Working Draft Scientific Basis Report for New and Revised Flow Requirements on the Sacramento River and Tributaries, Eastside Tributaries to the Delta, Delta Outflow, and Interior Delta Operations

Prepared By:

State Water Resources Control Board
California Environmental Protection Agency
P.O. Box 100
Sacramento, CA 95812-0100

With Assistance From:

ICF
630 K Street, Suite 400
Sacramento, CA 95814

October 2016

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Acronyms and Abbreviations

2009 Delta Reform Act	Sacramento-San Joaquin Delta Reform Act of 2009
2009 Staff Report	2009 Periodic Review Staff Report
7DADM	7-day average of daily maximum
AF	acre-feet
AFRP	Anadromous Fish Restoration Project
BAFF	bio-acoustic fish fence
Bay Study	San Francisco Bay Study
Bay-Delta	San Francisco Bay/Sacramento-San Joaquin River Delta Estuary
Bay-Delta DPS	Bay-Delta distinct population segment
Bay-Delta Plan	Water Quality Control Plan for the San Francisco Bay/Sacramento-San Joaquin Delta Estuary
BO	biological opinion
CAMT	Collaborative Adaptive Management Team
CCF	Clifton Court Forebay
CCV	California Central Valley
CCWD	Contra Costa Water District
CDEC	California Data Exchange Center
CDFW	California Department of Fish and Wildlife
CEQA	California Environmental Quality Act
CESA	California Endangered Species Act
CSAMP	Collaborative Science and Adaptive Management Program
CVP	Central Valley Project
CVPIA	Central Valley Project Improvement Act
CWT	coded wire tag
D-1644	State Water Board Decision 1644
D-893	State Water Board adopted Decision 893
DCC	Delta Cross-Channel
DEFG	Delta Environmental Flows Group
Delta	Sacramento-San Joaquin Delta
DETAW	Delta Evapotranspiration of Applied Water
DICU	Delta Island Consumptive Use
DJFMP	Delta Juvenile Fish Monitoring Program
DMC	Delta-Mendota Canal
DO	dissolved oxygen
DPIIC	Delta Plan Interagency Implementation Committee
DPS	distinct population segment
DSP	Delta Science Program

DWR	Department of Water Resources
EBMUD	East Bay Municipal Utility District
EC	salinity
EIR	environmental impact reports
ERI	eight river index
ESA	federal Endangered Species Act
ESU	evolutionary significant unit
F	Fahrenheit
FERC	Federal Energy Regulatory Commission
FERC	Federal Energy Regulatory Commission
FFGS	floating fish guidance structure
FMWT	fall midwater trawl
FMWT	Fall Midwater Trawl
FRFH	Feather River Fish hatchery
GLC	Grant Line Canal
HORB	Head of Old River Barrier
IEP	Interagency Ecological Program
IPM	Integrated Pest Management
IRP	Independent Review Panel
ISB	Independent Science Board
ISR	independent science review
ITP	Incidental Take Permit
ITP	incidental take permit
JSA	Joint Settlement Agreement
km	kilometer
LSNFH	Livingston Stone National Fish Hatchery
LSZ	low salinity zone
MAF	million acre-feet
MR	Middle River
MRDO	minimum required Delta outflow
NDO	net Delta outflow
NDOI	net Delta outflow index
NDOI	Net Delta Outflow Index
NH_3	un-ionized ammonia
NH_4	ammonium
NMFS	National Marine Fisheries Service
NTU	Nephelometric Turbidity Units
OC	Organochlorine
OCAP	Operational Criteria and Plan
OMR	Old and Middle River

ORT	Old River near Tracy
PCB	polychlorinated biphenyls
Projects	CVP and SWP
PTM	particle tracking model
RBDD	Red Bluff Diversion Dam
RBDD	Red Bluff Diversion Dam
Reclamation	U.S. Bureau of Reclamation
Report	Scientific Basis Report
SacWAM	Sacramento Water Allocation Model
SED	substitute environmental documentation
SEI	Stockholm Environment Institute
SKT	Spring Kodiak Trawl
SMP	Suisun Marsh Habitat Management Preservation, and Restoration Plan
SST	Salmonid Scoping Team
State Water Board	State Water Resource Control Board
STN	Summer Townet Survey
SVUFM	Sacramento Valley Unimpaired Flow Model
SWP	State Water Project
TAF	thousand acre-feet
TBI	The Bay Institute
TCP	temperature compliance points
TMDLs	total maximum daily loads
USACE	U.S. Army Corps of Engineers
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
WEAP	Water Evaluation and Planning

Chapter 1
Overview

1.1 Introduction

The State Water Resource Control Board's (State Water Board) mission is to preserve, enhance, and restore the quality of California's water resources and drinking water for the protection of the environment, public health, and all beneficial uses, and to ensure proper water resource allocation and efficient use, for the benefit of present and future generations. The State Water Board protects water quality that affects beneficial uses of water in the San Francisco Bay/Sacramento-San Joaquin River Delta Estuary (Bay-Delta) in part through its Water Quality Control Plan for the Bay-Delta (Bay-Delta Plan). The State Water Board is reviewing and updating the 2006 Bay-Delta Plan to ensure that Bay-Delta beneficial uses are reasonably protected.

This working draft Scientific Basis Report (Report) is being prepared to support the update of the Bay-Delta Plan's protection of fish and wildlife beneficial uses in the Sacramento River watershed and related areas, known as Phase II.[1] This update considers four categories of requirements: (1) new inflow requirements for the Sacramento River, its tributaries, and eastside tributaries to the Delta; (2) changes to Delta outflow requirements; (3) new and modified interior Delta flow requirements; and (4) new requirements for cold water habitat. A comprehensive regulatory approach is needed that protects Bay-Delta fish and wildlife throughout their migratory range, and that better integrates the regulatory framework addressing inflows, outflows, and water project operations. Such a framework will help avoid overreliance on one stream to meet flow and other water quality requirements by providing necessary flows on multiple tributaries to ensure suitable habitat and migratory pathways upstream of the Bay-Delta. Another goal is to employ a strategy that provides for timely action, flexibility, and integration with other planning, science, restoration, and regulatory efforts so action can be taken before imperiled species in the watershed are no longer able to be restored.

The Report identifies the best available science that supports potential changes to the Bay-Delta Plan. The Report is being circulated to obtain early input on the science supporting potential changes to the Bay-Delta Plan flow and water project operational requirements, including input from the Delta Independent Science Board (ISB), in keeping with the principle of "one Delta, one science" articulated in the Delta Science Plan. Based on the comments received on the working draft, the State Water Board will update the Report and prepare a final draft Report that will be submitted for external peer review pursuant to Public Health and Safety Code section 57004.

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[1] In a separate process, referred to as Phase I, the State Water Board is reviewing and considering updates to other elements of the Bay-Delta Plan, including flow requirements on the Lower San Joaquin River and salinity requirements in the southern Delta. The term "*Phase*" to describe these different processes is used for administrative convenience to distinguish the different proceedings. The two water quality proceedings, Phase I and Phase II, for example, involve different water quality objectives, largely different geographic areas, and can be developed and implemented independently of each other.

Phase II is in its early stages and there will be additional opportunities for public participation and comment as the planning process moves forward. The State Water Board will need to consider all other beneficial uses in the update, including municipal, industrial, agricultural, power production, and other environmental uses (including wetland and wildlife refuge supplies)).

In keeping with the State Water Board's authority and responsibility to protect the quality of the waters of the state and the beneficial uses of those waters, this Bay-Delta Plan update focuses largely on flow-related issues. The State Water Board recognizes, however, that other actions are important to protect the Bay-Delta ecosystem, such as habitat restoration. The State Water Board will work cooperatively with other agencies and organizations to promote such actions, which may or may not be within the State Water Board's authorities. The program of implementation will further address these actions in recommendations to other entities, and describe the tools that the State Water Board will employ to ensure that needed non-flow measures are pursued, including those that may result in the need for less flow to achieve the protection of fish and wildlife (e.g., temperature control may be achieved with a temperature control device more efficiently than through flow alone).

The State Water Board's Bay-Delta planning and implementation efforts are part of a multi-facetted approach needed to address ecological and water supply concerns in the Bay-Delta and reconcile an altered ecosystem. The State Water Board is committed to collaborating and coordinating with other science, regulatory, and restoration efforts that inform adaptive management and future decisions regarding needed flows and operational measures. The State Water Board also encourages the ongoing efforts of various parties to develop meaningful and effective voluntary agreements that can achieve greater and more durable benefits for the Bay-Delta in the short and long term than regulation alone.

1.1.1 The Bay-Delta Watershed

The Bay-Delta is a critically important natural resource for California and the nation. It is both the hub of California's water supply system and the most valuable estuary and wetlands on the western coast of the Americas. The Bay-Delta includes the Sacramento-San Joaquin Delta (Delta), Suisun Marsh, and the San Francisco Bay. The Delta is about 738,000 acres of which about 48,000 acres are riverine and Delta freshwater surface area; Suisun Marsh comprises approximately 85,000 acres of marshland and water ways; and San Francisco Bay includes about 306,400 acres of water surface area. The Delta and Suisun Marsh are located where California's two major river systems, the Sacramento and San Joaquin Rivers, converge to flow westward, meeting incoming seawater from the Pacific Ocean through San Francisco Bay.

The Sacramento and San Joaquin river systems drain water from about 40 percent of California's land area and support a variety of beneficial uses of water, including: drinking water for more than two thirds of Californians; numerous ecologically, commercially, and recreationally important species; and irrigation of millions of acres of productive farmland. The Bay-Delta Estuary is one of the largest and most important estuarine ecosystems for fish and waterfowl production on the Pacific Coast of the United States. About 90 species of fish are found in the Delta. The tributaries to the Delta and the Delta channels serve as spawning grounds, migratory corridors and nursery areas for numerous native species, several of which are listed as threatened or endangered under the

California Endangered Species Act (CESA) and under the federal Endangered Species Act (ESA), including four runs of Chinook salmon, white and green sturgeon, steelhead, Sacramento splittail, Delta smelt, and longfin smelt.

1.1.2 Purpose and Need for Bay-Delta Update

It is widely recognized that the Bay-Delta ecosystem is in a state of crisis. Changes in land use from natural landscapes to agriculture and urbanization combined with development of an extensive water management infrastructure, including the construction and operation of two large water projects, the Central Valley Project (CVP) and State Water Project (SWP) (collectively referred to as Project(s)), have been accompanied by declines in nearly all species of native fish. Fish species have not shown signs of recovery since adoption and implementation of the 1995 Bay-Delta Plan intended to protect fish and wildlife. In the early 2000s, scientists noted a steep and lasting decline in population abundance of several native estuarine fish species that has continued and worsened during the recent drought. Likewise, Central Valley salmon and steelhead have not recovered, and natural production of all runs remains near all-time lows.

While natural conditions have not existed in the Bay-Delta watershed for more than a hundred years, many of the native fish and wildlife species maintained healthy populations until the past several decades when water development intensified. In some streams, at certain times, flows are completely eliminated or significantly reduced. At other times, flows are increased, but then exported before contributing to Delta outflows. At the same time, the dams that impound that water block access to upstream habitat and may cause significant warming of flows. Further, Project operations in the southern Delta have altered water flow circulation patterns, leading to adverse transport flows, changes in water quality, degradation of Delta habitats, and entrainment of fish and other aquatic organisms. A significant and compelling amount of scientific information indicates that restoration of natural flow functions are needed now to halt and reverse the species declines in an integrated fashion with physical habitat improvements.

Upstream diversions and water exports in the Delta have reduced January to June outflows by an estimated 60 percent (average), and annual outflow by an estimated 48 percent (mean). Studies of river-delta-estuary ecosystems in Europe and Asia conclude that water quality and fish resources deteriorate beyond their ability to recover when spring and annual water withdrawals exceed 30 and 40-50 percent of unimpaired flow respectively (Rozengurt et al. 1987). Fish and wildlife have been significantly impacted by these reductions of flow, with many species currently on the verge of extinction. As discussed in Chapter 4, while there are also other factors involved in the decline of these species, water diversions and the corresponding reduction in flow are significant contributing factors for which the State Water Board has regulatory responsibility to address. As such, the proposed changes to the Bay-Delta Plan are focused on flow-related issues while also acknowledging the importance of coordination with other science, planning and regulatory and restoration efforts (discussed below) to address the Bay-Delta ecosystem as whole.

While various state and federal agencies have acted to adopt requirements to protect the Bay-Delta ecosystem, there is no comprehensive regulatory strategy addressing the watershed as a whole. Instead, there are various regulatory requirements that cover some areas of the watershed and not others. Many of these requirements are the sole responsibility of the Projects under the Bay-Delta

Plan, as implemented through Revised Water Right Decision 1641 (D-1641) and two biological opinions addressing Delta smelt and salmonids. The best available science, however, indicates that these requirements are insufficient to protect fish and wildlife. Further, these requirements address only portions of the watershed; there are a number of tributaries that do not have any requirements to protect fish and wildlife or that have requirements that are not integrated with other requirements such as the Bay-Delta Plan and CESA and ESA requirements. While conditions may be protective of fish and wildlife in some of these tributaries, action is needed to ensure that conditions are not degraded in the future. This Bay-Delta Plan update is intended to begin to address these issues in a more comprehensive way by looking at the Sacramento River watershed and related tributaries and Delta as a whole.

1.1.3 Bay-Delta Water Quality Control Planning Background

The State Water Board has authority to adopt statewide water quality control plans and adopts the Bay-Delta Plan because of its importance to the ecosystem and as a major water supply for the state. The Bay-Delta Plan addresses water diversions and use in the water quality planning context, in accordance with the state Porter-Cologne Water Quality Control Act and other laws. The current Bay-Delta Plan requirements were established in 1995 based in part on an agreement between State and federal agencies regarding measures for ecosystem protection in the Bay-Delta estuary. The State Water Board updated the 1995 Bay-Delta Plan in 2006 with minor modifications.

The Bay-Delta Plan identifies various beneficial uses of water in the Bay-Delta and establishes water quality objectives designed to protect those uses. Certain objectives are expressed as flows and others as salinity (electrical conductivity or chloride) and dissolved oxygen levels that are largely achieved through flows and Project operations. The Bay-Delta Plan also includes narrative fish and wildlife protection objectives for salmon and Suisun Marsh. The Bay-Delta Plan includes a program of implementation identifying how the objectives will be achieved, including a description of actions necessary to achieve the objectives, a time schedule for taking the actions, and measures to determine compliance with the objectives.

Currently, the Department of Water Resources (DWR) and U.S. Bureau of Reclamation (Reclamation) are the primary water users responsible for meeting Bay-Delta Plan objectives under D-1641, including existing Delta inflow, outflow, and salinity objectives, and Project export limits and Delta Cross-Channel (DCC) Gate operation requirements. . In D-1641, the State Water Board accepted various agreements between DWR and Reclamation and other water users to assume responsibility for meeting specified Bay-Delta Plan objectives for a period of time through conditions on DWR and Reclamation's water rights for the SWP and CVP, respectively.

In 2008, the State Water Board adopted the 2008 Bay-Delta Strategic Workplan, which prioritized State Water Board, Central Valley Regional Water Quality Control Board and San Francisco Bay Regional Water Quality Control Board Bay-Delta planning and regulatory activities to address environmental and water supply crises in the Bay-Delta, including the review and update of the Bay-Delta Plan. In 2009, the State Water Board conducted a periodic review of the Bay-Delta Plan, and prepared a Periodic Review Staff Report (2009 Staff Report) recommending further review of the following: (1) Delta outflow objectives, (2) export limit objectives, (3) DCC Gate closure objectives, (4) Suisun Marsh objectives, (5) potential new reverse flow objectives for Old and Middle Rivers, (6) potential new floodplain habitat flow objectives, (7) potential changes to the monitoring and special studies program, and (8) other potential changes to the program of implementation. In the 2010 Delta Flow Criteria Report, discussed in more detail below, the State Water Board found that inflows should generally be provided from tributaries to the Delta watershed in proportion to their contribution to unimpaired flows to provide for continuity and diversification of flows and increased Delta outflows for migratory and estuarine species.

1.1.4 The Delta Reform Act and Delta Flow Criteria Report

The Legislature acknowledged the ecosystem crisis in the Delta watershed in adopting the Sacramento-San Joaquin Delta Reform Act of 2009 (2009 Delta Reform Act) (Wat. Code, § 85000 et seq.). The 2009 Delta Reform Act established "coequal goals" for the Delta of providing a more reliable water supply for California and protecting, restoring, and enhancing the Delta ecosystem, all in a manner that preserves, protects and enhances its unique agricultural, cultural, and recreational characteristics. (Wat. Code, § 85054.) The Delta Stewardship Council, established under the Delta Reform Act, has identified updating the Bay-Delta Plan flow and water quality requirements as an important element in protecting the Delta ecosystem and the reliability of the Delta's water supplies. The Delta Stewardship Council's Delta Plan (DSC 2013) specifically calls for adequate seaward flows in Delta channels, on a schedule more closely mirroring historical rhythms (natural, functional flows), and specifically identifies the State Water Board as the agency charged with this task under its water rights and water quality authority.[2] In addition, the California Water Action Plan, which establishes actions to sustainably manage California's water resources, identifies completion of the Bay-Delta Plan update as a key element to achieve the coequal goals for the Delta.

To inform the State Water Board's review and update of the Bay-Delta Plan and other efforts, in August 2010, the State Water Board completed a technical report on the "Development of Flow Criteria for the Sacramento-San Joaquin Delta Ecosystem" (Delta Flow Criteria Report) pursuant to the requirements of the Delta Reform Act. The Delta Flow Criteria Report included a number of findings germane to the State Water Board's Bay-Delta Plan update, including the following:

- The effects of non-flow changes in the Delta ecosystem, such as nutrient composition, channelization, habitat, and invasive species, need to be addressed and integrated with flow measures.
- There is sufficient scientific information to support the need for increased flows to protect public trust resources; while there is uncertainty regarding specific numeric criteria, scientific certainty is not the standard for agency decision making.
- Recent Delta flows are insufficient to support native Delta fishes for today's habitats. Flow modification is one of the immediate actions available although the links between flows and fish response are often indirect and are not fully resolved. Flow and physical habitat interact in many ways, but they are not interchangeable.

[2] On June 24, 2016, the Sacramento Superior Court ruled to set aside the Delta Plan and any applicable regulations until specified revisions are completed to include quantified or otherwise measurable targets associated with achieving reduced Delta reliance, reduced environmental harm from invasive species, restoring more natural flows, and increased water supply reliability. The decision has been appealed.

The Delta Flow Criteria Report included the following non-regulatory criteria:

- 75% of unimpaired Delta outflow from January through June;
- 75% of unimpaired Sacramento River inflow from November through June;
- increased fall Delta outflow in wet and above normal years;
- fall pulse flows on the Sacramento River; and
- criteria in the Delta to help protect fish from mortality in the central and southern Delta resulting from operations of the Projects.

The Delta Flow Criteria Report further found that flow criteria should reflect the frequency, duration, timing, and rate of change of flows, and not just volumes or magnitudes, thus many of the criteria were expressed as a percentage of the unimpaired hydrograph. The report further found that inflows should generally be provided from tributaries to the Delta watershed in proportion to their contribution to unimpaired flow and that studies and demonstration projects for, and implementation of, floodplain restoration, improved connectivity and passage, and other habitat improvements should proceed to provide additional protection of public trust uses and potentially allow for the reduction of flows otherwise needed to protect public trust resources in the Delta. The report also found that it is important to establish seaward gradients and create more slough networks with natural channel geometry. The report emphasizes the importance of a strong science program and a flexible management regime in implementing flow requirements.

The 2010 Delta Flow Criteria Report did not take into account the effect that the identified criteria for the protection of fish resources would have on other uses of water. The requirements that are developed for Phase II will provide reasonable protection of fish and wildlife resources, including cold water habitat for anadromous fishes, with consideration of other uses of water, including municipal, industrial, agricultural, power production, and other environmental uses such as wetland and refuge water supplies. Additional analyses will inform the State Water Board's determination in Phase II.

1.1.5 Science and Technical Workshops to Inform Phase II

To further inform the Bay-Delta Plan update, the State Water Board held a series of three informational workshops in 2012 to receive additional information and conduct discussions regarding the scientific and technical basis for potential changes to the Bay-Delta Plan. The workshops focused on (1) Ecosystem Changes and the Low Salinity Zone, (2) Bay-Delta Fishery Resources, and (3) Analytical Tools for Evaluating the Water Supply, Hydrodynamic, and Hydropower Effects of the Bay-Delta Plan. Each workshop included the participation of an independent expert panel organized by the Delta Stewardship Council's Delta Science Program (DSP), technical presentations by panels representing interested parties, and public comment. The workshops were summarized in a report that focused on identifying areas of agreement, disagreement, and uncertainty (ICF 2013). Based on a recommendation from DSP, the State Water Board collaborated with DSP to hold two independent science workshops on Delta Outflows and Related Stressors (February 2013; summarized in Reed et al. 2014) and Interior Delta Flows and Related Stressors (April 2014; summarized in Monismith et al. 2014). An additional independent science workshop was held by the California Department of Fish and Wildlife (CDFW), DSP, and the National Marine Fisheries Service (NMFS) to address Fish Predation on Central Valley Salmonids in the Bay-Delta Watershed (July 2013; summarized in Grossman et al. 2013). The information presented in each of these workshops as well as the summary reports have informed the development of this Report. Numerous parties participated and contributed valuable input in the workshops and other processes described above. The State Water Board appreciates the continued efforts and public input as reconciliation of the Bay-Delta ecosystem will require an unprecedented level of coordination and cooperation with interested parties, including the DSP, fisheries and water management agencies, water users, environmental groups, and other parties.

1.2 Working Draft Scientific Basis Report

The Report provides a review and summary of the best available science supporting potential changes to the Bay-Delta Plan's flow and operational requirements, building on science contained in the Delta Flow Criteria Report. While perfect science is not available and exact mechanisms behind flow-related functions are not fully understood, there is a significant and compelling amount of information supporting the need for additional flow and related measures to protect fish and wildlife beneficial uses in the Bay-Delta, one of the most widely studied estuaries in the world. Adaptive implementation processes will be included in the program of implementation to ensure flexibility in managing flows on a real-time and long-term basis to best protect beneficial uses and to better respond to evolving scientific information.

This Chapter (Chapter 1) introduces the Report and provides a summary of its major findings. Chapter 2 provides an analysis of the flow regime within the Sacramento River and its tributaries, the Delta eastside tributaries, and the Delta, including how the magnitude, frequency, duration, timing, and rate of change of flows in these streams have been altered. Chapter 3 provides a summary of the underlying science supporting the need for flow and flow-related operational requirements for the protection of fish and wildlife beneficial uses. This chapter includes general information regarding the ecological needs for flows, life history information and population information for several indicator fish species of concern and information about flow needs for these species focused on population growth. Chapter 4 summarizes the various categories of other aquatic ecosystem stressors in the Bay-Delta Watershed, and how stressors interact in the ecosystem. Chapter 5 describes how the biological and hydrologic information provided in earlier sections of the Report were synthesized to develop potential modifications to the Bay-Delta Plan. To assist the State Water Board in evaluating a range of unimpaired flows, the Report compares a range of flows with multiple species needs to identify the range of protection that could be achieved at different flow levels. These protections could be enhanced through targeted adaptive management and when combined with other measures.

1.3 Potential Modifications to the Bay-Delta Plan

Following is a summary of the requirements that are recommended to be modified in the Bay-Delta Plan to reasonably protect fish and wildlife beneficial uses as well as a brief discussion regarding how these proposed changes interact with other related processes. The exact changes that will be recommended to the Bay-Delta Plan have not yet been developed, but the general categories of changes are summarized below. Based on agency and public comments on the working draft Report, the State Water Board will further develop changes to the Bay-Delta Plan to be included in the final draft Report that is submitted for peer review. The potential proposed changes to the Bay-Delta Plan will be determined based on the final Report and environmental, economic and other analyses prepared to determine what is reasonably needed to protect fish and wildlife. The categories of potential changes to the Bay-Delta Plan include: Sacramento River and Delta eastside tributary (Mokelumne, Cosumnes, and Calaveras Rivers) inflows, Delta outflows, cold water management and interior Delta flows. To the extent that existing Bay-Delta Plan requirements are not mentioned, no changes are recommended to those requirements at this time.

1.3.1 Coordination with other Science, Planning and Regulatory Efforts

The Report includes various recommendations for considering potential modifications to Bay-Delta Plan requirements that are related to other planning, science and regulatory efforts. Specifically the Report includes recommendations that are similar to requirements included in the 2008 U.S. Fish and Wildlife Service (USFWS) and 2009 NMFS biological opinions (BO) on the Long-Term Operational Criteria and Plan (OCAP) for coordination of the CVP and SWP (USFWS BO and NMFS BO respectively) and the 2009 CDFW's Incidental Take Permit for longfin smelt issued to DWR for the on-going and long-term operation of the SWP (CDFW ITP). Any Bay-Delta Plan requirements that are related to the BOs, ITP or other regulatory requirements are proposed to be coordinated to avoid unnecessary redundancy and inefficiencies while ensuring that the State Water Board meets its obligations to reasonably protect fish and wildlife beneficial uses.

In addition to having the ISB review the working draft Report, the State Water Board is also planning to have the hydrologic model that will be used to inform the Phase II Bay-Delta Planning efforts reviewed through DSP. The State Water Board will continue to coordinate with the DSP and ISB as appropriate through completion and implementation of updates to the Bay-Delta Plan. The State Water Board is also committed to collaborating and coordinating with other science efforts including the Delta Plan Interagency Implementation Committee (DPIIC), Interagency Ecological Program (IEP), the Collaborative Science and Adaptive Management Program (CSAMP) and other efforts. In particular, the State Water Board is interested in input from these groups on adaptive management, monitoring, reporting and analysis efforts.

The State Water Board recognizes that ecosystem recovery in the Delta depends on more than just adequate flows, and that a multi-faceted approach is needed to address Delta concerns and reconcile an altered ecosystem. The 2006 Bay-Delta Plan recognized that there are ongoing efforts by State agencies, the federal government, and agricultural, urban, and environmental interests to identify, fund, and implement measures to address multiple other aquatic ecosystem stressors, including improving fisheries management, addressing invasive and nonnative species, and restoring and protecting habitat. As part of this update process, many parties provided significant amounts of information regarding other aquatic ecosystem stressors and potential actions. This information will help inform revisions to Bay-Delta Plan, including recommendation to other entities. There are various planning and implementation activities that are underway or currently being planned by other agencies that the State Water Board also plans to coordinate and collaborate with including measures included in the: California Water Action Plan; species Recovery Plans required by the ESA; California ECORestore; the Water Quality, Supply, and Infrastructure Improvement Act and others. Successful implementation of these activities is expected to complement the State Water Board's water quality control planning and implementation efforts and will inform adaptive management decisions regarding needed flows and operational measures.

1.3.2 Use of Unimpaired Flows, Adaptive Management and Biological Goals

As with the State Water Board's update of the San Joaquin River flow objectives in the Bay-Delta Plan, for the purpose of developing and implementing regulatory requirements, this Report proposes the use of unimpaired flows and adaptive management that is informed by monitoring, reporting and evaluation activities to assess success at achieving identified biological goals to protect fish and wildlife. In a regulatory setting, use of unimpaired flows allows the State Water Board to allocate a certain amount of the available supply of a stream to the environment in order to balance the need for flows with other uses of water for human purposes. While unimpaired flows are not natural flows, they can be used to provide for more natural functional flows, especially when implemented in an adaptive management framework. The use of unimpaired flows is discussed further in Chapter 5 of this Report. When combined with the proposed adaptive management provisions, unimpaired flows can be sculpted to provide maximum benefits to fish and wildlife, including targeted pulses to cue migration, summer cold water releases, base flows and other functions. The recommended adaptive implementation provisions would also allow for flow to be increased or decreased within a specified range depending on success at achieving biological goals. Biological goals will incorporate "SMART" (specific, measurable, achievable, relevant and time bound) principles and will be tied to controllable factors within specific watersheds. The specific implementation parameters for use of unimpaired flows, adaptive management and biological goals will be provided in the draft proposed water quality objectives and program of implementation language.

1.3.3 Tributary Inflows

The Report describes the science supporting recommended inflow requirements for tributaries to the Sacramento River basin and Delta eastside tributaries to protect fish and wildlife beneficial uses. These tributaries are displayed in Figure 1.3-1.

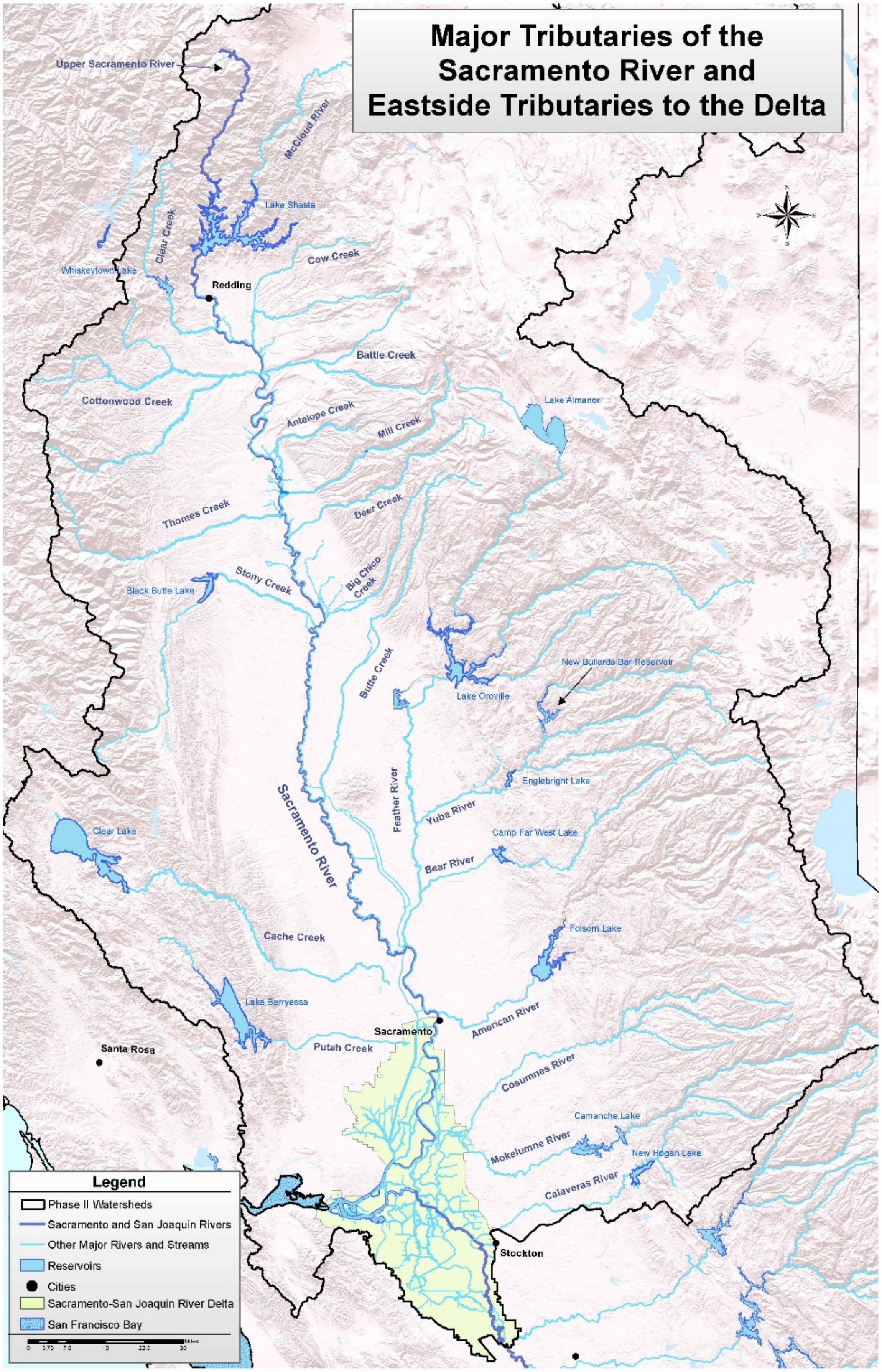


Figure 1.3-1. Major Tributaries of the Sacramento River and Eastside Tributaries to the Delta

Inflows to the Bay-Delta are highly modified by upstream water withdrawals and releases for water supply, power production, and flood control, as well as by channel modifications and obstructions, in ways that adversely affect fish and wildlife. Currently, there are no inflow requirements included in the Bay-Delta Plan for the Phase II area with the exception of minimal fall Sacramento River inflow requirements at Rio Vista. Existing outflow requirements result in inflows; however, only the Projects are responsible for those requirements and the means by which the Projects achieve those requirements and other Project purposes can be incompatible with other fish and wildlife needs within the tributaries, including preservation of cold water resources. There are some flow requirements for other tributaries, but those requirements are not consistent between tributaries or coordinated with Bay-Delta Plan Delta outflow requirements. Some tributaries also have no environmental flow requirements at all. While conditions may currently be protective of fish and wildlife in some of these tributaries, flow requirements may be needed to prevent future impacts to fish and wildlife. In addition, some of these tributaries may dry up at times of year due to the lack of flow requirements and others may have inadequate flow and water quality conditions to protect fisheries resources. Accordingly, the science and recommendations for inflows, outflows and project operations are necessarily interconnected to the extent possible.

With respect to inflow, the Report describes how year-round inflows are needed to protect anadromous and other fish and wildlife species that inhabit the Bay-Delta and its tributaries throughout the year as juveniles or adults. Those inflows are needed to provide appropriate habitat conditions for migration and rearing of anadromous fish species (primarily Chinook salmon and steelhead) that inhabit the Delta and its tributaries all year. Those flows are also needed to contribute to Delta outflows to protect estuarine species.

The Report specifically finds that flows are needed that more closely mimic the conditions to which native fish species have adapted, including the frequency, timing, magnitude and duration of flows, as well as the proportionality of flows from tributaries. These flow attributes are important to protecting native species populations by supporting key functions including floodplain inundation, temperature control, migratory cues, reduced stranding and straying and other functions. Providing appropriate flow conditions throughout the watershed and throughout the year is critical to genetic and life history diversity that allows native species to distribute the risks that disturbances from droughts, fires, disease, food availability and other natural and manmade stressors present to populations. Given the altered physical and hydrologic state of the watershed, the Report acknowledges that adaptive management should be provided to maximize the effectiveness of flow measures and to respond to additional science and changing conditions.

The Report includes recommendations for year-round Sacramento River mainstem and tributary and Delta eastside tributary inflow requirements to protect native fish and wildlife species rearing in and migrating through tributaries and to contribute to Delta outflows needed to protect estuarine and anadromous species. The Report recommends that inflow requirements be established as a percent of unimpaired flow from the mainstem Sacramento River and Sacramento and Delta eastside tributaries that could be adaptively managed within established parameters through the year to achieve critical functions (e.g., pulses, base flows) within the tributaries and downstream (connectivity, contribution to outflow needs, etc.). Similar to the proposed Phase I changes to the Bay-Delta Plan and in recognition of the complexities of the watershed and changing conditions, the Report recommends use of a range of unimpaired flows. The range would accommodate specific instream flow needs within different tributaries and provide for the implementation of non-flow measures that could reduce the need for flows within the range. Adaptive management of inflows is recommended to be conducted within yet to be developed parameters in coordination with the Delta outflow requirements described below. In tributaries where flows are already adequate to achieve the requirements, the requirements would ensure that flows are not reduced below protective levels. In tributaries where flows are above requirements and those higher flows are needed to protect fish and wildlife the Report includes a recommendation that those flows be held at that level.

The numeric alternatives currently under development fall within the range of 35 to 75 percent of unimpaired flow and will be further refined with modeling to evaluate needs to reserve cold water in storage and other considerations. This range of refined alternatives will be further described in the final draft Report and draft environmental and economic analyses. This range encompasses flows that are generally close to the lower bounds of flows occurring under current conditions at 35 percent and more optimal flows for fish species at 75 percent that were identified in the Delta Flow Criteria Report. However, as described in the hydrology chapter, current condition flows between tributaries and water years can vary significantly and flows on many tributaries in many months are currently well below 35% while other tributaries are above 35%. Given the poor status of many native species that are to some degree associated with reduced flows, flows lower than current conditions are generally not recommended.

1.3.4 Delta Outflows

The Report describes the science supporting recommended modifications to the existing Delta outflow requirements to protect fish and wildlife beneficial uses during winter, spring, summer, and fall periods. Since Delta outflows drive salinity and flow conditions in Suisun Marsh, this Report does not include separate substantive recommendations for Suisun Marsh, though it does recommend some non-substantive changes to the existing Suisun Marsh requirements.

Monitoring of fish and invertebrate abundance in the Bay-Delta Estuary continues to show the importance of Delta outflows to the protection of various species. The relationships between outflow and estuarine fish abundance and several other measures of the health of Bay-Delta estuary have been known for some time (Jassby et al. 1995) and are the basis for the current spring Delta outflow objectives. A more recent study determined that updated Delta outflow species relationships were similar to those previously reported and are seen in a wide variety of estuarine species (Kimmerer et al. 2009). Fish species that respond positively to increased outflow include longfin smelt, Sacramento splittail, white sturgeon and starry flounder. Invertebrate species that respond positively to increased outflow include California bay shrimp, *Eurytemora affinis* and *Neomysis mercedis*. Recent information also indicates that fall and summer outflows may also be important to Delta smelt and possibly other fish species.

Stream flow and Delta outflow are also important factors in the survival of Chinook salmon and steelhead (NMFS 2014). Delta outflows affect migration patterns of anadromous fish and the availability of estuarine habitat. Freshwater flow is an important cue for upstream spawning migration of adult salmon and other estuarine-dependent species, and is a factor in the survival of salmon smolts moving downstream through the Delta. Freshwater outflow influences chemical and biological conditions through its effects on loading of nutrients and organic matter, pollutant concentrations, and residence time. While the exact mechanisms that drive all of these relationships are not perfectly understood, perfect science is not required to move forward. Further, the proposed changes to the Bay-Delta Plan are proposed to be developed and implemented in a way that improves scientific understanding and responds to new information.

The last five years have provided a dramatic example of the importance of flow for native fish species. Following the wet conditions of 2011, population abundance of longfin smelt, Delta smelt, Sacramento splittail, and other species all increased. The next four years were very dry and the abundance of each of these species has fallen and is now at or near its all-time recorded lowest level. High flows have resulted in greater abundance of native fish while low flows produced population declines. These results are consistent with earlier observations and demonstrate that the aquatic estuarine community still responds positively to increased Delta outflow.

The effect of Delta outflows in protecting fish and wildlife involves complex interactions with other flows in the Delta and with other parameters including the physical configuration of the Delta. The recommended outflow modifications to the Bay-Delta Plan recognize the role of source inflows used to meet Delta outflows, Delta hydrodynamics, tidal action, hydrology, water diversions, water project operations, and cold water pool storage in upstream reservoirs. For estuarine-dependent species, the statistically significant declines in population size of Sacramento splittail and longfin and Delta smelt have continued since implementation of D-1641. The statistically significant declines suggest that D-1641 is not sufficiently protective for these species and additional actions are required to recover the species.

Based on the above issues, to protect native fish and wildlife species rearing in and migrating through the Delta, the Report includes recommendations for increased Delta outflow requirements during the winter, spring, and fall to protect native estuarine and anadromous fish species. Science regarding needed summer outflow requirements is still emerging. As that science matures through the process of developing this Report and the related Bay-Delta update, additional recommendations for summer outflows may be included. Adaptive management studies may also be recommended that rely on shifting some portion of the required flows from winter and spring to the summer and possibly fall when higher flow requirements are not in place.

The winter and spring Delta outflows would be structured similarly to the existing Delta outflow objectives, which are based on a measure of unimpaired inflows (Eight River Index) from the previous month. The Report includes a recommendation that this requirement be modified to use the current month's index in order to be compatible with the inflow requirements and more in concert with natural uncontrolled precipitation induced inflows to the system. The recommended range of potential alternative modifications to Delta outflow requirements corresponds to the recommended range of potential modifications to inflows which are no less than current conditions and up to 75 percent of unimpaired flows. As with inflows, this range will be further refined through modeling and analysis. To inform development and consideration of alternatives that optimize protection of numerous species, the Report evaluates known species-specific relationships to Delta outflows during the January through June time period. Adaptive management provisions are proposed to be consistent to the extent possible with adaptive implementation provisions for inflows.

1.3.5 Cold Water Management

The Report describes the science supporting a new narrative cold water habitat requirement to ensure the preservation of cold water for salmonids and other species. Specifically, the requirement would ensure that cold water releases from reservoirs are maintained and timed to provide suitable downstream temperatures and flows for aquatic species or that alternate measures are implemented to protect anadromous fish from temperature impacts (e.g. passage above dams). It would also ensure that adequate water remains in storage over time to provide for critical flows at other times, and prevent drawdown of reservoirs that may occur due to increased and existing water demands. Elevated temperatures during the salmonid egg incubation and rearing life stages reduce survival of juvenile salmonids. Needed temperature conditions throughout the year to protect against temperature induced mortality depend on the race of salmonid, life stage, and other factors. Specific actions needed to achieve temperature management in tributaries also depend on the specific circumstances of that tributary, such as availability of stored water, opportunities for passage to cold habitat areas, and opportunities for the use of reservoir temperature control devices. Specific implementation actions will need to be developed according to the needs of the fish in each tributary and the actions that are available to protect salmonids from temperature effects. As such, this Report includes a recommendation for a general narrative requirement for cold water management with specific implementation actions to be developed on a stream by stream basis.

1.3.6 Interior Delta Flows

The Report describes the science supporting new and potentially changed interior Delta flow requirements to protect fish and wildlife beneficial uses. Specifically, the report discusses the science supporting the need for interior Delta flow requirements to improve homing fidelity of adult salmonids, improve survival of outmigrating juvenile salmonids, and minimize entrainment of native fish in the interior Delta where survival is low due to predation, direct impingement and poor habitat conditions. Recommendations for specific numeric interior Delta flow requirements include modifications to the operations of the DCC Gates, SWP and CVP export constraints, and limitations on Old and Middle River reverse flows, discussed below.

1.3.6.1 Delta Cross Channel Gate Operations

When open, the DCC Gates allow high quality Sacramento River water to flow into the interior Delta channels toward the SWP and CVP export facilities. The DCC Gates are required to be closed at certain times pursuant to D-1641 and the NMFS BO to protect fish and wildlife (specifically migrating salmonids) from being entrained in the interior Delta channels where survival is reduced. The Report includes recommendations to consider extending the time period when the DCC Gates may be required to be closed based on monitoring information relative to fish presence in the vicinity of the DCC Gates consistent with the NMFS BO and in coordination with the implementation of the BO and any modified BO that may be issued in the future.

