Napa River Basin Limiting Factors Analysis

FINAL TECHNICAL REPORT

Prepared for

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Abstract

Although the abundance and distribution of salmon, steelhead, and other native aquatic species are believed to have declined substantially during the historical period, the Napa River and its tributaries continue to support an exceptionally diverse and almost entirely intact assemblage of native fishes including runs of steelhead, with habitat primarily in the tributaries, and fall-run Chinook salmon in the mainstem channel. In 1990, based on evidence of widespread erosion and concerns regarding adverse impacts to fisheries habitat, the Regional Board listed Napa River and its tributaries as impaired by too much sediment under Section 303(d) of the federal Clean Water Act. As such, the Regional Board is legally required to examine whether sediment is impairing habitat, and if so, to prepare a plan to reduce sediment supply as needed to facilitate self-sustaining populations of native aquatic species. The California State Coastal Conservancy (Coastal Conservancy) is a non-regulatory agency that is actively involved in restoration planning and project implementation in the Napa River watershed. It has a strong interest in funding additional projects in the Napa River watershed to restore and enhance natural habitats and processes throughout the watershed.

To serve the public trust, and to fulfill the responsibilities of our agencies, Regional Board and Coastal Conservancy funded a two-year study by the University of California, in collaboration with Stillwater Sciences, to evaluate factors limiting populations of three at-risk native species: 1) steelhead, which are federally listed as threatened in central California; 2) Chinook salmon, which are rare in Bay Area streams; and 3) California freshwater shrimp, which are federally listed as endangered. We conducted the study to evaluate the Regional Board's sediment listing and facilitate the Coastal Conservancy's restoration planning and project implementation, by addressing the following questions: 1) What are the primary factors currently limiting populations of steelhead, Chinook salmon, and California freshwater shrimp? 2) How important is sediment relative to other potential limiting factors? 3) What actions are needed to conserve or restore self-sustaining populations of these species?

The limiting factors study involved five sequential steps:

1) Review of available information and interview of local experts regarding the biological and physical attributes of the Napa River watershed to characterize the watershed and select initial sites for fieldwork;
2) The selection of three at-risk, analysis species for more in-depth study, the development of initial hypotheses regarding current habitat conditions and limiting factors, and reconnaissance field surveys to refine hypotheses and identify priorities for focused field studies;
3) Focused field studies to begin testing the most likely hypotheses about how current habitat conditions might limit analysis species;
4) Review and synthesis to identify significant limiting factors; and
5) Development of recommendations for future studies, to reduce uncertainty regarding limiting factors and determine cause-effect relationships, and to establish

interim priorities to facilitate the conservation or recovery of native aquatic species, including steelhead, salmon, and freshwater shrimp.

In our focused studies (step 3), we developed a large amount of original data to describe physical habitat attributes in the mainstem of the Napa River and its tributaries including:

1) Pool filling with fine sediment measured at 136 sites in 29 reaches of 18 tributaries;
2) Permeability, the flow rate of water through streambed gravels, was measured at 59 potential spawning sites in 28 reaches of 17 tributaries, and 5 sites in 3 reaches of the mainstem channel;
3) The duration of elevated turbidity following storms was measured at 18 sites in 16 tributaries following 4-to-5 storm events, and 6 mainstem sites following 5 storms;
4) Stream temperature was continuously monitored at 22 sites in 13 tributaries, and 6 mainstem sites over two dry seasons and one wet season; and
5) Late dry-season surface flow was described at 148 sites throughout the watershed.

We also compiled and extended previously collected fish passage barrier data, conducted a pilot study to examine juvenile steelhead growth during the summer months, interpreted historical and recent aerial photos, and conducted extensive field surveys of the mainstem channel (about 10 miles) and to describe current habitat (for salmon, freshwater shrimp, and steelhead) and geomorphic conditions, and changes in channel form between 1940's and present.

We found that pool filling with fine sediment is typically quite low with values less than 10 percent at 25 of 29 sites sampled. We also measured turbidity following storm runoff events and found that turbidity typically dropped to very low levels (less than 20 NTU) within 1-to-2 days to following peak runoff events. Therefore we concluded that pool filling and chronic turbidity do not appear to be significant limiting factors for the analysis species under present-day conditions. In contrast, measured values of permeability at potential spawning sites for steelhead and Chinook salmon were typically quite low as a result of fine sediment deposition in the streambed. Based on examination of data relating permeability to survival of incubating salmon eggs and larvae we predicted that mortality of incubating eggs and larvae in Napa River and its tributaries may often exceed 50 % between spawning and emergence. To help evaluate the effect of this level of mortality during incubation on steelhead run size, we performed a quantitative population dynamics modeling exercise using data from one tributary: Ritchie Creek. Based on this analysis, we concluded that current permeability values, although low, might only depress steelhead population by a small amount because it appears that available juvenile rearing habitat can be well seeded even with only 50 % survival during incubation. Our analysis also indicates however, that further reductions in permeability or spawning gravel quantity might cause a substantial decline in steelhead smolt production. Taking these findings into account, the Regional Board has concluded that the Clean Water Act sediment listing should be maintained. Additional studies are needed to determine whether the fine sediments causing low permeability are from natural or anthropogenic sources.

We also identified several other significant factors, in addition to low permeability, that appear to be limiting steelhead trout population size including: 1) the common occurrence of potentially stressful stream temperatures, with typical average daily summer temperatures in tributaries ranging from 15 to 20 °C, and a lack of dry season flow persistence over most riffles act in a synergistic fashion, and appear to severely limit growth of juvenile steelhead during summer months; 2) a large number of potential impediments and/or barriers in tributaries which may block or impede access to a large amount of otherwise suitable habitat; and 3) the amount of large wood in streams draining mixed evergreen forests, primarily the west side and Howell Mountain, appears to be much lower than would be expected for streams in unmanaged mixed evergreen forests (higher amounts of large wood would promote the retention of spawning gravels and an increase the frequency and quality of pools in tributaries).

Although large amounts of fine sediment are deposited throughout the mainstem channel[1], we do not conclude that this is a primary factor limiting the Chinook salmon population. Based on comparison of 1940 and 1998 aerial photographs of the mainstem channel, extensive channel surveys, and review of existing information, we conclude the mainstem channel has typically incised 4-6 ft (1-2 m), or more, between its mouth and a point upstream of Calistoga since the 1940s, and as a result the channel form has greatly simplified. Pervasive channel incision and habitat simplification have greatly reduced the quantity of habitat for spawning (gravel bars) and early juvenile rearing (riffle margins, side channels and sloughs), and greatly expanded habitat favored by introduced predator fish species (long deep pool-run habitat complexes). Channel incision and simplification appears to be the primary factor limiting salmon population. Considering the spatial extent, nature, and magnitude of the changes in channel form, we hypothesize that little increase in salmon population would occur as a result of a substantial reduction in total and/or fine bed material supply to the mainstem channel. Complex habitat structure must first be restored on a large scale before habitat quality as affected by sediment (e.g., redd scour and permeability, and pool depth and cover) would begin to influence Chinook salmon population size.

California freshwater shrimp (CFWS) are found in the mainstem and lower reaches of some tributaries. The details of the ecology and life history of CFWS are not well documented, however it is known that they require undercut bank habitat, in low velocity, moderately deep (1-3 feet [0.3-0.9 m]) stream reaches with overhanging riparian vegetation, aquatic vegetation, structurally complex streambanks with exposed roots, and submerged woody debris or live vegetation. CFWS are tolerant of warm stream temperatures and low flow, however they do not tolerate brackish water. We surveyed about 10 miles (16 km) of the mainstem channel, primarily between St. Helena and Calistoga, and found that on average about 3 percent by length of the stream surveyed possessed suitable habitat for CFWS. More information is needed to determine how the current distribution, abundance, and quality of habitat compares with historical conditions, together with more detailed understanding of the ecology and life history of CFWS.

[1]Based on surveys of about 10 miles (16 km) of the mainstem channel and measurement of permeability at potential spawning sites.

Based on the above findings, we developed several recommendations for interim priorities for management actions and additional research to reduce uncertainty regarding limiting factors and determine cause-effect relationships between limiting factors, natural disturbances, and human activities.
Recommendations include:

1) The development of detailed sediment budget to quantify relationships between land use and delivery of fine sediment to channels, and additional vigilance to prevent increased delivery, or preferably to reduce the delivery, of sediment to channels;
2) Conducting tributary surveys to identify potential barriers (and the amount of potential habitat affected) and quantify the amount and functions of large woody debris, coupled with studies to assess how various land and water use activities influence stream habitat quantity and quality, and actions to add large woody debris and increase woody riparian vegetation when opportunities arise;
3) Conducting more intensive historical analysis of mainstem, tributary, and estuary conditions and processes, and changes associated with human land and water uses to explore the potential costs and benefits associated with restoration actions designed to enhance the current runs of Chinook salmon or steelhead;
4) Conducting additional studies of the influence of flow, temperature, and food levels on juvenile steelhead growth rates and exploring opportunities to reduce water temperature by enhancing riparian vegetation to increase stream shading, reduce unnecessary or inefficient water use and thus increase summer baseflow in tributaries, and ensure that potential sources of turbidity are not increased or exacerbated; and
5) Conducting more studies on the distribution, abundance, and habitat needs of the California freshwater shrimp, investigate the geomorphic and ecological processes that create and maintain California freshwater shrimp habitat, and strongly encourage efforts to protect undercut bank habitat and associated riparian vegetation.

Preface

The San Francisco Bay Water Quality Control Board (Regional Board) regulates water quality throughout the Bay Area, including the Napa River watershed, to protect the beneficial uses of water for the use and enjoyment of the people of the state. Beneficial uses include water supply, recreation, navigation, and the preservation and enhancement of fish, wildlife, and other aquatic species. Based on evidence of widespread erosion and concerns regarding adverse impacts to fisheries habitat, the Regional Board listed the Napa River and its tributaries in 1990 as impaired by sediment under Section 303(d) of the federal Clean Water Act. As such, the Regional Board is legally required to prepare a total maximum daily load (TMDL). TMDL is a national program mandated by the Clean Water Act to identify pollution problems, determine pollution sources, and develop plans to restore the health of polluted bodies of water.

The California State Coastal Conservancy (Coastal Conservancy), a non-regulatory agency, was created by the state legislature in 1976 to work with agencies, nonprofits, and landowners to preserve, restore, and enhance natural resources along the coast for the use and enjoyment of the people of the state. Its legislative mandate was expanded in 1997 to include the nine-county San Francisco Bay Area. It is actively involved in restoration and planning projects in the Napa River watershed, including enhancement of the lower Napa River floodplain and restoration of approximately 10,000 acres (4000 ha) of former commercial salt ponds. The Coastal Conservancy has a strong interest in funding projects in the Napa River watershed to restore and enhance natural habitats and processes, and thus has helped fund this study, which includes recommendations for restoration activities.

To serve the public trust, and to fulfill the responsibilities of our agencies, the Regional Board and Coastal Conservancy funded a two-year study of stream and riparian habitat conditions in the Napa River watershed. The study, conducted by the University of California in collaboration with Stillwater Sciences, evaluated factors limiting populations of three species of rare or threatened native fish and aquatic wildlife in the Napa River watershed and was designed to help the Regional Board refine the TMDL problem statement and facilitate the Coastal Conservancy's restoration planning and project implementation.

The study, which represents the Phase I of a planned two-phase study, had three three primary objectives:

1. To help inform the Regional Board's sediment TMDL process;
2. To improve our understanding of current conditions in the Napa River system, develop and refine hypotheses related to impacts on salmonids and freshwater shrimp populations by sediment and other factors, and develop recommendations for additional (Phase II) studies to define cause-and-effect relationships between human land use activities in the watershed and their impacts on water quality and beneficial uses; and
3. To make recommendations regarding planning and implementation of restoration actions to protect and restore aquatic ecosystem functions and beneficial uses in the Napa River watershed. These recommendations are based on and commensurate with our current state of knowledge. We anticipate formulating more detailed recommendations once key uncertainties have been resolved during Phase II.

This Technical Report and the companion Executive Summary will be posted on the Regional Board website at http://www.swrcb.ca.gov/~rwqcb2 (under "Available Documents") and on the Coastal Conservancy website at http://www.coastalconservancy.ca.gov (under "News" and "Projects and Programs").

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We express special thanks to Michael Napolitano (Regional Water Quality Control Board) and Ann Buell (Coastal Conservancy) both of whom contributed to the success of this project in many ways, including many hours reviewing and helping us improve the Executive Summary and Technical Report. Paul Jones (U.S. Environmental Protection Agency) provided input throughout the project. Leslie Ferguson (Regional Water Quality Control Board and UC Davis) was the person primarily responsible for getting the project started, and she provided important technical input throughout this study. Martin Trso, R.G., contributed greatly to the geomorphic field surveys and analyses, and provided much useful input on the report. We thank Sayaka Araki (UC Berkeley) for her steadfast efforts in the field, and with many hours of data analysis and graphics editing. We had a number of productive discussions with Laurel Collins about Napa and Bay Area streams and geomorphic assessment.

Access

We are grateful to all of the private landowners who took an interest in this study and were kind enough to grant us permission to make channel observations and measurements on their property. Obtaining permissions for access would not have been possible without the help a large number of individuals and several organizations. We offer special thanks to the Conservation Committee, Directors, and staff of the Napa County Farm Bureau; the members of the Carneros, Dry, Huichica, and Sulfur Creeks tributary stewardship groups; the staff and Board of Directors of Napa County RCD; the staff of the Land Trust of Napa County; staff and members of the Napa Valley Vintners Association and Napa Valley Grape Growers Association; staff of the Bothe Napa Valley State Park and Las Posadas State Forest, and members of the Friends of the Napa River.

Technical Input

Numerous individuals provided us with existing data and provided critical input to our ideas and studies designs during the project. In particular, we'd like to thank Matt O'Connor of O'Connor Environmental); Robin Grosinger, Lester McKee, Sarah Newland, and others at the San Francisco Estuary Institute; Derrick Acomb, Bob Coey, John Emig, Mike Rugg, Gail Seymour, Bob Snyder, and Larry Week at California Department of Fish and Game; Phil Blake, Jonathon Koehler, Jennifer O'Leary, Dave Steiner, and Bob Zlomke at Napa RCD; David Graves (Carneros Creek Stewarship); Charles Dewberry and Chris Malan for providing data from the Friends of the Napa River steelhead and macroinvertebrate surveys; Volker Eisele and Tom Gamble of the Napa County Farm Bureau; and Mignon Everett, Trish Hornisher, Pat Kowta, John Lander, Patrick Lowe, Bob Peterson, Jeff Redding, John Stewart, and Charlie Wilson at various Napa County agencies.

Public Comment

We also thank all individuals and organizations that provided comments during the public review period and at the public meeting on June 10, 2002 in Yountville, Napa County.

Document Organization

Executive Summary

The draft Executive Summary was released separately on April 17, 2002. We expect that the Executive Summary, which is very comprehensive, will meet the needs of many, if not most, readers. Readers wanting a more detailed and technical description of the study and its findings may prefer to read the Technical Report, which includes all components of the Executive Summary.

Technical Report

The Technical Report includes all of the elements found in the Executive Summary and is organized as follows:

Chapter 1—Introduction. Explains the purpose and objectives of, and provides background for this two-phased study. This chapter is similar to the Objectives and Background sections in the Executive Summary.

Chapter 2—Study Approach. Describes the general approach used to conduct the Phase I limiting factors study. This chapter is similar to the Approach section in the Executive Summary.

Chapter 3—Watershed Characterization. Describes the physical and biological setting of the Napa River watershed, including the hydrology and structure of the drainage network, geology, land use and land cover, and fish communities.

Chapter 4—Analysis Species. Describes what is known about the life histories of the three analysis species: Chinook salmon, steelhead, and California freshwater shrimp.

Chapter 5—Identification and Screening of Potential Limiting Factors and Initial Hypotheses. Explains the range of factors that could limit the abundance of the analysis species and which factors were specifically incorporated into our study design.

Chapter 6—Focused Studies. Summarizes the rationale, approach, and results for the hypothesis-driven studies that were conducted to better understand factors potentially limiting analysis species.

Chapter 7—Limiting Factors Synthesis. Evaluates and synthesizes our current understanding of limiting factors for analysis species. This chapter is similar to the synthesis provided in the Executive Summary.

Chapter 8—Recommendations. Provides recommendations on restoration actions that are likely to increase analysis species populations and additional studies that are necessary to develop these restoration actions. This chapter is similar to the recommendations provided in the Executive Summary.

Appendix A—Methods and Data. Provides detailed descriptions of methods and data for many of the focused studies conducted during Phase I.

Appendix B—Analysis Species Summaries. Provides detailed summaries of the life history needs of the three analysis species.

Appendix C—Descriptions of Studies Proposed for Phase II. Provides the framework for studies proposed for Phase II.

Appendix D—Public Comments. Provides copies of comments received on the Draft Technical Report during the public comment period.

1 INTRODUCTION

This report presents the results of studies conducted by Stillwater Sciences and the University of California at Berkeley in the first phase of what will be a two-phase approach. This two-year, Phase I study was jointly funded by the San Francisco Bay Water Quality Control Board (Regional Board) and the California State Coastal Conservancy (Coastal Conservancy) as part of their efforts to gather the necessary information to guide the protection and restoration of beneficial uses and aquatic ecosystem functions in the Napa River watershed. The purpose of Phase I was to evaluate the current habitat conditions found in the Napa River and its tributaries using an iterative process of hypothesis development and testing to identify the factors that are most likely limiting populations of key aquatic species of concern.

As Phase I of a two-phase approach, this study was designed to provide a reliable assessment of current conditions from a watershed-wide perspective. Available resources were not sufficient, however, to support the more intensive sampling program that would be required to give a reliable and comprehensive assessment of current conditions at finer scales of resolution, such as individual tributaries. It should be noted that the water quality portion of our analysis was focused on sediment and temperature as potential limiting factors. Other water quality parameters, such as nutrients, pathogens, or chemical contaminants may affect the analysis species or other beneficial uses, but were outside the scope of this study because they initially appeared less likely to be as important as sediment, temperature, or changes in flow.

The watershed's extensive land use history, both for agricultural and urban uses (see Section 3.3), and existing assemblage of native fish species (see Section 3.4) make it an important watershed in which to focus restoration efforts. While priority restoration actions have been identified for other well-studied Bay-Delta watersheds, we lack even general knowledge of how and to what extent beneficial uses have been degraded in the Napa River watershed. Our study focused primarily on that portion of the watershed that lies upstream from the City of Napa since the estuary and lower reaches of the Napa River have already been well studied as part of ongoing flood control and river restoration efforts.

We report herein on the first phase of the planned two-phase research program, focused on a watershed-wide assessment of current conditions in the Napa River and its tributaries, and analysis of the factors that are most likely limiting the populations of three aquatic species chosen for focused study: Chinook salmon (*Oncorhynchus tshawytscha*), steelhead (*O. mykiss*) (also known as steelhead trout), and California freshwater shrimp (*Syncaris pacifica*). The study also includes a limited effort to reconstruct historical conditions using available information to document changes that have occurred in stream habitat conditions, particularly those most likely to affect the three analysis species. This limited historical analysis was intended to improve our understanding of current conditions, the nature and degree of water quality impairment by sediment and other factors, and generate hypotheses for future study during the planned second phase of our research program. We have recommended that a more detailed historical analysis be conducted during Phase II to help establish causal linkages between any observed impairment and processes operating at the watershed scale.

The results of the Phase I studies described herein are meant to serve three primary objectives:

1. To help inform the Regional Board's sediment TMDL process (the Napa River is listed as being impaired by sediment, requiring the Regional Board to implement the TMDL process as mandated under the Clean Water Act);

2. To improve our understanding of current conditions in the Napa River system, develop and refine hypotheses related to impacts on salmonids and freshwater shrimp populations by sediment and other factors, and develop a plan for Phase II studies to define cause-and-effect relationships between human land use activities in the watershed and the impacts of those activities on water quality and beneficial uses; and

3. To make recommendations regarding planning and implementation of restoration actions to protect and restore aquatic ecosystem functions and beneficial uses in the Napa River watershed. These recommendations are based on and commensurate with our current state of knowledge. We anticipate formulating more detailed recommendations once key uncertainties have been resolved during Phase II.

2 STUDY APPROACH

In response to the listing of since the Napa River as impaired by excessive sediment under section 303(d) of the Clean Water Act in 1990, the primary focus of this Phase I study was to characterize the nature and degree of water quality impairment by sediment, particularly with regard to its potential effects on selected analysis species. Our study approach, however, was intended to provide a more holistic assessment of current conditions within the watershed and to identify the most important factors limiting populations of key analysis species. Although this analysis considered sediment and its potential impacts on habitat suitability for key analysis species, we also investigated multiple additional factors to provide a broader context for evaluating the Napa River watershed's listing under the Clean Water Act, and for providing scientifically-based restoration recommendations.

Our approach was to explore factors potentially limiting the abundance of selected analysis species to determine possible causes of impact or decline. By identifying these factors, we can focus future restoration and management activities, help prioritize actions, and refine our current understanding of the ecosystem.

2.1 Phase I Approach

The purpose of using an iterative process of hypothesis development, testing, and refinement is to provide the most adaptive and effective mechanism possible for restoration planning and implementation in the Napa River watershed. This approach may be viewed as a model for longer-term adaptive management by stakeholders, who will prioritize, monitor, and refine watershed restoration actions over time.

The Phase I Limiting Factors Analysis was a five-step process:

Step 1. Assemble and Review Available Information. We assembled and reviewed relevant existing information, and interviewed local experts to characterize the general physical and biological attributes of the Napa River watershed and to identify key issues of concern. This step included development of various Geographic Information System (GIS) layers that reflected watershed conditions in a map-based format and allowed us to stratify the watershed and channel network to aid in hypothesis development and study site selection. Chapter 3 summarizes the results of Step 1.

Step 2. Develop Initial Hypotheses and Work Plan for Focused Studies. Building on the watershed characterization and other information developed in Step 1, we selected three at-risk species for more in-depth study and began developing hypotheses regarding current habitat conditions and potential limiting factors for the analysis species (specific hypotheses are presented in Chapter 5). We then conducted rapid reconnaissance of the watershed to begin refining hypotheses and identify priorities for focused studies. Two of the analysis species, steelhead and Chinook salmon, have exhibited marked declines within the Napa River watershed from historical conditions according to local experts. Less is known about the third analysis species, California freshwater shrimp, but it is federally listed as endangered and thought to have undergone a substantial decline in distribution and abundance from historical conditions. In addition to representing at-risk species, the three analysis species serve as indicators of general habitat needs of native cold-water fish species in the mainstem (Chinook salmon, and to a lesser extent, steelhead) and tributaries (steelhead), and other aquatic organisms in the mainstem and lower-gradient reaches of tributaries on the valley floor (California freshwater shrimp). Available information, scope, and budget constrained us from including consideration of additional analysis species. Chapters 4 and 5, and Appendix B, describe the results of Step 2.

