho salmon fry reared in beaver ponds find more food, refuge from flood and predators and may reach twice the size of juvenile salmon that are not raised in beaver ponds (Pollock 2004). Managing beaver populations can involve planting and replanting suitable forage vegetation in the riparian zone, and more intensive management of large woody debris. Beaver populations can be difficult to contain within prescribed reaches. Areas where they might be allowed, however, are severely entrenched reaches of the river in the valley and tributary reaches where their dams, ponds, and bank excavations do not present unacceptable management risks.

A beaver population has established itself in Reach 4 of the Rutherford Reach Restoration Project, and signs of beaver activity are also evident in Salvador Creek.

J. *Replacement of unnatural tributaries with reservoirs and injection wells on alluvial fans.* This is a major activity that would require extensive feasibility analysis. The concept is to restore some of the groundwater recharge and sediment entrapment functions of alluvial fans. Under natural conditions, the tributary watersheds that created and maintained the fans also recharged the local aquifers. Some of this groundwater emerged along the toes of the fans and on the valley floor, forming wetlands. In addition, some of the groundwater coming through the fans drained into the river through its banks, contributing to base flow. The challenge would be to restore selected fan functions without restoring the dynamic nature of the surface channels that naturally move freely and frequently across fans, depositing sediments along the way. Such channel behavior is not conducive to most existing land uses on fans.

The sediment delivery and groundwater recharge functions of some fans could be restored while eliminating the ditches on the fans and without having to manage natural channels that tend to wander across the fans. One approach would be to shunt the flows of water and sediment into small reservoirs constructed near the apexes of the fans. These reservoirs could be fitted with injection wells to control the depth and magnitude of groundwater recharge. The wells could be closed near the end of the wet season to impound late season runoff and thus increase overall water storage capacity for agriculture and other uses. Overflows could be directed down the existing ditches to other multi-use reservoirs on the valley floor, or into wetlands (see action H).

2 See http://vinigator.finewinepress.com/archives/51490.

The reservoirs on the fans could also be used to capture sediment from the tributary watershed, the coarse fractions of which could be harvested and used to augment the supplies of coarse sediment in the river (see action D). If designed properly, there might be no overflow and therefore no reason to retain the ditches that were historically constructed through these fans. Eliminating them and their riparian areas could increase the amount of arable land that might offset some losses of farmland due to this and other management actions (e.g., actions F-H). The increased ecological health of the river that would result from restoring fan functions might offset the concomitant loss of the ditches and associated narrow riparian areas on the fans. As noted, this is a major activity that would require extensive ecological, engineering, and economic feasibility analyses.

K. ***Removal of selected dams on tributaries.*** There are hundreds of small reservoirs on tributaries in the Napa River watershed. Almost all of these small reservoirs are used to impound runoff for irrigation. Some of them are fitted with standpipes and thus function as sediment retention basins. The overflow from reservoirs or debris basins that is essentially devoid of sediment is either directed to other reservoirs or into a tributary channel or directly into the river. During major storms in very wet years, almost all of these reservoirs discharge sediment-rich water into channels, increasing the likelihood of their erosion. Reservoirs of this size and location do not contribute to groundwater recharge because they tend to become sealed with clays. The removal of small reservoirs could also improve overall water supply by reducing evaporative losses. This action would require a survey and analysis of the small reservoirs to determine which, if any, might be removed or redesigned to restore more natural fluvial processes in tributary watersheds, improve fish passage, and improve the continuity of riparian corridors within the tributary watersheds.

L. ***Replacement of ditches, culverts, and other engineered crossings based on state-of-science designs.*** In general, artificial drainage channels and engineered crossings are designed to safely convey selected high flows, such as 50-yr or 100-yr floods. The flow data are usually inadequate to account for site-specific conditions or to calculate realistic flow volumes without substantial uncertainty. The built structures are seldom designed to convey sediment. As a result, many ditches and crossings become choked with sediment and thus do not meet their design objectives for conveying flow. This action would require a survey and analysis to determine which, if any, ditches and crossings should be reconstructed or replaced based on designs that better meet the needs for conveying sediment and water, and for restoring more natural fluvial processes in tributary watersheds.

Roadside ditches and erosion from roads in general comprise a major water quality concern. Proven BMPs for controlling erosion from roadways need to be implemented as already recommended (Napolitano et al., 2009). This action can help meet the restoration goals for salmonid habitat by significantly reducing the supply of fine sediment, and thus reduce the need to construct floodplains, augment the coarse sediment supply, or otherwise manage the fine sediment after it reaches the channels.

M. ***Increased extent of dry farming, water conservation for irrigation and use of new frost control BMPs.*** There is a growing concern among the affected interests that local climate change will greatly increase the demand for water while decreasing its availability. While the actions described above suggest ways to increase water availability through retention and reuse, this action and the next one address ways to generally reduce demand.

There are many ways to reduce the rate at which agriculture uses water, and to potentially decrease the total amount of water that it uses. One obvious alternative is to decrease the amount of agriculture. By all accounts, this is not a desirable outcome. Ways of conserving water through revised agricultural practices are preferable. These include many practices already in use that could be expanded. Commonly known practices include the use of drip irrigation, low volume water-based frost control, conversion from water-based frost control to other methods, grape varietal selection, and a return to historical dry farming practices (http://www.napawatersheds.org/files/managed/Document/3072/101905tm3.pdf). A number of state policies or regulations are being discussed by the State Water Resources Control Board and its Regional Water Boards to limit water use for frost control unless such use has no significant environmental impacts (http://www.swrcb.ca.gov/waterrights/water_issues/programs/instream_flows, North Coast Stream Flow Campaign, http://www.ourstreamsflow.org/ab_2121.html). Emphasizing water conservation methods will help minimize necessary reductions in water use for frost control.

N. ***Increased Low Impact Development (LID) practices in urbanized and rural areas.*** LID is the suite of conservation methods and the related body of science directed at reducing runoff through landscape design and other water conservation tools and practices.

This action involves promoting the implementation of LID in a coordinated way that adjusts the methods to maximize their downstream environmental benefits in the watershed context.

The extent to which runoff from hardscapes in rural and urban areas contributes to the hydrograph of the Napa River is not known, but is probably not significant. Most of the urban runoff comes from the cities of Napa and American Canyon, near the downstream end of the watershed. Urban runoff mostly occurs during storms, when the river stage is dominated by natural and agricultural runoff. Discharge from sewage treatment plants may contribute significantly to base flow (Faye 1973), but urban runoff apparently does not, except near the outfalls of local storm drains. The ecological value of urban runoff could be increased by using it to create wet swales, seasonal wetlands, and other aquatic habitats along the river corridor. The LID community has developed a variety of aquatic habitat designs based on reuse of urban runoff (SCCWRP 2003). Techniques applied in urban areas may also be applied in more rural settings that have a larger percentage of impervious landscape use on individual parcels.

Relationships among Management Actions

Many of the individual actions described above can be combined into synergistic management scenarios to increase their overall efficacy.

- Actions A-C combine different kinds of water releases that begin to reproduce a naturalistic hydrograph, each component of which can help to sustain a particular suite of healthy river attributes.

- Actions D-G are increasingly complex methods of creating the physiographic template upon which the naturalistic hydrograph can operate to create a complex, dynamic mosaic of aquatic and wetland habitats that focuses upon salmon and steelhead but also benefits a very broad array of fish and wildlife species.

- All actions A-G could be implemented together at carefully selected reaches where the actions are most likely to meet their individual and combined objectives.

- Actions H and I are major activities for restoring hydro-geomorphic and ecological functions at the scale of multiple reaches, centered on confluences of the river in the valley and selected tributaries. These two activities might be combined to reestablish functional connections between alluvial fans, the valley floor, and the river using proven water management methods. Actions A-G can be built into action H to increase its overall ecological value.

- Additional ecological restoration can be achieved by removing reservoirs from areas of high agricultural value and reconstructing them for wetland functions and water storage in areas of lesser value to agriculture, such as historical wetland locations.

- Actions J-N are specific land use practices that can be implemented at a variety of locations throughout the river ecosystem to restore ecological and hydro-geomorphic processes, while conserving water and other natural resources.

These actions will require substantial investments in feasibility analysis, design, and management. Coordinated restoration could improve success at both the individual project scale and the watershed scale – particularly in cases where significant changes in sediment and/or water supply from upstream restoration would change conditions for downstream projects. The application of BMPs for water or sediment management among different projects must be coordinated to significantly improve salmonid habitat or other functions of the river ecosystem. An approach that emphasizes cumulative, landscape-level planning and action will more readily address system-wide alluvial river functions and attributes.

Coordinated restoration and BMP application in the watershed context will require a new level of cooperation among private and public partners, based on shared goals to secure adequate, sustainable water supplies for agriculture in Napa Valley, and to recover the ecological health of the Napa Watershed.

According to the Napa RCD Central Napa River Assessment Project final report, "a total of 135 potential restoration opportunities have been identified, mapped, and ranked according to their relative importance and cost. These restoration sites include 67 sites with exotic vegetation, 47 bank erosion areas, five migration barriers, eight riparian canopy sites, four sites with elevated water temperatures, and one potential site for immediate woody debris placement. Within the surveyed reaches, stream bank erosion was most prevalent followed by lack of riparian canopy, presence of migration barriers, and lack of rearing habitat. Restoration priorities for each of the ten surveyed streams are available from the Napa County RCD as separate documents, and are subject to landowner confidentiality agreements (Koehler 2005)."

Information Gaps

There are gaps in information about the basic nature of the Napa River watershed and how it is managed that need to be filled to inform management choices and assess their effectiveness. The largest or most basic gaps are identified below.

- A comprehensive base map is needed that shows the entire drainage network of the Napa River watershed. This map should identify natural channels of all sizes including headwater channels, and artificial channels including storm drains, ditches, and agricultural sub-drains. The map should include springs, wetlands, riparian areas, and all natural and artificial surface storage features including lakes and reservoirs. It should also contain groundwater recharge areas (as called for in the Napa County General Plan) to insure that incompatible land uses do not inadvertently impact groundwater resource management options[3]. The base map should be consistent with federal and California state standards for mapping watershed boundaries, wetlands, and drainage networks. The lack of such a map is the most fundamental information gap. It should serve as the base map for all environmental planning and management. The Bay Area Aquatic Resources Inventory (BAARI) could serve as such a base map were it to be validated using local knowledge (BAARi 2011).

Once the base map is complete, it should be used to locate any on-the-ground-management action that is expected to influence aquatic resources. Such actions might include engineered channel crossings, BMPs, outfalls of storm drains and agricultural sub-drains, wells, diversions, flood infrastructure features, and other selected land use facilities.

The base map might also be used to characterize the watershed in terms of the distribution and abundance of land uses, the degree of connectivity between the drainage network and impervious surfaces, and the geographic scope of management plans. For instance, BMPs are being applied widely throughout the valley through both regulatory and voluntary initiatives. Fish Friendly Farming projects and the Napa RCD's erosion control plans are currently not fully documented on a case-by-case basis. This precludes full geographic analysis of the impact of these practices at the sub-watershed scale. Incorporating these BMPs into the base map would provide more spatially explicit GIS-based tracking of these efforts and would be essential to assess their impacts and effectiveness.

- The lack of information about water budgets for major tributaries and for the watershed as a whole is a major information gap. Filling this gap will become increasingly important as the demand for water grows to meet various watershed management objectives. Much of the needed data to develop a basic water budget are available, but other data will need to be developed.

  Each water budget should partition inputs, storage, and outputs among the major natural and unnatural land covers for each major tributary. The analysis of inputs should separately quantify precipitation and water imports as measured amounts, not estimates. Storage will have to be estimated and should separately account for storage in reservoirs, channels, wetlands, vegetation, soil, and aquifers. Outputs should be estimated for evaporation from reservoirs and evapotranspiration from different vegetation types including vineyards. Sources of water for and outputs due to frost control should be documented for each vineyard. Annual total discharge should be measured for each major tributary and for the river in the valley upstream of each major confluence. The measures of discharge should be used to rectify the estimates and measures of other outputs and storage. The water budgets should be balanced with the levels of precision needed to appropriately allocate water for its different uses, including efforts to restore the physiographic and ecological complexity of the river ecosystem.

- The effects of land use on the storm hydrographs and annual hydrographs of each major tributary need to be explained in terms of response times, peak flows, and base flows. The relative contribution of each tributary to

3 An example of how groundwater recharge areas can be impacted is dramatically exemplified by the square miles of warehouse and light industrial development along the foothills of the San Bernardino Mountains in Southern California.

the storm hydrograph and annual hydrograph of the river in the valley should also be determined. This will provide the basic information needed to manage each tributary as an integral part of the greater Napa River watershed.

- General information about broad classes of management practices and their extent have been compiled (see APPENDIX 1). What remains elusive, however, is the ability to document the cumulative, watershed-wide benefits of parcel- or project-specific applications of practices intended to minimize erosion from exposed soil surfaces, including major hillslopes, roads, and stream banks. The level of existing documentation did not allow evaluation of the extent to which actions may already have been taken to reduce drainage connectivity and effect impervious surfaces, (such as certain engineered hill slopes) or to quantify runoff reduction, infiltration, evapotranspiration, and runoff storage enhancements. What is essential is the creation of a process for reporting the locations of BMPs and sub-surface drainage systems to assess their impact and potential integration into solutions to the water-sediment problems.

- Acquiring the density of data needed to link parcel-scale BMP implementation to watershed benefits is extremely difficult. Estimating the anticipated benefits of large-scale actions can be much easier when undertaken jointly by multiple parties with fewer, yet representative data points. Greater value may be gained at this stage from identifying a few large-scale, watershed-based improvements that can be achieved through collaborations among multiple landowners. For example, goals might include reducing the discharge of storms with a 1-5 year recurrence interval, doubling summertime base flow, or reducing average maximum summertime water temperature in the river through the valley by a few degrees. These simple goals will translate into alternative scenarios for land use and landscape designs that are likely to involve much of the watershed. A precedent for these kinds of joint actions has recently been set by the Rutherford Dust Society in their joint Rutherford Reach restoration effort, including the creation of a joint funding mechanism for long-term project effectiveness monitoring.

- There is very little information about the hydrological relationships between groundwater and river flow. Continuing to regard these two basic elements of the hydrological system as separate sources of water rather than a single integrated water system will decrease the chances of meeting management objectives.

  The base map described above should be used to locate the usual distribution and extent of gaining reaches and losing reaches of the major tributaries and the river in the valley. This information would be essential to understand the relationship between groundwater use or management, perennial flow, and base flow.

  The use of sub-surface drains to manage water in the root zones of vineyards and to drain hillside vineyards is poorly documented. With regard to sub-surface drains, the base map described above should be annotated with information about installation dates, drain sizes, output points, and typical seasonal operations. It is especially important to know the volumes of water drained by each system, what portion of this drainage is captured and dedicated to irrigation or other agricultural uses, what portion is delivered to a natural or naturalized channel, and the usual schedule of such deliveries.

The use of groundwater for irrigation and frost control is poorly documented. The base map that shows wells used for groundwater extraction should be annotated with information about well depth, pump size, pump operation including the monthly amounts of water pumped, and how the water is used.

- Information about the nature of the riverbed is inadequate to support sediment management efforts. Sediment budgets for each major tributary and for the river in the valley could be useful but are probably not necessary. What is required at a minimum is a comprehensive survey of the perennial reaches of the river in the valley and major tributaries to identify areas where existing coarse sediment supplies would support efforts to improve conditions for salmon and steelhead. This survey should also include an overall geomorphic assessment of channel condition focusing on entrenchment, current channel response mode (degrading, aggrading, migrating, etc), and bank stability. There are a variety of established methods to support such a survey, such as Proper Functioning Condition and the California Rapid Assessment Method (PFC, http://el.erdc.usace.army.mil/emrrp/emris/emrishelp6/process_for_assessing_proper_functioning_condition_tools.htm; CRAM, http://www.cramwetlands.org).

- Efforts to model channel evolution for this project were not totally successful. There is a paucity of input data needed to run the models and calibrate the models. The numbers of simplifying assumptions required to apply the models to different field conditions limit their application. Existing models pertain to specific aspects of river ecosystem response to selected management actions. Predicting river responses to the actions involves linking together models of runoff, sediment transport, channel morphological change, and vegetation succession, each of which is likely to vary with management actions. Different sets of models might be needed to address the wide range of actions that might occur over time along the river course. One set of models might be needed to predict reach-specific effects of individual actions and another set might be needed to predict their interactions and cumulative effects among reaches over time. Any modeling will have to be calibrated by comparing predicted and actual conditions. It should be remembered that no predictions will be exactly correct. Any future modeling should be carefully designed to directly address management concerns directly with a level of certainty specified by the managers.

- There is a lack of documentation on existing parcel-level management practices and their desired effects. Access to this information would facilitate investment in effective management practices and learning about what practices work or don't work.

Important studies are underway that could help fill some information gaps. A collaborative groundwater study has been recommended to Napa County that will further identify required data to document the status of aquifers in Napa Valley (Center for Collaborative Policy 2010). The County has funded the 2050 Napa Valley Water Resources Study to understand local and imported water supply and use, and to make recommendations to address future water needs. New findings from these studies could be integrated with existing data to help develop a comprehensive water budget for Napa watershed. However, neither of these studies will elucidate the relationships between groundwater usage and river hydrology. The State Water Resources Control Board (SWRCB) funded the development of a map of surface waters throughout the Bay Area based on new California State and Federal mapping protocols[4]. The Napa River Watershed could serve as the base map requested in this report portion of BAARI.

4 See comparison of mapping tables at: http://www.wrmp.org/protocols.html.

MONITORING CONSIDERATIONS

Monitoring at Redwood Creek.
Photo courtesy of Jonathan Koehler.

Monitoring Considerations

Important but limited monitoring of the Napa River is ongoing. Most of this monitoring relates to recovering and protecting Chinook salmon and steelhead trout. The Napa Creek Salmon Monitoring Project, initiated by the Napa RCD and begun in 2006, has been counting spawning salmon and steelhead, locating their redds, and assessing in-stream habitat parameters (Koehler 2008). Since 2009, a rotary screw trap has been deployed to count outmigrating salmonids (Koehler and Blank 2010). The TMDL calls for monitoring of streambed scour and permeability to determine progress toward in-stream TMDL targets for salmon and steelhead habitats. These monitoring efforts can provide essential information about the effects of management actions on salmonid conservation but little information about many of the complex factors that determine the overall health of the river ecosystem. An additional concern is that the monitoring recommended in the TDML staff report is not funded, and there is no long-term funding for the monitoring that is currently conducted by the RCD. The monitoring plan for the Rutherford Dust Society's Rutherford Reach Restoration Project will generate a comprehensive dataset for channel morphology in this reach. The plan calls for repeated channel transect surveys, local longitudinal profiles and streambed monitoring (i.e., pebble counts). Riparian vegetation monitoring is also included. This monitoring could provide basic information about the evolution of the restoration project. It is unlikely, however, to shed light on the response of the restoration reach to upstream actions, or on the effects of the restoration effort on downstream conditions, since these areas are not being comparably monitored.

The effects of management actions are frequently not well-understood due to a lack of monitoring. For instance, several dams have been removed in the watershed, yet their impact on the hydrograph and sediment delivery has not been characterized. An example is the 2002 Sulphur Creek dam removal. Dam removal has presumably increased coarse sediment transport downstream. Unfortunately, monitoring has not been conducted to quantify the effects of dam removal on downstream processes and their benefits to wildlife or people.

The existing regulatory framework for assessing project performance does not promote comparison among projects or the assessment of their cumulative impacts. The basic problems are a lack of standardized assessment methods, a lack of ambient monitoring to distinguish management effects from background variability or climate change, and a lack of access to monitoring data. Adjustments in the regulatory framework are being planned to address these problems. The US Army Corps of Engineers (USACE) and the USEPA have promulgated new guidelines for compensatory mitigation requiring mitigation projects to be consistent with watershed plans (www.epa.gov/owow/wetlands/pdf/wetlands_mitigation_final_rule_4_10_08.pdf).

The SWRCB is working with USEPA to develop State policy for planning and monitoring restoration and mitigation actions in the context of ambient watershed assessment (http://www.swrcb.ca.gov/water_issues/programs/cwa401/wrapp.shtml). The emerging policy adds specificity to the USACE mitigation guidelines by outlining the contents of watershed profiles that will serve as the foundation for comprehensive watershed planning. This represents a significant shift from the conventional project-by-project monitoring approach to a broader approach for analyzing interactions and cumulative effects among management actions within watersheds. The policy lays the foundation for implementing standardized water quality monitoring as called for by the California Wetland Monitoring Workgroup (http://www.waterboards.ca.gov/water_issues/programs/monitoring_council/wetland_workgroup/) of the Water Quality Monitoring Council (http://www.swrcb.ca.gov/water_issues/programs/monitoring_council/). While project-specific monitoring will continue to be an integral part of the regulatory process, new emphasis will be placed on understanding monitoring results in the context of ambient condition. Assessment methods will be standardized through formal peer-review conducted by the SWRCB and implemented through existing state and federal environmental regulatory programs, and through the State's Surface Water Ambient Monitoring Program (SWAMP; www.swrcb.ca.gov/water_issues/programs/swamp/). A major component of the developing policy is public access to monitoring data and information through regional online portals. The model for these portals is the Wetland Tracker information system (www.californiawetlands.net). These portals will use interactive, common base maps, as called for above, to enable the public to visualize and access information about aquatic resources and related projects without violating privacy concerns by individual landowners.

The community of environmental scientists, managers, regulators, and special interests that are focused on the Napa River watershed would benefit from implementation of the proposed statewide monitoring approach. It could provide the framework and standardized assessment methods needed to address the information gaps identified above. Additional standard methods can be developed and added to the assessment toolkit through SWAMP. The basic approach can be augmented to meet the particular needs of local projects and initiatives, such as the Napa TMDL.

Climate change increases the importance of a robust watershed monitoring program that uses standardized methods to map, monitor, and assess mitigation and restoration projects relative to ambient condition. In the absence of such a system, it is unlikely that the effects of management actions can be differentiated from the effects of climate change.

The SWRCB policy for protecting wetlands, streams, and riparian areas will include guidance for developing watershed profiles. The Policy Development Team expects that the guidance will be revised based on pilot watershed assessments. These assessments will help determine how watershed profiles might accommodate local variations in watershed conditions and management objectives.

For the Napa watershed, the monitoring program will need to support the restoration and mitigation efforts that are underway or being planned, as well as implementation of the TMDL, Low Impact Development (LID), wastewater reuse, and agricultural BMPs. To meet these needs, the monitoring program will have to include two basic elements: ambient monitoring and project-specific or targeted monitoring.

Ambient Monitoring

The ambient monitoring will need to have four basic elements: development and maintenance of a comprehensive base map of aquatic habitats and related facilities, periodic comprehensive measurement of land use and land cover, continuous fixed-station monitoring of rainfall and in-channel flow, and probabilistic surveys of field conditions.

- The base map is described in the section above on Information Gaps. It will serve to locate and track environmental conditions.

- Land use affects runoff, which in turn affects the hydrographs of channels that receive the runoff. Land use can be monitored by maintaining standardized maps of land cover types, and by annotating the map with information about land use practices. The practices might include irrigation and other water management practices, erosion control practices, etc.

- The hydrograph can be regarded as the performance curve for assessing the effects of upstream land use on aquatic resources. Understanding the functional relationship between land use and the hydrograph is essential for successful watershed management. This understanding depends on accurate data about how the hydrograph responds to variations in the amount and intensity of rainfall. The responses will vary with land use, geology, and topography, and can be quantified at various spatial scales. At a minimum, the contributions of each major tributary to the annual and storm hydrographs of the river in the valley should be monitored. Adequate monitoring will require at least one rain gauge in each major tributary watershed, plus flow gauges on the river above and below each major confluence. Additional rain gauges and flow gauges are recommended to adequately assess rainfall across the tributary watersheds, and to assess the effects of local land use practices. For example, temporary flow gauges might be installed above and below runoff BMPs, LID

BMPs, or frost control BMPs to assess their effectiveness. These data are also needed to build and calibrate hydrological models that can reduce the need for empirical data collection. The monitoring data should be telemetered to a central database that is accessible online. The existing information system for the Watershed Information Center & Conservancy (WICC; http://www.napawatersheds.org) might serve as a local portal for the needed database. The ambient monitoring should rely on probabilistic sampling design (Stoddard et al., 2005; Aquatic Resources Monitoring. http://www.epa.gov/nheerl/arm/designing/design_intro.htm) that accounts for how much of the resource being sampled is represented by sample data points. This design yields cumulative frequency distributions of sampling results that enable managers to compare each sample site to the overall ambient conditions of the watershed, and to compare one watershed to another.

- To be cost effective, the methods used in probabilistic ambient surveys should focus on physical factors that are clearly responsive to management actions and that enable managers to assess the ability of the river ecosystem to meet management objectives, in aggregate. There are many candidate methods to choose from (see review in Shilling et al., 2005). The following basic monitoring elements should be considered for inclusion in a probabilistic ambient survey of physical conditions of the Napa River ecosystem:

    - With regard to sediment, the main objectives for the Napa River are to eliminate excessive scour and incision of the riverbed, and to increase the coarseness of the bed for selected reaches. The sediment-water problem as identified for the Napa Watershed by its TMDL is very difficult to track (WARSSS http://water.epa.gov/scitech/datait/tools/warsss/index.cfm). The problem must be monitored by looking at all three of its basic components. Two components are rainfall and flow, as discussed above. The third is the sediment load that is transported by the flow, separated into suspended load and bed load. Both can be very difficult and expensive to assess accurately. Sources and amounts are particularly difficult to quantify because of their spatial and temporal variability. Furthermore, all three components are strongly influenced by local climate, land use, geology, and topography. Comprehensive monitoring of the sediment-water problem can require stratifying its three basic components based on these influential factors. It is unlikely that such a complicated monitoring effort can be sustained. Instead, the effort to monitor sediment might focus on progress toward desired endpoints.

    - There are proven field methods to assess conditions relative to these objectives. Some of these methods have been assembled by the US Forest Service (USFS) into a standardized toolkit for assessing reach conditions (Harrelson et al., 1994). It includes longitudinal profiles of bed conditions (aka thalweg profiles), cross-sectional profiles, and standardized pebble counts (Wolman 1954; Bevenger and King 1995), to assess temporal changes in channel form and bed material. Pebble counts, are inexpensive and use widely accepted protocols. This standardization enables direct comparisons between different pebble count data sets. Additionally, scientific field studies have resulted in a body of literature to interpret pebble counts and relate results to habitat. The pebble counts should be adequate for assessing the effectiveness of efforts to increase the coarseness of channel beds. The TMDL Staff Report also calls for monitoring the bed's permeability. This is more expensive but relates more directly to salmonid habitat conditions. A probabilistic ambient survey design focusing on physical factors that clearly respond to land use and climate change and are easy and relatively inexpensive to monitor will greatly improve the managers' ability to assess the performance of policies and projects intended to protect and restore the Napa watershed.

- Rapid assessment methods (RAMs) can yield cost-effective, field-based assessments of overall conditions that more specific methods cannot provide. RAMs typically involve standardized indicators of visible conditions to answer a set list of questions relating to the ability of a site to provide a broad range of ecological functions or services. Many rapid assessment methods have been developed for wadeable river or riparian corridors (NRCS 2001). In California, the two most often used RAMs are PFC and CRAM. Of these two, CRAM is probably more suitable for monitoring because it is more strictly standardized and is supported by an online database (http://www.cramwetlands.org). Most RAMs could be easily integrated into an ambient monitoring program.

- Monitoring methods can be added to an ambient monitoring program as needed to address particular management concerns. For example, as mentioned above, concerns about the river bed serving as spawning habitat for salmon and steelhead might warrant monitoring bed permeability. Concerns about aquatic pathogens might warrant including standardized measures of them along with other routine water quality monitoring.

- Ambient surveys can also be conducted to assess changes in the distribution and abundance of selected habitats by re-mapping selected large-scale plots. This is the approach being used by the USEPA and other federal agencies to track net change in wetland acreages nationwide (National Wetland Condition Assessment http://www.epa.gov/owow/wetlands/survey/), and is being recommended as part of the California wetland and stream monitoring program.