1.3.6.2 Old and Middle River (OMR) Flows

Net OMR reverse flows are caused by the fact that the major freshwater source, the Sacramento River, enters on the northern side of the Delta while the two major pumping facilities, the SWP and CVP, are located in the south. This results in a net water movement across the Delta in a north-south direction along a web of channels including Old and Middle rivers instead of the more natural pattern from east to west or from land to sea. A negative value, or a reverse flow, indicates a net water movement across the Delta along Old and Middle river channels to the export facilities.

High net OMR reverse flows have several negative ecological consequences. First, net reverse OMR flows draw fish, especially the weaker swimming larval and juvenile forms, into the SWP and CVP export facilities. Second, net OMR reverse flows reduce spawning and rearing habitat for native species, like Delta smelt. Third, net OMR reverse flows result in a confusing environment for migrating juvenile salmonids leaving the San Joaquin River Basin. Finally, net OMR reverse flows reduce the natural variability in the Delta by drawing Sacramento River water across and into the interior Delta. Net OMR reverse flow restrictions are included in the USFWS BO, the NMFS BO, and the CDFW ITP. The Report includes recommendations to consider new reverse OMR flow limits for the Bay-Delta Plan for the protection of salmonids, Delta smelt and longfin smelt in coordination with the BOs and ITP discussed above or any new ESA or CESA requirements.

1.3.6.3 San Joaquin River Flows to Exports

The 2006 Bay-Delta Plan includes export limitations that constrain exports during a 30-day period in the spring to 100 percent of the San Joaquin River flow or minimal specified pumping levels (1,500 cfs) to minimize entrainment and salvage losses of outmigrating juvenile salmonids from the San Joaquin River. The 2009 NMFS BO includes more stringent constraints that are based on water year type and that extend for 60 days in the spring. The limited 30 day period included in the 2006 Bay-Delta Plan only covers a fraction of the time period when juvenile salmonids outmigrate from the San Joaquin River. In addition, the current requirements do not provide for much, if any of the San Joaquin River water to flow to the Delta so that smaller weaker swimming juvenile fish have positive flow cues to guide outmigration. The Report recommends consideration of more restrictive export constraints as a function of San Joaquin River flows up to and beyond the NMFS BO during the spring to protect outmigrating juvenile Chinook salmon and additional export constraints during October to protect migrating adult Chinook salmon from the San Joaquin River watershed. Any new requirements are proposed to be coordinated with the NMFS BO, Phase I and installation of the Head of Old River Barrier.

1.4 Next Steps

The Phase II Bay-Delta Plan update is in its early stages and there will be several additional opportunities for public participation and comment as the planning process moves forward. The scientific basis of any statewide plan, basin plan, plan amendment, guideline, policy, or regulation must undergo external scientific peer review before adoption by the State Water Board or Regional

Water Quality Control Boards (Health & Saf. Code, § 57004). Accordingly, after consideration of public comments on this working draft Report, the State Water Board will revise the Report as necessary and then submit a final draft of the Report to external scientific peer review.

In establishing water quality objectives, the State Water Board must ensure the reasonable protection of beneficial uses, and consider various factors including other beneficial uses of water, the environmental characteristics of the area, and economics. In addition, the State Water Board must comply with the California Environmental Quality Act (CEQA) in evaluating the effects of the project on the environment, as well as other applicable law.

State Water Board regulations (Cal. Code. of Regs., tit. 23, § 3777) require that any water quality control plan proposed for approval or adoption be accompanied by substitute environmental documentation (SED). The State Water Board's water quality control planning program is certified by the Secretary of the California Resources Agency as exempt from CEQA's requirements for the preparation of environmental impact reports (EIR), negative declarations, and initial studies (Pub. Resources Code, § 21080.5; Cal. Code Regs., tit. 14, § 15251, subd. (g)). Agencies qualifying for such exemptions must still comply with CEQA's goals and policies, including the policy of avoiding significant adverse effects on the environment where feasible.

The SED for any proposed amendments to the 2006 Bay-Delta Plan will include identification of any significant, or potentially significant, adverse environmental impacts of the proposed project, analysis of reasonable alternatives and mitigation measures to avoid or reduce impacts, environmental analysis of the reasonably foreseeable methods of compliance, and other documents the State Water Board may decide to include. The SED will include the identification of any potentially significant environmental impacts of any changed flow objectives in the watersheds in which Delta flows originate, in the Delta, and in the areas in which Delta water is used or from which Delta water is imported. It will also include an analysis of the economic impacts that could result from changed flow objectives. The public will have the opportunity to review and comment on the draft documents containing these evaluations.

Computer modeling will play an essential role in analyzing potential new or modified requirements. DWR and Reclamation have developed and extensively used the CalSim II model for planning, managing, and operating the Projects. The State Water Board's potential modifications to the 2006 Bay-Delta Plan may affect Central Valley and Delta operations that are included in the CalSim II model as well as operations that are not explicitly modeled in CalSim II. Thus, for its review of the Bay-Delta Plan, the State Water Board needs the following additional modeling capabilities that are not part of CalSim II's functionality: (1) the ability to predict flows at the mouths of tributaries to the Delta; (2) the ability to simulate water diversions on smaller tributaries and creeks; and (3) the ability to simulate operations of local agency reservoirs that are not part of the SWP or CVP. The State Water Board also needs a flexible, user friendly simulation tool to rapidly assess the impacts of various regulatory scenarios on flows into the Delta, within the Delta, and flows exported from the Delta.

The State Water Board has developed the Sacramento Water Allocation Model (SacWAM) for this purpose. SacWAM is a hydrology and system operations model that is an application of the Water Evaluation And Planning (WEAP) system, and was a collaborative effort between the State Water Board and Stockholm Environment Institute (SEI). The State Water Board may use modeling output from SacWAM to evaluate various regulatory requirements:

- To establish modeled baseline conditions.
- To estimate changes in stream and channel flows for use in an evaluation of the impacts of alternative regulatory requirements on fisheries, terrestrial biological resources, and recreation.
- To estimate changes in water diversion for use in an evaluation of the impacts of alternative regulatory requirements on agricultural resources, water suppliers and groundwater.
- To estimate changes in reservoir storage for use in an analysis of the impacts of alternative regulatory requirements on hydropower generation, recreation, and fisheries.
- To inform other analyses or models, such as Delta tidal hydrodynamics, water quality, temperature, economic, groundwater, and fisheries.

The DSP is conducting an independent science review (ISR) of SacWAM, and is planning to hold a review panel workshop on Wednesday, October 19. Additional information related to the ISR process can be found here: http://deltacouncil.ca.gov/event-detail/13662. Once reviewed and refined, the State Water Board expects to include analyses in this Report as appropriate using SacWAM.

Chapter 2
Hydrology

2.1 Introduction

This chapter provides a description of the hydrologic conditions of the Sacramento River, its major tributaries, and Eastside tributaries to the Delta, and provides a comparison of existing hydrologic conditions to unimpaired conditions. Unimpaired hydrology or "unimpaired flow" represents an index of the total water available to be stored or put to any beneficial use within a watershed under current physical conditions and land uses. This unimpaired flow index is different than the "natural flow" that would have occurred absent human development of land and water supply.

California has a Mediterranean climate that is characterized by mild, wet winters and dry, hot summers. Eighty-five percent of the annual precipitation falls in the winter months and in the summer, many parts of the watershed will go more than 90 days without any precipitation. California also shows great inter-annual variability in runoff ranging from an estimated 5.1 million acre-feet (MAF) in water-year 1977 to 37.7 MAF in water-year 1983 (DWR 2016d). For over 150 years humans have altered the Sacramento River and its tributaries to reclaim wetlands, tame floods and to provide irrigation during the dry months. Two of the largest water projects in the world, the State Water Project and the Central Valley Project, move water from the Sacramento watershed, through the Delta and deliver it to farmers and cities in southern California.

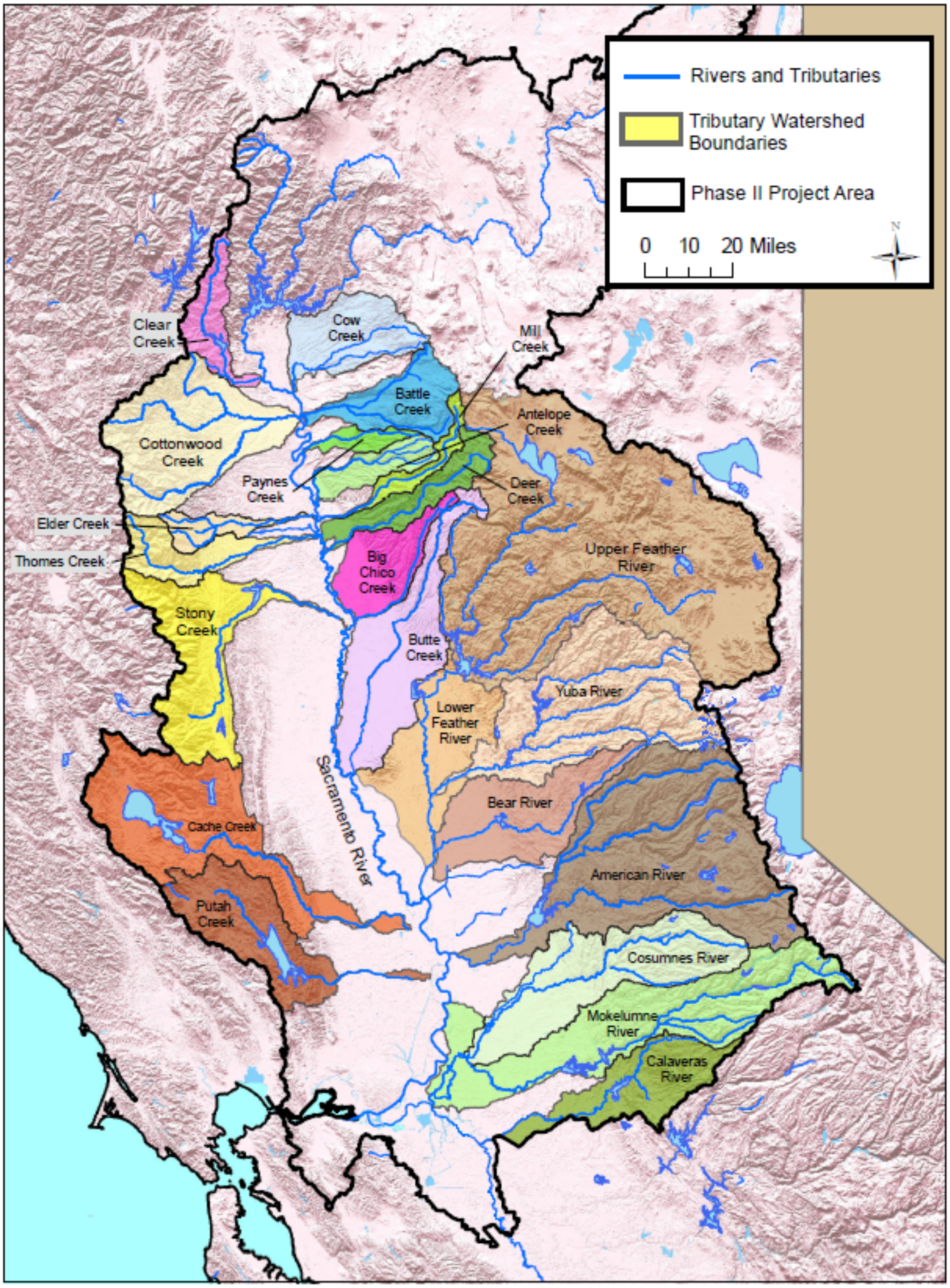
The Sacramento River extends from the Modoc Plateau and the southern Cascades near the Oregon Border to the Pacific Ocean draining an area of 27,000 square miles. The Sacramento River has a mean annual flow of more than 22 MAF, which is approximately one-third of the total runoff in California. It has more than 20 major salmon bearing tributaries, a number of other tributaries with intermittent flows that salmon do not inhabit on a sustained basis, a series of flood basins, and is home to an extensive community of fish and wildlife.

Below its source near Mount Shasta, the Sacramento River is impounded by the largest reservoir in California, Shasta Reservoir. Below Shasta, the Sacramento River proceeds southward through a series of leveed river channels bordered by overflow basins and weirs. The capacity of its reaches increases and decreases as it proceeds downstream. Its main tributaries are the Feather River fed by the Yuba and Bear Rivers and the American River. At the bottom of the watershed, the Sacramento River meets the San Joaquin River to form the Sacramento-San Joaquin Delta. Below the Delta, the river flows through San Francisco Bay to the Pacific Ocean.

The main hydrologic features of the Sacramento River, its tributaries, the flood basins bordering the streams, the Delta, and the Suisun Region are described below. The descriptions of the tributaries have been organized into the functional hydrological groups shown in the list below and is based on watershed drivers of local hydrology that include elevation, precipitation patterns, geology, surface water origins, groundwater contributions to surface flow, and shared geomorphic history. Some smaller, intermittent tributaries for which there is no or limited hydrologic information are not discussed in this report.

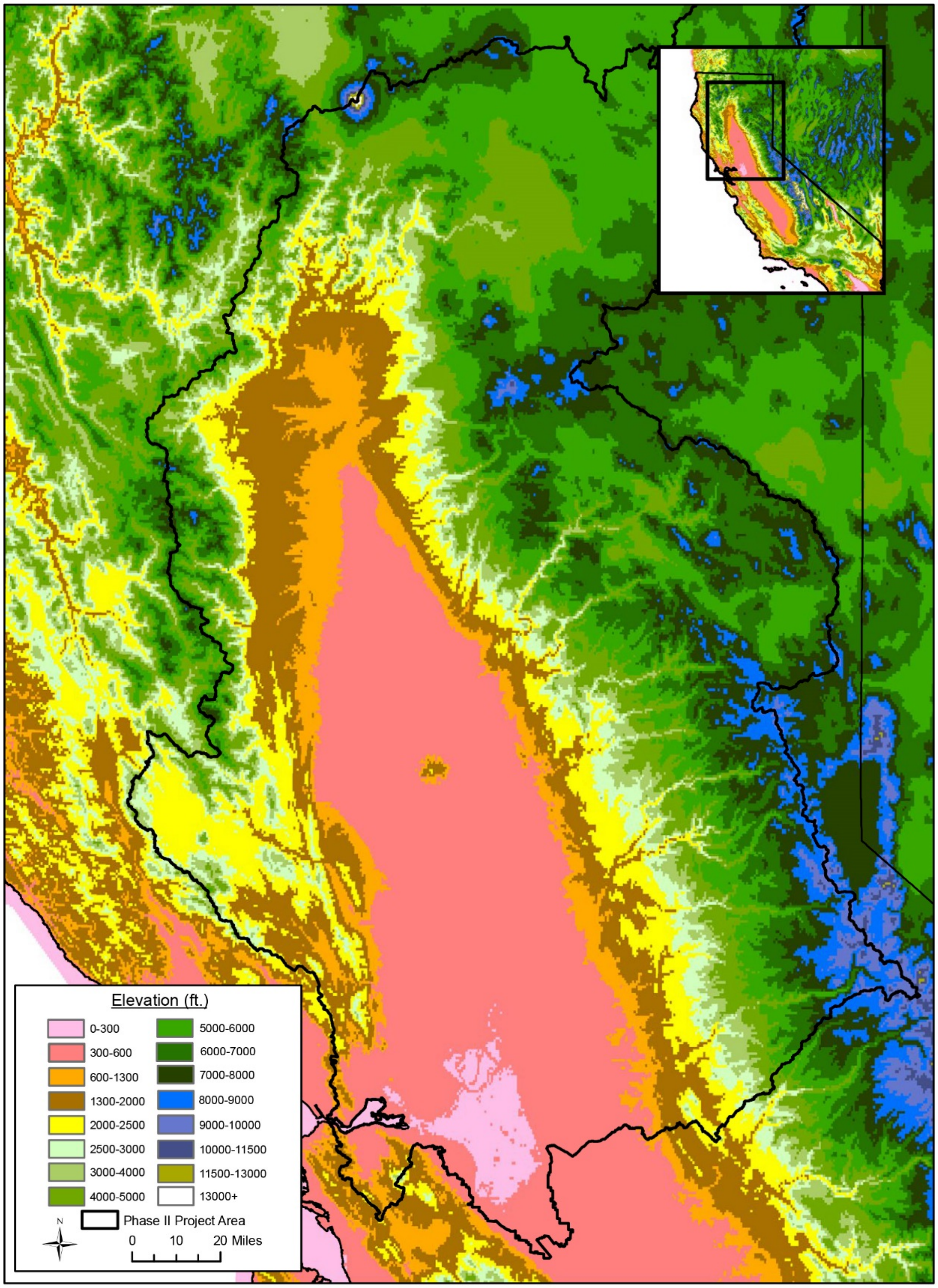
- Main Stem Sacramento
- Tributaries of Mt. Lassen
    - Cow Creek, Battle Creek
- Tributaries of the Chico Monocline
    - Antelope Creek, Deer Creek, Mill Creek, Paynes Creek
- Tributaries of the Klamath Mountains
    - Clear Creek
- Tributaries of the Paleochannels and Tuscan Formation
    - Butte Creek, Big Chico Creek
- Tributaries of the Northern Sierra Nevada
    - Feather River, Yuba River, Bear River, American River
- Tributaries of the Eastside of the Delta
    - Mokelumne River, Cosumnes River, Calaveras River
- Tributaries of the Northern Coast Range, Northern
    - Stony Creek, Cottonwood Creek, Thomes Creek, Elder Creek
- Tributaries of the Northern Coast Range, Southern
    - Cache Creek, Putah Creek

The Sacramento River, the major tributaries, and the major reservoirs are shown in Figure 2.1-1. The eastern tributaries from the Calaveras River in the south to the Yuba River in the north are Sierra Nevada streams. The Calaveras, Mokelumne, and Cosumnes rivers are tributaries of the San Joaquin River but could just as easily be described as tributaries of the Delta based on the fact that their convergences are all in tidewater. The North Fork of the Feather River is the general dividing line between the Sierra Nevada streams to the south and the Cascade Range streams to the north. Clear Creek is the sole Klamath Range stream. The western streams from Cottonwood Creek south to Stony Creek are Northern Inner Coast Range streams while Cache and Putah creeks, almost twin streams, originate in the Southern Inner Coast Range. Elevation in the Phase 2 project area varies enormously from east to west and from north to south (Figure 2.1-2). The Coast Range produces a significant rain shadow effect on its eastern slope and in the valley by wringing precipitation out of storms approaching from the west as storms typically do at this latitude. The Golden Gate/Carquinez Straight gap in the Coast Range has the effect of focusing storms directly at the watersheds of the American and Feather rivers. If the approach of the storm front is perpendicular to the slope of the Sierra Nevada large localized precipitation events will occur. However, if the storm strikes a glancing blow it will generate a low level south to north flowing atmospheric jet stream and turbulent updrafts that will distribute the precipitation over a much larger area for a longer period of time (Neiman et al. 2014). These factors are why the amount of precipitation shown in Figure 2.1-3 does not necessarily correspond to the highest areas of the mountain ranges and why the watersheds of the American and Feather receive so much precipitation. Mount Lassen is an exception to this pattern due to its high elevation and northern location. The Klamath Range is also exceptional as it is far enough north that it receives more frequent storms which results in more annual precipitation.



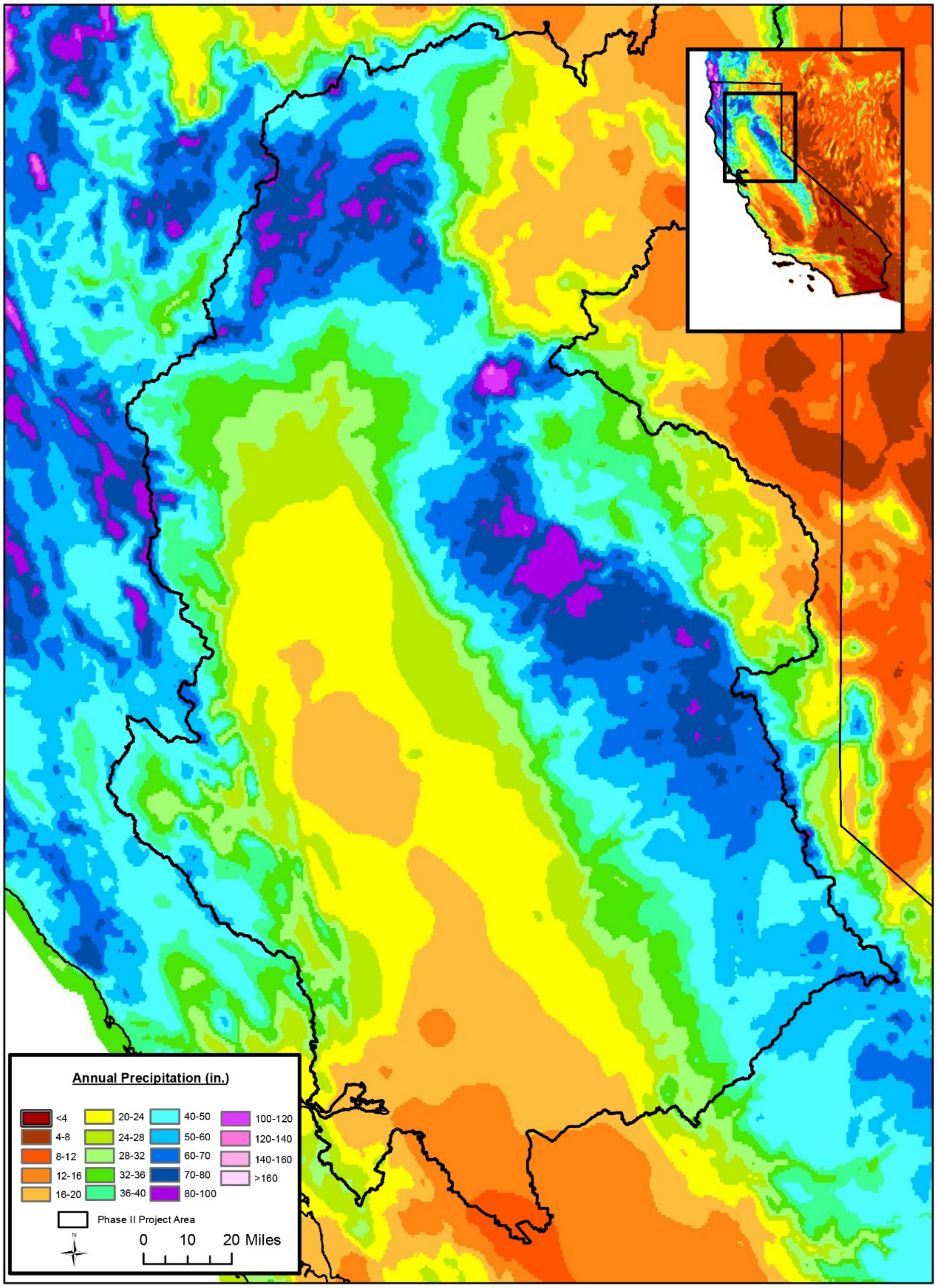
Source: State Water Resources Control Board, 2016 Data Source: SWRCB GIS Library

Figure 2.1-1. Major Tributaries and Watersheds in the Project Area



Source: State Water Resources Control Board, 2016 Data Source: www.prism.oregonstate.edu/normals/PRISM_us_dem_800m_bil.bil

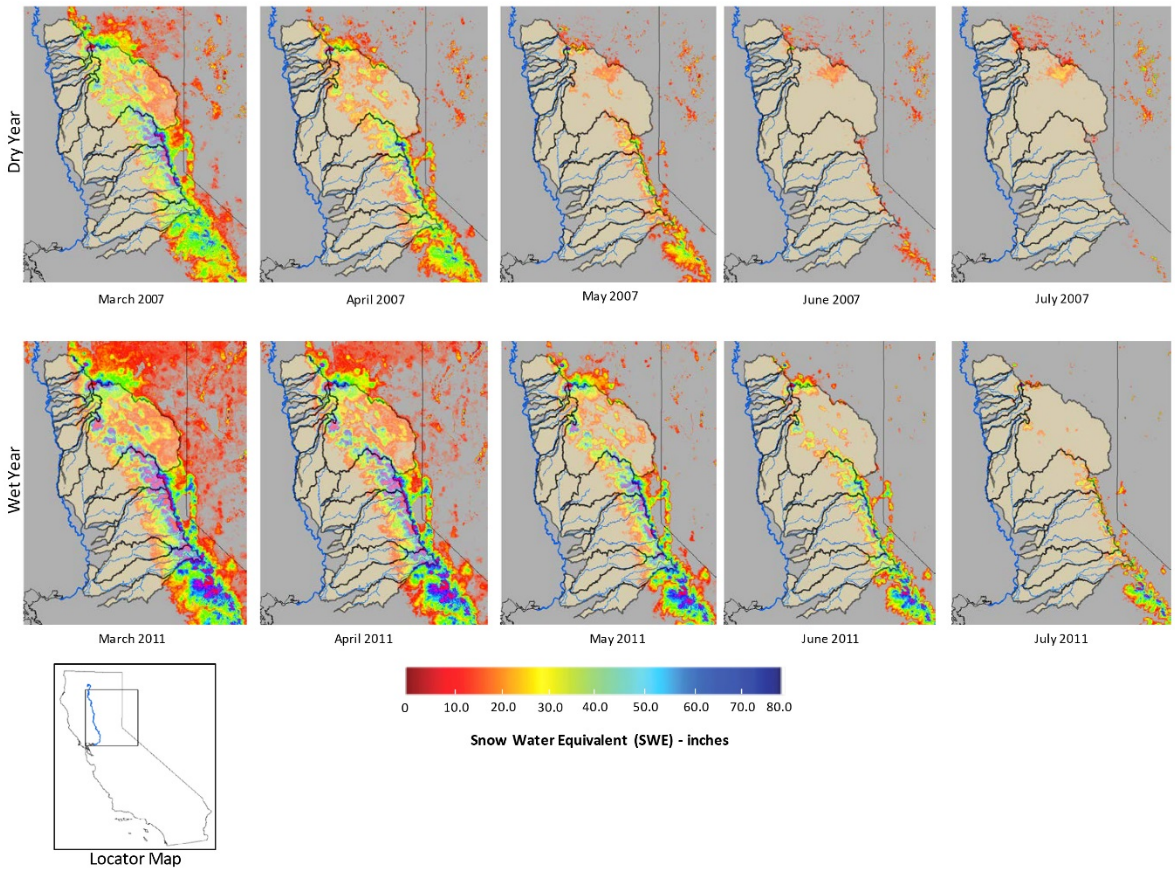
Figure 2.1-2. Elevation Map of Northern California



Source: State Water Resources Control Board, 2016 Data Source: www.prism.oregonstate.edu/normals/

Figure 2.1-3. Annual Precipitation in Northern California

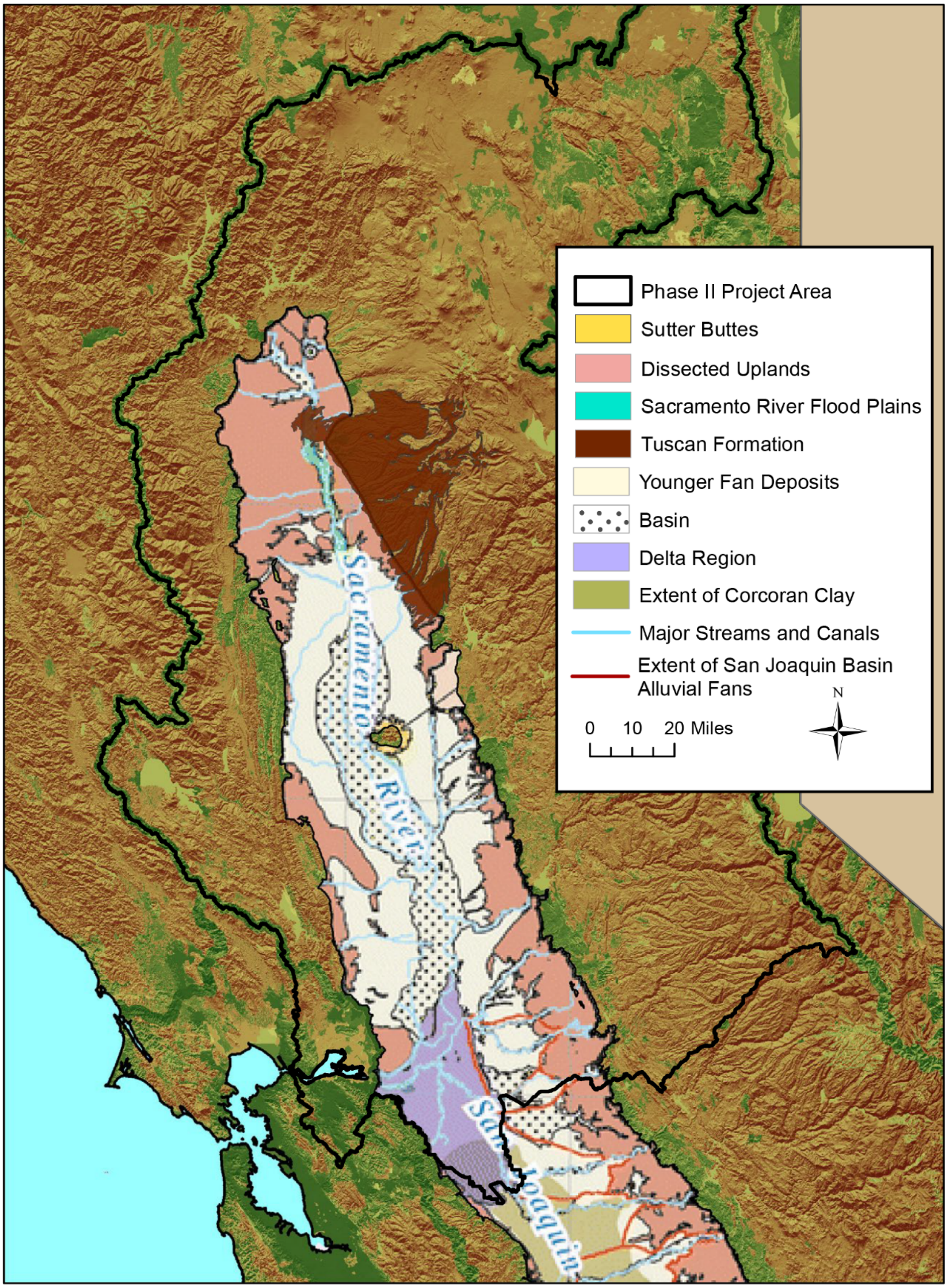
Elevation also affects the form of the precipitation with higher elevations receiving proportionally more precipitation as snow. This effect is constant for elevations above 7,000 feet but varies by water year type from 7,000 feet down to the 5,500-foot snow line. Figure 2.1-4 illustrates the differences in distribution and extent of the amount of water stored in the snow pack by month during dry and wet years. Additionally, storms originating in the southwest near Hawaii are much warmer than storms approaching from the northwest and if they produce rain-on-snow events can generate extremely large flood flows. Ultimately, the amount, form, and temperature of the precipitation determine the hydrological responses of the streams and the ability to capture the runoff above dams.



Source: State Water Resources Control Board, 2016 Data Source: Karl Rittger, http://alexandria.ucsb.edu/lib/ark:/48907/f3gm8581

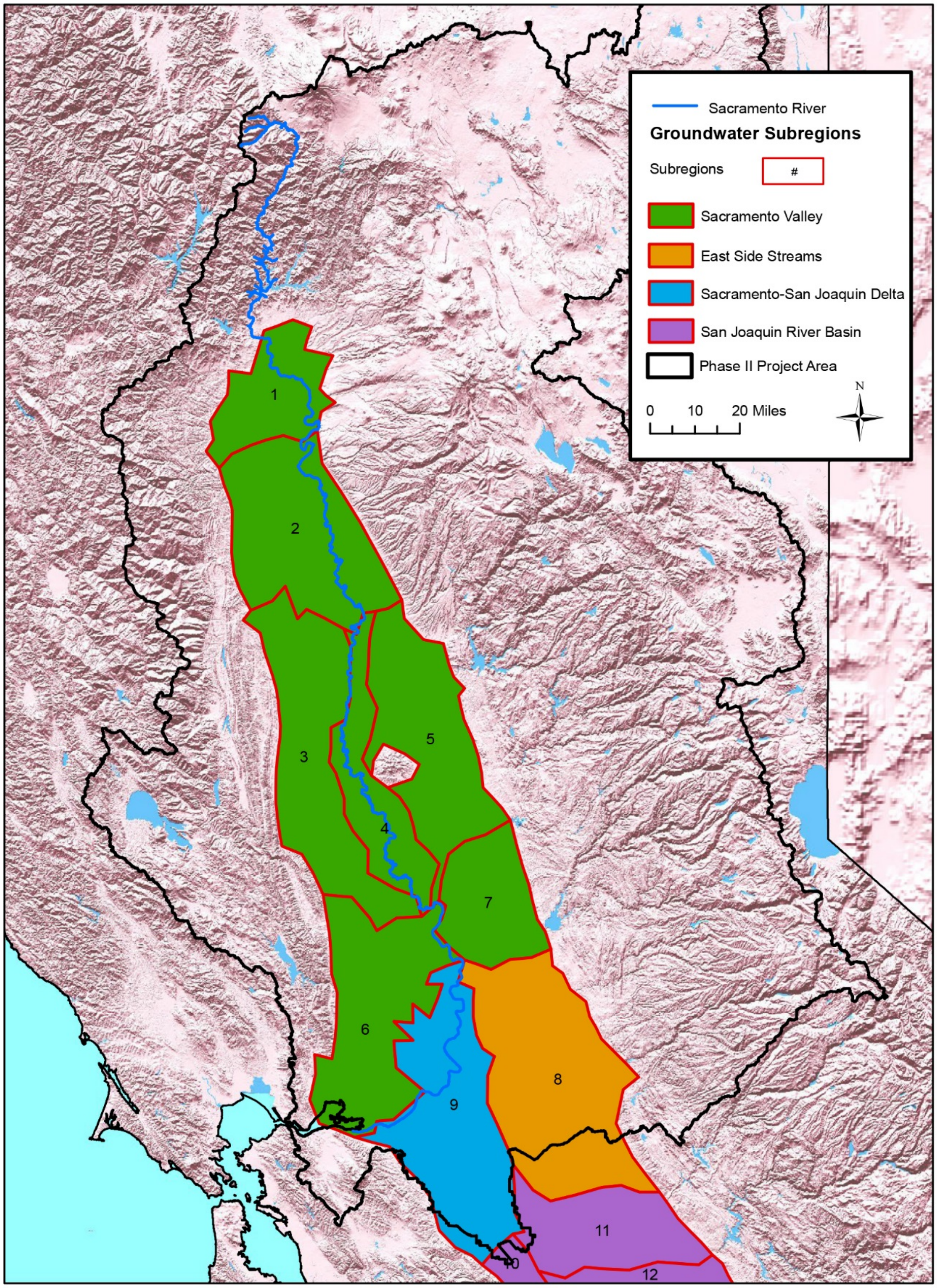
Figure 2.1-4. Water Year Type Snow Water Equivalents

As the streams leave the foothills their lowest reaches interact with the many different sedimentary rock formations of the valley (Figure 2.1-5) and the stream channels running over those formations have complex groundwater/aquifer and surface water interactions that vary by each stream. The natural boundaries of aquifers are difficult to map but groundwater models require subdivisons to reduce the computational requirements. Figure 2.1-6 shows the subregions used for the C2VSim model that has been widely adopted for use in the Central Valley (Brush et al. 2013).



Source: State Water Resources Control Board, 2016 Data Source: SWRCB GIS Library, Water33

Figure 2.1-5. Generalized Geologic Map of the Valley Floor



Source: State Water Resources Control Board, 2016 Data Source: http://www.arcgis.com/home/item.html?id=911b4394e1304e6ca3bdaba786641c9e

Figure 2.1-6. Map-C2VSim Model Groundwater Subregions

Many of the tributaries in the Sacramento Watershed have been extensively developed for hydropower, flood control, and agricultural and urban uses primarily in the valley floor. The altered hydrology of each tributary has a unique story, however in general, winter and spring runoff peaks are now lower and summer flows are now higher and warmer. The descriptions of the tributaries that follow discuss the factors that contribute to their unique hydrographs. The flood basin section follows the descriptions of the tributaries and is in turn followed by the description of the Sacramento/San Joaquin Delta. The description of the Suisun region follows that of the Delta.

To illustrate the hydrology under current conditions, a current hydrologic conditions simulation is shown as simulated by DWR using CalSim II in the 2015 Delivery Capability Report (DWR 2015). Modeled streamflows were used to represent current hydrologic conditions rather than observed data because stream gages are not located at the mouth of most Sacramento tributaries. Therefore to better describe the impairment of each entire tributary CalSim II results were used. CalSim II has a simplified representation of many Sacramento tributaries so at some locations gaged data was used where CalSim II modeled data was not available. Future studies should include results from a more spatially resolved hydrologic simulation model. Unimpaired flows used in this analysis have been estimated using the Sacramento Valley Unimpaired Flow Model (SVUFM) developed by DWR. Documentation of the SVUFM model can be found in Appendix A. The plots in the discussion that follows characterize the impairment of each tributary by comparing the simulated “current conditions” to the “unimpaired flows” to illustrate the general levels of impairment and trends in impairments.

The models used to estimate impaired flows and unimpaired flows presented here are currently the best available tools to simulate the hydrology in the Sacramento Watershed. However, because the models use different inflow hydrologies, simulate the hydrologic processes on the valley floor differently, and have different resolutions, the comparisons at some locations are not possible and are less accurate at some locations. To more accurately characterize the level of impairment of the Sacramento River and its tributaries, the State Water Board plans to use the SacWAM model in the final report to simulate both impaired and unimpaired flows using the same inflows and processes on the valley floor.

The following analysis provides information on the level of impairment in the mainstem Sacramento River and various tributaries on a monthly and seasonal basis given different hydrologic conditions (percent exceedances). These analyses show significant differences in impairment between months, hydrologic conditions, and streams with generally much greater impairment during drier years when unimpaired flows are already low.

Figure 2.1-7 shows simulated impaired flows as a percentage of unimpaired flows for the Sacramento River and its major tributaries ranked by water year index for the spring months of January–June. The water year index is an index of total runoff, 3.11 being the driest year and 15.29 being the wettest. The red color indicates that the flow at this location is more impaired and the blue color indicates that the flow is less impaired or higher than the unimpaired flow. Regulated tributaries with large reservoirs such as the American, Bear, Yuba, and Feather Rivers have lower percent of unimpaired flow in the spring in drier years, whereas unregulated tributaries show a higher percent of unimpaired flow in all years.