Step 3. Conduct Focused Studies. We conducted focused studies to begin testing the most likely hypotheses. We also assessed the uncertainty associated with the results of the focused studies. Focused studies included field measurement of general habitat conditions for Chinook salmon, steelhead, and freshwater shrimp, water temperature, turbidity, pool filling, spawning gravel permeability, bed mobility, potential barriers to fish passage, and summer baseflow persistence, as well as a study to determine summer growth rates of juvenile steelhead. When appropriate, we used the GIS map layers to develop stratified random sampling designs for selecting field sites. Access limitations, however, sometimes prevented us from fully implementing our desired sampling designs. Other focused studies involved more detailed analysis of existing information, such as review of historical and recent aerial photographs of the mainstem Napa River to document changes in channel morphology, and aquatic and riparian habitats, and review of fish survey data to document current fish community composition and identify likely changes from historical conditions. The results of focused studies led, in some cases, to development of new hypotheses and additional field studies. Chapter 6 describes the general methods and results of the focused studies conducted during Phase I. More detailed methods and data are provided in Appendix A for some of the focused studies.

Step 4. Conduct Limiting Factors Analysis. This step involved review and synthesis of available data from the focused studies and other sources to evaluate the factors most likely to be limiting populations of the three analysis species under current conditions. This analysis of limiting factors helped provide the context for rejecting, accepting, or refining hypotheses based on the results of the focused studies, and improved our understanding of key uncertainties that might affect our ability to manage and restore aquatic ecosystems in the watershed. The results of the limiting factors analysis are summarized in Chapter 7.

Step 5. Develop Recommendations. Based on information currently available and information and hypotheses developed during Phase I studies, we identified restoration actions and priorities and developed recommendations for future studies to establish cause-and-effect relationships between limiting factors and human land use activities (proposed Phase II studies). Our preliminary recommendations from Phase I are summarized in Chapter 8, with additional details on proposed Phase II studies provided in Appendix C.

3 WATERSHED CHARACTERIZATION

This chapter provides a general description of the Napa River watershed based on our initial review of available information, GIS analysis, and reconnaissance surveys. This watershed characterization and the review of life history requirements of our three analysis species (Chapter 4) provide the foundation for subsequent identification of potential limiting factors and development of initial hypotheses (Chapter 5) and focused studies to begin testing key hypotheses (Chapter 6).

3.1 Climate and Hydrology

The Napa River drains a 426-mi^2 (1,103-km^2) watershed that discharges into San Pablo Bay near the mouth of the Sacramento-San Joaquin estuary (Map 1). The Napa Valley has a Mediterranean climate characterized by warm, dry summers and cold, moist winters. The majority of annual precipitation occurs as rain that falls during the winter and early spring. The highest rainfall occurs on the western side of the watershed. Between 1961 and 1990, the average annual precipitation was 35–40 inches (89–102 cm) in the western portion of the watershed, and 20–25 inches (51–64 cm) in the eastern portion of the watershed (Western Regional Climate Center 2002). Rainfall gages also show a north-south trend of precipitation in the watershed. Precipitation decreases southward through the Napa Valley with average annual precipitation equal to 38 inches (96 cm) at Calistoga[2], 35 inches (89 cm) in St. Helena[3], and 25 inches (64 cm) at the Napa State Hospital[4] (Western Regional Climate Center 2002). The average daily maximum temperature decreases to the south (Western Regional Climate Center 2002), because coastal fog keeps the lower valley cooler.

There are 28 dams in the Napa River watershed with individual water storage capacities greater than 28 acre-feet[5] ($3.4x10^4$ m^3) (DSOD 2000), The total storage capacity of these 28 dams is 43,800 acre-feet ($5.4x10^7$ m^3), which is approximately 30 percent of the average annual runoff of 148,000 acre-feet ($1.82x10^8$ m^3) (as measured at the US Geological Survey [USGS] Napa River gage at Napa). Seventy-one percent of the total reservoir storage in the watershed is in Conn Creek Reservoir (Lake Hennessey), which was built in 1948. Other significant dams include Rector Creek, Bell Canyon, and Milliken dams, which along with Conn Creek Dam provide over 91 percent of the total reservoir storage in the watershed. All of these dams are located on the tributary streams along the eastern side of the watershed, and effectively block every major east side tributary between St. Helena and Napa, except Soda Creek. The dams were constructed between the late 1800s and 1990, with the majority constructed in the 1940s and 1950s.

We reviewed data from three USGS gages on the Napa River mainstem near Calistoga, St. Helena, and the City of Napa, and five gages on tributaries to the Napa River (Table 3-1). The period of record at the mainstem gages at both St. Helena and Napa are relatively long. Considering its long period of record and the fact that only a small portion of its watershed is regulated by dams, we used streamflow data for the mainstem Napa River near St. Helena to evaluate chronic turbidity (Section 6.2.1) and bed mobility (Section 6.2.3). Figure 3-1 shows a flow duration curve for daily average flows for the mainstem Napa River near St. Helena gage. The median flow over the period of record was about 8 cubic feet per second (cfs) (0.2 cubic meters per second [cms]), and about 18 percent of the time the flow is less than 1 cfs (0.03 cms)

[2] Period of record: 1948-2000
[3] Period of record: 1931-2000
[4] Period of record: 1917-2000
[5] An acre-foot is the volume of water that would inundate one acre of land to a depth of one foot and is equivalent to approximately 326,000 gallons (1.23×10^6 liters).

(Figure 3-1). At the Napa gage the median flow is about 13 cfs (0.37 cms), and the flow is less than 1 cfs (0.03 cms) about 15 percent of the year (Figure 3-2).

Table 3-1. USGS stream gages in the Napa River watershed.

Gage name	Number	Period of record (water year)	Drainage area (miles^2)	Drainage area (km^2)
Napa River near Calistoga	11455900	1975-1983	21.9	56.7
Napa River near St. Helena	11456000	1930-1932, 1940-present	81.4	211
Napa River near Napa	11458000	1930-1932, 1960-present	218	565
Sulphur Creek near St. Helena	11455950	1966-1967	4.5	17
Conn Creek near Oakville	11456500	1929-1975	55.4	143
Dry Creek near Napa	11457000	1951-1966	17.4	45.1
Dry Creek near Yountville	11457500	1940-1941	18.7	48.4
Milliken Creek near Napa	11458100	1970-1983	17.3	44.8

Source: USGS

We ranked the water years[6] at the St. Helena gage based on total annual runoff between 1930 and 2001, and divided them into wet, normal, and dry years. Wet years had an exceedence percentage of 1–25 percent, normal years had an exceedence of 26–75 percent, and dry years had an exceedence of 76–100 percent. The wettest year on record was 1983 (195,430 acre-feet [241,033,000m^3] of runoff at St. Helena), while the driest year was 1977 (1,379 acre-feet [1,701,000m^3] of runoff at St. Helena). Figures 3-3 through 3-5 show typical hydrographs for typical dry, normal, and wet years, respectively. These hydrographs are similar in that flows are typically less than 10 cfs (0.3 cms) in the summer, and that rainfall-induced peaks occur in winter and early spring. During dry years there are 0–1 peaks greater than 1,000 cfs (30 cms), fewer smaller peaks than in normal years, and about 6–9 months with flow less than 10 cfs (0.3 cms) (Figure 3-5). The mean daily average flow in 1987, a typical dry water year, was about 25 cfs (0.71 cms). During normal years, there can be 1–2 peaks above 1,000 cfs and 5–6 months of flow less than 10 cfs (0.3 cms) (Figure 3-4). The mean daily flow during 1966, a typical normal water year, was about 73 cfs (2.1 cms). In general, during wet years there are several peaks over 1,000 cfs (30 cms) and flow is below 10 cfs (0.3 cms) for about 3.5 months (Figure 3-3). The mean daily flow in 1974, a typical wet water year, was about 180 cfs (5.1 cms).

Peak flows in the Napa River are rainfall-dominated and occur between November and early April, with the majority in December through February. We analyzed peak flows using instantaneous peaks from the USGS Napa River near St. Helena gage between 1929 and 1996 (Table 3-2). Based on the discharge record, the 1.5-year recurrence interval flow (a typical recurrence interval for bankfull flow) at St. Helena was approximately 4,200 cfs (120 cms), while the 10-year flow was approximately 12,500 cfs (354 cms). The flood of record at the St. Helena gage between 1929 and 1996 was 16,900 cfs (478 cms) in February 1987. Water year 2001, during which most of this work was conducted, had a total runoff of 30,200 acre-feet (3.72x10^5 m^3), a yield exceeded during 72 percent of the water years analyzed.

[6] The water year begins on October 1 and ends on September 30 of the indicated year. For example, water year 1983 began on October 1, 1982 and ended on September 30, 1983.

Table 3-2. Instantaneous peak flow magnitudes for the Napa River at St. Helena gage (number 11456000) between 1929 and 1996.

Return Period (years)	Discharge (cfs)
1.5	4,225
2	6,007
5	10,157
10	12,450
50	16,155
100	17,271

Source: USGS

3.2 Geologic Setting

The Napa River watershed is a northwest-trending structural and topographic depression (Map 2) (Hearn et al. 1988) that has largely evolved since the early Pleistocene (about 2 million years ago) as a result of downwarping associated with regional folding and faulting (Wright and Smith 1992). The watershed is located at the southern end of the northern California Coast Range province. This area is an active zone of tectonic deformation associated with the San Andreas Fault. The San Andreas Fault is located about 35 miles (56 km) southwest of the watershed. The local deformation zone is bounded by two major faults: the north-west striking Green Valley Fault in the east (about 7 miles [11 km] to the northeast of the watershed boundary), and north-west striking Healdsburg-Rodgers Fault in the west (about 15 miles [24 km] to the southwest of the watershed boundary). Both of these faults have experienced major earthquakes in the last 100 years (Eberhart-Phillips 1988, Burcham and Van Houten 1992).

Based on review of available geologic maps and literature, the modern topography, including the formation of large tributary fans and the valley floor, is the result of erosion and deposition that has occurred since the mid-Pleistocene or roughly within the past one million years (Kunkel and Upson 1960, Johnson 1977). The elevations of surrounding peaks range between less than 1,000 (300 m) to more than 4,000 feet (1,200 m). Many isolated small hills also protrude from the valley floor now and are composed of rock types that are similar to those in the adjacent mountain fronts. The elevation of the valley floor drops from about 340 feet (104 m) near Calistoga to about 50 feet (15 m) near Napa.

The extent and location of geologic units presented in Table 3-3 and Map 3 are derived from the State of California Geologic Map (1:750,000 scale). The Napa Valley makes up about 28 percent of the watershed area, and is underlain by Quaternary alluvial fan and valley fill deposits (Q, Map 3, Table 3-3). The uplands are composed of Jurassic to Tertiary age volcanic and sedimentary rocks. Approximately 27 percent of the Napa River watershed is underlain by Tertiary volcanic flow rocks (Tv, Map 3, Table 3-3). These volcanics are primarily located in the eastern and northwestern portions of the watershed (Map 3). Jurassic and Cretaceous Franciscan rocks and Cretaceous marine sediments form the bedrock in the western, northeastern, and southeastern portions of the watershed. About 9 percent of bedrock geology in the watershed is underlain by the Cretaceous and Jurassic Franciscan complex rocks (KJf, KJfm), while 13 percent of the watershed is made up of the Cretaceous marine sediments (K, Ku, Kl). The uplands in the northern portion of the watershed are mostly composed of soft Tertiary pyroclastic and volcanic mudflow deposits (Tvp, Map 3, Table 3-3), which make up approximately 8.5 percent of the watershed area. The remainder of the bedrock units is shown on Map 3 and Table 3-3.

Table 3-3. Geologic units in the Napa River watershed.

Geologic Formation	Lithology	Acres	mi^2	km^2	Total (%)
W: Open water	n/a	4,667	7.3	18.9	1.7
Q: Quaternary alluvium	lake, playa, and terrace deposits	76,926	120.0	311.6	28.4
Qpc: Pliocene and/or Pleistocene Non-marine sediments	sandstone, shale, and gravel deposits	14,703	22.9	59.5	5.4
Tv: Tertiary (Oligocene) volcanic flow rocks	andesite, basalt, and minor rhyolite	74,327	116.0	301.0	27.4
Tvp: Tertiary (Oligocene) pyroclastic and volcanic mudflow deposits	welded tuffs, breccias, and pumice	23,058	36.0	93.4	8.5
um: Tertiary ultramafic rocks	serpentine with minor peridotite, gabbro, and diabase	6,372	9.9	25.8	2.3
M: Miocene marine sedimentary rocks	sandstone, shale, siltstone, conglomerate, breccia	2,887	4.5	11.7	1.1
E: Eocene marine sedimentary rocks	shale, sandstone, and minor limestone	9,064	14.1	36.7	3.3
K: Cretaceous undivided marine sediments	sandstone, shale, and conglomerate	340	0.5	1.4	0.1
Kl: Lower Cretaceous marine sediments	sandstone, shale, and conglomerate	13,753	21.5	55.7	5.1
Ku: Upper Cretaceous marine sediments	sandstone, shale, and conglomerate	21,262	33.2	86.1	7.8
KJf: Cretaceous and Jurassic fragmented and sheared Franciscan complex rocks.	sandstone with smaller amounts of shale, chert, limestone, and conglomerate	15,262	23.8	61.8	5.6
KJfm: Cretaceous and Jurassic Franciscan complex	sandstone with smaller amounts of shale, chert, limestone, and conglomerate	8,436	13.2	34.2	3.1
J: Jurassic marine sediments	shale, sandstone, minor conglomerate, chert, slate, limestones minor pyroclastics	217	0.3	0.9	0.1
TOTAL		**271,274**	**423.2**	**1,098.7**	**100**

Source: USGS digital version of a 1977 edition, 1:750,000 State Geology of California Map

3.2.1 Mass Wasting

Large rainstorms that sweep across the Napa watershed periodically induce shallow and deep-seated landsliding. These landslides pose a risk to structures and roads, and may introduce large quantities of sediment to specific reaches of channels. The USGS, in cooperation with California Geological Survey and California Department of Forestry and Fire Protection, have mapped shallow and deep-seated landslides, debris flows, earthflows, and gullies in portions of the Napa River watershed (Nilsen and Turner 1975, Dwyer et al. 1976, Durham 1979a, Durham 1979b, Nilsen et al. 1979, Ellen et al. 1997, Wentworth et al. 1997, Godt et al. 1999). The maps reveal a dense network of gullies in the southwestern portion of the watershed, with numerous shallow landslides and small earthflows scattered across the watershed. While the gully mapping agrees with observed conditions in the Carneros and Redwood creek watersheds, the shallow landslide and debris flow mapping likely underestimate the current conditions. For instance, the recent shallow landslides we observed on mid-slopes in the Ritchie Creek watershed, and streamside shallow landsliding along Dry and Redwood creeks, are not captured by the USGS preliminary maps.

As part of the Phase I Limiting Factor Analysis presented here, we did not attempt to map existing landslide features. Instead, we analyzed relative potential for shallow landsliding using the available digital elevation data. The USGS has produced a "debris-source areas" map for Napa County (Wieczorek et al. 1988, Ellen et al. 1997), which is based on empirical analysis of topographic data distributed at 30 m (100 ft) intervals. We used higher resolution data at 10 m (33 ft) intervals, and the model SHALSTAB (Dietrich et al. 2001) to produce maps of the relative potential for shallow landsliding based on identification of areas where groundwater flow is concentrated during storms, and hence, increases the probability of a shallow landslide. SHALSTAB is based on the physical processes of subsurface runoff and slope instability, with high hazard potential predicted where little subsurface runoff is needed to generate a landslide, and low potential where much is needed. It does not delineate what rainfall intensity is needed for instability, but it does tend to identify areas where shallow landsliding is most likely. It also does not account for the local effects of road construction and other such activities unless the topographic changes are captured in the digital elevation data. The landslide hazard potential generated from this analysis has not been compared to field observations. Our analysis was intended only to provide a simple way to estimate the relative importance of shallow landslides as sediment sources at different locations within the watershed. A detailed sediment source assessment is planned for Phase II (see Appendix C), mapping shallow- and deep-seated landslide, earthflow, and gully locations and their relative contributions of sediment to channels. The results of such studies could be used to evaluate the usefulness of numerical modeling for sediment sources in the Napa River watershed.

Based on comparison with landslide occurrence elsewhere, the data were classified into the following hazard classes: stable areas, low instability areas, moderate instability areas, high instability areas, and chronic instability areas. Areas classified as "stable" are locations where the landscape is not sufficiently steep to expect shallow landslides to occur. Deep-seated landslides involving the underlying bedrock may occur in such areas but are not included in the model. The shallow landslide hazard modeling showed that the majority of the Napa River watershed is stable, with few areas of high or chronic instability (Map 4, Table 3-4, Appendix A1).

Table 3-4. Summary of SHALSTAB results for the Napa River watershed.

Hazard Class	Area (acres)	Total (%)
Stable	206,437	83.6
Low instability	23,361	9.5
Moderate instability	14,763	6
High instability	2,287	0.9
Chronic instability	22	<0.1
TOTAL	**246,870**	**100**

The areas of highest instability are in the northern portion of the watershed (Map 4). This area has the greatest relief of any part in the Napa River watershed, and also the steepest slope. The hills on the southeastern portion of the watershed are the most stable portion of the watershed, with regard to potential for shallow landsliding, excluding the valley floor (Map 4).

3.2.2 The Valley Floor and Alluvial Fans

The valley bottom area of the Napa Valley can be differentiated into two important geomorphic units: alluvial fans and valley fill (Map 5). Important differences in topography, geology, and geomorphic processes between these two units exert important influences on stream morphology and ecological functions.

Alluvial fans

Alluvial fans are low, cone-shaped fluvial deposits formed where a stream undergoes an abrupt reduction in slope. Generally, this occurs between a mountain front (where the channels are narrow and confined by valley walls; in this case, the tributary streams) and low-gradient, broad valleys (where channels are wide and unconfined by valley walls; in this case, the mainstem Napa River). Typically, the size of an alluvial fan reflects the size of tributary basin. Coarse materials generally dominate the steeper, upper slopes of the fan, while finer materials dominate the lower, gentler slopes. Channels cutting across alluvial fans can be confined (between the cut banks), unconfined, or even discontinuous. We inferred the extent of the fans from topographic maps, geologic maps, and other data.

In addition to tectonic features, Quaternary alluvial fan deposits in the Napa River watershed (12 percent of the total watershed area, Q on Map 3) exert a fundamental control on the course and location of the mainstem Napa River. The fans are coarse in texture and generally tens of feet thick (Fox et al. 1973). Alluvial fans increase in size and age towards the southern end of the watershed (see Map 5). As a result, the degree of alluvium consolidation, and thus resistance to erosion, likely increases to the south. In addition, alluvial fans on the western side of the watershed are larger than the eastern side of the watershed. Consequently, the western fans have had a more pronounced effect on the location of the mainstem Napa River. Vegetation on fans is typically grassland/herbaceous, with lesser amounts of evergreen forest and orchards and vineyards.

Surface erosion, primarily gullying, rilling, and sheetwash, is expected to be the dominant erosion mechanism in the alluvial fan units. Mass wasting in this unit is expected to be solely associated with fluvial streambank erosion. SHALSTAB analysis shows that almost all of the alluvial fan unit is predicted to be stable.

Valley Fill

Quaternary alluvial valley fill or valley floor deposits are located in areas between large tributary fans that coalesce on the valley floor from the tributary basins. Because we sought finer resolution of information than could be gathered from available geology maps (such as Map 3), we delineated the boundary of the valley floor using topographic maps, soil maps, larger scale geologic maps, and aerial photographs. The valley fill unit consists of modern and old fluvial deposits of the mainstem Napa River and its tributaries, and the San Francisco Bay (Q). We separated the valley fill unit into three subunits:

- Valley fill (alluvial terraces and floodplains),
- Valley fill (alluvial fan-valley fill mix), and
- Valley fill (estuary).

The valley fill (alluvial terraces and floodplains) subunit, making up 7 percent of the total watershed area, lies within the mainstem Napa River and the downstream ends of larger tributaries. These deposits are generally fine-grained, unconsolidated, and poorly sorted. According to soil surveys (USDA-NRCS 1978), soil types characteristic of floodplains occupy most of the valley floor. Due to recent channel incision of the mainstem Napa River, these floodplains were abandoned and are now alluvial terraces (WET, 1990; Stillwater Sciences' field observations). The modern floodplain deposits in the Napa River watershed are patchy, and alluvial terraces underlie most of the valley floor.

The valley fill (alluvial fan-valley fill mix) subunit, making up 1 percent of the total watershed area, is located in the northern-most portion of the Napa Valley near Calistoga (Map 5). Due to lack of high-resolution topographic data, we could not differentiate the valley floor from the generally lower relief alluvial fans in this area.

The valley fill (estuary) subunit, making up 10 percent of the total watershed area, is composed of estuarine deposits into the Napa River Estuary.

All of the valley floor deposits are very porous and permeable. The Napa River has intermittent flow for most of its course in the valley floor during the dry summer period, except in the lower reaches, where groundwater recharge creates a perennial stream. The dominant vegetation in the valley floor terrain is agricultural crops, orchards, and vineyards, along with grassland/herbaceous areas.

3.2.3 Channel Network

To improve our ability to characterize the watershed and develop a channel stratification scheme that could be used in developing hypotheses and selecting field survey sites, we used the GIS to (1) expand the USGS “blueline channels” to create a more complete channel network, and (2) delineate reaches in the channel network and classify them by average gradient and predicted median grain size of sediment particles on the stream bed (see Appendix A1 for details on the GIS methods used). Generally, channel characteristics and habitat attributes vary with channel slope (as described in Montgomery and Buffington 1998), hence a map of channel gradient through the network gives a first approximation of expected channel morphology and processes. Slopes steeper than 0.2 (20 percent) are often shallow cuts into hillslope materials, are frequently dry, and provide very limited habitat. Channels with slopes between 0.1 and 0.2 are commonly dominated by bedrock, boulders, and frequently crossed by woody debris, creating what is known as cascade topography. Finer gravel may be locally trapped in small pockets on the rough bed or behind woody debris jams. These channels, which typically drain small areas, tend to dry seasonally as well, and have very limited annual sediment transport. Channel slopes between 0.05 and 0.10 commonly have boulder-rich beds that are organized into shallow and relatively immobile steps between small pools, creating what is known as step-pool topography. This topography may include channels with slopes as low as about 0.02. Channels with slopes between 0.001 and 0.02 are usually gravel-bedded with bar and pool topography, the gravels in which tend to move on an annual basis. The presence of large woody debris in streams with slopes in the 0.001 to 0.10 range has the potential to substantially alter channel morphology, creating deeper pools, more abundant patches of finer gravels and complex habitat favorable to fish. On the Napa River, the bed becomes sand-dominated where the channel slope drops below about 0.001, which occurs in the vicinity of Imola Avenue in Napa (WET, Inc. 1990). The river downstream of this area has experienced historic aggradation with sand and associated flooding (WET, Inc. 1990).