- Any method or indicator used to monitor ambient conditions within the Napa watershed should relate directly to a clearly defined management concern or objective.

Targeted Monitoring

Targeted monitoring is site-specific and has two components: projects and reference sites. Projects might include any effort on the ground that alters physical conditions of the river ecosystem. Such efforts certainly would include the restoration, mitigation, enhancement, or creation of aquatic or wetland or riparian habitats. Targeted monitoring would probably also include the installation, repair, or replacement of facilities or infrastructure that impacts aquatic habitats, such as culverts, ditches, bridges, sub-surface drains, etc. Many of these activities will include monitoring as a condition of their permits. Monitoring results should be tracked on the base map described above.

The concept of targeted monitoring also pertains to sites that are not part of any project but must be repeatedly monitored to address a particular management concern. For example, there are a few reaches of the river in the valley that tend to be selected by salmon for spawning, and these reaches have to be monitoring each year to assess spawning success. Other examples of targeted sites are those above and below wastewater outfalls or confluences that must be monitored to assess permit compliance or land use management effects.

To the extent possible, the targeted monitoring should include identical methods to those that are used in the ambient surveys. For example, thalweg profiles, cross-sections, and bed conditions of restoration projects, mitigation projects, and ambient assessment sites should be monitored using exactly the same methods. This is the only way to compare one project to another, to track change from an individual project over time, and to assess how projects perform relative to ambient condition. Method development will need to involve peer-review and vetting among the responsible agencies.

Concepts of reference condition are evolving. Standardized ambient surveys provide a reference framework for assessing conditions of projects and other specific sites, relative to overall or background conditions. In this context, there are no fixed reference sites because the ambient assessment relies on a probabilistic sample design. The sample design might be augmented with fixed reference sites used to understand how changes within sites contribute to the statistical variability of ambient surveys (Olsen and Peck 2008, Stein and Bernstein 2008).For example, individual reaches along the river in the valley might naturally change from one year to the next in ways that cannot be elucidated by less frequent ambient surveys (although the surveys should reveal net change).

The response of the river ecosystem to climate change or to large-scale management actions may take place over decadal or longer periods. This further increases the need to standardize methods among projects and ambient surveys to maximize their value across timeframes.

Significant public and private funds are being spent to protect, restore, enhance, and manage the Napa River ecosystem. Managers and the concerned public are not always able to evaluate the return on these investments, however, because ambient conditions are not being monitored, projects are monitored in disparate ways, data quality is variable, and the monitoring results are not readily available to analysts and decision makers. These shortcomings can be corrected by carefully building a monitoring program around a common base map and standardized methods to track fundamental aspects of ecosystem condition, as outlined above. Improving the health of the Napa River ecosystem requires a commitment to monitor the effects of the health care efforts.

CONCLUSIONS

Cobbles and boulders along Sarco Creek.
Photograph courtesy of Jonathan Koehler.

Over the past two centuries, the Napa River in Napa Valley has undergone significant changes in form and function due to land use. Simply stated, the river in the valley has become overly connected to surface runoff and shallow groundwater, and disconnected from much of its coarse sediment supply. The resulting increase in flow and reduction in coarse sediment load has caused the channel to become deeply entrenched within its valley. Land use has encroached far into the riparian zone, eliminating many of the natural riparian functions. The river has become an efficient conduit for runoff and sediment, with little of its historical ecological value. In short, many of the attributes of a healthy river are greatly diminised.

Landowners and other stakeholders in the Napa River watershed are well-positioned to use these findings to guide recovery of the river's health. Measure A funding may be one avenue for planning and implementing management and restoration projects at the watershed scale that address multiple healthy river attributes. Measure A funds have partially enabled the Rutherford Reach and the Oakville Cross Road to Oak Knoll Avenue restoration projects. Large-scale, coordinated restoration efforts have been initiated that are a great improvement over uncoordinated small-scale projects. These restoration efforts have demonstrated that large-scale projects designed in the watershed context can be implemented, despite some significant institutional challenges. These projects required the involvement of multiple landowners, combined funding from multiple private and public sources, a long-term adaptive management approach, and the support of multiple state and local permitting and implementation agencies. Highly coordinated, truly watershed-scale efforts to improve the Napa River's function can reference lessons learned about collaboration and cooperation from these projects. The technical advisory teams for these projects might find this report relevant for future phases of implementation.

The Napa River community has an engaged set of stakeholders particularly within the winegrower community. Landowner participation in the Fish Friendly Farming program demonstrates a commitment to stewardship of the watershed. Napa Sustainable Winegrowing Group (NSWG) seminars, annual Napa County Watershed Symposia and the WICC are well-established avenues to continue outreach and education using this report and its findings. Steps should be taken to translate the findings from this report into readily understood, actionable products for the Napa River community. Over time, a menu of approaches could be developed for enhancing the river's capacity for pollution filtration, groundwater recharge, flood protection, landscape, native riparian and aquatic species support and, of course, salmonid support.

The need for ongoing research and monitoring will not wane. A better understanding of the relationships between land use and river health will certainly lead to better land use designs and decisions. The scientific understanding will need to be translated into public commitment to restore the ecological health of the Napa River.

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APPENDICES

Appendix I

Napa River Watershed BMP Analysis

Appendix II

Stream Flow Model Methods and Results

Appendix III

Reservoir Storage Capacity and Evaporative Losses: Napa River Watershed

Appendix IV

Napa River Watershed – Reservoir Sediment Trapping

Appendix V

Historical Cross Sections

Appendix VI

Landscape Evolution – Historical

APPENDIX I

Napa River Watershed BMP Analysis

Prepared by Napa County Resource Conservation District

At the request of San Francisco Estuary Institute (SFEI), Napa County Resource Conservation District (RCD) performed a Geographic Information Systems (GIS) analysis to estimate the acreage within each subwatershed of the Napa River Watershed that is currently being managed under various Best Management Practices (BMPs), and to further divide the BMP areas by erodibility risk. The BMPs include the:

- Napa County Erosion Control Plan (ECP) Program;
- Fish-Friendly Farming® (FFF) Certification Program; and,
- State of California Timber Harvest Plan (THP) Program.

Best Management Practice Data

RCD obtained BMP data from the County of Napa and the California Land Stewardship Institute. The data are described in the TABLE 1.

Subwatersheds

The County of Napa has divided the Napa River Watershed into subwatersheds. The *cnty_drainages.shp* layer was prepared manually by County staff from USGS contour lines, and broke the river basin into 93 subwatersheds.

In 2005, the County created a new layer called *cnty_drainages_2005.shp* that was generated from the County's 1-meter Digital Elevation Model (DEM), and is more accurate than the original layer, but broke the river basin into 102 subwatersheds. Fewer subwatersheds were desirable for this project, so RCD began with the *cnty_drainages_2005.shp layer*, and merged the subbasins by major river tributary, resulting in a total of 33 subwatersheds. The merging was carefully done in such a way as to also be representative of any subbasins in the cnty_drainages.shp layer that contained 2003 FFF areas. The new layer is called *sfei_subs.shp* and includes the subwatershed name and area in acres.

TABLE 1. BMP Datasets.

Data	Description
ECP	GIS point shapefile in which each point represents an area managed under an ECP and is located on the parcel associated with the ECP. The area in acres associated with each ECP was provided as an attribute of each point.
FFF	List of vineyard acres and total acres managed under the FFF program by subwatershed. Provided in two datasets, called 2003 and 2006. The 2003 dataset was organized using the older cnty_drainges.shp subwatershed layer. The 2006 data are organized using the cnty_drainages_2005.shp layer, except for the valley floor areas that drain directly to the Napa River. These areas are broken out based on the Oak Knoll and Zinfandel bridges, which do not correspond with subwatershed boundaries.
THP	GIS polygon shapefile in which each polygon represents the area managed under a THP.

Subwatersheds

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Erodibility Risk

RCD received a spreadsheet from SFEI that included RKLS* values by multiple unit symbol (musym), an attribute in the Napa County soils layer *nap_ssurgo.shp*. SFEI also provided RCD with the desired risk categories, as shown in TABLE 2.

TABLE 2. Erodibility Risk Categories.

RKLS	Risk Category
2 - 31	1
32 - 84	2
85 - 174	3
175 - 304	4
305 - 584	5

RCD added a column to the spreadsheet containing the erodibility risk category for each musym, then joined the spreadsheet to the soils layer. A new layer, *risk.shp*, was created and dissolved based on erodibility risk category. RKLS values were not provided for musym 174 (riverwash), 175 (rock outcrop), 183 (water), 184 (dam), and 185 (pits, quarry). These areas were lumped into risk category 0. In nearly all cases, risk category 0 areas were found to be associated with either open water or rock outcrop. Although these areas should not coincide with BMP areas, they did, to a small degree, due to soil mapping errors and overlap between datasets. RCD evaluated each subwatershed in which BMP areas coincided with risk category 0 areas, and noted the dominant surrounding risk category (TABLE 3). Category 0 areas were then added to the acreage for that category.

Timber Harvest Plans

THP areas have been mapped, and therefore calculation of THP area by subwatershed in each erodibility risk category was a simple task. The THP data were clipped to the Napa River Watershed, then unioned with the subwatershed layer to add the subwatershed as an attribute to each THP. Using the Tabulate Area tool in Spatial Analyst, the THP layer, by subwatershed, and the risk layer, by risk category, were converted to 50-foot gridded data and the common areas were computed. No THP areas were located within risk category 0 areas, so no correction was necessary. RCD converted the results in square feet to acres. The total acreage after the calculation was 421.1 acres, compared to an actual total of 422.6 acres. The 0.35% difference is due to THP areas that fall into a gap between the erodibility risk data and the subwatershed layer, ultimately due to incomplete soil data near the Napa River Watershed boundary, and the conversion of the data to a grid.

Friendly Fish Farms

FFF areas have not been mapped. RCD was only able to obtain FFF acreage by subwatershed. In order to estimate the erodibility risk of these areas, it was necessary to select a proxy for the FFF areas. FFF includes vineyards, roads, and riparian zones, however, vineyard area is always a significant element and usually the major element in any FFF project. Therefore, RCD computed the erodibility risk based on total vineyard in each subwatershed, and scaled the result appropriately to match the actual FFF area.

*RKLS is an indicator of erodibility as determined by the Universal Soil Loss Equation. RKLS takes into account rainfall (R), soil characteristics (K), and length/slope factors (LS).

TABLE 3. Risk Category to Which Category 0 Area was Added.

Subwatershed	Risk Category	Percentage of Total Vineyard Acres in Category 0	Percentage of ECP Vineyard Acres in Category 0
American Canyon Creek	NA		
Arroyo Creek	NA		
Bale Slough	4	0.15%	
Bell Canyon Creek	4	1.53%	2.66%
Blossom Creek	NA		
Carneros Creek	1	0.18%	0.18%
Congress Valley Creek	1	0.19%	0.23%
Conn Creek	5	1.59%	1.73%
Cyrus Creek	NA		
Dry Creek	1	0.29%	0.03%
Fagan Creek	NA		
Garnett Creek	1	0.63%	
Huichica Creek	3		0.01%
Kimball Reservoir	NA		
Kortum Canyon Creek	1	0.13%	
Mill Creek	NA		
Milliken Creek	4	0.97%	3.28%
Napa Creek	NA		
Napa River – Lower Reach	1	0.85%	0.45%
Napa River – Middle Reach	1	0.10%	0.05%
Napa River – Upper Reach	1	1.50%	1.17%
Napa River Marshes	1	0.30%	0.08%
Ritchie Creek	1	0.05%	
Salvador Channel	1	0.01%	
Selby Creek	1	10.99%	
Sheehy Creek	NA		
Simmons Canyon Creek	NA		
Soda Creek	NA		
South Creek	NA		
Sulphur Creek	1	0.60%	
Suscol Creek	NA		
Tulucay Creek	4	0.72%	
York Creek	NA		

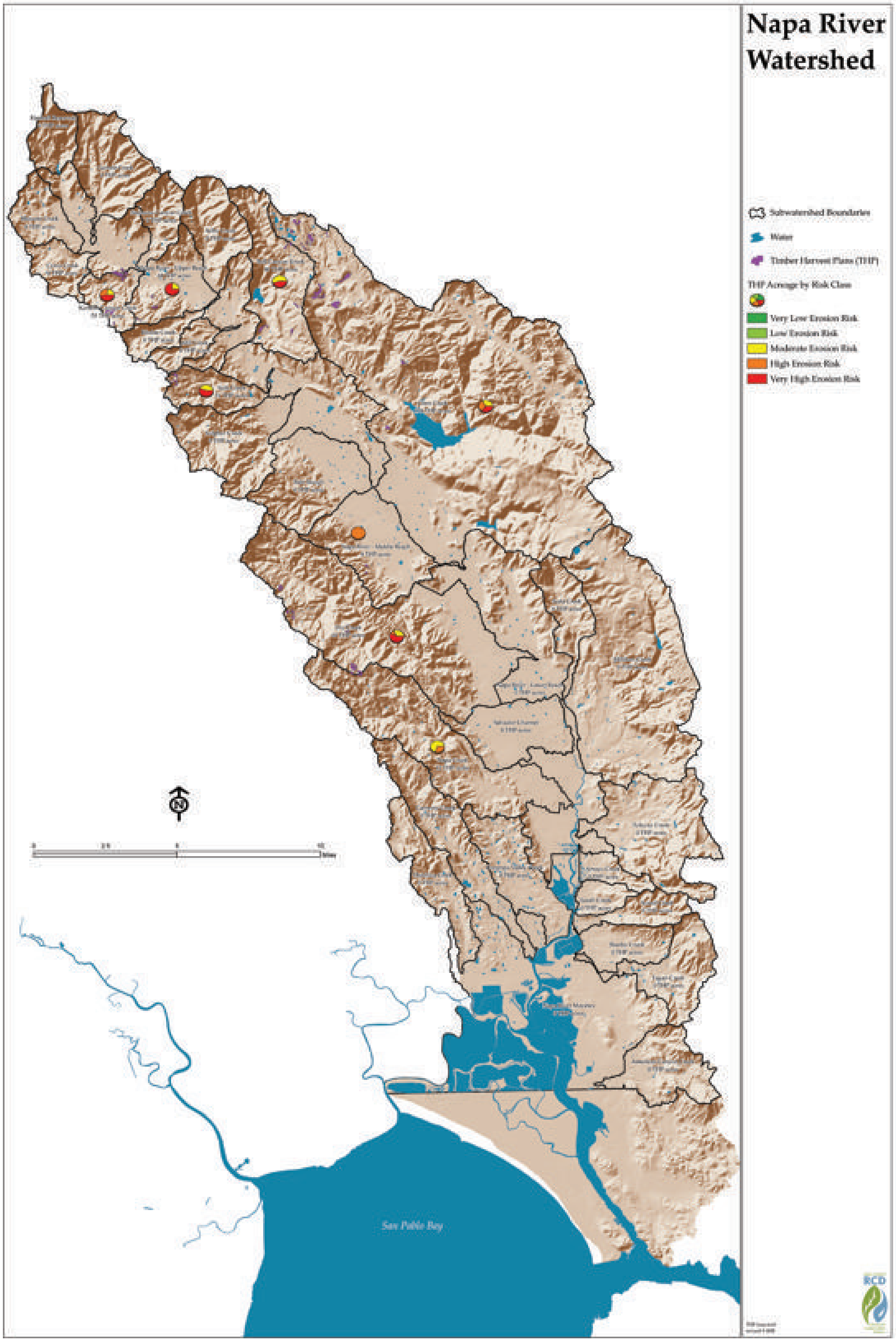
Two sets of FFF data were received, one from 2003 with vineyard and total acreages organized by old County subwatershed, and one from 2006 with vineyard and total acreages organized by new County subwatershed. A comparison revealed that the 2006 data do not include the 2003 data, therefore they could be summed into total FFF area. First, RCD had to appropriately group the areas to match the subwatershed layer for the project. The layer had been carefully created so that drainages with FFF acres in either of the County layers could be lumped into it. It was however based on the *cnty_drainages_2005.shp layer*, so there is a potential for error in the 2003 FFF data near the subwatershed boundaries. Also, the 2006 FFF data from the valley floor were lumped into Upper, Middle, and Lower Napa River with respect to bridges, and not drainage boundaries. These data were assigned to the respective Upper, Middle, and Lower Napa River reaches in the new subwatershed layer, even though the potential for error between them was quite large. Fortunately, the valley floor is dominantly mapped as risk category 1.

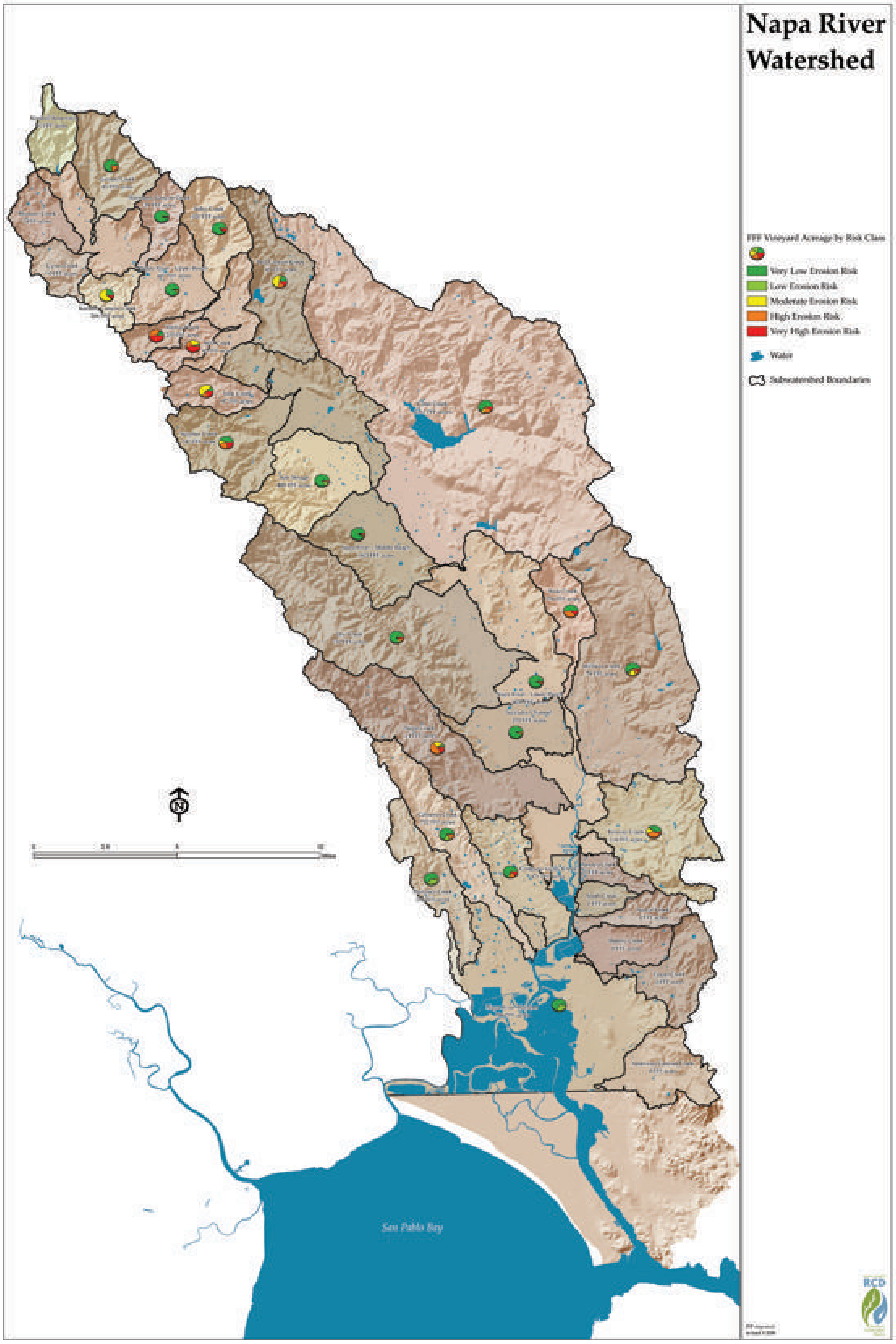
RCD grouped the total vineyard area by subwatershed, and computed area by risk category as described above in the THP section. The total acreage after the calculation was 42,760, compared to the actual total of 43,157.6 acres. The majority of this 0.92% difference is due to approximately 260 acres of vineyards that fall in the gap between the risk and subwatershed layers. Risk category 0 areas totaled 0.67% and were added to the appropriate risk category as shown in Table 3. The calculated vineyard by risk areas were converted to percentages of the subwatershed total, and multiplied by the actual subwatershed FFF area.

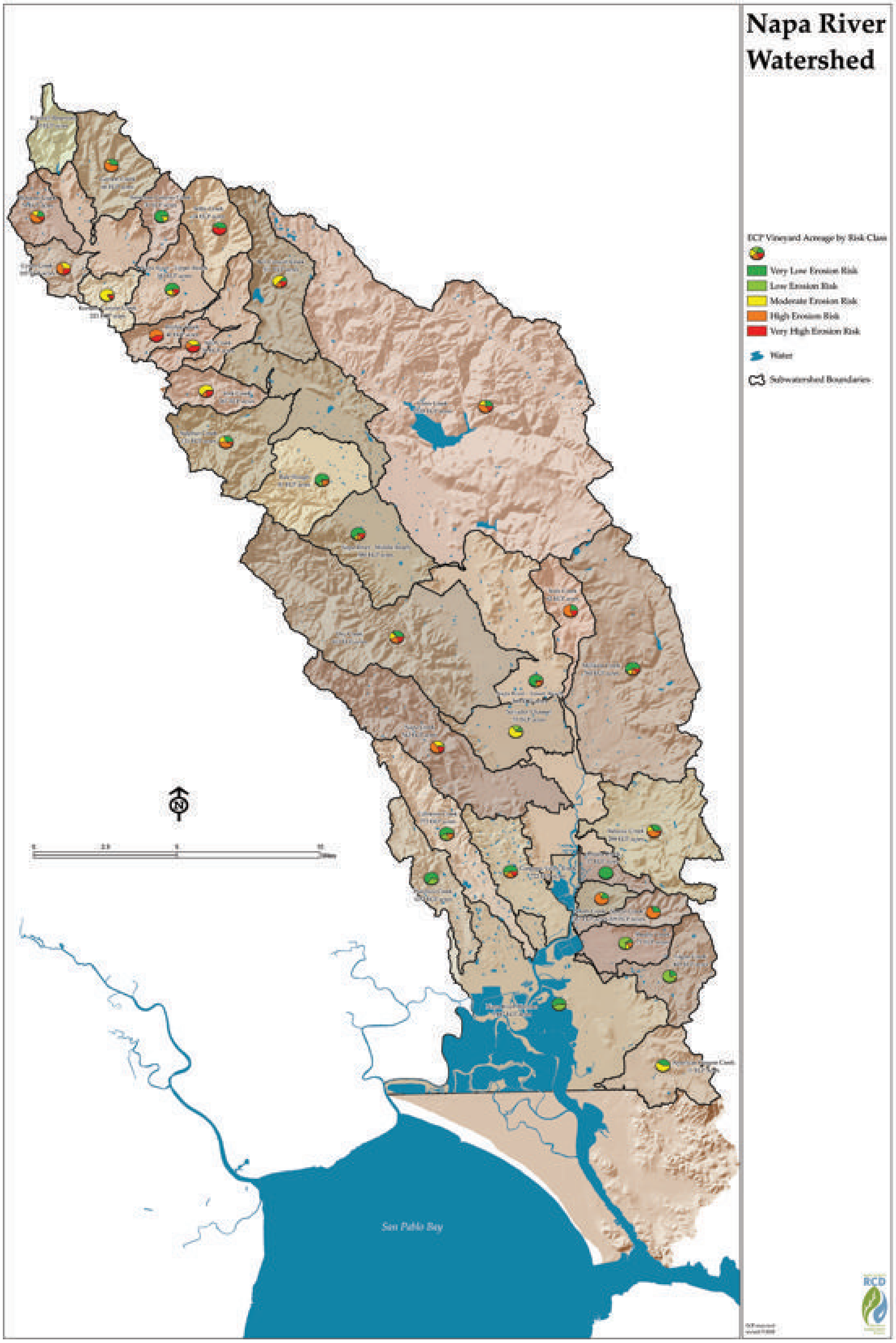
Erosion Control Plans

ECP areas have also not been mapped, however the parcel associated with each ECP is known. RCD selected specific vineyard polygons that intersected the ECP parcels resulting in a selection of 15,157 acres, much closer to the ECP project area of 13,094 acres than the 43,158 total vineyard acres in the Napa River Watershed. First, RCD used the ECP point file obtained from the County to group the ECP project acreage by subwatershed. This may introduce error between neighboring subwatersheds because it is possible that, if near a drainage boundary, the point (associated with a parcel) could fall in one subwatershed while all or some of the corresponding vineyard could be in the adjacent subwatershed. RCD then grouped the selected vineyards by subwatershed, and computed area by risk category. The total acreage after the calculation was 14,876.3 acres. The vast majority of the 1.85% difference being the same 260 acres (approx.) of vineyard described in the FFF section. Risk category 0 areas totaled 0.57% and were added to the appropriate risk category as shown in TABLE 3. The calculated ECP vineyard by risk areas were converted to percentages of the subwatershed total, and multiplied by the actual subwatershed project area.

■


Napa River Watershed
Subwatershed Boundaries
Water
Timber Harvest Plans (THP)
THP Acreage by Risk Class
Very Low Erosion Risk
Low Erosion Risk
Moderate Erosion Risk
High Erosion Risk
Very High Erosion Risk
San Pablo Bay


Napa River Watershed
FFF Vineyard Acreage by Risk Class
Very Low Erosion Risk
Low Erosion Risk
Moderate Erosion Risk
High Erosion Risk
Very High Erosion Risk
Water
Subwatershed Boundaries
San Pablo Bay
RCD


Napa River Watershed
ECP Vineyard Acreage by Risk Class
Very Low Erosion Risk
Low Erosion Risk
Moderate Erosion Risk
High Erosion Risk
Very High Erosion Risk
Water
Subwatershed Boundaries
San Pablo Bay
RCD

APPENDIX II

Stream Flow Model Methods and Results

Introduction: Building Confidence in Napa Modeling Outcomes

This technical memorandum is designed to help provide document the validity of modeling outcomes. Here we strive to present model methods and outcomes in a transparent and relevant manner. This appendix also documents results of intended to characterize model uncertainty and robustness.

The basic objective of this modeling effort was to shed light on the relationships between land-use practices, hydrology, and geomorphic change in the Napa River as a means to evaluate effective additional options for reducing fine sediment inputs to the river. Two nested models were developed to meet this objective. First, a hydrologic model was developed to estimate the effects of land-use change on streamflow. Second, a model of in-stream geomorphic processes was developed to estimate the response of channel sediments (bed and bank) to changes in streamflow.

More specifically, these models were intended to identify the relative value of alternative management scenarios for three broad fine-sediment reduction strategies: (1) Minimizing excessive soil erosion (with "excessive" being defined as off-site soil transport in excess of conditions prevailing under natural land cover); (2) preventing excessive sediment from reaching the drainage network or storing it in the floodplains; and (3) minimizing bank and bed erosion. Theses models can also be used to generate more specific testable hypotheses along the following lines:

1) The altered hydrograph contributes to channel instability and significant bank and bed erosion.

2) An increase in the duration and flow during the declining limb of a storm hydrograph is capable of decreasing fine sediment and restoring salmonid spawning and rearing habitat.

3) A decrease in drainage connectivity is capable of reducing shear stress on bed and banks and will lead to a more stable channel without excessive erosion of fine sediment from banks and bed.

4) Multiple land and water management options exist that could produce a hydrograph conducive to greater bed and bank stability.

Hydrologic Model

Background

The watershed modeling software Hydrological Simulation Program – FORTRAN (HSPF) was chosen for this project, as it is a comprehensive watershed model of hydrology and water quality. HSPF is public-domain software jointly supported and maintained by the U.S. EPA and the USGS and it is widely used across the United States for watershed modeling. HSPF has been used locally to model hydromodification in the Bay Area Hydrological Model (http://www.bayareahydrologymodel.org/) and to estimate copper in urban runoff by the Brakepad Partnership (http://www.suscon.org/bpp/index.php).