WYT	Water Year Index	Delta Outflow	American	Bear	Yuba	Feather Above Conf. Yuba	Feather Confluence with Sac R.	Sacramento River at Bend Bridge	Sacramento at Freeport	Mokelumne	Calaveras	Cache	Putah below Diversion Dam	Clear Creek	Stony Creek	Antelope, Mill, Deer	Battle	Big Chico	Cosumnes	Cottonwood	Cow	Thomes & Elder Creeks	Paynes Creek	Butte
3.11	C	63%	35%	34%	85%	85%	62%	184%	111%	29%	0%	0%	207%	147%	83%	58%	94%	100%	76%	116%	101%	61%	72%	
3.66	C	44%	46%	15%	53%	53%	64%	132%	81%	17%	23%	7%		61%	8%	79%	83%	101%	84%	250%	61%	138%	71%	
3.87	C	52%	40%	49%	71%	71%	94%	142%	93%	33%	0%	9%		125%	27%	55%	66%	120%	83%	215%	44%	112%	63%	
4.06	C	43%	48%	106%	38%	38%	29%	88%	72%	10%	20%	8%	14%	21%	4%	94%	95%	76%	84%	105%	103%	116%	79%	
4.07	C	39%	65%	8%	40%	40%	57%	93%	67%	16%	7%	19%		55%	6%	89%	86%	101%	88%	174%	92%	132%	90%	
4.21	C	38%	35%	5%	36%	36%	28%	94%	64%	13%	19%	11%	9%	60%	4%	89%	97%	64%	81%	112%	106%	120%	51%	
4.63	C	33%	47%	9%	37%	37%	47%	81%	60%	16%	6%	15%		24%	6%	81%	85%	101%	84%	141%	105%	123%	77%	
4.65	C	42%	23%	8%	38%	38%	40%	101%	63%	14%	31%	29%	14%	60%	39%	86%	96%	68%	83%	116%	107%	115%	54%	
4.81	C	32%	35%	29%	41%	41%	20%	84%	57%	15%	4%	12%	22%	52%	6%	87%	97%	78%	84%	100%	107%	128%	55%	
5.02	C	41%	49%	36%	41%	41%	31%	114%	77%	21%	18%	15%	24%	79%	13%	85%	97%	74%	78%	120%	108%	112%	52%	
5.22	C	35%	40%	8%	46%	46%	54%	102%	67%	19%	3%	20%		95%	16%	82%	84%	99%	83%	128%	39%	134%	57%	
5.29	C	39%	60%	123%	53%	53%	45%	105%	74%	33%	0%	0%	93%	84%	8%	68%	97%	100%	82%	95%	105%	106%	38%	
5.48	D	27%	41%	30%	35%	35%	21%	71%	48%	6%	7%	20%		34%	8%	90%	88%	101%	87%	230%	84%	125%	62%	
5.58	D	35%	46%	22%	51%	51%	66%	105%	63%	21%	4%	9%		93%	15%	74%	84%	101%	83%	146%	51%	117%	55%	
5.61	D	37%	46%	26%	50%	50%	39%	85%	63%	17%	1%	17%		83%	7%	86%	82%	101%	85%	108%	70%	122%	68%	
5.68	D	40%	33%	8%	38%	38%	27%	83%	62%	12%	25%	20%	22%	44%	73%	91%	86%	101%	79%	111%	107%	118%	80%	167%
5.75	D	42%	52%	56%	64%	64%	28%	92%	68%	17%	12%	44%		30%	46%	83%	76%	88%	89%	146%	64%	116%	63%	
5.76	D	44%	39%	6%	43%	43%	42%	93%	72%	17%	55%	25%	12%	31%	26%	90%	95%	65%	80%	111%	105%	93%	57%	
5.86	D	42%	29%	26%	46%	46%	43%	98%	68%	22%	30%	13%	17%	67%	8%	90%	98%	78%	58%	109%	107%	112%	53%	
5.9	D	38%	49%	53%	42%	42%	25%	82%	60%	10%	9%	28%		44%	4%	94%	91%	83%	85%	140%	82%	121%	65%	
6.09	D	38%	44%	40%	39%	39%	36%	83%	63%	12%	6%	29%		37%	12%	88%	84%	101%	90%	115%	83%	118%	61%	
6.13	D	34%	45%	60%	40%	40%	19%	70%	61%	7%	8%	10%	13%	41%	4%	94%	100%	84%	85%	109%	108%	114%	41%	
6.14	D	32%	33%	26%	33%	33%	36%	84%	56%	14%	43%	16%		79%	12%	81%	81%	101%	87%	119%	107%	119%	70%	
6.2	D	31%	30%	20%	36%	36%	26%	71%	53%	10%	12%	24%	10%	46%	24%	91%	84%	101%	86%	99%	102%	114%	78%	129%
6.21	D	40%	34%	44%	40%	40%	38%	88%	65%	17%	18%	26%	9%	34%	43%	90%	97%	101%	85%	110%	105%	111%	69%	
6.35	D	36%	42%	34%	40%	40%	36%	82%	59%	14%	12%	28%		97%	5%	88%	84%	101%	88%	110%	85%	134%	67%	
6.35	D	43%	51%	218%	35%	35%	18%	92%	66%	10%	12%	50%	9%	35%	71%	89%	97%	85%	84%	113%	108%	72%	55%	
6.39	D	39%	48%	56%	38%	38%	19%	69%	61%	9%	21%	39%		17%	46%	84%	77%	86%	90%	117%	60%	110%	64%	
6.41	D	36%	48%	56%	39%	39%	32%	98%	62%	17%	22%	18%	21%	66%	40%	79%	96%	101%	85%	115%	105%	110%	61%	149%
6.47	D	35%	42%	92%	40%	40%	44%	111%	64%	15%	6%	17%	13%	107%	8%	80%	96%	100%	81%	106%	106%	107%	51%	
6.62	BN	35%	50%	51%	54%	54%	10%	76%	55%	23%	5%	22%		73%	23%	93%	89%	101%	91%	102%	108%	121%	83%	
6.65	BN	33%	32%	28%	39%	39%	19%	83%	55%	9%	12%	47%	10%	39%	57%	93%	98%	101%	86%	105%	104%	115%	81%	113%
6.67	BN	40%	50%	66%	38%	38%	29%	76%	61%	23%	79%	18%	7%	48%	31%	91%	98%	101%	99%	99%	105%	117%	67%	
6.75	BN	40%	31%	33%	41%	41%	38%	82%	63%	17%	24%	38%		37%	96%	87%	84%	101%	84%	101%	102%	110%	77%	83%
6.8	BN	36%	50%	42%	52%	52%	21%	72%	58%	21%	59%	22%		52%	29%	93%	88%	101%	92%	112%	90%	123%	76%	
6.87	BN	44%	49%	51%	47%	47%	33%	74%	66%	23%	84%	35%		36%	13%	94%	82%	101%	92%	98%	109%	114%	75%	
6.98	BN	38%	42%	81%	41%	41%	10%	67%	61%	8%	5%	43%		30%	16%	97%	90%	101%	90%	87%	122%	118%	80%	
7.06	BN	40%	55%	92%	47%	47%	22%	92%	60%	23%	48%	34%		49%	44%	80%	89%	81%	94%	200%	69%	117%	65%	
7.12	BN	35%	37%	7%	45%	45%	13%	67%	55%	10%	0%	11%		42%	4%	100%	93%	101%	89%	104%	100%	120%	52%	
7.16	BN	39%	33%	69%	43%	43%	32%	85%	61%	15%	21%	64%	31%	34%	51%	86%	96%	101%	87%	115%	108%	111%	71%	161%
7.24	BN	49%	51%	89%	50%	50%	50%	88%	72%	15%	6%	60%	26%	42%	66%	92%	98%	101%	90%	106%	105%	109%	74%	126%
7.29	BN	35%	49%	94%	43%	43%	25%	82%	55%	17%	0%	13%	44%	51%	15%	85%	98%	100%	93%	104%	108%	111%	43%	177%
7.7	BN	42%	53%	105%	58%	58%	24%	84%	62%	24%	18%	63%		58%	62%	86%	86%	100%	94%	115%	65%	116%	57%	
7.75	BN	44%	69%	88%	58%	58%	13%	67%	68%	38%	82%	57%		22%	60%	99%	90%	101%	93%	140%	124%	117%	101%	
7.83	AN	34%	39%	65%	49%	49%	23%	68%	53%	16%	3%	26%		34%	64%	92%	89%	101%	90%	105%	105%	113%	71%	
8.21	AN	49%	50%	103%	56%	56%	15%	89%	76%	10%	5%	64%	38%	24%	52%	97%	100%	64%	84%	108%	107%	82%	48%	
8.27	AN	49%	57%	95%	59%	59%	30%	82%	74%	21%	35%	46%		25%	45%	88%	85%	79%	92%	212%	71%	109%	52%	
8.51	AN	48%	49%	84%	63%	63%	28%	88%	72%	14%	3%	52%		24%	47%	97%	90%	101%	90%	108%	104%	109%	81%	
8.54	AN	43%	56%	73%	48%	48%	27%	55%	72%	13%	23%	59%	6%	17%	69%	98%	101%	66%	104%	103%	106%	111%	52%	
8.58	AN	55%	67%	89%	61%	61%	24%	91%	80%	31%	87%	74%	17%	19%	71%	95%	99%	101%	90%	107%	105%	109%	101%	
8.65	AN	44%	49%	74%	48%	48%	16%	68%	72%	7%	42%	43%	5%	13%	71%	99%	100%	101%	90%	107%	104%	112%	83%	
8.88	AN	52%	61%	71%	51%	51%	28%	83%	77%	24%	49%	59%		20%	53%	99%	89%	101%	93%	88%	123%	110%	91%	
8.94	AN	51%	50%	90%	61%	61%	29%	83%	67%	26%	94%	37%	16%	16%	40%	96%	98%	69%	91%	105%	104%	82%	58%	
8.97	AN	45%	58%	69%	62%	62%	41%	66%	69%	36%	86%	34%		31%	10%	95%	92%	68%	93%	139%	71%	108%	47%	
9.04	AN	60%	74%	108%	66%	66%	29%	97%	78%	47%	104%	70%	7%	25%	75%	98%	99%	100%	86%	108%	105%	107%	93%	
9.18	AN	57%	68%	124%	70%	70%	54%	89%	80%	37%	74%	68%		38%	49%	94%	88%	101%	97%	108%	106%	113%	79%	
9.35	W	50%	52%	58%	56%	56%	46%	81%	74%	23%	78%	51%	29%	21%	67%	96%	99%	101%	94%	105%	104%	109%	66%	
9.52	W	57%	68%	100%	73%	73%	22%	93%	80%	24%	35%	76%		20%	58%	92%	89%	80%	92%	118%	80%	107%	65%	
9.55	W	55%	52%	93%	59%	59%	60%	87%	68%	26%	47%	70%		28%	56%	97%	90%	100%	90%	109%	106%	109%	77%	
9.63	W	53%	68%	113%	56%	56%	49%	87%	78%	30%	5%	69%	15%	30%	73%	98%	99%	101%	94%	109%	106%	111%	81%	123%
9.77	W	56%	71%	114%	65%	65%	54%	82%	78%	44%	99%	58%		51%	51%	98%	95%	101%	95%	104%	100%	111%	63%	
9.8	W	58%	66%	103%	62%	62%	65%	86%	79%	34%	66%	78%	54%	24%	40%	94%	99%	114%	92%	111%	106%	75%	60%	
9.96	W	61%	70%	88%	68%	68%	43%	92%	72%	49%	107%	72%	49%	20%	76%	99%	100%	100%	91%	102%	103%	108%	86%	
10	W	53%	51%	146%	63%	63%	57%	82%	71%	38%	36%	102%	126%	46%	33%	90%	98%	100%	88%	105%	106%	97%	64%	
10.15	W	56%	70%	131%	71%	71%	53%	87%	79%	40%	59%	88%	87%	34%	55%	97%	99%	100%	96%	110%	107%	109%	82%	130%
10.2	W	56%	70%	81%	65%	65%	38%	86%	81%	42%	65%	76%	78%	23%	58%	99%	99%	101%	94%	105%	107%	110%	80%	119%
10.26	W	64%	71%	113%	66%	66%	74%	86%	88%	39%	65%	75%	43%	27%	66%	97%	99%	81%	92%	108%	105%	107%	61%	
10.37	W	47%	56%	97%	61%	61%	28%	84%	68%	29%	32%	63%	55%	26%	50%	94%	99%	100%	106%	111%	107%	108%	56%	142%
10.4	W	70%	77%	111%	74%	74%	70%	98%	87%	43%	81%	83%	82%	28%	85%	97%	100%	100%	94%	102%	102%	104%	102%	106%
10.82	W	77%	83%	115%	80%	80%	77%	100%	83%	50%	93%	85%	77%	33%	77%	98%	112%	96%	89%	106%	102%	68%	96%	
11.05	W	63%	75%	81%	68%	68%	48%	91%	86%	47%	99%	82%	71%	18%	69%	99%	100%	100%	93%	106%	105%	107%	100%	106%
11.27	W	64%	69%	108%	67%	67%	66%	88%	79%	41%	76%	97%		22%	58%	99%	94%	101%	93%	106%	145%	105%	95%	
11.38	W	67%	72%	116%	71%	71%	57%	93%	83%	47%	94%	105%		22%	77%	99%	94%	100%	96%	106%	104%	108%	83%	
11.47	W	70%	61%	88%	69%	69%	46%	96%	92%	33%	72%	117%		12%	74%	100%	94%	100%	93%	108%	134%	105%	89%	
12.16	W	68%	70%	87%	70%	70%	48%	97%	92%	44%	85%	103%		11%	84%	101%	94%	100%	94%	104%	103%	107%	86%	
12.38	W	64%	73%	90%	74%	74%	58%	90%	95%	52%	98%	97%		26%	57%	99%	92%	100%	95%	109%	107%	110%	84%	
12.62	W	70%	72%	101%	74%	74%	58%	91%	91%	50%	97%	107%		16%	62%	96%	89%	100%	94%	65%	129%	103%	91%	
12.76	W	63%	82%	107%	78%	78%	71%	73%	91%	58%	86%	89%	63%	20%	62%	99%	99%	101%	98%	65%	87%	107%	98%	
12.89	W	63%	75%	94%	68%	68%	58%	79%	90%	46%	55%	80%	4%	11%	78%	100%	101%	68%	91%	100%	102%	108%	63%	
12.99	W	68%	73%	107%	74%	74%	72%	93%	88%	37%	66%	92%	91%	15%	69%	99%	100%	100%	94%	109%	105%	106%	80%	
13.31	W	66%	71%	91%	64%	64%	51%	87%	85%	46%	78%	89%	75%	13%	81%	99%	101%	66%	92%	103%	105%	88%	56%	
15.29	W	82%	78%	89%	77%	77%	78%	97%	97%	61%	92%	104%	94%	9%	83%	97%	100%	100%	97%	105%	104%	106%	82%	

More Impaired — Less Impaired

Figure 2.1-7. Simulated Impaired Flows as a Percentage of Unimpaired Flows Ranked by Water Year Index for the Sacramento River, Its Major Tributaries, and Eastside Tributaries to the Delta for January–June.

2.2 Hydrology of the Sacramento River and Major Tributaries

2.2.1 Sacramento River

The Sacramento River is the longest river in the state of California. There are many factors such as elevation, geology, reservoir operations, flood control structures, and imports to the watershed from the Trinity River system that affect the Sacramento River's hydrology. The main stem Sacramento River flows through the Sacramento Valley from Mount Shasta to the Sacramento-San Joaquin Delta.

The Sacramento River watershed above Shasta and Keswick dams is 6,500 square miles (DWR 2013). The Pit River and the McCloud River are two major tributaries. The high desert region above Shasta Reservoir produces runoff from winter rains, spring snowmelt and summer base flows sustained by large springs. Shasta Reservoir is the largest reservoir in California with a capacity of 4.55 MAF. Releases from Shasta are typically made through the Shasta Power Plant timed for efficient energy production. Nine miles downstream of Shasta Dam is Keswick Reservoir with a capacity of 28 thousand acre-feet (TAF) which re-regulates the flow from Shasta Powerhouse.

The Sacramento River also receives imports from the Trinity River system through operations of the CVP. Annual imports from the Trinity River into Keswick Reservoir averaged 734 TAF per year from water year 1985–2009 (Figure 2.2-1).

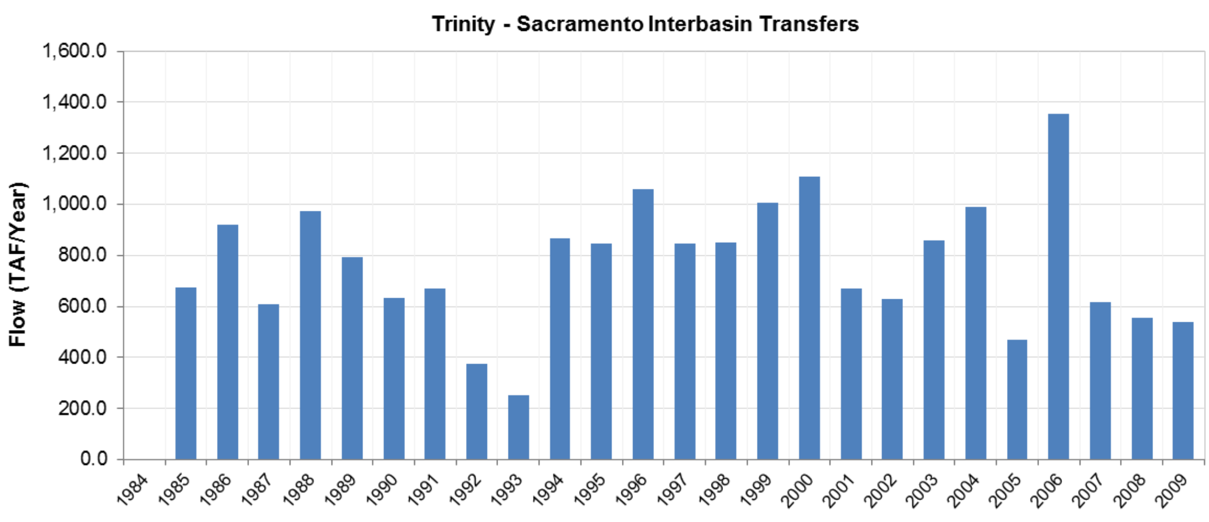


Figure 2.2-1. Annual Total Observed Imports from the Trinity River to the Sacramento Watershed for Water Years 1985–2009 (Source: CDEC)

From Keswick Dam downstream to the city of Redding the channel is generally straight, stable, and bedrock controlled as it runs across the erosion resistant metamorphic rock of the Copley Formation (DWR 2013). From Redding downstream to Red Bluff the channel continues to be bedrock controlled as it runs across the Tehama and Tuscan formations although there are a couple of reaches where the channel can meander. Here the channel, while stable, is no longer straight but has cut deep and sinuous bends into the Tehama and Tuscan formations as well as through basalt flows (WET 1998, DWR 2013).

Releases from Keswick Reservoir are generally lower than unimpaired conditions in the winter and spring, and higher in the summer and fall as shown in the Sacramento River at Bend Bridge boxplot below (Figure 2.2-2). Boxplots within this chapter summarize monthly current hydrologic conditions (gray box) and unimpaired flow (white box) at various locations. Shown in the plots are maximum and minimum flows (top and bottom whiskers), upper quartile (top of box), median (line within box) and lower quartile (bottom of box) of the flow data.

Releases from Shasta and Keswick Reservoirs are controlled by flood operations, agricultural demands in the Sacramento Valley, stream temperature requirements, Delta demands (including salinity control and fish and wildlife protection) and for exports to the Central Valley. Mean annual current flow conditions are higher than mean annual unimpaired flow conditions at Bend Bridge because of imports from the Trinity River. In all but the most extreme years, the Sacramento River at Bend Bridge under current conditions is greater than 70% of unimpaired flow on average during the winter-spring period, although monthly wet season flows are often more impaired, with monthly average flows in the winter and spring of drier years less than 40% (Table 2.2-1).

The Sacramento River, as in other systems dependent on snow pack and snow melt, the typical components of the unimpaired flow regime generally include: fall storm flows, winter storm flows, spring snowmelt and summer baseflows (Kondolf et al. 2001; Cain et al. 2003, Epke 2011, Yarnell et al. 2010, Kondolf et al. 2012, Yarnell et al. 2013). These characteristics are present in the Sacramento Valley streams in nearly all years, with wide temporal variations in magnitude throughout the year and from year to year. These characteristics are illustrated below for a Wet water-year (2011) (Figure 2.2-3) and a Critically Dry water-year (2008) (Figure 2.2-4) respectively for the Sacramento River at Bend Bridge. Though the overall flow magnitudes may be different, the other characteristics of the flow regimes of the other tributaries are all similar. Water diversion and storage has significantly changed the shape of the instream hydrograph. In both water-year types, fall and winter peak flows are reduced. The recession limb of the spring snowmelt is truncated or absent, and summer base flows are augmented. Table 2.2-2 demonstrates a characteristic that is generally common to the watershed where, in drier years when unimpaired flows are already relatively low, a much greater proportional share of the unimpaired flow is diverted from the stream during the wet season, which has a compounding effect on the dry conditions on fish and wildlife.

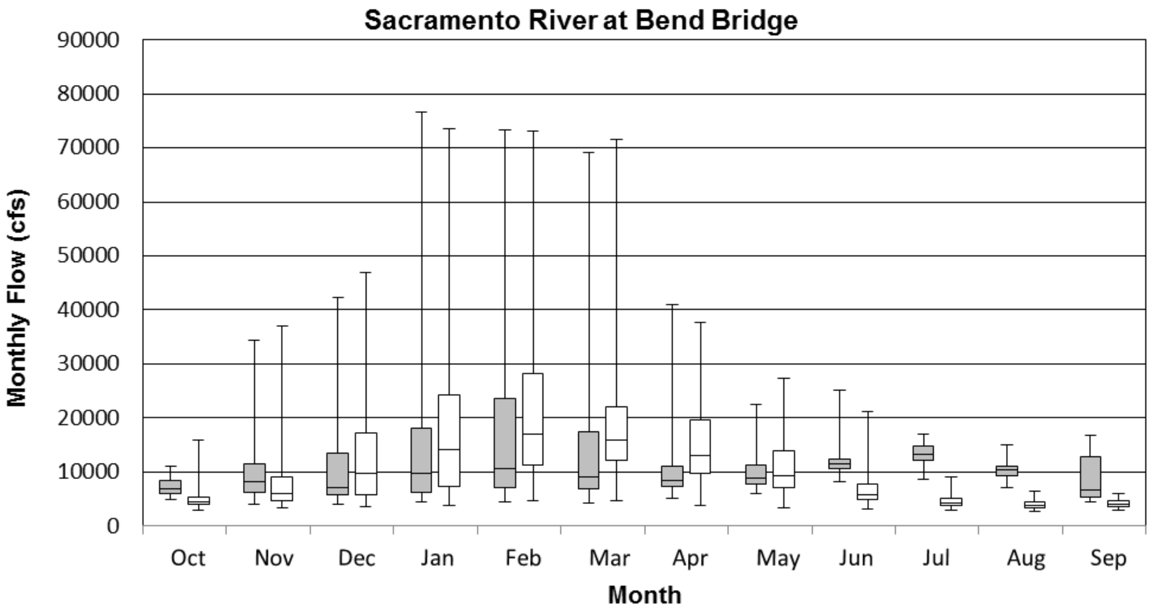


Figure 2.2-2. Sacramento River at Bend Bridge Simulated Current Hydrologic Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-1. Statistics of Impaired Flow as Percent of Unimpaired Flow for the Sacramento River at Bend Bridge

Impaired Flow as a percent of Unimpaired Flow (%)													Seasonal Impairment	
Percentile	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan-Jun	Jul-Dec
0% tile	70	43	38	39	39	34	36	48	99	161	142	79	55	116
10% tile	108	74	63	59	55	48	49	68	111	215	213	129	70	125
20% tile	126	84	68	66	58	53	53	76	132	245	230	141	80	134
30% tile	140	96	73	71	62	56	57	83	152	272	243	150	82	144
40% tile	150	112	81	77	65	59	61	90	166	289	251	159	84	149
50% tile	155	119	88	80	70	64	65	95	185	312	260	176	87	158
60% tile	167	143	93	84	76	69	73	100	209	336	272	212	89	170
70% tile	175	156	98	92	87	74	79	111	223	355	286	247	92	183
80% tile	179	183	107	97	100	82	90	138	255	371	298	279	95	191
90% tile	191	215	112	104	104	96	109	155	293	391	330	331	101	199
100% tile	244	266	155	204	115	161	276	241	398	476	419	448	184	221

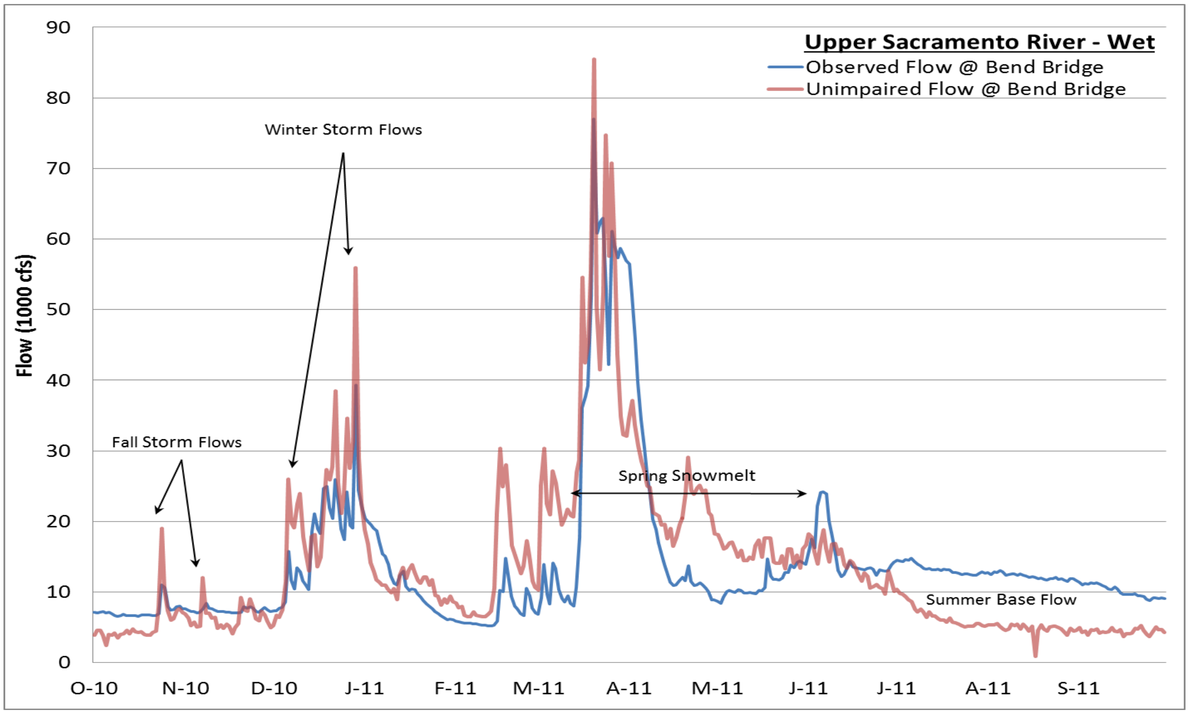


Figure 2.2-3. Daily Hydrograph of the Sacramento River at Bend Bridge for WY 2011 with Unimpaired Flow and Observed Flow[1]

[1] Daily unimpaired flows presented here are produced by DWR as Full Natural Flows (FNF). Source: CDEC.

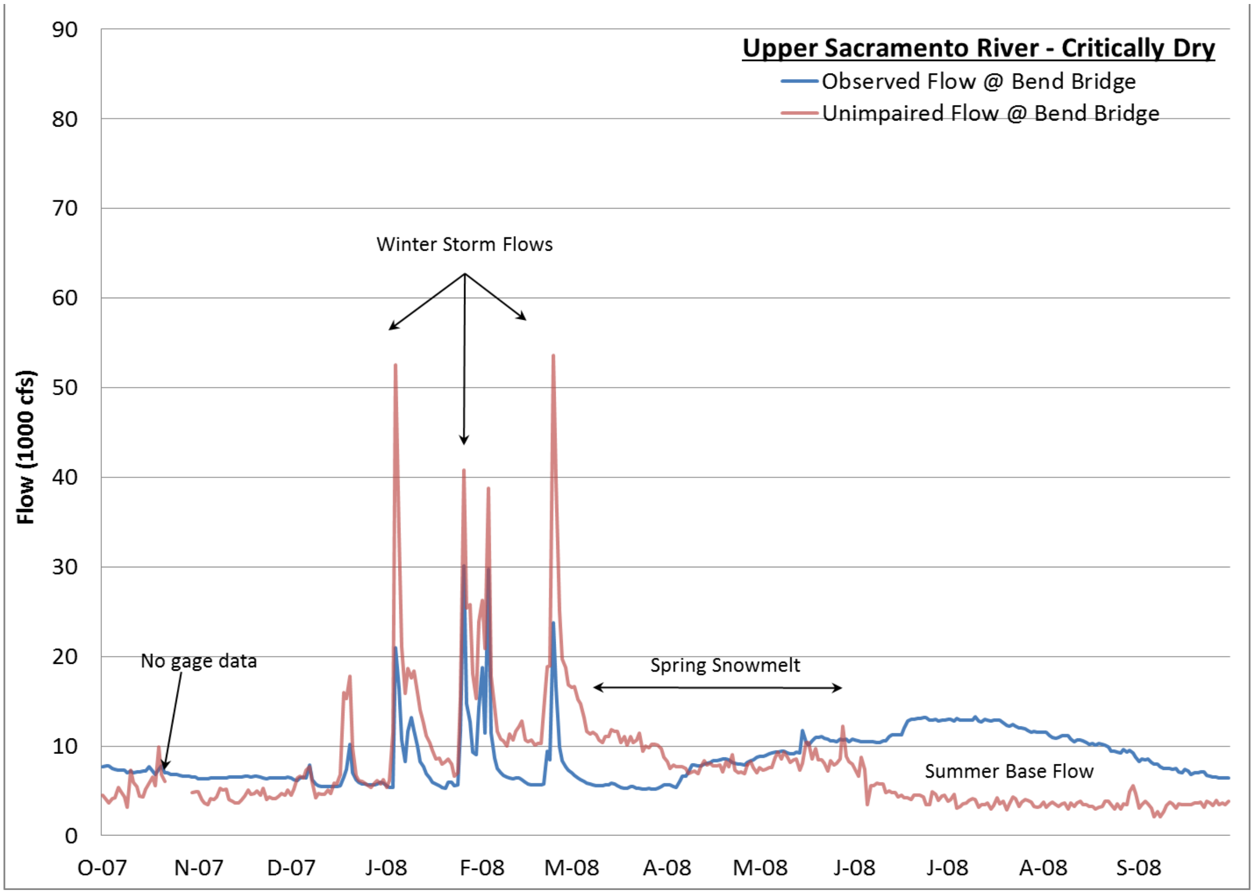


Figure 2.2-4. Daily Hydrograph of the Sacramento River at Bend Bridge for WY 2008 with Unimpaired Flow and Observed Flow[2]

Table 2.2-2. Statistics of Impaired Flow as Percent of Unimpaired Flow for the Sacramento River at Freeport

Impaired Flow as a percent of Unimpaired Flow (%)													Seasonal Impairment	
Percentile	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan-Jun	Jul-Dec
0% tile	63	47	39	44	41	37	29	27	48	66	64	75	48	80
10% tile	85	63	59	60	64	49	36	33	55	103	128	115	57	103
20% tile	98	71	66	73	75	54	38	36	59	138	140	124	61	110
30% tile	104	81	73	79	80	58	41	39	60	175	146	144	63	114
40% tile	110	94	79	86	83	62	44	42	66	205	169	166	67	119
50% tile	116	100	83	92	91	70	47	45	73	230	176	188	70	123
60% tile	127	111	92	97	94	76	50	51	78	256	186	223	73	135
70% tile	133	127	102	102	99	82	67	56	89	291	200	309	78	140
80% tile	138	144	110	107	103	97	76	67	108	339	214	358	81	150
90% tile	149	178	124	116	111	105	86	76	135	374	233	388	90	169
100% tile	204	236	168	159	136	122	146	89	212	582	261	452	111	191

[2] Daily unimpaired flows presented are produced by DWR as Full Natural Flows (FNF). Source: CDEC.

Downstream of Red Bluff the general location of the channel within the Sacramento Valley and its reach specific geomorphology are controlled by geologic fault systems and river sediment loads that are primarily delivered from westside tributaries (Jones et al. 1972, Wet 1998, Schumm 2000, Larsen et al. 2002, DWR 2013). Between Red Bluff to just above Stony Creek the Sacramento River has established a wide flood plain and has a sandy and gravelly bottom. From Stony Creek through the Delta to the town of Clarksburg the channel runs between natural levees and the outboard flood basins (Bryan 1923, Olmsted and Davis 1961, DWR 1994, 2010a, 2010b, Whipple et al. 2012).

Downstream of the city of Sacramento, the river enters the Delta where the hydrograph has been modified by diversions, flood basins and inflows discussed below. At Freeport, the Sacramento River has a greater level of impairment than it does upstream at Bend Bridge (Figure 2.2-5). The largest difference between current conditions and unimpaired flows are in the months of April and May where 20% of the years the flows are below 38% and 36% of unimpaired flows respectively (Table 2.2-2).

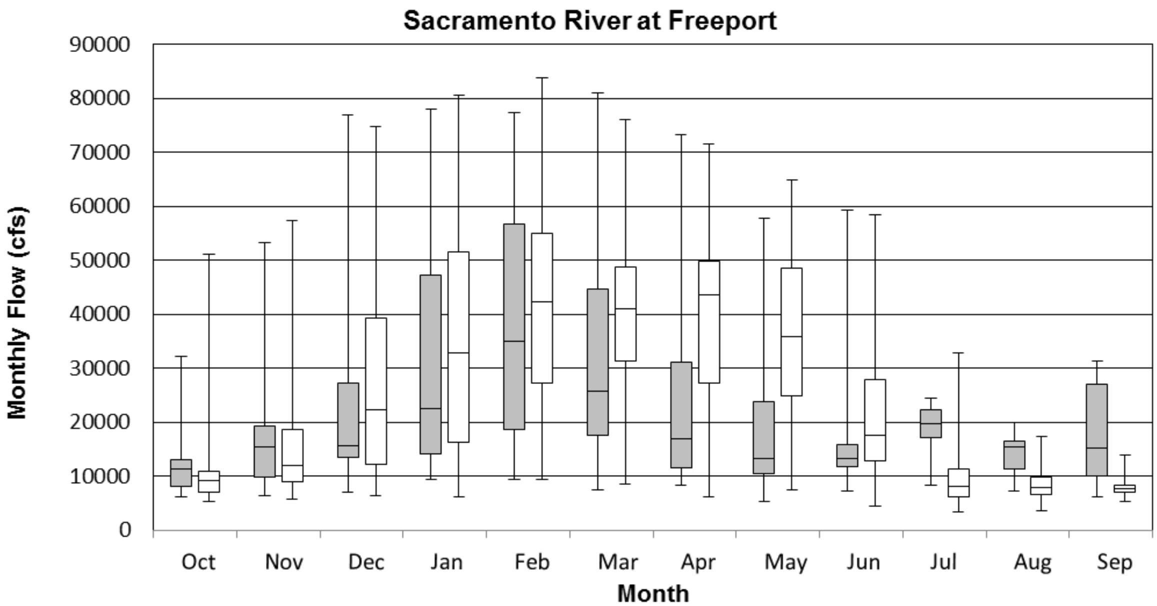


Figure 2.2-5. Sacramento River at Freeport Simulated Current Hydrologic Conditions (gray) and Unimpaired (white) Monthly Flows

2.2.2 Tributaries of Mount Lassen and Volcanic Buttes Region

2.2.2.1 Battle Creek

Battle Creek has a relatively large watershed of 357 square miles most of which is spread among a number of relatively high elevation tributaries (Jones & Stokes 2005, Myers 2012). It has three significant tributaries with headwaters on Mount Lassen (10,500 feet) and two other with headwaters in basins encircled by 7,000-foot peaks. The main stem, north and south forks, and the tributaries run across very complex terrain over volcanic rock of various types and ages (Helley et al 1981, DWR 1984, Clynne and Muffler 2010).

The north fork of Battle Creek is especially unique as it has an unusually low precipitation to runoff ratio and a number of large cold-water springs that discharge at low elevations immediately above impassable fish migration barriers (Jones & Stokes 2005, Myers 2012). The locations of the springs are due to the relatively high elevation of the watershed which favors slower and extended infiltration from melting snow compared to infiltration plus rapid runoff from rain.

Because of the high elevation of most of its watershed Battle Creek has a mixed snow/rainfall runoff regime (Myers 2012). Snow accumulations in the upper watershed store a significant amount of water, dampen large precipitation events, and shift discharge later in the spring. Rain-on-snow events are significant in terms of large stream pulse flows with the largest daily discharge recorded being 35,000 cubic feet per secondf (cfs) (Reclamation 2001). The numerous springs in the watershed contribute to a relatively high late-summer and fall baseflow of 250 cfs and to cool stream water temperatures below the springs (Jones & Stokes 2005, Myers 2012) (Figure 2.2-6). Stream groundwater interaction studies generally indicate that most of Battle Creek receives groundwater discharge (DWR 1984).

Battle Creek has few diversions for consumptive use but has been developed for hydropower and has an extensive system of small dams, diversions, and canals (Jones & Stokes 2005). A restoration program that is nearing completion has removed migration barriers and adjusted or eliminated power generating operations to preserve cold water temperatures and migratory cues for salmonids within the watershed (Jones & Stokes 2005, Greater Battle Creek Watershed Working Group 2016).

Hydropower operations in the Battle Creek Watershed primarily affect flows on a sub-monthly timescale, however Figure 2.2-6 shows on average Battle Creek is lower than unimpaired flows especially in the summer months (see also Table 2.2-3).

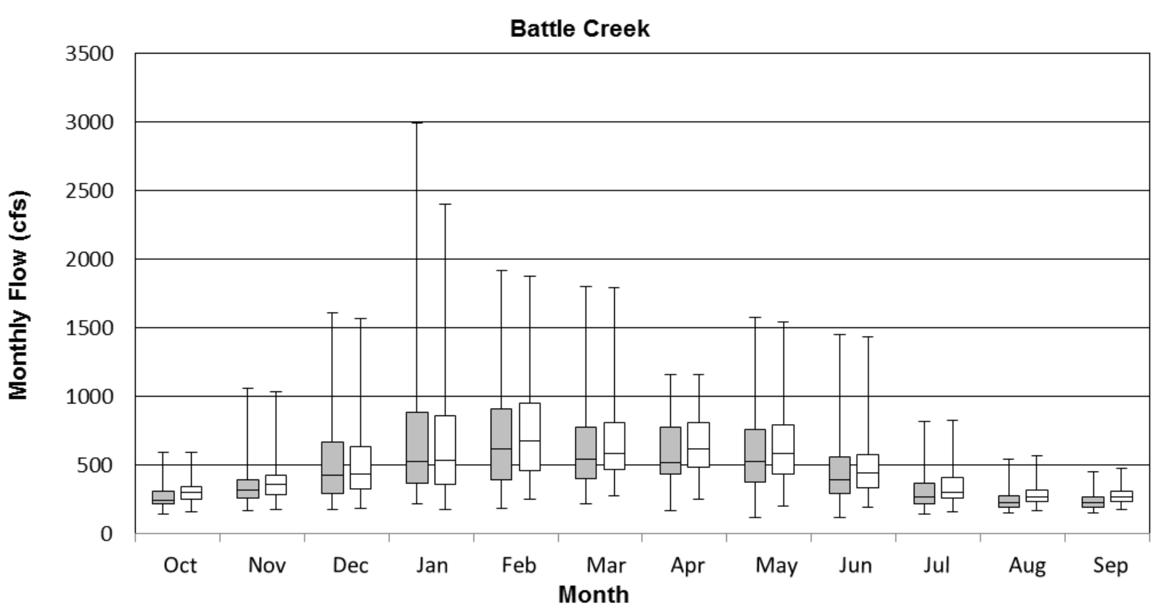


Figure 2.2-6. Battle Creek Simulated Current Hydrologic Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-3. Statistics of Impaired Flow as Percent of Unimpaired Flow in Battle Creek

	Impaired Flow as a percent of Unimpaired Flow (%)												Seasonal Impairment	
Percentile	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan-Jun	Jul-Dec
0% tile	63	71	73	74	41	67	59	59	56	60	51	50	66	62
10% tile	74	79	81	86	72	79	72	81	76	70	68	69	84	75
20% tile	77	81	92	94	78	84	78	86	82	74	72	71	86	81
30% tile	84	88	94	96	85	88	86	90	91	82	80	77	89	86
40% tile	92	92	95	98	93	92	92	93	92	90	89	88	92	93
50% tile	93	93	97	99	95	96	95	95	94	91	90	91	95	94
60% tile	94	95	98	100	96	98	97	96	96	92	91	91	97	95
70% tile	95	96	99	102	98	99	98	97	97	94	92	92	98	96
80% tile	96	97	100	123	99	99	98	99	98	96	94	93	99	97
90% tile	97	98	102	133	100	100	100	100	100	106	98	94	100	99
100% tile	110	103	404	163	102	104	102	102	102	114	103	97	112	158

2.2.2.2 Cow Creek

Cow Creek has a broad and relatively large watershed of 430 square miles that is almost equally divided into fifths among the main stem and four essentially coequal tributaries (SHN 2001, Western Shasta Resource Conservation District 2005). Its headwaters reach peaks that are generally 6,500 to 7,300 feet in elevation so it has a mixed snow/rain precipitation regime. Significant rain-on-snow events can occur with 48,700 cfs being the highest recorded event (SHN 2001). There are no impassable fish migration barriers in the main stem. There are no significant dams in the watershed and therefore simulated current hydrologic conditions are very similar to unimpaired flows (Figure 2.2-7, Table 2.2-4). Stream flow in the lower and middle reaches during the summer and fall is typically very low due to diversions for irrigation, recreation, and hydropower (Western Shasta Resource Conservation District 2005, VESTRA Resources Inc. 2007).

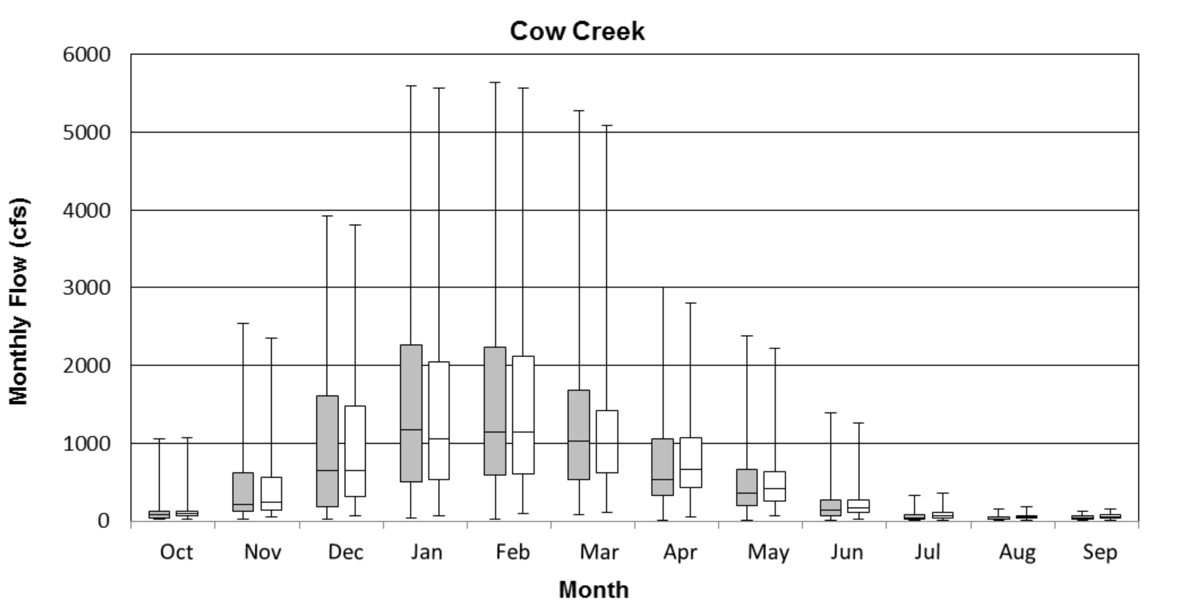


Figure 2.2-7. Cow Creek Simulated Current Hydrologic Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-4. Statistics of Impaired Flow as Percent of Unimpaired Flow in Cow Creek

	Impaired Flow as a percent of Unimpaired Flow (%)												Seasonal Impairment	
Percentile	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan-Jun	Jul-Dec
0% tile	33	21	8	12	5	31	8	13	15	4	5	24	39	29
10% tile	53	53	38	78	58	50	38	40	38	33	35	44	70	59
20% tile	70	85	73	97	75	85	65	71	63	43	40	57	88	81
30% tile	86	94	97	102	98	103	99	95	78	53	50	64	102	90
40% tile	89	98	102	104	101	105	103	101	83	57	57	70	104	94
50% tile	93	101	103	105	104	107	106	103	87	62	62	74	105	97
60% tile	95	103	107	106	105	108	108	104	90	66	65	76	105	98
70% tile	98	105	108	107	107	109	109	107	95	72	68	78	106	100
80% tile	100	109	110	109	108	111	110	109	99	79	74	82	107	101
90% tile	106	114	112	134	110	113	112	111	104	83	80	89	108	105
100% tile	209	184	198	249	146	260	157	267	186	122	104	137	145	162

2.2.3 Tributaries of the Chico Monocline

Tributaries of the Chico Monocline include Antelope, Mill, Deer, and Paynes Creeks. These tributaries are not separately modeled in CalSim II. Antelope Creek, Mill Creek, and Deer Creek are combined in the model, so the box plots showing the current conditions and the estimated unimpaired flow are also combined for these three tributaries. The hydrology for Paynes Creek, like many of the tributaries, has been modeled using very simple methods in CalSim II.

2.2.3.1 Antelope Creek

Antelope Creek has a long and narrow watershed of 202 square miles of which 123 square miles are above the valley floor (Armentrout et al. 1998, Tehama County Resource Conservation District 2010, Stillwater Sciences 2011, 2015). The three forks of Antelope Creek originate on the west and south slopes of 6,900 foot Mount Turner.

Because of the relatively high elevation of its upper watershed Antelope Creek has a mixed snow/rainfall runoff regime (Tehama County Resource Conservation District 2010). Snow accumulations in the upper watershed store a significant amount of water, damp large precipitation events, and shift discharge later in the spring. However, rain-on-snow events can create large daily flows with the largest recorded being 17,200 cfs. The lower elevation portion of the upper watershed receives precipitation primarily as rain and local runoff is rapid due to the shallow soil and impervious surface of the Tuscan Formation which underlies this portion of the watershed. The numerous springs discharging from the canyon walls of the upper watershed also contribute to summer base flow and lower water temperatures (Armentrout et al. 1998) (Figure 2.2-8).

There are few diversions in the upper watershed, but immediately downstream of the mouth of its canyon, Antelope Creek is blocked by the Edwards Ranch/Los Molinos Mutual Water Company diversion dam and water is diverted north and south (Tehama County Resource Conservation District 2010; Stillwater Sciences 2011, 2015). There are several other smaller diversions below the diversion dam. Stream/groundwater interactions on Antelope Creek, while not well understood, are most likely very small.