We calculated channel gradient throughout the Napa River watershed by intersecting our channel network GIS layer with 40-ft contours generated from USGS topographic maps (see Appendix A1 for more details). Except for gradients less than 0.001, the channel network is relatively evenly distributed among our gradient categories (Map 6, Table 3-5). The majority of the mainstem Napa River has slopes between 0.001 and 0.02 (0.1-2 percent).

Table 3-5. The distribution of channel gradients throughout the Napa River watershed.

Channel gradient	Length (miles)	Length (km)
> 0.2	261	421
0.1-0.2	296	476
0.05-0.1	226	364
0.02-0.05	233	376
0.001-0.02	295	475
< 0.001	23	36

The median channel bed grain size was predicted based on the local slope and on the estimated bankfull depth (calculated using regional hydrologic relationships with drainage area) (Map 7). These values were incorporated into a "threshold channel"-based formula that builds on the dimensionless critical shear stress (the Shields number) and the boundary shear stress at bankfull flow (Dietrich et al. 1989, Montgomery and Buffington 1993, Buffington 1995). This predicted grain size should tend to systematically over-predict the observed grain size because of additional resistance due to bars, bank irregularities, and large woody debris that is not included in the model calculations. We therefore used very coarse-level grain size categories that correspond with biologically-relevant habitat characteristics (Table 3-6). Cobble and boulder/bedrock streambeds are expected to have very limited spawning gravel, whereas we would expect gravel reaches to have more abundant spawning gravels. The gravel-sand transition on the Napa River is farther upstream than predicted in this model because of the additional in-channel resistance not accounted for in the model and limitations of slope estimations in low-gradient areas.

Table 3-6. The distribution of predicted grain size categories throughout the Napa River watershed.

Grain size category	Length (miles)	Length (km)
Boulder or Bedrock (> 256 mm)	674	1085
Cobble (64-256 mm)	425	685
Gravel (2-64 mm)	227	366
Sand/Silt/Clay (< 2 mm)	7.1	12.2

A simple pattern emerges from the crude grain size calculations and the slope determinations (Map 7). The numerous steep channels entering as small drainages to the main tributaries of the Napa River are expected to be boulder- and bedrock-dominated. Gravel would be found there, but only behind boulders, tree roots, wood, and in shallow pools. Each of the major tributaries (e.g. Redwood, Dry, Sulphur, and Conn creeks, etc.) is predicted to be cobble-bedded, with the smaller tributaries having only step-pool topography. Overall, these channels would tend to have relatively shallow pools and an absence of spawning gravels, except where large woody debris, bed irregularities, and bends in the channel paths occur. In contrast, much of the length of the mainstem Napa River is predicted to have a gravel bed. Although field data were not systematically collected to evaluate these predictions, field observations generally agree with these data.

3.3 Land Use and Land Cover

By the 1840s, the primary land uses in the Napa River watershed were agricultural activities, including grazing, field crops, and timber production. Vineyards were first developed in the

1860s, and up until 1960 the valley floor was used primarily for a combination of orchards, field crops, and vineyards, with localized urban development in the cities of Napa, Yountville, St. Helena, and Calistoga. The area under grape production in the Napa River watershed rapidly increased from approximately 15 mi^2 (39 km^2) in 1970 to 49 mi^2 (130 km^2) in 1996 (about 25 percent of which occur on hillsides, and the remainder on the valley floor and alluvial fans) (Napa County RCD 1997). Timber was intensively harvested in certain parts of the watershed until the 1950s. Groundwater pumping rates peaked between 1910 and 1950 and gradually decreased until frost pumping once again increased groundwater extraction. However there was relatively little frost pumping between 1973 and 2000 (D. Graves, pers. comm., 2002). Approximately 34 mi^2 (88 km^2) of the watershed are currently developed for urban uses, including areas that are managed for recreational use, industrial and commercial development, and both high and low density residential housing (Table 3-7). Regulation of approximately 17 percent of the watershed occurred when three major dams (Conn, Bell, and Rector dams) were built on the major tributaries to the Napa River within a short time period (1946 to 1959). Direct in-channel alterations include river-bottom dredging on the mainstem Napa River from its mouth to about 15 river miles upstream to improve navigation, intensive removal of large woody debris (LWD) and channel clearing, and levee construction in the 1960s and 1990s for flood control. These land cover changes, in-channel activities, and water use practices have altered the physical processes that shape the quality, abundance, and connection of habitat for salmonids and other native fish and wildlife species.

According to USGS map data, forests (evergreen, deciduous, and mixed) cover approximately 35 percent of the watershed (Table 3-7, Map 8). Residential (low and high intensity) and industrial/commercial/transportation development categories combined account for a little under 8 percent of the watershed. All agricultural cover types combined, including orchards and vineyards (12.9 percent), pasture/hay (5.6 percent), row crops and small grains (each < 0.1 percent), account for nearly 19 percent of the watershed, with another 22.6 percent in grasslands and other herbaceous cover types that are often used as rangeland.

Table 3-7. Areal extent of land use/land cover types in the Napa River watershed.

Land Use/Cover Type	Acres	Mi^2	Km^2	Total (%)
Open Water	14,110	22.0	56.7	5.2
Low Intensity Residential	16,630	25.9	66.9	6.1
High Intensity Residential	106	0.2	0.4	< 0.1
Industrial/Commercial/Transportation	4,181	6.5	16.8	1.5
Bare Rock/Sand/Clay	1,,363	2.1	5.5	0.5
Quarries/Mines/Gravel Pits	758	1.2	3.1	0.3
Transitional Barren	203	0.3	0.8	0.1
Deciduous Forest	1,578	21.2	54.6	5.0
Evergreen Forest	58,277	90.9	234.3	21.5
Mixed Forest	25,205	39.3	101.3	9.3
Shrubland	18,966	29.6	76.2	7.0
Orchards/Vineyards	34,902	54.4	140.3	12.9
Grasslands/Herbaceous	61,428	95.8	246.9	22.6
Pasture/Hay	15,100	23.6	60.7	5.6
Row Crop	335	0.5	1.3	0.1
Small Grains	343	0.5	1.4	0.1
Urban/Recreation Grass	1,030	1.6	4.1	0.4
Woody Wetland	392	0.6	1.6	0.1

Land Use/Cover Type	Acres	Mi^2	Km^2	Total (%)
Emergent Herbaceous Wetland	4,388	6.8	17.6	1.6
Totals	**257,932**	**423**	**1,091**	**100**

Source: USGS, land use/land cover GIS coverage (based on 1992 Landsat imagery).

3.4 Fish Community Composition

The watershed supports an assemblage of sixteen native fish species, including several threatened and/or rare species such as steelhead/rainbow trout, fall-run Chinook salmon, Pacific and river lamprey (*Lampetra tridentata, L. ayresi*), hardhead (*Mylopharodon conocephalus*), hitch (*Lavinia exilicauda)*, tule perch (*Hysterocarpus traski*), and Sacramento splittail (*Pogonichthys macrolepidotus*) (Leidy 1997). The Napa River is estimated to have historically supported a run of 6,000–8,000 steelhead, and as many 2,000–4,000 coho salmon (USFWS 1968). By the late 1960s, coho salmon had been extirpated, and steelhead had declined to an estimated run of less than 2,000 adults (USFWS 1968, Anderson 1969). The present-day run of steelhead is believed to be less than a few hundred adults (J. Emig and M. Rugg, pers. comm., 2000). Much less information is available to determine the historical abundance of Chinook salmon. However, examination of Napa River habitat and hydrology indicate that potential habitat was historically, and is presently, available and captures of wild Chinook juveniles in the mainstem Napa River (CDFG 1987, Stillwater Sciences 2002) indicate that successful reproduction occurs under present conditions. Furthermore, historical ecology work indicates that Sonoma Creek watershed (an adjacent watershed with similar physical form and hydrology) supported fall run Chinook in the 1880s (Sonoma Ecology Center 2002). California freshwater shrimp, which are known to occur in the Napa River and a few of its tributaries, are federally listed as endangered (USFWS 1988) and are currently restricted to only a few watersheds in the North Bay and coastal Marin and Sonoma counties (USFWS 1998).

Introductions of exotic fish species have impacted most freshwater ecosystems in California, and in some cases have dramatically altered food web dynamics and the species composition of fish communities (Moyle 2002). In addition, habitat alterations can have a dramatic impact on the species composition of a fish community by deleteriously affecting some species and favoring others. The impacts of introduced fish generally occur episodically and unpredictably, depending upon factors such as the fecundity of the introduced species, its feeding habits, and habitat requirements. Habitat alterations, however, generally occur gradually with somewhat more predictable impacts on the composition of the fish community. For example, the shift of a river system from a pool-riffle morphology to a morphology dominated by large, deep pools with increased water temperatures and slow-moving water often provide the preferred habitat of predatory fish species, many of which are exotic, such as largemouth bass (*Micropterus salmoides*).

To determine changes in the fish community of the Napa River watershed, we reviewed literature from the California Department of Fish and Game (CDFG) dating back to the 1950's and more recent surveys by the US Environmental Protection Agency (USEPA) (Leidy 1997). Data from the CDFG and USEPA documents were compiled into a simple database (See Appendix A2). A total of 27 species were reported in the surveys we reviewed, 13 non-native (exotic) species and 14 native species. A total of 24 species were observed in one or more surveys in the mainstem Napa River, while 14 species were found in one or more tributaries (Table 3-9). To summarize the results of this analysis, species were grouped into guilds of freshwater fish (organized according to cold-water, warm-water, or estuarine habitat associations and exotic versus native status) so that a basic analysis could be performed to determine changes in the fish community over time (Table 3-8).

Table 3-8. Freshwater fish species guilds currently or historically occurring in the Napa River watershed.

Guild	Common Name	Scientific Name	Family Name
Cold – Exotic	American shad	*Alosa sapidissima*	Clupeidae
Estuarine – Exotic	yellowfin goby	*Acanthogobius flavimanus*	Gobiidae
	striped bass	*Morone saxatilis*	Percichthyidae
Warm – Exotic	goldfish	*Carassius auratus*	Cyprinidae
	carp	*Cyprinus carpio*	Cyprinidae
	mosquitofish	*Gambusia affinis*	Poeciliidae
	white catfish	*Ameiurus catus*	Ictaluridae
	channel catfish	*Ictalurus punctatus*	Ictaluridae
	green sunfish	*Lepomis cyanellus*	Centrarchidae
	bluegill	*Lepomis macrochirus*	Centrarchidae
	inland silverside	*Menidia beryllina*	Atherinidae
	smallmouth bass	*Micropterus dolomieui*	Centrarchidae
	largemouth bass	*Micropterus salmoides*	Centrarchidae
Cold – Salmonid	Steelhead/rainbow trout	*Oncorhynchus mykiss*	Salmonidae
	Chinook salmon	*Oncorhynchus tshawytscha*	Salmonidae
Cold – Native (Non-Salmonid)	Sacramento sucker	*Catostomus occidentalis*	Catostomidae
	prickly sculpin	*Cottus asper*	Cottidae
	riffle sculpin	*Cottus gulosus*	Cottidae
	Pacific lamprey	*Lampetra tridentata*	Petromyzontidae
	hardhead	*Mylopharodon conocephalus*	Cyprinidae
	Sacramento pikeminnow	*Ptychocheilus grandis*	Cyprinidae
Warm – Native	threespine stickleback	*Gasterosteus aculeatus*	Gasterosteidae
	California roach	*Hesperoleucus symmetricus*	Cyprinidae
	tule perch	*Hysterocarpus traski*	Embiotocidae
	Sacramento splittail	*Pogonichthys macrolepidotus*	Cyprinidae
Estuarine – Native	white sturgeon	*Acipenser transmontanus*	Acipenseridae
	Pacific staghorn sculpin	*Leptocottus armatus*	Cottidae

Source: Based on information derived from Leidy 1997, CDFG surveys (see Appendix A2), and Moyle 2002.

Guilds used were defined as “salmonids,” “warm-water natives,” “cold-water natives,” “warm-water exotics,” “estuarine natives,” and “estuarine exotics” (note that, while American shad [*Alosa sapidissima*] was observed on single occasions in the 1970s and 1980s, these observations occurred in the estuary and there are no other historical records of cold water exotics that we are aware of, hence a "cold water- exotics" guild was not used in this analysis). A review of the historical fish survey data since the 1950s shows that at the level of the entire watershed: (1) the frequency of salmonid observations has declined, and (2) the river system has experienced invasions by exotic, warm-water fish species (Figure 3-6). The trends for warm- and cold-water native guilds other than salmonids are not as clear, with native species occurrence generally increasing a small amount over time. (Note that these results need to be considered in the context of the high level of uncertainty associated with this analysis. Sampling methods, locations, and intensity of survey effort undoubtedly varied dramatically among surveys conducted by various people and agencies over a 50-year period.)

Additional information on the current distribution of juvenile steelhead in the Napa River watershed was provided by snorkel surveys conducted in a number of tributaries in 2001 (Friends of the Napa River 2001). Their surveys categorized presence of juveniles into four categories: no presence, low presence (0–0.5 steelhead/m^2), medium presence (0.5–1 steelhead/m^2), and high presence (greater than 1 steelhead/m^2). These survey results indicate that a number of western tributaries (Redwood Creek, Pickle Canyon, Dry Creek, Heath Creek, Sulphur Creek, York Creek, Mill Creek, Ritchie Creek) have reaches with medium to high abundance of juveniles. Survey effort in eastern and northern tributaries was less extensive, but several creeks (Jericho, Dutch Henry, Milliken creeks) had at least short reaches with medium or high abundance.

Table 3-9. Distribution of fish species in the Napa River and its tributaries (salmon and steelhead data are shaded for easy reference) observed during surveys from the 1950s to 1997 conducted by CDFG and Napa County RCD.

Stream or Reach Name	Species Observed																																		
	Total Number of Surveys	*Oncorhynchus mykiss*	*Oncorhynchus tshawytscha*	Unspecified salmonid species	*Acanthogobius flavimanus*	*Acipenser transmontanus*	*Alosa sapidissima*	*Carassius auratus*	*Catostomus occidentalis*	*Cottus asper*	*Cottus gulosus*	Unidentified cyprinid species	*Cyprinus carpio*	*Gambusia affinis*	*Gasterosteus aculeatus*	*Hesperoleucus symmetricus*	*Hysterocarpus traski*	*Ameiurus catus*	*Ictalurus punctatus*	*Lampetra tridentata*	Unidentified lamprey species	*Lepomis cyanellus*	*Lepomis macrochirus*	*Leptocottus armatus*	*Menidia beryllina*	*Micropterus dolomieui*	*Micropterus salmoides*	*Morone saxatilis*	*Mylopharodon conocephalus*	*Pogonichthys macrolepidotus*	*Ptychocheilus grandis*	Unidentified sculpin species	Unidentified sucker species	Unidentified sunfish species	Unidentified fry
Mainstem Reaches																																			
Above Calistoga	21	x							x	x	x			x	x	x						x	x								x	x			
Below Trancas	30	x	x		x	x	x		x								x		x					x	x		x	x		x					
Trancas to Calistoga	35	x	x	x					x	x	x				x	x	x	x				x	x			x			x		x	x			
Tributaries																																			
Bear Canyon	6	x							x																							x			
Bell	29	x											x		x	x					x	x					x				x	x	x	x	
Carneros*	1																																		
Chiles	10	x										x				x															x	x	x		
Conn	17	x							x	x	x				x	x				x											x	x			
Cyrus	7	x										x				x																x			

Stream or Reach Name	**Species Observed**																																		
	Total Number of Surveys	*Oncorhynchus mykiss*	*Oncorhynchus tshawytscha*	Unspecified salmonid species	*Acanthogobius flavimanus*	*Acipenser transmontanus*	*Alosa sapidissima*	*Carassius auratus*	*Catostomus occidentalis*	*Cottus asper*	*Cottus gulosus*	Unidentified cyprinid species	*Cyprinus carpio*	*Gambusia affinis*	*Gasterosteus aculeatus*	*Hesperoleucus symmetricus*	*Hysterocarpus traski*	*Ameiurus catus*	*Ictalurus punctatus*	*Lampetra tridentata*	Unidentified lamprey species	*Lepomis cyanellus*	*Lepomis macrochirus*	*Leptocottus armatus*	*Menidia beryllina*	*Micropterus dolomieui*	*Micropterus salmoides*	*Morone saxatilis*	*Mylopharodon conocephalus*	*Pogonichthys macrolepidotus*	*Ptychocheilus grandis*	Unidentified sculpin species	Unidentified sucker species	Unidentified sunfish species	Unidentified fry
Dry	37	x							x		x	x	x		x	x					x											x			
Dutch Henry	3	x																																	
Garnett	13	x							x						x	x						x										x			
Hopper*	2																																		
Huichica	17	x													x	x					x		x												
Kimball Canyon	8	x									x					x						x	x				x								
Milliken	33	x						x	x		x			x	x	x						x				x						x			
Montgomery/Dry*	1																																		
Moore	1	x																																	
Murphy/Tulocay	7	x							x						x	x																x			
Napa	4	x							x	x						x																			
Nash*	1																																		
Pickle/Redwood	4	x														x																			

Stream or Reach Name	**Species Observed**																																		
	Total Number of Surveys	*Oncorhynchus mykiss*	*Oncorhynchus tshawytscha*	Unspecified salmonid species	*Acanthogobius flavimanus*	*Acipenser transmontanus*	*Alosa sapidissima*	*Carassius auratus*	*Catostomus occidentalis*	*Cottus asper*	*Cottus gulosus*	Unidentified cyprinid species	*Cyprinus carpio*	*Gambusia affinis*	*Gasterosteus aculeatus*	*Hesperoleucus symmetricus*	*Hysterocarpus traski*	*Ameiurus catus*	*Ictalurus punctatus*	*Lampetra tridentata*	Unidentified lamprey species	*Lepomis cyanellus*	*Lepomis macrochirus*	*Leptocottus armatus*	*Menidia beryllina*	*Micropterus dolomieui*	*Micropterus salmoides*	*Morone saxatilis*	*Mylopharodon conocephalus*	*Pogonichthys macrolepidotus*	*Ptychocheilus grandis*	Unidentified sculpin species	Unidentified sucker species	Unidentified sunfish species	Unidentified fry
Rector	2	x																																	
Redwood	17	x		x					x						x	x																			
Ritchie	13	x		x												x																x			
Sage	5	x														x																			
Sarco	4	x								x					x	x																			
Soda	6	x																														x			
Sulphur	10	x													x	x					x											x			x
Suscol	16	x							x	x				x	x	x						x	x									x			
Tulucay	1	x																																	
York	8	x		x					x							x						x										x			

x = fish species observed during one or more surveys
* = no fish of any species observed during the recorded surveys
Source: CDFG and Napa County RCD fish surveys from the 1950s through 1997.

4 ANALYSIS SPECIES

We selected three at-risk species within the Napa River system as target species for our analysis: Chinook salmon, steelhead, and California freshwater shrimp. The two fish species have exhibited marked declines from historical conditions in the Napa River watershed (Emig, pers. comm., 2000; Rugg, pers. comm., 2000), while the freshwater shrimp has generally declined from historical conditions throughout its limited range in Marin, Napa, and Sonoma counties (USFWS, 1998). Our approach to selecting these species and using analysis species to identify potential issues of concern within the watershed, as well as to indicate the potential benefits of various restoration efforts, is described below.

4.1 The Analysis Species Approach

One of the premises of the limiting factors analysis for the Napa River watershed was that a select group of "analysis species" could be used as focal species for evaluating the impacts of watershed activities on a range of aquatic species historically and currently found within the basin. There were two primary goals in selecting the analysis species: (1) identify species whose distributions and requirements overlap with other native fish and aquatic wildlife species found within the freshwater reaches of the Napa River system; and (2) pay particular attention to sensitive and/or at-risk species found within the watershed. In other words, the selected species are generally sensitive to overall watershed conditions and likely represent the needs and sensitivities of many species within the system.

An analysis of the life history and habitat requirements of certain species is necessary for improving our understanding of the relative importance of various habitat features in the Napa River watershed, identifying factors currently limiting the distribution and abundance of these species in the basin, and for evaluating the degree to which ecosystem-level management strategies may benefit individual species. Specifically, assessing habitat requirements throughout the life cycle of analysis species helped identify important habitat features to be evaluated and managed for, and was the basis for conducting limiting factors analyses. The selection of the analysis species is described in more detail below.

4.2 Selection of Analysis Species

As a first step in selecting analysis species, we assembled a list of the aquatic species historically or currently occurring in the Napa River watershed. This list was derived from information contained in various reports, stream surveys, scientific literature, and personal communications with local and regional biologists. We also obtained information regarding the listing status of each of these species under the state and federal Endangered Species Acts. Other criteria considered in selecting analysis species were species that: (1) have other special-status designation, (2) have high economic or public interest value, (3) have narrow habitat requirements, (4) are weak dispersers, (5) are dependent on habitats that have likely been reduced in quality and quantity from historical conditions because of anthropogenic land use within the basin, and (6) are suspected to be in decline locally and/or regionally.

Identifying life histories and distributions of species that would represent a broad range of habitat needs within the watershed proved to be difficult, however, because the ecological requirements of many of the native fish and wildlife species found in the Napa River watershed are not well described or studied. The budget and schedule constraints of the current project did not allow for detailed species censuses or original life history research. The three analysis species were selected by considering available information on species' biology, the criteria described above, and the budget and scope of the current effort.

Steelhead and Chinook salmon are believed to have occupied a large proportion of the total channel length within the tributaries and mainstem Napa River, respectively, and their life histories have been studied in more detail than native resident species. Habitat requirements of both salmonids represent the needs of a suite of native coldwater fish species. Restoring or maintaining habitat connectivity and habitat-forming processes targeted at salmonids will likely benefit other native coldwater species found in the basin. California freshwater shrimp have a very limited distribution within the Napa River watershed. Their potential sensitivity to land use practices within the watershed, as well as their limited distribution, represents a clear example of a species in decline for which habitat conservation is an important consideration. Although relatively little is known about the life history and habitat requirements of the species, its endangered status under both the federal and state Endangered Species Acts warrants its inclusion as an analysis species representing the ecological niche using low-gradient reaches of the mainstem, and tributaries in the Valley Fill geomorphic terrain.

We were not successful in identifying a species that occurs in headwater or ephemeral stream channels that could be used in this analysis. Although the foothill yellow-legged frog (*Rana boylei boylei*) was considered, not enough information regarding its distribution and specific habitat requirements within the Napa River watershed was available to conduct a full analysis. Also, coho salmon were not included in the limiting factors analysis because the species is considered to be extirpated from the Napa River watershed, and little is known of its historical distribution.

4.3 Life History and Habitat Requirements

A summary of the life history and habitat requirements of the three analysis species is provided below. Detailed information regarding each of these species is provided in Appendix B.