The model requires watershed geometry (size, slope), land-use, and soil characteristics as basic setup parameters. As inputs, time-series of precipitation and evaporation are required. Time-series of temperature can be used as input to the model but are not required (temperature is most important when evaporation data are not available). In order to model a hydrologic system accurately, all water sources and sinks must be included. For undeveloped watersheds, specifically those with no hydromodification, precipitation (source) and evaporation (sink) data drive the model simulations. However, hydromodified watersheds can have numerous other water sources, such as subsurface drains, reservoir releases and irrigation, and other water sinks, such as diversions and percolation ponds. For a given watershed to be modeled, all pertinent water data, including water management practices, must be obtained or estimated for the simulation time period. Often, the lack of these data constrains the simulation period and overall model performance. However, it is important to understand the intended uses and desired performance criteria of the hydrologic model when evaluating which data to include.

Setups

For this study, a spatially averaged (i.e., one-box) HSPF model of the Napa River Watershed was constructed to estimate the effects of land-use change on streamflow. Precipitation records were obtained from the St. Helena and Napa State Hospital weather stations for the period 1987 to 2006. This time period corresponds to the period when daily mean flow data required for model calibration were also available. Evaporation records were obtained from the California Irrigated Management Information System (CIMIS). Land-use/land-cover data for the Napa River watershed were obtained from the EPA's Spatial Data Library.

Calibration

Calibration of the hydrologic model was performed by comparing modeled daily-averaged streamflow to observed daily-averaged streamflow at USGS gage #11458000 (Napa River near Napa) from 1987 to 2006. Calibration was performed by both graphical and statistical analysis (e.g., correlation coefficients). Calibration was achieved by adjusting storage volumes and flux rates until the model *reasonably* reproduced the observed streamflow.

Defining what constitutes a *reasonable* simulation of observed streamflow requires knowledge of anticipated uses of simulated streamflow. For this project, simulated streamflow was used for two specific purposes: 1) to reconstruct the historical hydrograph and 2) to drive an in-stream sediment transport model under various stream-connectivity modification scenarios (i.e., to assess the effects of "disconnecting" portions of the watershed drainage on stream stabilization). The required level of certainty needed for these uses of simulation results determine what is a *reasonable* simulation.

Reconstructing a historical (pre-colonial) hydrograph has many intrinsic uncertainties, many of which are greater than the uncertainties of any given hydrologic model. It is difficult to know for certain what the landscape and weather patterns were like. Where were the main channel and its tributaries? What was the channel geometry? Where were the most erodible soils? What was the infiltration capacity of the soils? What were the prevailing precipitation patterns? Given these unknowns, the simplest approach to reconstruct the hydrograph is to calibrate a hydrologic model to current conditions and then change the model parameters to reflect some of the landscape differences mentioned above. It is difficult to assess the accuracy of the resulting reconstructed hydrograph; and it is certainly unreasonable to expect that it captures the day-to-day variability of the historical system. It is, however, reasonable to expect that the reconstructed hydrograph captures the overall shape of the historical hydrograph. Thus, for the purpose of historical hydrograph reconstruction, a reasonable calibration of the hydrologic model is one that captures observed hydrograph variability on the scale of weeks to months.

TABLE A3-1. HSPF model parameters used in this study compared to values reported elsewhere.

Name	Definition	Typical values (Basin Tech Note 6)	Local values (various studies)	Current Conditions					Est. Historic Conditions		
				Urban	**Ag**	**Range land**	**Forest**	**Wetland**	**Grass land**	**Forest**	**Wetland**
LZSN	Lower zone nominal soil moisture storage	3.0 - 8.0	3.5 - 11.0	4.0	4.0	6.0	7.0	6.0	13.0	15.0	12.0
INFILT	Index to Infiltration Capacity	0.01 - 0.25	0.02 - 0.70	0.04	0.04	0.04	0.08	0.06	0.20	0.30	0.20
LSUR	Length of overland flow	200 - 500	200 - 400	250	250	250	250	250	250	250	250
SLSUR	Slope of overland flow	0.01 - 0.15	0.05 - 0.25	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
AGWRC	Base groundwater (GW) recession	0.92 - 0.99	0.950 - 0.997	0.95	0.95	0.95	0.96	0.97	0.98	0.99	0.99
INFEXP	Exponent in infiltration equation	2	2 - 3	2	2	2	2	2	2	2	2
INFILD	Ratio of max/mean infiltration capacities	2	2	2	2	2	2	2	2	2	2
DEEPFR	Fraction of GW inflow to deep recharge	0.0 - 0.2	0.02 - 0.45	0.4	0.4	0.4	0.3	0.3	0.04	0.02	0.02
BASETP	Fraction of remaining ET from baseflow	0.00 - 0.05	0.03 - 0.15	0.02	0.02	0.02	0.05	0.05	0.02	0.03	0.03
AGWETP	Fraction of remaining ET from active GW	0.00 - 0.05	0	0	0	0	0	0.04	0	0	0.20
CEPSC	Interception storage capacity	0.03 - 0.20	0.02 - 0.20	0.1	0.1	0.1	0.15	0.15	0.2	0.4	0.3
UZSN	Upper zone nominal soil moisture storage	0.10 - 1.00	0.3 - 1.5	1.0	1.0	1.0	1.2	1.2	1.4	1.5	1.5
NSUR	Manning's n for overland flow	0.15 - 0.35	0.25 -0.35	0.2	0.2	0.2	0.2	0.2	0.35	0.40	0.40
INTFW	Interflow inflow parameter	1.0 - 3.0	0.35 - 6.0	0.8	0.8	0.8	1.0	1.0	5.0	6.0	6.0
IRC	Interflow recession parameter	0.5 - 0.7	0.3 - 0.8	0.5	0.5	0.5	0.5	0.5	0.85	0.90	0.90
LZETP	Lower zone ET parameter	0.2 - 0.7	0.0 - 0.8	0.5 - 0.7	0.5 - 0.7	0.5 - 0.7	0.6 - 0.8	0.6 - 0.8	0.6 - 0.8	0.6 - 0.8	0.6 - 0.8

Local values were obtained from several bay area HSPF modeling efforts:
Aqua Terra - Alameda Ck & Castro Valley Ck Watersheds HSPF calibration report
Clear Creek Solutions - Ross Ck & Thompson Ck Watersheds HSPF calibration report
Brown and Caldwell - Contra Costa Co. Clean Water Program HMP HSPF modeling memorandum

Likewise, assessing the effects of disconnecting portions of the watershed from the main channel on in-stream geomorphic change has many intrinsic uncertainties. There are, for example, uncertainties associated with the field methods used to assess geomorphic change and with the geomorphic model used to predict further change (see discussion later in this report for description of the geomorphic model used in this study). Furthermore, geomorphic processes operate over a range of time-scales ranging from single events (i.e., days) to millennia. The relative contribution of these time-scales to overall geomorphology is difficult to assess. Thus, similar to the example above, a reasonable calibration for the hydrologic model used to drive the in-stream geomorphic model is one that captures the variability of the observed hydrograph on the scale of weeks to months.

Sensitivity Analysis

The sensitivity of model outcomes to variations in individual model input parameters was tested to identify key parameters governing model outcomes. This analysis serves as a test of the internal mechanics of the hydrologic model and, when results are conceptually acceptable, helps build confidence in model outcomes.

The sensitivity (S) of each model parameter was determined as:

$$S = \frac{(O-O_0)}{O_0} + \frac{(P-P_0)}{P_0} \qquad (1)$$

Where O is the perturbed model outcome, O_0 is the original or 'baseline' model outcome, P is the perturbed model input parameter, and P_0 is the best estimate (i.e., calibrated value) of the given model input parameter. Expressing model sensitivity in this way allows the individual model input parameters to be ranked relative to one another. The goal of the hydrologic model in this study was to estimate stream discharge under varying land-use and stream connectivity conditions. Thus, total annual stream discharge was deemed the most useful outcome to assess the sensitivity of the hydrologic model to changes in input parameters.

Results of the sensitivity analysis are presented in **TABLE 1**. It must be noted that due to the non-linear nature of many of the modeled processes and the complex interactions of the various processes, the sensitivities determined here only apply to the ranges over which they were calculated.

Results indicate that the hydrologic model is most sensitive to precipitation and evaporation. Actually, the model is more sensitive to an increase in precipitation than it is to any other parameter; a 50% increase in the precipitation nearly quadrupled the estimated total annual stream discharge. No other single model parameter elicited this response. Fortunately, precipitation and evaporation are fairly well characterized in the Napa watershed. Model sensitivity to these parameters is, thus, not of major concern. To the contrary, model sensitivity to these parameters is positive reinforcement that the internal mechanics of the model are functioning appropriately. Precipitation and evaporation are the main drivers of streamflow in semi-arid environments.

The other model parameters tested all have to do with how water is moved between surface and subsurface compartments. Model results are substantially less sensitive to these parameters than they are to precipitation and evaporation. However, these parameters are not as well characterized in the field as precipitation and evaporation are. 'Best' values are thus obtained by iterative model calibration. In an attempt to minimize the impact of uncertainty in these model parameters on model results, care was taken during model calibration to keep the parameter values within typically reported ranges (**TABLE A.1**). This approach not only minimizes the translation of parameter uncertainty into uncertain model results but also ensures overall model robustness (i.e., the ability to simulate a wide range of conditions).

TABLE 2. Sensitivity of total annual stream discharge to changes in model input parameters. Sensitivity (S) was calculated using Equation 1.

Parameter	Variable[1]	$(O-O_o)/O_o$	$(P-P_o)/P_o$	S
Precipitation		1.42	0.50	2.85
Precipitation		-0.88	-0.50	1.76
Evaporation		-0.20	0.50	-0.40
Evaporation		0.49	-0.50	-0.99
Infiltration	INFILT	-0.05	0.50	-0.09
Infiltration	INFILT	0.10	-0.50	0.19
Upper Zone Soil Moisture	UZSN	-0.10	0.50	-0.21
Upper Zone Soil Moisture	UZSN	0.09	-0.50	-0.18
Lower Zone Soil Moisture	LZSN	-0.22	0.50	-0.44
Lower Zone Soil Moisture	LZSN	0.36	-0.50	-0.71
Groundwater Recharge	DEEPFR	-0.12	0.50	-0.25
Groundwater Recharge	DEEPFR	0.12	-0.50	-0.25

1 – 'Variable' refers to the HSPF variable name. It is included here for ease of comparison with Table A.1

FIGURE 1. Comparison of observed and estimated streamflow at Napa River near Napa (USGS Gauge #11458000) using precipitation from the St. Helena weather station.

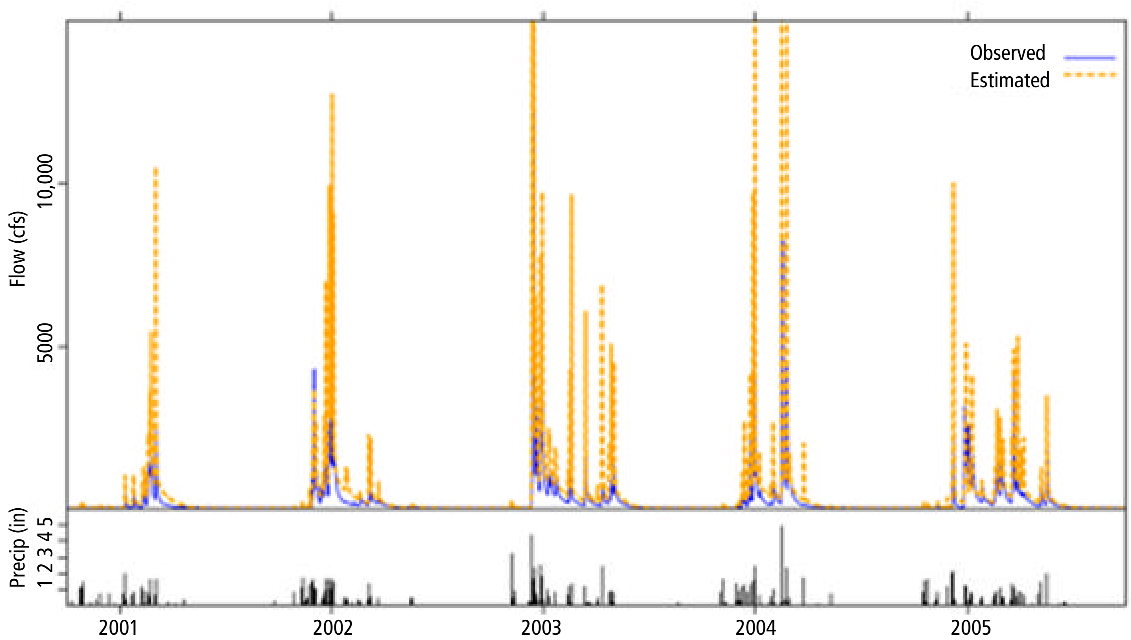


FIGURE 2. Comparison of observed and estimated streamflow at Napa River near Napa (USGS Gauge #11458000) using precipitation from the Napa State Hospital weather station.

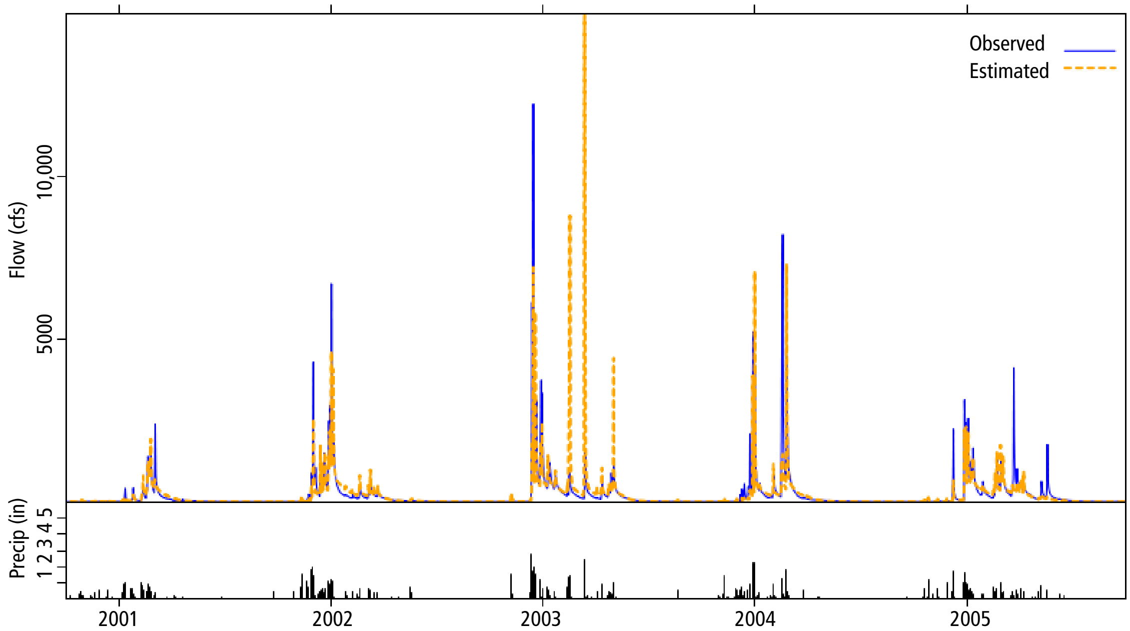
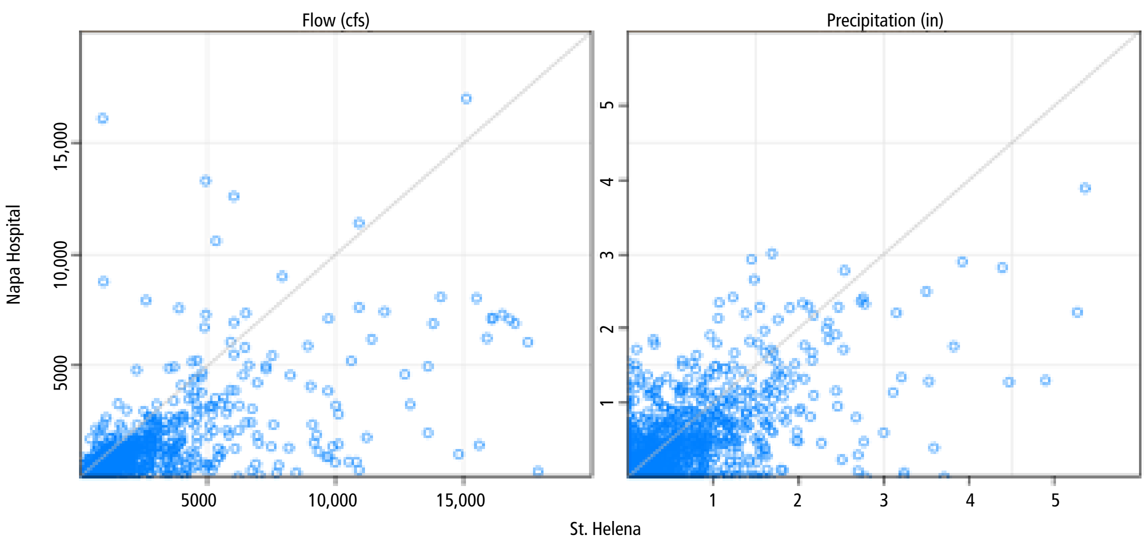


FIGURE 3. Comparison of simulated streamflows using precipitation records from two different locations: Napa State Hospital and St. Helena. The diagonal line indicates a perfect one-to-one correlation. Points below this line indicate higher simulated streamflow (left panel) or precipitation (right panel) at the St. Helena relative to the Napa State Hospital. Points above the line indicate the opposite trend. In general, these plots indicate that precipitation is greater at St. Helena relative to Napa State Hospital. Streamflows simulated from the St. Helena precipitation record are therefore larger than those simulated from the Napa State Hospital precipitation record.



Results

Calibrated hydrologic model results for Napa River near Napa using precipitation from St. Helena and Napa State Hospital are shown in FIGURES 1 and 2, respectively. It is evident from these figures that the hydrologic model performs *reasonably* well. Given the definition of *reasonable*, above, the model captures the overall variability of the observed streamflow on the scale of weeks to months. In fact, in some cases the model does better than that and actually captures the daily flows quite well.

As indicated earlier, the hydrologic model is highly sensitive to precipitation. Fortunately, the precipitation records at St. Helena and Napa State Hospital are quite good. These precipitation records do, however, produce different simulated streamflows (FIGURE 3). In general, precipitation at the St. Helena is greater than at Napa State Hospital (FIGURE 3). Streamflows simulated with precipitation from St. Helena are therefore slightly larger and more episodic (i.e., more peak flows) than those that use precipitation from Napa State Hospital. While both precipitation records produce *reasonable* simulations, Napa State Hospital seemed to reproduce observed flows slightly better.

This example highlights the general inability of the hydrologic model, as configured, to capture the spatial variability of precipitation as it relates to streamflow. It is possible to reconfigure the hydrologic model to be more spatially explicit and to use multiple precipitation records. However, given the uses of the hydrologic model and the definition of a *reasonable* calibration (as mentioned above) such a model reconfiguration was not deemed necessary.

Calibrated model parameters are included in TABLE A.1. Also included in TABLE A.1 are typical values (both national and local) for these model parameters. Care was taken during model calibration to keep these model parameters within typical ranges. This approach ensures that the model produces the right results for the right reasons and ensures the overall robustness of the model (i.e., the ability of the model to *reasonably* simulate a wide range of conditions).

Application

Simulated streamflow was used for two specific purposes: 1) to reconstruct the historical hydrograph and 2) to drive an in-stream sediment transport model under various stream-connectivity modification scenarios (i.e., to assess the effects of "disconnecting" portions of the watershed on stream stabilization). Reconstruction of the historical hydrograph is discussed here. The stream-connectivity scenarios are discussed in later in this report.

The reconstructed historical hydrograph of the main channel was estimated by altering the land-use/land-cover categories and relevant parameters of the hydrologic model. Historical precipitation and evaporation patterns were assumed to be similar to current conditions. By overlaying a current land-use/land-cover map and historic habitat map (Grossinger, 2012), the proportions of different habitats converted to urban and agriculture uses were estimated. Approximately 50% of current urban and agricultural lands were converted from grassland/savanna, 25% from forest and 25% from wetlands. The estimated historic land-use/land-cover breakdown used in the model is shown in TABLE 2.

TABLE 3. Current and [estimated] historic land-use/land-cover for the Napa watershed.

Land Use/ Cover	Current Acreage	Current %	Est. Historic Acreage	Est. Historic %
Urban/ Built-up	6,669	2.4	0	0
Agriculture	64,211	23.0	0	0
Grassland/ Range	10,790	3.9	46,230	16.6
Forest	195,445	70.1	213,165	76.4
Wetland/ Water	1,832	0.6	19,552	7.0

In addition to land-use/land-cover modifications, relevant model parameters were adjusted to reflect a less human-impacted landscape (TABLE A.1). Soil moisture storage capacity was increased since soil would have been less eroded and compacted before road construction, timber felling, grazing and agriculture. Similarly, infiltration rates and interflow parameters were increased to represent water movement through less disturbed and compacted soil. The groundwater recession rate was increased to represent soil that could hold more moisture. Evapotranspiration and interception parameters were increased to account for more vegetation, especially more canopy cover. The overland flow friction (Manning's n) parameter was increased to represent a less homogenous and human-impacted environment. Finally, loss to deep groundwater was decreased to account for more vegetative interception and demand for water, as well as a historically higher water table.

The results suggest the historical hydrograph was broader and flater, with more base flow and lower peak flows than the modern hydrograph (FIGURES 4, 5, and 6). Additionally, results indicate the stream was perennial in most reaches, likely owing to disconnected subordinate systems and considerable above- and below-ground storage.

Of course, as mentioned above, considerable uncertainties are associated with reconstruction of the historical hydrograph. The modifications made to the hydrologic model were informed by a conceptual understanding of pre-colonial conditions in the Napa watershed (including weather patterns). It is difficult to estimate the uncertainties associated with this conceptual understanding of pre-colonial conditions. It is therefore impossible to quantify the uncertainty in the resulting historical hydrograph due to uncertainties in our conceptual understanding. The reconstructed historical hydrograph is thus specific to these conceptualized pre-colonial conditions and should not be extended to other conceptualizations. The hydrologic model should be updated as the conceptual understanding of pre-colonial conditions evolves (e.g. calibration of dendrology records to contemporary rainfall records).

What can be estimated is the uncertainty in the historical hydrograph due to uncertainties in model parameters. Using the results of the sensitivity analysis

FIGURE 4. Mean flow of reconstructed historical hydrograph compared to modern hydrograph at Napa River near Napa. Both hydrographs represent long-term daily averages.

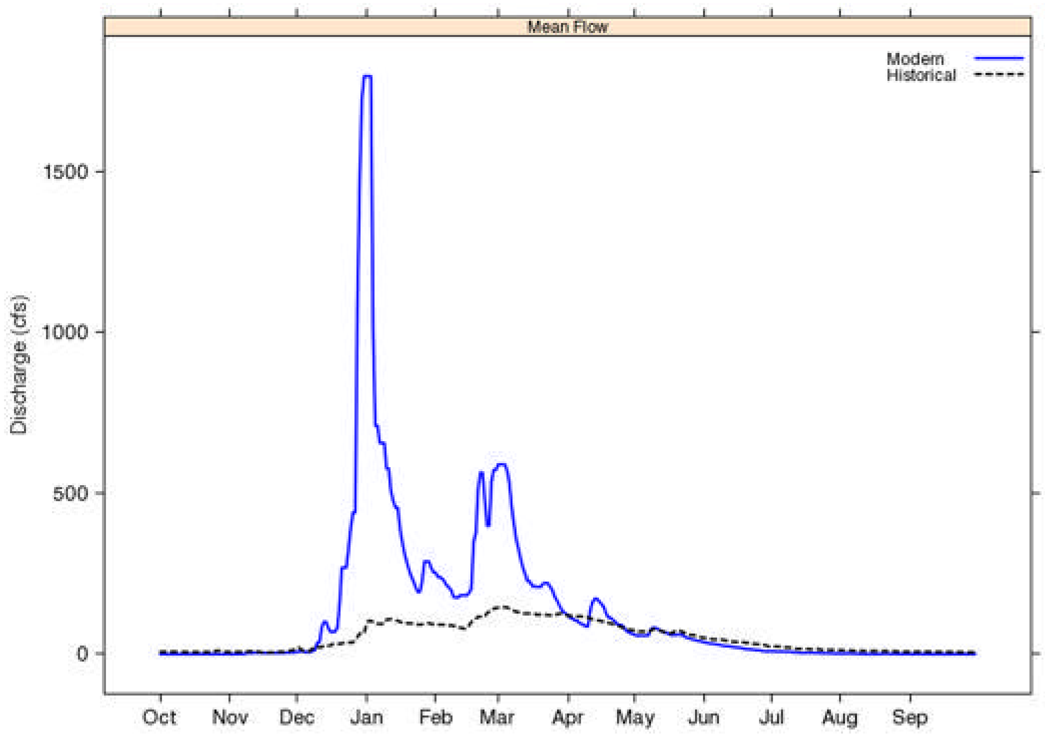


FIGURE 5. Minimum flow of reconstructed historical hydrograph compared to modern hydrograph at Napa River near Napa. Both hydrographs represent long-term daily minima.

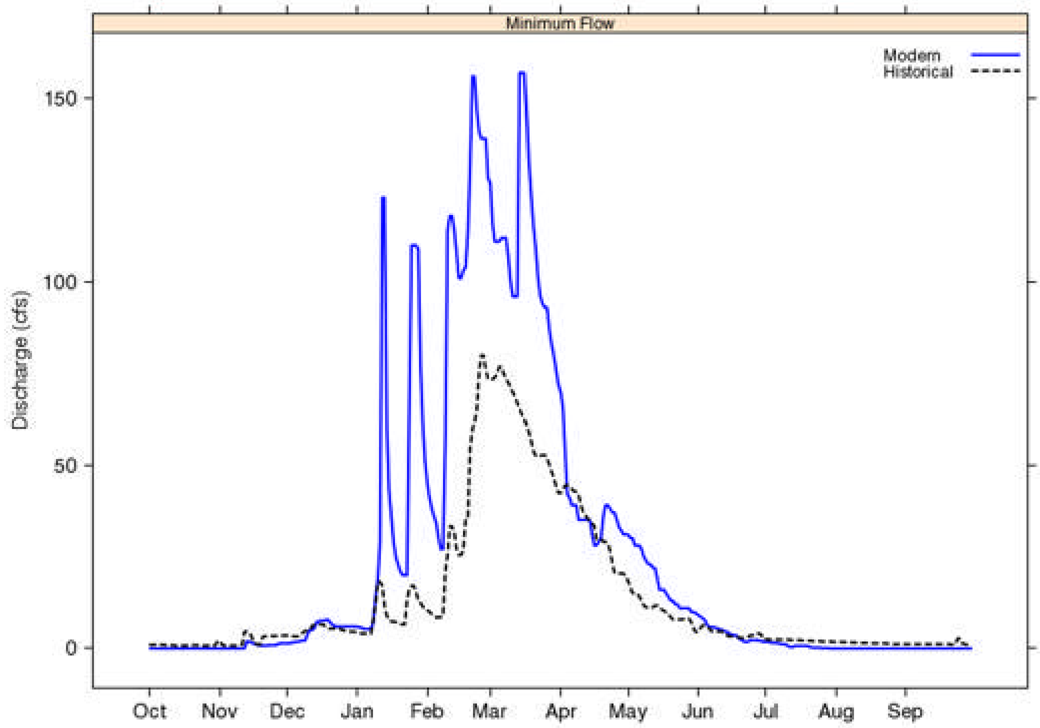


FIGURE 6. Peak flow of reconstructed historical hydrograph compared to modern hydrograph at Napa River near Napa. Both hydrographs represent long-term daily maxima (i.e., peak flows).