Fish migration is blocked approximately two to three miles above the confluences of each of the three forks Antelope Creek (Armentrout et al. 1998). Flow related constraints on fisheries are low summer flows from the canyon mouth to the Sacramento River and numerous beaver dams that have the potential to cause stranding and impair migration (Stillwater Sciences 2011, 2015). Mill, Deer and Antelope Creeks have not been significantly impaired on a monthly timescale except in the summer months when diversions reduce the flow making it to the confluence with the Sacramento River (Figure 2.2-8, Table 2.2-5).

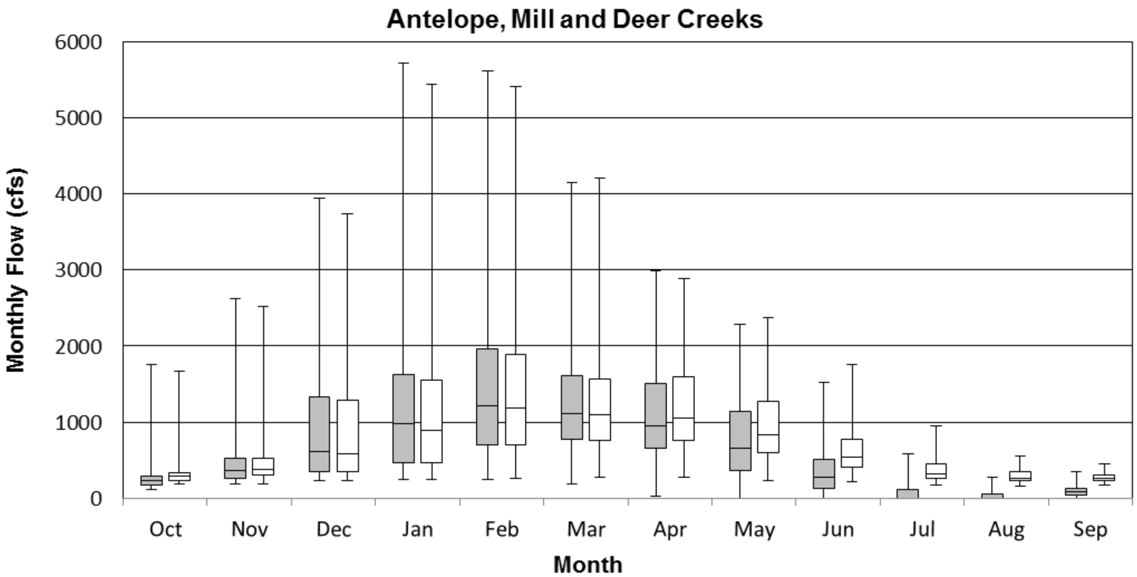


Figure 2.2-8. Antelope, Mill and Deer Creeks Simulated Current Hydrologic Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-5. Statistics of Impaired Flow as Percent of Unimpaired Flow in Antelope, Mill, and Deer Creeks

	Impaired Flow as a percent of Unimpaired Flow (%)												Seasonal Impairment	
Percentile	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan-Jun	Jul-Dec
0% tile	61	74	93	95	77	68	7	0	0	0	0	0	55	41
10% tile	65	92	96	99	97	95	72	50	4	0	0	0	81	52
20% tile	70	94	99	102	99	98	80	62	27	0	0	11	86	57
30% tile	75	96	102	103	101	99	87	68	34	0	0	18	89	61
40% tile	79	98	103	104	102	100	90	73	44	0	0	26	91	63
50% tile	82	99	104	105	103	101	93	79	50	0	0	31	94	66
60% tile	88	101	105	106	104	102	97	82	56	5	3	35	95	69
70% tile	92	102	106	108	104	103	99	85	63	18	12	38	97	74
80% tile	95	103	107	111	105	104	102	90	72	30	20	42	98	78
90% tile	98	104	110	116	106	104	103	94	80	40	28	51	99	84
100% tile	105	111	115	157	110	107	105	99	87	62	49	96	101	91

A zero (0) indicates that simulated current conditions are zero.

2.2.3.2 Deer Creek

Deer Creek has a watershed area of 298 square miles (including the valley reach) (Armentrout et al. 1998, Tompkins and Kondolf 2007) and originates from a number of tributaries flowing from the Mill Creek Plateau, the Lost Creek Plateau, and a number of individual peaks with Butt Mountain, at an elevation of approximately 7,900 feet, being the highest. Because of the relatively high elevation of its upper watershed Deer Creek has a mixed snow/rainfall runoff regime (Armentrout et al. 1998, Tompkins and Kondolf 2007). Snow accumulations and the relatively large area of the meadow system in the upper watershed store a significant amount of water, damp large precipitation events, and shift discharge later in the spring. However, rain-on-snow events can create large daily flows with the largest recorded being 24,000 cfs (Tompkins and Kondolf 2007). The lower elevation areas of the upper watershed receive precipitation primarily as rain and local runoff is rapid due to the shallow soil and impervious surface of the Tuscan Formation.

The late spring and summer hydrology of the valley floor section of Deer Creek has been extensively modified by three diversion dams: Stanford–Vina Ranch Diversion Dam; Cone-Kimball Diversion Dam, and; the Deer Creek Irrigation District Diversion Dam (Tompkins and Kondolf 2007). There is also a flood control levee system that constrains and diverts flood flows up to peak flows of approximately 16,000 cfs (Tompkins and Kondolf 2007) (Figure 2.2-8, Table 2.2-5).

Studies have shown that minimal streamflow is lost to shallow aquifers on the lower portion of Deer Creek (Brown and Caldwell 2013a) (DWR 2004, 2009a).

Fish migration is blocked at Upper Deer Creek Falls (Armentrout et al. 1998). Fishery constraints are restricted to the valley floor reach and include diversion dams that impede or block passage, elevated water temperatures, and low flows in late spring and summer (Armentrout et al. 1998).

2.2.3.3 Mill Creek

Mill Creek has a watershed area of 130 square miles (Armentrout et al. 1998, Kondolf et al. 2001). Its watershed is very narrow and elongated and originates on the upper slopes of Mount Lassen (10,500 feet), flows southward to the Mill Creek Plateau, and soon afterwards bends to the southwest towards the Sacramento Valley (Armentrout et al. 1998, Kondolf et al. 2001, DFW 2014). Mill Creek runs in its deep canyon and has no significant tributaries (Armentrout et al. 1998, Kondolf et al. 2001, Clynne and Muffler 2010, DWR 2014a, Muffler and Clynne 2015).

Because of the relatively high elevation of its upper watershed Mill Creek has a mixed snow/rainfall runoff regime (Armentrout et al. 1998, Kondolf et al. 2001). Snow accumulations on the sides of the high elevation peaks in the upper watershed store a significant amount of water, damp large precipitation events, and shift discharge later in the spring. However, rain-on-snow events can create large daily flows with the largest recorded being 36,400 cfs (Kondolf et al. 2001). The lower elevation areas of the upper watershed receive precipitation primarily as rain and local runoff is rapid due to the shallow soil and impervious surface of the Tuscan Formation. A significant amount of summer and fall baseflow originates from hydrothermal springs on Brokeoff Mountain, Bumpass Mountain, and Diamond Peak (Armentrout et al. 1998, Clynne and Muffler 2010, Muffler and Clynne 2015).

The hydrology of the flood plain section of Mill Creek has been impacted by two diversion dams: Upper Diversion Dam, and; Ward Dam Diversion (Armentrout et al. 1998, Tompkins and Kondolf 2007, DFW 2014, Ta 2015, Tehama Environmental Solutions 2015). Diversions from those dams significantly impact late spring, summer, and fall flows but those impacts are partially mitigated through surface water transfer and groundwater conjunctive use agreements (Reclamation 2002, LMMWC 2007, Ta 2015) (Figure 2.2-8). A stream and groundwater interaction study for a Mill Creek found that that interactions were very small (Brown and Caldwell 2013a).

Fish migration is blocked in Mill Creek 48 miles above the Sacramento River near the Little Mill Creek confluence. (Armentrout et al. 1998). The primary impairments for anadromous fish in the Mill Creek Watershed are low late spring, summer, and fall flows and related temperature issues (Armentrout et al. 1998, Reclamation 2002, LMMWC 2007).

2.2.3.4 Paynes Creek

Paynes Creek has a watershed area of 93 square miles (Tehama County Resource Conservation District 2010) with its origin at an elevation of approximately 5,300 feet. The upper watershed of Paynes Creek receives precipitation primarily as rain and runoff is rapid due to the shallow soil and impervious surface of the Tuscan Formation, which underlies this portion of the watershed. A peak daily flow of 10,600 cfs has been recorded and flows during the summer are very small and the stream can become intermittent (Tehama County Resource Conservation District 2010). There are no dams on Paynes Creek but there are several small diversions that reduce the spring and summer monthly flows significantly as shown below (Tehama County Resource Conservation District 2010) (Figure 2.2-9, Table 2.2-6). Low summer flow is the primary fishery issue for Paynes Creek with summer flows under 10% of unimpaired for almost all of the July-September periods. There are also very significant impairments in the fall, winter and spring of drier years and most years in June and October.

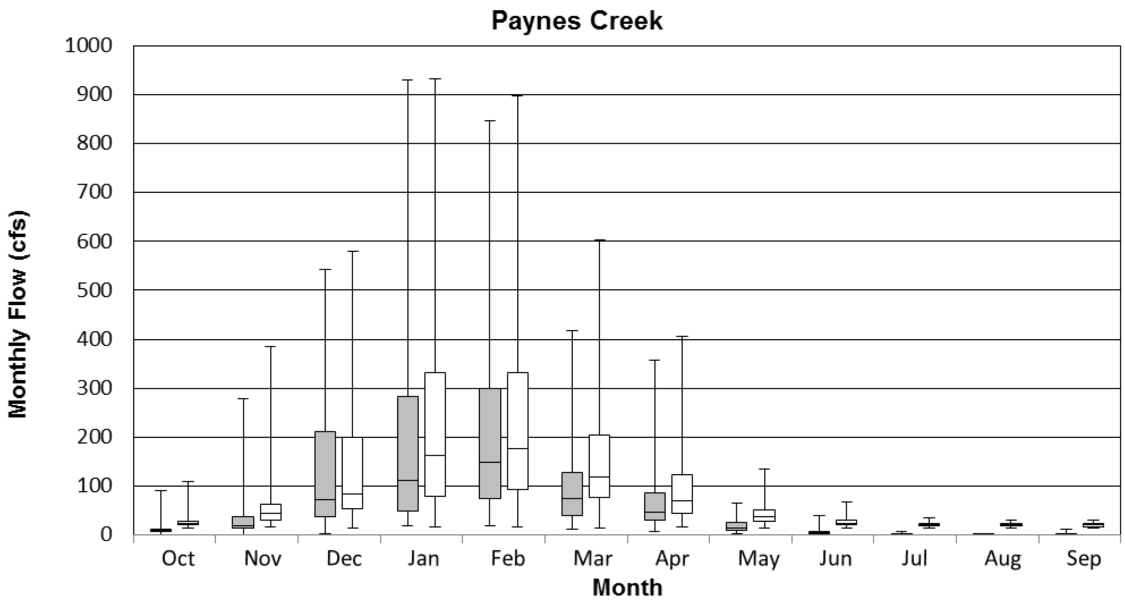


Figure 2.2-9. Paynes Creek Simulated Current Hydrologic Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-6. Statistics of Impaired Flow as Percent of Unimpaired Flow in Paynes Creek

	Impaired Flow as a percent of Unimpaired Flow (%)												Seasonal Impairment	
Percentile	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan-Jun	Jul-Dec
0% tile	1	8	15	33	27	18	30	8	1	0	0	0	38	6
10% tile	10	32	54	53	59	35	46	25	11	2	1	1	52	33
20% tile	27	38	64	60	67	41	52	29	13	3	1	4	56	37
30% tile	32	41	70	64	71	44	57	31	15	3	1	5	61	40
40% tile	33	45	80	67	75	49	62	35	18	3	2	5	64	45
50% tile	35	48	84	74	83	59	67	37	20	4	2	6	69	49
60% tile	36	52	88	80	86	66	70	44	22	5	2	7	76	53
70% tile	39	55	90	85	89	73	80	50	23	5	2	7	80	65
80% tile	42	61	95	89	95	78	87	55	26	5	2	8	83	73
90% tile	47	75	112	100	117	86	97	59	30	6	2	8	91	77
100% tile	81	87	179	131	156	123	238	121	60	22	9	39	102	119

A zero (0) indicates that simulated current conditions are zero.

2.2.4 Tributaries of the Klamath Mountains

2.2.4.1 Clear Creek

Clear Creek has a watershed area of 249 square miles but only 49 square miles and 16 river miles are below the Whiskeytown Dam, as a result reservoir operations completely dominate the hydrology of Lower Clear Creek (Western Shasta Resource Conservation District 1996). Above the reservoir numerous small tributaries head into the Trinity Mountains and a number of isolated peaks with maximum elevations of 6,200 feet (Tetra Tech Inc. 1998). Occasionally there are large winter peak flow events and snow can remain on the peaks through June. Approximately 21% of the volume of water in the Whiskeytown reservoir is from Upper Clear Creek and the other 79% is imported from the Trinity River. Approximately 13% of the stored water is released into Lower Clear Creek and the remaining 87% is diverted to the Spring Creek Powerhouse and discharged into the Sacramento River which reduces the instream flow in Clear Creek to very low levels most of the year (Figure 2.2-10).

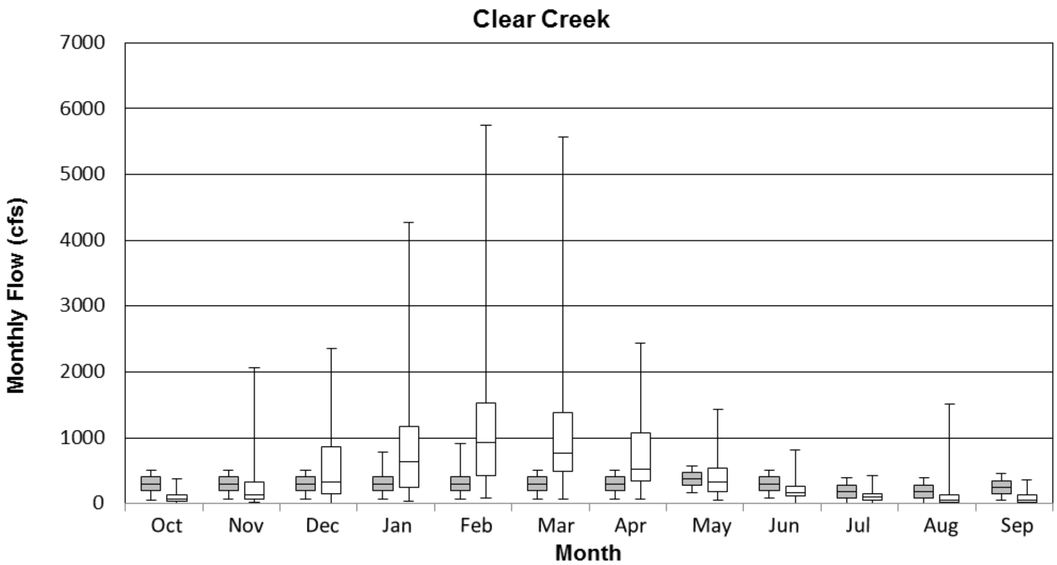


Figure 2.2-10. Clear Creek Simulated Current Hydrologic Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-7. Statistics of Impaired Flow as Percent of Unimpaired Flow in Clear Creek

	Impaired Flow as a percent of Unimpaired Flow (%)												Seasonal Impairment	
Percentile	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan-Jun	Jul-Dec
0% tile	33	10	8	4	3	4	8	19	25	20	6	32	9	20
10% tile	105	28	13	11	8	10	12	36	45	39	43	78	16	39
20% tile	130	48	19	14	11	13	16	45	69	47	59	111	20	49
30% tile	164	74	30	20	15	18	20	55	74	60	77	141	24	57
40% tile	221	104	41	25	18	20	27	66	85	72	114	212	28	72
50% tile	312	155	62	31	22	24	37	85	98	85	160	300	34	82
60% tile	389	175	74	46	30	28	43	111	119	109	223	454	38	106
70% tile	516	232	95	67	41	36	51	129	139	146	325	741	46	145
80% tile	670	308	189	88	50	51	62	146	176	197	387	1623	57	213
90% tile	AZ	454	331	146	74	72	83	220	AZ	AZ	AZ	AZ	79	317
100% tile	-	1700	3843	485	261	279	338	345	-	-	-	-	147	610

A dash (-) indicates that the simulated unimpaired flow is zero.
"AZ" indicates that the unimpaired flow is approaching zero and is very low.

2.2.5 Tributaries of the Paleochannels and Tuscan Formation

2.2.5.1 Butte Creek

Butte Creek is formed by the convergence of a number of small tributaries flowing from the 7,000 foot peaks surrounding the relatively large Jonesville Basin which is at an elevation of 6,000 feet (Butte Creek Watershed Project 1998). Its upper watershed comprises 140 square miles of its total 797 square miles. During the irrigation season Butte Creek discharges through the Butte Slough Outfall Gates at the western side of the Sutter Buttes but otherwise it drains southward into Butte Slough in the Sutter Bypass, passes through large areas of irrigated agriculture, and discharges through the Sacramento Slough into the Sacramento River (Butte Creek Watershed Project 1998).

Because of the relatively high elevation of its upper watershed Butte Creek has a mixed snow/rainfall runoff regime (Butte Creek Watershed Project 1998). Snow accumulations in the upper watershed store a significant amount of water, dampen large precipitation events, and shift discharge later in the spring. The lower elevation portion of the upper watershed receives precipitation primarily as rain and local runoff is rapid due to the shallow soil and impervious surface of the Tuscan Formation which underlies this portion of the watershed. There are infrequent rain-on-snow events which have generated daily flows of up to 26,600 cfs and minimum wet season flows during drought are approximately 500 cfs (Butte Creek Watershed Project 1998).

The hydrology of Butte Creek has been extensively modified and developed. In the upper watershed there are a number of dams, hydroelectric projects, and diversions, and imported water from the Feather River watershed that significantly alter the timing and magnitude of flows and also impact water temperature (Butte Creek Watershed Project 1998). The lower watershed also has a number of diversions and flood control structures and flows are supplemented by imported water from the Feather River watershed (Butte Creek Watershed Project 1998, Williams et al. 2002).

Sacramento River flood flows often completely overtop the valley floor reach of Butte Creek in the Butte and Sutter basins. These combined flows start in the upper two thirds of the Butte Basin and drain into the wide upper end of the Butte Sink area which is the southernmost section and remaining one quarter of Butte Basin. The combined flows enter Butte Sink at the 60-foot elevation contour near the Moulton Weir (Bryan 1923), converge southward, and wrap around the west side of the Sutter Buttes. Butte Sink is bounded to the west by the 30-foot high natural levee of the Sacramento River which forces Butte Creek to the southeast and is bounded to the east by the Sutter Buttes. The naturally incised channel of Butte Creek, while sometimes immersed deeply by basin and sink flood flows, persists as a defined channel that discharges into Butte Slough which drains into the Sutter Basin (USGS 1913, Bryan 1923, Carpenter et al. 1926, Olmsted and Davis 1961, DWR 2012).

Sacramento River flows can enter the Butte Basin through six locations (DWR 2010a, 2010b, 2012). When flows in the Sacramento River exceed 30,000 cfs flood waters flow over the Colusa Weir (70,000 cfs designed capacity) into the main section of the Butte Sink (DWR 2010a, 2012). When flows in the Sacramento River exceed 70,000 cfs, flood waters flow into the upper end of the Butte Sink over the Moulton Weir (25,000 cfs designed capacity) (DWR 2010a, 2012). When flows in the Sacramento River exceed 100,000 cfs water can pass into the basin at its upper end through the M&T and Parrot Plug flow relief structures, the Three-Bs overflow area, and an emergency overflow roadway (DFW 2010a, 2012).

The valley floor reach is known to lose surface water to groundwater recharge where it traverses the Chico alluvial fan but the amount of that loss has not been determined (Moran et al. 2005).

The Quartz Bowl Falls, about a mile below the DeSabla Powerhouse, blocks fish passage (Butte Creek Watershed Project 1998). Low flows and high water temperatures during the summer, imported water obscuring migratory cues from natal stream water, and the lack of a defined channel from the lower Butte Basin to the Sacramento River are the primary fishery issues.

Imported water in the foothill reach provides beneficial colder water during the summer, and runoff from rice fields in the Feather River Service Area augments the flows in other months (Figure 2.2-11, Table 2.2-8). Observed data was used instead of simulated impaired data for Butte Creek because the simplified CalSim II schematic does not represent return flow from Feather River Service Area diverters to Butte Creek and therefore underestimates the flow on Butte Creek. The gage at Durham only partially includes these return flows because many of the return flows such as from Durham MWC, Western Canal WD, Pacific Realty Associates (formerly M&T Chico Ranch), Richvale ID, RD 1004, Biggs-West Gridley WD, and Biggs-West Gridley WD enter Butte Creek below the gage.

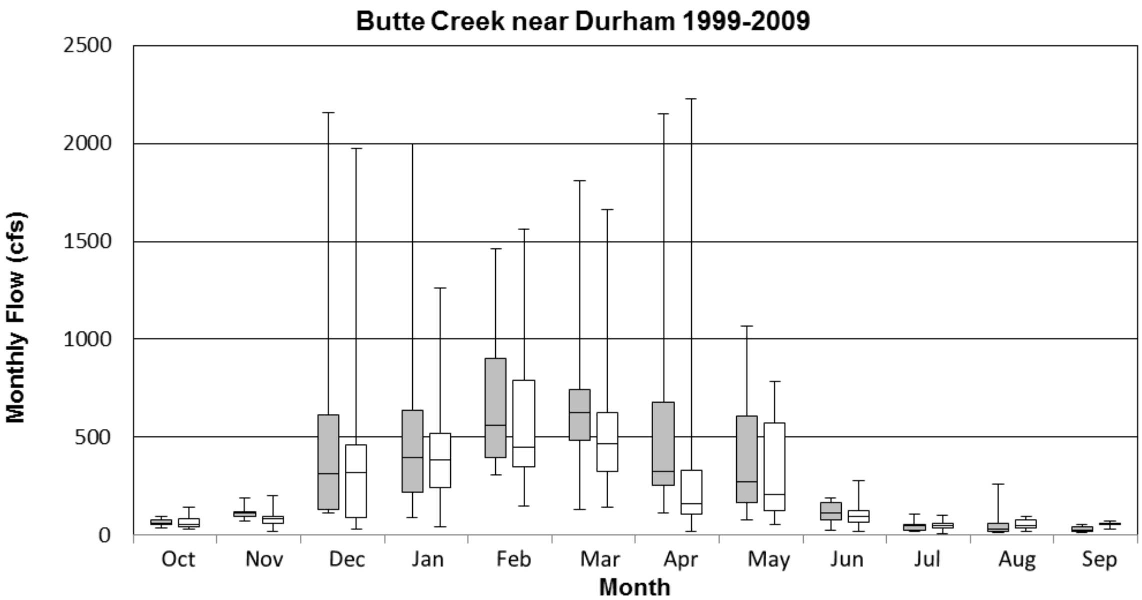


Figure 2.2-11. Butte Current Hydrologic Conditions (gray) as Observed near Durham and Unimpaired (white) Monthly Flows for 1999–2009

Table 2.2-8. Statistics of Observed Flow (Butte Creek near Durham) as Percent of Unimpaired Flow in Butte Creek

	Impaired Flow as a percent of Unimpaired Flow (%)												Seasonal Impairment	
Percentile	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan-Jun	Jul-Dec
0% tile	38	35	12	79	74	90	96	60	55	60	27	25	99	30
10% tile	69	72	42	84	84	91	108	84	57	66	29	28	102	55
20% tile	76	78	50	96	89	105	147	100	96	74	41	28	105	66
30% tile	87	104	70	108	97	110	157	115	120	78	51	45	112	87
40% tile	95	117	99	118	108	112	180	124	126	83	59	54	116	97
50% tile	102	129	141	123	115	125	223	130	131	88	64	55	124	103
60% tile	121	151	187	136	122	143	252	134	139	89	70	60	132	130
70% tile	146	166	220	154	133	153	283	138	146	94	79	67	138	180
80% tile	152	232	332	157	144	157	359	151	150	133	88	70	149	242
90% tile	165	539	838	188	162	164	446	187	158	250	224	82	156	326
100% tile	239	967	2081	452	260	202	900	245	172	345	1379	102	164	331

2.2.5.2 Big Chico Creek

Big Chico Creek originates from surface runoff and springs from Colb Mountain and has a 72 square mile watershed in the foothills (Big Chico Creek Watershed Alliance 2007) and a combined valley/foothill watershed of 359 square miles. Because of Colb Mountain's relatively low maximum elevation of 5,400 feet, most of its precipitation falls as rain but colder winter storms often produce significant amounts of snow which can persist in the shade of the mountain's mixed coniferous forest reducing the peak storm runoff and increasing the duration of winter flows. However, rainfall is the dominant source of precipitation over most of the watershed and runoff is rapid due to the shallow soil and impervious surface of the Tuscan Formation which underlies the entire upland watershed. Big Chico Creek has two significant tributaries, Mud and Rock creeks which originate in the foothills at elevations below 4,000 feet. Their watersheds are also on the Tuscan Formation and therefor runoff is rapid.

There are no large reservoirs or diversions on the upland reaches of Big Chico Creek or its tributaries (Big Chico Creek Watershed Alliance 2007). At the lower end of Butte Meadows at an elevation of 4,400 feet there is a small dam that creates a swimming pond. Big Chico Creek is free flowing from the Butte Meadows to the Five Mile Dam flood control structure which diverts winter flood flows into the Lido Flood Control Channel. Those flows and the flows of the Sycamore Diversion Canal rejoin Big Chico Creek 2.5 miles upstream of its confluence with the Sacramento River. Mud and Rock Creeks join Big Chico Creek below the Lido Flood Control Channel confluence. Below Five Mile Dam is One Mile Dam, an inflatable dam and fish ladder complex that is operated during the warm season to create a swimming pond within the channel of Big Chico Creek. There are a number of small water diversions from Big Chico Creek and its tributaries. Big Chico Creek maintains a summer baseflow of 20–25 cfs in its reach across the valley floor to the Sacramento River while its tributaries become dry before reaching the valley floor.

The valley floor reach is known to lose surface water to groundwater recharge where it and the Lido Flood Control Channel traverse the Chico alluvial fan but the amount of that loss has not been determined (Moran et al. 2005).

The waterfall above the Higgins Hole at river mile 24 on Big Chico Creek is an impassable barrier for anadromous fish. That hole and a number of other holes immediately downstream generally provide excellent over summer holding habitat for spring-run Chinook salmon (Big Chico Creek Watershed Alliance 2007). The reach from the Sacramento River to just upstream of the Lido Flood Control Channel provides good rearing habitat. Juveniles are sometimes stranded in the Lido Flood Control Channel when flood flows drop rapidly. The primary impairments for anadromous fish in the Big Chico Creek Watershed are low late-spring and summer flows and deficiencies of the Iron Canyon Fish Ladder. The hydrology of Big Chico Creek has not been significantly impaired on a monthly timescale by upstream diversions (Figure 2.2-12, Table 2.2-9).

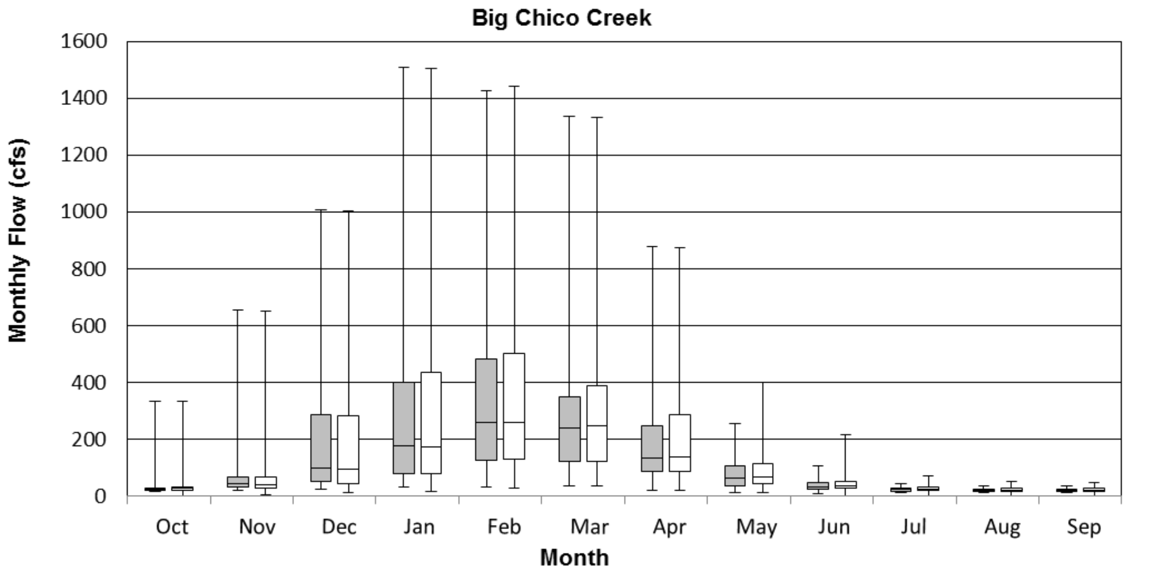


Figure 2.2-12. Big Chico Creek Simulated Current Hydrologic Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-9. Statistics of Impaired Flow as Percent of Unimpaired Flow in Big Chico Creek

	Impaired Flow as a percent of Unimpaired Flow (%)												Seasonal Impairment	
Percentile	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan-Jun	Jul-Dec
0% tile	45	80	59	44	47	51	56	39	32	38	39	40	64	67
10% tile	77	99	100	89	78	73	78	50	52	62	65	69	70	91
20% tile	100	100	100	100	100	89	100	75	99	99	99	99	82	100
30% tile	100	100	101	100	100	100	101	100	100	99	99	99	100	100
40% tile	100	101	101	101	100	100	101	100	100	100	100	99	100	100
50% tile	100	101	101	101	101	100	101	100	100	100	100	100	100	100
60% tile	101	101	101	101	101	101	101	100	100	100	100	100	101	100
70% tile	101	101	101	101	101	101	101	101	100	100	100	100	101	101
80% tile	110	110	107	101	101	101	101	101	100	104	131	122	101	101
90% tile	292	162	141	109	107	101	109	101	102	205	417	343	101	159
100% tile	1194	1208	316	243	165	171	195	198	518	1686	4625	7453	120	400

2.2.6 Tributaries of the Northern Sierra Nevada

2.2.6.1 Feather River

The Feather River has a watershed of 4,400 square miles with 3,600 square miles above Lake Oroville and the remainder below—not counting the watersheds of the Yuba and Bear rivers and other foothill tributaries (Koczot et al. 2005, Sacramento River Watershed Program 2010). It runs to its confluence with the Sacramento River from an elevation of 10,400 feet on Mount Lassen although most of its headwaters in the Sierra Nevada and Diamond Mountains are below 7,000 feet (Koczot et al. 2005).

Above Lake Oroville there are four main forks that include the West Branch, the North Fork, the Middle Fork, and the South Fork. Additionally, the North Fork is often considered to have an Upper North Fork (upstream of Lake Almanor – 1.3 MAF capacity) and an East Branch. The four river forks and two branches of the North Fork provide an average annual inflow to Lake Oroville (3.54 MAF capacity) of 4.54 MAF. PG&E diverts approximately 45 TAF from the West Branch through the Toadtown Canal to Butte Creek. The South Feather Power Project diverts approximately 85 TAF per year from Slate Creek (tributary of the North Yuba River) into the Feather Watershed. Additionally, Sierra Valley on the Middle Fork and Indian Valley on the East Branch contain large areas of irrigated agriculture for forage and hay (Koczot et al. 2005, George et al. 2007).

With the generally low elevation of the ranges and because approximately 60% of the watershed lies below the 5,500 foot snow line, the type of precipitation is very sensitive to temperature frequently with rain-on-snow during the day and snow at night (Koczot et al. 2005). The Feather River watershed is responsive to large rain-on-snow events and during February 1986 instantaneous inflow to Lake Oroville reached 266,000 cfs (USGS 2013). The timing of peak monthly inflow into Lake Oroville varies from March through May according to the phase of the Pacific Decadal Oscillation and hydropower operations (Koczot et al. 2005).

Oroville Dam is an impassable fish barrier and the loss of habitat is a major impact to fisheries although spawning habitat restoration actions are being implemented in the Lower Feather River (DWR 2007). Flows in the Lower Feather river are highly dependent on releases from Oroville Dam and diversions from Thermalito Afterbay. Additional diversions for agriculture by water rights holders as well as SWP contractors reduce instream flows above the confluence with the Yuba River. The large effect of SWP operations on the Feather River are shown in Figure 2.2-13 and Table 2.2-10, where under current conditions winter and spring flows are greatly reduced and summer flows are much higher than unimpaired flows. The January-June impairment of the Feather River above the confluence with the Yuba River ranges between 10% and 94%, and more than half of the years modeled, the impaired flow is only 38% of the estimated unimpaired flow (Table 2.2-10).

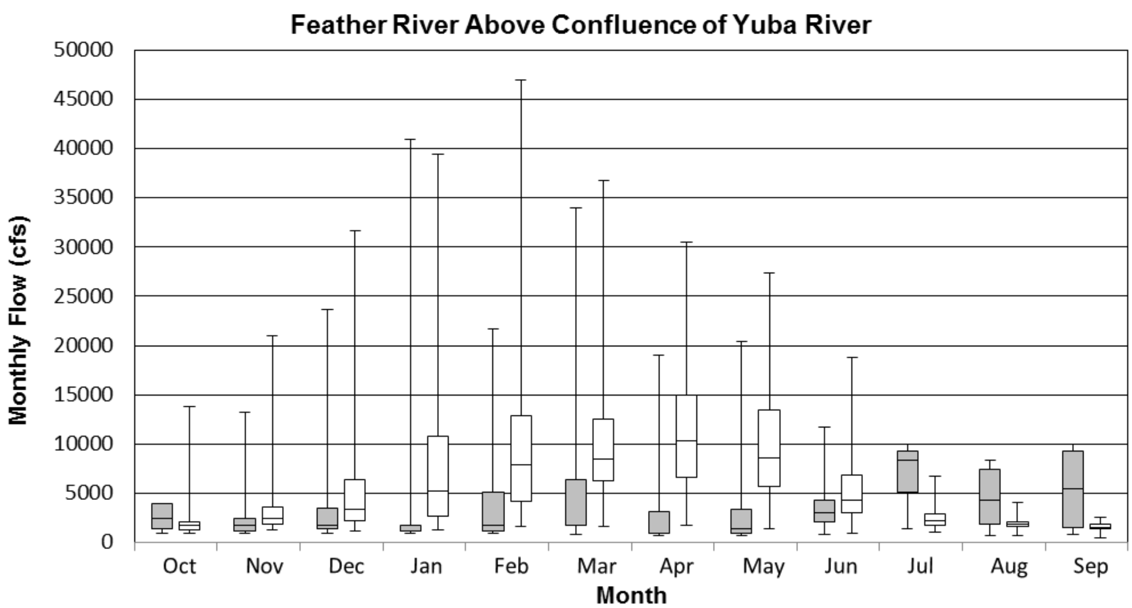


Figure 2.2-13. Feather River above the Confluence with the Yuba River Simulated Current Hydrologic Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-10. Statistics of Impaired Flow as Percent of Unimpaired Flow in Feather River above Confluence with Yuba River

	Impaired Flow as a percent of Unimpaired Flow (%)												Seasonal Impairment	
Percentile	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan-Jun	Jul-Dec
0% tile	9	6	5	5	4	3	4	6	11	28	25	52	10	44
10% tile	66	35	16	15	10	14	7	10	26	108	65	74	19	79
20% tile	81	46	24	20	17	15	9	12	40	183	90	120	24	107
30% tile	94	56	33	24	22	19	11	14	51	233	133	164	28	119
40% tile	121	64	42	33	31	25	13	17	55	278	203	268	30	137
50% tile	163	71	52	41	36	31	19	23	64	332	246	345	38	150
60% tile	184	81	64	49	46	39	22	36	82	385	273	392	44	168
70% tile	200	98	79	63	53	58	28	44	106	430	355	468	50	195
80% tile	211	106	98	75	66	75	40	52	131	465	402	502	57	214
90% tile	235	123	178	95	88	90	53	64	160	527	431	550	66	250
100% tile	314	174	271	146	103	125	94	151	307	792	489	648	94	337

Groundwater interactions are complex along the Lower Feather River as they respond to droughts, seasonal groundwater pumping, seepage from the Thermalito Reservoir, local expression of the underlying geologic formations, and flows from the river channel through underlying paleochannels of the Feather River (Busacca et al. 1989, Baker and Pavlik 1990, Blair et al. 1992, CDM 2008, Springhorn 2008, Wood Rodgers 2012).

Below inflows from the Yuba and Bear Rivers, the much larger Feather River (Figure 2.2-14) meanders for 12 miles where two minor agricultural diversions exist before meeting with the Sacramento River. The Yuba and Bear Rivers add more flow in the spring to the Feather River, often increasing the percent of unimpaired flow reaching the Sacramento River. Above the confluence with the Sacramento River, the January-June impaired flow as a percentage of unimpaired flow ranges from 28%-114% and is less than 53% in half of the years. Monthly average unimpaired flows during the fall, winter and spring are significantly lower in drier conditions, with flows less than 10% in some months of the driest years (Table 2.2-11).

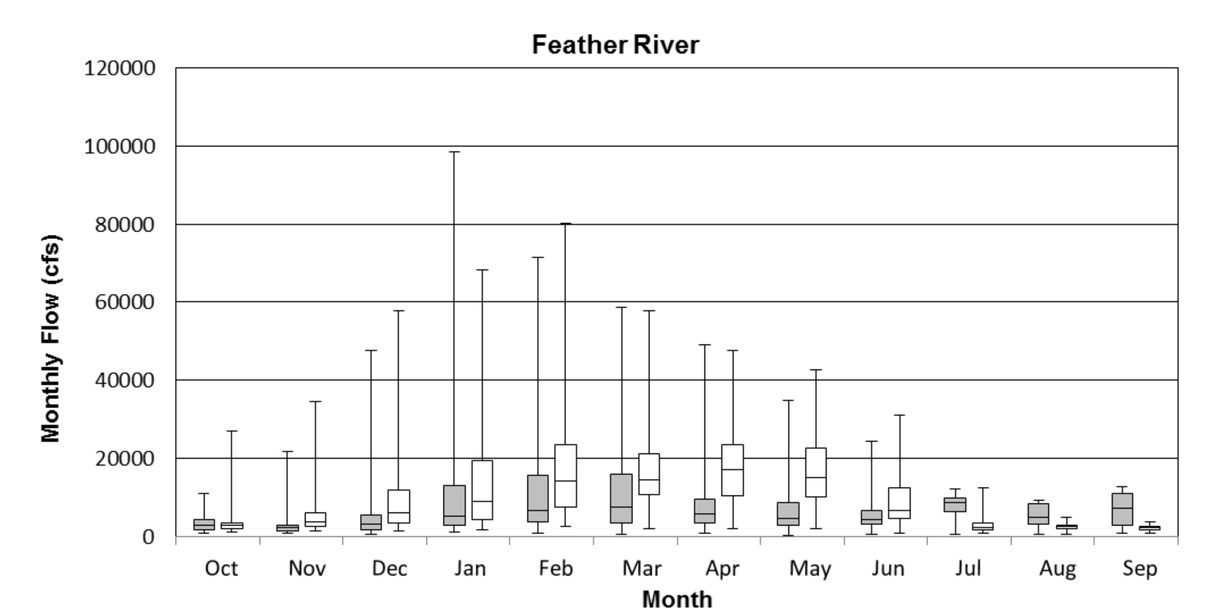


Figure 2.2-14. Feather River at the Confluence with the Sacramento River Simulated Current Hydrologic Conditions and Unimpaired Monthly Flows

Table 2.2-11. Statistics of Impaired Flow as Percent of Unimpaired Flow in Feather River above Confluence with Sacramento River

	Impaired Flow as a percent of Unimpaired Flow (%)												Seasonal Impairment	
Percentile	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan-Jun	Jul-Dec
0% tile	36	15	4	10	7	5	13	16	34	40	41	60	28	45
10% tile	53	30	17	35	27	24	26	22	40	84	74	117	37	75
20% tile	67	41	27	49	38	32	29	26	47	142	106	150	43	85
30% tile	83	47	35	56	43	36	31	29	51	204	143	204	46	100
40% tile	93	53	44	65	52	45	34	33	59	256	167	253	47	109
50% tile	108	61	52	70	57	56	38	36	67	308	197	291	53	123
60% tile	124	67	62	79	62	67	44	42	73	347	248	360	58	137
70% tile	128	73	68	88	71	79	47	50	87	385	292	420	62	151
80% tile	136	87	83	104	88	95	59	58	110	439	311	454	70	172
90% tile	166	93	143	120	109	106	75	67	131	546	362	530	80	197
100% tile	272	119	222	151	194	152	115	115	271	1048	442	621	114	243

2.2.6.2 Yuba River

The Yuba River has a watershed of 1,339 square miles and runs to its confluence with the Feather River from an elevation of 8,600 feet at the crest of the Sierra Nevada (HDR and SWRI 2007). There are three forks with the following watershed areas: North Fork, 490 square miles, Middle Fork, 210 square miles, and; South Fork 350 square miles (UYRSPST 2007). The Yuba River watershed is responsive to rain-on-snow events and during the January 1997 rain-on-snow event instantaneous flow at Marysville reached 180,000 cfs (Entrix 2003). Historically, prior to the construction of New Bullards Bar and Englebright dams, peak monthly runoff was generated by snow melt during April and May (Pasternack 2009). Flows in the Lower Yuba River during the July to January low-flow season appear to have increased since construction of the dams (Pasternack 2009) but stream flow gage records only began after most of the high elevation dams had been constructed.

The North and Middle forks of the Yuba River join in the foothills just below New Bullards Bar Reservoir and a few miles more downstream are joined by the South Fork. Yuba River can be naturally divided into three sections. The upper sections of each of the three forks run through a series of glaciated basins at elevations ranging from 5,500 feet to 7,000 feet (James et al. 2002, James 2003, NID 2011). Below the glaciated basins to the toe of the foothills just below Englebright Reservoir the three forks and main stem run through deep and narrow parallel canyons with relatively steep gradients (NID 2011).

There are many hydropower reservoirs and diversions in the upper watershed which affect the timing of inflows to New Bullards Bar Reservoir. Additionally there are major transfers of water out of the watershed. The Slate Creek Diversion (discussed above in the Feather River section) diverts on average about 85 TAF per year from the North Fork Yuba River into the Feather River watershed and the Drum Canal diverts on average about 350 TAF per year from the South Fork Yuba River to the Bear River.