4.3.1 Chinook Salmon

Fall-run Chinook salmon have been observed in the Napa River in recent years (Jones 1999, as cited in NMFS 1999; Leidy and Sisco 1999), upstream to the base of the Kimball Canyon Dam north of Calistoga (Leidy and Sisco 1999). Fall Chinook returns to the Napa River are thought to be small and sporadic, with only occasional observations of spawning primarily between Zinfandel Lane, slightly downstream of St. Helena, and the City of Calistoga (Leidy and Sisco 1999; S. Anderson, pers. comm., 2000; Emig, pers. comm., 2000; Rugg, pers. comm., 2000). The National Marine Fisheries Service believes that these populations are not self-sustaining and likely consist of strays from other basins and are more likely present only on an intermittent basis during favorable periods (NMFS 1999).

Adult Chinook salmon migrate up rivers from the ocean to spawn in their natal streams during the fall, although a small percentage may stray into other streams, especially during high water years (Moyle et al. 1989). In the Napa River, adult returns to upstream areas are likely delayed until flows increase with the onset of winter rains.

Chinook salmon spawn primarily in riffles and pool tailouts. Substrate size and intragravel flow conditions are important factors affecting Chinook salmon spawning distribution and incubation success (Harrison 1923, Hobbs 1937, McNeil 1964, Cooper 1965, Platts et al. 1979). Median particle sizes of spawning substrates used by Chinook salmon have been found to range from ½ inch (1.3 cm) to 3 inches (7.6 cm) (Kondolf and Wolman 1993). The presence of fine sediment and sand in the bed can reduce intragravel flow in the redd and is detrimental to egg survival and development (McNeil 1964, Cooper 1965).

During spawning, the female Chinook salmon excavates a nest, referred to as a "redd," into the gravel and cobble substrate. As she excavates the nest, she deposits eggs, which the male fertilizes, into several pockets in the redd and covers the eggs with gravel. Chinook salmon redds are large, typically 110–190 ft^2 (10.2–17.7 m^2) in size (Healey 1991). The female remains at the redd to defend the site from excavation by later-arriving salmon until she dies, usually within a few days after spawning. The fertilized eggs incubate in the gravel for a period of 6–13 weeks, depending on water temperature (Vernier 1969, and Heming 1982, both as cited in Bjornn and Reiser 1991). The larvae that hatch from the eggs, called "alevins," are equipped with yolk sacs that provide nourishment. These larvae remain in the substrate until the yolk sac is absorbed, approximately two to three weeks, then swim up through the gravel substrate and begin rearing in open water. After emerging, fry either disperse downstream or move to stream margins or backwater areas near their natal redd.

The period of fry emergence varies depending upon the timing of adult arrival and incubation temperature, but typically occurs from January through May. Chinook may disperse downstream as fry soon after emergence, early in their first summer as fingerlings, in the fall as flows increase, or after overwintering in freshwater as yearlings (Healey 1991). Juvenile Chinook feed and grow as they move downstream in spring and summer; larger individuals are more likely to move downstream earlier than smaller juveniles (Nicholas and Hankin 1989). In the Sacramento-San Joaquin system, fall Chinook smolt outmigration generally occurs from March to July (Maragni 2001). No data on smolt outmigration are available for the Napa River.

Water temperature is an important factor affecting incubation and juvenile rearing success. Temperature directly affects survival, growth rates, and smoltification. Temperature also indirectly affects vulnerability to disease and predation and further influences juvenile growth indirectly, through its impacts on food availability.

In addition to temperature, delivery of dissolved oxygen to the egg pocket is a major factor affecting survival-to-emergence and is impacted by the deposition of fine sediment in the spawning substrate. Several studies have correlated reduced dissolved oxygen levels with mortality, impaired or abnormal development, delayed hatching and emergence, and reduced fry size at emergence in anadromous salmonids (Wickett 1954, Alderdice et al. 1958, Coble 1961, Silver et al. 1963, McNeil 1964, Shumway et al. 1964, Cooper 1965, Koski 1981).

4.3.2 Steelhead

Steelhead is the term commonly used for the anadromous life history form of rainbow trout *(Oncorhynchus mykiss)*. Steelhead exhibit highly variable life history patterns throughout their range, but are broadly categorized into winter and summer reproductive ecotypes. The relationship between anadromous and resident life history forms of *O. mykiss* is poorly understood, but evidence suggests that the two forms are capable of interbreeding and that, under some conditions, either life history form can produce offspring that exhibit the alternate form (i.e., resident rainbow trout can produce anadromous progeny and vice versa) (Shapovalov and Taft 1954, Burgner et al. 1992, Hallock 1989). The fact that little to no genetic differentiation has been found between resident and anadromous life history forms inhabiting the same basin supports this hypothesis (Busby et al. 1993, Nielsen 1994).

Steelhead found in the Napa River watershed belong to the Central California Coast evolutionarily significant unit (ESU) (NMFS 1997). This ESU extends from the Russian River to Aptos Creek, and includes tributaries to San Francisco and San Pablo bays eastward to the Napa River, excluding the Sacramento-San Joaquin River basin. Winter runs of steelhead occur in the Napa River mainstem and tributaries. Critical habitat is designated to include all river reaches and estuarine areas accessible to listed steelhead in coastal river basins from the Russian River to Aptos Creek, and the tributaries to San Francisco and San Pablo bays (NMFS 2000).

Accurate population estimates for the Napa River watershed as a whole are not available (Skinner 1962, Leidy 1984, Leidy 2001). However, snorkel surveys for juvenile steelhead conducted in many tributaries provide a partial picture of current patterns of steelhead distribution and abundance in the Napa River watershed (Friends of the Napa River 2001). In general, steelhead stocks throughout California have declined substantially. The current population of steelhead in California is roughly 250,000 adults, which is roughly half the adult population that existed 30 years ago (McEwan and Jackson 1996). Estimates indicate that 19 tributaries to San Francisco Bay currently support runs of steelhead, with most streams having runs of 100 or fewer spawning adults (Leidy 2001). The Napa River watershed appears to support one of the larger steelhead runs in the Bay Area. Anderson (1969) estimated that the Napa River watershed at that time might have supported a steelhead run of approximately 500 to 2,000 spawners.

Steelhead return to spawn in their natal stream, usually in their fourth or fifth year of life, with males typically returning to freshwater earlier than females (Shapovalov and Taft 1954, Behnke 1992). A small percentage of steelhead may stray into streams other than those in which they were born. Winter-run steelhead generally enter spawning streams from fall through spring as sexually mature adults, and spawn a few months later in late winter or spring (Roelofs 1985, Meehan and Bjornn 1991, Behnke 1992). Spawning occurs primarily from January through March, but may begin as early as late December and may extend through April (Hallock et al. 1961).

Similar to fall Chinook salmon, female steelhead construct redds in suitable gravels, primarily in pool tailouts and heads of riffles. Steelhead eggs incubate in the redds for 3–14 weeks, depending on water temperatures (Shapovalov and Taft 1954, Barnhart 1991). After hatching, alevins remain in the gravel for an additional 2–5 weeks while absorbing their yolk sacs, and then emerge in spring or early summer (Barnhart 1991).

After emergence, steelhead fry move to shallow-water, low-velocity habitats, such as stream margins and low-gradient riffles, and forage in open areas lacking instream cover (Hartman 1965, Everest et al. 1986, Fontaine 1988). As fry grow and improve their swimming abilities in late summer and fall, they increasingly use areas with cover and show a preference for higher velocity, deeper mid-channel areas near the thalweg (the deepest part of the channel) (Hartman 1965, Everest and Chapman 1972, Fontaine 1988).

Juvenile steelhead occupy a wide range of habitats, preferring deep pools as well as higher velocity rapid and cascade habitats (Bisson et al. 1982, Bisson et al. 1988). During the winter period of inactivity, steelhead prefer low-velocity pool habitats with large rocky substrate or woody debris for cover (Hartman 1965, Raleigh et al. 1984, Swales et al. 1986, Fontaine 1988). During periods of low temperatures and high flows that occur in winter months, steelhead seek refuge in interstitial spaces in cobble and boulder substrates (Bustard and Narver 1975, Everest et al. 1986). Juvenile emigration typically occurs from April through June. Emigration appears to be more closely associated with size than age, with 6–8 inches (15–20 cm) being most common for downstream migrants.

Steelhead have variable life histories and may migrate downstream to estuaries as age 0+ juveniles or may rear in streams for up to four years before outmigrating to the estuary and ocean (Shapovalov and Taft 1954). Steelhead migrating downstream as juveniles may rear for one to six months in the estuary before entering the ocean (Barnhart 1991).

As for Chinook salmon, water temperature is an important factor affecting steelhead incubation and juvenile rearing success. Temperature directly affects survival, growth rates, and smoltification. Temperature also indirectly affects disease vulnerability to disease and predation.

In addition to the effects of temperature on incubation and smoltification time and success, increased temperature can increase susceptibility to pathogens and disease. The effects of water temperature on pathogens, however, is not well understood. On-going evaluation of these indirect effects of temperature on steelhead should be considered when making management and restoration recommendations.

4.3.3 California Freshwater Shrimp

The historical distribution of California freshwater shrimp is unknown, but the species probably once inhabited most perennial lowland streams in Marin, Napa, and Sonoma counties (USFWS 1998). Biologists believe that widespread alteration of lowland perennial streams has probably resulted in significant reductions in the species' range and abundance. California freshwater shrimp were listed as federally endangered by the U.S. Fish and Wildlife Service in 1988 (USFWS 1988). California freshwater shrimp are also listed as endangered under the California Endangered Species Act (CDFG 1992).

The reproductive biology of the California freshwater shrimp has not been formally described. Reproduction seems to occur once a year, with mating beginning in September. The shrimp exhibit relatively low fecundity; adult females produce approximately 50 to 120 eggs. The eggs adhere to the female’s anterior appendages through the winter months (December through March), and young postlarvae (approximately 0.2 inch [6 mm] in length) hatch between late May and early June (USFWS 1998, Cox 2000). Larvae grow rapidly during the summer through a series of molts and reach a mean postorbital length of about 0.75 inch (19 mm) by fall, although no data are available regarding the timing and conditions that induce molting. The growth rate declines during summer months, although feeding continues throughout the year. Age 1+ shrimp are sexually mature and indistinguishable from adult shrimp by autumn (Cox 2000). Some shrimp apparently reproduce a second time.

California freshwater shrimp are found in low-elevation (<380 ft [116 m]), low-gradient (generally <1 percent) coastal lowland streams that flow year-round or contain perennial pools (USFWS 1998). They are typically observed in quiet, moderately deep (1-3 ft [0.30-0.91 m]), stream reaches with riparian and aquatic vegetation and structurally complex banks, exposed roots, overhanging woody debris, or overhanging vegetation. This species can tolerate seasonal temperature extremes, but not salty or brackish water (Cox et al. 1994). No data are currently available for defining the species’ optimal temperature and/or stream flow requirements, or its temperature tolerances. It appears to be able to tolerate water temperatures >73^{o}F (23^{o}C) and non-flowing stream conditions that would be detrimental to native salmonids (USFWS 1998).

Under laboratory conditions, juvenile and mature shrimp have been observed to tolerate standing water at 80^{o}F (27^{o}C) for extended periods (USFWS 1998).

5 IDENTIFICATION AND SCREENING OF POTENTIAL LIMITING FACTORS AND INITIAL HYPOTHESES

In this section, we describe the range of potential limiting factors known to affect populations of the three analysis species. We then briefly discuss how existing information and reconnaissance survey results were used to screen the initial list of potential limiting factors to develop a list of hypotheses specific to the Napa River watershed, and to identify priorities for focused studies during Phase I to begin testing those hypotheses.

5.1 Potential Limiting Factors

Generally speaking, a wide range of factors may limit the size and growth potential of a population of organisms. While each of these factors may serve as the primary limiting factor under specific circumstances, our goal was to identify the factor or factors that appeared to be limiting the populations of the three analysis species in this study under current conditions in the Napa River and its tributaries. The primary aim of Phase I was to use knowledge of various potential limiting factors combined with focused studies to identify key data gaps and uncertainties that need to be addressed during Phase II. In Phase II, limiting factors analysis will be more fully developed to elucidate the cause-and-effect relationships between land and water use activities in the watershed and their effects on the analysis species and general aquatic ecosystem health. This will yield a more quantitative understanding of the viability of potential restoration and management strategies and actions that are available to restore analysis species.

In performing the initial phase of this limiting factors analysis, to identify priorities for Phase I, we found it most useful to organize the analysis of potential limiting factors by life stages.

5.1.1 Chinook Salmon and Steelhead

Anadromous salmonids spend a considerable portion of their life cycle in fresh water. This period includes what are generally considered to be the most vulnerable salmonid life stages. During this time they are subject to a variety of physical and biological factors that may cause direct or indirect mortality, thereby limiting the size and health of the population. Because environmental requirements change for each salmonid life stage, different factors are important during different life stages.

For the two anadromous salmonid species of interest in the Napa River watershed, Chinook salmon and steelhead, the timing and duration of certain life stages is different. These species may also have different physiological tolerances and differ in their use of space and food resources. Whereas juvenile Chinook salmon spend only a short period rearing in fresh water before moving downstream to the ocean, steelhead may rear in their natal stream for one or more years before entering salt water. Despite these differences, these two species overlap considerably in time and space and therefore experience similar environmental conditions during the freshwater portions of their life cycle.

This study has focused on the freshwater phase of the salmonid life cycle. Factors affecting the amount and quality of available estuary rearing habitat may be important, but are beyond the scope of the Phase I study (although some study of this issue has been proposed for Phase II). Ocean harvesting and others factors affecting growth and survival of salmon during the ocean phase of their life cycle may also be very important limiting factors, but are beyond the scope of this study.

Adult Upstream Migration

As adult salmonids migrate upstream to spawn, they frequently must overcome a variety of natural and anthropogenic obstacles before reaching suitable spawning areas. These include:

- *Attraction flows.* The initiation of upstream migration by adult salmonids generally requires an environmental cue in the form of an "attraction flow," which provides a chemical or other type of signal to the fish that upstream conditions are suitable for migration and spawning. Alterations in the timing, duration, or magnitude of attraction flows may disrupt successful spawning migration by anadromous salmonids.

- *Physical migration barriers.* Natural or man-made features such as dams, dewatered reaches, inadequate flows, "hanging" tributaries, natural falls, or culverts may compromise the success of spawning salmonids by preventing access to spawning habitat, or, in the case of partial barriers, by critically depleting the fish's energy reserves as it attempts to get past the obstacle.

- *Environmental migration barriers.* Upstream migration by adult salmonids may also be blocked or curtailed by environmental conditions, such as elevated water temperatures, that prevent fish from reaching spawning grounds. If water temperatures remain prohibitively high, spawning may not occur or may take place in suboptimal habitats.

- *Migration corridor hazards.* Other hazards that may be encountered by adult salmonids as they migrate upstream include poaching and false migration pathways presented by bypasses and diversions. These hazards can interfere with spawning migrations and limit the success of salmonid populations.

Spawning and Incubation

Environmental conditions play a crucial role in successful salmonid spawning, egg incubation, and survival to emergence. The range of environmental tolerance of salmonids during this life stage is narrow, and many factors may limit survival. These factors include:

- *Spawning gravel quantity and redd superimposition.* Limited availability of spawning gravel is a problem faced by salmonids where access to spawning habitat has been blocked or suitable substrates have been dewatered. This problem can be further exacerbated in areas where limited habitat availability results in competition for space and leads to redd superimposition.

- *Spawning gravel quality.* Suboptimal spawning gravel quality can limit spawning and incubation success by rendering gravel unusable by spawners, creating unsuitable incubation conditions, and preventing fry from emerging after hatching.

- *Water quality and temperature.* During spawning, poor water quality or elevated water temperature may reduce the ability of adult salmonids to reach spawning grounds and successfully deposit eggs. Survival to emergence is dependent on successful incubation of eggs, which are especially vulnerable to low dissolved oxygen levels and high water temperature.

- *Substrate mobility/scouring.* Successful hatching and emergence require stable gravels in and around the egg pocket. Scouring of redd gravels can alter redd hydraulics and cause abrasion or displacement of eggs, resulting in reduced survival rates or direct egg mortality.

- *Redd dewatering.* Partial or complete dewatering of redds can result in low survival rates due to reduced delivery of water and oxygen and buildup of toxic metabolic byproducts, and may cause egg mortality due to desiccation.

Juvenile Rearing

Following emergence from the gravel, juvenile salmonids must begin feeding and competing for resources under varying environmental conditions. Factors that may limit survival of rearing juvenile salmonids include:

- *Availability of summer rearing habitat.* During summer, when flows are typically lowest and water temperatures highest, pools, substrate interstices, and other complex habitats provide rearing salmonids with important refugia from high temperatures and predation. A lack of summer rearing habitat can reduce the success of juvenile salmonids already faced with reduced food availability, increased competition for food and space, and increased predation.

- *Availability of overwintering habitat.* Displacement or mortality caused by high winter flows frequently limits production of juvenile salmonids that do not have access to protected microsites associated with LWD, large substrates such as boulders, interstitial spaces, off-channel habitat, or other features that provide velocity refuges. Certain habitat elements, such as substrate interstices, may also increase winter survival by providing resting or hiding sites for fish when water temperatures are coldest.

- *Stranding by low flows.* Stranding can cause direct mortality of juvenile salmonids when low flows or rapidly receding water levels isolate fish in disconnected or dewatered habitats, subjecting them to predation, desiccation, or other hazards.

- *Displacement by high flows.* Extremely high flows, especially in areas devoid of bed or bank roughness elements, can displace rearing salmonids and lead to reduced rearing success or mortality.

- *Predation.* Predation limits population success through direct mortality. Predation pressure on rearing salmonids may be increased by removal of instream and overhead cover, low flows, migration barriers, and changes in channel geometry.

- *Food availability.* An inadequate food supply can cause increased interspecific and intraspecific competition, and may lead to reduced fitness and, in some cases, mortality.

- *Interspecific interactions between native species.* Interspecific interactions between native species, which include competition for food and space, are usually related to reduced availability of food and suitable habitat. Juvenile salmonids may suffer reduced fitness and population success may be limited by these interactions.

- *Competition with introduced species.* Introduced species can compete for food and space with native salmonids, reducing access to these important resources and potentially limiting fitness and survival.

- *Water quality/ temperature.* The quality and temperature of stream water has a direct impact on the success of rearing juvenile salmonids. Prolonged periods of elevated water temperature, as well as acute or chronic water pollution, can lead to direct and indirect mortality of juvenile salmonids.

Outmigration

A variety of environmental factors may serve as outmigration cues to juvenile salmonids in streams. Outmigrating fish are subject to a range of conditions that influence their ability to successfully reach the ocean. These include:

- *Adequate flows for outmigration.* Juvenile salmonids undergo physiological changes and initiate outmigration when adequate river flows occur, usually during spring. Reduced flow duration or magnitude during the outmigration period can render some portions of the river corridor impassible and may subject emigrating juveniles to increased predation, thereby reducing the chances of successful outmigration.

- *Water quality and temperature.* Water quality and temperature may be especially important to outmigrating salmonids during low-flow periods. Lethal or sublethal effects may result from pollutants or prolonged exposure to high water temperatures.

- *Predation.* Predation, especially by introduced warmwater, piscivorous fish, is believed to be a significant source of mortality of outmigrating salmonids in some rivers. Outmigrant juveniles may also be subject to predation by terrestrial or avian predators.

- *Diversion hazards.* Water diversions, such as canals, pumps, and bypasses, can act as “blind pathways,” preventing fish from reaching the ocean. They may also be directly lethal to fish or may expose them to high water temperatures, pollutants, predation, or desiccation.

5.1.2 California Freshwater Shrimp

The life history and factors that potentially limit the abundance and distribution of California freshwater shrimp are not as well known as for salmonids. It appears that potential limiting factors are similar for all life history stages of California freshwater shrimp especially given the use of common habitat areas by all life history stages of the California freshwater shrimp. Until more specific information is available, the requirements for courtship and mating, incubation, larval release, and summer rearing will be considered together.. A review of the available information suggests the following list of potential limiting factors for all life history stages.

- *Water quality*. High temperatures, low dissolved oxygen, and toxic contaminants in the main channel could potentially impact shrimp populations.

- *Cover habitat*. Undercut banks with overhanging vegetation are a preferred habitat type for shrimp. Reduction of this habitat could limit shrimp populations and historical loss of this habitat might have caused declining population numbers.

- *Sediment*. Pool filling by sediment may eliminate undercut bank habitat and thereby reduce the amount of available habitat for shrimp.

- *Flow*. Sufficient flows may be required to maintain undercut bank habitat, particularly if these habitats become filled with sediment.
- *Predation*. It is not known to what extent native and exotic fish species prey on shrimp. Little is known regarding their food web interactions, which could potentially limit the population.
- *Disease and parasites.* No information regarding disease or parasites is available for shrimp.
- *Interactive affects.* An interaction of flow, bank substrate conditions, and riparian vegetation may be important factors affecting the natural creation or maintenance of suitable undercut bank habitat.

5.2 Development and Screening of Potential Limiting Factors and Initial Hypotheses

Given the limited time and funding available for Phase I, we approached the limiting factors analysis as an iterative process designed to narrow the focus of the analysis in a rapid and efficient manner. After development of the broad lists of potential limiting factors presented above, we used information gleaned from existing reports, conversations with local experts, and our initial reconnaissance surveys conducted during summer 2000 to identify those factors and hypotheses that appeared to warrant attention during Phase I (this information is summarized in Chapters 3 and 4). The highest priority potential limiting factors then became the focus of hypothesis-driven studies conducted during Phase I. These "focused studies" and the specific hypotheses tested are described in detail in Chapter 6.

[Note: In the following discussion of the refinement of the list of potential limiting factors that have been considered in this study, potential limiting factors are shown in ***bold italics*** for clarity.]

5.2.1 Factors Excluded from Consideration in this Study

Based on review of initial information, it was determined that, while dams are widespread in the Napa River system, flow regulation does not completely eliminate peak flows or create excessive flow fluctuations. For example, with less than 20 percent of the area in the Napa River watershed located upstream of large dams, capture of runoff from early storms is not expected to be of sufficient magnitude to eliminate ***attraction flows*** to a significant extent. The large dams in the Napa River watershed are operated mainly for municipal water supply and thus do not cause dramatic downstream fluctuations of flows that could cause ***dewatered redds*** or ***juvenile stranding***. In addition, while significant amounts of dredging and floodplain manipulation have been conducted for flood control and navigation purposes, these activities have not dramatically altered the route that fish must follow to find the system, thus ***migration corridor hazards*** to adult upstream migration were not considered further.

A lack of reports of serious pollution and the relatively short length of the migration corridor in the mainstem Napa River (compared with Central Valley rivers, where migration distances may be upwards of 150 miles [241 km]) suggest that ***environmental migration barriers,*** such as high levels of pollution or acutely lethal temperatures during the migration periods, may not be significant issues in the Napa system. While ***water quality*** is a potential concern for various life history stages of salmonids and California freshwater shrimp, water quality issues other than those related to sediment and temperature were outside the scope of this project and were not addressed.