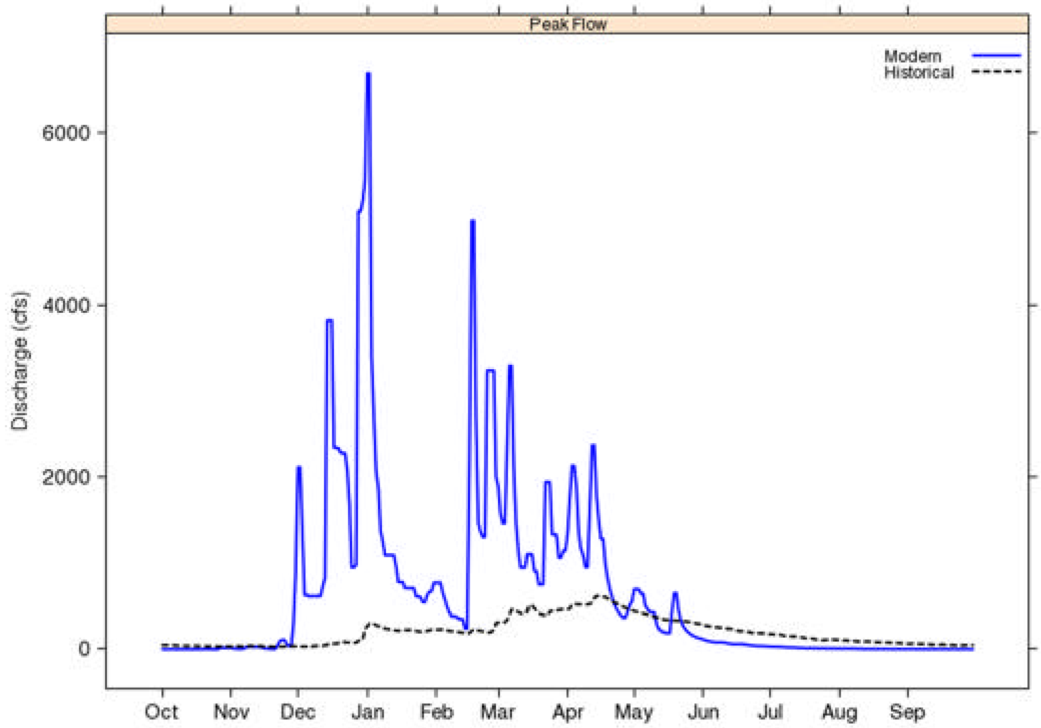
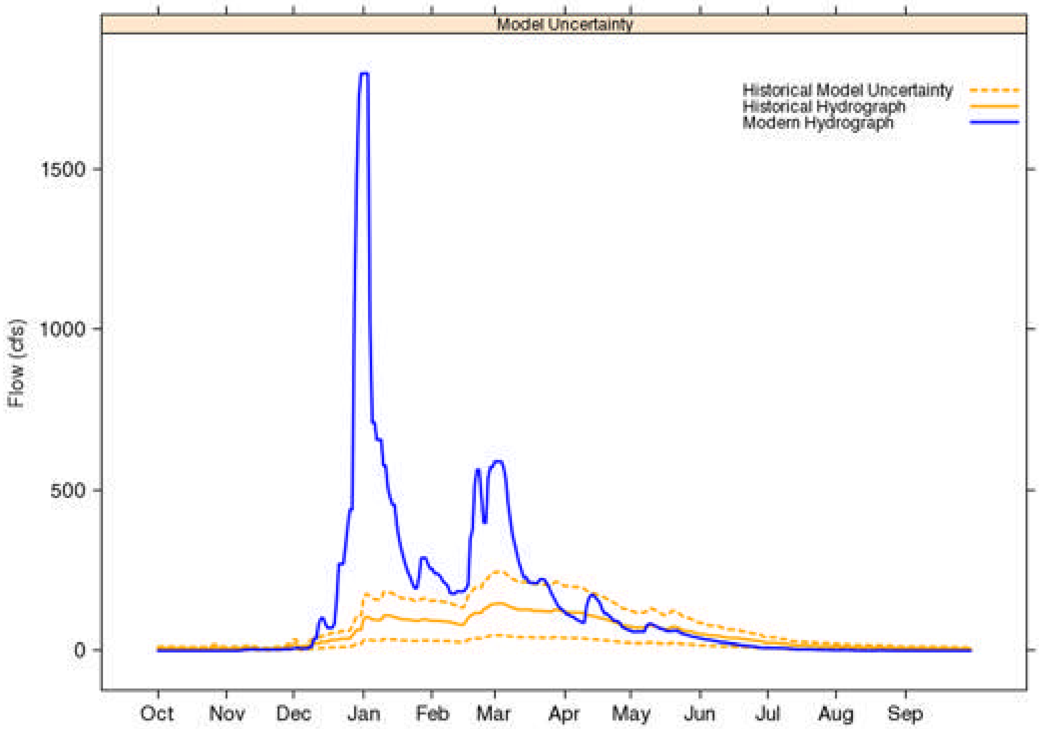


FIGURE 7. Uncertainty of the reconstructed historical hydrograph due to uncertainty in model input parameters. All hydrographs represent long-term daily mean flows.



in TABLE 1, uncertainties in model parameters were extended to the historical hydrograph. Precipitation and evaporation were not included in this analysis as it was assumed in our conceptualization of historic conditions that precipitation and evaporation were similar to current conditions. The remaining model parameters (those related to the exchange of water between surface and subsurface compartments) were used to evaluate upper and lower confidence bounds according to the following equation:

$$O = O_0(\Delta O + 1) \qquad (2)$$

where ΔO is the value in the third column of TABLE 1 (the numerator in EQUATION 1). The maximum value of ΔO for the remaining model parameters is 0.36. This value, however, is for a single model parameter and therefore does not account for interaction between multiple variables. In an attempt to account for this potential interaction, and assuming the interactions are additive, the sum of all ΔO values for INFILT (0.10), UZSN (0.10), LZSN (0.36), and DEEPR (0.12) was used. The resulting hydrograph uncertainty is shown in FIGURE 7. Results indicate that, even in light of model uncertainties, the historical hydrograph was broad and flat with more base flow and lower peak flow relative to the modern hydrograph.

Summary

A spatially averaged, time-variant hydrologic model of the Napa River watershed was developed for two specific purposes: 1) to reconstruct the historical hydrograph and 2) to drive an in-stream sediment transport model under various stream-connectivity modification scenarios (i.e., to assess the effects of "disconnecting" portions of the watershed on stream stabilization). The model was calibrated over multiple years using two precipitation stations within the watershed (St. Helena 047643 and Napa State Hospital 046074) and a single stream gage (Napa River near Napa, USGS #11458000). Detailed sensitivity analyses were conducted to identify key parameters governing model outcomes and to test the internal mechanics of the model. Precipitation and evaporation were identified as the most sensitive model parameters. The model performs reasonably well at estimating streamflow on time-scales ranging from weeks to months (and longer). After calibration, the hydrologic model was altered to represent the historical landscape with the goal of estimating the historical hydrograph. Results suggest the historical hydrograph was broad and flat with considerably more base flow and lower peak flows than the modern hydrograph.

Geomorphic Model

Background

A modified version of Cui's watershed network model (Cui, 2005) was selected to model sediment transport and bed evolution for the Napa watershed. This mechanistic sediment routing model allows study of changes in sediment supply and channel evolution based on various flow, sediment loading, or channel stability scenarios. This model was selected for the following reasons:

1) It was written specifically for medium to small rivers (watershed area < 1000 mi^2)

2) It explicitly models the full stream network, enabling the investigation of geomorphic change at the sub-watershed scale

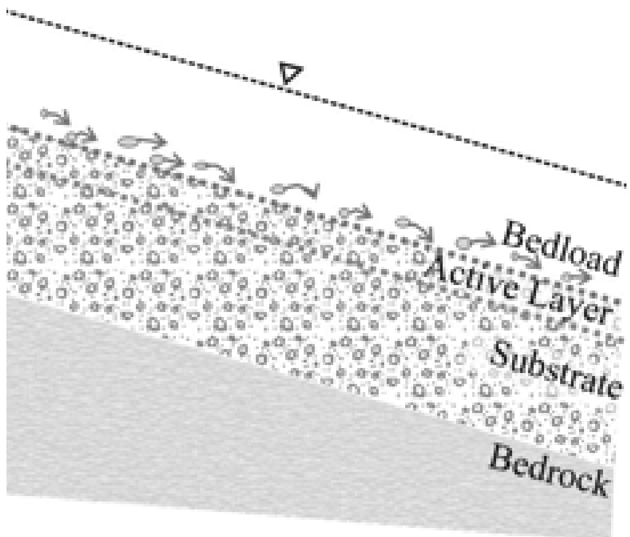
3) It is capable of performing simulations over multi-decadal timescales so that significant geomorphic changes can be evaluated.

4) It is complex enough to provide useful simulations but simple enough to generate computational results over many decades.

Formulation

The sediment transport model of Wilcock and Crowe (2003) serves as the basis of the Cui model wherein the transported sand and gravel fractions are partitioned into particle size fractions. The streambed is described by three layers: bedload, active, and substrate layers (FIGURE 8). Bedload transport is accomplished by mobilization of grains exposed on the bed surface. Substrate particles participate in bedload only when local or global scour results in their exposure on the surface. Calculation of the bedload transport rate for mixtures is based on the availability of each size range in the surface layer. Active layer and interchange layer fractions characterize the way in which sediment is exchanged between the bedload and subsurface as bed elevation changes.

FIGURE 8. The three-layer model of a streambed.



Annual sediment input is distributed daily in the model based on daily stream flow. The parameters controlling daily sediment loads at the headwaters are modulated to balance erosional and depositional processes in the stream. This ensures a stable bed elevation for the first stream segment of the model in the absence of sediment pulses. Sediment transport is calculated as a function of shear stress of water in the channel. Shear stress is calculated based on the input hydrograph and upstream channel geometry, which determine water velocity and elevation. Because the Napa River has a low slope along most of its length, the flow is predominantly sub-critical (Froude number <0.75). Accordingly, the model uses a backwater formulation to generate flow depth values along stream length. These parameters determine sediment transport depending on the initial alluvium depth and grain size distribution of each reach segment in the model. The results of the transport – bed elevation, channel width, floodplain processes, etc. – are then predicted using conservation of sediment via the Exner equation, which governs the relative amount of aggradation and degradation as a function of sediment entrainment and settling.

In order to simulate the complexities of geomorphic change accurately and efficiently, the following key assumptions/simplifications are made by the model:

- Grain size and channel geometry are reach-averaged.
- Local features, such as point bars, pools, and riffles, are not modeled.
- Grain size distribution is limited to 8 grain size classes.
- Only bedload is considered in the model (suspended load/washload is not considered).
- Discharge is limited to daily averaged flows
- Channel cross-sections are simplified as rectangles of bankfull channel width.
- Hydrologic properties of soils are averaged across the entire watershed.
- The downstream boundary conditions assume constant bed elevation and normal flow[1].
- The model requires that the stream network end point be far from the study reach in order to avoid error introduced by boundary condition assumptions.

A more complete description of the governing equations and solution techniques can be found in Cui et al. (2003), Cui and Parker (2005), and Cui (2005).

Setup

The modeled stream network was constructed on a 50m grid with each grid point approximating the bed profile as a rectangular cross-section. Thawleg surveys conducted by the Napa Resource Conservation District (RCD) were combined with a 30m DEM to initialize the cross-sectional profiles and channel slope of the modeled stream network. The longitudinal locations of the confluence point for each tributary in the watershed were explicitly included in the stream network.

The upstream boundary condition of the model consisted of a hydrograph of mean daily discharge and headwaters sediment input. When modeling current conditions, data from the USGS gaging station, Napa River at Napa (#11458000), were used as model input. Daily discharge from the hydrologic model (discussed above) was used as input when modeling historical conditions and alternative future scenarios.

TABLE 4. Magnitude of key input parameters to the geomorphic model of Napa River.

Parameter	Range
Bulk sediment density	1600 - 2600 kg/m^3
Sand D_{50}	0.0001 – 0.001 m
Gravel D_{50}	0.01 – 0.1 m
Sand fraction	0.3 – 0.7
Gravel fraction	= 1 – sand fraction
Reference shear stress for sand	1.1 – 3
Reference shear stress for gravel	0.025 – 0.03

Limited information exists regarding current and historical streambed characteristics (particle sizes, densities, etc.). Therefore, some assumptions about initial substrate conditions were required (TABLE 3). For

1. Normal flow refers to steady, uniform channel flow

most of the simulations, initial grain-size distributions were assumed to be the same as those measured between 2000 and 2008.

Sensitivity Analysis

Applications of the model in geographical regions other than Napa show that it satisfactorily reproduced field observations (Lewicki et al., in review; Hansler, 1999; Cui et al. 2003). However, to the best of our knowledge, this is the first application of this sediment transport model to locations in the Bay Area and possibly even in California. It was therefore important to analyze the sensitivity of model outcomes to uncertainties in key input parameters. Sensitivity analysis was performed exactly as was done for the hydrologic model. Sensitivity (*S*) was defined by EQUATION 1.

Results of the sensitivity analysis are presented in TABLE 4. It must be noted that due to the non-linear nature of many of the modeled processes and the complex interactions among them, the sensitivities determined here only apply to the ranges over which they were calculated.

Sensitivity results indicate that model outcomes are most sensitive to sediment characteristics (bulk density, D_{50}), channel geometry (flow depth, width, slope), and channel roughness. Perturbations to each of these parameters caused considerable change in model outcomes. Fortunately, information specific to the Napa Watershed exists for many of these model input parameters. Surveys of channel geometry, for example, have been taken as described in the main report. Model sensitivity to channel geometry is, therefore, not of major concern. To the contrary, model sensitivity to these parameters is positive reinforcement that the internal mechanics of the model are functioning appropriately. Sediment transport is modeled as a function of shear stress, which is directly related to channel geometry and streamflow. The model is therefore expected to be sensitive to channel geometry

Similarly, model sensitivity to sediment characteristics (bulk density, D_{50}) is neither a surprise nor a major concern. While these sediment characteristics are important model input parameters, standard methods exist for estimating their value in the field. Model sensitivity to these parameters simply highlights the need to obtain site-specific sediment characteristics.

On the other hand, there is no direct method for reducing model sensitivity to channel roughness, reference shear stress, and active sediment layer depth. Field and/or laboratory methods to estimate these parameters are highly uncertain and site-specific. It is therefore prudent to make model simulations using a range of values for these parameters and examine the central tendency of model outcomes.

TABLE 5. Sensitivity of total annual sediment discharge to changes in model input parameters. Sensitivity (S) was calculated using Equation 1.

Parameter	(O-Oo)/Oo	(P-Po)/Po	S
Channel flow depth	0.33	-0.10	-3.3
Channel flow depth	-0.31	0.10	-3.1
Channel (bankfull) width	0.46	-0.10	-4.6
Channel (bankfull) width	-0.27	0.10	-2.7
Channel slope	-0.26	-0.10	-2.6
Channel slope	0.26	0.10	2.6
Channel roughness	-0.48	-0.50	0.96
Channel roughness	0.52	0.50	1.0
Bulk density – gravel	1.13	-0.10	-11.3
Bulk density – gravel	-0.52	0.10	-5.2
Bulk density – sand	0.75	-0.10	-7.5
Bulk density - sand	-0.37	0.10	-3.7
D_{50} gravel	0.20	-0.50	-0.4
D_{50} gravel	0.30	1.00	0.30
D_{50} sand	0.41	-0.50	-0.81
D_{50} sand	0.20	1.00	0.20
Active layer depth	0.07	-0.50	-0.14
Active layer depth	0.07	0.50	0.14
Reference shear stress – gravel	0.35	-0.5	-0.70
Reference shear stress – gravel	0.01	1.0	0.01
Reference shear stress – sand	0.41	-0.5	0.81
Reference shear stress – sand	0.63	1.0	0.63

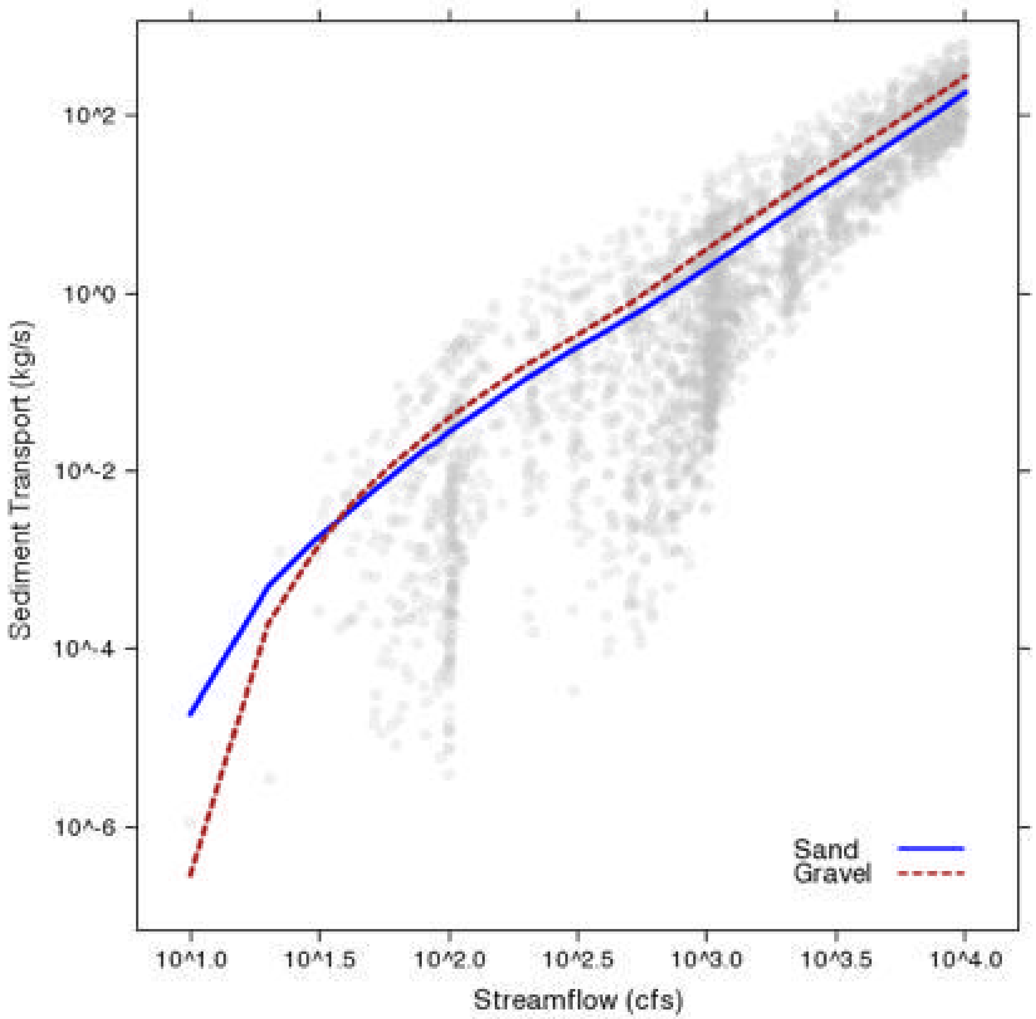
Results

The in-stream sediment transport model was used to evaluate two distinct desired outcomes: (1) the potential for increasing fine sediment pass-through without scouring the channel of coarse sediments; and (2) the potential for channel stabilization under reduced effective discharge scenarios achieved through disconnecting tributaries to the main-stem.

Increasing Fine Sediment Pass-through

Selective transport of fine over coarse material would, over time, coarsen the channel bed and create conditions suitable for spawning by salmon and steelhead trout. The concept is that flood flows bring fine sediment onto the river bed but fail to remove it because the flows recede too rapidly. The question is, can carefully timed flow augmentation extend the falling limb of the flood hydrograph such that fine sediment is flushed from the river bed.

FIGURE 9. Results of a Monte-Carlo simulation of in-stream sediment transport. Two thousand model simulations were made with model input parameters drawn at random from a uniform distribution. The solid lines indicate the central tendency of all model simulations. The gray scatter points indicate the streamflow at which transport of coarse material (gravel) begins to exceed transport of fine material (sand). The intensity of the gray points indicates the relative number of times transport of coarse material intersected transport of fine material at a given streamflow.



In order to evaluate if such preferential sediment transport is possible in the Napa River, a single reach with characteristics typical of the Napa River (20-m width and a gentle slope equal to 0.03) was modeled. In order to account for the sensitivity of model outcomes to uncertainties in input parameters, as previously described, the model was run in a probabilistic Monte-Carlo framework. In this approach, 2,000 model simulations were made with input parameters drawn at random from uniform distributions. These uniform distributions were generated using the range of values in Table 3. The central tendency of all 2,000 runs was evaluated to inform the question of whether or not preferential transport of fine over coarse material is possible for the modeled reach. The behavior of each individual model run was used to identify maximum stream flows below which fine sediment is preferentially transported over coarse sediment.

Results indicate that, indeed, preferential transport is possible (FIGURE 9). However, results were not conclusive in terms of identifying the precise stream flows at which preferential transport occurs, as evidenced by the gray scatter points in FIGURE 9. These gray scatter points indicate the stream flow at which coarse sediment (gravel) transport begins to exceed fine sediment (sand) transport. The intensity of these gray scatter points indicates the number of times, out of the 2,000 model simulations, transport of coarse material begins to exceed transport of fine material at a given stream flow. The wide range of stream flows over which preferential transport of fine over coarse material occurs is a result of the wide uncertainty in model input parameters (TABLE 3). Obtaining values of these model input parameters specific to the Napa River would, in theory, reduce the range over which the intersection of sand and coarse material transport occurs and thereby allow for a more conclusive estimate of actual flows needed to maintain preferential transport of fine sediment. In addition, modeling the system at finer spatial and temporal scales should be performed to help refine estimates presented here. Still, the results presented here suggest that carefully timed flow augmentation is a realistic management option to coarsen the channel bed.

Decreasing Effective Discharge to Stabilize Channel

The other purpose of the in-stream sediment model, in conjunction with the hydrologic model, was to estimate stream flows required to stabilize the Napa River in its present cross-sectional and plan forms. To this end, the magnitude of streamflow records from the Napa River gauging station (USGS #11458000; 1995-2005) was scaled (i.e., reduced) iteratively and used as input to the sediment model. The sediment model was run iteratively until a stable channel was predicted. The watershed area of the hydrologic model was then iteratively adjusted until the simulated streamflow record matched the streamflow record that produced the stable river channel.

This approach was meant to test the concept that channel stabilization can be achieved by "disconnecting" tributaries from the main-stem of the Napa River. Results indicate that a reduction of approximately 20% of the drainage area of the main-stem above the Napa River Gauging Station would help drive the system towards a stabile condition similar to its present cross-sectional and plan forms.

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APPENDIX III

Reservoir Storage Capacity and Evaporative Losses: Napa River Watershed

Introduction

The objective of this task is two-fold: 1) to calculate the cumulative acreage and storage capacity of irrigation reservoirs within the Napa River watershed, 2) to estimate the annual evaporative losses from these reservoirs. This information aids in refining the watershed's annual water budget and allows for further calculations and explorations relating to alternative water management practices.

Data Source

We used two main datasets to complete these calculations.

- Napa reservoirs shapefile with corresponding data table. Originally created as part of the National Wetland Inventory or other wetland mapping. Edited by staff at SFEI. (S:\HistoricalEcology\GIS\Napa\arc_data\Napawatershed_Riparian_06\Napa_ponds.shp.[1]

- CIMIS Climate Data for Oakville (CIMIS #77) and Carneros (CIMIS #109) stations. Included all years of record of daily data. (http://www.ipm.ucdavis.edu/WEATHER/wxretrieve.html or http://www.cimis.water.ca.gov/cimis/data.jsp)

Methods

To achieve the first objective, we exported the attribute table associated with a GIS shapefile of reservoirs within the Napa River watershed. This table includes a calculated field of total surface area for each reservoir polygon. we used Excel to calculate total area. The layer used incorporates all reservoirs in the watershed, regardless of type (irrigation, municipal, other). With no clear classification within the layer given, and no easy access to such distinctions, we determined that size may be a reasonable proxy for whether a reservoir was used for irrigation or not. With this assumption, we found the total surface area in seven reservoir size classes. We also calculated total surface area excluding the 10 largest reservoirs and secondly excluding five known large public reservoirs: Lake Hennessey, Rector Reservoir, Bell Canyon Reservoir, Kimball Canyon Reservoir, and Milliken Reservoir.

Next, to determine the volume of storage, we used a maximum assumed reservoir depth of 15 feet, and a minimum depth of 8 feet. This gave us a maximum and minimum volume of storage for each of my seven reservoir size classes and for the summaries with excluded reservoirs.

For the second objective, we used the daily reference evapotranspiration rates reported by CIMIS. We used data collected at the Oakville (CIMIS #77) and the Carneros (CIMIS #109) stations and averaged the total yearly evaporation amounts for both stations for

1. Mami Odaya, Sept 16, 2007. Personally Communication

all years of record. We then took the average of both stations as a representative annual reference evapor-transpiration rate for the Napa watershed. To convert this value to evaporation from open water, we used a conversion factor of 1.1, which represents only a rough estimate, considering evaporation rates also depend upon the depth of water[2].

To determine the volume of evaporation lost from Napa reservoirs, we multiplied the average annual evaporation by the surface area (for each of the seven size classes). We found the maximum and minimum percent loss by dividing the volume of evaporation by the maximum and minimum total reservoir volume.

Results

The total reservoir surface area within the Napa watershed is 2,484 acres out of a total of 1,278 reservoirs. The second size class, "<100 acres," eliminates a single reservoir that is 741 acres, and the sum is reduced to 1,743 acres. Eliminating the five known public reservoirs reveals 1,573 acres and removing the 10 largest reservoirs yields a total of 1,438 acres. These values and the count and cumulative area for other classes are presented in **FIGURE 1** and included in **TABLE 1**. The majority of reservoirs fall below 4 acres in surface area (**FIGURE 2**).

The total volume for all reservoirs is 19,871 acre-feet, under a minimum assumed average 8-foot reservoir depth for a box-shaped reservoir. Under a maximum assumed depth of 15 feet, the total volume is 37,258 acre-feet. Please refer to Table 1 for these values and those for other summaries.

Annual evaporative losses under open water conditions are estimated to be 51.62 inches. This is an average of the 50.26 inches annual average in Carneros and the 52.97 inches annual average in Oakville.

Evaporative losses are thus estimated to be 10,684 acre-feet for the total reservoir surface area in the Napa watershed. Within the "<100 ac" class, evaporation drops to 7,498 acre-feet (Table 2). The percent loss to evaporation for the minimum reservoir volume is estimated at 54%, while the loss for the maximum reservoir volume is 29%.

Additional Questions

In the process of making these calculations, additional questions arose for possible future calculations.

- It may be valuable to obtain or determine reservoirs that are or are not agricultural irrigation supply reservoirs. Perhaps Napa County may have a data source that makes this distinction.
- It is known that the accuracy of the reservoir layer could be improved given that some polygons do not accurately represent the surface area of a given reservoir.
- The reservoir volume is bound by the assumed average maximum and minimum depth. Further research may produce a better estimate of the average depth given a certain surface area.
- Estimations of evaporation may be improved if the values are based on reservoir depths.

2. California Agricultural Technology Institute. Estimating evaporation rates from open water surfaces. Summer 2007. http://cati.csufresno.edu/update/index.asp?isquery=True&selectedarticle=335.

FIGURE 1. Number of acres within each size category.