Engelbright Dam blocks fish passage on the Yuba River and the major impacts to fisheries are primarily due to the loss of spawning habitat above Engelbright and the other dams. There have been a number of operations agreements to maintain flow and water temperature below Englbright Dam (Pasternack 2009, NID 2011, USACE 2013, 2014) and provide spawning habitat restoration actions in the Lower Yuba River (Pasternack 2009, NID 2011, USACE 2013, 2014). Plans for fish passage above Englebright Reservoir and New Bullards Bar Reservoir are being discussed as part of the Biological Opinion for continued operation of Englebright Reservoir and Daguerre Point Dam and the multiple Federal Energy Regulatory Commission (FERC) projects going through relicensing in the Yuba River Watershed (DWR 2016b).

Groundwater interactions are complex along the Lower Yuba River as they respond to droughts, seasonal groundwater pumping, and movement of stream water into and out of the large deposits of hydraulic mining sediment (Entrix 2003). However, despite those complexities, flow in the Lower Yuba River is dominated by the operations of New Bullards Bar Reservoir and diversions at Daguerre Point. Reservoir storage and diversions on the Yuba River have greatly reduced flows on the lower Yuba during the spring months, have reduced winter peak flows and have reduced the variability in monthly flows (Figure 2.2-15). The winter-spring Yuba River impaired flow as a percentage of unimpaired flow ranges from 33%-85% and is less than 53% half of the years. Flows in drier years of all months are also significantly reduced (Table 2.2-12).

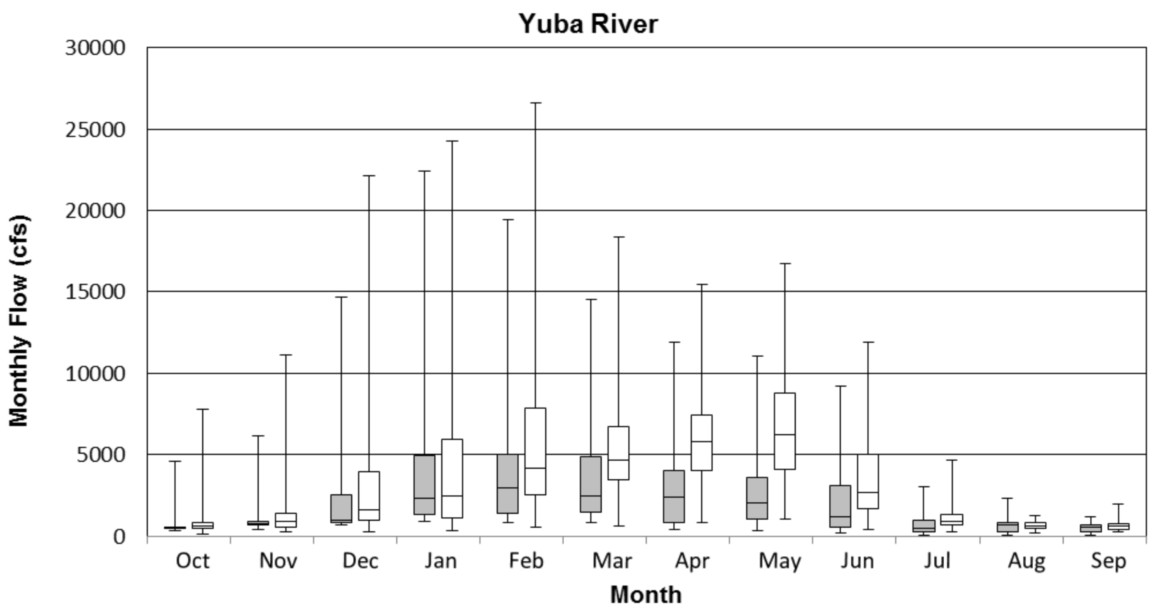


Figure 2.2-15. Yuba River at the Confluence with the Feather River Simulated Current Hydrologic Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-12. Statistics of Impaired Flow as Percent of Unimpaired Flow in Yuba River

	Impaired Flow as a percent of Unimpaired Flow (%)												Seasonal Impairment	
Percentile	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan-Jun	Jul-Dec
0% tile	36	31	25	38	32	31	12	16	10	15	16	13	33	38
10% tile	56	47	46	53	50	37	19	20	26	28	33	38	38	60
20% tile	62	54	53	63	54	44	22	23	33	34	39	43	40	63
30% tile	66	61	62	73	61	48	25	28	37	39	48	59	43	67
40% tile	75	72	68	86	65	53	32	31	45	43	68	66	48	69
50% tile	80	82	73	92	69	55	38	34	53	53	83	80	53	72
60% tile	87	98	82	105	74	61	46	38	58	62	99	91	59	75
70% tile	92	110	92	116	86	79	50	41	61	74	110	96	64	78
80% tile	101	131	102	141	89	86	53	48	66	85	119	103	68	84
90% tile	130	150	132	159	107	92	60	59	72	99	133	116	72	92
100% tile	274	299	242	360	197	145	77	75	97	154	190	172	85	147

2.2.6.3 Bear River

The Bear River has a watershed of 292 square miles and runs from an elevation of 5,500 feet in the Sierra Nevada to its confluence with the Feather River. The Bear River can be divided into an upper section above Rollins Reservoir, a middle section above Camp Far West Reservoir, and a lower section in the Sacramento Valley from Camp Far West Reservoir to the Feather River Confluence (James 1989).

The hydrology of the Bear River has been extensively altered through a complex series of power diversion and storage dams, exports and imports of water to and from adjacent watersheds, and the filling and subsequent incision of the hydraulic mining sediment in the channel (SWRB 1955, James 1989, NID 2008, 2010,2011, NMFS 2014). Low minimum flow releases from Camp Far West Reservoir during most of the year are the largest impact on anadromous fish in the river (NMFS 2014), with flows below 20% of unimpaired in nearly all months of drier years (Figure 2.2-16).

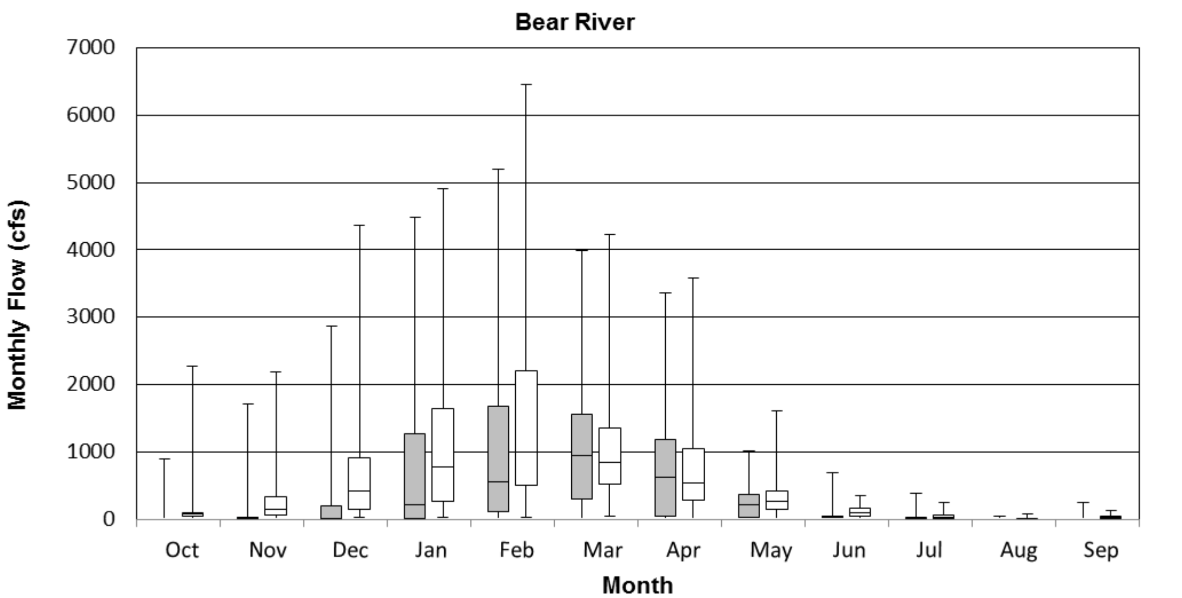


Figure 2.2-16. Bear River at the Confluence with the Feather River Simulated Current Hydrologic Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-13. Statistics of Impaired Flow as Percent of Unimpaired Flow in Bear River

Impaired Flow as a percent of Unimpaired Flow (%)													Seasonal Impairment	
Percentile	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan-Jun	Jul-Dec
0% tile	0	2	1	1	2	2	3	0	7	8	0	0	5	4
10% tile	8	3	2	3	4	8	11	12	17	16	32	11	15	7
20% tile	9	4	3	4	7	50	21	28	21	22	50	16	31	8
30% tile	11	5	4	6	31	67	50	42	25	30	89	20	50	10
40% tile	12	7	7	8	45	90	83	68	36	36	AZ	29	62	13
50% tile	13	10	8	33	62	104	99	79	48	53	-	35	81	19
60% tile	15	12	11	60	78	111	116	96	60	83	-	45	89	23
70% tile	19	17	27	78	92	118	130	101	72	AZ	-	AZ	93	33
80% tile	25	26	67	96	102	134	145	105	AZ	-	-	-	105	55
90% tile	37	62	85	110	128	152	AZ	AZ	-	-	-	-	113	73
100% tile	110	646	139	167	248	422	-	-	-	-	-	-	218	108

A zero (0) indicates that the simulated current conditions are zero.
A dash (-) indicates that the simulated unimpaired flow is zero.
"AZ" indicates that the unimpaired flow is approaching zero and is very low.

2.2.6.4 American River

The American River has a watershed of 1,900 square miles that ranges in elevation from 23 to more than 10,000 feet (USFWS 1995). In the lower foothills, the river branches into the North, Middle, and South Forks. Additionally, the South and Middle forks have significant tributaries, Silver Creek and the Rubicon River, respectively (PCWA 2007; FERC 2008; NID 2008). The American River watershed is very responsive to rain-on-snow events as it has an almost equal proportion of rain and snow, a significant area of its watershed at moderate elevations, is located where storms are most likely to produce intense precipitation, and is in the relatively small region of the Sierra Nevada and Cascade Range that becomes warmest during rain-on-snow events (Dettinger 2005). During the January 1997 rain-on-snow event instantaneous inflow to Folsom Reservoir reached 253,000 cfs (NOAA 2016).

There are a large number of diversions in the watershed, 13 major reservoirs, imports of water as well as transfers between the three forks (USFWS 1995, PCWA 2007, FERC 2008, NID 2008, NID 2011). Hydropower reservoirs, diversions and inter-basin transfers upstream of Folsom Reservoir reduce the inflow to Folsom Reservoir during the spring and increase the inflow during the summer months. There are two transfers of water into the American Watershed; one via the South Canal from the Bear River which transfers about 100 TAF per year on average and one from Sly Park Creek, a tributary of the Cosumnes River, of approximately 20 TAF per year. There are two main diversions above Folsom Reservoir to Placer County Water Agency and El Dorado Irrigation District.

Folsom Reservoir is operated for flood control, urban uses within the basin, Delta salinity control, and agricultural uses south of the Delta. How each of these uses control releases can be complex, however flows on the lower American are lower in the spring and higher in the summer when compared to unimpaired conditions (Figure 2.2-17). Table 2.2-14 shows that current conditions are less than 50% of unimpaired flow at the mouth of the American River nearly 80% of the time in April and 90% of the time in May. January – June unimpaired flows ranges from 23% to 83%.

Groundwater interactions north of the current channel are dominated by well pumping in the Mehrten and Laguna formations (DWR 1974) and now is considered to be a losing reach (DWR 2013a).

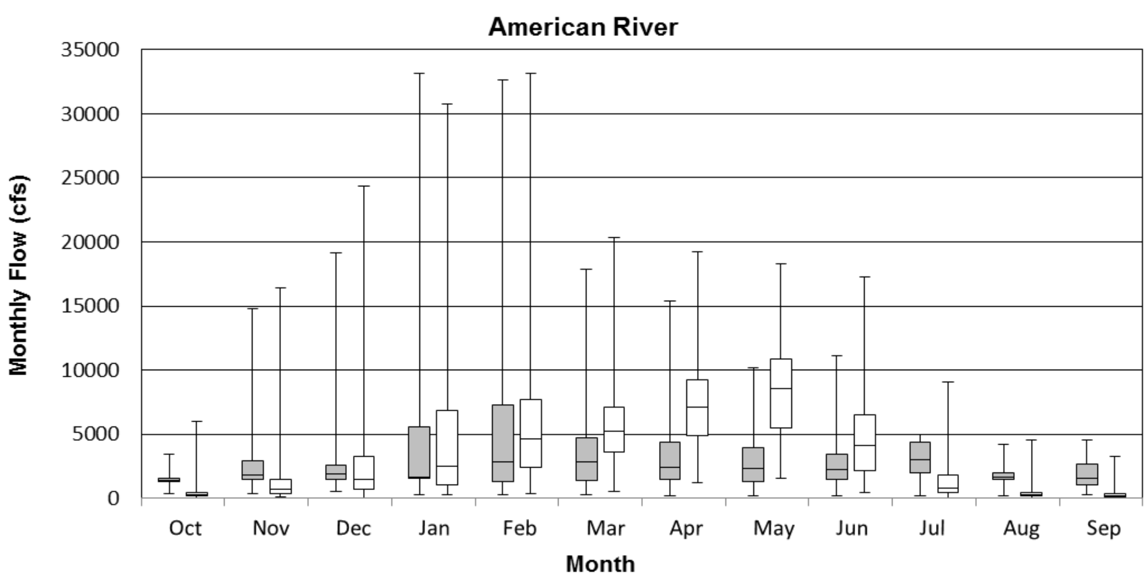


Figure 2.2-17. American River at the Confluence with the Sacramento River Simulated Current Hydrologic Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-14. Statistics of Impaired Flow as Percent of Unimpaired Flow in American River

	Impaired Flow as a percent of Unimpaired Flow (%)												Seasonal Impairment	
Percentile	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan-Jun	Jul-Dec
0% tile	24	39	16	19	14	11	8	9	20	15	13	30	23	26
10% tile	139	70	50	35	36	22	17	17	37	80	136	231	34	109
20% tile	297	118	70	67	55	33	23	23	44	97	359	430	40	147
30% tile	363	148	79	88	66	40	30	25	48	167	464	590	46	177
40% tile	447	189	93	92	80	48	33	26	54	235	533	728	49	206
50% tile	506	271	117	99	85	55	36	30	58	321	579	860	50	248
60% tile	561	351	151	102	94	63	41	34	63	466	627	1036	55	290
70% tile	727	464	236	108	98	68	44	37	70	612	719	1142	66	433
80% tile	895	596	294	159	102	75	51	42	81	805	848	1440	70	494
90% tile	1210	806	512	212	114	79	58	50	132	1064	1150	1895	73	622
100% tile	2095	2240	1454	314	172	91	80	122	384	4542	3638	4760	83	1042

2.2.7 Tributaries of Eastside of the Delta

Three rivers with very different hydrological responses comprise this grouping. The Mokelumne and Calaveras Rivers are within the San Joaquin fluvial fan system while the Cosumnes River occupies a small geological and hydrological gap between that system and the northern Sierra Nevada tributaries.

2.2.7.1 Mokelumne

The Mokelumne River watershed is 660 square miles and extends from 10,400 feet in the Sierra Nevada to sea level at its confluence with the San Joaquin River in the Delta (RMC 2006, 2007). The watershed is generally divided into an upper section with three large forks, a middle section with the Pardee and Camanche reservoirs and no significant tributaries, and a lower section which connects to the San Joaquin River and the Cosumnes River and Dry Creek (historically). It is highly regulated with hydropower dams and diversions in the upper watershed, large storage reservoirs in its middle section, a diversion dam, channel modifications, and flood control levees on its lower section. The hydrology of the Mokelumne River is dominated by the flows of its North Fork and the many dams and diversions on its mainstem and tributaries.

The North Fork is its largest tributary at 370 square miles and produces 85% of the river's flow (RMC 2006). Because of the high elevation of its catchment, much of the North Fork's flow originates from melting snowpack which, while reduced and truncated by power generating dams (Ahearn et al. 2005), sustains high flows into Pardee and Camanche reservoirs through July in wet years and through May in dry years (Piper et al. 1939, RMC 2006, 2007).

Pardee and Camanche reservoirs are operated by East Bay Municipal Utility District (EBMUD) with the purposes of flood control, urban uses and hydropower. EBMUD diverts approximately 200 TAF per year on average from Pardee Reservoir through the Mokelumne Aqueduct. Below Camanche Reservoir, the lower Mokelumne River winds through a pattern of incised channels. There are many diversions on the Mokelumne River for agricultural uses, the largest at Woodbridge Diversion Dam.

Current simulated flow conditions on the Mokelumne River above the confluence with the Cosumnes River are much lower for all months except the late summer and fall when compared with the unimpaired simulation (Figure 2.2-18). The unimpaired flow reaches zero frequently in July through December and is zero in 80% of the years in July (Table 2.2-15). Reservoir operations and diversions on the Mokelumne River have reduced the current flows to below 25% of the unimpaired January-June flows in 60% of the years.

During the Federal Energy Regulatory Commission license modification process for the Lower Mokelumne River negative fishery effects were identified as insufficient flow, insufficient habitat, migration barriers, and predatory fish. In 1996 the Joint Settlement Accord was concluded and East Bay Metropolitan Utility District assumed responsibility for a range of stream flow, reservoir cold-water pool, habitat restoration, and predator control responsibilities (EBMUD 1996).

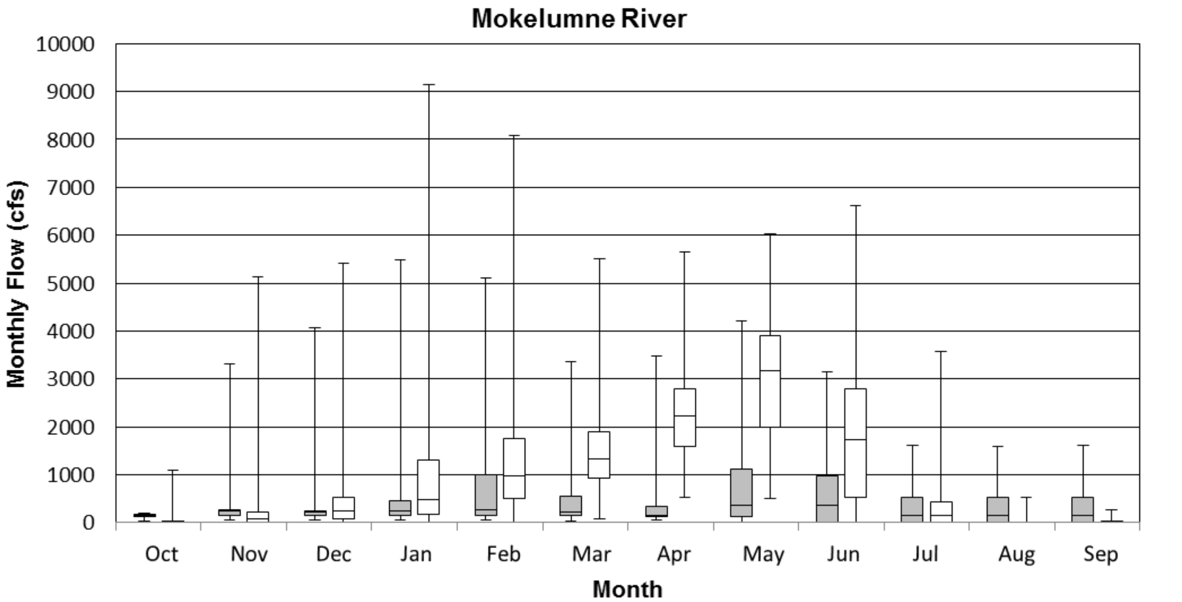


Figure 2.2-18. Mokelumne River at the Confluence with the San Joaquin River Simulated Current Hydrologic Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-15. Statistics of Impaired Flow as Percent of Unimpaired Flow in Mokelumne River

	Impaired Flow as a percent of Unimpaired Flow (%)												Seasonal Impairment	
Percentile	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan-Jun	Jul-Dec
0% tile	10	12	12	2	4	1	4	0	0	0	70	39	6	36
10% tile	144	74	30	19	11	10	5	4	0	0	AZ	3598	10	80
20% tile	266	102	41	31	23	13	6	6	0	14	-	AZ	14	97
30% tile	530	116	60	41	30	16	7	7	0	66	-	-	16	116
40% tile	961	145	68	54	43	20	9	9	10	92	-	-	17	131
50% tile	3026	232	76	65	52	24	11	14	17	124	-	-	23	149
60% tile	AZ	564	115	68	57	29	13	19	32	157	-	-	25	202
70% tile	-	2853	156	79	63	34	15	24	37	AZ	-	-	33	264
80% tile	-	AZ	297	156	73	39	17	37	44	-	-	-	40	513
90% tile	-	-	AZ	AZ	AZ	50	40	48	48	-	-	-	47	AZ
100% tile	-	-	-	-	-	146	70	80	95	-	-	-	61	-

A zero (0) indicates that the simulated current conditions are zero.
A dash (-) indicates that the simulated unimpaired flow is zero.
“AZ” indicates that the unimpaired flow is approaching zero and is very low.

2.2.7.2 Cosumnes River

The Cosumnes River watershed is 940 square miles that extends from an elevation of 7,500 feet in the Sierra Nevada to a few feet above sea level at its confluence near the mouth of the Mokelumne River (Robertson-Bryan 2006a). There are three main tributaries to the Cosumnes River – the North, Middle, and South Forks – which all converge in the foothills immediately above the Central Valley.

The watershed of the Cosumnes River is unique among those of the Sierra Nevada as there are no major dams on its mainstem and only one significant dam (Sly Park 41 TAF; 5% of average total flow which is exported to the American River watershed) on an upstream tributary, so it retains a relatively natural hydrograph for wet season flows (Mount et al. 2001, Robertson-Bryan 2006a) (Figure 2.2-19). In contrast to the Mokelumne River, while the headwaters of the Cosumnes River receives similar mean annual precipitation, the elevation of the headwaters is lower, between 5,000 and 7,000 feet, and any precipitation falling as snow generally melts during the wet season and does not produce high flows during late spring and summer (DWR 1974, Booth 2006, Ahearn et al. 2004, 2005, Epke 2011). Rain-on-snow events can occur and the largest recorded maximum flow was 93,000 cfs in January 1997 (USGS 1999). While its wet season hydrology is largely intact (shown in Figure 2.2-19 and Table 2.2-16), summer and fall baseflows in the reach that runs through the alluvium filled trench have been diminished by extensive groundwater pumping and a large number of small diversions throughout the watershed (Piper et al. 1939, DWR 1974, Mount et al. 2001, Fleckenstein et al 2006, Meirovitz 2010). Currently, because of diversions and lowered groundwater levels, the lower reach across the valley floor loses significant amounts of streamflow and becomes intermittent in the late summer and fall.

Historically, groundwater discharge maintained several large perennial ponds in the lowest reach on the valley floor (USGS 1908, USGS 1910, Shlemon et al. 2000). Currently, groundwater approaches the surface in this same area but does not discharge into the channel (Mount et al. 2001, Fleckenstein et al. 2006, Meirovitz 2010).

Latrobe Falls, in the foothills just above the valley floor, blocks fish migration (Moyle et al. 2003). Impacts to fisheries have been identified as the intermittent flow characteristics of the valley floor reach due to lowered local and regional water tables and the loss of tidal marsh spawning and rearing habitat. In 2005, a fisheries enhancement study determined the feasibility and water cost of enhancing natural fall flows in the valley floor reach by pre-wetting the stream bed (Robertson-Bryan 2006b). The study began in October 2005 and a wetting front was established and reached tide water by the end of November 2005 at a water cost of less than 1,000 acre-feet (AF). An intentional levee breach to restore floodplain habitat along a portion of the channel immediately above tide water was successful for some native fish species (Crain et al 2004).

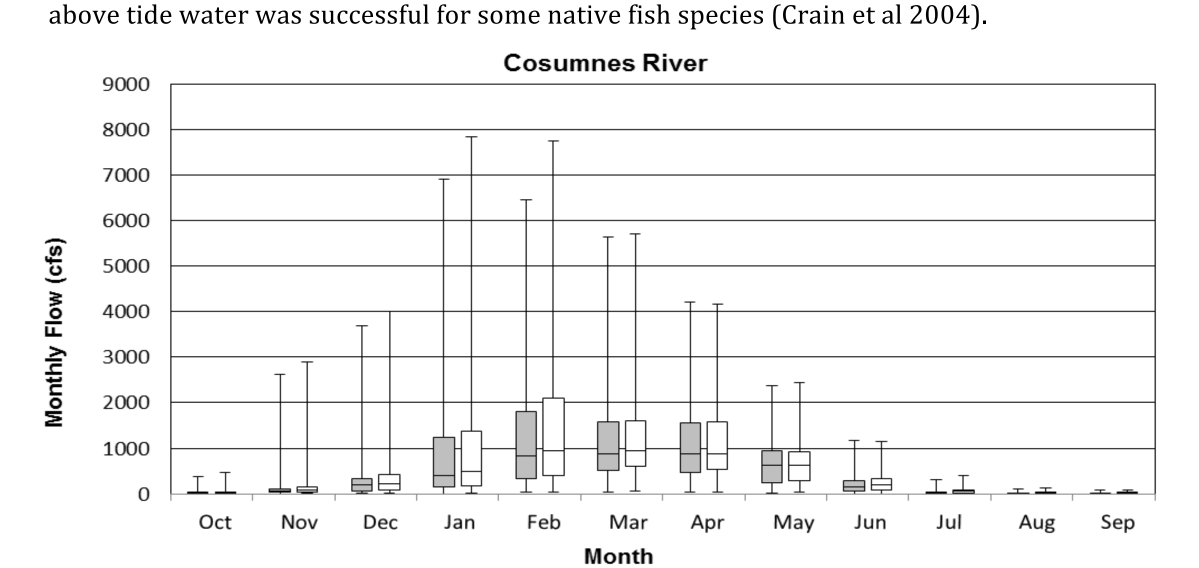


Figure 2.2-19. Cosumnes River above the Confluence with the Mokelumne River Simulated Current Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-16. Statistics of Impaired Flow as Percent of Unimpaired Flow in Cosumnes River

	Impaired Flow as a percent of Unimpaired Flow (%)												Seasonal Impairment	
Percentile	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan-Jun	Jul-Dec
0% tile	0	0	33	0	57	59	40	34	0	0	0	0	58	31
10% tile	0	56	72	82	80	85	79	70	33	0	0	0	83	53
20% tile	0	65	79	84	82	87	82	77	63	14	13	0	84	68
30% tile	38	76	83	86	84	89	84	84	70	18	23	0	86	70
40% tile	59	79	85	87	84	90	91	93	75	21	28	16	88	73
50% tile	74	82	87	87	85	91	94	97	78	27	35	31	90	76
60% tile	83	87	88	88	86	94	97	98	83	39	39	45	91	79
70% tile	93	89	89	89	89	95	98	99	85	45	49	65	93	82
80% tile	101	91	90	90	91	96	99	101	90	54	69	AZ	94	84
90% tile	106	98	92	94	93	99	101	102	94	AZ	AZ	-	95	87
100% tile	165	126	115	148	104	115	136	115	106	-	-	-	106	101

A zero (0) indicates that the simulated current conditions are zero.
A dash (-) indicates that the simulated unimpaired flow is zero.
"AZ" indicates that the unimpaired flow is approaching zero and is very low.

2.2.7.3 Calaveras River

The watershed of the Calaveras River extends from 4,400 feet in elevation to sea level, is 470 square miles, and produces an average runoff of 157 TAF at the New Hogan Reservoir (DWR 2007). The hydrology of the watershed of the Calaveras River is entirely rain-fed and inflow to New Hogan Reservoir drops to base-levels in April (DWR 2007) (Figure 2.2-20).

New Hogan Reservoir has a capacity of approximately twice the mean annual runoff of the watershed and the only spills occur in wet years to maintain storage capacity for flood control (DWR 2007). Imports of up to 105 TAF may occur annually from New Melones Reservoir and is used for irrigation, groundwater recharge, and drinking water from March to November (DWR 2007). There are a large number of diversions below New Hogan Reservoir.

Below New Hogan Reservoir the Calaveras River splits into two channels on the alluvial fan with the primary channel, Mormon Slough, to the south and Old Calaveras River to the north. The primary controls on channel flows are the Calaveras Headworks which prevents New Melones flood control releases from entering the Old Calaveras River, the Bellota Weir near the head of Mormon Slough which controls irrigation releases during the April through October irrigation season, and the Stockton Diversion Channel which shunts local runoff from the Old Calaveras River to Mormon Slough (DWR 2007).

Except for infrequent flood spills, the Calaveras River dries up before it connects to the San Joaquin River shown by zeros in Table 2.2-17 and in Figure 2.2-20. In the Unimpaired simulation, river flows peak in February and cease between April and October (Table 2.2-17). In January – June the current conditions for the Calaveras River are less than 31% of the unimpaired conditions in half of the years.

Impacts to fisheries have been identified as the large number of migration barriers in the lower watershed, lack of attraction flows, rapid dewatering in the Old Calaveras River and Mormon Slough channels, and the lack of connecting flow from the San Joaquin River to the reach between the Bellota Weir and the New Hogan Dam (DWR 2007).

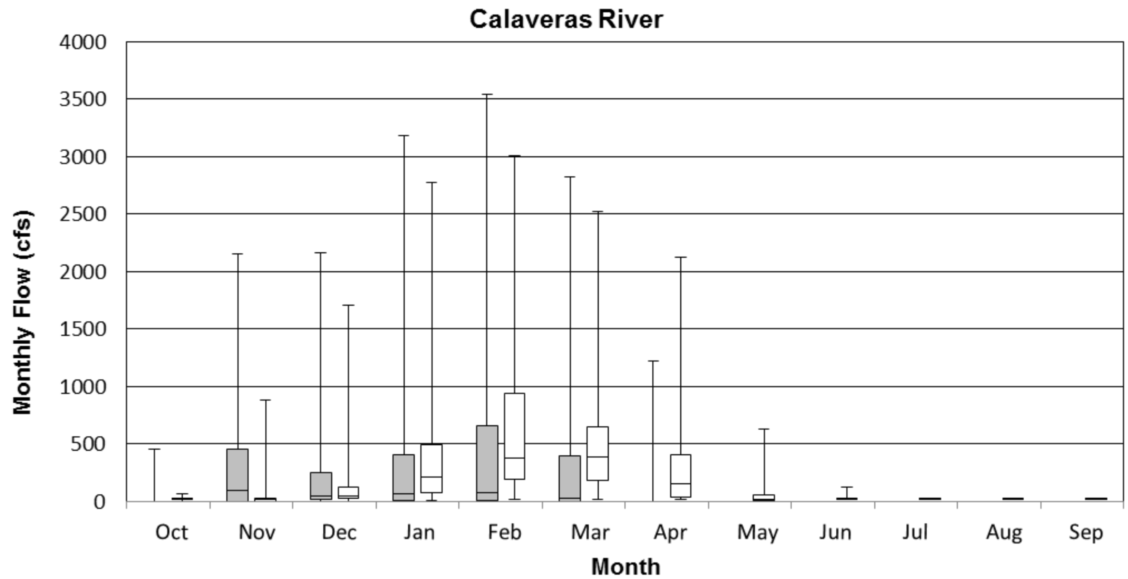


Figure 2.2-20. Calaveras River above the Confluence with the San Joaquin River Simulated Current Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-17. Statistics of Impaired Flow as Percent of Unimpaired Flow in Calaveras River

	Impaired Flow as a percent of Unimpaired Flow (%)												Seasonal Impairment	
Percentile	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan-Jun	Jul-Dec
0% tile	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10% tile	0	0	0	0	0	0	0	0	0	0	0	0	3	0
20% tile	0	0	13	0	0	0	0	0	0	0	0	0	6	9
30% tile	0	11	36	11	5	0	0	0	0	0	0	0	12	16
40% tile	0	50	63	15	12	3	0	0	0	0	0	0	20	39
50% tile	0	509	113	28	22	7	0	0	0	0	0	0	31	126
60% tile	0	AZ	140	65	42	13	0	0	0	0	0	0	47	187
70% tile	0	-	160	91	89	49	0	0	0	0	0	0	66	249
80% tile	0	-	226	114	108	89	0	0	0	0	0	0	81	445
90% tile	0	-	AZ	116	115	112	0	0	0	0	0	0	93	561
100% tile	-	-	-	AZ	207	116	57	-	0	0	0	0	107	AZ

A zero (0) indicates that the simulated current conditions are zero.
A dash (-) indicates that the simulated unimpaired flow is zero.
"AZ" indicates that the unimpaired flow is approaching zero and is very low.

2.2.8 Tributaries of the Northern Coast Range, Northern

2.2.8.1 Stony Creek

Stony Creek has a watershed of 741 square miles with a mean annual flow of about 425 TAF per year. It has three reservoirs operated for flood control and agricultural irrigation. Reclamation operates two reservoirs: East Park Reservoir (50,000 AF) and Stony Gorge Reservoir (50,000 AF) as part of the Orland Project. Black Butte Reservoir (160,000 AF) is the lowest reservoir and is managed from November to March for flood control and April to October for irrigation. Prior to Black Butte Dam, daily flood flows exceeded 30,000 cfs about every five years with maximum flows over 80,000 cfs (HT Harvey and Associates 2007b). Orland Project operations have greatly reduced flows and variability on Stony Creek (Figure 2.2-21). For example, during March, impaired flows are less than 5% of unimpaired flows in half of the modeled years (Table 2.2-18).

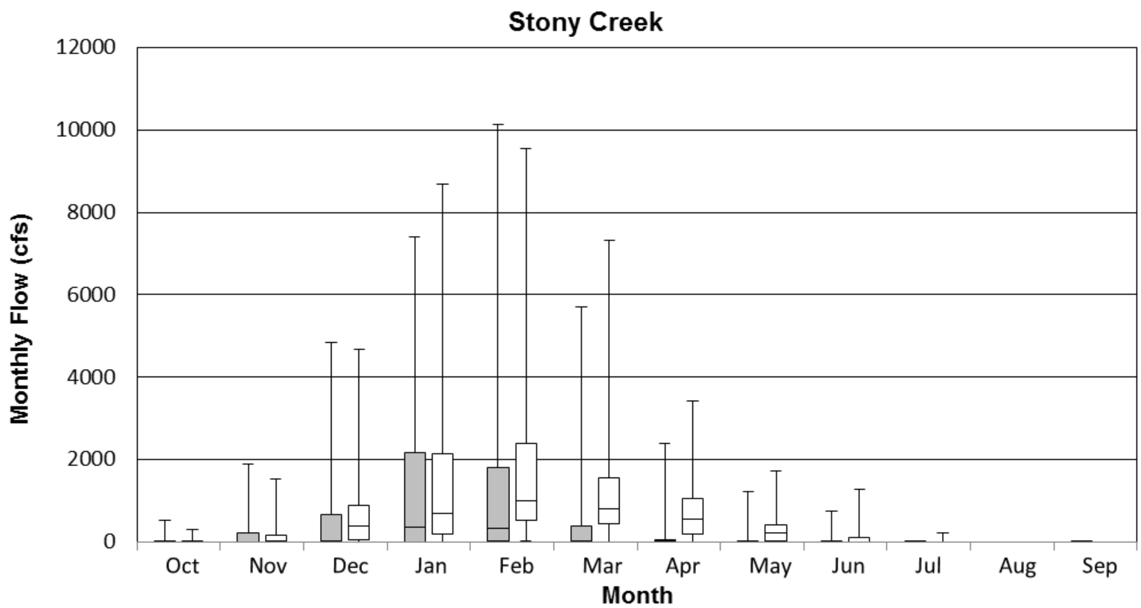


Figure 2.2-21. Stony Creek above the Confluence with the Sacramento River Simulated Current Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-18. Statistics of Impaired Flow as Percent of Unimpaired Flow in Stony Creek

	Impaired Flow as a percent of Unimpaired Flow (%)												Seasonal Impairment	
Percentile	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan-Jun	Jul-Dec
0% tile	0	1	1	1	2	0	0	0	0	0	0	0	4	3
10% tile	13	5	3	4	4	1	2	5	3	-	-	-	6	11
20% tile	44	11	9	8	6	2	3	7	7	-	-	-	12	20
30% tile	AZ	26	22	16	11	3	4	11	14	-	-	-	23	35
40% tile	-	46	32	42	17	3	6	13	34	-	-	-	40	53
50% tile	-	80	44	67	36	5	11	21	AZ	-	-	-	48	63
60% tile	-	178	60	87	66	8	15	36	-	-	-	-	56	83
70% tile	-	AZ	69	97	77	24	18	52	-	-	-	-	62	113
80% tile	-	-	87	101	92	41	33	AZ	-	-	-	-	70	182
90% tile	-	-	AZ	106	98	61	AZ	-	-	-	-	-	77	355
100% tile	-	-	-	284	147	146	-	-	-	-	-	-	96	-

A zero (0) indicates that the simulated current conditions are zero.
A dash (-) indicates that the simulated unimpaired flow is zero.
"AZ" indicates that the unimpaired flow is approaching zero and is very low.

2.2.8.2 Cottonwood Creek

Cottonwood Creek has a watershed of 927 square miles with three forks that head in the North Coast Range (8,000 feet) and the southernmost peaks of the Klamath Range (CH2M Hill 2002, Graham Matthews and Associates 2003b). The hydrology of the watershed is extremely variable with a peak recorded flow of 86,000 cfs and annual flow volumes that range from 68,000 AF to 2

MAF (CH2M Hill 2002, Graham Matthews and Associates 2003b). Cottonwood Creek, like all of the larger creeks with headwaters in the North Coast Range, produces large amounts of gravel, sand, and sediment during floods.

Late fall flows are low and variable but generally around 60 cfs. Cottonwood Creek is unique in that 18 miles of its lowest section run within a 1-mile-wide alluvium-filled trench to its confluence with the Sacramento River. There is one small 4,800 AF reservoir on the North Fork, but otherwise, Cottonwood Creek is unregulated; therefore, current conditions and unimpaired simulations are very similar (Figure 2.2-22). Impaired flows simulated with CalSim II are likely too high, resulting in impaired flows that are greater than unimpaired flows much of the time, especially times of low flow (Table 2.2-19).

Most of the lower reaches gain flow from groundwater discharges during the period when flows are greater than 600 cfs and are variable, gaining or losing reaches, at lower flows (Blodgett et al. 1992). The Anderson-Cottonwood Irrigation District imports approximately 18,000 AF of Sacramento River water to the watershed for irrigation that through losses and return flows contributes significantly to summer baseflows and groundwater recharge in Cottonwood Creek (Blodgett et al. 1992).

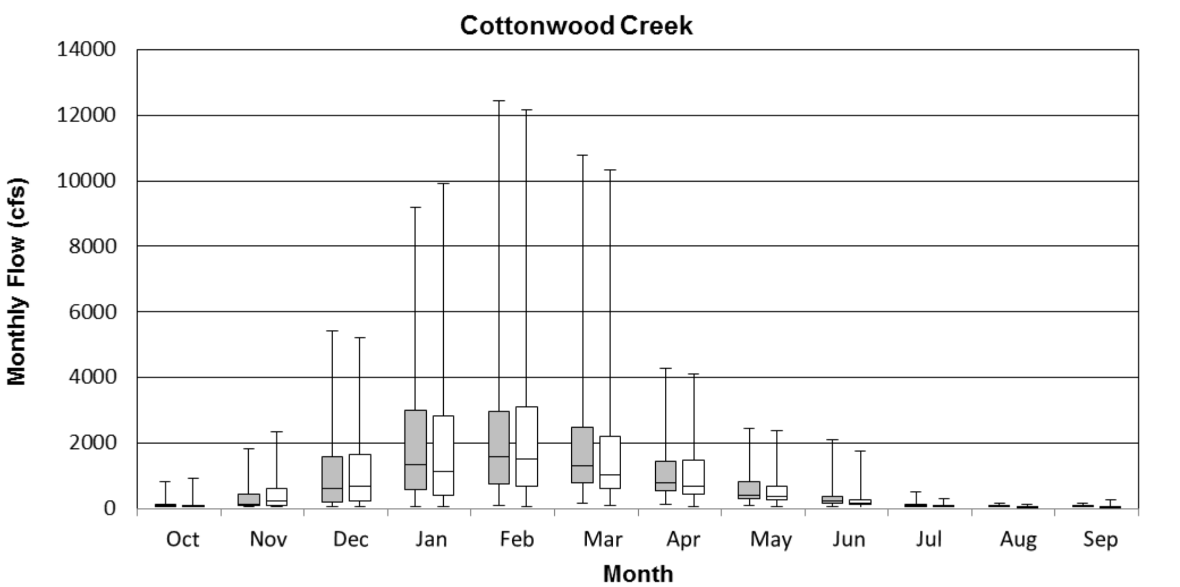


Figure 2.2-22. Cottonwood Creek above the Confluence with the Sacramento River Simulated Current Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-19. Statistics of Impaired Flow as Percent of Unimpaired Flow in Cottonwood Creek

	Impaired Flow as a percent of Unimpaired Flow (%)												Seasonal Impairment	
Percentile	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan-Jun	Jul-Dec
0% tile	29	15	34	49	34	26	51	66	75	95	100	50	65	67
10% tile	78	45	59	75	86	92	96	104	112	115	122	152	100	79
20% tile	104	57	76	88	93	104	103	113	120	123	135	187	104	84
30% tile	130	65	83	93	99	109	107	116	125	134	155	200	105	89
40% tile	144	74	92	97	104	111	113	118	127	148	174	211	106	91
50% tile	154	86	96	102	108	115	116	120	129	157	191	229	108	96
60% tile	172	92	102	108	111	118	117	123	132	165	201	233	110	103
70% tile	187	99	109	113	115	122	121	126	136	176	215	245	112	111
80% tile	218	108	122	123	123	131	125	131	142	208	250	273	117	121
90% tile	252	118	157	228	132	170	137	135	159	246	295	344	141	133
100% tile	662	168	364	736	299	389	250	265	433	401	428	1008	250	283

2.2.8.3 Thomes Creek

Thomes Creek has a watershed area of 301 square miles which heads in the Inner North Coast Range at an elevation of 6,600 feet (Vestra 2006, Tehama County Flood Control and Water Conservation District 2012). It has an extremely variable hydrology with a maximum daily recorded flow of 37,800 cfs and very low late-summer flows of approximately 6 cfs that can fall to zero in dry years. Thomes Creek, like all of the larger creeks with headwaters in the North Coast Range, produces large amounts of gravel, sand, and sediment during floods. After leaving the foothills its channel flows 25 miles through a narrow alluvial valley cut into relatively impermeable Tehama and Red Bluff formations to the Sacramento River (Tehama County Flood Control and Water Conservation District 2012). There are no significant dams on the watershed and few surface diversions. In the current conditions simulation, Thomes and Elder Creek are combined because of the available data from CalSim II (Figure 2.2-23). The current conditions simulation shows very similar hydrology when compared with the unimpaired flows (Figure 2.2-23, Table 2.2-20). Diversions during the summer months reduce flows compared with unimpaired conditions. Impaired flows are higher than unimpaired at times due to differences in methods used to estimate the two flow types. About 88% of the water used in the region is obtained from groundwater for irrigated agriculture (Vestra Resources 2006).