5.2.2 Factors Considered in this Study

We formulated initial hypotheses based on review of existing information, interviews with local experts, and reconnaissance surveys. The potential limiting factors identified for further examination as part of this study were grouped into the following categories.

Salmonid Adult Upstream Migration

The Napa River watershed is heavily developed and thus impacted by many in-channel structures such as bridges, culverts, or dams that have the potential to form ***physical migration barriers***. Other sorts of barriers include “hanging” tributaries and natural barriers such as waterfalls or seasonally dry reaches. To address these issues, a comprehensive review of available information on natural and artificial barriers was performed (see Section 6.4) and the issue of “hanging tributaries” was addressed (see Section 6.1).

Salmonid Spawning and Incubation

Changes in the physical processes controlling the ***quantity of spawning gravel*** in the system were characterized (see Section 6.1)

The ***quality of spawning gravel*** is a critical factor in the success of salmonids and gravel permeability was assessed at 29 sites throughout the basin (see Section 6.2). The issue of ***substrate mobility/scouring*** was addressed in an intensive study of two sites on the mainstem (see Section 6.2).

Due to the warm summer temperatures of the Napa River system, there was some concern that elevated ***water temperature*** could be deleterious for spawning (see Section 6.3).

Salmonid Juvenile Rearing

In a Mediterranean climate such as occurs in the Napa River watershed, lack of snowmelt runoff and low summer flows result in elevated water temperatures. As a result, ***availability of summer rearing habitat*** and ***water temperature*** were major concerns. To determine the status of oversummering habitat, a review of the general state of habitat was undertaken (see Section 6.1) and an extensive survey was conducted to determine the extent of channel drying within the basin (see Section 6.5). To determine whether water temperatures reach levels harmful to juvenile salmonids, temperature monitoring was conducted throughout the basin (see Section 6.3).

It was suspected after early reconnaissance surveys that insufficient ***food availability*** may reduce growth of juvenile fish due to a compound effect of low flows and high temperatures (addressed in Section 6.6).

As in many streams in California, numerous exotic species have become established in the Napa River watershed, potentially resulting in increased ***predation on and competition with native species***, and substantial habitat change, which has the potential to influence ***interspecific interactions between native species***. To assess whether these food web interactions were occurring, we compared historical and current fish survey data (see Section 3.4).

The ***availability of overwintering habitat*** and potential ***displacement by high flows*** by juveniles was deferred for consideration in Phase II.

Salmonid Outmigration

Due to the warming of surface waters in the spring, ***water temperature*** during the period of smolt outmigration was a concern for this study (see Section 6.3). In addition, due to the lack of highly turbid snowmelt pulse flows in the Napa River watershed, smolts are highly vulnerable to ***predation*** as they leave the system. To evaluate this issue, changes in the abundance of predator habitat and the fish community were studied (see Section 6.1 and Section 3.4, respectively). Whether ***adequate flows for outmigration*** would be available for juvenile outmigration was deferred for consideration in Phase II.

California Freshwater Shrimp

Very little is known about California freshwater shrimp and, thus, it was not possible to develop refined hypotheses about potential limiting factors for this species. However, undercut bank habitat with overhanging vegetation is well known to be an important habitat requirement for California freshwater shrimp. To determine the abundance of suitable habitat and generate hypotheses about the types of geomorphic processes that create and maintain this habitat, surveys were conducted in the mainstem Napa River (see Section 6.7).

5.2.3 Phase II Scope of Work

To continue the progress toward understanding the factors and processes controlling salmonid abundance in the Napa River watershed, we have identified a set of Phase II studies to be considered for further funding (see Table 5-1 and Appendix C). One of the primary objectives of Phase II is to quantify sediment inputs and to develop a mechanistic understanding of the links between land use practices and sediment delivery to channels and channel condition. Phase II studies will further address issues identified during Phase I, and will examine new hypotheses developed during Phase I studies. Phase II would also undertake detailed life history surveys to fully understand the patterns of use of the system by analysis species. Furthermore, Phase II would address a number of potential limiting factors that were identified as part of Phase I, but which were either outside the scope of the project or were not feasible given the resources available. Phase II studies would also address questions about the distribution of California freshwater shrimp within the basin and develop a detailed understanding of the habitat requirements of California freshwater shrimp and likely population-level responses to changes in habitat quality, quantity, and distribution.

Phase II studies that address linkages between land use practices and in-channel habitat will make extensive use of high-resolution laser-swath mapping that will be conducted in 2002 and early 2003 through a CALFED grant. This mapping effort will produce topographic maps of the basin of unprecedented resolution and greatly enhance our ability to perform analyses of stream geomorphology, habitat suitability, migration barriers, and other factors affecting fish populations and aquatic ecosystem health in the Napa River watershed.

Table 5-1. Factors potentially limiting salmon and steelhead populations in freshwater environments and their relevance to Phases I and II of this study.

Life History Stage	Study Phase	Potential Limiting Factor
Adult Upstream Migration	I-II	Physical migration barriers
	I-II	Environmental migration barriers
Spawning and Incubation	I-II	Spawning gravel quantity and redd superimposition
	I-II	Spawning gravel quality
	I-II	Water quality and temperature
	I-II	Substrate mobility/scouring
	II	Redd dewatering
Juvenile Rearing	I-II	Availability of summer rearing habitat
	II	Availability of overwintering habitat
	II	Stranding by low flows
	II	Displacement by high flows
	I-II	Predation
	I-II	Food availability
	II	Interspecific interactions between native species
	II	Competition with introduced species
	I-II	Water quality/ temperature
	II	Availability of estuary rearing habitat
Outmigration	II	Adequate flows for outmigration
	I-II	Water quality and temperature
	I-II	Predation
	II	Diversion hazards

6 FOCUSED STUDIES

Based on initial reconnaissance surveys of the Napa River and its tributaries, along with more in-depth surveys in selected reaches and review of published literature and other existing information, we developed a number of hypotheses and general conceptual models of historical (or reference) and current physical habitat conditions in the mainstem and tributaries. The results of this initial study are described in Section 6.1.

We then used these conceptual models, available information, in view of knowledge of the life history and habitat requirements of the three analysis species (see Section 4.3) to generate hypotheses and develop focused studies examining key factors limiting populations of these analysis species in the Napa River watershed. These studies include:

- Sediment-related factors (turbidity, pool filling, gravel permeability, and bed mobility) (Section 6.2);
- Water temperature (Section 6.3);
- Fish passage barriers (Section 6.4);
- Patterns of dry season surface flow (Section 6.5);
- Juvenile steelhead growth rates (Section 6.6); and
- Distribution and abundance of potential freshwater shrimp habitat (Section 6.7).

6.1 Changes in Physical Habitat

Our current conceptual models and hypotheses regarding general changes to the physical habitat in the mainstem and tributaries of the Napa River are presented below.

6.1.1 Mainstem Napa River

Aerial photographs taken in the 1940s show the mainstem Napa River valley fully developed into agriculture. At this time, the mainstem Napa River, above the city of Napa was a low gradient, gravel-bedded stream exhibiting bar-pool morphology, with point bars, mid-channel or island bars and multiple channels in the unconfined reaches. These reaches were bordered by floodplains that appeared to be inundated annually with well-established vegetation. There were well-developed wetlands located in the transitional areas between alluvial fans and the valley floor, and on the floodplains. In confined reaches, the Napa River was a single-thread channel with the extent of the active floodplain generally constrained by coarse-textured, erosion resistant tributary alluvial fans.

Prior to major anthropogenic disturbances in the basin, the Napa River would have had numerous side channels that provided backwater rearing habitat for salmonids. The mainstem channel would have been connected to its floodplain in most locations, with the floodplain inundated during several storms per year. In contrast, 1998 aerial photographs depict a simplified river-floodplain system in which the channel has narrowed, incised, and largely abandoned its former floodplain, resulting in a loss of backwater rearing habitat. Review of channel cross-section records, published reports, and recent field observations indicate that the river has incised at least 4–6 ft (1.2–1.8 m) on average from the mouth of the river to a point upstream of Calistoga, and is currently in the process of active channel incision upstream of Calistoga. Figure 6-1 illustrates some of the changes that occurred between 1940 and 1998 in three reaches. The abandonment of the floodplain and the present-day channel entrenchment are most likely caused by anthropogenic impacts, such as draining and diking of the valley floor, filling of side channels to facilitate development of the floodplain, mainstem channel straightening, mainstem bank stabilization, levee construction, gravel dredging downstream of the City of Napa, gravel bar skimming, loss of bedload supply due to dam construction, and large woody debris (LWD) removal on the mainstem.

These types of alterations of the mainstem river appear to have generally occurred throughout the valley floor, from Calistoga downstream to the City of Napa. Our interpretations of aerial photographs are supported by observations made during surveys of mainstem reaches (approximately 10 miles [16 km], reaches are shown in Map 9), and data from previously published studies. These alterations to the mainstem have affected the quality and abundance of suitable aquatic and riparian habitat for native species. The natural bar-pool morphology evident in the 1940s aerial photos and expected in a wandering river such as the Napa River, with its alternating sequence of pools and riffles, has been converted in many reaches into a series of long run-pools (i.e., long pools that are shallow relative to their length) separated by very small bars. These long run-pools create lake-like habitat for non-native predatory fish, increasing the exposure of native salmonids to predation during rearing and outmigration.

Some pool filling by fine sediment was noted in the long run-pool habitats. Channel incision may have increased bed mobilization, which in turn may have increased frequency and intensity of scour of salmonid redds during the winter months (see Section 6.2). Floodplain abandonment has resulted in the loss of side channel, backwater, and slough habitats that would have provided high quality rearing habitat. Throughout most of its length, the mainstem Napa River now has only a narrow band of riparian vegetation.

6.1.2 Tributaries

Tributaries of the Napa River are generally steep, coarse gravel- or cobble-bedded streams with small or non-existent floodplains, few deep pools suitable for steelhead rearing, and limited spawning gravel. We hypothesize that prior to European-American settlement, the wooded tributaries would have had relatively frequent log jams that created deep pools and locally reduced transport capacity, inducing deposition of spawning-size gravel in patches. Based on observations gathered during reconnaissance surveys and other records, there were likely abundant redwood and mixed evergreen forests along many of the tributaries within the Napa River watershed, providing long-lasting woody debris to stream channels. The frequency of woody debris in channels was extremely low in channels observed throughout the watershed. These levels are lower than those common in many similar systems in the region, and are probably indicative of woody debris clearing. The clearing of LWD appears to have altered the morphology and local hydraulics of many tributary streams. Removal of woody debris, logging (and loss of wood recruitment) construction of extensive streamside road networks, construction of dams, and other land use practices appear to have resulted in a simplified channel morphology (including reduction in the size and frequency of spawning gravel patches), locally higher flow velocities, some channel incision, a loss of deep pools, and some presumed local coarsening of the channel bed.

Many tributaries, particularly those on the west side of the basin, cross extensive alluvial fans that encroach onto the valley floor. These alluvial fan surfaces have been highly altered by historical and current land use practices (including grazing, vineyards, and urbanization), which has led to channel incision and possibly widening (causing increased sediment production and transport to the mainstem), large woody debris (LWD) clearing (exacerbating channel bank instability), and general channel simplification (including abandonment of floodplains on large fans). Larger tributaries, such as Dry, Conn, and Soda creeks, show signs of recent incision and have graded to the incised current level of the mainstem Napa River. In some cases, smaller tributaries cutting across the valley floor have not fully adjusted to the lowered level of the mainstem and are elevated at their confluence with the mainstem, forming potential barriers to upstream fish migration referred to as "hanging tributaries."

Based on field reconnaissance of Napa River tributaries, we conclude that pools appear to be less frequent than would be expected under historical conditions, where large woody debris loading would have created obstructions and forced deep pools to form. Our field observations in several tributaries, particularly those on the west side, indicate that large woody debris loading (amount per length of channel) is much lower than would be typical of streams in unmanaged mixed evergreen forests. Although the history of wood removal from the Napa River and its tributaries is poorly known (there are some records of stream clearing projects in the 1960s and 1970s), large woody debris has likely been reduced by direct removal from many or most streams for a variety of reasons. The reduction in large woody debris loading has likely increased the mobility of spawning gravels and reduced the diversity of in-channel habitats in Napa River tributaries. Additionally, loss of large woody debris has likely reduced cover for juvenile steelhead rearing in tributaries. A channel lacking sufficient deep-water refugia would likely increase exposure of fish to higher temperatures and greater predation pressure by terrestrial predators such as birds, snakes, and mammals. Large woody debris may also be reduced because of increases in the magnitude and duration of peak flows capable of dislodging debris jams, possibly as a result of land use changes.

Several large dams were built between 1924 and 1959 on major eastside tributaries (Conn, Rector, Milliken, and Bell dams) and the northern headwaters of the Napa River (Kimball Dam). In addition, many smaller dams can be found throughout the basin. Many of these dams intercept coarse sediment supply, and thereby reduce delivery to downstream reaches, which can cause bed coarsening and channel incision (although incision may be limited by bedrock and bed coarsening).

6.2 Sediment-Related Impacts on Salmonid Habitat

We examined sediment-related impacts on salmonid habitat in the Napa River watershed by examining factors that are: (1) known to affect salmonid reproductive success directly, (2) targeted by proposed habitat rehabilitation efforts, and (3) cost-effective and efficient given the size of the study area. Sediment-related factors evaluated during Phase I included:

- Turbidity (which can affect salmonid feeding efficiency, growth, and survival);
- Spawning gravel permeability in the mainstem and the tributaries (which affects survival-to-emergence of steelhead and Chinook salmon eggs);
- Bed mobility in the mainstem (which also affects survival-to-emergence for steelhead and Chinook); and
- Filling of pools in the tributaries (which reduces the quality and quantity of juvenile rearing habitat).

6.2.1 Turbidity and Juvenile Feeding and Growth

High turbidity and suspended sediment concentrations can have detrimental effects on aquatic biota in river systems (e.g., Bisson and Bilby 1982, Berg and Northcote 1985, Newcombe and Jensen 1996). While very high turbidity levels may cause acute physiological stress and tissue damage to some aquatic organisms during peak flows, fish tend to survive high turbidity levels over short periods of time. Lower levels of turbidity over longer time periods can be more harmful to fish than higher intensity short-duration events (Newcombe and Jensen 1996). Therefore, chronic sediment sources that continue to supply sediment to channels after peak flow events can be particularly harmful to juvenile salmonids. Based on a synthesis of the literature (e.g, Berg and Northcote 1985, Newcombe and Jensen 1996), we assumed that chronic turbidity greater than 20 nephalometric turbidity units (NTU) may adversely affect the ability of steelhead to capture prey. Effects of reduced visibility, including reduced feeding efficiency and disrupted territorial behavior, can occur at relatively low turbidity levels and have the potential to impact the population dynamics of an affected species primarily by reducing growth rates. The reduced size of smolts due to increased periods of turbidity has been identified as a potentially important limiting factor in several northwestern California streams (Reid 1998, B. Trush pers. comm. 2000).

Any process that delivers fine sediment (fine sand, silt, and clay) to channels can increase turbidity levels. The delivery of sediment from hillslopes to channels is a function of the underlying geology, local climate, vegetation, topography, and land use. Common delivery processes that provide significant fine sediment to channels include:

- hillslope mass wasting processes (such as debris flows and earthflows);
- gullies;
- sheetwash and rill erosion; and
- channel bank erosion.

Human activities such as road construction and use, hillslope and streambank vegetation removal, agricultural activities, and construction of dams can alter the magnitude, timing, and spatial pattern of these processes. Secondary effects of land use, such as channel incision and river bank destabilization, can also accelerate delivery of fine sediment to channels.

In some watersheds, increased sediment production caused by human activities may result in longer periods of elevated turbidity following storms. Increased duration and frequency of sediment transport (and associated turbidity) make it much more difficult for juvenile salmonids to see and capture prey successfully.

Turbidity within the Napa River watershed

The Napa Valley is heavily developed for both agricultural and residential land uses, and hillslope erosion has been identified as a clear concern for many stakeholders in the watershed (Napa River Watershed Task Force 2000). Previous studies indicate that land use activities have increased the supply of fine sediment to channels in the Napa River watershed (e.g., WET, Inc. 1990, USDA-SCS 1994). Based on these observations, we hypothesized that turbidity levels may be elevated in the basin relative to historical conditions. Little data were available, however, on recent or historical turbidity levels in the Napa River watershed.

Hypothesis

Based on initial information review and field reconnaissance surveys conducted in summer 2000, we hypothesized that feeding opportunities for juvenile steelhead during the rainy season (particularly in the late fall and early spring when temperatures are not too cold to inhibit feeding and growth) have been reduced by elevated turbidity levels. Reduced growth may affect subsequent survival (see Section 6.6 for a discussion of possible mechanisms). If prolonged high turbidity occurred only after infrequent flood events (e.g., flood events with a recurrence interval of several years or greater), then high turbidity would probably not have a significant impact on steelhead production in the Napa River watershed. We hypothesized that to be deleterious, prolonged high turbidity would have to occur after relatively common storms.

Study methods

To determine whether turbidity at winter baseflow levels is elevated to a degree that would be expected to reduce rainy season feeding opportunities for juvenile steelhead in the Napa River watershed, a turbidity sampling project was undertaken during winter and spring 2001 and on a limited basis in winter 2002. We were particularly interested in the receding limb of the hydrograph and rainy season baseflow conditions, to examine whether chronic sediment sources were creating turbidity levels unsuitable for juvenile steelhead feeding and growth. To test this hypothesis, we conducted turbidity monitoring at a total of 19 sites following four of the first five peaks greater than 100 cfs[7] (2.83 cms) during water year 2001 (Map 10). Five additional sites were sampled on a more limited basis during the 2001 sampling effort. To document conditions after a relatively large storm event during water year 2002, which was much wetter than 2001, turbidity was re-measured at 22 of the 24 original sites in a limited sampling effort.

Each storm was sampled shortly after the time that peak flows occurred and approximately one, three and seven days after the peak unless another storm occurred. Turbidity measurements were taken with grab samples using an air displacement sampler. A storm in January 2002 was also sampled 3 and 10 days after the peak event, to assess the decline in turbidity following a near-bankfull event with high antecedent rainfall. The sampling methods, dates, and locations are described in detail in Appendix A7.

Results and discussion

Figure 6-2 shows the hydrograph at the St. Helena gage and turbidity measurements from water year 2001 at four of the sampled sites:

- the mainstem Napa River at Trancas Road,
- Carneros Creek at Route 121,
- Dry Creek at Solano Avenue, and
- Redwood Creek at Redwood Drive.

The St. Helena hydrograph is included on Figure 6-2 solely as a frame of reference for data comparison. We expect that the timing and magnitude of peaks on the tributaries were different than on the mainstem. The Napa River at Trancas Road is representative of turbidity conditions in the mainstem, and reflects sediment inputs from most of the geologic units in the basin. Carneros Creek is located in the Miocene marine sedimentary unit, and had the highest turbidity measurements in the basin. Dry Creek flows through the upper Cretaceous marine sediments, and Redwood Creeks drains both the Tertiary volcanic and upper Cretaceous marine sediments terrain. Dry and Redwood creeks generally had turbidity intermediate between Carneros Creek and the mainstem. The turbidity data for all sites are presented in Appendix A7.

Four of the five storms from January to mid-March 2001 were sampled during the recession limb of the storm runoff. These storms had recurrence intervals ranging from 1.0 to 1.4 years, as

[7] Measured at the USGS Napa River near St. Helena gage (number 11456000).

measured at the USGS St. Helena gage. Measured peak turbidity values exceeded 100 NTU[8], but quickly dropped to values below 20 NTU (the conservative threshold of concern value). Turbidity was less than 20 NTU for all samples taken following the January 2, 2002 storm (these data are included Appendix A7). These data imply that during this sampling period at these sites, there were not active sediment sources causing sustained fine sediment loading. This does not imply, however, that on other tributaries or for other periods, turbidity levels would not be significantly elevated. Nonetheless, this test failed to identify a chronic turbidity problem that would adversely affect juvenile steelhead.

Our results indicate that feeding opportunities were probably not lost for more than one or two days following the sampled storms (based on the 20 NTU threshold). Therefore, turbidity probably did not pose a significant limitation to feeding by steelhead during the period studied. We did not perform a sediment source analysis, and therefore do not know if potential significant sources of fine sediment and clays (dirt roads, freshly ploughed agricultural fields, etc.) were exposed during the period of measurement. Within the time frame of this study, no turbidity effects were found, despite our examination of 17 tributaries and 7 sites on the mainstem Napa River. This suggests that there is not a permanently elevated chronic source of sediment causing deleterious turbidity levels. However, our results reflect conditions during only two water years and may not have captured the effects of episodic or rare phenomena such as periods with higher rates of land conversion or road construction or infrequently-occurring natural events, such as landslides or extremely large storms.

6.2.2 Spawning Gravel Permeability

The key factor determining survival of salmonids during egg incubation through fry emergence is the presence of sufficient flow of cool, clean water through the spawning gravels to ensure delivery of dissolved oxygen and elimination of metabolic wastes. When a high percentage of fine sediment is deposited in or on the streambed, gravel permeability (or flow rate of water through the gravels) can be substantially reduced. Reduction of gravel permeability results in progressively less oxygen and greater concentrations of metabolic wastes around incubating eggs and alevins (newly hatched fish larvae or sac-fry) as they develop in the pore spaces between gravels, resulting in higher mortality (McNeil 1964, Cooper 1965, Platts 1979, Barnard and McBain 1994).

The standard method of measuring the amount of fine sediment in spawning patches is bulk sampling of the bed material. Analysis of the grain-size distribution of the bed requires collection of large bulk sediment samples, which are labor-intensive and expensive to collect and analyze. In addition, grain size distributions are still an indirect measure of water circulation around eggs and larvae, which is the relevant biological parameter of interest. Because fine sediment deposition in gravel-bed rivers is often heterogeneous, repeated measurements of bed material composition are required. This makes bulk sampling particularly cumbersome in a study area as large as the Napa River watershed.

Instead of bulk sampling, we used standpipe gravel permeability measurements to provide a rapid and cost-effective indicator of both fine sediment quantity and egg survival (Terhune 1958, Barnard and McBain 1994). Permeability[9] is the only descriptor of spawning gravel quality that is

[8] The turbidity may have been much higher at peak flows which were not included in our sampling design since our focus was on patterns of turbidity during peak recession and baseflow periods.
[9] Our use of the term 'permeability' (expressed in units of length/time), is consistent with the established convention in fisheries biology. However the property being measured is more accurately termed 'hydraulic conductivity,' as defined in the hydrology literature.

(1) known to directly affect salmonid survival during egg incubation through fry emergence, and (2) affected directly by fine sediment deposition. Measured permeability rates can be converted into an index of predicted mortality rates for salmonid egg and larval incubation using relationships derived from field observations of redds with differing permeabilities (Taggart 1976) and experiments where the permeability of artificial redds was manipulated experimentally (McCuddin 1977) (Figure 6-3). Because of the lower cost of permeability measurements, we were able to sample substantially more sites within the study area than we would have using bulk sampling.