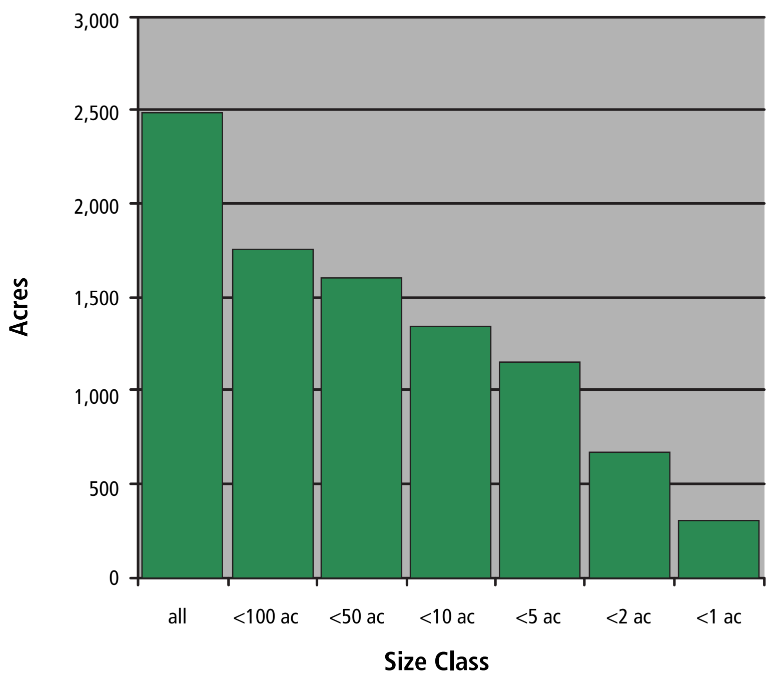


TABLE 1. Reported values for cumulative acreage and volume of Napa watershed reservoirs, broken into seven size classes

	Number	Area (ac)	Volume (ac-ft)		Area (m^2)	Volume (m^3)	
			min	max		min	max
all	1278	2,484	19,871	37,258	1.01E+07	2.45E+07	4.60E+07
<100 ac	1277	1,743	13,945	26,147	7.05E+06	1.72E+07	3.23E+07
<50 ac	1275	1,590	12,722	23,853	6.44E+06	1.57E+07	2.94E+07
<10 ac	1260	1,337	10,693	20,049	5.41E+06	1.32E+07	2.47E+07
<5 ac	1234	1,159	9,271	17,383	4.69E+06	1.14E+07	2.14E+07
<2 ac	1081	680	5,439	10,199	2.75E+06	6.71E+06	1.26E+07
<1 ac	826	316	2,524	4,733	1.28E+06	3.11E+06	5.84E+06

Excluding Hennessey, Rector, Bell, Kimball, and Milliken Reservoirs

Number	Area (ac)	Volume (ac-ft)		Area (m^2)	Volume (m^3)	
		min	max		min	max
1273	1,573	12,583	23,593	6.37E+06	1.55E+07	2.91E+07

Excluding 10 Largest Reservoirs

Number	Area (ac)	Volume (ac-ft)		Area (m^2)	Volume (m^3)	
		min	max		min	max
1268	1,438	11,504	21,570	5.82E+06	1.42E+07	2.66E+07

FIGURE 2. The number of reservoirs within each size bin.

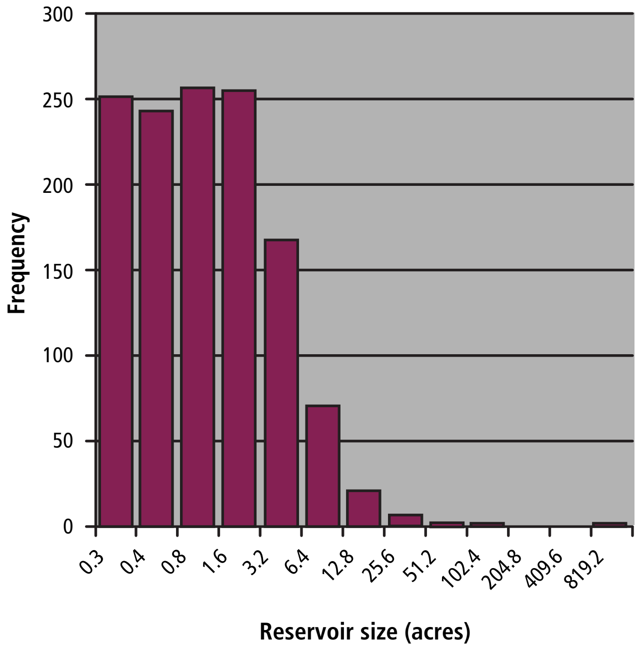


TABLE 2. Estimated evaporation for each reservoir size class and the reported percentage loss for the minimum and maximum cumulative reservoir storage.

	Evaporation (ac-in)	Evaporation (ac-ft)	Evaporation (m^3)
all	128,205	10,684	1.32E+07
<100 ac	89,974	7,498	9.25E+06
<50 ac	82,079	6,840	8.44E+06
<10 ac	68,988	5,749	7.09E+06
<5 ac	59,815	4,985	6.15E+06
<2 ac	35,095	2,925	3.61E+06
<1 ac	16,285	1,357	1.67E+06

Excluding Hennessey, Rector, Bell, Kimball, and Milliken Reservoirs

Evaporation (ac-in)	Evaporation (ac-ft)	Evaporation (m^3)
81,185	6,765	8.35E+06

Excluding 10 Largest Reservoirs

Evaporation (ac-in)	Evaporation (ac-ft)	Evaporation (m^3)
74,224	6,185	7.63E+06

Percent Loss

min vol	max vol
54%	29%

Appendix IV

Napa River Watershed- Reservoir Sediment Trapping

This appendix includes results of work to identify tributary sub-watersheds that may potentially be trapping large volumes of coarse sediment in on-channel reservoirs, rather than transporting it further downstream into the mainstem Napa River. This task aims to be an initial assessment, to help prioritize further more detailed investigation.

Methods: This task is entirely a desktop study, completed using GIS. First we gathered the necessary datasets:

- Napa River sub-watersheds. This shapefile was created by the Napa County Resource Conservation District, using input data from Napa County. The RCD took the 100+ sub-watersheds and combined them into the 33 major tributary sub-watersheds that drain directly into the mainstem Napa River. The set of 33 includes four sub-watersheds that represent area on the valley floor that drains directly into the mainstem Napa River (Napa River Upper Reach, Napa River Middle Reach, Napa River Lower Reach, Napa River Marshes) (FIGURE 1).

- Bedrock geology. This shapefile is a geologic map created by Carl Wentworth (USGS) showing the distribution of geologic materials in the San Francisco Bay Area. Because of the large area covered by this map, we first clipped the shapefile to the Napa River watershed. Within the watershed, a total of 46 different geologic units are mapped (FIGURE 2). Rather than show each geologic unit with a unique symbol, we grouped similar units by color to simplify the map (e.g. all Sonoma Volcanics are shown in a shade of pink).

- Slope map. This shapefile calculates the hillslope gradient (in 10 m cells) for the entire watershed using the 10m DEMs. From this map, a mean gradient for each tributary sub-watershed was calculated, and used as a coarse estimate of which sub-watersheds were "steep" or "gentle".

- Streams. This shapefile shows the entire drainage network of the Napa Valley based upon internal mapping completed by SFEI.

- Reservoirs and Ponds. This DRAFT shapefile shows the 367 mapped on-channel reservoirs and ponds in the Napa Valley (out of 1313 total ponds and reservoirs mapped in the entire watershed). This layer was created by SFEI staff, as a part of mapping standards development for the Bay Area Wetland Inventory, using the Napa River Watershed as a pilot area. The layer was originally created in 2005, but has had on-going updates. FIGURE 3 shows both the streams and reservoirs and ponds mapped in the watershed.

FIGURE 1. Map illustrating the 33 sub-watersheds considered in this assessment.

FIGURE 2. Map illustrating the bedrock geologic units mapped in the Napa River watershed (Wentworth, 1997).

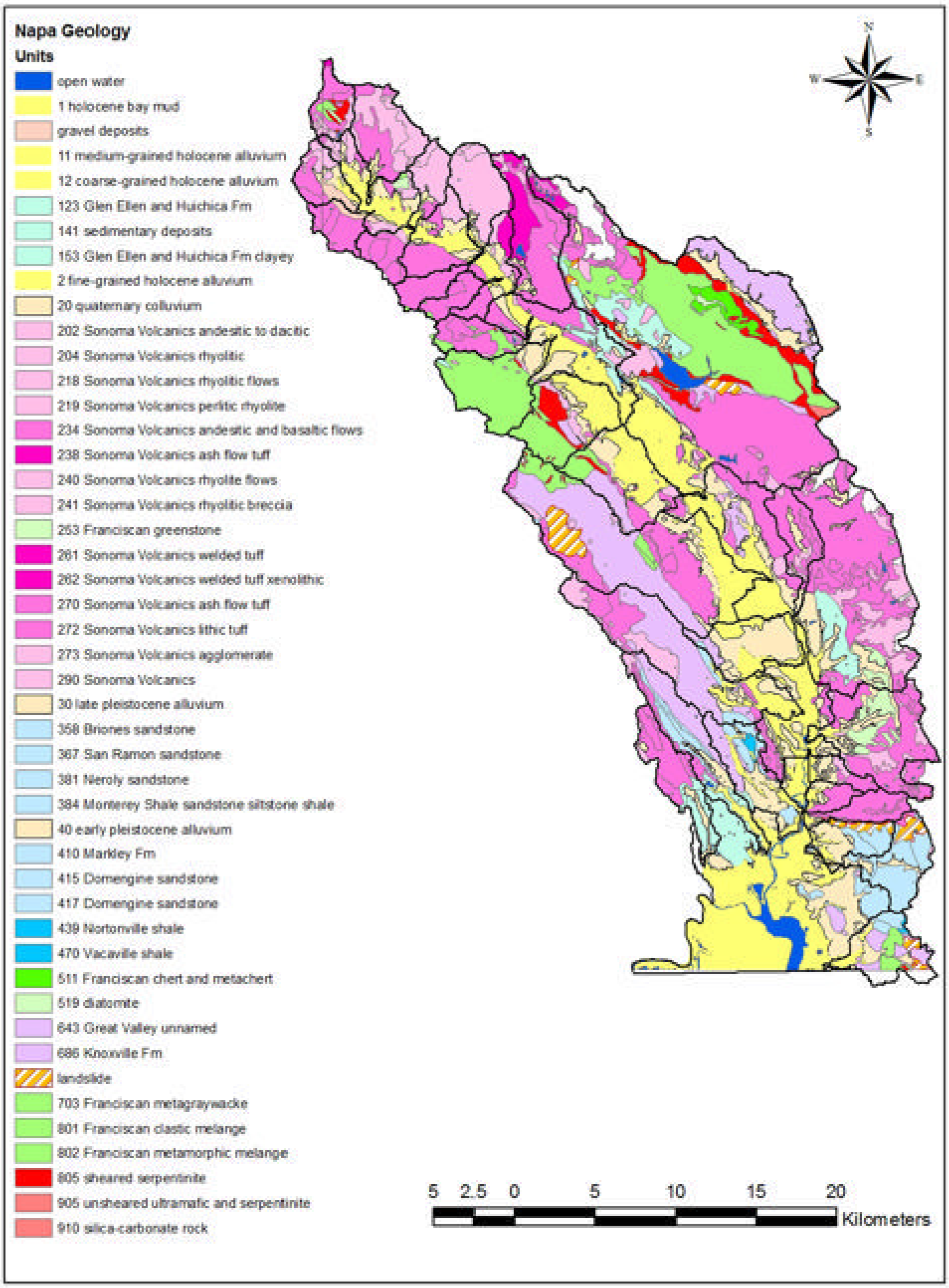
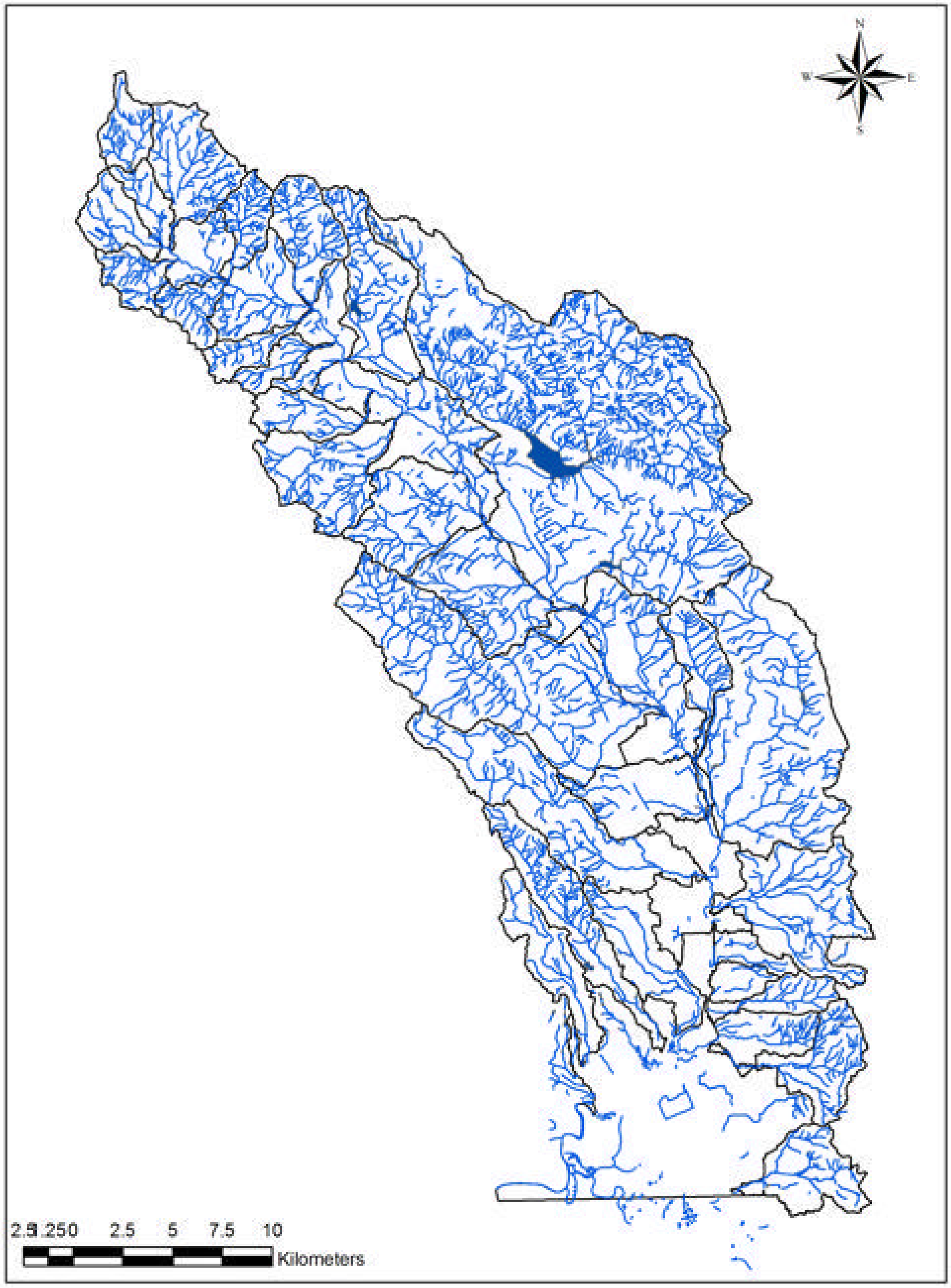


FIGURE 3. Streams, reservoirs and ponds mapped in the Napa River watershed.



With all of the necessary data in hand, we began to assess and rank each of the sub-watersheds based upon its physical characteristics. The first task was to assign a dominant geologic type for each sub-watershed, to get a general idea of the distribution of rock types across the entire Napa River watershed (**FIGURE 4**). Next, we assigned each tributary sub-watershed a single primary and secondary geologic unit. This was completed by individually assessing each sub-watershed, and based upon the visual total amount of area of outcrop for each unit, the primary and secondary geologic units were assigned (**TABLE 1**).

FIGURE 4. Dominant geologic type for each sub-watershed within the Napa River watershed.

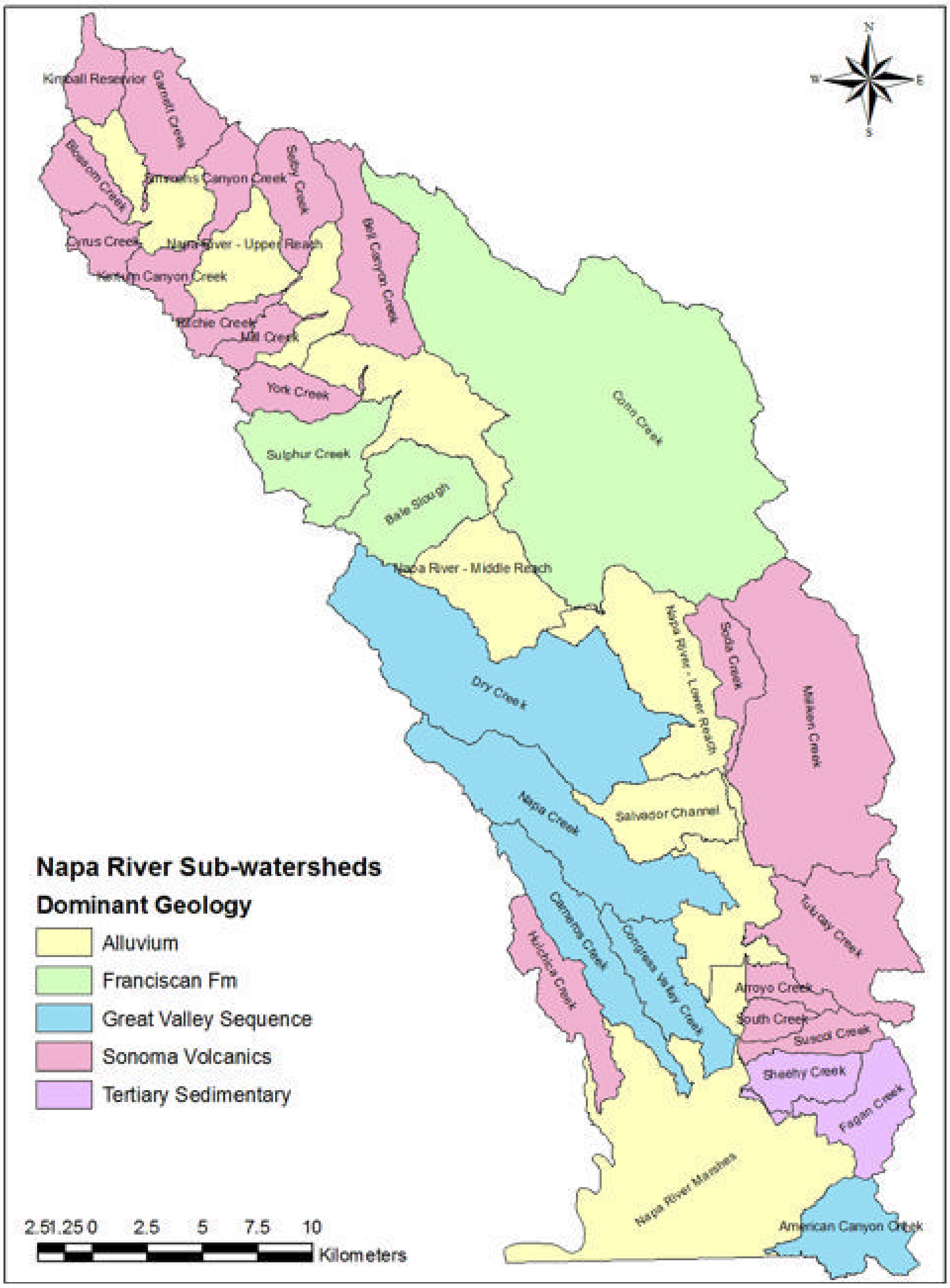


TABLE 1. Napa River sub-watersheds, dominant geologic type, primary and secondary geologic units, defined by SFEI using mapping by Wentworth, 2007.

Sub-watershed	Dominant Geology Type	Primary Geologic Unit	Secondary Geologic Unit
American Canyon Creek	Great Valley Sequence	Great Valley unnamed	Franciscan clastic melange
Arroyo Creek	Sonoma Volcanics	Andesitic and basaltic flows	Late Pleistocene alluvium
Bale Slough	Franciscan Fm	Franciscan clastic melange	Sheared serpentinite
Bell Canyon Creek	Sonoma Volcanics	Ash flow tuff	Ash flow tuff
Blossom Creek	Sonoma Volcanics	Andesitic and basaltic flows	Rhyolite flows
Carneros Creek	Great Valley Sequence	Great Valley unnamed	Neroly sandstone
Congress Valley Creek	Great Valley Sequence	Great Valley unnamed	Domengine sandstone
Conn Creek	Franciscan Fm	Franciscan metagraywacke	Andesitic and basaltic flows
Cyrus Creek	Sonoma Volcanics	Ash flow tuff	Andesitic and basaltic flows
Dry Creek	Great Valley Sequence	Great Valley unnamed	Andesitic and basaltic flows
Fagan Creek	Tertiary Sedimentary	Markley Fm	Briones sandstone
Garnett Creek	Sonoma Volcanics	Rhyolite flows	Andesitic and basaltic flows
Huichica Creek	Sonoma Volcanics	Andesitic and basaltic flows	Glen Ellen and Huichica Fm
Kimball Reservoir	Sonoma Volcanics	Lithic tuff	Sheared serpentinite
Kortum Canyon Creek	Sonoma Volcanics	Ash flow tuff	Andesitic and basaltic flows
Mill Creek	Sonoma Volcanics	Ash flow tuff	Andesitic and basaltic flows
Milliken Creek	Sonoma Volcanics	Andesitic and basaltic flows	Ash flow tuff
Napa Creek	Great Valley Sequence	Great Valley unnamed	Rhyolitic flows
Napa River- Lower Reach	Alluvium	Holocene alluvium	Andesitic and basaltic flows
Napa River Marshes	Alluvium	Holocene bay mud	Late Pleistocene alluvium
Napa River- Middle Reach	Alluvium	Holocene alluvium	Great Valley unnamed
Napa River- Upper Reach	Alluvium	Holocene alluvium	Ash flow tuff
Ritchie Creek	Sonoma Volcanics	Ash flow tuff	None
Salvador Channel	Alluvium	Late Pleistocene alluvium	Great Valley unnamed
Selby Creek	Sonoma Volcanics	Rhyolite flows	Agglomerate
Sheehy Creek	Tertiary Sedimentary	Markley Fm	Briones sandstone
Simmons Canyon Creek	Sonoma Volcanics	Rhyolite flows	Agglomerate
Soda Creek	Sonoma Volcanics	Andesitic and basaltic flows	Ash flow tuff
South Creek	Sonoma Volcanics	Andesitic and basaltic flows	Late Pleistocene alluvium
Sulphur Creek	Franciscan Fm	Franciscan clastic melange	Rhyolitic flows
Suscol Creek	Sonoma Volcanics	Andesitic and basaltic flows	Ash flow tuff
Tulucay Creek	Sonoma Volcanics	Andesitic and basaltic flows	Diatomite
York Creek	Sonoma Volcanics	Ash flow tuff	Franciscan clastic melange

After geologic units were assigned to each sub-watershed, we then ranked each geologic unit in terms of the amount of sediment that it is capable of producing. The ranking scheme primarily relied upon field observations completed for the TMDL (Napolitano et al., 2007; Mike Napolitano, pers. comm), but also included other diverse sources of information, including: SFEI and RCD field observation, previous sub-watershed studies, and partial sediment budget calculations associated with the TMDL. The three characteristics of sediment production that we looked at were: coarse sediment generation, fine sediment generation, and total sediment generation. We qualitatively assessed each characteristic, assigning a score of 1-5 (low to high) to represent the sediment production potential, relative to other units in the Napa River watershed (TABLE 2). Using this ranking for each geologic unit, we combined the score with the defined primary (weighted to represent 75% of the watershed area) and secondary geologic units (weighted to represent 25%

TABLE 2. Geologic unit ranking for sediment production potential. Rankings range from 1 = low sediment production to 5 = high sediment production.

Unit Name	Total Supply	Coarse Supply	Fine Supply
Agglomerate	3	3	3
Andesitic and basaltic flows	1	1	2
Ash flow tuff	4	2	5
Briones sandstone	3	3	3
Diatomite	3	3	3
Domengine sandstone	3	3	3
Franciscan clastic melange	5	4	4
Franciscan metagraywacke	4	4	4
Glen Ellen and Huichica Fm	4	3	4
Great Valley unnamed	5	2	5
Holocene alluvium	3	4	4
Holocene bay mud	3	1	3
Late Pleistocene alluvium	3	2	4
Lithic tuff	3	3	3
Markley Fm	3	3	3
Neroly sandstone	3	3	4
Rhyolite flows	1	1	2
Sheared serpentinite	5	4	3

of the watershed area) identified for each sub-watershed to produce a unitless sediment generation potential. We assumed the 75:25% ratio based upon our observations of the geologic mapping of each sub-watershed, and also because computing exact proportions was beyond the scope of this task. This sediment generation potential ranges from 1 to 5, with low scores representing watersheds that produce low amounts of sediment, and high scores representing watersheds that produce high amounts of sediment, based upon their outcropping geologic units, relative to other sub-watersheds with Napa. We mapped separately the total sediment generation (FIGURE 5) and the coarse sediment generation (FIGURE 6) to illustrate which sub-watersheds were capable of producing large total amounts of sediment, and which were capable of producing large amounts of particularly coarse sediment (important for fisheries habitat and channel stability). For each sub-watershed, we compared the calculated sediment generation potential with a gestalt assessment of sediment generation based upon our field observation and experience, to confirm the methodology was producing reasonable results.

FIGURE 5. Predicted unitless sub-watershed total sediment generation potential. Rankings of 1 = low sediment generation while rankings of 5 = high sediment generation.