2.2.8.4 Elder Creek

Elder Creek has a watershed area of 151 square miles which heads in the Inner North Coast Range at an elevation of 5,500 feet (Vestra 2006, Tehama County Flood Control and Water Conservation District 2012). It has an extremely variable hydrology with a maximum daily recorded flow of 17,700 cfs and very low late-summer baseflow that frequently falls to zero. After leaving the foothills its channel flows 20 miles through a narrow alluvial valley cut into relatively impermeable Tehama and Red Bluff formations to the Sacramento River (Tehama County Flood Control and Water Conservation District 2012). There are no significant dams on the watershed and few surface diversions, therefore, like Thomes Creek, little impairment has occurred on a monthly timescale (Figure 2.2-23). About 88% of the water used in the region is obtained from groundwater for irrigated agriculture (Vestra Resources 2006).

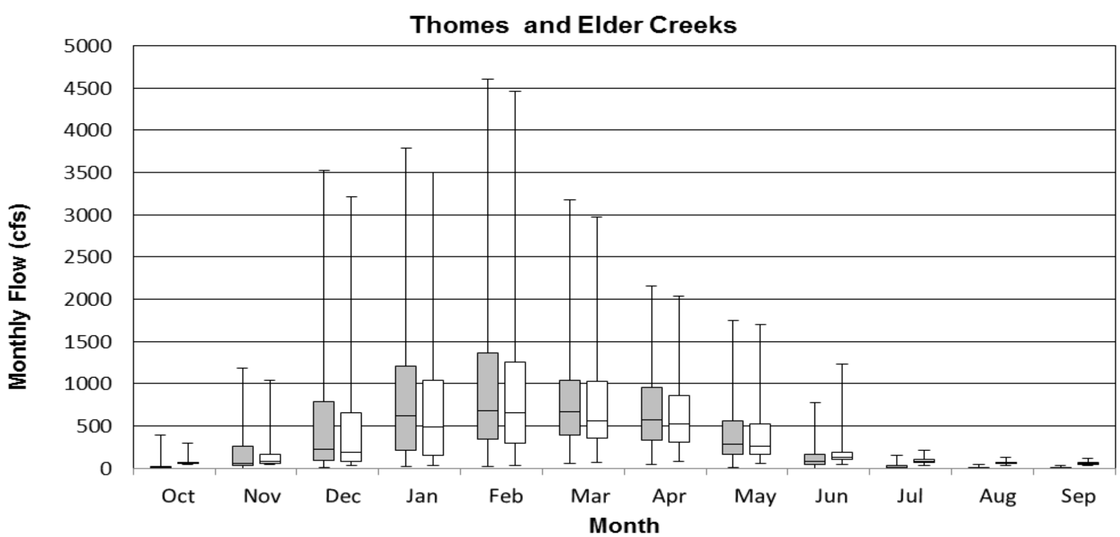


Figure 2.2-23. Combined Thomes and Elder Creeks above the Confluence with the Sacramento River Simulated Current Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-20. Statistics of Impaired Flow as Percent of Unimpaired Flow in Thomes and Elder Creeks

	Impaired Flow as a percent of Unimpaired Flow (%)												Seasonal Impairment	
Percentile	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan-Jun	Jul-Dec
0% tile	0	0	21	44	34	61	52	24	0	0	0	0	61	8
10% tile	0	12	43	81	101	102	97	70	28	0	0	0	97	20
20% tile	0	32	68	109	108	106	103	92	38	1	0	0	107	35
30% tile	3	53	107	112	110	109	105	100	46	9	0	0	108	53
40% tile	6	66	112	115	111	110	107	104	60	12	0	0	109	65
50% tile	10	90	117	120	114	113	109	105	68	15	0	0	111	78
60% tile	17	115	122	127	119	116	111	108	80	22	2	0	112	86
70% tile	26	126	131	131	123	118	114	110	87	33	7	4	115	92
80% tile	46	136	139	141	127	122	115	115	96	41	12	7	118	98
90% tile	92	161	151	158	146	132	121	119	103	51	18	13	122	101
100% tile	179	321	274	240	441	173	134	138	132	73	32	49	138	112

A zero (0) indicates that the simulated current conditions are zero.

2.2.9 Tributaries of the Northern Coast Range, Southern

2.2.9.1 Cache Creek

Cache Creek has a watershed area of 1,139 square miles with 1,044 square miles occurring in the Interior Southern Coast Range (Yolo County 2006, Water Resources Association of Yolo County 2007). The headwaters of its south fork extend from elevations of 4,000 feet and accumulate in Clear Lake, a large, shallow, natural lake, before flowing through a narrow canyon to the Sacramento Valley. The volume of the lake and the small natural outlet from Clear Lake significantly reduce the magnitude of peak flows into the canyon (Water Resources Association of Yolo County 2007). The headwaters of the north fork are at slightly lower elevations but also run through a narrow canyon. The river canyon opens into the Capay Valley immediately above the Sacramento Valley. Cache Creek, like all of the larger creeks with headwaters in the North Coast Range, produces large amounts of gravel, sand, and sediment during floods.

In its natural state, the lower reach of Cache Creek flowed as a wide braided stream from the mouth of Capay Valley to the Yolo Basin where its waters mixed with waters from overflow from the Sacramento River, Willow Slough, and Putah Creek and the combined flow drained southward to the confluence of the Yolo Basin with the Sacramento River (Water Resources Association of Yolo County 2007). When flows exceeded approximately 20,000 cfs at the mouth of the Capay Valley the excess flow would overtop the low natural levees and flood the Hungry Hollow Basin to the north and the much larger Cache-Putah Basins to the south. Because of these overflows to flood basins there are no records of flows exceeding 20,000 cfs in Cache Creek prior to its regulation by dams (Water Resources Association of Yolo County 2007) but peak flows likely exceeded 80,000 cfs. Overbank flood basin flows in the Cache-Putah basin merged with overbank flood flows from Putah Creek and flowed through Willow Slough into the Yolo Basin. The Sacramento Valley section of Cache Creek has been extensively modified by instream gravel mining, flood levees at its lower end with designed capacities of 36,800 cfs, and a sediment settling basing immediately adjacent to the Yolo Basin.

There are three significant dams on Cache Creek. The Clear lake Impoundment Dam is immediately below the outlet from Clear Lake and regulates outflows from the lake but doesn’t significantly affect lake carryover capacity. Both irrigation releases and flood releases are regulated under the Solano and Bemmerly decrees. Indian Valley Reservoir on the north fork has a capacity of 301TAF and is used for irrigation storage and flood control. The Capay Diversion dam at the mouth of Capay Valley is a 15 foot high structure that can be raised an additional 5 feet with an inflatable bladder. The diverted water supports agriculture in the basins on either side of Cache Creek.

Cache Creek has been severely impaired by upstream diversions and storage and under current conditions; it is much lower than unimpaired flows in all months (Figure 2.2-24). Maximum simulated monthly unimpaired flows peak over 13,000 cfs in February 1998. Unimpaired flows are sustained into the Yolo Bypass in about half of the years whereas under current conditions, the river dries up in about 80% of the years (Table 2.2-21). In about 10% of the years, Cache Creek observed flows are close to unimpaired flows between January – June, but in half of the years, the observed flows are less than 44% of unimpaired flows.

Surface water in the channel of Cache Creek loses water to ground water from the Capay Dam to the Dunnigan Hills where it is briefly a gaining reach before becoming a losing reach again all the way to the Yolo Basin (Yolo County 2006).

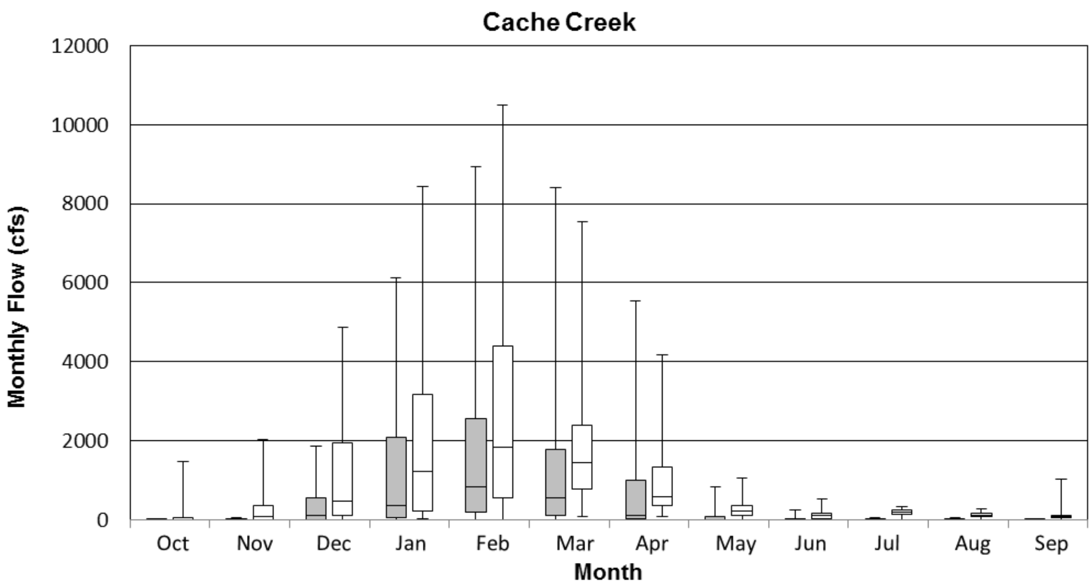


Figure 2.2-24. Cache Creek Observed Current Conditions near Yolo (gray) and Unimpaired (white) Monthly Flows

Table 2.2-21. Statistics of Observed Flow as Percent of Unimpaired Flow in Cache Creek

	Impaired Flow as a percent of Unimpaired Flow (%)												Annual Impairment	
Percentile	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan-Jun	Jul-Dec
0% tile	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10% tile	0	0	0	4	18	6	0	0	0	0	0	0	11	0
20% tile	0	0	0	14	23	12	3	0	0	0	0	0	17	0
30% tile	0	0	6	22	29	18	10	0	0	0	0	0	23	3
40% tile	13	7	16	27	33	25	16	2	0	0	0	0	31	10
50% tile	AZ	11	21	32	43	36	21	8	0	0	0	0	44	13
60% tile	-	20	29	44	63	53	36	14	3	0	0	0	58	18
70% tile	-	AZ	34	54	90	78	57	27	8	1	0	1	69	25
80% tile	-	-	41	73	105	97	82	37	26	4	7	20	78	28
90% tile	-	-	59	92	AZ	124	114	AZ	AZ	17	AZ	AZ	91	36
100% tile	-	-	-	AZ	-	252	233	-	-	395	-	-	117	71

A zero (0) indicates that the simulated current conditions are zero.
A dash (-) indicates that the simulated unimpaired flow is zero.
“AZ” indicates that the unimpaired flow is approaching zero and is very low.

2.2.9.2 Putah Creek

Putah Creek has a watershed area of 710 square miles with 600 square miles occurring in the Interior Southern Coast Range (Water Resources Association of Yolo County 2007). Its headwaters extend from elevations of 4,800 in the Mayacamas Mountains and its various tributaries flowing through a series of small valleys and narrow canyons. Putah Creek, like all of the larger creeks with headwaters in the North Coast Range, produces large amounts of gravel, sand, and sediment during floods but all are trapped behind Monticello Dam. At the mouth of its last canyon Putah Creek flows over its large alluvial fan as it enters the Sacramento Valley. Historically, from the lower edge of the alluvial fan Putah Creek flowed between low natural levees with occasional breaches leading to intermittent sloughs that drained either northward into the Cache-Putah Basin or southward across the Putah Plains. The main channel flowed through what is now the town of Davis and emptied into a section of the Yolo Basin known as the Putah Sink where its waters mixed with waters from overflow from the Sacramento River, Willow Slough, and Cache Creek and the combined flow drained southward to the confluence of the Yolo Basin with the Sacramento River (EDAW 2005, Water Resources Association of Yolo County 2007). Flood control modifications to the channels near the City of Davis isolated the main channel to the Yolo Basin and forced Putah Creek to flow through a bypass channel with constructed levees from the City of Davis to the Yolo Basin.

Monticello Dam forms Lake Berryessa, which is located in the upper end of the last canyon before the Sacramento Valley, and has a capacity of 1.6 MAF. The maximum recorded flood prior to the dam was 81,000 cfs and predicted 100-year flood events post-dam are 32,000 cfs (Water Resources Association of Yolo County 2007). The Putah Creek Diversion Dam, 29 feet high, is located at the end of the canyon and diverts water south into Solano County (Redmond 2000). The minimum flow requirements below the dam under the water right license have been supplemented with flows designed to maintain salmonids in the lower section of Putah Creek under the Putah Creek Accord (EDAW 2005).

Observed flows on Putah Creek were used to estimate current conditions because Putah Creek is not simulated in CalSim II, which allowed for fewer years to compare with the SVUFM results. Refined results using SacWAM will be provided in the final draft report. Observed flows below Putah Diversion Dam are much lower than the unimpaired flows throughout the spring, with variability of flow conditions greatly reduced (Figure 2.2-25). Putah Creek goes dry under unimpaired conditions from June – November in about 70% of the years (Table 2.2-22). In more than half of the years, current conditions are less than 51% of unimpaired flows from January – June.

Groundwater pumping for agriculture and municipalities has lowered the regional groundwater table but historically Putah Creek was a losing stream from the top of its alluvial fan to the Yolo Bypass except for the short reach that crosses the Plainfield Ridge (Bryan 1923, Thomasson et al. 1960). Self-sustaining populations of anadromous fish have returned to Putah Creek in response to the flow releases of the Putah Accord and extensive restoration efforts (EDAW 2005) and in 2015, the fifth year of drought, 500 fall-run Chinook salmon spawned in lower Putah Creek (Shaw 2015).

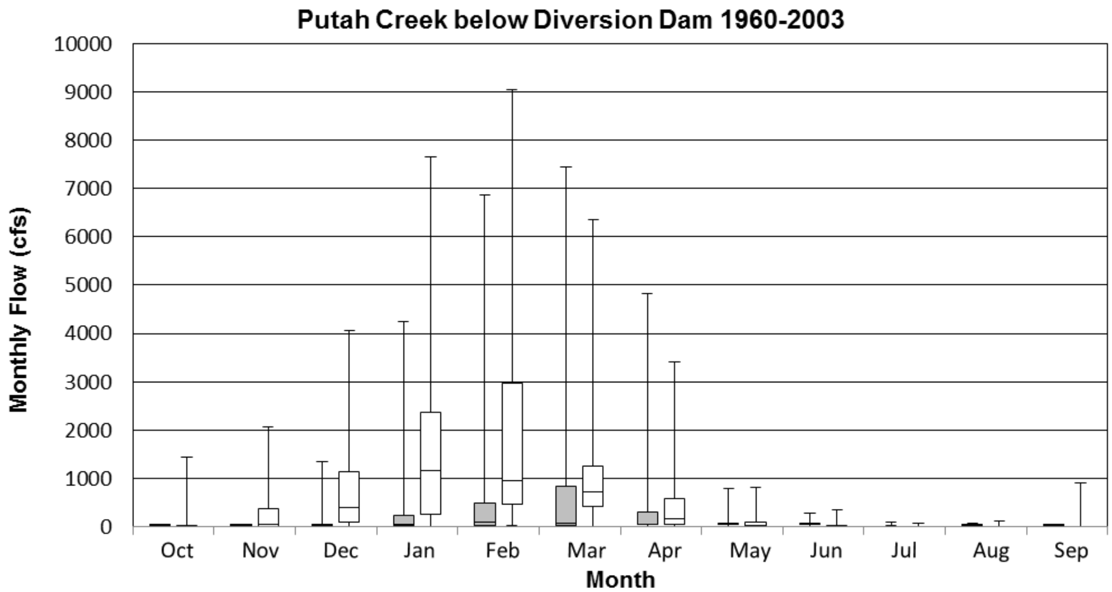


Figure 2.2-25. Putah Creek Observed Current Conditions near Winters (gray) and Unimpaired (white) Monthly for years 1990-2003

Table 2.2-22. Statistics of Observed Flow as Percent of Unimpaired Flow in Putah Creek for Years 1990–2003

	Impaired Flow as a percent of Unimpaired Flow (%)												Seasonal Impairment	
Percentile	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan-Jun	Jul-Dec
0% tile	2	1	2	2	2	2	1	1	7	51	AZ	AZ	23	26
10% tile	61	4	3	3	3	4	18	28	56	AZ	-	-	32	88
20% tile	AZ	6	4	4	4	6	33	47	232	-	-	-	35	115
30% tile	-	15	4	5	5	9	46	57	AZ	-	-	-	45	147
40% tile	-	30	6	6	6	19	75	98	-	-	-	-	49	191
50% tile	-	62	8	7	9	50	94	171	-	-	-	-	51	218
60% tile	-	AZ	11	18	23	67	111	384	-	-	-	-	56	266
70% tile	-	-	22	32	39	97	128	AZ	-	-	-	-	68	340
80% tile	-	-	AZ	62	56	119	AZ	-	-	-	-	-	71	475
90% tile	-	-	-	AZ	99	AZ	-	-	-	-	-	-	75	AZ
100% tile	-	-	-	-	218	-	-	-	-	-	-	-	83	-

A dash (-) indicates that the simulated unimpaired flow is zero.
“AZ” indicates that the unimpaired flow is approaching zero and is very low.

2.3 Flood Basins

Land development over the past century in the Sacramento Valley has been made possible by reclaiming the “inland sea” by routing the Sacramento River through a series of flood basins. Beginning just above Stony Creek near Hamilton City and continuing to Rio Vista in the Delta, the Sacramento River runs between natural levees and the outboard flood basins (Bryan 1923, Olmsted and Davis 1961, DWR 1994, 2010a, 2010b, Whipple et al. 2012). There are six flood basins which in order from upper to lower are: Butte, Colusa, Sutter, Yolo, American, and Sacramento. Because the flow of the Sacramento River is highly variable and can range from approximately 3,000 cfs in the summer during droughts to 500,000 cfs during floods, the flood basins function both as short term storage reservoirs and as the main channels of the Sacramento River during floods. Additionally, the lower halves of the Yolo and Sacramento Basins are tidal and experience two high and two low tides each day with greater and then lesser tidal ranges over the 14-day spring/neap tidal cycle. At their upstream ends the levees along the Sacramento River are broad and low, three to five miles apart, and historically were often cut by active meander channels. Each cut was relatively permanent and discharged channel water into the Butte and Colusa flood basins at flows significantly below flood stage. The frequency of the levee cuts decreased downstream to zero near the town of Colusa.

Functionally, flood basins differ from floodplains because they drain more slowly and may contain areas of permanent open water. The upper flood basins of the Sacramento River have greater slopes than the lower and tend to drain more rapidly. The flood waters transport sediment to the basins and small clay-size particles of sediment remain suspended longer while the coarser sediment remains in or adjacent to the Sacramento River. The relatively slow moving water of the basins traps the slowly sinking clay particles and causes the bottoms and sides of the basins to be lined with clay soils. Percolation of flood basin water to ground water is blocked by those extensive impermeable clay soils.

The precise boundaries of the transitions from flood basins upward onto the lower floodplains of the tributaries are difficult to determine as the change in elevation is very gradual and the depth and duration of flood waters highly variable. However, the consistently longer inundation of the deeper sections of the flood basins produces vegetation and habitat types that are distinct from those of the floodplains.

The natural hydrology of all of the basins has been extensively altered. A flood control system of levees and weirs has been constructed along the Sacramento River adjacent to the flood basins and bypass floodways run through the Sutter and Yolo basins (DWR 2010a, 2010b, 2012). All of the basins have been extensively modified by reclamation actions and are intensively farmed with irrigation intensive crops such as rice, alfalfa, row crops, and orchards. Additionally, each basin has areas permanently set aside as habitat for water fowl with nearby agricultural lands providing incidental habitat during the cropping season and managed habitat during fall and winter (Garone 2011).

2.3.1 Butte Flood Basin

The Butte flood basin combines attributes of both a flood basin and a flood plain; Holmes and Nelson (1913) describe it as a semibasin and Olmsted and Davis (1961) uniquely describe it as the Butte Creek Lowland. Olmsted and Davis (1961) note that its slope of two-feet per mile is greater than any of the other flood basins, and Bryan (1923) describes it in flood stage as a vast sheet of slowly moving water. The transit time of flood waters through the basin is two days (DWR 2012).

Flood flows from the upper two thirds of the basin merge and drain into the wide upper end of the Butte Sink area which is the southernmost section and remaining one quarter of the basin. The combined flows enter Butte Sink at the 60-foot elevation contour near the Moulton Weir (Bryan 1923), converge southward, and wrap around the west side of the Sutter Buttes. Butte Sink is bounded to the west by the 30-foot high levee of the Sacramento River which forces Butte Creek to the southeast and is bounded to the east by the Sutter Buttes. The naturally incised channel of Butte Creek, while sometimes immersed deeply by basin and sink flood flows, persists as a defined channel that discharges into Butte Slough which drains into the Sutter Basin (USGS 1913, Bryan 1923, Carpenter et al. 1926, Olmsted and Davis 1961, DWR 2012).

The vegetation of the Butte Basin outside of the Butte Sink was rapidly converted to extensive agriculture when California became a state and as late as 1912, agriculture within the Butte Basin was primarily grazing and areas of dry-farmed grain (Strahorn 1911). Commercial rice production of 1,400 acres began in the same area in 1912 (Robertson 1917, Adams 1920, Dunshee 1928), expanded to almost 95,000 acres by 1920 (Division of Public Works 1923). To irrigate the rapidly growing acreage of rice fields, water was diverted from the Feather River and run down existing sloughs and transferred to lateral canals to irrigate rice fields west and northwest of Biggs and Gridley as well as the area of eastern Colusa County that lies within the Butte Basin and rice field drainage water was released into natural channels running to the Butte Sink (USGS 1912a, State Water Commission 1917, Carpenter et al. 1926).

Butte Basin is unique among the basins because flood waters are not specifically directed within the basin through engineered structures such as bypasses, drains, or systems of levees (Garone 2011, DWR 2012). When the Butte Basin is full it holds approximately 1 MAF of water which enters the basin from the Sacramento River through six locations (DWR 2010a, 2010b, 2012). When flows in the Sacramento River exceed 30,000 cfs flood waters flow over the Colusa Weir into the main section of the Butte Sink which has a designed capacity of 70,000 cfs (DFW 2010a, 2012). When flows in the Sacramento River exceed 70,000 cfs flood waters flow into the upper end of the Butte Sink over the Moulton Weir which has a designed capacity of 25,000 cfs (DFW 2010a, 2012). When flows in the Sacramento River exceed 100,000 cfs water can pass into the basin at its upper end through the M&T and Parrot Plug flow relief structures, the Three-Bs overflow area, and an emergency overflow roadway (DFW 2010a, 2012). The Butte Slough outfall gates at the lower end of the Butte Sink direct low flows within the basin and irrigation flows back into the Sacramento River but are otherwise closed.

2.3.2 Colusa Flood Basin

The Colusa flood basin is an irregular 50-mile long trough lying between the coalesced, clay-soil alluvial fans of the small creeks flowing eastward from the Coast Range and the western natural levee of the Sacramento River. Lengthwise, it extends from the border of Glenn and Colusa counties to the Knights Landing ridge and consists of two functionally distinct sub-basins located above and below the alluvial ridge of Upper Sycamore Slough (Bryan 1923, Olmsted and Davis 1961, DWR 1962).

Historically, floodwaters entered the Colusa Basin at its upper end between the towns of Princeton and Glenn when flows in the Sacramento River exceeded summer base flows, along its entire western margin when creeks such as Willow Creek began flowing eastward out of the Coast Range, and through levee breaks immediately above and below the town of Colusa (Department of Engineering 1914, McComish and Lambert 1918, DWR 1964, Kelley 1989). Flood water in the upper sub-basin drains relatively rapidly through a generally smooth and slightly concave trough while flows through the lower sub-basin historically drained through the defined channel of lower Sycamore Slough but backed up at the Knights Landing Ridge. Historically, in the lower sub-basin, several permanent breaches in the natural levee of the Sacramento River, upper Sycamore Slough being the largest, discharged flood flows into the Colusa Basin when the Sacramento River was at flood stage (Mann et al. 1911, State Water Commission 1917, Bryan 1923). As noted in the Butte Basin discussion, at the highest Sacramento Valley flood flows the combined Butte Basin flows consisting of the local streams, the sloughs draining the cuts in the Sacramento River levee, and the Feather River flood water pouring into the Butte Basin sometimes overtopped the Sacramento River levees and forced floodwater westward into the Colusa Basin (Department of Engineering 1914).

The start of rice growing in the Colusa Basin was two years later than in the Butte Basin. Commercial rice production of 147 acres began in the Colusa Basin in 1914 (McComish and Lambert 1918) and rapidly expanded to 170,000 acres by 1920 (Division of Public Works 1923).

Flood protection in the Colusa Basin is designed to prevent flooding by the Sacramento River, to reduce winter and spring flooding from the creeks flowing eastward from the Coast Range, and to provide drainage for large amounts of summer and fall rice irrigation water (State Water Commission 1917, DWR 1964). A levee system was constructed along the Sacramento River from the Stony Creek alluvial fan to the Knights Landing Ridge Cut which prevents flooding of the Colusa Basin by the Sacramento River (DWR 1964, DWR 2010a, 2012). Along the west side of the basin a back levee with an upslope drain constructed in the borrow pit of the levee conveys winter flows from the Coast Range tributaries and summer flows from rice fields south through the basin, through the Knights Landing Ridge Cut, and into the Yolo Basin (DWR 1964, 2010a). Before the Knight's Landing Ridge Cut was dredged, natural flows in Colusa Basin drained back into the Sacramento River through the lower end of Sycamore Slough. However, because the Sacramento River was typically at a high stage during the spring, the water ponded above the Knights landing Ridge could not drain which causing prolonged flooding in the lower end of the lower sub-basin (DWR 1964). The Colusa Drain and the Knights Landing Ridge Cut have a design capacity of 20,000 cfs (DWR 2010b, 2012). At low Sacramento River flows the basin can drain into the Sacramento River through the Sycamore Slough Outfall Gates (DWR 2012).

2.3.3 Sutter Flood Basin

The Sutter Basin runs 30 miles, generally north to south, from Butte Slough at the southern edge of the Sutter Buttes to Verona on the Sacramento River. It lies between the natural levees of the Sacramento River to the west and the natural levees of the Feather River to the east (Singer et al. 2008, 2009, DWR 2012). Today and historically, the majority of its flood waters originate from Butte Slough (Bryan 1923, Singer et al. 2008, 2009, DWR 2012, Kelley et al 1989). Historically, the Sutter Basin also received flood waters through permanent breaks in the levee of the Sacramento River such as the Cole Grove Point break which is north of Kirkville, from overflows of the Feather River through permanent breaks in its levee such as Gilsizer Slough, as well as periodic overflow near the confluence of the Feather and Sacramento rivers (Bryan 1923).

The conversion of the wetlands of the basin to agriculture was slower than the conversions in the Butte and Colusa basins because the Sutter Basin was the main flood way of the Sacramento River. Early attempts to prevent flooding in the basin by the Park's Dam initiated what are known as the levee wars and eventually resulted in the construction of a series of flood bypasses (Kelley 1989, Singer et al 2008, 2009). The Sutter Bypass was established to convey flood flows down the central portion of the basin. The bypass receives flows from Butte Slough (150,000 cfs), the Tisdale Weir (38,000), and the Feather River (300,000 cfs), and has a designed flow of 416,500 cfs in the section that joins the Sacramento River (DWR 2010a, 2010b, 2012).

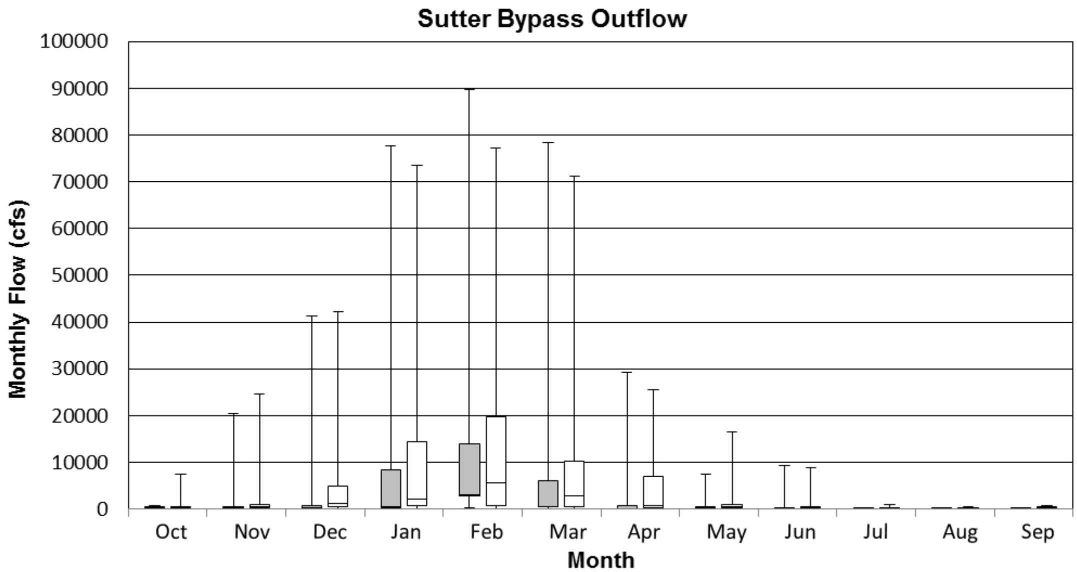


Figure 2.3-1. Sutter Bypass above the Confluence with the Sacramento River Simulated Current Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.3-1. Statistics of Observed Flow as Percent of Unimpaired Flow in Sutter Bypass

	Impaired Flow as a percent of Unimpaired Flow (%)												Seasonal Impairment	
Percentile	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan-Jun	Jul-Dec
0% tile	4	4	6	5	24	1	0	0	1	1	3	2	17	8
10% tile	31	13	14	13	50	11	0	2	1	1	4	19	31	18
20% tile	40	18	17	20	60	19	1	6	1	2	5	30	37	21
30% tile	46	24	20	24	81	29	1	12	1	3	6	38	52	26
40% tile	55	31	28	35	107	46	2	19	3	4	7	43	65	31
50% tile	67	38	34	43	117	66	3	24	3	6	9	55	75	35
60% tile	78	45	49	53	144	72	8	31	6	8	12	61	90	42
70% tile	90	79	58	67	222	83	12	45	8	9	13	76	99	49
80% tile	95	101	78	90	331	98	29	56	10	13	15	91	111	60
90% tile	117	159	106	106	742	135	50	67	22	26	22	112	158	74
100% tile	262	40251	792	159	2416	224	115	635	135	142	56	176	291	103

A zero (0) indicates that the simulated current conditions are zero.

2.3.4 American Flood Basin

The American Basin is a small basin that lies immediately east of the confluence of the Feather and Sacramento rivers, is immediately north of the American River, and historically received the flows of the Feather River and the tributaries of the Sierra foothills (Bryan 1923, DWR 2012). It lies between the plains of the foothills and the levees of the bounding rivers (Olmsted and Davis 1961). Historically, the basin drained to the Sacramento River through a number of deep sloughs (Bryan 1923). Currently, the basin is drained by a network of canals that merge into the Natomas Cross Canal which has a capacity of 22,000 cfs and which discharges into the Sacramento River (DWR 2010a, 2012).

2.3.5 Yolo Flood Basin

The Yolo Bypass is the last large floodplain with a direct connection to the Delta. The Bypass is a 57,000-acre flood conveyance system created to divert Sacramento River water around the City of Sacramento during flood conditions. The Yolo Basin is 40 miles long and runs north to south along the west bank of the Sacramento River from the Knights Landing Ridge to the town of Clarksburg where it continues south immediately west of the river's secondary channel, Elk/Sutter/Steamboat Slough, to the confluence with Cache Slough (Bryan 1923, Whipple et al. 2012). The western edge of the basin transitions into the broad alluvial fans of Cache and Putah creeks (Bryan 1923, Graymer et al. 2002, Whipple et al. 2012).

Historically, the basin filled when the combined flows of the Sacramento, Feather, and American rivers overtopped the natural levee of the Sacramento River, and when the Coast Range streams, principally Cache and Putah creeks, flooded (Bryan 1923, Water Resources Association of Yolo County 2005). The main upstream entry point for floodwater into the current managed bypass is at the Fremont Weir. The 343,000 cfs capacity weir is a passive cement structure that begins to spill into the Bypass when Sacramento River flows at Verona exceed 55,000 cfs (Sommer et al. 2001b), (DWR 2010a, 2010b, 2012). Overtopping events that lead to at least two weeks of downstream floodplain inundation only occur in about 40% of years (DWR 2012). Water also enters the Bypass from the Sacramento Weir and from Putah and Cache Creeks. The Sacramento Weir is another operable weir near the town of Sacramento that discharges into the Yolo Bypass with a design capacity of 112,000 cfs (DWR 2010a, 2010b, 2012).

All these sources join the Toe drain, a perennial channel on the eastside of the Bypass that discharges back to Cache Slough and the Delta several miles above Rio Vista. The Toe drain begins to spill onto the floodplain when flows exceed 3,500 cfs at the Lisbon Weir (Feyrer et al. 2006b). Some portion of the Yolo Bypass typically floods in about 60 percent of years with peak inundation occurring between January and March (DWR 2012; Feyrer et al 2006a; Sommer et al 2001b).

In contrast to the upstream basins, the Yolo basin is tidally influenced and the higher high tide of spring tides extends to just above the sink of Putah Creek (Bryan 1923, Jones and Stokes 2001, Whipple et al 2012).

As was the case with the Butte and Colusa basins, rice was the first crop grown on the clay soils of the Yolo Basin's floor and sides with 14,210 acres grown in the upper portion of the basin by 1920 (Department of Public Works 1923). Rice was not grown in the lower section of the basin because of that section's cooler summer temperatures due to its proximity to the Delta's marine influenced climate (Jones & Stokes 2001). As with the other basins, not only are agricultural fields used by wildlife during the cropping season but they often have a substantial role in supporting water fowl in the late fall and during the wet season (DFG 2008). Additionally, both the upper and lower sections of the basin support spawning habitat for floodplain adapted fish such as Sacramento splittail and provide valuable rearing habitat for Chinook salmon and steelhead (Sommer et al. 2005, Feyrer et al. 2006a, 2006b, DFG 2008, Sommer et al. 2014).

Within the bypass there is a network of drainage canals that convey flows from the Coast Range creeks, Delta waters, agricultural drainage, and irrigation water (Jones & Stokes 2001, NHC 2012). The primary north to south conduits are the Tule Canal/Toe Drain on the east side and the Conway Canal on the west side (Jones & Stokes 2001). The Lisbon Weir spans the Toe Drain approximately 8.5 miles south of the Sacramento Weir (Jones & Stokes 2001). The top of the weir is 2.5 feet above mean sea level, the tops of the banks of the Toe Drain are 8.5 feet above mean sea level, and the higher high tides during each spring tide cycle range to approximately 4.5 feet above mean sea level. The maximum design capacity of the upper end of the bypass is 377,000 cfs and is 490,000 cfs where it discharges into the Delta (DWR 2010a, 2010b). Under current conditions outflow from the Yolo Bypass is lower than unimpaired simulations especially during the winter and spring months due to less frequent weir spills and less inflow from Cache and Putah Creeks (Figure 2.3-2). Yolo Bypass outflows under simulated current conditions and unimpaired conditions have maximum monthly flows of over 100,000 cfs for January – March.

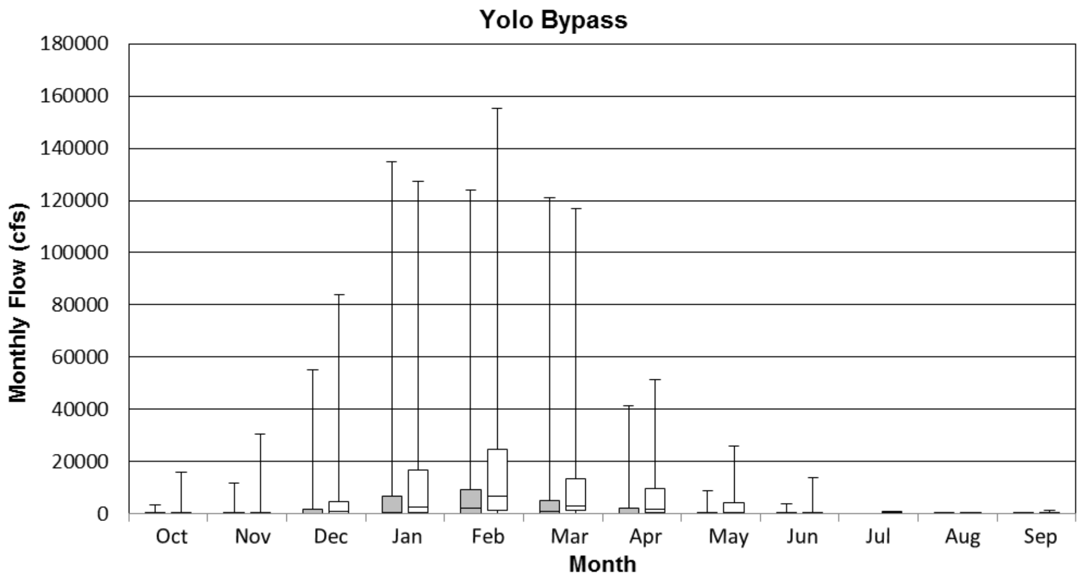


Figure 2.3-2. Yolo Bypass above the Confluence with the Sacramento River Simulated Current Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.3-2. Statistics of Observed Flow as Percent of Unimpaired Flow in Yolo Bypass

	Impaired Flow as a percent of Unimpaired Flow (%)												Seasonal Impairment	
Percentile	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan-Jun	Jul-Dec
0% tile	0	0	0	0	0	0	1	0	1	6	11	2	4	5
10% tile	3	0	0	7	0	1	3	1	12	8	15	21	13	13
20% tile	11	0	0	17	13	4	6	4	16	11	18	24	20	17
30% tile	22	0	9	24	19	9	9	8	21	12	19	25	26	19
40% tile	31	4	19	37	28	18	11	13	26	13	21	27	29	22
50% tile	37	6	27	50	36	23	16	20	38	15	22	32	34	25
60% tile	41	7	32	67	55	32	23	35	49	16	24	36	42	28
70% tile	44	14	43	87	82	43	27	67	89	18	26	41	53	31
80% tile	48	26	75	AZ	93	61	37	AZ	171	19	31	66	65	36
90% tile	AZ	37	AZ	-	AZ	87	64	-	AZ	21	69	AZ	78	45
100% tile	-	931	-	-	-	166	196	-	-	40	262	-	146	88

A zero (0) indicates that the simulated current conditions are zero.
A dash (-) indicates that the simulated unimpaired flow is zero.
“AZ” indicates that the unimpaired flow is approaching zero and is very low.

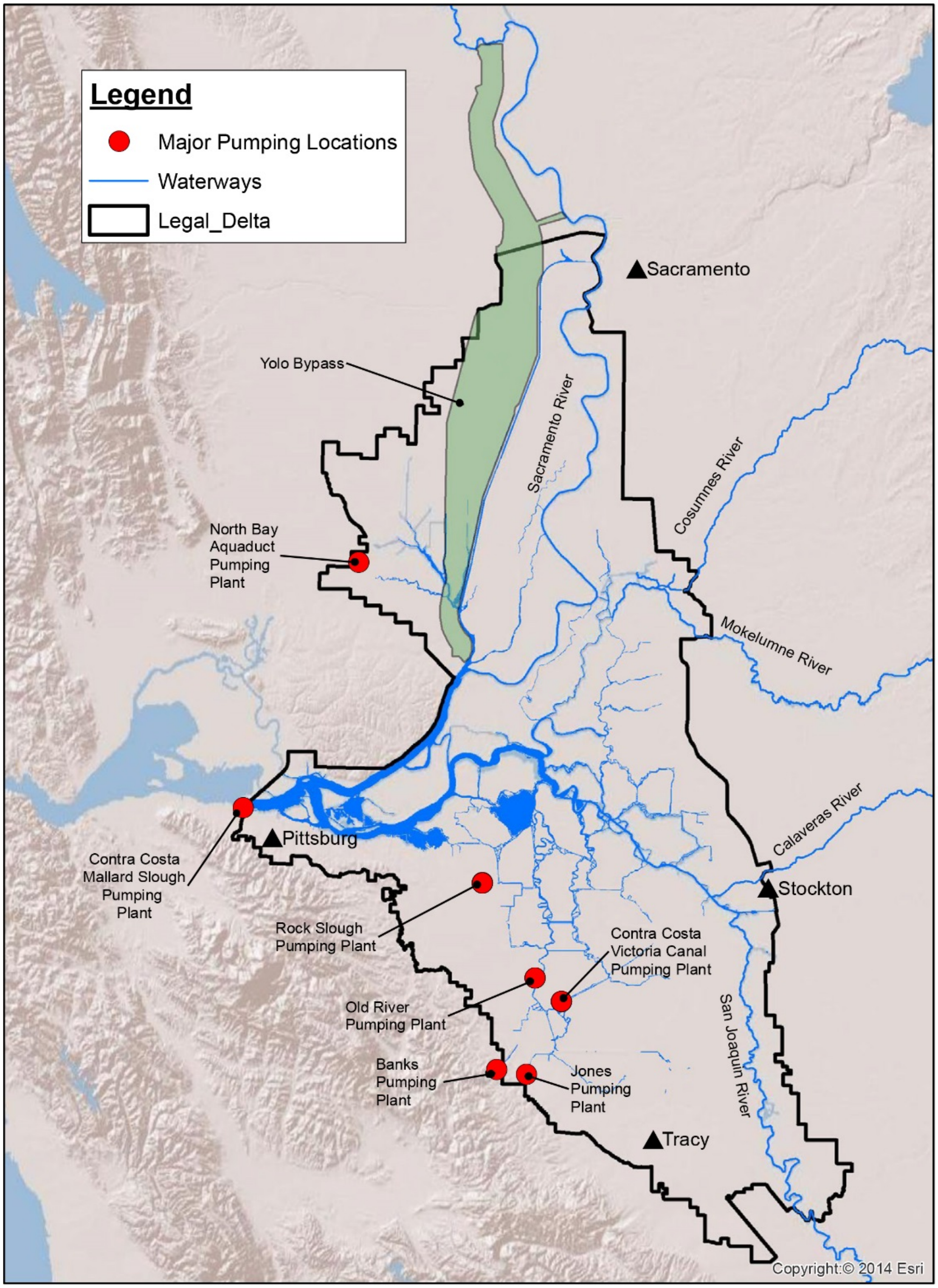
2.3.6 Sacramento Flood Basin

The Sacramento Basin is approximately 20 miles long and extends from near the current southern border of the City of Sacramento to just beyond the southern end of Snodgrass Slough near the north and south Delta forks of the Mokelumne River (Whipple et al. 2012).