Spawning gravel permeability in the Napa River watershed

Data from previous studies (e.g., WET, Inc. 1990, USDA-SCS 1994) indicated that land use changes since the mid-1900s (if not earlier) may have increased the amount of fine sediment supplied to spawning streams in the Napa basin. The increased sediment load could have increased the amount of fine sediment on the streambed sufficiently to adversely impact salmonid survival-to-emergence. Reconnaissance surveys in summer 2000, however, found little sand on the surface of spawning patches in tributaries to the Napa River. These tributaries are the primary spawning areas for steelhead, and are not used by Chinook salmon. We also observed few spawning patches during our site visits regardless of upstream geology, indicating that regardless of the quality of spawning habitat, the quantity appears to be limited. Mainstem surveys conducted in fall 2000, however, did yield evidence of potential fine sediment problems in gravels that could be used for spawning by Chinook salmon or steelhead.

Hypothesis

Based on these observations, we hypothesized that gravel permeability at potential spawning sites was not impaired in tributaries of the Napa River. We also hypothesized that gravel permeability was poor (i.e., low enough to substantially impair egg-to-fry survival and emergence) in the Napa River mainstem.

Study methods

To determine the quality of tributary streambed gravels for steelhead egg incubation and early rearing, substrate permeability was measured using a modified Mark IV standpipe (Terhune 1958, Barnard and McBain 1994). The recharge rate (the rate at which water moves through the substrate) derived from these measurements was converted to permeability using a rating table with a temperature and viscosity correction from Barnard and McBain (1994). We measured permeability at 28 reaches in 17 tributaries during field surveys conducted in 2002 (Map 10). The number of permeability measurements in each reach depended on the number of spawning patches. A technical discussion of the field methods and a description of locations used in the permeability sampling is given in Appendix A8.

We used relationships between survival-to-emergence and permeability from two data sets (McCuddin 1977, Taggart 1976). We used the following simple linear regression on the combined data sets to estimate survival based on our permeability measurements:

$$\text{Survival} = 0.1488 * \ln(\text{Permeability}) - 0.8253 \qquad (1)$$

where permeability is in units of cm/hr and:

$$\text{Mortality Index} = (1 - \text{Survival})*100 \qquad (2)$$

Results and discussion

The regression of survival to emergence versus permeability for coho and Chinook salmon, with 90 and 95 percent confidence limits is given in Figure 6-3. The high r^2 value of 0.85 indicates that permeability accounts for most of the variability observed in egg survival. The regression is based on data from two different species from the Pacific Northwest rather than species-specific data from Bay Area streams. Because of these limitations, we recommend that the results be interpreted with caution and treated more as an index rather than a precise quantitative prediction of survival and mortality.

Based on the tributary permeability measurements at the 28 potential steelhead spawning sites, the median predicted mortality index value was 55 percent, with three of 28 sites having mortality index values greater than 75 percent and no sites having mortality index values lower than 25 percent. Permeability measured at three potential Chinook/steelhead spawning sites on the mainstem were comparable to the results for the tributaries, with mortality index values of 33, 54, and 57 percent. We concluded that our original hypothesis, that gravel permeability at potential tributary spawning sites was sufficient to support high egg survival, is incorrect, and that elevated fine sediment concentrations in the channel bed subsurface may be a widespread problem in the Napa River watershed. We also noted that suitable gravel patches were infrequent and small in size[10], exacerbating the poor quality found during the permeability studies. Our hypothesis regarding poor gravel quality in the mainstem Napa River was supported.

Surprisingly, given the permeability results, extensive surveys of the Napa River watershed in the summer of 2001 found that many tributaries are relatively well seeded with juvenile steelhead (Friends of the Napa River 2001). This is an unexpected result given the paucity and poor quality of the gravels. This discrepancy could be due to three factors:

- the sites where we measured permeability are not representative of the tributary conditions;
- the sites where we measured permeability are representative of conditions in the tributaries, but survival-to-emergence may actually be higher than we predicted; and
- only limited spawning habitat is needed to effectively seed available rearing habitat in tributaries sampled by Friends of the Napa River.

The survey conducted for Friends of the Napa River (FONR) covered 62 miles of habitat and included 12 of the tributaries that we surveyed (Table 6-1). Comparing the FONR juvenile abundance results with the permeability results shows that there is no apparent correlation between the calculated survival index and the abundance of juvenile salmonids (Table 6-1).

[10] Note: we did not conduct a systematic analysis on the availability and size of steelhead spawning patches.

Table 6-1. Comparison of Egg-Larvae Survival Index (from permeability measurement) to estimated abundance of juvenile steelhead in tributaries.

Abundance Categories							
High (>1 steelhead/m^2)		**Medium (0.5-1 steelhead/m^2)**		**Low (0-0.5 steelhead/m^2)**		**Absent (0 steelhead)**	
Tributary*	Average Survival Index	Tributary	Average Survival Index	Tributary	Average Survival Index	Tributary	Average Survival Index
Dry (3) Ritchie (1) Mill (2) Dutch Henry (2)	50% 70% 50% 52%	Redwood (3) Sulfur[11] (1) Sarco (1)	52% 28% 72%	Garnett (1) Soscol (1)	52% 68%	Diamond Mtn (2) Cyrus (2) Bell (1)	62% 58% 75%
Average	**56%**	**Average**	**51%**	**Average**	**60%**	**Average**	**65%**

*the number of reaches in the permeability analysis is shown in parentheses
Source: Friends of Napa River (2001).

The apparent discrepancy between the limited spawning habitat and abundant juveniles is not altogether surprising. Empirical and theoretical evidence suggests that spawning gravel quality and quantity are rarely the primary factors limiting population levels of species such as steelhead and resident trout (Elliot 1984), but they may be important contributing factors. The relative importance of reduced permeability as compared with factors such as the availability of rearing habitat for juveniles is discussed in the context of a limiting factors analysis in Section 7.

6.2.3 Bed Mobility and Redd Scour

Salmonid spawning success requires that deep scour of the bed does not occur during the time the eggs are incubating in gravel deposits (or redds). Seasonal bed mobility, on the other hand, enhances food production and reduces the accumulation of fines in the bed. Relative bed mobility varies naturally among gravel bedded rivers and it is typically higher where the gravel supply is higher, where the bed is composed of fine gravel, and perhaps where flows are more flashy. Increased bed mobility on a river, therefore, occurs when land use increases gravel loading from hillslope and stream bank erosion, reduces resistance to flow (by removing large woody debris or riparian vegetation or through channel straightening), or increases the frequency or duration of peak flows (due to increased storm runoff or entrenchment of the channel and confinement of high flows between channel banks).

Bed mobility on the Napa River mainstem

Bed mobility of the Napa may have gone through a complex history of change due to land use effects. The mainstem has probably cut down at least 4 to 6 ft (1.2-1.8 m) since at least the 1960s up to the city of Calistoga due to the combined effects of dams, dredging, wood removal and possibly increased flows (WET Inc. 1990; observations made during our extensive mainstem surveys). Incision commonly coarsens the bed, which tends to reduce its mobility, and it is this coarsening that commonly arrests further channel incision, unless the channel reaches bedrock, which it has in many places along the Napa River. Incision, however, can also lead to destabilization of sediment rich banks and adjacent fans, resulting in an increased sediment load on the channel. Incision also causes flood flows to be confined within the incised banks, thereby increasing the likelihood of bed mobility. Continued land development may also introduce sediment to the channel subsequent to the incision. Field inspection, therefore, can be used to determine whether the channel will have relatively high or low bed mobility.

Hypothesis

We hypothesized that bed mobility is high in the Napa River mainstem, which might lead to frequent scour of redds and subsequent mortality of Chinook salmon and steelhead eggs and alevins. This hypothesis was not rigorously tested during Phase I, but we have proposed quantitative assessment under Phase II.

Study methods

We conducted extensive geomorphic surveys in the mainstem Napa River in fall 2000 and reconnaissance-level geomorphic surveys in the tributaries to provide a non-quantitative assessment of bed mobility in the basin. We surveyed seven reaches in the mainstem Napa River with an average length of 1.3 miles (2.1 km) (see Map 9 and Appendix A6 for the locations of the surveys). We noted the median grain size, condition of the bed and banks, and other geomorphic characteristics during this survey.

During the tributary reconnaissance surveys we noted geomorphic characteristics of over 40 tributary sites in summer and fall 2000 (see Map 9 for the locations of the surveys). Observations of the tributaries were also made during the permeability (section 6.2.2) and pool filling surveys (section 6.2.4).

Results

Our extensive surveys indicated that the mainstem Napa River had very few spawning gravel patches. At the few potential spawning patches observed, the gravels were finer than expected, very loose, and poorly sorted. These observations are typical of channels with relatively high sediment supply and frequent bed mobility (i.e., bed movement occurs during most storms).

As opposed to the mainstem, observations in the tributaries indicated that the channel bed was typically much more coarse (coarse gravel to cobble sized particles predominated), and therefore we did not predict elevated bed mobility in the tributaries. During our permeability studies we did note that there was a high proportion of fines in the channel bed (as opposed to on the surface of the bed), indicating that the bed has potentially coarsened and fines have infiltrated through the immobile surface layer.

We did not attempt a quantitative analysis of bed mobility in the Napa River mainstem or its tributaries. Additional questions regarding bed mobility will be analyzed in Phase II of the study. We have recommended that a quantitative stream bed mobility study in combination with deployment of scour chains or scour cores be used to examine not only the frequency of bed mobility, but the depth of scour as well[9] (see Appendix C) so that the likely effects on salmonid redds can be evaluated.

6.2.4 Pool Filling and Juvenile Rearing Habitat

If the total and/or fine sediment load (sand and fine gravels) is high relative to transport capacity of a channel, large deposits of fine bed material (predominantly sand and very fine gravels) may accumulate in pools. Reduction in pool volume caused by fine sediment deposition is biologically important because it has the potential to reduce the amount of juvenile rearing habitat for salmonids and other native fish and aquatic wildlife. Reductions in pool depth, in addition to reducing the total quantity of juvenile rearing habitat, may also adversely affect thermal and velocity refugia that are often associated with deep pools, as well as reduce areas used for cover to avoid predators.

Pool filling often occurs when sediment supply is increased relative to the equilibrium conditions in which the pool formed. The channel's response to high sediment loading depends on its sediment transport capacity. In general, because of their high sediment transport capacity, pools in steeper channels are less likely to be filled with sediment than those in shallower channels (Montgomery and Buffington 1993, 1997). Fine sediment deposition in pools, however, has been observed in streams with gradients as high as 0.065 in areas with high sediment loading. The size of the pool is also important, because larger pools can withstand filling a greater proportion of their volume than smaller pools without substantial loss of habitat, because, for aquatic organisms using pools as habitat, the depth of the pool is more important than the proportion of the pool filled with fine sediment.

A measurement of the amount of pool filling with fine sediment is V*, the ratio of the volume of fine sediment in a pool to the total pool volume (Lisle and Hilton 1991, 1992; Hilton and Lisle 1993). V* also relates to spawning habitat quality, since mobilization of fine sediment accumulations in pools can result in infiltration of redds constructed in the downstream tails of pools, particularly those with high V* values (Lisle and Hilton 1991, Peterson et al. 1992). It should be noted that V* for a given pool is not static through time, as the amount of fine sediment filling can change in response to high-flow events, which can scour the pools and in response to local variations in sediment supply. Local mass wasting such as landslides and bank failures can also fill pools temporarily until a sufficiently high flow scours the sediment. Lisle and Hilton (1992) indicate that values of V* greater than 0.3 (30 percent pool filling) reflect high sediment supply, whereas V* values less than 0.1 (10 percent pool filling) indicate a relatively low fine sediment supply (Lisle and Hilton 1992).

Hypothesis

Based on a lack of observations of pool filling during reconnaissance surveys and other field visits, we hypothesized that reduction of juvenile rearing habitat due to pool filling by fine sediment was not a widespread problem in the Napa Basin.

Study methods

While we did not observe extensive pool filling during the tributary reconnaissance surveys, there is evidence from previous studies of an elevated supply of fine sediment in the Napa River watershed due to erosion (e.g., WET, Inc. 1990, USDA-SCS 1994). We therefore conducted field surveys during 2001–2002 to corroborate the initial reconnaissance observations and to document the amount of sediment filling.

The V* methodology described by Hilton and Lisle (1993) can be used to compare changes in pool filling through time. Using their methodology, it is possible for a two-person crew to measure about one pool per 1.5 hours. Considering the size of the Napa River watershed and the need to estimate pool filling in well over 120 pools given the available budget and schedule, we developed a somewhat less precise, faster methodology of assessing pool filling that entails measuring average pool dimensions and the area and depth of each patch of fine sediment. The key benefit of this method is that it requires only 10 minutes per pool. We conducted a comparison of methods and found that the rapid method of assessing pool filling was consistently within 10 percent of results using Lisle and Hilton's V* method. A further discussion of the methodology and accuracy of the rapid method of assessing pool filling is explained in detail in Appendix A9.

Results and discussion

We surveyed pool filling during 2002 at 29 reaches in 18 tributaries to the Napa River (Map 10). Our results indicated a median basin-wide level of pool filling of only 2 percent, and confirmed the initial reconnaissance observations that pool filling is not high in the Napa River watershed. Twenty-five of the 29 surveyed reaches had index values of less than 10 percent, of which 21 sites had values less than 5 percent. One reach on Dry Creek had a pool filling between 10 and 20 percent. Three reaches had a pool filling greater than 20 percent. Two of these reaches were on Carneros Creek, which has a bedrock geology (Miocene marine sediments) that would be expected to produce relatively high sediment loads. The third reach with a pool filling greater than 20 percent is downstream of a large, well-documented landslide on Sulphur Creek. Further study is needed to establish the causes of the few high values, since they may be due either to natural or anthropogenic sediment sources located upstream of the survey sites.

The results of the pool filling analysis indicate that pool filling by fine sediment likely does not adversely impact steelhead rearing habitat. However, casual observations during the study indicated a generally low abundance of pools throughout the basin, which has the potential to be a significant limiting factor to fish. While it was not possible to explore this phenomenon further during Phase I, it is a key hypothesis for Phase II that the lack of pools is primarily due to a lack of large woody debris (LWD) in the channels. We hypothesize that LWD was historically well distributed throughout the basin, particularly in areas with redwood or mixed evergreen forest, but that delivery of wood to channels has been reduced, either by active removal from the stream, and/or by land use activities that have reduced the number of mature trees in potential recruitment sites in riparian corridors and/or adjacent steep slopes.

6.3 Water Temperature

Changes in environmental temperatures have profound direct and indirect impacts on fish and other cold-blooded organisms because they are unable to internally regulate their body temperature. While it is important to consider water temperature as a potential limiting factor for any salmonid population, it is a particularly relevant parameter for understanding constraints on steelhead because steelhead rear as juveniles in freshwater for one or more years. Steelhead may experience several summer seasons while rearing, during which they may be subject to warm water temperatures and the resulting thermal stresses. In addition, water temperatures during the rest of the year determine, in part, whether juvenile steelhead can remain mobile enough to feed and grow beyond the summer. Growth during the fall or spring, for example, may be of particular importance to steelhead populations in the southern portion of their range (including the Napa River watershed).

The direct impacts of high temperatures may include both acute and chronic effects. Acute effects tend to involve decreased or disrupted enzyme function, which may compromise a wide range of physiological functions and result in total incapacitation and death of the organism. Chronic effects tend to involve changes that slowly degrade the condition of the organism, such as increased metabolic rate (which reduces growth efficiency), reduced immune system function (which increases susceptibility to disease), or an increased tendency to become exhausted (which reduces foraging efficiency).

Changes in water temperature may also have substantial indirect effects on fish by altering the physical properties of the water on which the fish depend. For coldwater fish such as steelhead and Chinook salmon, reduced dissolved oxygen associated with high water temperatures is frequently an important problem (the dissolved oxygen capacity of water is inversely related to temperature). Other indirect temperature-related issues include temperature-dependent changes in the biological activity of a pollutant, and changes in behavior or physiology that affect the competitive balance among species and hence may result in a shift in fish species composition or relative abundance.

In addition, because steelhead and Chinook salmon are sensitive to increases in temperature, any additional factors that might increase physiological stress, such as disease, food limitations, elevated turbidity, or increased competition between species, have the potential to worsen the impact of elevated temperatures.

The amount of direct solar radiation reaching the water surface is the primary factor influencing water temperature. Removal of riparian vegetation that would otherwise shade the stream surface can increase the exposure of the water surface to solar radiation, resulting in warmer water temperatures. In addition, alterations of channel geomorphology that lead to an increased width-to-depth ratio increase water surface area per unit flow volume, thus increasing the potential for solar heat gain. The Napa River mainstem, however, has been incising and is fully entrenched, which has most likely led to a reduction in the high flow width-to-depth ratio. Groundwater inputs to the stream system typically have a local cooling effect, at least during the summer months, and may be of particular importance in providing local pockets of cold water within the generally warmer stream network. Actions that reduce groundwater inputs into the stream channel during summer months can therefore affect the thermal environment of salmonids and other aquatic organisms.

The Mediterranean climate of the Napa River watershed results in naturally higher summer water temperatures compared with other steelhead streams in the Pacific Northwest. It is therefore likely that Napa River watershed steelhead populations are reasonably well adapted to these conditions. However, the naturally low summer flows also result in the system being particularly susceptible to impacts that further exacerbate naturally high water temperatures, including anthropogenic reduction of riparian shading, direct pumping of groundwater, or indirect land use effects that reduce the quantity of groundwater inputs to the system.

Hypothesis

Considering evidence of low flows, riparian clearing, and channel modification, we initially hypothesized that summer water temperatures in the Napa River watershed may be high enough to cause chronic adverse impacts to steelhead.

Study methods

While we did not test whether temperature was elevated relative to historical reference conditions (which is proposed for Phase II), we did characterize existing temperature patterns in the Napa River watershed using continuous recording thermographs (set to record temperature at 15-minute intervals) that were deployed at 22 sites on 13 tributaries throughout the basin, as well as six sites on the mainstem Napa River (Map 10). These thermographs were deployed in early August 2000, checked in November 2000, and then left in place until November 2001, when we were able to recover 24 of the 28 thermographs.

Results and discussion

We found that summer water temperatures were typically warm, but generally not high enough to be acutely lethal to steelhead (Figure 6-4, Appendix A10). Data for the monitoring sites at Ritchie Creek and on the mainstem at the Rutherford Road Bridge (Figure 6-4) are largely representative of temperature patterns observed in the basin as a whole. Daily average temperature in the tributaries was 59–68°F (15–20°C) in the summer and 41–50°F (5–10°C) in the winter. Daily average temperatures in mainstem reaches were somewhat warmer and generally ranged from about 63–77°F (17–25°C) during the summer to about 43–54°F (6–12°C) in the winter, with a trend toward progressively warmer temperatures downstream, particularly in the summer months. In both the tributaries and the mainstem, the summer pattern occurred in May–September and the winter temperature pattern was evident in November–March. Spring and fall temperature patterns represented a transition between winter and summer thermal regimes, as would be expected.

In addition to this general variability, there were noticeable differences in mean temperature and daily temperature variations among some sites. For example, a spring-fed site in the upper reaches of Moore Creek in Las Posadas State Park exhibited remarkably low variability throughout the year (Figure 6-4). The near-constant temperatures observed at this site were probably due to the influence of groundwater at the site combined with the dense shading provided by the redwood-dominated riparian zone. This contrasts with the Middle Sage Creek site, about a half mile upstream of Lake Hennessey, which exhibited higher daily average temperatures and large, regular, daily fluctuations compared with other sites (Figure 6-4). These elevated temperatures and large fluctuations were likely due to a high width:depth ratio of the channel (likely due to a backwater effect from Lake Hennessey), low topographic and riparian shading of this portion of the creek, and its east-west orientation—all of which contribute to relatively high solar heat gain.

During Phase II, we will continue monitoring temperatures at a subset of the sites monitored in Phase I, and perform temperature modeling in selected reaches to better understand temperature patterns at the basin-wide scale. We will also perform intensive temperature monitoring during manipulative fish growth studies (see Appendix C).

6.4 Fish Migration Barriers

6.4.1 Structural Fish Passage Barriers

Barriers to fish movement can cause significant adverse impacts on fish populations within a basin by restricting the ability of anadromous fish to leave and return to the system and the ability of rearing juveniles and resident adults to track resources within the system. The impact of barriers on salmonids should ultimately be assessed with respect to: (1) the quantity and quality of upstream habitat that is being permanently blocked to spawning anadromous fish; and (2) any partial or temporary barriers to fish movement during the freshwater phase of the life cycle. By disrupting habitat connectivity, even a small number of barriers can have a disproportionately large impact on a population if the barriers obstruct access to large amounts of habitat.

In addition to dams, in-channel structures (such as flow diversions, culverts, and road crossings) may create steep drops in the channel that cannot be jumped by fish or may concentrate flows to such a degree that fish cannot overcome the current to move upstream. Even barriers that fish are able to pass after some effort may be significant if the level of effort required exhausts fish and reduces their reproductive fitness or longevity. Although most attention is typically focused on barriers to upstream passage, some structures may also impair downstream movement of juvenile salmonids or outmigrating smolts.

We interviewed a number of local fisheries experts and conducted extensive stream surveys on over ten miles (16 km) of the mainstem Napa River between Yountville and Calistoga (Map 10). We did not discover, and were not made aware of, any significant impediments to upstream migration of Chinook salmon or steelhead on the mainstem of the Napa River. Therefore, we focused our analysis of potential fish passage barriers on Napa River tributaries and the migration and movement of steelhead. Historically, about 300 miles (480 km) of the 1,300 miles (210 km) of stream channels within the Napa River watershed were likely accessible and suitable for spawning and rearing of steelhead in most years (USFWS 1968). Between 1946 and 1959, three large dams on Conn, Bell Canyon, and Rector creeks were constructed, reducing historically available habitat by approximately 17 percent (based on the proportion of the drainage basin that was blocked by these dams). Prior to the construction of Conn Reservoir in 1946, the Conn Creek system, with its many perennial reaches and likely high-quality habitat, may have been one of the more important tributary watersheds for steelhead spawning and rearing in the Napa Rive basin.

Hypothesis

Due to the extensive development of the Napa Basin for agricultural and residential land use, and attendant number of road crossings and in-channel structures, we hypothesized that many potential barriers to fish movement exist in the Napa Basin. The corollary hypothesis, which we were not able to test (but which should be tested during Phase II), is that the number and location of artificial barriers is sufficient to substantially limit production of steelhead in the basin.