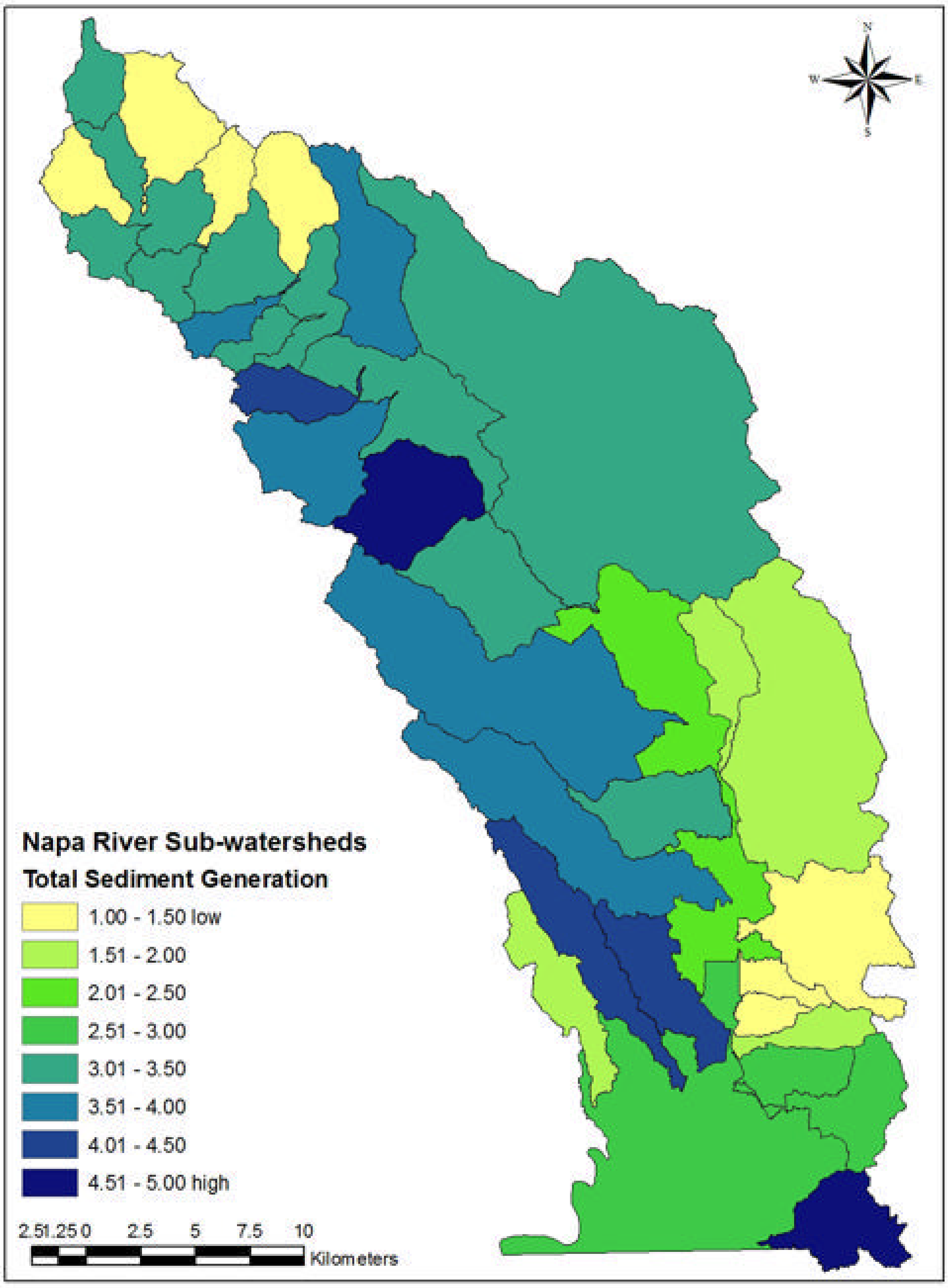
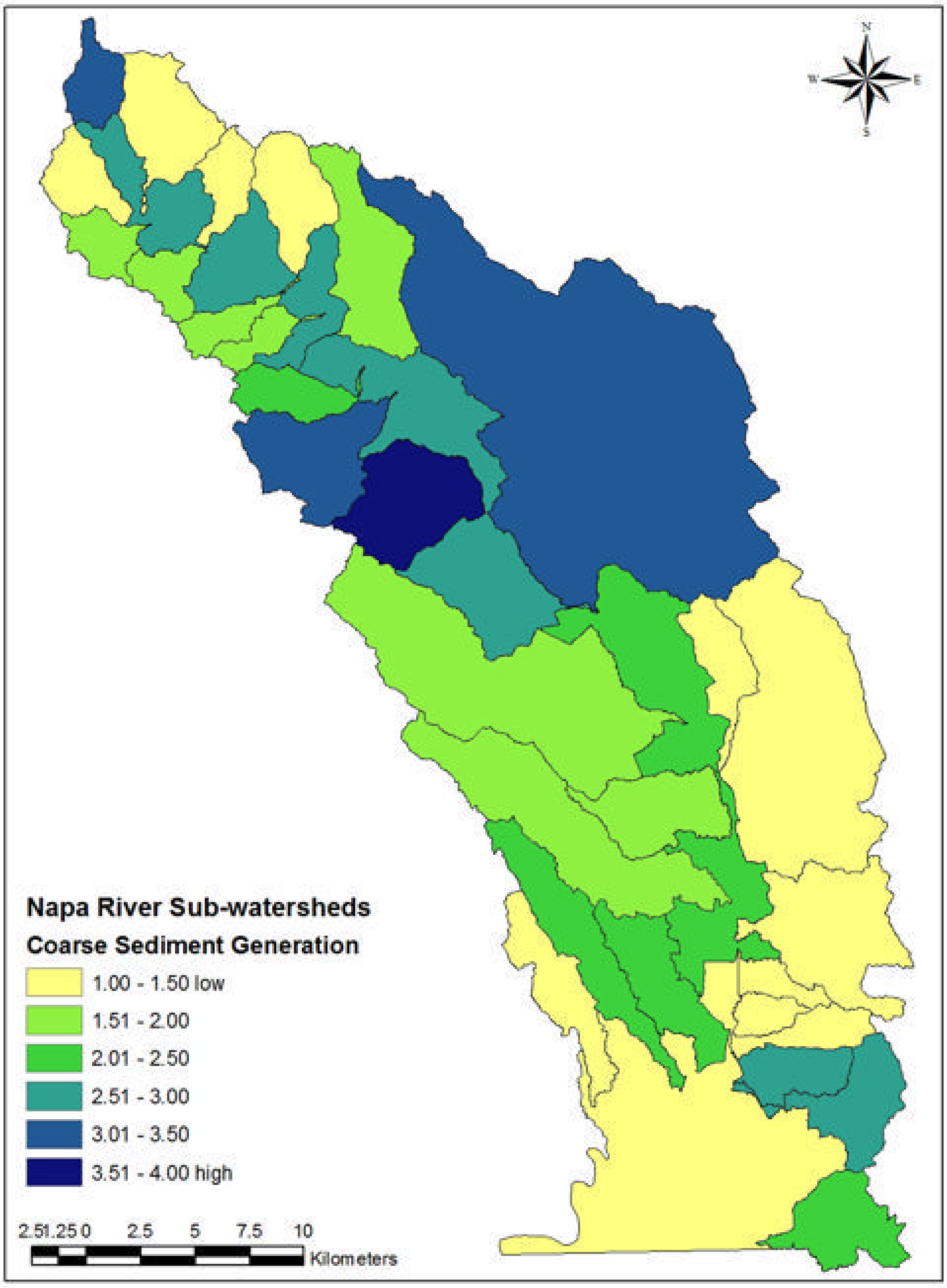


FIGURE 6. Predicted unitless sub-watershed coarse sediment generation potential. Rankings of 1 = low sediment generation while rankings of 5 = high sediment generation.



After completing the sediment generation potential maps, we then assessed two other physical characteristics, mean sub-watershed slope and sub-watershed drainage density. Using the 10m DEM slope map, in GIS we calculated the mean slope (%) of each sub-watershed to quickly estimate which were "steep" and which were "gentle" (**FIGURE 7**). Our working hypothesis is that steeper sub-watersheds will generate more sediment, and that that sediment will have a greater chance of being transported to the mainstem Napa River (less hillslope and in-channel storage) compared to the more gentle sub-watersheds. We also calculated drainage density using the total length of channel and the drainage basin area for each sub-watershed (**FIGURE 8**). Our working hypothesis is that drainage density is a reasonable surrogate for climate and geologic properties; watersheds that receive higher amounts of rainfall, have more tectonically mature settings, and have less resistant rock types will have proportionally higher drainage densities. Thus, the higher drainage density sub-watersheds will likely have greater sediment generation (via hillslope processes such as landslides, slumps, gullies, etc.) and transport capabilities (greater stream power)

FIGURE 7. Mean slope (%) for each sub-watershed.

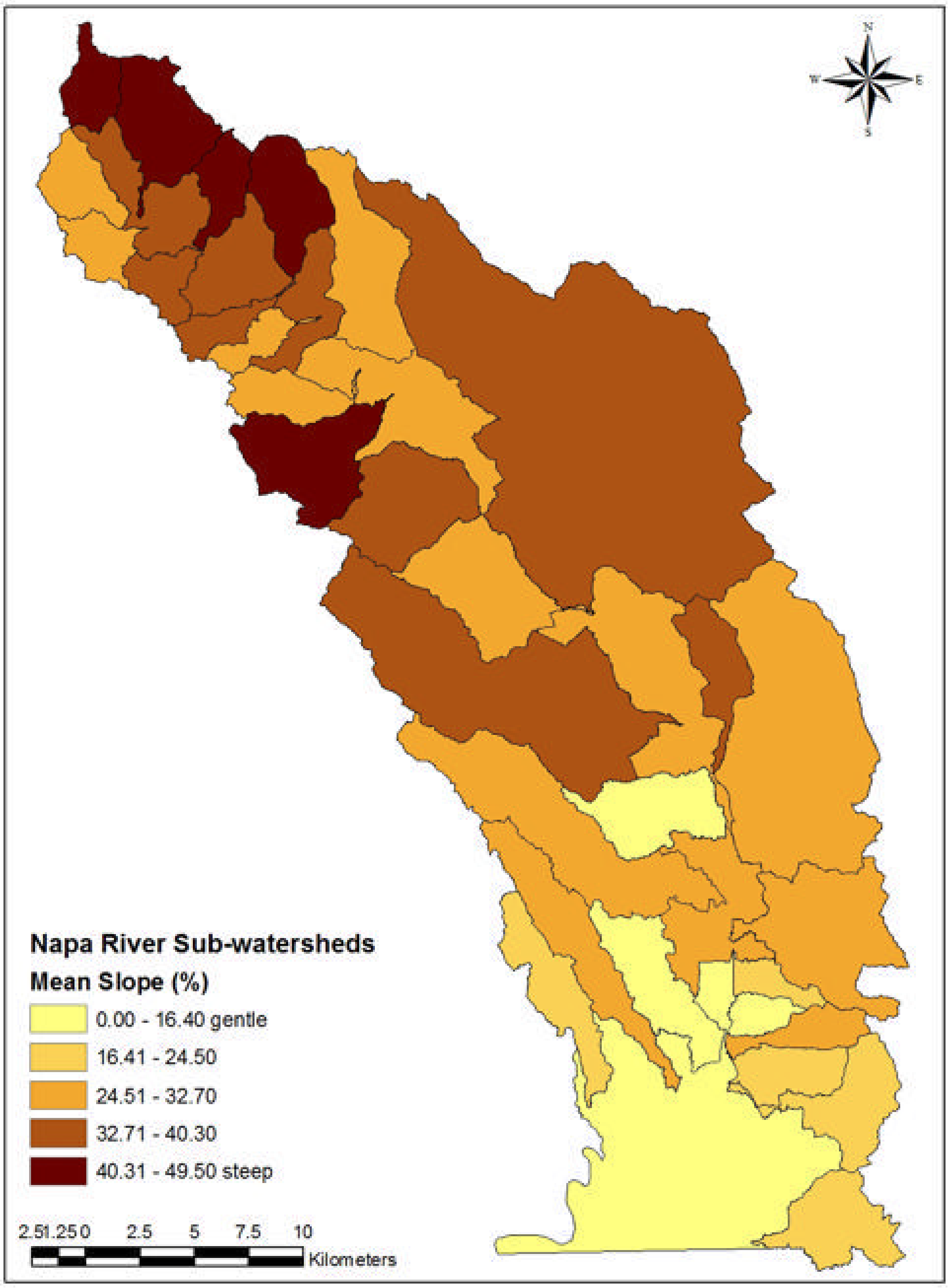
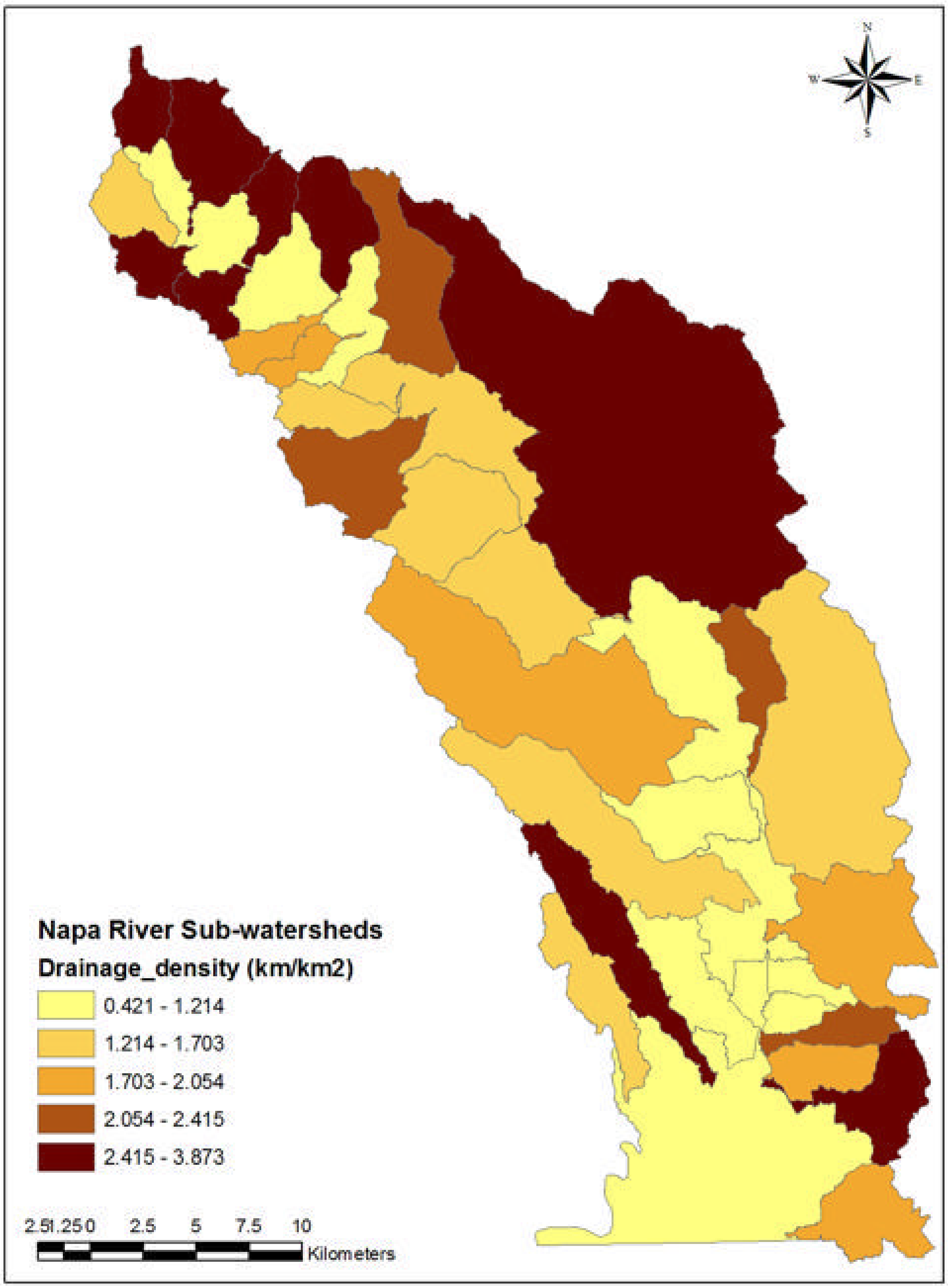


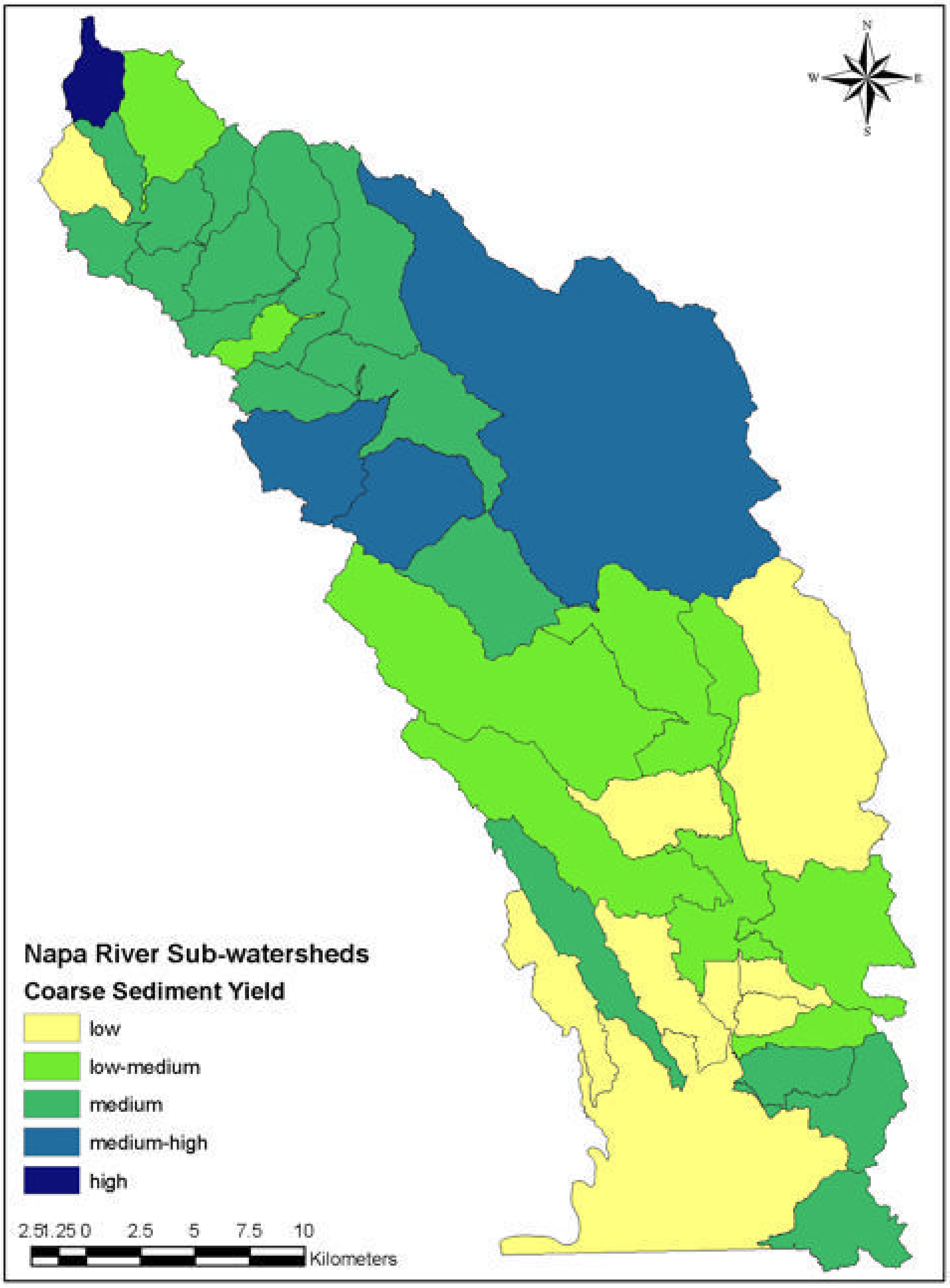
FIGURE 8. Drainage density (km/km²) for each sub-watershed.



With the sediment generation, slope, and drainage density maps complete, the next step was to focus on the coarse sediment, and combine these maps to create a coarse sediment yield map. In excel, we created an equation that multiplied the sediment generation potential score, the mean sub-watershed slope, and the drainage density, to produce a unitless coarse sediment yield score. We then mapped this score, to show the variation in sub-watershed sediment yield (that is, sediment production and transport), grouping the scores into five categories, low to high (**FIGURE 9**).

Finally, we overlaid the on-channel reservoirs and ponds shapefile onto the watershed, to observe the number, size, and position within the watershed of on-channel reservoirs or ponds that exist in each sub-watershed (**TABLE 3**). Our working hypothesis is that each on-channel feature acts to trap the coarse sediment that is supplied to it, while passing the fine sediment (especially during high flow events), and causing additional fine sediment generation in the channel reach downstream due to incision/erosion. Also, features that exist in the lowest reaches of each sub-watershed have a greater im-

FIGURE 9. Coarse sediment yield, categorized into five classes.



pact because they effectively trap sediment from the entire contributing sub-watershed area, essentially providing zero coarse sediment to the mainstem Napa River. For each sub-watershed we visually assessed the number and position of on-channel features, and assigned a ranking of 1-5 (low impact to high impact) as to the likely impact that the reservoirs and ponds are having upon the sediment delivery to the mainstem Napa River. We assumed that reservoirs closer to the tributary mouth or that intercepted large portions of the watershed had a greater impact than those located near the headwaters or on small zero and first order channels. Figure 10 shows the coarse sediment yield and the pond location impact for each sub-watershed. From this map, we can begin to explore which of the sub-watersheds have the greatest potential to supply coarse sediment to the mainstem Napa River, and potential reasons why other sub-watersheds do not have as large of a supply (TABLE 4).

TABLE 3. Mapped reservoirs and ponds in each sub-watershed of the Napa River.

Sub-watershed	Total number of ponds/ reservoirs in sub-watershed	Number of on-channel ponds/ reservoirs	Ratio of on-channel to total (%)	Total pond area (km2)	% pond area : watershed area
American Canyon Creek	48	20	42	0.051	0.30
Arroyo Creek	19	10	53	0.035	0.68
Bale Slough	46	2	4	0.008	0.03
Bell Canyon Creek	27	9	33	0.327	1.31
Blossom Creek	11	6	55	0.063	0.63
Carneros Creek	81	24	30	0.200	0.87
Congress Valley Creek	80	17	21	0.094	0.51
Conn Creek	189	88	47	3.983	2.07
Cyrus Creek	16	9	56	0.034	0.43
Dry Creek	74	12	16	0.043	0.06
Fagan Creek	53	14	26	0.072	0.42
Garnett Creek	10	2	20	0.007	0.04
Huichica Creek	21	9	43	0.060	0.37
Kimball Reservoir	2	2	100	0.066	0.76
Kortum Canyon Creek	11	4	36	0.012	0.16
Mill Creek	8	1	13	0.005	0.09
Milliken Creek	90	41	46	0.580	0.76
Napa Creek	42	8	19	0.030	0.07
Napa River- Lower Reach	77	11	14	0.065	0.12
Napa River Marshes	53	10	19	0.084	0.09
Napa River- Middle Reach	106	13	12	0.090	0.17
Napa River- Upper Reach	68	9	13	0.037	0.09
Ritchie Creek	5	1	20	0.001	0.02
Salvador Channel	30	8	27	0.033	0.18
Selby Creek	6	3	50	0.014	0.10
Sheehy Creek	14	3	21	0.029	0.27
Simmons Canyon Creek	4	3	75	0.018	0.22
Soda Creek	8	2	25	0.019	0.16
South Creek	2	0	0	0	0
Sulphur Creek	11	5	45	0.027	0.12
Suscol Creek	3	1	33	0.005	0.06
Tulucay Creek	48	21	44	0.084	0.25
York Creek	15	0	0	0	0

FIGURE 10. Relative impact of existing on-channel reservoirs and ponds on transport of coarse sediment to the mainstem Napa River. Impact is a function of location and size of storage within drainage network of the sub watershed. Impact 1 = low impact (most sediment is transported to mainstem), 5 = high impact (most sediment is trapped).

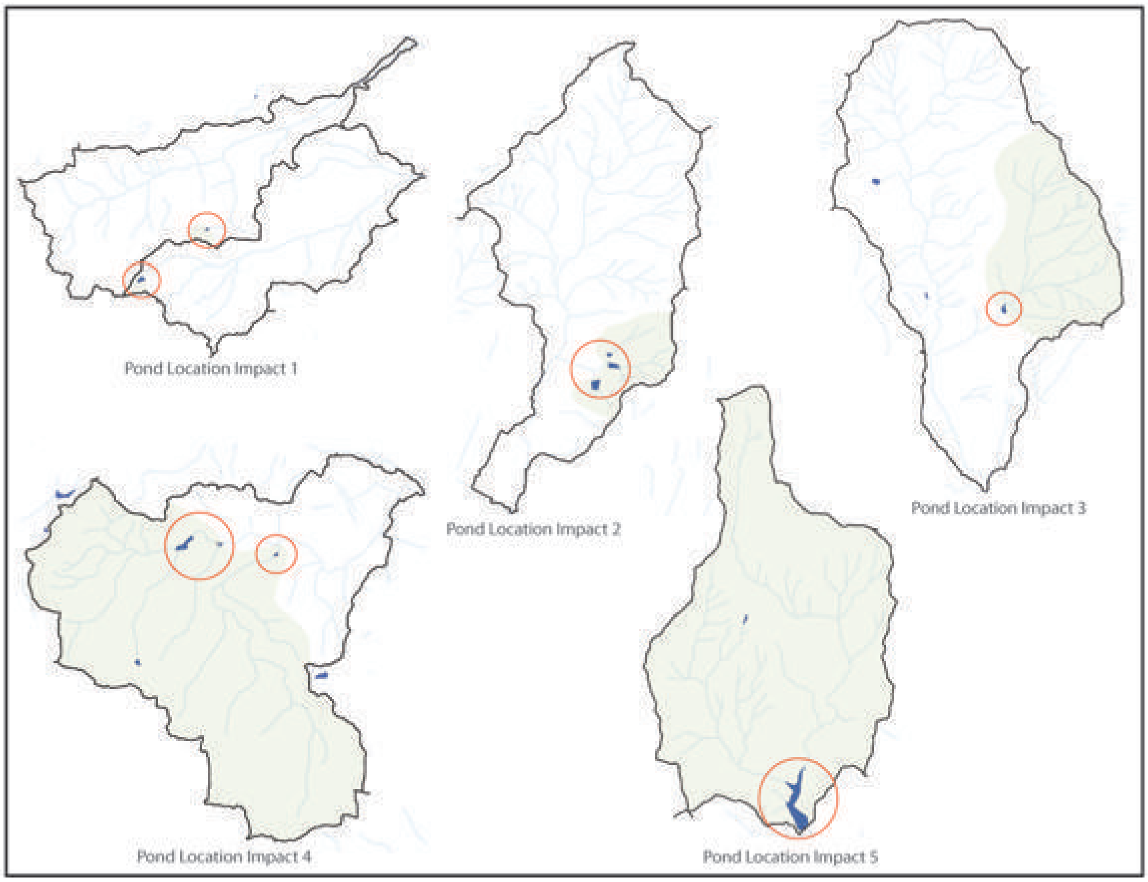
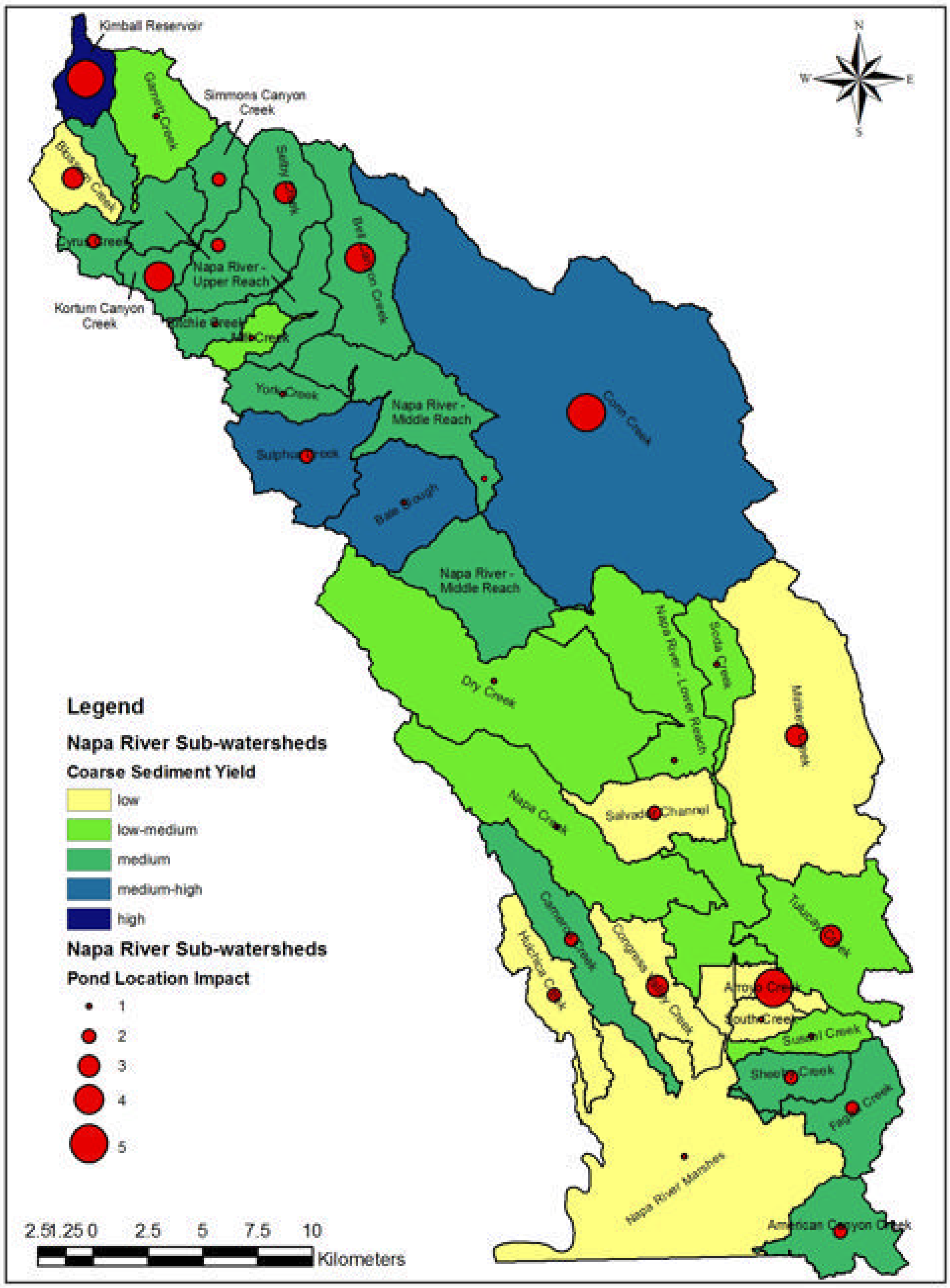


TABLE 4. Coarse sediment yield, pond/reservoir impact, potential limitations to coarse sediment delivery, and initial assessment of future opportunity to increase coarse sediment supply to the mainstem Napa River.