The State Plan Flood Control levee runs along the east bank of the Sacramento River which has a capacity of 56,500 cfs in this area (DWR 2010a). However, the basin discharges through the Mokelumne River into the San Joaquin River and not into the Sacramento River. A discontinuous series of non-project levees direct flow through Sutter and Snodgrass sloughs to the Mokelumne River and constrain flows within the Cosumnes and Mokelumne Rivers (DWR 2010a). These levees have been breached by large floods and have also been intentionally breached to restore floodplain habitat (Swenson et al. 2003).

2.4 Sacramento – San Joaquin Delta

The Sacramento-San Joaquin Delta is the region where channels of the Sacramento and San Joaquin Rivers meet and mix with saline water from the Pacific Ocean. The “Legal Delta” is a geographic boundary of the region that encompasses 1,150 square miles roughly between the City of Sacramento to the north, Stockton to the east, Tracy to the south and Pittsburg to the west. There are over 1,000 miles of levees lining hundreds of miles of Delta watercourses (DWR 2010a) (Figure 2.4-1). Historically, the Delta contained innumerable channels of various sizes but only a few of the largest channels remain and many of those have been altered by meander cuts and dredging to make navigation more efficient (Whipple et al 2012). The largest sources of fresh water to the Delta are the Sacramento River and Yolo Bypass to the north, the Mokelumne and Calaveras Rivers to the east, and the San Joaquin River to the south. An additional and essentially unlimited source of saline water to the Delta is the Pacific Ocean and its daily and seasonal tidal cycles that propagate up Suisun Bay and influence the entire Delta.



Source: State Water Resources Control Board, 2016 Data Source: SWRCB GIS library, Water33

Figure 2.4-1. Generalized Delta Map

The natural geomorphology of the Delta and Suisun Marsh has been greatly altered by anthropogenic changes in sediment supply, flood control projects including levee building and draining, mosquito ditches in Suisun Marsh, and by large dam and diversion projects throughout its watershed. Levees and various land uses have reduced the depth of peat soils within the confines of the levees to depths of -24 feet (-7.25 meters) (Drexler et al. 2009b), which creates an enormous volume of space that, in the event of a levee break, will bring saline and brackish water from the west further into the Delta (Mount and Twiss 2005).

There are a large number of agricultural diversions directly from the channels of the Delta (DWR 2010a). Additionally, there are large diversions and pumping plants for distant municipal, industrial, and agricultural uses (DWR 2010a). In the north, East Bay Municipal Utility District diverts from the Sacramento River at Freeport, and the North Bay Aqueduct and the City of Vallejo Pipeline divert water from sloughs at the lower end of the Yolo Bypass. In the east, the City of Stockton diverts from the main stem of the San Joaquin River near Medford Island. In the southwest, the Federal Central Valley Project, the State Water Project, the Contra Costa Water District, the East Contra Costa Irrigation District, and the Byron-Bethany Irrigation District divert from the Old River channel of the San Joaquin River. The Sacramento River is a major source of the fresh water in the Old River channel which is pulled upstream through Georgiana Slough and the Delta Cross Channel Gates (DWR 2010a).

2.4.1 Delta Inflows

Despite its name, the Sacramento-San Joaquin Delta is not simply the merging of two river deltas, but is instead an elongated complex network of deltas and flood basins. Based on current unimpaired flow estimates, the Sacramento River is the largest source of flows and contributes an average of 61 percent of inflows to the Delta; the Yolo Bypass contributes about 14 percent, the east-side tributaries including the Mokelumne River contribute about 4 percent, and the San Joaquin River contributes 21 percent.

Currently, during flood stages, approximately 82 percent of flows from the Sacramento River pass through the Yolo Bypass (Roos 2006). The flood stage flows can have many sources including direct flows from tributaries such as the Feather and American rivers as well as through a system of passive and active weirs (James and Singer 2008, Singer et al. 2008, Singer and Aalto 2009, DWR 2010a, 2012). The San Joaquin River discharges into a broad network of sloughs and channels, and the Mokelumne River delta merges with the San Joaquin River delta on the eastern side of the Delta. On the southwest side of the Delta, the Marsh Creek delta merges with the San Joaquin River delta.

Under pre-development conditions, inflows from both the Sacramento and San Joaquin Rivers were much lower from July through November compared to the December to June period (The Bay Institute 1998). This difference was more dramatic in the San Joaquin River. The San Joaquin River has an upper watershed consisting of impermeable granitic rock. In contrast, the upper watershed of the Sacramento River is composed of permeable volcanic rock. As a result, ground water discharge from this volcanic system historically maintained a summer base flow at Red Bluff of approximately 4,000 cfs without which the Sacramento River would have nearly dried up during the fall (The Bay Institute 1998). Water diversions in the San Joaquin Valley began earlier than those in the Sacramento Valley and, by 1870, flows of the San Joaquin River were significantly reduced (DWR 1931, Jackson and Patterson 1977). Sacramento River diversions, particularly those in late spring and summer for rice irrigation, increased dramatically from 1912 to 1929 and the combination of significant drought periods and increased diversion during the annual low flow period resulted in an unprecedented salinity intrusion into the Delta in the fall of 1918 (DWR 1931, Jackson and Patterson 1977, Bay Institute 1998). The economic impacts of these diversion-caused salt water intrusions ultimately led to the creation of the Central Valley Project and the construction of dams for the release of freshwater flow to prevent salinity intrusion (Jackson and Patterson 1977). Construction of dams and diversions on all major rivers contributing to the Delta between the 1930s and 1960s resulted in substantial changes to Delta inflows. Winter flood peaks and spring snowmelt runoff from Delta tributaries have been greatly reduced by upstream storage and replaced by increased flows in summer and early fall, compared to pre-project hydrology (Kimmerer 2002b; Kimmerer 2004). Reductions in April-June inflows are largely the result of San Joaquin River diversions (Fleenor et al. 2010).

2.4.2 Delta Hydrodynamics

Human management of water and changes to the physical structure of the Delta have significantly changed the timing, magnitude, and flow paths through the Delta, with adverse effects on fish and wildlife. During the summer-fall dry season, the Delta channels essentially serve as a conveyance system for moving water from reservoirs in the north to the CVP and SWP export facilities, which are operated jointly under the Coordinated Operations Agreement, as well as the smaller Contra Costa Water District facility, for subsequent delivery to farms and cities in the San Joaquin Valley, southern California, and/or other areas outside the watershed (Kimmerer 2002b).

The CVP delta facilities consist of the C.W. “Bill” Jones Pumping Plant (formerly Tracy Pumping Plant), Tracy Fish Collection Facility, and Delta-Mendota Canal (DMC). The design capacity of the Jones Pumping Plant is 4,600 cfs, but until 2012 a variety of factors, including subsidence in the DMC, limited the maximum pumping rate to approximately 4,200 cfs. In April 2012, an intertie (two 108-inch-diameter pipes) was completed from the SWP to the CVP. The intertie allows up to 900 cfs to gravity flow from the California Aqueduct to the DMC. Completion of the intertie is expected to have some effects on the tidal elevations at the DMC intake and smaller effects on tidal elevations, flows, and velocities in south Delta channels (Reclamation 2009). Water is pumped by the Jones Pumping Plant into the DMC for delivery to CVP contractors in the Central Valley or storage in San Luis Reservoir, a shared CVP/SWP facility.

The SWP delta facilities consist of the Harvey O. Banks Pumping Plant, the Clifton Court Forebay (CCF), and the California Aqueduct. The installed capacity of the Banks Pumping Plant is 10,300 cfs. However, a U.S. Army Corps of Engineers (USACE) permit limited diversions into CCF at the historic maximum daily average rate of 6,680 cfs (USACE 1981). When San Joaquin River flow at Vernalis exceeds 1,000 cfs during the period from mid-December to mid-March, the diversion into CCF may be increased by one-third of the Vernalis flow (USACE 1981). Banks is operated to minimize the impact on power loads on the California electrical grid to the extent practical, using the CCF as a holding reservoir and running all available pumps at night and a reduced number during the higher energy demand hours, even when the CCF is admitting the maximum permitted inflow. Banks pumping plant is almost always operated to the maximum extent possible, subject to the limitation of water quality, Delta standards, and other variables, until all needs are satisfied and all storage south of Delta is full (Reclamation 2008). Water is pumped by the Banks Pumping Plant for delivery to SWP contractors in the San Joaquin Valley and southern California and for storage in San Luis Reservoir and multiple terminal and local reservoirs, the largest and newest being Diamond Valley Lake in Riverside County, which was completed in 2003, with a capacity of 800 TAF.

Export operations combined with changes in channel geometry, gates, and barriers and have greatly altered the natural direction of flow in the Delta with effects on water quality, fish migration, and habitat suitability (DSC 2012). Historically, the natural flow of freshwater through the Delta was generally from the Sacramento, San Joaquin and Eastside tributaries westwards towards San Francisco Bay. Currently, net flow is generally from the Sacramento River southwards towards the export pumps, except during high flow events (Figure 2.4-2). The San Joaquin River's small relative flow contribution combined with high export pumping rates has caused reverse flows in the southern Delta and reduced outflow from the Delta into the San Francisco Bay.

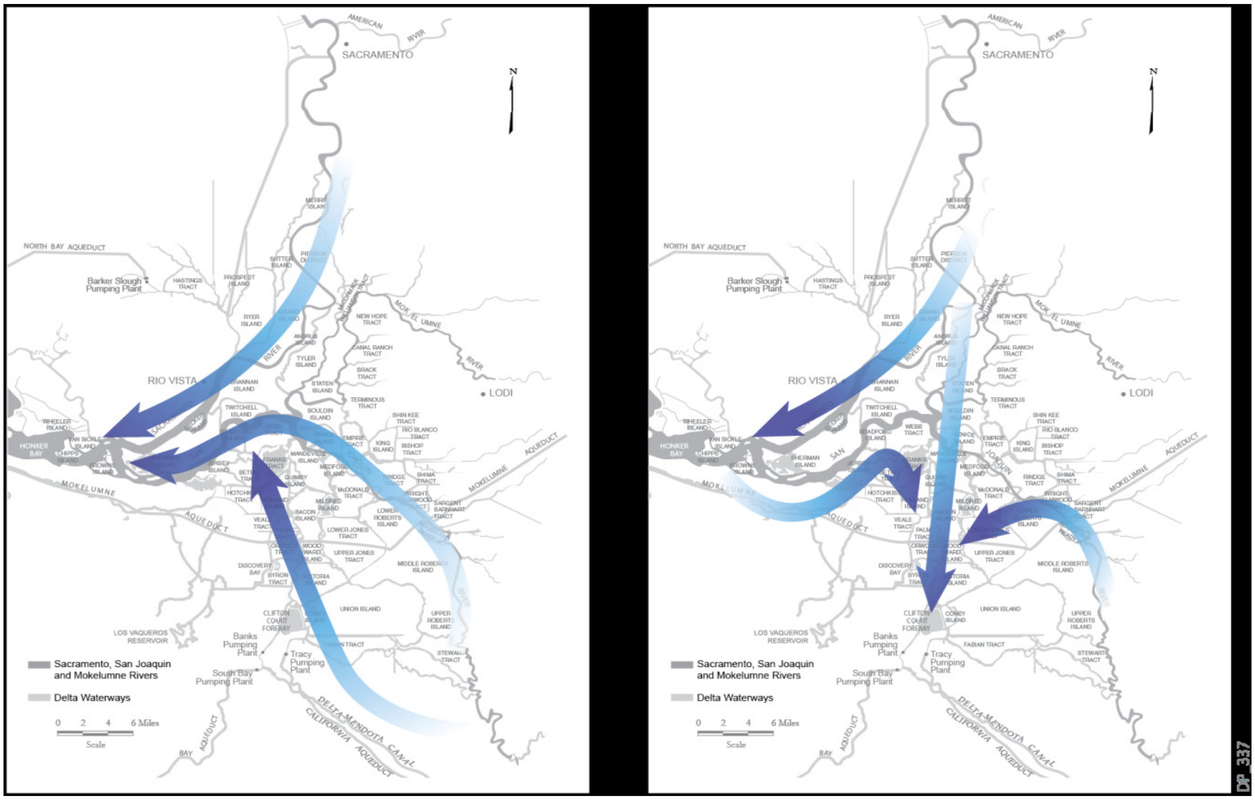


Figure 2.4-2. Flow Direction in the South Delta. The left panel depicts the tidally averaged flow direction in the absence of export pumping. The right panel depicts reversal of tidally averaged flows that occurs during times of high exports (pumping) and low inflows to the Delta (DSC 2012).

Delta gates and diversions can substantially redirect tidal and river flows creating net flow patterns and salinity and turbidity distributions that did not occur prior to development. Barriers are used in the Delta to control water quality in various locations in the Delta by changing the hydrodynamics.

2.4.3 Delta Barriers

Hydrodynamics in the south Delta are affected by four seasonal rock barriers installed to improve water quality for agricultural diverters and to reduce entrainment of native fish. The south Delta Temporary Barriers Project includes three agricultural barriers at Old River near Tracy (ORT), Middle River (MR), and on Grant Line Canal (GLC), and one fisheries barrier, the Head of Old River Barrier (HORB) (NMFS 2012).

The three agricultural barriers are installed seasonally from April 15 to September 30, on Old River near Tracy, Middle River near its confluence with Victoria and North Canals, and on Grant Line Canal. The tops of the barriers are below the mean high tide level, allowing flow to enter on the flood tide, but restricting it from exiting on the ebb tide. This trapped water provides sufficient draft for agricultural pumps in the south Delta to operate without interruption, but also blocks the natural flow and circulation patterns of these streams (NMFS 2009).

The HORB is installed in the spring to keep migrating San Joaquin Chinook salmon in the main San Joaquin River channel and away from the pumps and predators in the interior Delta and again in the fall to improve low dissolved oxygen (DO) conditions in the Stockton Deep Water Ship Channel by increasing flow (NMFS 2012). When the HORB is installed in the fall, it goes in in mid-September, at the discretion of CDFW, and is completely removed by November 30th. Throughout this period, the barrier is notched to allow a minimum of 500 cfs to flow into Old River for the upstream passage of adult salmon and steelhead (NMFS 2012). Unlike the agricultural barriers, the HORB is not submerged at high tide.

Installation of the south Delta barriers alters the circulation of water in the south Delta. The barriers create a delay in the tidal signal and difference in elevation between the channels upstream and downstream of the barriers. Installation of the barriers also alters the magnitude and direction of net flows (NMFS 2012). There is evidence that the presence of the HORB magnifies negative OMR, thus increasing entrainment of delta smelt (NMFS 2009b). Once the barriers are installed, net flows above the ORT and MR barriers generally become negative and proceed in an upstream direction. Flows in GLC remain positive and proceed downstream towards the CVP and SWP water intakes. Once the HORB is removed, net positive flows resume in the upper portion of Old River (NMFS 2012).

The barriers can also create areas of null flows (flows with no upstream or downstream motion) in the interior sections of the channels. Null flows become more common when south Delta irrigation demands are high and inflow from the San Joaquin River is low. The flow patterns in the interior of the south Delta under these conditions create a “hydraulic trap” for particles (or fish) moving with the river’s flow. These null flow areas are also associated with low DO and poor water quality (NMFS 2012).

During the period when all of the barriers are installed in the south Delta, the hydrodynamics of the Delta interior to the north are also affected. Under the influence of pumping at the CVP and SWP, water is drawn southwards from the lower San Joaquin River creating net negative flows in Old River, Middle River, Columbia Cut, and Turner Cut as water moves upstream towards the CVP and SWP diversion points.

2.4.4 Delta Cross Channel Gate Operations

The Delta Cross Channel (DCC) is a man-made controlled diversion built in 1951, located in Walnut Grove and operated and maintained by the San Luis Delta-Mendota Water Authority at the direction of Reclamation. The gates have a physical capacity of 3,500 cfs and can divert a significant portion of the Sacramento River flows into the eastern Delta, particularly in the fall (SWRCB 2010). The DCC significantly affects Delta hydrodynamics by sending Sacramento River water into Snodgrass Slough and the North Fork of the Mokelumne River and then to the interior Delta (USBR 2006). This diversion significantly improves water quality in the southern Delta and at the export pumps, but also increases the probability of entrainment for juvenile salmon migrating past its gates. When the gates are open, 40-50% of the Sacramento River flow enters the interior Delta via the DCC and Georgiana Slough. When the gates are closed, only 15-20% of the Sacramento River enters the interior Delta (Low et al. 2006). The gates are closed during migration periods to protect winter-run Chinook salmon and also at high flows to prevent flooding (Reclamation 2006).

2.4.5 South Delta Exports and Old and Middle River Reverse Flows

Exports from the south Delta include SWP's Banks Pumping Plant, CVP's Jones Pumping Plant and Contra Costa Water District's (CCWD's) Victoria Canal and Old River Pumping Plants. The combined capacity of the CVP and SWP south Delta pumping plants is about 15,000 cfs, with median and maximum daily combined diversions since water year 2000 of 6,854 and 13,720 cfs, respectively (DAYFLOW). The combined capacity of CCWD south Delta intakes is about 500 cfs, with median and maximum daily combined diversions since water year 2000 of 133 and 460 cfs, respectively (DAYFLOW). Exports from south Delta channels can greatly reduce Delta outflow and alter Delta hydrodynamics by drawing water from the central Delta towards the export facilities in the south Delta. South Delta exports have slowly increased since the late 1950s when Jones Pumping plant was developed. The highest pumping rates have occurred in the years 2000-2009 after the adoption of D-1641, particularly in the summer and fall (Figure 2.4-3). During 2010–2015 south Delta exports have been reduced by the implementation of the biological opinions to protect endangered species (NMFS 2009, USDOI 2008) and reduced available water for export due to drought conditions.

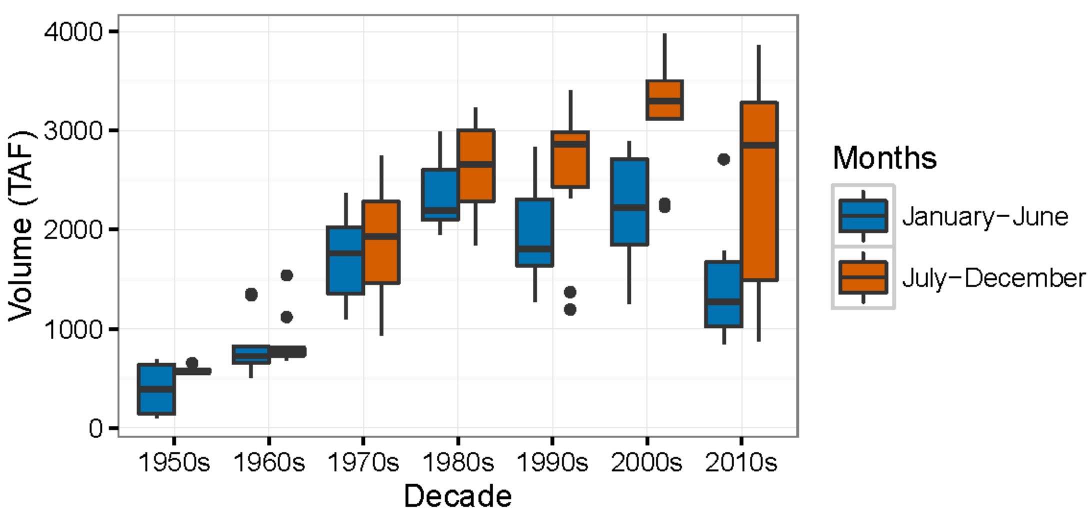


Figure 2.4-3. Total Seasonal SWP and CVP South Delta Exports by Decade (Source: DAYFLOW). The year shown on the x-axis represents the start year of the decade, for example "2000s" represents 2000–2009 and "2010s" represents 2010–2015.

The most prominent example of changes in flow direction in the Delta occurs in the Old River and Middle River channels of the San Joaquin River. Fleenor et al. (2010) documented the change in both the magnitude and frequency of net OMR reverse flows as water development occurred in the Delta (Figure 2.4-4). The disparity between pumping rates as compared to the streamflow in the San Joaquin River creates net reverse flows (water flowing upstream) on the Old and Middle Rivers. The magnitude of these reverse flows can at times be as great as 12,000 cfs flowing from the central Delta towards the export pumps. These reverse flows can entrain fish into the pumps, confuse migratory cues that juvenile salmonids use to navigate towards the ocean, and affect water quality in the Delta (Jassby 2005, Kimmerer 2008).

The 1925-2000 unimpaired line in Figure 2.4-4 represents the best estimate of "quasi-natural" or net OMR values before most modern water development (Fleenor et al. 2010). The other three lines represent changes in the frequency and magnitude of net OMR flows with increasing development. Net OMR reverse flows are estimated to have occurred naturally about 15% of the time before modern water development (Figure 2.4-4, point A). The magnitude of natural net OMR reverse flows was seldom more negative than a couple of thousand cfs. In contrast, between 1986 and 2005 net OMR reverse flows had become more frequent than 90 percent of the time (Figure 2.4-4, Point B).

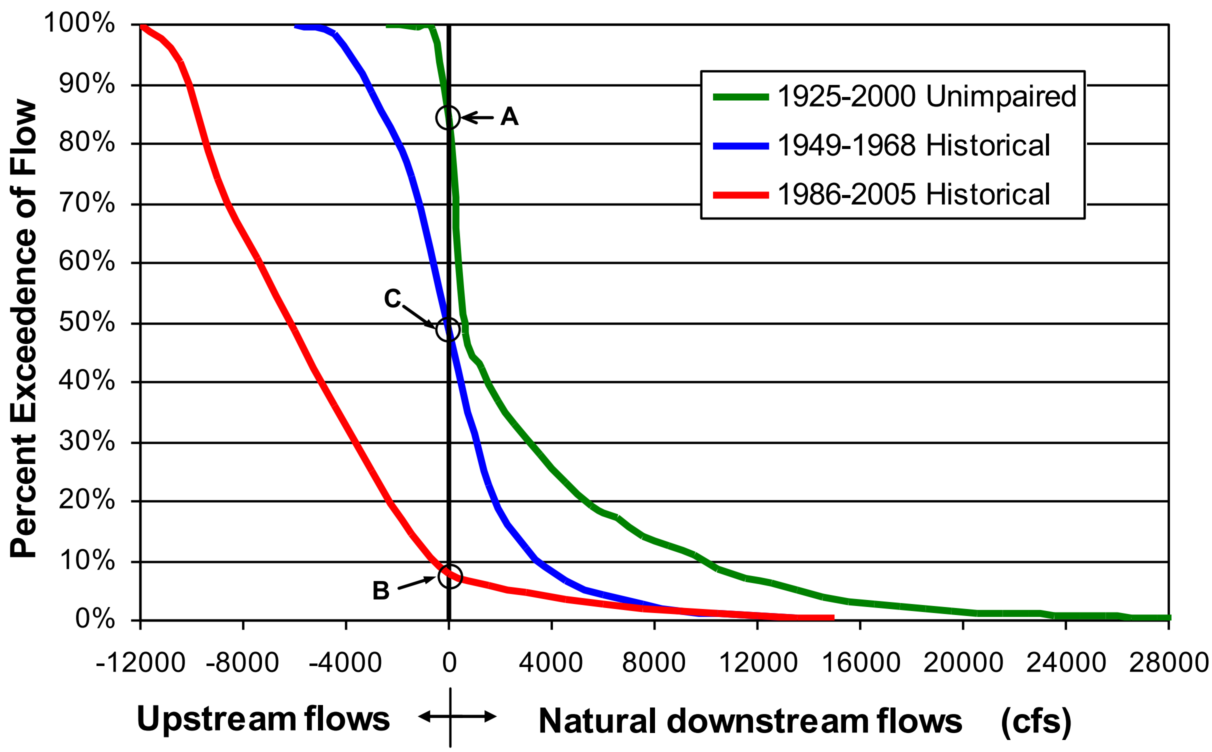


Figure 2.4-4. Cumulative Probability of OMR Flows from Fleenor et al. 2010

Old and Middle River flows are monitored by the U.S. Geological Survey (USGS) at two sites using rated velocity meters combined with stage to estimate discharge every 15 minutes. Tidal influences are digitally "filtered" out, which results in a measured net OMR flow. The tidal filter uses past and future measurements which imposes a delay of 35 hours until the net flow data is available to operators, enforcement agencies and to the public. The USGS measured net OMR flow has been criticized as being a poor compliance index and difficult to operate to due to the time delay and frequent missing or erroneous data (CCWD 2012).

Starting in early 2014, Reclamation and DWR, with concurrence from NMFS and USFWS, began a one-year demonstration project, which was later extended, to test the ability to manage OMR thorough a numerical index developed by Metropolitan Water District of Southern California. During the project duration, the State Water Project and Central Valley Project will monitor and compare both the USGS tidally filtered OMR measurements and the index values. The index is intended to be equally protective of fish and more predictable to operate to (USBR 2014; NMFS 2014).

2.4.6 Delta Outflow and X2

Two commonly used metrics of flow magnitude through the Delta are outflow and X2. Outflow is expressed as a net flow from the Delta to the San Francisco Bay with the tidal signal removed. X2 is defined as the horizontal distance in kilometers up the axis of the estuary from the Golden Gate Bridge to where the tidally averaged near-bottom salinity is 2 practical salinity units (Jassby et al. 1995). Delta outflow and the position of X2 are closely and inversely related with a time lag of about 2 weeks (Jassby et al. 1995; Kimmerer 2004).

Tides are driven by gravitational pull by the sun and the moon, air pressure and wind currents. The flow driven by the tides is greatest near the mouth of the estuary where summer maximums can reach up to 340,000 cfs and are weaker upstream on the Sacramento and San Joaquin Rivers (Figure 2.4-5). Large tidal exchanges below the confluence of the Sacramento and the San Joaquin Rivers make it difficult to measure flow through the large channels. Recently the USGS installed monitoring stations to measure Delta outflow, however, they are subject to frequent outages, imprecision and error. To better account for hydrology within the Delta in the absence of measured data, tools such as Dayflow have been developed to estimate interior Delta flows and net Delta outflow.

Dayflow is a model developed by DWR in 1978 as an accounting tool for water in the Delta. State Water Board Water Rights Decision D-1485 set Delta outflow standards, however the technology to gage the large flow exchange at the mouth of the Delta was not available. Dayflow was developed to provide an estimate of outflow and to gain estimates of historic Delta outflow. Dayflow calculates the daily average net Delta outflow index (NDOI) based on precipitation gages, inflow gages, project exports, channel depletions and agricultural consumptive uses. In addition to NDOI, Dayflow provides estimates of net flow through the DCC and Georgiana Slough, net flow at Jersey Point (QWEST), and X2. Recently studies have shown that NDOI is an inaccurate measure of Delta outflow during certain times of the year and particularly at times of low Delta outflow (Brown and Huber 2015, DWR 2016c).

DWR and UC Davis have been working to improve the estimates of in-Delta consumptive uses and channel depletion which will improve the estimates of Delta outflow and ultimately hydrodynamics and the low salinity zone. These new tools include: Delta Island Consumptive Use (DICU) and Delta Evapotranspiration of Applied Water (DETAW). Remote sensing techniques have the potential to improve the accuracy of these tools, however the new methods are still under development and may require significant resources to be applied to the entire Delta. Current Dayflow estimates tend to underestimate Delta consumptive uses in the summer, which affects outflow and low salinity zone estimates when compared to newer estimates using DETAW (DWR 2016c). The future release of DETAW will hopefully more accurately estimate Delta uses and improve estimates of Delta salinity, outflow, and hydrodynamics.

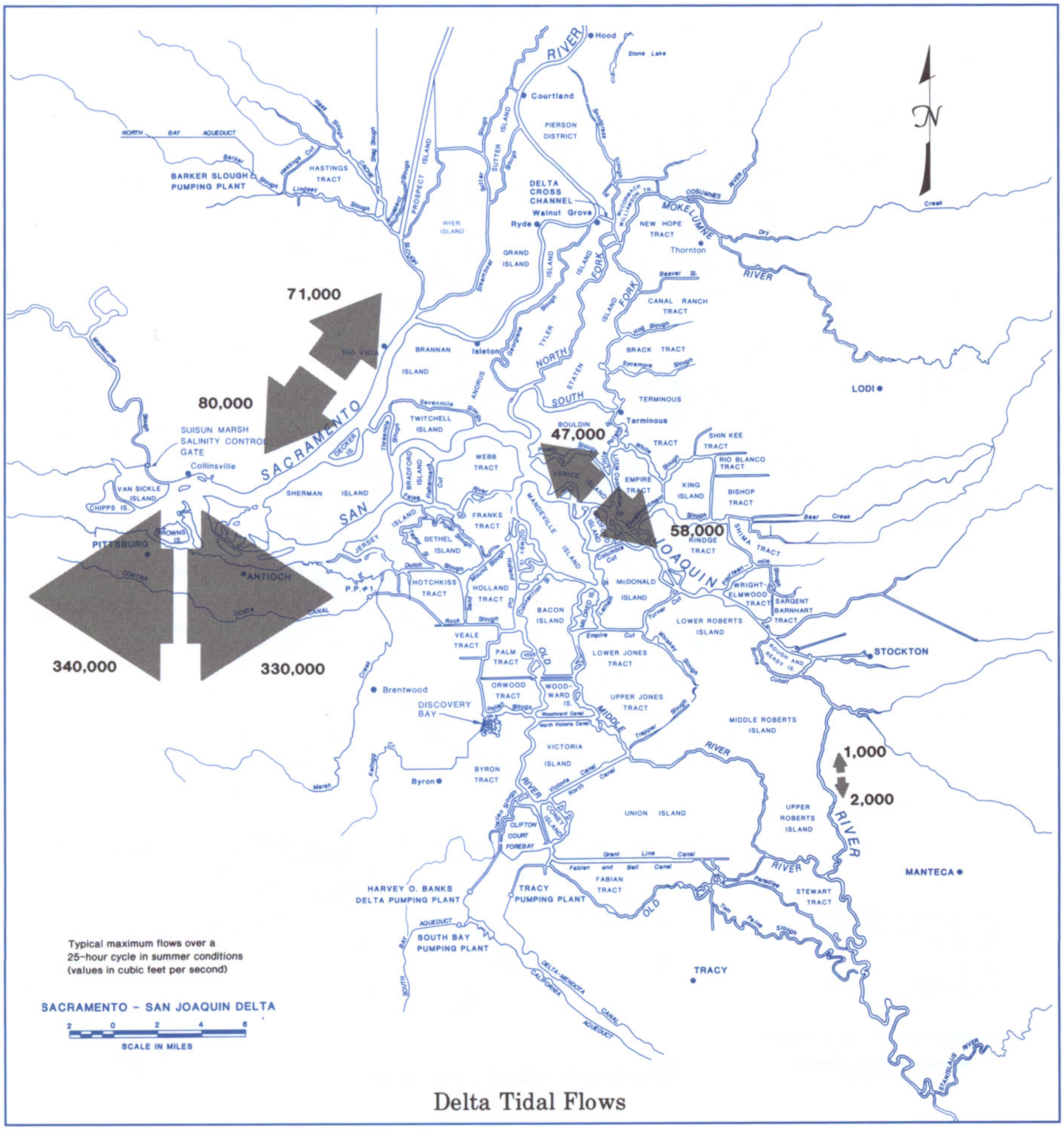


Figure 2.4-5. Delta Tidal Flows over a 25-hour Cycle in Summer Conditions (values in cfs) (DWR 1995)

USGS has installed a monitoring station network that now allows for a comparison between direct estimates of net Delta outflow (NDO) and Dayflow NDOI, however because of the large tidal fluctuations, the measured net flow is prone to errors (DWR 2016c). NDO and NDOI are similar except at times of large tidal exchanges such as during the spring – neap cycle and times of very low NDOI. The spring – neap tidal cycle causes the Delta to fill and drain over a two week period and causes short periods of negative NDO. A notable limitation of Dayflow is that during these times of negative NDO, NDOI is positive (DWR 2012). The State Water Board is currently conducting a review through the Delta Stewardship Council's Delta Science Program of the above issues to provide recommendations on improvements to Delta outflow estimates.

The combined effects of water exports and upstream diversions have reduced the average annual net outflow from the Delta by 33% and 48% during the 1948 – 1968 and 1986 – 2005 periods, respectively, as compared to unimpaired conditions (Fleenor et al. 2010) which corresponds with results presented here. May and June show the largest impairment where in 80% of the those months Delta outflow is less than 40% of the unimpaired flow (Table 2.4-1). For simulated current conditions, Delta outflow is much lower in the spring and higher in September compared with unimpaired Delta outflow, and variability is reduced in all months (Figure 2.4-6). Table 2.4-2 shows the contributing sources of unimpaired Delta outflow by season. The Sacramento River contributes 57% of the outflow in the winter-spring, and 72% in the summer and fall. Since 2000, there has been a reduction in spring outflow and a reduction in the variability of Delta outflow throughout the year (Figure 2.4-7) due to the combined effects of exports and variable hydrology.

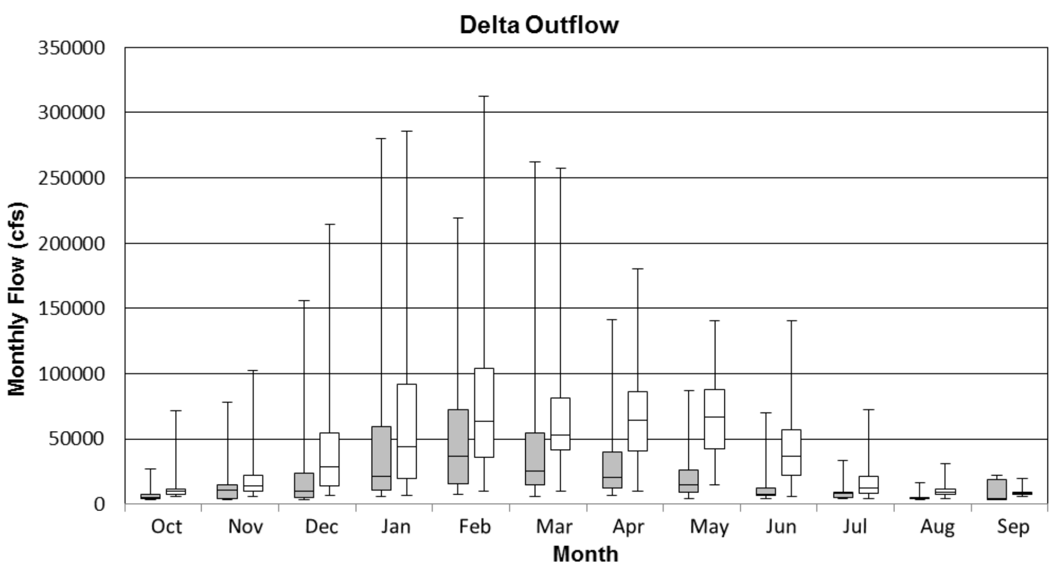


Figure 2.4-6. Net Delta Outflow Simulated Current Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.4-1. Statistics of Impaired Flow as Percent of Unimpaired Delta Outflow

Impaired Flow as a percent of Unimpaired Flow (%)													Seasonal Impairment	
Percentile	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan-Jun	Jul-Dec
0% tile	21	18	22	34	30	23	22	15	13	22	24	32	27	32
10% tile	36	26	27	43	43	31	26	19	17	28	30	36	35	39
20% tile	43	34	31	46	51	37	29	21	19	35	34	38	36	45
30% tile	47	43	35	52	54	39	32	22	21	38	36	42	39	48
40% tile	50	45	38	56	58	44	34	24	23	45	40	47	42	48
50% tile	55	52	40	61	61	48	36	26	26	50	46	54	44	52
60% tile	60	58	43	65	65	53	38	27	29	57	47	117	49	56
70% tile	67	72	46	72	74	61	44	30	36	69	51	147	55	58
80% tile	69	97	51	79	81	75	55	40	38	84	56	210	60	62
90% tile	75	116	61	89	89	82	66	44	46	98	61	233	66	68
100% tile	114	147	95	146	107	110	84	63	79	122	102	272	82	87

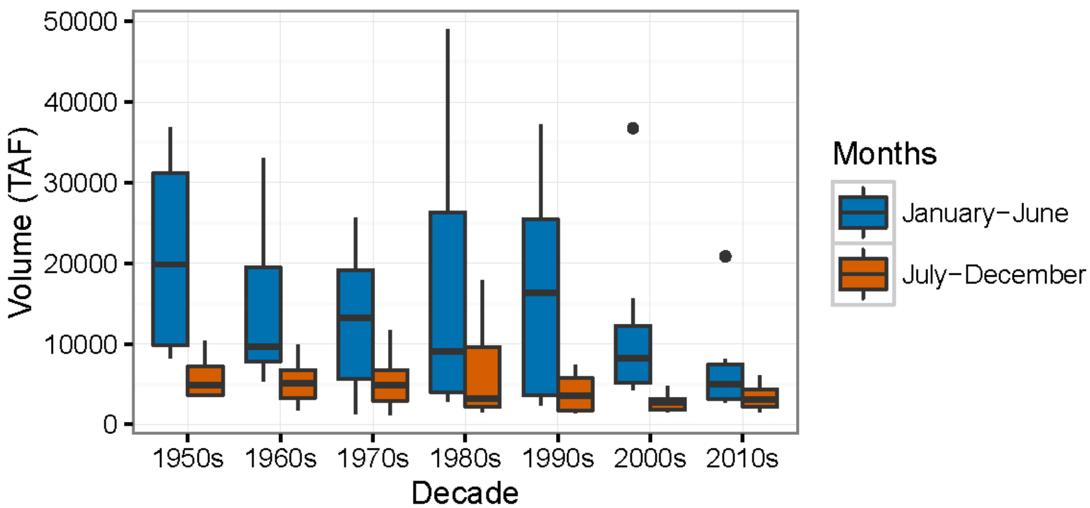


Figure 2.4-7. Seasonal Net Delta Outflow Index by Decade (Source: DAYFLOW). The year shown on the x-axis represents the start year of the decade, for example “2000s” represents 2000–2009 and “2010s” represents 2010–2015.

Table 2.4-2. Simulated Unimpaired Contributions to Total Delta Outflow from Various Locations in the Project Area

Location	% of Unimpaired Delta Outflow (Jan-Jun)	% of Unimpaired Delta Outflow (Jul-Dec)	% of Unimpaired Delta Outflow (Annual Average)
Sacramento River at Bend Bridge	25.3%	35.0%	26.5%
Sacramento River at Freeport	56.6%	72.1%	60.1%
Cow Creek at Confluence with Sacramento River	1.5%	1.6%	1.5%
Battle Creek at Confluence with Sacramento River	1.0%	1.9%	1.2%
Butte Creek near Durham	0.7%	0.8%	0.7%
Antelope Creek at Confluence with Sacramento River	1.8%	2.4%	1.9%
Deer Creek	0.7%	0.9%	0.8%
Mill Creek	0.7%	1.0%	0.7%
Paynes Creek	0.2%	0.3%	0.2%
Clear Creek	1.1%	1.1%	1.1%
Big Chico Creek	0.3%	0.3%	0.3%
Feather River at Confluence with Sacramento River	24.5%	24.7%	24.6%
Feather River Above Confluence with Yuba River	14.6%	15.6%	14.8%
Feather River Upstream of Oroville Dam	14.6%	15.5%	14.8%
Yuba River	8.3%	7.3%	8.1%
Bear River at Confluence with Feather River	1.2%	1.1%	1.2%
American River at Confluence with Sacramento River	9.8%	6.8%	9.1%
Mokelumne River above the confluence with Cosumnes	3.0%	1.2%	2.6%
Cosumnes River at confluence with Mokelumne	1.5%	0.8%	1.3%
Calaveras River	0.5%	0.3%	0.5%
Stony Creek	1.4%	0.9%	1.3%
Cottonwood Creek	2.0%	1.7%	1.9%
Thomes Creek	0.9%	0.8%	0.9%
Cache Creek	2.2%	1.9%	2.3%
Putah Creek	1.3%	1.0%	1.2%
Sutter Bypass Outflow	10.0%	7.4%	9.4%
Yolo Bypass	14.6%	9.5%	13.4%
San Joaquin River at Vernalis	22.5%	15.3%	20.8%
Delta Outflow	100.0%	100.0%	100.0%

Delta outflow and X2 are closely and inversely related, higher Delta outflows push saline waters from the pacific further toward the Golden Gate Bridge therefore reducing the value of X2, which scales as the logarithm of net Delta outflow. However because antecedent conditions are also important, times when there is a large daily variability in outflow, the relationship between outflow and X2 weakens (Monismith et. al. 2002). On a monthly time step, the relationship between outflow and X2 is quite clear as shown in Figure 2.4-8.

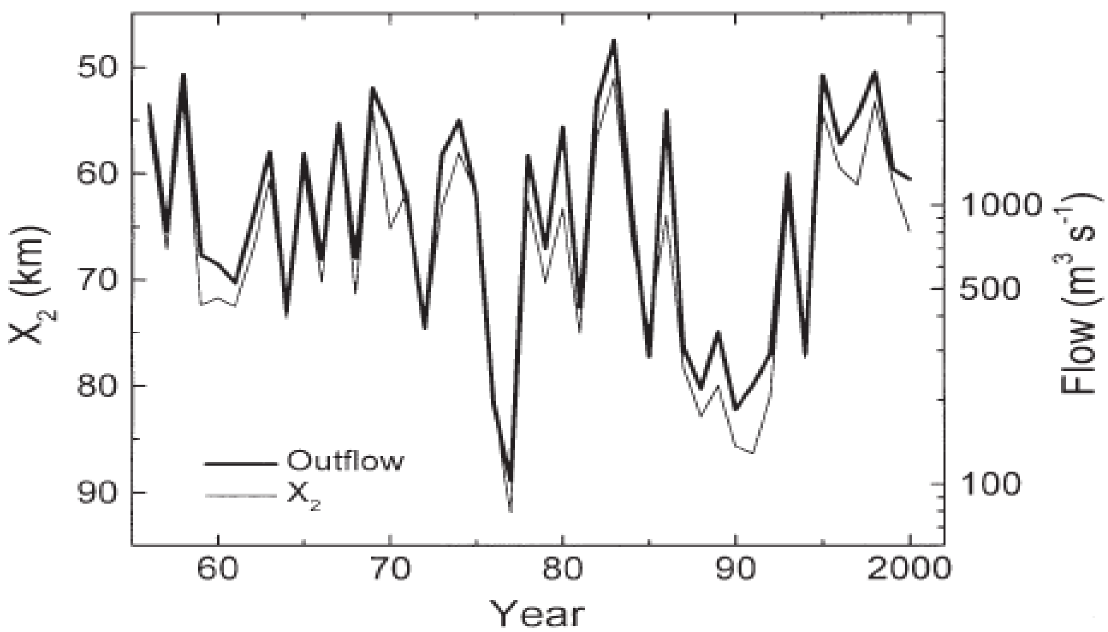


Figure 2.4-8. Time Series of X2 (thin line, left axis, scale reversed) and Outflow (heavy line, right axis, log scale), Annual Averages for January to June. Flow data from DWR; X2 calculated as in Jassby et al. (1995) (Source: Kimmerer 2002a, Figure 3).