Study Methods

To identify potential barriers to fish passage on tributaries, we reviewed data collected by CDFG from the 1950s to the present, reviewed recent stream surveys by the Napa County Resource Conservation District (RCD) on a number of northern tributaries, and analyzed USGS topographic map data (1:24,000 scale) on roads and streams. We identified 69 in-channel structures that were known or suspected to be impediments or complete barriers to migration of steelhead in tributary streams at some point during the past 50 years (Map 12). We do not have any information on the current status of most of these potential barriers. USGS maps indicate numerous lakes or reservoirs (over 220, most of which are not included in the CDFG or RCD surveys) that overlap with the mapped locations of tributary channels, suggesting that the actual number of barriers could be much greater than 69. In addition, GIS analysis of USGS data indicates that there are over 400 sites where roads cross streams in the basin, many of which are expected to be impediments or barriers to fish passage. If many of the tributary barriers identified during this analysis actually impede or block fish passage, then it is likely that barriers exert an important control on the population of steelhead within the basin.

While is our understanding that the CDFG and RCD stream surveys were conducted by qualified individuals with sound professional judgment, the criteria for assessing barriers likely differed among surveys and did not consistently include the detailed measurements required to definitively evaluate passability to fish. In addition, some sites have not been revisited for several years, and previously reported conditions could differ greatly from current conditions. Furthermore, the geographic scope of the CDFG and RCD surveys was limited by staff time constraints and access to private property. Considering that several tributary reaches have never been surveyed, or have not been revisited for many years, we conclude that the number of barriers identified by the available stream survey data likely underestimates the total number of potential barriers that exist within the basin. In contrast, the GIS analysis of channel impoundments may overestimate the number of barriers because some of the reservoirs identified on the USGS maps may be natural (probably very few) or may be located on small tributary channels that never provided steelhead habitat or may no longer exist.

We propose to analyze the impacts of barriers in relation to the quantity and quality of suitable habitat blocked and the occurrence of natural barriers during Phase II (see Appendix C).

6.4.2 Flow-related Barriers

Besides natural and human-made structural barriers, inadequate flow can also present a barrier to fish migration and movement. While upstream spawning migration by adult salmonids typically occurs during the wet season when flows are generally sufficient (unless the onset of rains is late), inadequate flows in the spring can pose a potentially significant barrier to fish movement within the basin and to smolts migrating out of the system. Dry reaches can also impact juvenile steelhead at other times of the year by eliminating or restricting access to habitat during the rearing period.

The duration and spatial extent of channel drying in the Napa River tributaries may be exacerbated by surface and/or groundwater withdrawals, and/or land cover changes that might affect patterns of runoff and infiltration of rainfall into the soil and bedrock. If so, the likely result would be that tributaries become dry earlier in the season and to a greater spatial extent than under historical conditions, thus reducing the amount of available habitat and potentially limiting fish migration and movement within the river system.

Widespread drying of tributaries was observed during surveys we conducted late in the dry season of 2001 (see Section 6.5). Not enough is known, however, about steelhead life history in the Napa River watershed (particularly the timing of movement of juveniles within the basin) to understand how these dry reaches specifically affect steelhead population dynamics. Furthermore, while the magnitude and timing of diversions and groundwater pumping are poorly understood, they could result in ecologically significant flow alterations.

Studies to address fish life history and changes in hydrology related to these issues have been proposed for Phase II (see Appendix C).

6.5 Patterns of Dry-season Surface Flow

No factor is as fundamental to the health of a stream system as flow. Flow not only ensures maintenance of aquatic conditions, it also serves to connect habitat types, allowing organisms to track resources between habitats. Without sufficient flows, juvenile steelhead and other coldwater species may experience low growth, weight loss, or mortality. Reduced flows or dry reaches may also impede migration, increase predation and competition for increasingly scarce food and habitat, result in increased water temperatures, or affect territorial behavior and aggression among members of the same species.

As a result of the Mediterranean climate, numerous streams in the Central California region, including the Napa River, typically become discontinuously wetted or completely dry during the summer or fall. The wet-winter/dry-summer seasonal pattern of the Napa River watershed results in summer conditions that are warmer and characterized by less flow than “classic” steelhead streams to the north. To some degree, steelhead using the waters of the Napa River watershed would be expected to be adapted to these natural summer conditions of low flow and warm water.

Given the natural flow conditions, streams in this region are vulnerable to adverse effects from even small flow alterations during late spring, summer, and fall low-flow periods. Groundwater pumping, small dams and flow diversions all may reduce baseflow. Larger dams may increase baseflow or reduce this flow depending on how their flows are managed. Channel incision will draw the water table down and agricultural drains will reduce recharge to the groundwater system, while summer irrigation (when using water from distant sources) may increase baseflow. Increased baseflow in urban areas may occur due to watering of gardens and lawns. Many long-time observers of stream conditions in the Napa River watershed suspect there has been a substantial reduction in dry-season low flow over the past 40 years in stream reaches important to steelhead, California freshwater shrimp, and other native aquatic species (USFWS 1968, F. Kerr, pers. comm., 2000, J. Emig and M. Rugg, CDFG, pers. comm., 2001). Despite the presumed adaptation of steelhead to high temperatures in southern portions of their range, the degree to which Napa basin steelhead share these adaptations and can tolerate conditions such as prolonged increases in water temperature and reduced access to preferred habitat is unknown.

Reconnaissance surveys were conducted during the summer of 2000 to assess the general conditions in the basin. These surveys indicated that riffles, and frequently all associated in-channel aquatic habitat, were commonly dry in many tributaries, particularly in alluvial fan areas. During the reconnaissance surveys, behavioral signs of food stress were observed in salmonids over-summering in isolated pools at several locations in Napa River tributaries. It is possible that low summer flows result in a substantial reduction or lack of macroinvertebrate production in riffles and/or isolation of juveniles in adjacent pools from this primary source of food.

Based on the high frequency of very low flows and discontinuously wetted channels (dry riffles alternating with wetted pools) combined with relatively high water temperatures (which increase metabolic demands on the fish) it is possible that lack of food production due to low flows over riffles may result in low or negative growth rates during the summer months. Pilot studies to measure summer growth of juvenile steelhead are discussed in detail later in this chapter. It is also possible that loss of habitat connectivity may subject fish in isolated habitats to greater levels of predation and competition between species, further stressing individuals and populations.

Hypothesis

Because we observed many dry reaches during field surveys conducted in the basin in summer 2000, we hypothesized that completely dry reaches, or reaches with no flow over riffles, were common during the summer-fall dry season.

Study methods

To characterize the pattern of surface flows in the basin and develop a baseline understanding of the extent of channel drying in the basin, we conducted an extensive survey of stream channels in late October to early November 2001, just prior to the onset of winter rains. An analysis of flow data from the St. Helena gage showed that flows at this mainstem site averaged 1.8 cfs (0.05 cms) during the preceding dry months (June through October) in 2001. Flows of this level or greater have been observed at the St. Helena gage in approximately 65 percent of the past 62 years, indicating that the dry season of 2001 was slightly dryer than average. The flow status of each survey reach was qualitatively assigned to one of four “flow states.” These were: (1) “dry” where the channel was completely dry or where the only water present was clearly associated with an artificial in-channel structure, such as a bridge, that caused subsurface flow to come to the surface; (2) "semi-wet" where pools were wet and riffles were dry, thus fragmenting in-channel habitat types; (3) "stagnant" where all habitat units were wet, but there was no noticeable flow between units, thus functionally fragmenting to some degree in-channel habitat; and (4) "flowing" where habitat units were covered with noticeably flowing water between units.

To address whether summer flow reduction and riffle dewatering may limit food availability and growth potential for salmonids, a pilot study of juvenile steelhead growth was conducted in summer 2001. This study is described in Section 6.6. Other hypotheses related to low flows, such as impacts on predation rates, or preventing movement and migration, could not be evaluated in Phase I, but are planned for further study in Phase II.

Results and discussion

We surveyed a total of 148 sites during 2001. Approximately 30 percent of reaches surveyed were fully wetted across all of the habitat units and had noticeable flow (Map 13, Table 6-3). Portions of the alluvial fan/valley floor reaches of all tributaries surveyed were completely or partially dry by the end of the summer/fall low flow period, which was also likely the case historically. Tributaries such as Sulphur and Napa creeks, which flow through urban areas, tended to have more flow than other alluvial fan/valley floor reaches. In general, most streams that were dry started flowing again in the vicinity of the mainstem Napa River, probably as a result of shallower groundwater near the mainstem. While the alluvial fan/valley floor reaches of most tributaries were likely always marginal habitat due to summer drying, even under undisturbed historical conditions, the upland areas of the valley would have always been important for rearing by juvenile steelhead. In our surveys, these areas tended to have more substantial flow than the alluvial fan/valley floor. Only 38 percent of the reaches surveyed, however, exhibited full connection with flow between all habitat units, and 39 percent of reaches were completely dry, thus offering no habitat, while 26 percent of reaches had dry riffles or stagnant water on the riffles, offering only marginal habitat to over-summering salmonids.

Table 6-3. Flow conditions for all sites, alluvial fan/valley floor sites, and upland sites of the Napa River watershed.

Flow Class[1]	Number of Sites	Percentage of Total Number of Sites	Alluvial Fan/Valley Floor Sites	Percentage of All Alluvial Fan/Valley Floor Sites	Upland Sites	Percentage of All Upland Sites
Flowing	44	30%	5	11%	39	38%
Stagnant	26	18%	15	33%	11	11%
Semi-Wet	18	12%	5	11%	13	13%
Dry	60	41%	20	44%	40	39%
Totals	**148**		**45**		**103**	

[1] "Flowing" where habitat units were covered with noticeably flowing water between units; "Stagnant" where all habitat units were wet, but there was no noticeable flow between units; "Semi-wet" where pools were wet and riffles were dry, thus fragmenting in-channel habitat types; and "Dry" where the channel was completely dry or where the only water present was clearly associated with an artificial in-channel structure, such as a bridge, that caused subsurface flow to come to the surface.

The results of this study indicate that channel drying likely substantially reduces the connectivity between habitat units and the amount and quality of habitat available to juvenile steelhead in the tributaries. Channel drying may also interfere with salmonid movement patterns from late spring through early fall. The intensity of water resource development and extent of land cover changes associated with urban, rural, resort, and agricultural uses in the Napa River watershed, and opinions of several long time observers of stream conditions in the basin suggest that baseflow magnitude and persistence may be reduced. The ecological significance of such reductions, the principal mechanisms for baseflow reduction, and potential management solutions (where applicable) warrant future investigation, as proposed for Phase II of this study (see Appendix C).

6.6 Juvenile Steelhead Growth Rates

Growth of juvenile steelhead during rearing in freshwater environments is critical to their success in the marine stage of their life history and to the overall viability of the population. This is due, in large part, to the strong relationship between the size at which steelhead migrate to the ocean as smolts and the probability that the adult returns to freshwater to spawn. In a mark-recapture study on Caspar Creek, a small coastal stream in Mendocino County, Kabel and German (1967) demonstrated an exponential relationship between smolt size at the time of outmigration and chances of successful return as an adult (Figure 6-5). This study indicated that increased size of smolts strongly increased the probably of successful return of adults to the system. The underlying cause of this pattern is probably the intense predation faced by smolts when they enter the marine environment.

Fish growth is controlled by two principal factors: (1) the availability of food; and (2) water temperature, which affects metabolic rate and hence the efficiency of the conversion of food to body tissue. Figure 6-6 illustrates the relationship between food availability, temperature, and growth rates of steelhead in a laboratory experiment in which groups of steelhead juveniles were held at a variety of temperatures and fed different levels of rations (Brett et al. 1969). The data indicate that at a given ration level, increasing temperatures result in increased growth rate up to some optimal point, beyond which growth rates decline.

The most important food source to juvenile salmonids in most streams is invertebrate drift from riffles (Stolz and Schell, 1991). Benthic macroinvertebrate production in riffles is high and fish are able to “drift feed” by establishing feeding stations at the inlets where riffles enter pools and capture prey items effectively with relatively little energy expense. Other potential sources of food include benthic (bottom-dwelling) invertebrates in riffles and pools and terrestrial insects, including those falling from overhanging or adjacent riparian vegetation, all of which typically require substantially more energy expenditure by the fish for foraging than does feeding on invertebrate drift.

Invertebrate production in riffles may be reduced by decreased surface flows over riffles; changes in channel geomorphology (such as sedimentation) that reduce available habitat for benthic macroinvertebrates; and poor water quality due to urban runoff or wastewater discharge that may kill or reduce productivity of primary and secondary consumers. During reconnaissance surveys of tributaries conducted in summer 2000, we observed numerous occurrences of dewatered riffles and isolated pools, some of the latter with dense aggregations of steelhead. These fish showed behavioral signs of food stress, leading to the supposition that food stress may be limiting growth and overall fitness of salmonids. In addition, temperature monitoring during summer 2000 (see Section 6.3) indicated that temperatures reached levels high enough to cause chronic stress and significant increases in fish metabolic rate. Such impacts would be sufficient to impact fish growth. These observations led us to speculate that low surface flows over riffles, whether natural or exacerbated by human activities, combined with high summer temperatures, result in low levels of steelhead food resources during the summer months.

Hypothesis

We hypothesized that high metabolic demands caused by warm water temperatures and limited food supply caused by partial or complete dewatering of riffles combine to severely limit the potential for significant growth during summer months in the Napa River watershed.

Study methods

To test this hypothesis, we conducted a pilot study in summer of 2001 in eight pools located in two Napa River tributaries, including sites believed to have relatively favorable flow conditions. We measured and weighed fish at the beginning of the summer and gave them individual marks. At the end of the summer, fish were recaptured, and growth rates were assessed on an individual basis.

Results and discussion

We documented very limited or negative growth rates for young-of-the-year steelhead at all sites (Figure 6-7), implying that food resources in the study reaches were insufficient in summer 2001 to satisfy metabolic demands. Significant weight loss during the summer may stress fish and lead to subsequently higher mortality during the remaining juvenile rearing period. These findings indicate that reduced prey availability due to dry riffles and increased metabolic costs resulting from warm temperatures could result in smaller smolts, which would be expected to have poor survival during emigration, thereby limiting the production of steelhead in the Napa River watershed. It is currently unknown to what extent feeding and growth during the rest of the year, particularly during spring and fall, might be able to offset the observed lack of good summer growth by juvenile steelhead.

Results of this pilot study indicate that most steelhead lost a significant amount of weight over the course of the study, with only the smallest fish making consistent, but extremely small positive gains. The tendency of the smallest fish to demonstrate consistently positive growth rates while larger fish consistently showed negative growth rates may be an indication of a bioenergetic effect, whereby the energetic cost of pursuing the average prey item is higher for a large fish than for a small fish. Thus, while the energetic return of the average prey item is sufficient to allow growth by small individuals, the return is not sufficient to compensate the higher energetic expenditure by large individuals.

Due to the importance of smolt size in determining probability of return from the ocean for spawning, understanding the role of environmental factors on food availability and fish growth are critical components of Phase II work (see Appendix C), and include the following tasks.

- Investigations of baseflow reduction and hydrograph change;
- Temperature monitoring and modeling to compare current with reference conditions and explore potential effects of riparian vegetation enhancement on stream temperature; and
- Steelhead growth and food availability studies in more streams and during fall and spring as well as summer.

6.7 Distribution and Abundance of California Freshwater Shrimp Habitat

The historical distribution of California freshwater shrimp is unknown, but the species probably once occurred in suitable habitat in most perennial lowland streams in the Marin, Napa, and

Sonoma county areas (USFWS 1998). Biologists believe that widespread alteration of lowland perennial streams has likely resulted in significant reductions in the species' range and abundance. This has led to concern over the persistence of the species, particularly in view of its extremely limited geographic distribution and its listing as a federally endangered species.

The details of the ecology and life history of California freshwater shrimp are not well documented. It appears, however, that all life stages from larvae to adults graze on microbial and/or organic detritus. In terms of physical habitat, California freshwater shrimp require undercut streambanks in quiet, moderately deep (1–3 ft [0.3–0.9 m]) streams with overhanging riparian vegetation, aquatic vegetation, exposed roots and submerged woody debris or live vegetation. The presence of submerged organic material is probably important as a source of cover and also as surface area for microbial and detrital food production on roots and vegetation that extend into the water. The water quality needs of California freshwater shrimp are not well understood, but while the species does not appear to be tolerant of brackish water, it is tolerant of low flows and temperatures as high as 81^{o}F (27^{o}C), at least under laboratory conditions (USFWS 1998).

Review of historical documents and our initial reconnaissance surveys indicate signs of dramatic changes in channel morphology in the Napa River mainstem, which may have altered the abundance or quality of undercut bank habitat for California freshwater shrimp (see Section 6.1). Recently, riparian groundcover, and sometimes canopy vegetation, have been removed by some vineyard managers as a means of controlling the blue-green sharpshooter (*Graphocephala atropunctata*), a vector for Pierce's disease, which attacks grape vines. Overly-aggressive vegetation removal adjacent to California freshwater shrimp habitat is very likely to impair the persistence and recovery of shrimp populations.

Hypothesis

We hypothesized that suitable habitat for California freshwater shrimp in the mainstem channel was limited, and occurred only in discrete patches.

Study Methods

In October 2000, we conducted surveys for potential California freshwater shrimp habitat in six reaches of the mainstem channel between St. Helena and Calistoga, covering a total length of 8.4 miles (13.5 km) (see mainstem survey reaches in Map 9). The purpose of these surveys was to determine the distribution and abundance of potential California freshwater shrimp habitat in the mainstem and identify areas with high concentrations of likely California freshwater shrimp habitat for further focused studies.

Results

We identified a total of 35 sections of undercut bank habitat with some degree of adjacent overhanging vegetation that matched descriptions of suitable habitat for California freshwater shrimp. These sections of undercut bank ranged in length from approximately 6 to 230 ft (2 to 70 m), with an average length of 37 ft (11 m). These surveys indicated that approximately three percent of the channel length (152 ft per mile [28.5 m per km]) in the six reaches surveyed possessed suitable habitat for California freshwater shrimp. Abundance ranged from a high of 340 ft (104 m) of appropriate habitat per mile (distributed among 11 patches in the 0.6-mile [1-km] reach between Deer Park Road and Lodi Lane near St. Helena) to a low of 42 ft per mile (7.9m per km) in six patches (distributed along a 1.6-mile [2.6-km] reach extending from Dunawael

Lane to Lincoln Avenue, near Calistoga). More information is needed to determine how the current distribution, abundance, and quality of habitat compares with historical conditions. In addition, more information is needed on the ecology and life history of California freshwater shrimp to determine how the distribution, abundance and quality of habitat specifically affects population dynamics (see Appendix C for proposed Phase II study of this issue).

7 LIMITING FACTORS SYNTHESIS

In conducting the limiting factors analysis we attempted to: (1) systematically review the life history requirements of each analysis species, (2) identify the full range of potential limiting factors that might be operating to limit these populations in the Napa River watershed, (3) screen these potential limiting factors using available information and initial reconnaissance observations on current watershed conditions to develop hypotheses about those factors thought to be of greatest likely importance in the basin, and (4) test and refine hypotheses using the focused studies described above. Because of limitations in our understanding of current conditions and how limiting factors have operated in the basin, there are various degrees of uncertainty associated with our identification and ranking of key limiting factors for each analysis species. Phase II studies, including a more quantitative population modeling approach to explore the relative importance of potential limiting factors, have been proposed to address what we feel are the most important uncertainties related to restoration and management of aquatic resources in the Napa River watershed.

7.1 Chinook Salmon

The analysis of limiting factors for Chinook salmon production in the mainstem Napa River concludes that human land use activities that have resulted in documented alterations to the Napa River have lead to a dramatic reduction in the potential of the system to support a viable run of Chinook salmon. These alterations to the mainstem include: (1) channel incision; (2) conversion from a river system with zones containing multiple channels with relatively broad floodplains to a confined, single-thread channel, with substantial loss of floodplain area and habitat complexity; (3) conversion of a riffle-pool morphology to a series of long run-pools that provide habitat for exotic predators; and (4) possibly increased mobility of the bed. (See section 6.1.1 of this report for a full discussion of mainstem channel status).

These changes from reference conditions have certainly had dramatic effects on the productivity of Chinook salmon in the system. The Napa River likely supported a large, sustainable population of Chinook salmon under historical conditions. As a result of the various alterations to the mainstem and its floodplain, the Napa River currently has an extremely limited potential to support a viable population of at least 4 to 6 ft (1.2-1.8 m) Chinook salmon. In particular, the dramatic reduction in spawning gravel quantity and quality, coupled with the current high density of exotic predators in the mainstem and loss of off-channel rearing habitat, appear to be the most important limiting factors currently operating in the system. A comparison of the 1940s condition versus current conditions for the various freshwater life history stages of Chinook salmon is provided in Table 7-1.

Table 7-1. Summary of conceptual models and hypotheses developed during this Phase I study regarding historical and current conditions in the mainstem Napa River and their potential effects on various life stages of Chinook salmon.

Life History Stage	1940s Condition	Current Condition
Upstream migration	Upstream migration might have been delayed until first substantial rains (typically in November or December) provided sufficient flow for fish to negotiate bars that created barriers at low flows. The population was probably	Probably similar to historical condition, with fewer bars to negotiate but possibly increased groundwater withdrawals resulting in lower flows (and possibly dry reaches) creating temporary barriers

Life History Stage	1940s Condition	Current Condition
	late fall-run.	
Spawning and incubation	Spawning habitat was relatively abundant, and probably of good quality (but actual quality unknown).	Changes in the geomorphology of the system have resulted in diminished abundance of spawning habitat. Fine sediments in gravels and bed mobility may be increased.
Rearing	Abundant, good quality fry rearing habitat (riffle margins, side channels, sloughs) with abundant food supply likely to have been present in the Napa River. The estuary may have provided important rearing habitat for juvenile Chinook. Some juveniles might have migrated to the estuary for rearing soon after emergence (within 1-2 weeks), while others might have reared in the river until warmer temperatures in late spring or summer triggered migration to the estuary.	Very limited rearing habitat is present in the Napa River (slough, side channel, and riffle margin habitats have decreased substantially). High mortality is likely from exotic predators now found in the dominant long run-pool habitat. Loss and degradation of estuarine habitat may substantially limit the potential for rearing in the estuary. In addition, downstream migration may be limited or prevented by lack of flow (some reaches of the mainstem go dry).
Outmigration	Unlike many Central Valley rivers draining the Sierra Nevada, the natural hydrograph did not include a spring snowmelt runoff peak that would have facilitated outmigration, but outmigrants had only a relatively short distance to travel to reach the bay (and did not require a long journey through the Delta region). Exotic predators were limited or absent. It is possible that warm temperatures occurred during outmigration in some years (such effects would be exacerbated in years when late spawning occurred due to late onset of winter baseflows).	It is likely that outmigrants experience high mortality because of the persistence of exotic predators in the long run-pools now present in the mainstem. There is a possible decrease in spring flows, which were probably already low under historical conditions, caused by water extraction and diversion that might reduce outmigrant success.
Summary of Chinook production potential	Overall, the Napa River likely had relatively high Chinook salmon production, with low fall flows and spring temperatures as the most likely key limiting factors. Likely supported a sustainable population of Chinook.	Currently Chinook salmon production is extremely limited. Spawning gravel quantity and quality, redd scour, reduced riverine and estuarine rearing habitat, and introduced predators are likely key limiting factors. Delayed upstream adult migration caused by low fall flows may also be a key factor limiting production in some years. There is evidence that some, but very limited, successful spawning has occurred in recent years.