Sub-watershed	Coarse sediment yield	Pond location impact (1-5)	Coarse sediment delivery issues	Potential future opportunity?
American Canyon Creek	Medium	2	Discharges to tidal	no
Arroyo Creek	Low	5	Discharges to tidal	no
Bale Slough	Medium-high	1	None	yes
Bell Canyon Creek	Medium	4	Major reservoir	dredging
Blossom Creek	Low	3	Geologic type	no
Carneros Creek	Medium	2	Discharges to tidal	no
Congress Valley Creek	Low	3	Discharges to tidal	no
Conn Creek	Medium-high	5	Major reservoir	dredging
Cyrus Creek	Medium	2	Small reservoirs	maybe
Dry Creek	Low-medium	1	None- Single lower watershed pond removed in 2008	maybe
Fagan Creek	Medium	2	Discharges to tidal	no
Garnett Creek	Low-medium	1	Geologic type	maybe
Huichica Creek	Low	2	Discharges to tidal	no
Kimball Reservoir	High	5	Major reservoir	dredging
Kortum Canyon Creek	Medium	4	Small reservoirs	yes
Mill Creek	Low-medium	1	Geologic type	no
Milliken Creek	Low	3	Major reservoir	no
Napa Creek	Low-medium	1	None	no
Napa River- Lower Reach	Low-medium	1	Geologic type	no
Napa River Marshes	Low	1	Tidal	no
Napa River- Middle Reach	Medium	1	None	maybe
Napa River- Upper Reach	Medium	2	Small reservoirs	maybe
Ritchie Creek	Medium	1	None	maybe
Salvador Channel	Low	2	Geologic type	no
Selby Creek	Medium	3	Small reservoirs	yes
Sheehy Creek	Medium	2	Discharges to tidal	no
Simmons Canyon Creek	Medium	2	Small reservoirs	maybe
Soda Creek	Low-medium	1	None	no
South Creek	Low	1	Discharges to tidal	no
Sulphur Creek	Medium-high	2	Small reservoirs	yes
Suscol Creek	Low-medium	1	Discharges to tidal	no
Tulucay Creek	Low-medium	3	Discharges to tidal	no
York Creek	Medium	1	None	maybe

FIGURE 11. Napa River sub-watershed coarse sediment yield and predicted impact of existing on-channel reservoirs and ponds on transport of coarse sediment to the mainstem Napa River. Impact 1 = low impact (most sediment is transported to mainstem), 5 = high impact (most sediment is trapped).



Appendix V

Historical Cross Sections Analysis

Introduction/Objectives

This technical memo summarizes the data sources and findings of the Historical Ecology analysis of historic Napa River watershed cross sections.

How has the Napa River changed through time? This question and many others regarding channel form and function are essential for understanding the current river form and planning for the future. The answers to these questions can best be found by analyzing definitive and quantitative geomorphic data describing the river's physical form from the time of European contact through to the present. However, this depth of data simply does not exist. Instead, there are a number of scattered historical documents and datasets that qualitatively and sometimes semi-quantitatively address this question for discrete segments of the river. For lack of a definitive answer to this question, many working within the watershed simply use the assumption that the mainstem has incised approximately 6-8 feet over the past 50 or 60 years (Stillwater and Dietrich, 2002). As a part of the larger study, the Historical Ecology team aims to gather additional evidence to support or refute this assumption, quantify the amount of incision as best as possible, and provide the complete dataset.

In order to address the numerous questions regarding historic channel form, the Historical Ecology team gathered a diverse set of data, especially channel cross sectional data. In working with this data, one must remember that cross sections are a snapshot in time, recording a quantitative measure of the channel shape. Often historical cross sections are limited to channel crossings, such as roads, bridges, or pipelines. In these instances, the data are often very robust (surveyed by engineers) but may be biased towards channel locations that are "more stable". However, cross sections typically provide the most quantitative and reproducible data through time in any given watershed.

The objective of this task was to obtain historic cross sections or other descriptive channel data that exist for the mainstem Napa River, to allow direct comparison with current channel cross sections and observations. The analysis will quantitatively document amounts of incision for specific reaches of the Napa River mainstem, and provide the data for future projects.

Methods

Data collection

The collection of historic cross sections was only a small portion of the data collection effort for the Historical Ecology study of the Napa River Watershed. However, the cross sections, photographs, and accounts of the channel network were specifically targeted for collection because many research questions can be addressed through this data. For example, these datasets can not only provide insight into channel incision through time, but also habitat quality and quantity, persistence of flow, bed sediment characteristics, bank stability, etc. However, this analysis focuses solely upon measureable channel change, either incision or aggradation, through time for the fluvial portion of the mainstem river.

Many types of historical documents can provide information about channel shape and condition. Ideally, professionally surveyed cross sections of the channel provide the most accurate and reliable data, despite the purpose of the survey (bridge construction or remodel, flood protection, habitat survey, channel restoration, etc). However, qualitative data can be nearly as useful; for example, an historic photograph (including the historic bridges collection) can be used for comparison to a present-day photograph, or an historic habitat condition survey may provide descriptions of the channel in multiple locations throughout the watershed. Additionally, written accounts of the channel are available from numerous sources, including court transcripts of rancho boundaries, General Land Office surveys, x, x. The team was successful in collecting data from a variety of sources including Napa County Public Works, California Department of Fish and Game, Bancroft Library, x, x, x. (Shari Gardner of Friends of the Napa River assisted in this effort.) For example, the Napa County Public Works Department houses the as-built drawings for a number of road crossings along both the mainstem and tributaries throughout the watershed. And the California Department of Fish and Game (DFG) office in Yountville houses historic documents and reports made by DFG staff on each river reach and tributary. These files were searched for drawings (surveyed or sketches) or verbal accounts of the historic mainstem condition. For example, the collection contained a 1959 survey of fish habitat conditions along the mainstem which provided descriptions of the mainstem, including depth, at a number of road crossings in the middle and upper watershed.

In addition to historic cross sectional data, recent cross sections were acquired from the Napa County Resource Conservation District (RCD) for comparison to the older data. The RCD collected cross sectional data during projects in 1996 and 2006. The 1996 project surveyed a channel cross section approximately every 300 m along the entire mainstem from Kimball Dam, downstream to the SFEI Monitoring station near Mare Island. The 2006 data surveyed a channel cross section approximately every 150 m in the Oak Knoll Avenue to Oakville reach.

Field Reconnaissance

For a number of the locations where historic as-built cross section drawings exist, SFEI and RCD staff conducted a field reconnaissance (Sept and Oct 2006) to observe current channel dimensions and conditions. At each location, the field team accurately sketched the current channel geometry, rapidily measured channel width and depth, and took numerous photographs, especially photographs from a similar vantage point as the historic photos. Each cross section characterization focused upon documenting the depth of the thalweg compared to stable (typically bridge or valley floor) features. Unfortunately, accurate cross sectional resurveys (rod and level) were beyond the scope of this reconnaissance task. Each of the current channel geometry sketches were overlain on the historic as-built, using bridge measurements shown on each as-built for scale. This allowed visual comparison of cross section change, as well as more accurate measurement of incision depths.

Results

We report the full collection of relevant gathered data (**TABLE 1**), organized by location from downstream to upstream, highlighting the reported channel depth (relative to the valley floor elevation, unless otherwise noted) and the channel depth change through time (comparing the earliest and the latest records for each location). We also present a summary table (**TABLE 2**) with our best estimate of long term (comparing the earliest record and the 2006 record for each location) incision depths. An assessment of confidence level is also associated with each location. A low confidence level represents uncertainties in as-built and present-day field measurements; a medium confidence level represents some uncertainty in interpreting historical observations; a high confidence level represents accurate measurements of as-built and present-day field measurements.

TABLE 1. Compilation of all historic and modern cross section information gathered for the mainstem Napa River. Table is organized downstream to upstream.

Location	Year	Channel Depth (ft)	Channel Depth (m)	Depth Change through time (m)	Source	Notes
Third Street	ca 1849					"…at a point near the foot of Third Street. There was a ford near this point, passable at low tide. At high water men swam their horses previous to the establishment of the ferry." Indicates the location of Mean Lower Low Water; Third Street as the head of low tide.
Third Street	1861	4 below MLLW	1.2 below MLLW		Rodgers and Alden, 1861	
Third Street	1996	29.5	9			
The Embarcadero	ca 1850					"The Embarcadero, or landing, at the head of navigation, and the ford just above it, determined the location of the town. There being no bridges in those days, gave the ford much importance."
Napa Creek confluence	1996	32.8	10		Napa RCD survey	
First Street	ca 1850					Steamboat Landing at south side of First Street
First Street	1996	29.5	9		Napa RCD survey	
Las Trancas	ca 1841					Las Trancas, erected about 1841 by the Vallejos at the head of the tidewater on Napa River to prevent cattle from crossing at low tide, was a well-known landmark before the Gold Rush
Trancas Street	1885	main channel 10 to 12 deep	main channel 3.0 to 3.6 deep		Vallejo, 1885; Tortorolo, 1978	Height to "valley floor" would be greater
Trancas Street	1913	~ 35 to deck bottom	~ 10.7 to deck bottom		Napa County As built	Earlier stone arch bridge
Trancas Street	1960	~35 to deck bottom	~ 10.7 to deck bottom	0	Napa County As built	
Trancas Street	1996	45.9	14	-3.3	Napa RCD survey	
Trancas Street	2006	~36.1 to 42.6???	~11 to 13???		SFEI obs.	Tidal, could not measure bed elevation
Trancas Street	2006	20 to 25???	6.1 to 7.6???		Trancas Dam project	
Oak Knoll Ave	1922	~ 35 to deck bottom	~ 10.7 to deck bottom		Napa County As built	
Oak Knoll Ave	1989	~ 30 to deck bottom	~ 9.1 to deck bottom	+1.6	Napa County As built	
Oak Knoll Ave	1996	29.5	9	+0.1	Napa RCD survey	
Oak Knoll Ave	2006	~ 37 to deck bottom	~ 11.3 to deck bottom	-2.3	SFEI obs.	40 ft depth due to localized scour around bridge footers
Oak Knoll Ave	2006	28	8.5		Napa RCD survey	Section located ~27 m upstream of bridge

TABLE 1. (continued)

Location	Year	Channel Depth (ft)	Channel Depth (m)	Depth Change through time (m)	Source	Notes
Yountville at Conn Creek	ca 1840					Description of early fords by a local historian: "In passing through or to the Yountville Camp Grounds, it was necessary to drive one's horses or cattle through the waters of either Napa River or Conn Creek or both, if the water level was shallow or low.
105 m down-stream of Conn Creek confluence	1996	24.6 to top of levee	7.5 to top of levee		Napa RCD survey	
118 m upstream of Yountville Cross road	1996	21.3 to top of levee	6.5 to top of levee		Napa RCD survey	
Yount Mill Road	1959	Incised meanders 12 ft high	Incised meanders 3.7 m high		Fisher, 1959	
Approxi-mately at Yount Mill Road	1996	18 (23 to top of levee)	5.5 (7 to top of levee)	-1.8	Napa RCD survey	
Yount Mill Road	2006	25	7.6	-2.1	Napa RCD survey	
Oakville Cross Road	1959	Stream in incised meander about 10 feet deep	Stream in incised meander about 3 m deep		Fisher, 1959	
Oakville Cross Road	1996	19.7 or 32.8	6 or 10	-3	Napa RCD survey	Depends on which bank is measured
Oakville Cross Road	2006	19.7	~6	0	SFEI obs.	Based on measures taken at the right bank bridge footer
Oakville Cross Road	2006	23	7	-1	Napa RCD survey	Section located ~ 34 m downstream of bridge- 1m knickpoint on down-stream side of bridge
Rutherford Cross Road	1921	20 to deck bottom, 22 to road surface	6.1 to deck bottom, 6.7 to road surface		Napa County As built	
Rutherford Cross Road	1996	16.4 (26.2 to top of levee)	5 (8 to top of levee)	+1.1	Napa RCD survey	
Rutherford Cross Road	2006	23 to 26	7 to 8	-2.0	SFEI obs.	Although based upon the 1981 bridge pillar, incision is not very obvious
Zinfandel Lane	?				Historic photo	Look at gravel fill height compared to bridge footers
Zinfandel Lane, includ-ing 1/4 mile further downstream	1959	Stream in incised meander banks 12-15 ft above stream level	Stream in incised meander banks 3.7-4.6 m above stream level		Fisher, 1959	
Approxi-mately 100 m downstream of Zinfandel Lane	1996	26.2	8		Napa RCD survey	This is deeper due to a knickpoint downstream of the bridge

TABLE 1. (continued)

Location	Year	Channel Depth (ft)	Channel Depth (m)	Depth Change through time (m)	Source	Notes
Zinfa ndel Lane	2006	18 to 19.7	5.5 to 6	-1.5	SFEI obs.	Measure is from concrete bed to "valley floor". The exposed bridge footer illustrates 1.5 m of incision since the historic photo of this location
Pope Street	1894				Historic photo	Bridge date stamped in keystone on bridge
Pope Street	1996	26.2	8	-0.9	Napa RCD survey	
Pope Street	2006	~26.2	~8	-0.1	SFEI obs.	0.9 m height of bridge footers now exposed, likely were not exposed when built. Additional 0.1 m depth of thalweg
Pratt Ave	1921	12-13				
5.5		Napa County As built				
Pratt Ave	1996	26.2	8			
-2.5	Napa RCD survey					
Pratt Ave	2006	24.9 to valley floor	7.6 to valley floor	+0.4	SFEI obs.	
Lodi Lane	un-known (1919-1950)	14-15	4.3-4.6		Napa County As built	
Lodi Lane	1996	9.8 (16.4 to top of levee)	3 (5 to top of levee)	+1.3	Napa RCD survey	
Lodi Lane	2006	15.7 to 16.4 to "valley floor"	4.8 to 5.0 to "valley floor"	-1.8	SFEI obs.	~ 5 m to valley floor surface
Bale Lane (Ritchey Lane)	1959	Stream in incised meander 12 ft high	Stream in incised meander 3.7 m high		Fisher, 1959	
Bale Lane (Ritchey Lane)	un-known	18-19	5.5-5.8	-2.1	Napa County As built	
Approxi-mately at Bale Lane (Ritchey Lane)	1996	19.7	6	-0.2	Napa RCD survey	
Bale Lane (Ritchey Lane)	2006	19 to deck bottom	5.8 to deck bottom	+0.2	SFEI obs.	
Larkmead Lane	1959	Stream in incised meander 10 ft high	Stream in incised meander 3.0 m high		Fisher, 1959	
Larkmead Lane	1996	19.7	6	-3	Napa RCD survey	

TABLE 1. (continued)

Location	Year	Channel Depth (ft)	Channel Depth (m)	Depth Change through time (m)	Source	Notes
Maple Lane	1959	Stream in incised meander 10 feet high, width 10-25 feet, averaging 18 feet	Stream in incised meander 3 m high, width 3-7.6 m, averaging 5.5 m		Fisher, 1959	
Approximately 300 m downstream of Maple Lane	1996	19.7	6	-3	Napa RCD survey	
Dunaweal Lane	1959	Stream in incised meander 10 feet high, stream averaging 18 feet wide	Stream in incised meander 3 m high, stream averaging 5.5 m wide		Fisher, 1959	
Approximately 100 m downstream of Dunaweal Lane	1996	18 (26 to top of levee)	5.5 (8 to top of levee)	-2.5	Napa RCD survey	
Highway 29	1959	Incised meander 12 feet high. Stream is 5 to 15 feet wide	Incised meander 3.7 m high. Stream is 1.5 to 4.6 m wide		Fisher, 1959	
Approximately at Highway 29	1996	16.4 to 18	5.0 to 5.5	-1.3	Napa RCD survey	

TABLE 2. Summary table illustrating the long term best estimate of incision depth (meters) for each location.

Location	Incision estimate (m)	Timeframe (yrs)	Confidence level
Trancas Street	2.0	93 (1913-2006)	low
Oak Knoll Avenue	0.5	84 (1922-2006)	high
Yount Mill Road	3.9	47 (1959-2006)	medium
Oakville Cross Road	3.0	47 (1959-2006)	medium
Rutherford Cross Road	2.0	85 (1921-2006)	medium
Zinfandel Lane	1.5	>47 (photo pre-1959 – 2006)	medium
Pope Street	1.0	112 (1894-2006)	medium
Pratt Avenue	2.1	85 (1921-2006)	high
Lodi Lane	0.5	Between 87 and 56 (1919-1950 – 2006)	high
Bale Lane (Ritchey Lane)	2.0	47 (1959-2006)	medium
Larkmead Lane	3.0	37 (1959-1996)	medium
Maple Lane	3.0	37 (1959-1996)	medium
Dunaweal Lane	2.5	37 (1959-1996)	medium
Highway 29, Calistoga	1.3	37 (1959-1996)	medium

FIGURE 1. Photograph pair showing the historic photograph (upper) (courtesy of Al Edminster) and current photograph (lower) looking downstream at the Zinfandel Lane bridge.

Examples of Channel Incision Interpretation

In this section, we show examples from five locations, illustrating field reconnaissance re-photography and channel measurements upon which our incision estimates are based. The selected examples are from: Zinfandel Lane, Pope Street, Pratt Avenue, Lodi Lane, and Oak Knoll Avenue.

Zinfandel Lane

This example shows how historic photographs can be used to infer incision depths given a lack of quantitative as-built surveyed cross sections. Although the exact date of this photograph is not known, it clearly shows that the historic bed elevation (although likely not the thalweg) was at the base of the stone portion of the bridge. Currently the channel bed has incised, requiring the pouring of a concrete slab underneath the bridge footers. The 1.5 m of observed incision is based upon the height between the concrete slab and the base of the stone portion of the bridge.

Pope Street

This example also uses historic photographs to infer channel change through time. Because of the scale of the historic photo, we have less confidence in this estimate than that made at Zinfandel Lane. In the historic photo it appears as if the bed elevation is at the base of the stone portion of the footer, although the obvious construction modifications obscure the view. Presently the channel thalweg is located ~1.0 m below the stone portion, exposing a rough concrete base of the footer, which was likely not exposed post-construction.

FIGURE 2. Close-up of the now-exposed bridge pillar concrete footer. The concrete portion of the footer is approximately 1.5 m in height.

FIGURE 3. Historic photograph looking downstream at the construction of Pope Street bridge (courtesy of Al Edminster). Note the bed elevation in comparison to the center-right footer.

FIGURE 4. Photograph looking downstream at the center-right bridge footer. Note the exposure of the concrete base, approximately 0.9 m above the current bed elevation.

Pratt Avenue

This example makes use of an as-built drawing for the bridge from 1921 and our field observations and rough channel dimension measures. The present bridge appears to be the original, based upon architectural details observed and shown on the drawing. While in the field we made measures of the channel dimensions compared to the bridge footers and deck, and sketched the current channel form onto the drawing for comparison. Based upon these measures, we can see that the channel has incised approximately 2.1 m (comparing thalweg bed elevations) since the bridge was built. The right bank side has also undergone a significant amount of erosion, although this is likely a very localized change.

FIGURE 5. As-built of Pratt Avenue showing 1921 channel bed elevation in black, and 2006 bed elevation in red.

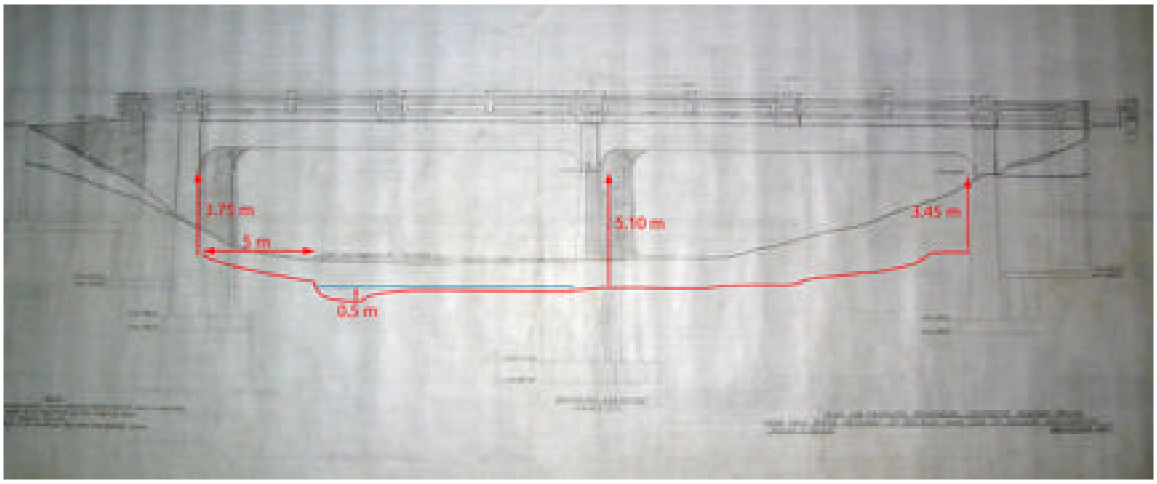


FIGURE 6. Photograph looking downstream at Pratt Avenue bridge.

Lodi Lane

This example is similar to Pratt Avenue, where current channel measures and sketches are overlain upon the historic as-built drawing. In contrast to Pratt Avenue, here at Lodi Lane we see a significant shift in the location of the channel thalweg (and localized significant erosion along the right bank), and only minor amounts of incision. Because this as-built is not dated (housed in a file containing drawings from 1919-1950), it makes quantifying the exact rate of incision difficult.

FIGURE 7. Historic as-built for the bridge at Lodi Lane. Note the change in channel shape from the historic condition (black line) to the current condition (red line). However, despite the change, the thalweg depth has only incised by 0.5 m.

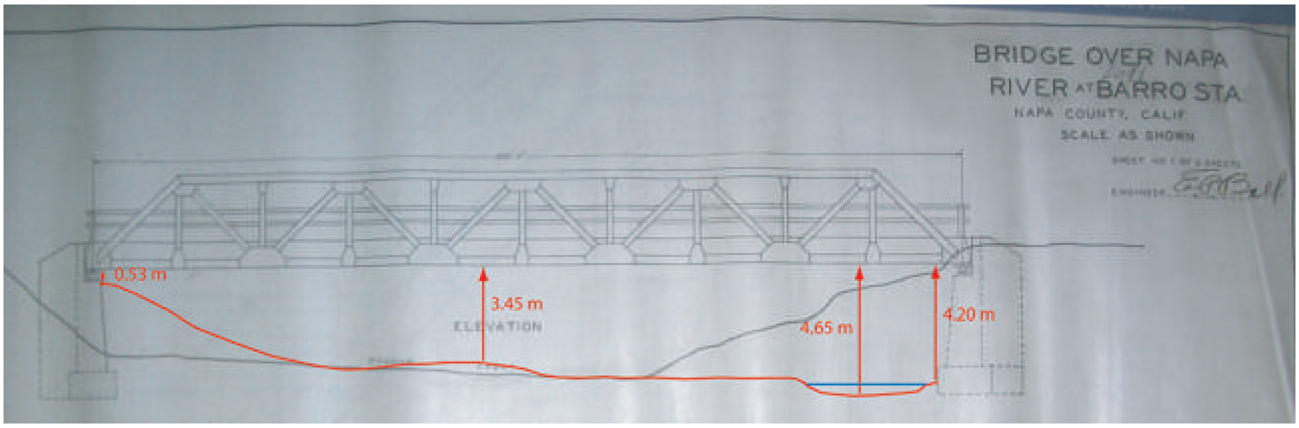


FIGURE 8. Photograph looking downstream at the bridge at Lodi Lane.

Oak Knoll Avenue

This example also uses current channel measures and sketches overlain upon the historic as-built drawing, however in this location an additional survey completed in the 1980s gives a more complete history of the dynamic nature of the channel. The survey data suggests that the channel eroded both banks (at least immediately at the survey location) after the bridge was built in 1922. By the 1980s survey, the channel bed had aggraded compared to the 1922 thalweg elevation, possibly representing a slug of sediment that was being transported downstream. It is important to note that we have no information on the bed elevation between these two dates; it may have incised or aggraded much more than shown on this drawing. And then after the 1980s, the channel incised to its current elevation, exposing the concrete bases of each footer. The incision estimate of 0.5 m that we report is the difference between the 1922 and 2006 thalweg elevations, and not the highly localized scour that is immediately adjacent to each footer.

FIGURE 9. Historic as-built of Oak Knoll Avenue showing the 1922 bed elevation (blue), the 1980s survey (long pink dashes), and the 2006 sketch (short red dashes).

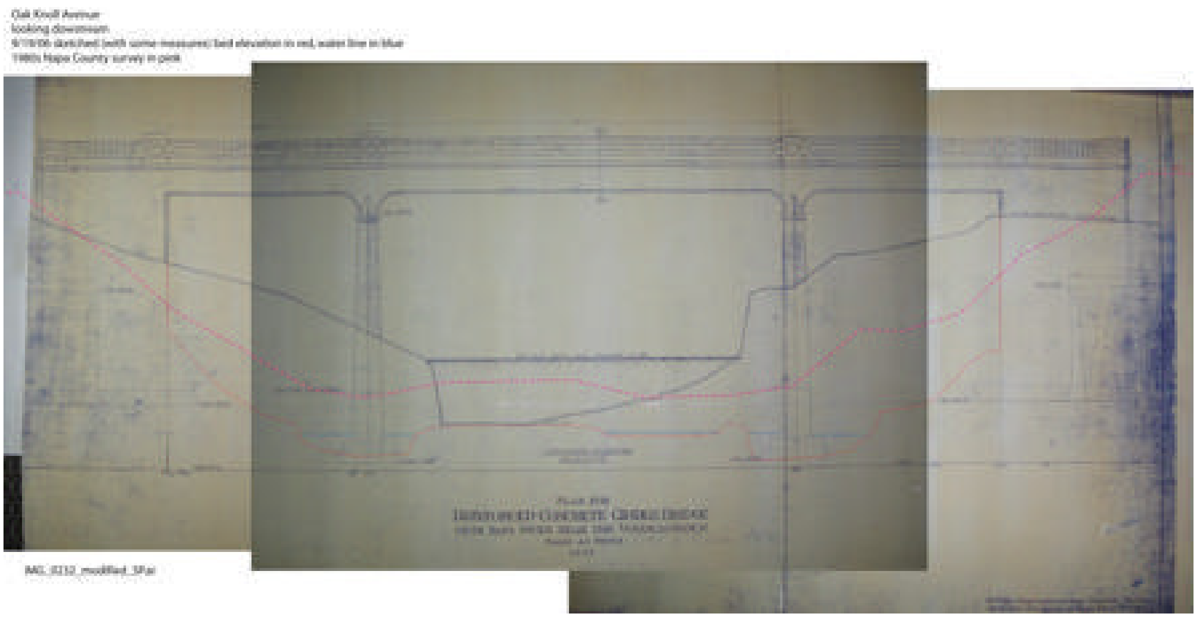


FIGURE 10. Photograph looking downstream at the left bank bridge footer. Arrow is pointing to the change in concrete texture representing "end of batter" shown on the as-built.

Discussion

Comparison of recent (1996, 2006) and historical cross-sectional data (ranging from 1894-1959) confirms a general trend of overall incision on the mainstem Napa River from Calistoga to Napa during the 20th century. These data suggest that incision over the last 40-100 years was commonly in the 2-3 m range, with larger and smaller values also observed. These data are consistent with other recent estimates of channel incision, which were based largely on analysis of field conditions and aerial photography, such as Napolitano (2007; average incision value of 3.0 m) and Stillwater and Dietrich (2002; estimate of 6-8 ft incision). More qualitative 19th-century information, such as the use of the mainstem river for agriculture and to power gristmills also suggests a significantly shallower channel than observed today.