7.2 Steelhead

Steelhead probably spawned and reared throughout much of the Napa River system, including the mainstem and the major tributaries, particularly the tributaries on the east side that are now dammed for water supply. The alterations to the mainstem have likely affected steelhead in a fashion similar to that described above for Chinook salmon, although the impact on the overall population should have been proportionately less since the mainstem likely provided a smaller portion of the potential spawning and rearing habitat historically present in the basin.

Our limiting factors analysis for steelhead has therefore focused primarily on the tributaries. Tributaries to the Napa River are generally steep, coarse-bedded channels with limited pools, except those due to obstructions (wood, boulders, bedrock) or bends (see section 6.1.2 of this report for a full discussion of tributary status). Our permeability study shows that under current conditions, fine sediment intrusion into spawning gravels is causing low permeability which likely reduces survival of steelhead eggs and larvae, although our analysis indicates that the decline in steelhead population levels cannot be attributed to this factor alone. In addition, because Phase I focused on current conditions, we have not established whether the observed levels of fines in spawning gravels are due to natural or anthropogenic causes. The sources of fine sediment and the explanation for its high levels in the gravels will be explored in Phase II.

Other documented or inferred alterations to tributaries include numerous dams and road crossings, which serve as barriers or potential impediments to fish passage; reduced LWD levels; and the likely reduction in flow caused by surface water diversion, groundwater pumping, and various other land use activities and changes to the system. Summer water temperatures in the tributaries are generally warm enough to stress juvenile steelhead, although they are not high enough to be lethal. We do not know whether human land use activities have contributed to temperature increases, but we hypothesize that removal or alteration of riparian vegetation coupled with reduced flows due to landuse activities have likely increased summer water temperatures above historical reference conditions. Testing of this hypothesis has been proposed for Phase II.

Alluvial fans may have provided spawning habitat (although they may naturally have tended to be seasonally dry or intermittent), which coupled with estuary or lower mainstem rearing, could have led to high steelhead production under historical conditions. Due mainly to habitat loss caused by channel incision, current conditions do not appear favorable for steelhead spawning in the alluvial fan reaches of tributaries or in the mainstem, and the potential for estuary rearing may have been greatly reduced by diking, dredging, or introduction of exotic predators (although we did not evaluate this during Phase I). Testing of this hypothesis has been proposed for Phase II.

To help synthesize the information collected on steelhead habitat conditions, we conducted a population dynamics modeling exercise based on data collected in Ritchie Creek (Appendix A12). The modeling results indicate that, under current conditions, the combination of limited spawning gravel quantity and low gravel permeability may be limiting steelhead production to some degree. Furthermore, our results indicate that current conditions are near a threshold, such that any substantial decrease in spawning gravel quantity or permeability would tend to lead to a decline in steelhead smolt production.

Our current hypotheses regarding changes from historical conditions and their likely effects on various life stages of steelhead are summarized in Table 7-2.

Table 7-2. Summary of Phase I conceptual models and hypotheses; regarding hypothesized historical and current conditions in the mainstem Napa River and its tributaries and their potential effects on different life stages of steelhead.

Life History Stage	Hypothesized Historical Condition	Current Condition
Upstream migration	*Mainstem.* There were no significant barriers or impediments to upstream migration of spawners. Steelhead return later in the season than fall-run Chinook, hence they would have been less likely to be affected by low flows during years when the onset of winter rains occurred later than normal. *Tributaries*. There were relatively few natural barriers present. LWD formed deep pools, providing holding habitat for spawners.	*Mainstem.* Probably similar to historical condition. *Tributaries.* As a result of dams, road crossings, and numerous other barriers, there are numerous potential barriers or impediments to upstream passage by spawners. Eastside tributaries (particularly tributaries to Conn Creek), which were probably historically important for steelhead production in the system, have been blocked by major dams. Reductions in LWD may have resulted in fewer deep pools and reduced holding habitat for spawners.
Spawning and incubation	*Mainstem.* Similar to Chinook salmon, see Table 7-1. *Tributaries.* The steep tributaries of the Napa River would tend to have relatively limited areas of spawning gravel and poorly developed pools. LWD, however, would provide both, and we hypothesize that historical levels of LWD probably would have retained sufficient patches of gravel with good hydraulics to allow spawners to fully seed the system. It is not known how important alluvial fans were for spawning habitat (see comment below).	*Mainstem.* Similar to Chinook salmon, see Table 7-1. *Tributaries.* We hypothesize that under current conditions, reduced LWD has decreased the quantity and quality of spawning habitat. The relatively rare patches of spawning habitat that are presently available have fine sediment intrusion, which has reduced permeability and survival of steelhead eggs and larvae. Alluvial fans have likely been subject to large-scale incision and alteration, due to urbanization and other development, which may have reduced their value as spawning habitat.
Rearing	*Mainstem.* Similar to Chinook salmon, see Table 7-1. *Tributaries.* Flows were probably lower and temperatures higher than steelhead streams to the north, but the local steelhead race was probably at least partially adapted to cope with these conditions. Flows were probably higher prior to extensive diversions and groundwater pumping, supporting higher production of macroinvertebrates in riffles and thus greater prey abundance for juvenile steelhead. Tributaries to the Napa River were generally steep channels with a coarse bed that provided good over-wintering habitat.	*Mainstem.* Similar to Chinook salmon, see Table 7-1. *Tributaries.* Warm summer temperatures and low food supply appear to severely limit summer growth. We have not assessed the cause of these conditions or whether they differ significantly from historical conditions. Additional studies are needed to test the hypothesis that riparian vegetation clearing or alteration has increased summer water temperatures above historical or pre-development conditions, and that summer flows are lower due to surface and groundwater extraction, leading to the observed summer growth limitation. As a result, the period in which fish can feed and grow is probably limited to the fall and spring. This hypothesis will be tested

Life History Stage	Hypothesized Historical Condition	Current Condition
	Tributaries would have had limited pools except those due to obstructions (LWD, boulders) or bends. However, well-developed forests around tributaries, particularly on the west side of the basin, would have provided large amounts of LWD, leading to increased frequency of deeper pools. The Napa River has a large estuary that would have been available for steelhead rearing. More information is needed to determine the role played by the estuary in steelhead life history.	with additional growth studies during Phase II. Channels tend to have fewer pools due to reduction in LWD levels, but the amount of over-wintering habitat provided by interstitial spaces in coarse substrates is probably about the same as what occurred historically. Turbidity levels during the rainy season do not appear to be limiting juvenile steelhead feeding and growth. The estuary of the Napa River has been dramatically altered by dredging and diking, as well as introduction of exotic species. These activities may have greatly reduced suitability of the estuary for rearing.
Outmigration	*Mainstem.* Similar to Chinook salmon, see Table 7-1. *Tributaries.* Occasional interruption by reaches drying in spring likely occurred under historical conditions.	*Mainstem.* Similar to Chinook salmon, see Table 7-1. *Tributaries.* Outmigration may be interrupted more frequently by early drying of reaches on the alluvial fans due to groundwater pumping and spring frost protection.
Summary of steelhead production potential	Steelhead production would have been high, in general. Production would have been limited occasionally during drought years, but the availability of suitable spawning habitat in both tributaries and the mainstem would have spread risks and reduced the odds of substantial year-class failures.	Steelhead production apparently remains sufficient to maintain a population, although at substantially reduced levels compared to historical conditions. Summer growth of steelhead in tributaries appears to be substantially limited by warm temperatures coupled with limited food supply—a limitation that may be sensitive to water extraction. Reduction in frequency of deep pools, caused by LWD removal, may have reduced carrying capacity of juveniles in the tributaries. Reduction in the abundance of spawning gravel in tributaries, due to LWD removal, has almost certainly occurred. Reduction in gravel permeability as a result of increased fine sediments in gravels may also have occurred. Mainstem spawning and rearing potential has been greatly reduced, while outmigration hazards have increased, similar to that described in Table 7-1 for Chinook salmon.

7.3 California freshwater shrimp

Based on the surveys of the mainstem Napa River conducted during Phase I, potential habitat for California freshwater shrimp appears to be relatively abundant. However, a more quantitative assessment is needed to: (1) link abundance with habitat quality and quantity; (2) determine the distribution of habitat in the Napa River watershed as a whole; and (3) understand the geomorphic processes responsible for forming and maintaining freshwater shrimp habitat. In particular, the importance of overhanging vegetation should be further explored, particularly to assess impacts of cutting back riparian vegetation to minimize blue-green sharpshooter habitat (the vector for Pierce's disease which attacks grapevines).

8 RECOMMENDATIONS

Concern for the short- and long-term health of the Napa River watershed has motivated many individuals, non-profits, and public agencies to either lead, expand, or participate in programs and initiatives focused on protecting, restoring, and enhancing the watershed's beauty, natural resources, agricultural heritage and economic viability. A sampling of the past and current efforts aimed at accomplishing these goals includes: (1) development of Napa County conservation regulations and recent discussions of their modification; (2) establishment of a watershed information center and conservancy; (3) development of a high-resolution vegetation map, high-resolution aerial photography, and topographic mapping (see below) for Napa County; (4) various types of monitoring, including but not limited to steelhead, benthic macroinvertebrates, stream flow, groundwater, barriers to fish passage; (5) projects enacted by landowners alone or as part of a tributary stewardship group, in some cases with assistance from public agencies such as the Napa County RCD and USDA Natural Resources Conservation Service; (6) research about the historical ecology of the watershed; (7) the work of the Napa Sustainable Winegrowing Group; (8) the proposed Green Certification Program for grape growers and ranchers; and (9) the work of the Watershed Task Force.

A critical component of restoration efforts is to develop a more refined understanding of the cumulative effects of land and water use on in-channel habitat and prioritizing and predicting the cumulative outcome of restoration efforts in the Napa Valley. Such restoration efforts could be dramatically improved by use of a detailed model of the physical topography of the watershed. To this end the Regional Board, University of California, and Stillwater Sciences recently applied for, and were awarded, a CALFED grant to develop high-resolution topographic maps and watershed analysis modeling products for the entire Napa River watershed. This effort will provide much information that could be used in the proposed Phase II studies (see Appendix C and below for recommended future studies). This high-resolution mapping project will be completed by June 2003 and could be used to:

- delineate the complete channel network within the watershed, define stream reach types, and predict habitat structure and potential distributions of native fish and aquatic wildlife species;
- identify shallow landslide hazard areas and other important upslope sources of sediment delivery to channels (road crossings, hillslope hollows, deep-seated landslides, etc.);
- measure vegetation height and canopy structure to model stream temperature, estimate potential recruitment of large wood to channels, and evaluate habitat quality, quantity; and diversity for riparian and aquatic species.

These tools should also be tremendously useful to land owners, managers, and the Napa County Planning Department for site-specific to watershed-scale evaluation of the ecological benefits of stream setbacks, and in the identification of hillslope areas that may be susceptible to increases in peak flow and mass wasting that could occur as a result of vineyard, rural residential, resort, or other type of development. The watershed mapping and analyses developed from this project will provide residents and land managers with a common frame of reference, and means for exploring the opportunities and constraints of various land and water management decisions. We expect to make the mapping products available as GIS layers (stream channels, landslide hazard areas, etc.) that could be accessed by the public at the County Assessor's Office.

The recommendations for additional studies and restoration actions presented below (many of which we hope to address in more detail during Phase II of our study, see Appendix C for additional information on the proposed studies) may be facilitated or enhanced through coordination with existing and/or proposed programs, some of which are listed above. For each of the key issues listed below, we have identified important information needs and restoration actions that seem warranted based on currently available information and hypotheses. We expect that local knowledge and experience, conveyed through input from local stakeholders, will enhance and bring specificity to the recommendations provided herein prior to implementation. Although some stakeholders expressed an interest in having us rank these recommendations in terms of priorities, we felt it was premature to develop basin-wide restoration priorities given the current state of our knowledge and scientific uncertainties. The results of future studies, including those currently underway or planned for many tributaries and the Phase II studies we have proposed (see below and Appendix C), should be used to develop a better understanding of restoration needs and priorities for each major tributary and for the mainstem and Napa River watershed as a whole.

8.1 Physical Habitat and Chinook Salmon in the Mainstem Napa River

The mainstem of the Napa River has undergone significant geomorphic transformation, which has converted a system with potentially high salmonid productivity into a system with little potential for salmonid production in the mainstem.

We have identified the following key information needs and studies:

- No further studies to characterize the current state of the mainstem with respect to salmonid spawning have been identified as high priority studies, although further field testing of the redd scour hypothesis and in-depth historical analysis to document pre-European settlement conditions and the extent and timing of channel alternations may be useful (see “Analysis of changes in channel and estuary conditions,” pages C-4 and C-5, and “Population Dynamics Analysis,” page C-6, Appendix C).

- The most significant information gaps relate to the effects of mainstem conditions, including exotic predator populations, on outmigrating steelhead smolts. Monitoring of mainstem fish populations, especially of potential salmonid predators, and mortality of outmigrating smolts would be valuable (see “Mechanistic Studies and Life History Assessments of Analysis Species,” page C-5, Appendix C).

- In addition, assessment of historical and current rearing conditions for juvenile Chinook salmon in the estuary (see “Analysis of changes in channel and estuary conditions,” pages C-4 and C-5, Appendix C) could contribute to an improved understanding of salmonid limiting factors in the Napa Basin and might lead to development of more effective restoration or enhancement strategies.

Given current information, and pending completion of Phase II studies to address the information needs mentioned above, we believe the following actions are warranted:

- Enhancement of Chinook salmon production in the Napa River appears to be of interest to a number of local stakeholders. However, due to the expected high social and economic costs of potential mainstem restoration activities such as riparian and levee setbacks, and gravel augmentation, no immediate actions can be recommended for Chinook salmon restoration without substantial further exploration and discussion regarding what is feasible and desirable to stakeholders. The possibility of creating a

Chinook restoration reach in the lower mainstem, including preliminary development of several alternative strategies, should be considered if there is sufficient stakeholder interest.

- Other recommended mainstem actions are addressed below under California freshwater shrimp habitat.

8.2 Physical Habitat Structure in Tributaries

Deep pools in the tributaries are currently rare. In addition, tributaries tend to retain little spawnable gravel. In pre-settlement channels, large woody debris probably created significant deep pool rearing habitat. Information and actions focused on the effects of enhancing large woody debris levels in tributaries appear warranted.

We have identified the following key information needs and studies:

- Stream surveys should be conducted to quantify the amount and existing physical habitat functions of large wood (these surveys could be conducted by stewardship groups). These surveys could be combined with field surveys of barriers and efforts should be made to reconstruct historical LWD loading. (See “Large woody debris (LWD) assessment” and “Physical barriers to fish passage,” page C-3, Appendix C.)

- Examine how land use, geology, LWD, and dam construction impact sediment supply to tributaries and how this affects the quality and quantity of pools and spawning gravels. (See “Sediment dynamics,” pages C-2 and C-3, Appendix C.)

- In addition, assessment of historical and current rearing conditions for juvenile steelhead in the estuary (see “Analysis of changes in channel and estuary conditions,” pages C-4 and C-5, Appendix C) could contribute to an improved understanding of salmonid limiting factors in the Napa Basin and might lead to development of more effective restoration or enhancement strategies.

Given current information, and pending completion of Phase II studies to address the information needs mentioned above, we believe the following actions are warranted:

- Increase retention of spawning gravels and the abundance of pools and cover in tributaries by adding large woody debris. Measures to add large wood to channels should be actively encouraged, carefully planned, and executed (as appropriate) to promote pool formation and gravel retention in tributaries. The effects of these efforts should be carefully monitored. Careful consideration of potential adverse impacts to downstream structures, such as bridges, that might be caused by movement of large woody debris during high flows is needed prior to implementation of any wood enhancement projects.

- Efforts to enhance woody riparian vegetation are also recommended to help provide potential sources for recruitment of in-channel large woody debris in the future (i.e., through natural processes of tree mortality in the riparian zone).

8.3 Gravel Permeability and Fine Sediment

Low gravel permeability in the Napa River mainstem and tributaries potentially reduces salmonid fry emergence by 50 percent or more. While the quantitative limiting factors analysis example for Ritchie Creek indicates that the benefits of increasing egg/larval survivorship may be limited, this analysis also demonstrates a potentially drastic negative response of steelhead populations to any further reduction in egg/larval survival compared with current conditions.

We have identified the following key information needs and studies:

- Additional permeability studies should be conducted to better characterize variability within and among tributaries and to provide long-term permeability monitoring to track changes over time. (See “Steelhead,” page C-5, Appendix C.)

- Because the system may be near a critical threshold in terms of egg/larval mortality, it is critical the relationship between land use and fine sediment delivery to the channel be characterized as completely as possible. Therefore, a detailed sediment budget should be performed and field studies undertaken to quantify the relationship between different types of land use and the delivery of fine sediment to the channels (See “Sediment dynamics,” pages C-2 and C-3, Appendix C.)

- To improve our understanding of the impact of permeability on the steelhead population in the Napa River watershed, detailed habitat surveys and life history studies are needed to refine and then apply the limiting factors analysis to the whole basin. (See “Steelhead,” page C-5, and “Population Dynamics Analysis,” page C-6, Appendix C.)

Given current information, and pending completion of Phase II studies to address the information needs mentioned above, we believe the following action is warranted:

- Identify opportunities to prevent increased delivery of sediment to channels, and preferably reduce sediment delivery, should be pursued.

8.4 Fish Passage Barriers

Our results indicate that there are a large number of known or potential barriers and impediments to fish passage in the Napa River watershed. The scope of our barrier study was limited so uncertainty remains. However, even if only 25 percent of these sites actually serve as barriers limiting access to suitable habitat, the impact on steelhead production in the basin could be substantial.

We have identified the following key information needs and studies (much of this work should be done in cooperation with local watershed stewardship groups) (see “Physical barriers to fish passage,” page C-3, Appendix C):

- Fully verify and document potential barriers on streams with potentially important salmonid habitat.

- Fully document the extent of suitable habitat and the locations of natural barriers to provide sufficient background for assessing the impact of barriers to help prioritize allocation of resources for barrier removal efforts.

Given current information, and pending completion of Phase II studies to address the information needs mentioned above, we believe the following actions are warranted:

- Considering the potential efficacy of barrier remediation projects, we strongly encourage that barrier remediation projects be emphasized in any strategy to restore the steelhead run. Artificial barriers that block fish access to usable habitat should be identified and removed or made passable, with emphasis given to those barriers obstructing access to large amounts of suitable habitat.

8.5 Effects of Temperature, Food, and Flow on Growth of Juvenile Steelhead

Summer growth rates of juvenile steelhead observed during our pilot study were very low, and in most cases negative, supporting our hypothesis that warm summer temperatures and low food supply (caused by low baseflows and very low or discontinuous flow during the dry season over productive riffle habitats) are important factors limiting steelhead production in the Napa River watershed. Levels of rainy season turbidity measured during our studies did not indicate a significant problem for steelhead, but increases in chronic turbidity beyond the 20 NTU threshold during rainy season baseflows (especially during the fall or spring growth seasons that we hypothesize are particularly critical for steelhead growth) could have adverse impacts on steelhead feeding and growth.

We have identified the following key information needs and studies.

- Further fish growth studies should be conducted in a larger sample of tributaries and extended into the spring and fall to confirm whether or not lack of summer growth is a spatially extensive phenomena, and whether low or negative summer growth can be offset by growth during the spring and fall.

- To improve our understanding of the relationship between flows and fish growth, studies should be performed that involve manipulating flows and measuring fish growth. The relative importance of macroinvertebrate and habitat availability versus temperature should be determined to better define the relationship between flows and fish growth. (See “Steelhead,” page C-5, Appendix C.)

- Studies to assess historical and current levels of baseflow reduction and hydrograph change should be conducted to determine how much land and water use activities have affected summer baseflow levels. This analysis should include potential effects of both surface and ground water pumping on baseflow. (See “Baseflow reduction and hydrograph change,” pages C-3 and C-4, Appendix C.)

- Further turbidity work should be conducted to characterize the turbidity response of the system under a broader range of conditions than was observed in Phase I, and to develop plans for long-term monitoring. (See “Sediment dynamics,” page C-2, and “Steelhead,” page C-5, Appendix C.)

- When they become available, the high-resolution topographic maps and other products to be developed under the CALFED grant should be used to perform GIS and digital terrain computer modeling to identify reaches with high current summer temperatures that might benefit from increased stream shading achieved through enhancement of riparian vegetation. (See “Sediment dynamics,” page C-2, Appendix C.)

Given current information, and pending completion of Phase II studies to address the information needs mentioned above, we believe the following actions are warranted:

- Reduce water temperatures where feasible by increasing stream shading through enhancement of riparian tree cover.

- Explore opportunities to reduce unnecessary or inefficient water use and thus increase summer baseflow in tributaries to increase macroinvertebrate production. (For example, efforts to provide diverters with flow information, through dial-up flow gages, should be funded and the benefits of sustained minimum flows should be monitored.)

- Ensure that potential sources of turbidity, such as sites of mass wasting and active gullies, are not increased or exacerbated.

8.6 Protection of California Freshwater Shrimp Habitat

California freshwater shrimp habitat appears to be relatively well distributed in the Napa River mainstem, at least in the reaches we surveyed. However, we have little knowledge of the current or historical distribution and abundance of this species throughout suitable habitats in the Napa River watershed.

We have identified the following key information needs and studies (see "California freshwater shrimp," pages C-5 and C-6, Appendix C):

- Further surveys to document the distribution and abundance of undercut bank habitat should be conducted in all low gradient valley-floor streams, especially those known to support California freshwater shrimp (i.e., the Napa River, Garnett and Huichica creeks).

- While undercut banks with overhanging vegetation are clearly associated with California freshwater shrimp populations, the relationship between other aspects of habitat quality and production of California freshwater shrimp should be better developed to make restoration actions more focused and efficient.

- Conduct studies to determine the important geomorphic processes creating and/ or maintaining California freshwater shrimp habitat.

Given current information, and pending completion of Phase II studies to address the information needs mentioned above, we believe the following actions are warranted:

- Given the limited knowledge of this species, it is not possible to make detailed recommendations. However, the association of California freshwater shrimp with undercut bank habitat and overhanging vegetation and roots is well documented and protection of this habitat in the mainstem Napa River and tributaries known to support this species (i.e., Garnett and Huichica creeks) should be strongly encouraged. In addition, projects should be promoted that seek to retain or establish riparian vegetation that extends to the water's edge. Opportunites to develop riparian setbacks and conservation easements should be encouraged. Given the potential cost of such actions, however, better information on California freshwater shrimp habitat and population density may be required to help determine which areas might yield the greatest ecological benefits per unit cost.

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