Substantial variability in incision depths is also observed from these data. This likely reflects the temporal and spatial complexity of channel processes, especially local variations in channel bed material (the channel may incise more slowly through bedrock and hard clay surfaces) and anthropogenic effects (e.g. bed/bank stabilization efforts). In fact, because a number of the historical cross-sections and photographs focus on bridges, which tend to be built in relatively stable areas and often are actively protected from erosion through the construction of concrete aprons (e.g. Zinfandel Lane) or placement of in-channel riprap, these data may be biased slightly towards areas with less incision. Localized bed aggradation may also occur within the context of a general incision trend, as sediment pulses slowly move downstream, potentially explaining some of the data variability. It should also be noted that additional incision to that measured here may have taken place in the earlier decades of the historical era, prior to these data, due to hillside vegetation changes and/or increasing channel connectivity.

As an additional task within the larger Napa Ag project, SFEI conducted an assessment of channel change using longitudinal profiles and channel cross sections. The longitudinal profile comparison between the USGS topographic quadrangle (essentially 1950s bed elevation) and the 1996 thalweg profile did corroborate 3-4 m of incision downstream of approximately St. Helena, however lesser amounts of incision were observed upstream of St. Helena. Comparisons between the 1996 and 2006 longitudinal profiles in the Oakville to Oak Knoll reach were inconclusive, suggesting little to no incision during this time frame. In addition to longitudinal profiles, surveyed cross sections from 1996 and 2006 for the Oakville to Oak Knoll reach were also assessed to quantify incision over this time period. This assessment showed variable results, both incision and aggradation, for sub-reaches within this reach, similar to the results from the longitudinal profile assessment. We suggest that the current existing data are not adequate for quantifying any potential incisional trends within this reach.

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APPENDIX VI

Napa River Watershed Profile: Landscape Evolution

This Appendix includes a compilation of pictorial representation of events related to settlement and population increases in the watershed over time.

The historical landscape had been managed by the indigenous population through practices such as controlled fire, selective harvesting of plants and wildlife, and cross-valley trails. Although people have inhabited the Napa Watershed for more than 3,000 years (Heizer 1953, Milliken 1978), the indigenous population did not practice agriculture in the European sense. Rather, their approach to land use emphasized selective enhancement of existing ecological processes (Lightfoot and Parrish 2009). However, their use of fire to manage ecosystems probably had significant influences on the composition and overall structure of the local flora (Storm and Shebitz 2006), which in turn would have influenced runoff and land surface erosion (e.g., Istanbulluoglu and Bras 2005, Michaelides et al. 2009).

The river system had adjusted to indigenous land management long before the local advent of European land use. This does not mean that the river was not dynamic - migrating or in other ways adjusting to natural variations in water supplies, sediment supplies, inputs of large woody debris, etc. However, the channel was probably not chronically aggrading or incising due to land use as it has been more recently. Also, the human population was small, and is not expected to have significantly interfered with the river's function. FIGURE 1 provides a conceptual illustration of land use during this period and highlights many of the undisturbed alluvial river attributes.

Upon the arrival of European settlers, land use practices changed significantly. The timeline in FIGURE 2 tracks landscape changes.

1769-1823: Cultural Contact

During this period, Spanish colonization initiates decline of indigenous culture and alters land use practices in the SF Bay Area. Tribes of the southern part of Napa Valley may have experienced population declines by the 1810s, but cultural practices such as burning appear to have continued. In contrast to other parts of the Bay Area, no direct Euro-American land use activities took place in the Napa Valley during this time.

1769	First Spanish expedition to the Bay Area
1776	First Bay area Mission established (San Francisco)
1812	Russian colony at Fort Ross established
1823	Mission established at Sonoma

FIGURE 1. Pre-European settlement landscape features.

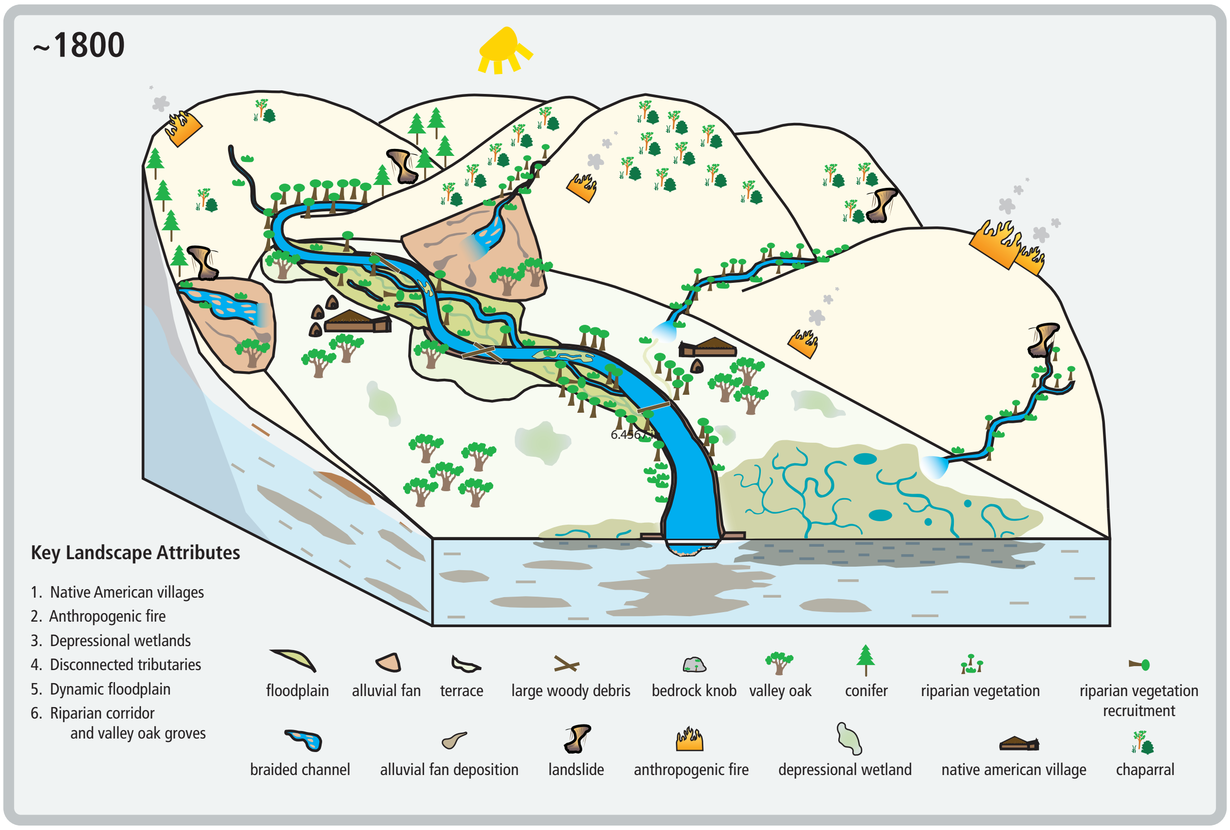
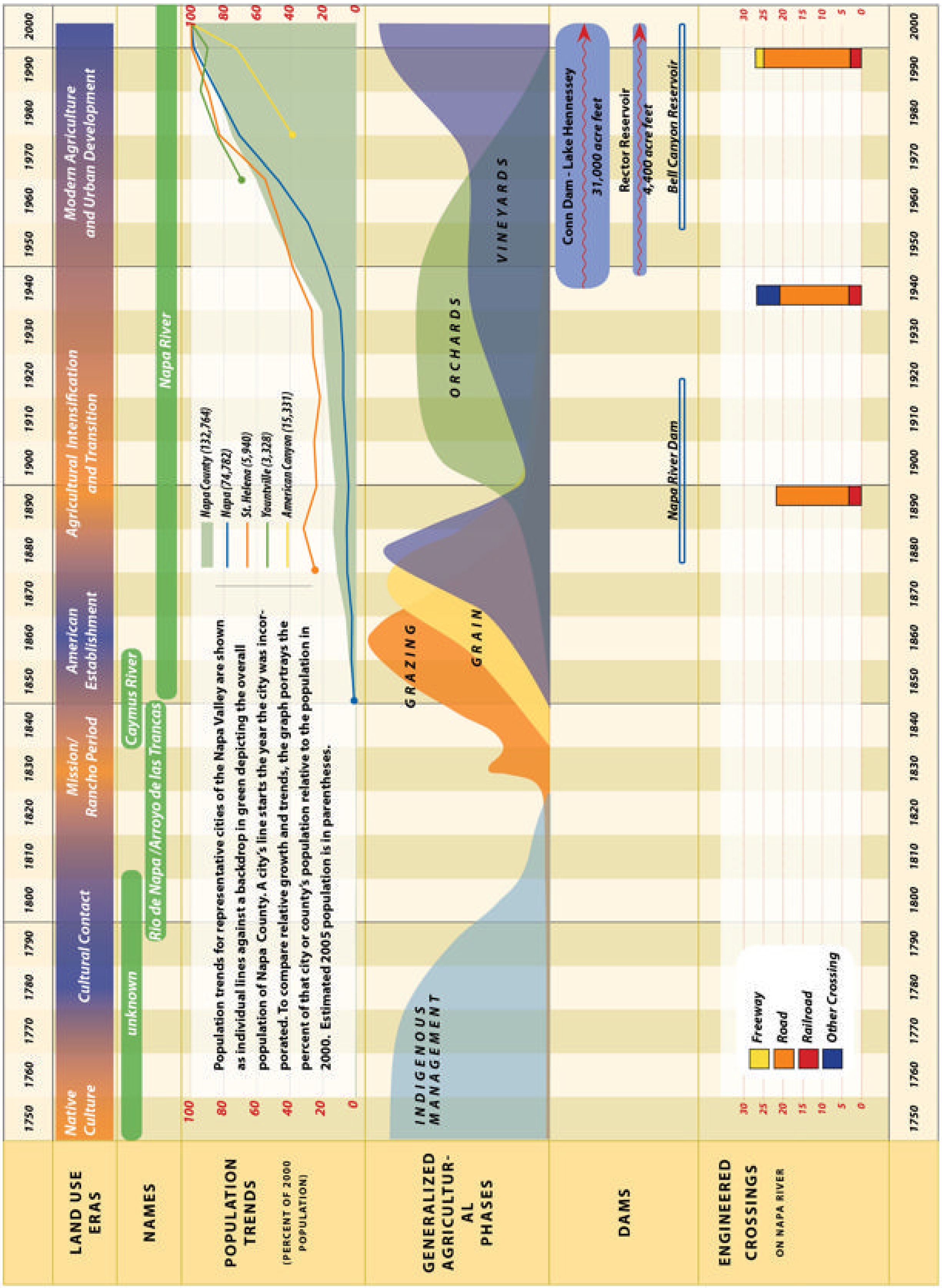


FIGURE 2. History of Napa Valley landscape relative to major changes in human activities.

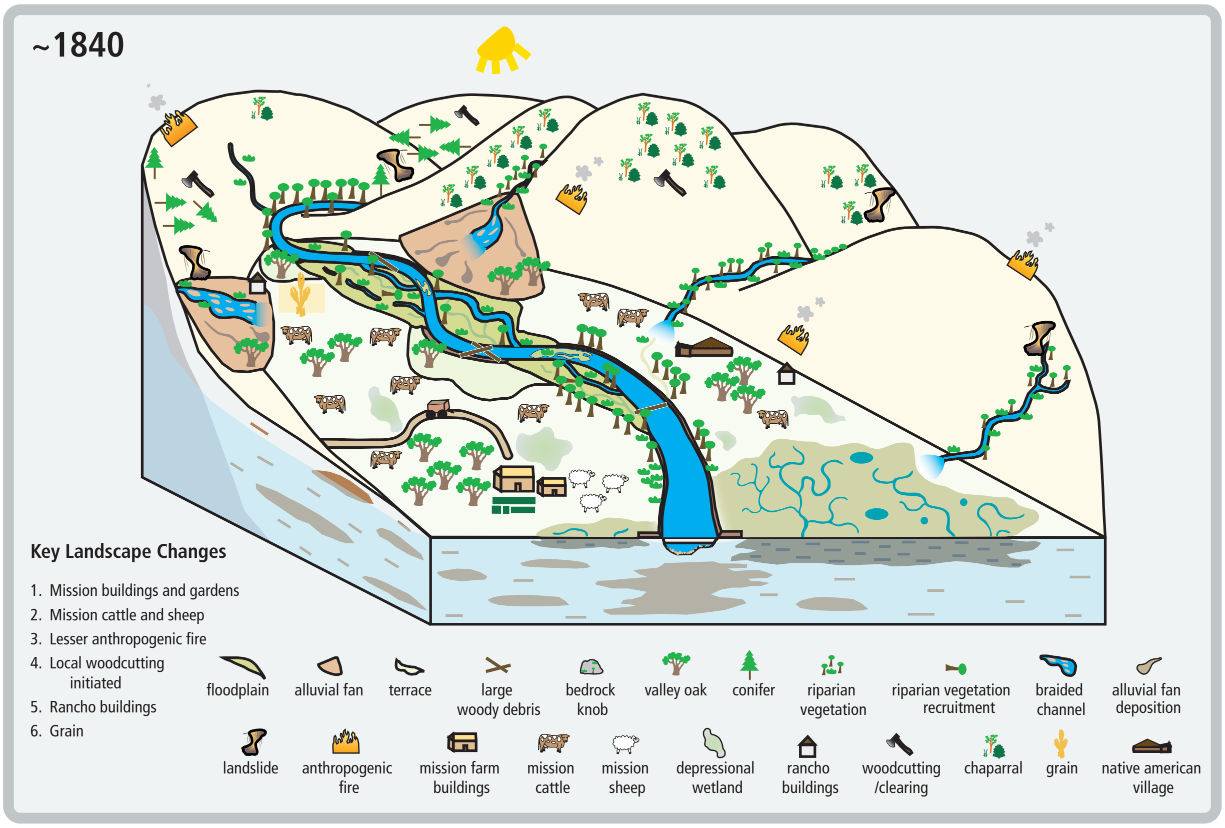


1823-1848: Mission/Rancho Period

In the 1820s, the Napa Valley is dedicated for the first time to Euro-American land use. Sheep and cattle ranching are initiated, with intensity increasing following land grants in the 1840s. The first limited farming and associated water use in the Napa Valley took place during this era but was spatially limited to small areas near the Rancho homesteads. Logging was started for local use.

1834	Secularization of Mission lands
1836	Yount receives Rancho Caymus; Higuera receives Rancho Entré Napa
1836-1846	Napa Ranchos established andgranted
ca 1840	Earthen dam built across Mill Creek by Bale to construct a mill pond, likely Napa Valley's first reservoir
1848	US takeover

FIGURE 3. Mission era landscape.

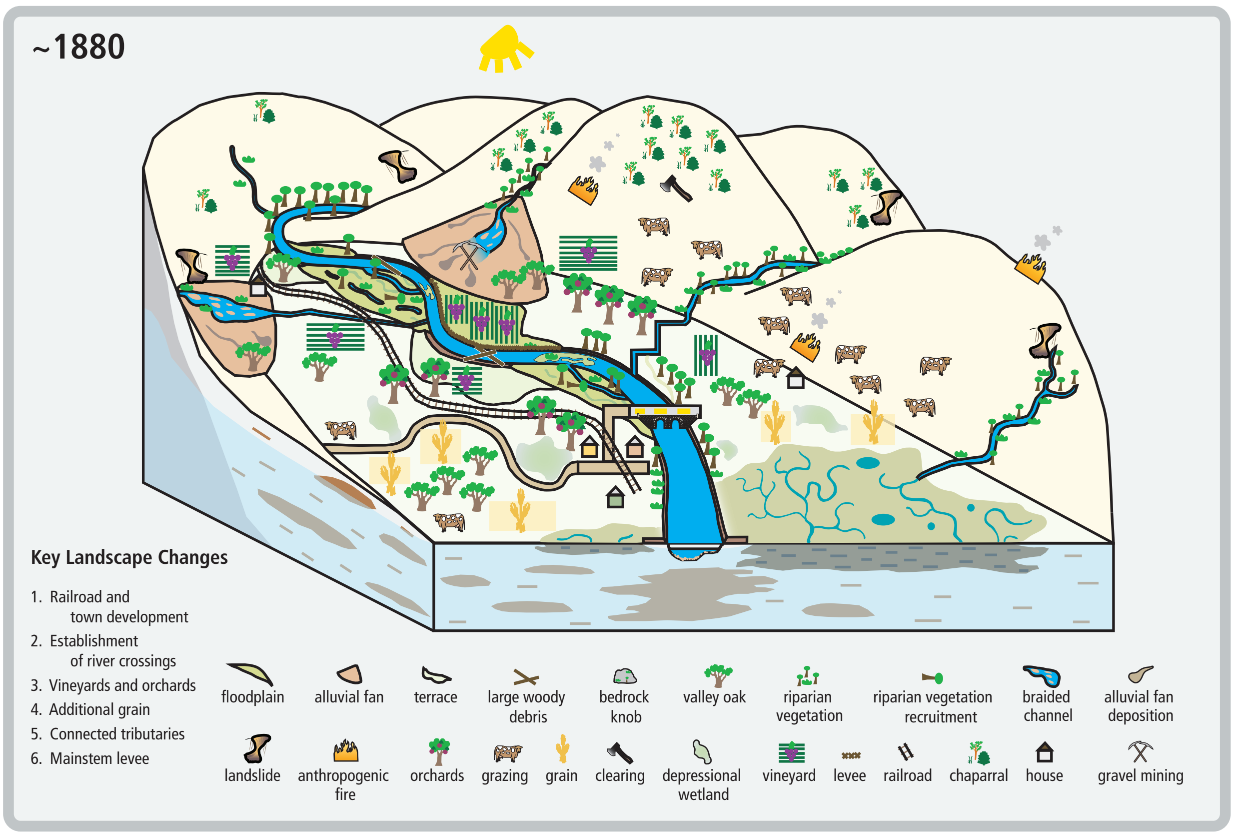


1848-1870s: American Establishment

A range of intensive American land uses are rapidly introduced during this period including agriculture, with grain replacing cattle (after initial intensification) on the valley floor. Pockets of redwoods are mostly eliminated and lumber imported from counties to the north by 1873. Commerce is transported during this era through high tide landings in Napa City. As agriculture expands, drainage efforts begin to extend the channel network through ditches and constructed channels. Springs, small dams and diversions from mountain streams, and wells (sometimes powered by windmills) are used for drinking water and gardens ("house and grounds"), but most crops are dry farmed. In place of irrigation, deep plowing is used to access soil moisture. Roads and bridges are constructed.

1850	First bridge across Napa River approved by City Council (Menefee 1873)
1852	Commercial steamboat service begins between Napa and San Francisco
1852	SuscolCreekchannelextendedthrough wet meadows to improve drainage for Thompson's Soscol Orchards (Menefee 1873)
1860s	Drought and fencing legislation hasten the decline of ranching (Carpenter and Cosby 1938)
1862	Large flood
1864-68	Napa Valley Railroad constructed between Napa City and Calistoga

FIGURE 4. Landscape following establishment of American influence.

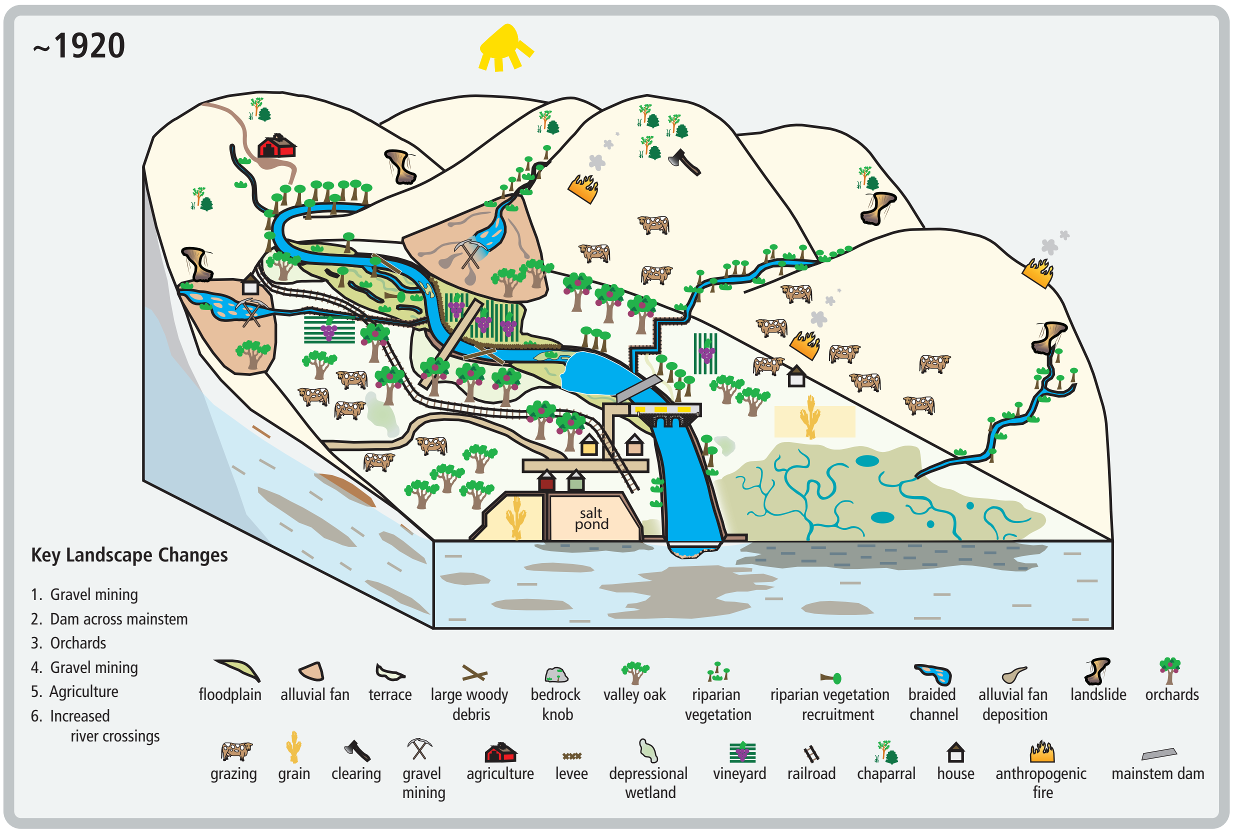


1870s-1930s: Agricultural Intensification and Transition

Viticulture replaced grain as the predominant crop by the 1880s but was decimated by disease in the 1890s, leading to substantial conversion to orchards. By 1910 the acreage of land bearing vines recovered to 1890 levels, but orchards remained important. Grapes and prunes became the dominant crops, with smaller amounts of pears, walnuts, and dairies. Continuing pressure on the tidal reaches of Napa River for commercial transportation leads to the establishment of an Army Corps dredging program. The expansion of drainage continues, and remains a greater concern than irrigation in the valley as most crops are still dry farmed.

1870s	Rapid expansion of the vineyard industry (Carpenter and Cosby 1938)
ca 1883	Napa River Dam built on main stem near Trancas (Tortorolo 1978)
1883	French prunes introduced to the valley, eventually becoming a dominant crop
1888	Army Corps of Engineers dredging project initiated on Napa River downstream of Napa City (Rees et al. 1914)
1889-1892	Massive loss of vineyards to phylloxera
1919-33	Prohibition inhibits wine industry
1924	Milliken Creek Dam completed
ca 1930	Napa River Dam removed as larger water supplies are developed.
1930s	Drought

FIGURE 5. Landscape during agricultural intensification and transition.



1940s-present: Modern Agricultural and Urban Development

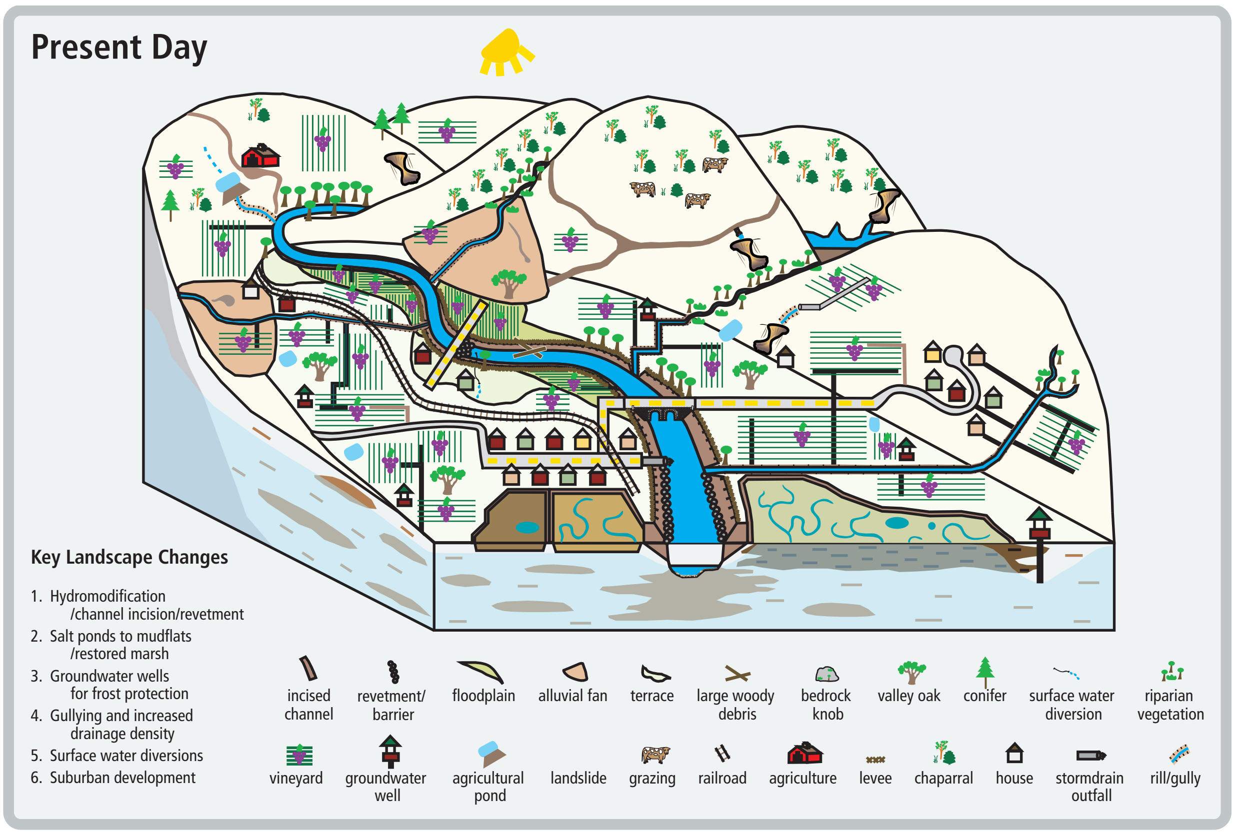
In the 1940s, residential housing begins to expand to support Mare Island activities during World War II and then more rapidly as part of the general post-World War II suburban expansion and growing popularity of the region. The combined population of Napa Valley towns, about 26,000 in 1960, has increased by 14,000-25,000 people each decade since. Large reservoirs are constructed on tributaries to supply municipal water use. Viticulture gradually recovers from Prohibition and begins to expand rapidly beginning in the 1960s. Agricultural irrigation becomes widespread for the first time in the late 1960s, as groundwater is used for frost protection, leading to the construction of numerous reservoirs. Agricultural preservation and environmental restoration efforts are initiated.

The 1970's see an intensification of urbanization accompanied by more impervious areas and storm drains, increases in artificial bank revetments to deter property loss, and increases in grade control to minimize local bed incision.

As grape production grows in late 1960's, there is an increase in sub-surface drains, to facilitate vineyards expansion into more marginal lands with poor drainage. More water diversions were used for frost control purposes. Many ditches were lined with rocks which increased their hydraulic efficiency and reduced their erosion. The county began to impose stricter standards for erosion control as hillside vineyards became more common.

1948-59	Conn Dam and Reservoir (Lake Hennessey, 31,000 acre-feet capacity), Rector Dam and Reservoir, Bell Canyon Dam completed
ca 1960	State Water Project imports commence
1968	Napa County Agricultural Preserve is implemented
1976-77	Drought
1996	"Living River" Concept initiated

FIGURE 6. Representation of prominent features of the present day Napa Valley landscape.



The signature of the changes in land use can be found in changes in the structure of the channel and its riparian corridor. Land use practices have directly impacted the presence and extent of healthy alluvial river attributes. Some attributes are still present on the valley floor, while for some, only faint remnants are evident, and others have all but disappeared. Aerial photographs from a range of time periods illustrate the evolution of the channel and its floodplain.

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