Hydrodynamic simulations conducted by Fleenor et al. (2010) indicate that the position of X2 has been skewed eastward in the recent past, as compared to pre-development conditions and earlier impaired periods, and that the variability of salinity in the western Delta and Suisun Bay has been significantly reduced (Figure 2.4-9).

Figure 2.4-9 shows the cumulative probability distributions of daily X2 locations showing unimpaired flows[3] (green solid line) and three historical periods, 1949-1968 (light solid blue line), 1969-1985 (long-dashed brown line) and 1986-2005 (short-dashed red line), illustrating progressive reduction in salinity variability from unimpaired conditions. Paired letters indicate geographical landmarks: CQ, Carquinez Bridge; MZ, Martinez Bridge; CH, Chipps Island; CO, Collinsville; EM, Emmaton; and RV, Rio Vista. The higher X2 values shown in this figure (refer to Point 'B') indicate the low salinity zone is farther upstream for a more prolonged period of time. Point 'B' demonstrates that during the period from 1986 to 2005 the position of X2 was located upstream of 71 km nearly 80% of the time, as opposed to unimpaired flows which were equally likely to place X2 upstream or downstream of the 71 km location (50% probability). (Fleenor et al. 2010.)

[3] Daily unimpaired flows shown here are estimated using DWR's previous method of estimating unimpaired flows described in California Central Valley Unimpaired Flow Data, Fourth Edition (DWR 2007).

Historically, X2 exhibited a wide seasonal range tracking the unimpaired Delta outflows; however, seasonal variation in X2 range has been reduced by nearly 40%, as compared to pre-dam conditions. (TBI 2003)

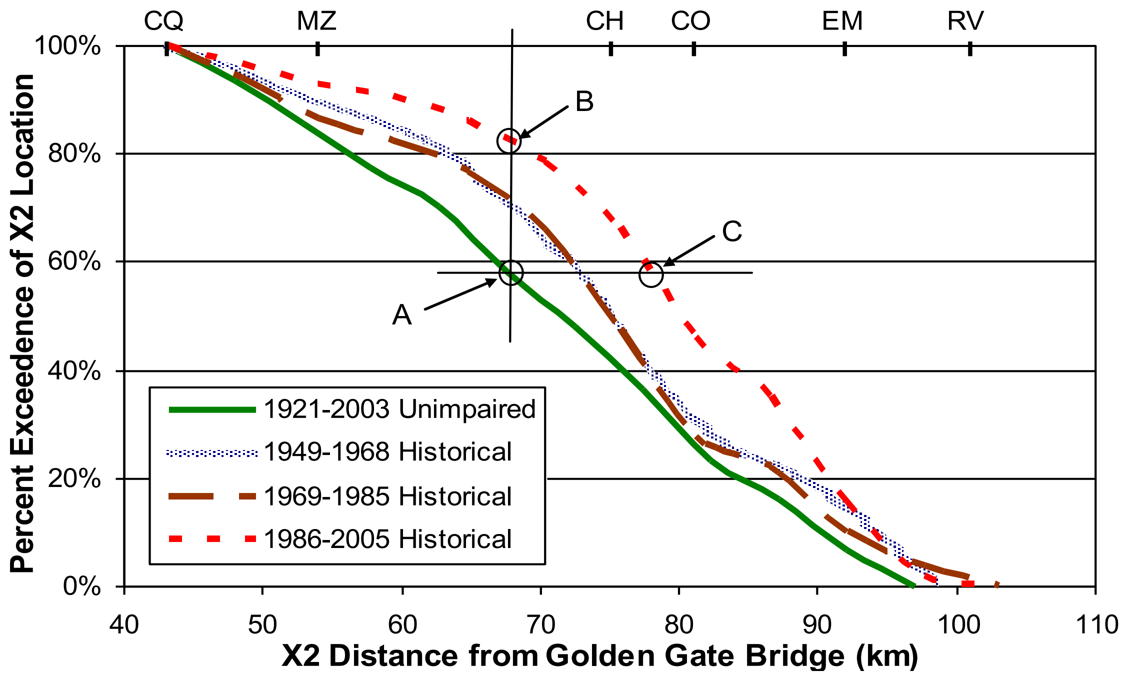


Figure 2.4-9. Cumulative Probability of Daily X2 Locations, from Fleenor et al. 2010

Although X2 was originally conceived of as a regulatory parameter for the winter-spring period (Jassby et al. 1995), more recent research has suggested that the position of X2 in fall may affect Delta smelt populations (Chapter 3, Scientific Knowledge to Inform Fish and Wildlife Flow Recommendations). Fall X2 has increased and variability has decreased through time (Figure 2.4-10; USFWS 2011).

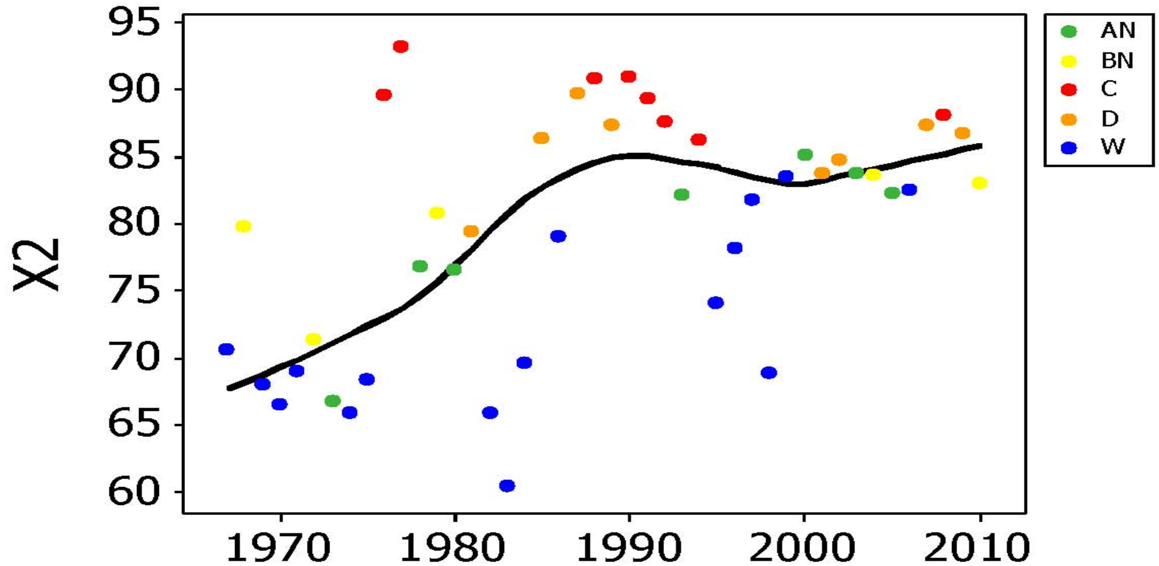


Figure 2.4-10. Time Series of Fall X2 since 1967. Water year types represent the preceding spring. A LOESS smooth is fitted to the data (USFWS 2011).

The Dayflow methodology is often used to estimate X2 based on outflow for operational and management decisions. Daylow's X2 estimate is based on a 20 year-old autoregressive equation, which produces significant discrepancies from measured values recorded by the California Data Exchange Center (CDEC) (Figure 2.4-11) (Mueller-Solger 2012). To improve its accuracy, the Dayflow X2 equation should be updated using more salinity and flow data which is now available to reduce uncertainty in the relationship between Delta outflow and daily average X2 (Mueller-Solger 2012, Bourez 2012). In addition, updates to the Dayflow X2 equation should also account for variable stratification (MacWilliams et al. 2015).

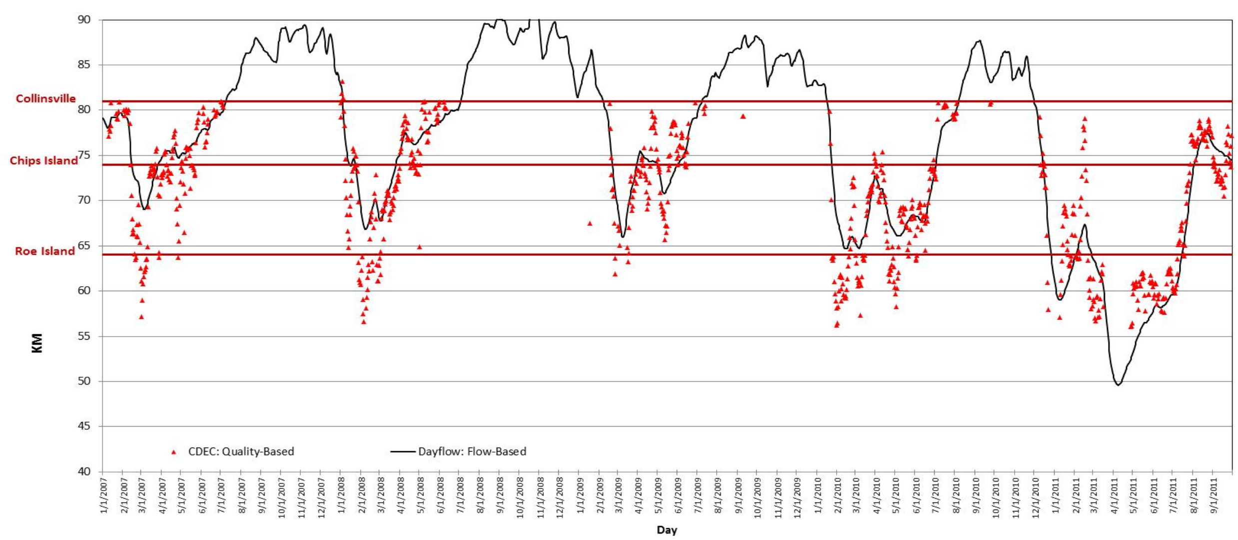


Figure 2.4-11. Dayflow, Flow-Based Estimation of X2 and CDEC Water-Quality Based X2 Values (Bourez, 2012)

2.5 Suisun Region

Functionally, Suisun Marsh is similar to the larger Sacramento-San Joaquin Delta in having a delta (Green Valley Creek/Suisun Creek/Cordelia Slough) embedded within a tidal marsh. It differs because it lies between the Sacramento-San Joaquin Delta and the San Francisco Bay Estuary. While Sacramento-San Joaquin River flows have a significant effect on flow and salinity gradients in the Suisun region, localized factors can have large effects on flows and salinity gradients within the marsh. The vegetation of brackish tidal marsh wetlands and non-tidal managed wetlands are biological expressions of those gradients and the wetlands and sloughs are particularly important habitat.

Suisun Creek and Green Valley Creek are regulated by dams and have an estimated combined average annual runoff of 16,420 AF (Jones & Stokes Associates Inc. and EDAW Inc. 1975). Summer base flow in both creeks is currently <1 cfs (Resource Management Associates 2009). In addition to the discharge of the two creeks, the Fairfield-Suisun Sewer District Treatment Plant discharges approximately 20 cfs of treated wastewater into Boynton Slough during the dry season and significantly more during the wet season (San Francisco Bay Regional Water Quality Control Board 2009, 2014). Boynton Slough drains into the upper reach of Suisun Slough. Natural flows for other creeks in the Suisun region have not been reported and those creeks flow through developed areas that have significant treated wastewater or irrigation base flows during the summer.

Tides in the Suisun region are mixed semi-diurnal (two dissimilar high tides and two dissimilar low tides each day) (Malamud-Roam 2000, Resource Management Associates 2009) and present day tidal flows in the main channel range from approximately 300,000 cfs at the eastern end to approximately 600,000 cfs at the western end (Siegel et al. 2010, Enright 2014). The timing of the asymmetrical daily pattern of high tides and low tides flips from winter to summer and then back again. That unique cycling of the tides combined with a tidal marsh ecosystem that only floods during the highest of the high tides and then only during the period of the highest tides each month has large effects on the temperature and salinity of water in adjacent tidal channels and on soil salinity in the tidal marsh. Those factors in turn control the distribution of plants and animals on the marsh plains and channels.

The 2006 Bay-Delta Plan contains salinity objectives for the Suisun region. The Suisun Marsh Salinity Control Gates are operated to assist in meeting those objectives and have been shown to be very effective at conveying relatively fresh water from Collinsville downstream in Montezuma Slough and through Hunter Cut into Suisun Slough (Enright 2008). The net flow during the fall can be approximately 2,800 cfs through the gates at times when the Delta Outflow Index ranges from 2,000 to 8,000 cfs (Enright 2008). Operation of the gates has a significant freshening effect on high and low tide salinity at the Suisun Slough salinity compliance point (S-42) and at high tide at the Chadbourne Slough compliance site (S-21) (Enright 2008). Operation of the gates has a significant effect on tidal dynamics with effects that range from damping to increasing the range of tides. Additionally, the operation of the gates during the fall period causes increases in salinity in the Delta resulting in a 3 km upstream shift in X2 (Enright 2008).

2.6 Drought

The Sacramento-San Joaquin Bay-Delta hydrology has historically been defined by extreme events ranging from large winter and spring floods to multi-year droughts. From water year 2012 through 2016 runoff into the Delta has been below normal with three very dry years in a row (2013–2015). Modeling data is not available for the current drought period and therefore has not been included in the analysis throughout this chapter, however similar historical drought periods such as the 1988–1992 drought, 1976–1977 drought and the 1929–1934 drought are captured.

The recent drought period was severe, however it is similar to previous droughts captured in the 82-year analysis in both severity and duration. The average Sacramento Valley annual runoff estimated by DWR from 2012–2015 was 10.2 MAF which is slightly higher than the longer 1988-1992 and 1929–1934 droughts (Table 2.6-1). The 1976–1977 drought was short and severe even when compared with 2014-2105 which were the driest two years of the recent drought.

Table 2.6-1. Sacramento Valley Unimpaired Runoff (DWR 2016d)

Period (Water Years)	Average Annual Runoff (MAF)
2012–2015	10.2
2014–2015	8.4
1988–1992	10.1
1976–1977	6.7
1929–1934	9.8

Many studies indicate that the next 82 years will likely be very different than the 82-years analyzed above (Null et. al. 2010, Milly, et al. 2008, Barnett, et al. 2008, Null and Viers 2013) but exactly how the hydrology of the Sacramento Watershed will be affected by climate change is uncertain. California will likely experience more extreme winter floods and longer, more severe droughts in years to come.

2.7 Conclusions

Current hydrologic conditions in the Sacramento Watershed are very different than simulated unimpaired hydrologic conditions. The Sacramento River has been termed “The hardest working river in the state” because of the many beneficial uses it provides (LA Times 1989). It provides drinking water for millions of people throughout the state and it is the primary supply for agriculture throughout the Central Valley. In general, this development has reduced winter and spring flows and increased summer flows while reducing the hydrologic variability for regulated tributaries. In unregulated tributaries hydrologic development has reduced flows during the irrigation season resulting in low, warm flows particularly in the summer.

Regulated tributaries show the largest difference between current conditions and unimpaired conditions in the January through June months. These differences are largest for non-project tributaries such as the Mokelumne River, Putah Creek, and Cache Creek where flows are less than 23%, 51%, and 44% of unimpaired flow in half of the years respectively. Project tributaries such as Clear Creek and the Feather and American Rivers have higher flows than non-project tributaries most of the years, however during dry years they still show a large decrease in flows. For example, Clear Creek, the Feather and American Rivers are below 16%, 37%, and 34% in 10% of the years respectively.

Current water management has increased the stability of the Delta's annual inflows and salinity. Annual incursions of saline water into the Delta still occur each summer, but have been substantially muted compared to their historical levels by the release of summer water from the reservoirs (Herbold and Moyle 1989). Simulated current conditions Delta outflow is less than 40% of unimpaired Delta outflow during January-June in half of the years, with the greatest impairment generally occurring during April–June.

Chapter 3
Scientific Knowledge to Inform Fish and Wildlife Flow Recommendations

3.1 Introduction

This chapter provides a review and summary of the best available science on flow needs for the protection of aquatic fish and wildlife beneficial uses. Specifically, this chapter describes the ecosystem functions provided by flows and describes the distribution and abundance of several native Bay-Delta aquatic species and their relationships to flow building on the State Water Board's 2010 Delta Flow Criteria Report. As discussed in the introduction, the Delta Flow Criteria Report presented a technical assessment of non-regulatory flow criteria and operational requirements intended to protect aquatic resources, but did not consider other competing uses of water or tributary-specific needs for cold water and other purposes that will be considered in the Phase II process.

This chapter focuses on flows to support native species and aquatic habitat and will inform the analyses in Chapter 5 on recommended changes to the Bay-Delta Plan to protect fish and wildlife including changes to Sacramento and Delta eastside tributary inflows, Delta outflow, interior Delta flow, and cold water habitat requirements. Other important uses such as municipal, agricultural and hydropower will also factor into the State Water Board decision-making regarding updates to the Bay-Delta Plan.

Many others stressors other than flows can also affect ecosystem processes. Each of these stressors has the potential to interact with flow to affect available aquatic habitat. As discussed in more detail in Chapters 4 and 5, fish and wildlife protection cannot be achieved solely through flows – habitat restoration and stressor reduction are also needed. The dynamic nature of flow interacts with the physical environment to produce aquatic habitats suitable for native fish and wildlife. The function and ability of ecosystems to support these species can be reduced by stressors. One cannot substitute one for another; flow improvements, stressor reduction, and habitat restoration are all essential for protecting fish and wildlife resources. Suitable flows are a critical element of protection and restoration and are the subject of this chapter.

This chapter relies on scientific and empirical evidence from published and peer reviewed articles, exhibits and testimony in the record of the 2010 Delta Flow Criteria Report proceeding and original analyses prepared by State Water Board staff. Where information is available, this Report identifies flows that are predicted to either produce population growth of specific native indicator aquatic species populations more than half of the time or maintain populations near abundance goals previously identified in the Delta Flow Criteria Report.

The following specific scientific information is relied upon in this Report:

- Ecological function-based analyses for desirable species and ecosystem attributes.
- Statistical relationships between flow and species abundance; and
- Unimpaired flows and historical impaired flows that supported more desirable ecological conditions.

3.2 Flow and the Ecosystem

This section describes the importance of the flow regime in protecting the aquatic ecosystem that supports fish and wildlife beneficial uses. In general, naturally variable flow conditions provide the conditions needed to support the biological and ecosystem processes which are imperative to the protection of fish and wildlife beneficial uses. Conversely, altered flow regimes have been shown to be a major source of degradation to aquatic ecosystems worldwide (Petts 2009).

Flow is commonly regarded as a key driver or "master variable" governing the environmental processes in riverine and estuarine systems such as the Bay-Delta and its watershed (Poff et al. 1997; Bunn and Arthington 2002; Kimmerer 2002b; Petts 2009; Montagna et al. 2013; Yarnell et al. 2015). Flow is not simply the volume of water, but also the direction, timing, duration, rate of change, and frequency of specific flow conditions. Bunn and Arthington (2002) present four key principles underlying the links between hydrology and aquatic biodiversity and the impacts of altered flow regimes: 1) flow is a major determinant of physical habitat; 2) aquatic species have evolved life history strategies based on natural flow regimes; 3) upstream-downstream and lateral connectivity are essential to organism viability; and 4) invasion and success of nonnative species is facilitated by flow alterations.

The effects of flow modifications on biological resources have been reviewed by several authors who have found that fish abundance and diversity declined in response to reductions in flow across a wide range of biological communities all over the world (Lloyd et al. 2004; Poff and Zimmerman 2010; Rozengurt et al. 1987). Although there is no universal quantitative relationship between flow alteration and ecological response, the risk of ecological change increases with greater magnitudes of flow alteration (Poff and Zimmerman 2010). Studies of river-delta-estuary ecosystems in Europe and Asia have concluded that water quality and fish resources deteriorate beyond their ability to recover when spring and annual water withdrawals exceed 30 and 40 to 50 percent of unimpaired flow, respectively (Rozengurt et al. 1987). Upstream diversions and water exports in the Delta have reduced median January to June and average annual outflow by 56 and 48 percent, respectively (Fleenor et al. 2010; Chapter 2).

3.2.1 Riverine Flows

Altered flow regimes negatively affect native fish communities and their aquatic ecosystem (Pringle et al. 2000, Freeman et al. 2001, Bunn and Arthington 2002, Moyle and Mount 2007). An assessment of streams across the conterminous U.S. shows a strong correlation between simplified or diminished streamflows and impaired biological communities including fish (Carlisle et al. 2011). In addition, when streams are dammed and flow regimes are simplified by dam releases, stream fish communities tend to become simplified and more predictable, usually dominated by species that thrive in simplified and less variable habitats (Brown and Bauer 2009; Kiernan et al. 2012). This has been found to be the case in the Bay-Delta watershed, where native fish and other aquatic organisms have been increasingly replaced by non-native species (Feyrer and Healey 2003; Brown and May 2006; Brown and Michniuk 2007; Brown and Bauer 2009). Within the watershed, the regions of greatest flow alteration are the most dominated by non-native species (Brown and May 2006; Brown and Michniuk 2007), where the altered hydrology likely creates conditions more favorable for spawning and rearing of non-natives than natives (Brown and Bauer 2009). Implementation of a more natural flow regime with high spring flows has been shown to favor native over non-native species in Putah Creek, although non-natives still dominate in the lowermost reach (Kiernan et al. 2012).

Native communities of fish and other aquatic species are adapted to spatial and temporal variations in river flows under which those species evolved, including extreme events such as floods and droughts (Sparks 1995; Lytle and Poff 2004). On the other hand, permanent or more constant flows, created by damming or diverting river flows, favor introduced species (Moyle 2002; Moyle and Mount 2007; Poff et al. 2007; Brown and Bauer 2009; Kiernan et al. 2012). Long-term success (i.e., integration) of an invading species is much more likely in an aquatic system, like the Bay-Delta watershed, that has been permanently altered by human activity. Systems altered by human activity tend to resemble one another across broad geographical areas and favor introduced species that are valued by humans as game or food fish (Gido and Brown 1999; Moyle and Mount 2007).

More natural flow regimes support the various life history characteristics of native aquatic organisms that are adapted to the natural flow regime (Bunn and Arthington 2002; King et al. 2003; Lytle and Poff 2004). For example, most fish species native to California in general, and the Bay-Delta in particular, have evolved to spawn during the spring or otherwise use spring flows to access spawning and rearing habitat (Moyle 2002). A more natural flow regime, including variation in tributary inflows, provides additional protection of genetically distinct sub-populations of aquatic organisms that evolved from individual rivers and their tributaries. Sub-populations are important in maintaining genetic diversity and the resilience of aquatic communities. Sub-populations exhibit important genetic diversity that when preserved allows use of a wider array of environments than without it (McElhany et al. 2000; Moyle 2002; NMFS 2014). Maintaining the diversity of sub-populations of salmonids on the major Bay-Delta tributaries has been identified as an important factor for achieving population viability (Moyle 2002; Carlson and Satterthwaite 2011; NMFS 2014).

The genetic and life-cycle diversity provided by maintaining sub-populations and varied life history timing of Central Valley salmonids through achieving a more natural flow regime with improved temporal and spatial variability would help protect populations against both short-term and long-term environmental disturbances. Fish with differing characteristics among sub-populations (i.e., greater diversity) have different likelihoods of persisting, depending on local environmental conditions. Thus, the more diverse a species is, the greater the probability that some individuals will survive and reproduce when presented with environmental variation (McElhany et al. 2000; TBI/NRDC 2010a; Carlson and Satterthwaite 2011). Genetic diversity also provides the raw material for surviving long-term environmental changes. Salmonids regularly face cyclic or directional change in their freshwater, estuarine, and ocean environments due to natural and human causes. Sustaining genetic and life-cycle diversity allows them to persist through these changes (McElhany et al. 2000; Moore et al. 2010; Carlson and Satterthwaite 2011).

While hydrological conditions in the region have been changing as a result of global climate change, these changes are not outside of the range under which native species adapted. Prior to 1900, California experienced much longer and more severe droughts and floods than anything seen since 1900 (summarized in Ingram and Malamud-Roam 2013), and native species were able to persist under those conditions due to their adaptations. Continuing to support those adaptations of genetic and life history diversity through providing more naturally variable flows is an important management strategy in addressing climate change effects. This is particularly important for salmonid species, but also applies to the aquatic ecosystem as a whole, including the food web and other native warm and cold water fish communities.

Ocean conditions constantly change, and will continue to cycle between more and less favorable conditions. As seen recently in the mid-2000's, poor ocean conditions caused a collapse in near-shore oceanic food supplies that eventually resulted in the collapse of the ocean salmon fishery. The extent of the collapse was exacerbated by weak salmon runs that have lost much of their genetic and life history variability that normally affords them greater resilience to poor ocean conditions (Lindley et al. 2009).

Preserving genetic and life history diversity in wild stocks helps protect salmon populations from significant loss of genetic diversity from the use of hatcheries. Fall-run Chinook salmon and other salmon hatcheries have artificially selected for characteristics beneficial to fish in a hatchery and then unintentionally reduced and degraded genetic diversity within wild populations due to their interbreeding with stocked strains of hatchery salmon. In addition, the greater quantity of hatchery fish within the river system has caused declines in native salmon, and further reduced the genetic viability of naturally produced strains due to predation and competition for spawning grounds, food, and space (Nehlsen et al. 1991). A more natural flow regime is anticipated to maintain, and perhaps even enhance the remaining genetic variability of natural stocks and reduce the negative effects of hatcheries on naturally produced populations.

The rim dams and altered flow regimes have caused a loss of geomorphic processes related to the movement of water and sediment that are important to the ecosystem (Poff et al.1997). Important benefits that these processes provide include increased complexity and diversity of the channel, riparian, and floodplain habitats, and mobilization of the streambed and upstream sediment (Grant 1997b). Floods, and their associated sediment transport, are important drivers of the river-riparian system. Small magnitude, frequent floods maintain channel size, shape, and bed texture, while larger, infrequent floods provide beneficial disturbance to both the channel and its adjacent floodplain and riparian corridor.

A more natural flow regime generates processes that create a less homogenous channel with structures that are important for fish habitat, such as meanders, pools, riffles, overhanging banks, and gravel substrates of appropriate sizes (Thompson and Larsen 2002, Mount and Moyle 2007). Scour and bed mobilization, associated with geomorphic processes that are driven by more variable flows, rejuvenate riparian forests and clean gravel for salmon, benthic macroinvertebrates, and benthic diatoms (Poff et al. 1997). Native fish and other aquatic species have adapted their life cycle to these processes and exploit the diversity of physical habitats these processes create (Poff et al. 1997; Thompson and Larsen 2002; Lytle and Poff 2004).

Increasing turbidity events from more variable flows and the associated geomorphic processes also decreases predation and provides environmental cues needed to stimulate migration (Gregory and Levings 1998; Baxter et al. 2008; NMFS 2009). Juvenile salmonids emigrate during periods of increased turbidity that arise from the winter storm and spring snowmelt phases of the flow regime. Turbidity reduces predation on young salmon by providing a form of protective cover, enabling them to evade detection or capture (Gregory 1993; Gregory and Levings 1998).

Altered flow regimes tend to decrease habitat connectivity in riverine and deltaic systems which results in a loss of longitudinal and lateral connectivity (Bunn and Arthington 2002). A more natural flow regime in the Bay-Delta watershed can increase longitudinal connectivity, create more beneficial migration transport, less hostile rearing conditions (protection from predators), greater net downstream flow, and connectivity with the estuary and near-shore ocean during periods that are beneficial for aquatic organisms who have adapted to this system (Kondolf et al. 2006; Poff et al. 2007). A more natural flow regime can also increase the frequency and duration of lateral connectivity to riparian and floodplain habitats, allowing for energy flow between wetland areas and the river, and providing the river and estuary with nutrients and food. Floodplain inundation provides flood peak attenuation and promotes exchange of nutrients, organic matter, organisms, sediment, and energy between the terrestrial and aquatic systems (Sommer et al. 2001; TBI 1998; Whipple et al. 2012). It also improves juvenile fish survival by improving food availability in addition to providing refuges from predators during the critical spawning, rearing and migration period of several native Central Valley fish species, especially Sacramento splittail and salmonids (Sommer et al. 2001; Jeffres et al. 2008; TBI/NRDC 2010a).

Floodplain inundation, particularly when associated with the ascending and descending limbs of the hydrograph, often provides most of the organic matter that drives aquatic food webs downstream (Sommer et al. 2001). Jeffres et al (2008) found floodplain habitat promotes rapid growth of juvenile salmon. Properly managed floodplains can have widespread benefits at multiple levels ranging from individual organisms to ecosystems (Junk et al. 1989; Moyle et al. 2007). Floodplain inundation is a function of precipitation, weir and gate design, flood control operations, and flow requirements.

Dams and reservoirs, and their associated operations, alter the temperature regime of rivers, often to the detriment of cold water species such as salmonids and other aquatic plants and animals that have adapted to colder waters and the variability associated with a more natural flow regime (Richter and Thomas 2007; NMFS 2014). Water stored in reservoirs is warmer at the surface and cooler below, often with a sharp thermocline in deeper waters. In California, there is a strong seasonal aspect to thermal dynamics; typically surface waters of reservoirs warm during summer due to high solar radiation and low inflow, which results in strong stratification in the large reservoirs at the low end of most Central Valley tributaries. Low reservoir volume, high reservoir inflows or high winds can all alter the thermal structure of reservoirs. The temperature of water within these layers is generally different than the temperature of water entering the reservoir at any given time depending on the season, and is also dissimilar to downstream water temperatures that would occur under a natural flow regime (USACE 1987; Bartholow 2001).

Temperature control devices can control the temperature of water released from dams for the protection of downstream fisheries by varying operations of release gates. Shasta was fitted with shutters to allow water to be drawn from different levels in order to conserve cold water for the spawning of winter-run salmon. Similar outlet shutters, to benefit resident trout and fall-run salmon, are found on Folsom and Oroville dams. A horizontal thermal curtain is used in Lewiston and Whiskeytown reservoirs to isolate cold inflowing waters on the Trinity River to maintain cold water outflows (Deas and Lowney 2000). The other rim dams of the Central Valley lack temperature control devices, so temperature management can only be achieved directly through flow management (NMFS 2009).

Often, water released from reservoirs is colder in the summer and warmer in the winter compared to water temperatures that would have occurred in the absence of dams and reservoirs (Williams 2006). Water temperatures are dominated by reservoir release temperatures immediately below dams, but are dominated by meteorological conditions further downstream, such that ambient water temperatures are approached exponentially with distance downstream (Deas and Lowney 2000; Kimmerer 2004).

In addition to changes in temperature due to reservoir storage and releases, reservoirs and diversions also modify the temperature regime of downstream river reaches by altering the volume and thermal mass of water. A smaller quantity of water has less thermal mass, and therefore, a decreased ability to absorb temperatures from the surrounding environment (air and solar radiation) without being impacted (USACE 1987). The greatest impact occurs with less flow (less thermal mass) and warmer climate (increased solar radiation), usually in the late spring, summer, and early fall periods (Deas and Lowney 2000). The colder summer temperatures may mitigate to some extent for loss of cooler habitat for salmonids upstream of dams and other habitat alterations that impact summer survival of aquatic organisms. At the same time, warmer temperatures (8° Celsius [C] to 25°C) during salmonid rearing periods may also promote optimal growth if food is readily available. However, temperatures that exceed these levels can raise metabolic rates above the ability of fish to forage and thereby decrease salmonid growth and survival rates, and reduce the amount of suitable habitat for rearing (McCullough 1999; Myrick and Cech, Jr. 2001).

3.2.2 Freshwater Flow and Estuarine Resources

The declining ecological and economic value of estuaries is a national (Correigh et al. 2015) and world-wide (Barbier et al. 2011; Vasconcelos et al. 2015; Lotze et al. 2006) concern. Freshwater flow is the primary source of physical and chemical variability in estuaries, and thus plays an important role in structuring estuarine habitat, species distributions, and biotic interactions (Drinkwater and Frank 1994; Jassby et al. 1995; Kimmerer 2002b; Kimmerer 2004, Montagna et al. 2013). In particular, variation in freshwater flow affects the spatial and temporal overlap of dynamic components of estuarine habitat such as salinity gradients and circulation patterns with more stationary components such as bathymetry and marshes (Peterson 2003; Moyle et al. 2010).

In their key points to the State Water Board, the Delta Environmental Flows Group (DEFG) expert panel noted that "[e]cological theory and observations overwhelmingly support the argument that enhancing variability and complexity across the estuarine landscape will support native species." (DEFG 2010) "High winter-spring inflows to the Delta cue native fish spawning migrations (Harrell and Sommer 2003; Grimaldo et al. 2009), improve the reproductive success of resident native fishes (Meng et al. 1994; Sommer et al. 1997; Matern et al. 2002; Feyrer 2004), increase the survival of juvenile anadromous fishes migrating seaward (Sommer et al. 2001; Newman 2003), and disperse native fishes spawned in prior years (Feyrer and Healey 2003; Nobriga et al. 2006)." Similarly, winter and spring outflows benefit species further down in the estuary, including starry flounder, bay shrimp, and longfin smelt through various mechanisms including larval-juvenile dispersal, floodplain inundation, reduced entrainment, and increased up-estuary transport flows. "The estuary's fish assemblages vary along the salinity gradient (Matern et al. 2002; Kimmerer 2004), and along the gradient between predominantly tidal and purely river flow. In tidal freshwater regions, fish assemblages also vary along a gradient in water clarity and submerged vegetation (Nobriga et al. 2005; Brown & Michniuk 2007), and smaller scale, gradients of flow, turbidity, temperature and other habitat features (Matern et al. 2002; Feyrer & Healey 2003). Generally, native fishes have their highest relative abundance in Suisun Marsh and the Sacramento River side of the Delta, which are more spatially and temporally variable in salinity, turbidity, temperature, and nutrient concentration and form than other regions." Over the past several decades, persistent low fall outflows (Feyrer et al. 2007) and other related stressors such as submerged vegetation, in both Suisun Marsh and the Delta have led to the decline of native fishes (Matern et al. 2002; Brown and Michniuk 2007). A greater sensitivity to these stressors exists in the summer and fall when many native fishes are "near their thermal limits." (SWRCB 2010, p. 32.)

Natural flows from upstream tributaries create habitat by pushing the salt field down the estuary in the spring during snowmelt events as temperatures warm. Historical evidence suggests that water at the confluence of the Sacramento and San Joaquin rivers was often fresh enough to drink prior to major water withdrawals and physical modification of the Delta (Whipple et al. 2012). While there is high interannual variability in unimpaired flows because of the highly variable climate of California, both Delta outflow and the position of the low salinity zone (X2) (measured in kilometers [km] from the Golden Gate) have been altered as a result of numerous factors. The removal of wetlands and restriction of the rivers to leveed channels removed the absorptive nature of the original landscape and facilitated more rapid runoff in the spring and seasonal intrusion of salinity when the river flows declined. The construction of reservoirs and diversions also allowed flows to be removed from the system or changed in time to create a more homogenous flow regime (Whipple et al. 2012; Kelley 1998). Hydrodynamic simulations conducted by Fleenor et al. (2010) indicate that the position of the low salinity zone has skewed eastward in the recent past, as compared to unimpaired conditions and earlier impaired periods, and that the variability of salinity in the western Delta and Suisun Bay has been significantly reduced (Chapter 2). Analyses show a clear trend in the movement of the low salinity zone in fall months as well into the deeper channels of the western Delta and a restriction in its area since 1980 (MacWilliams et al. 2016) with a further reduction since 2000 (Cloern and Jassby 2012). As a result of climate change and associated changes in precipitation and sea level rise, outflow and the position of the low salinity zone may continue to shift dramatically in coming years (Knowles and Cayan 2002, 2004).

In the Bay-Delta Estuary, the low salinity zone is an important nursery habitat for several estuarine-dependent fish species (Moyle 2002), and is maximized in area and volume in Suisun or San Pablo Bays (Kimmerer et al. 2013). The intersection of fresh and salt water historically created a diversity of habitat due to broad ranges of channels and wetland habitat that flood during spring and fall flow events into the estuary (TBI 1998; Whipple et al. 2012).

Statistically significant inverse relationships have been demonstrated between the landward extent of X2 and the abundance of a diverse array of estuarine species ranging from phytoplankton-derived particulate organic carbon at the base of the food web through primary consumers, benthic fish, pelagic fish and piscivores (Jassby et al. 1995). The diverse taxonomy, biology and distribution of these estuarine organisms showing these strong relationships indicates a broad positive response of the estuarine community to increasing outflow (Jassby et al. 1995). The X2-abundance relationships of many estuarine species have persisted since systematic sampling programs began in 1967. In some cases the statistical relationships have weakened or shown downward step changes in response following the 1987 spread of the invasive clam *Corbula* (Kimmerer 2002; Kimmerer et al. 2009) but nevertheless persist and continue to explain a large fraction of the variation in the abundances of these species. Updated flow-abundance analyses performed by State Water Board staff are included in the species profiles later in this chapter.

As discussed in more detail below, the specific mechanisms underlying the flow-abundance relationships are generally not resolved. Salinity changes and flow are inseparable so these relationships are referred to as either flow-abundance relationships or fish-X2 relationships. Further investigations are recommended and ongoing (Kimmerer 2002a; Kimmerer 20004; Reed et al. 2014). However, most of the relationships continue to remain strong since first described and better understanding of the likely mechanisms is rapidly developing.

Effects of high river flows in freshwater areas are difficult to separate from impacts in the more saline areas of the estuary. For instance, floodplain inundation happens when river flows overtop the weirs into flood bypasses. Floodplain inundation has a variety of beneficial effects including providing spawning and rearing opportunities for Sacramento splittail (Sommer et al. 2002, Moyle et al. 2004 and Feyrer et al. 2006), improved growth for salmon smolts (Sommer et al. 2001, 2005), including endangered winter-run Chinook salmon (del Rosario and Redler 2010), increased turbidity downstream, and mobilization of sediment and food to downstream habitats (Schemel et al. 2004).

Increased turbidity from high flows triggers movement of Delta smelt into the Delta (Bennett and Burau 2015) and outmigration of young salmon from the Delta. Increased turbidity also enhances feeding of young smelt (Haselbein et al. 2013) and reduces predation on young salmon (deRobertis et al. 2003). Turbidity increases in the lower estuary when winds mobilize sediments in the shoals of Grizzly and Honker bays. Delta smelt are found most frequently in samples from these bays, rather than the nearby channels (Bever et al. 2016).

Longfin smelt show the strongest statistical relationship with X2. Longfin smelt's relation to X2 has undergone a downward step change in response since the overbite clam invaded, but the relationship before and after the clam's invasion is equally strong (Kimmerer 2002). This similar relationship suggests that the mechanism is not food based. Results of recent investigations show high abundance of longfin smelt in intertidal channels in Suisun and San Pablo bays when salinity in those areas is low (Grimaldo et al. 2014; Grimaldo 2016). This suggests that, like Sacramento splittail spawning in the bypass when it is wet, longfin smelt spawn in greater abundance in springs of high flow conditions when their wetland spawning habitat is fresh. Such tidal channels are much more common in Suisun Bay and San Pablo Bay than among the rip-rapped levees lining the Delta and so longfin smelt have much greater spawning habitat when those bays are fresh.

Because the low salinity zone is an important nursery habitat in many estuaries (e.g., Dance and Rooker 2015; Mapes et al. 2015), much work has been done to attempt to identify a mechanism relating the fish-X2 relationships to changes in area of the low salinity zone. Changes in the area of the low salinity zone at different X2 values are inadequate to explain the fish-X2 relationships (Kimmerer et al. 2009; Kimmerer et al. 2013). The position of the low salinity zone combines with the bathymetry at each location to provide different depths and areas of the low salinity zone (MacWilliams et al. 2015). If the low salinity zone is defined as the water between 0.5 and 6 practical salinity unit (psu), the resultant volume does not change as the area changes and so changes in area are accompanied by concomitant changes in depth (Kimmerer et al. 2009). The area of the low salinity zone varies between 50 and 100 square kilometers with a significant decline since 1980 in the area of the low salinity zone from September through November in both areal extent and the percentage of time the zone has occupied more than 75 square kilometers (MacWilliams et al. 2016). When the low salinity zone is in Suisun Bay, Delta smelt are much more regularly found in the shoals of Grizzly and Honker bays than in the deeper channels to the south (Bever et al. 2016). Delta smelt are visual feeders; greater depth of the low salinity zone decreases the volume of their habitat within the photic zone, where visual feeding generally occurs. Since food limitation in the late summer and autumn has been identified as a bottleneck in the growth and survival of Delta smelt (Baxter et al. 2010, Baxter et al. 2015; Hammock et al. 2015), the decrease in the extent of suitable feeding area in these months has been a crucial concern in the protection of Delta smelt since first addressed in the USFWS BO (USFWS 2008).

World-wide, many near shore marine fish and invertebrates use gravitational circulation to help move their young into the usually richer food environment of estuaries (a recent case study and review of the literature is Abrantes et al. 2015). Gravitational flows occur because the outflow of less dense freshwater at the surface draws denser salt water into the bay; such flows are greater generally as outflows increase. Upstream transport flows in the San Francisco Estuary occur mostly seaward of Carquinez Strait, and involve larval stages of various species including Dungeness crab, California bay shrimp, English sole, Pacific herring and starry flounder and are one mechanism for increased recruitment of some of these species following high Delta outflow in winter and spring (Tasto 1983; Herbold et al. 1992; Kimmerer 2004).

3.2.3 Interior Delta Flows and Entrainment

Delta hydrodynamics have been modified as a result of CVP and SWP operations. Within the central and southern Delta, net water movement is towards the pumping facilities, altering the migratory cues for emigrating fish in these regions. Operations of upstream reservoir releases and diversion of water from the southern Delta have been manipulated to maintain a "static" salinity profile in the western Delta near Chipps Island and provide a steady supply of freshwater for export from the south Delta.

When the Delta Cross Channel Gates are open, water flows into the central Delta to supply export volumes. These cross-Delta flows draw Sacramento River water into the San Joaquin River, Franks Tract, and Old and Middle rivers. Such water movements reduce the natural flow pattern and variability in the Delta. Migratory fish and other aquatic organisms, as well as sediment transported with flood flows, accompany the water as it is diverted from the Sacramento River.

Anadromous species use a variety of tools to guide their migrations. In the ocean they may use magnetic, chemical, and astral cues to return to their natal stream to spawn. Within estuaries and meandering Delta channels, they primarily use chemical scents to identify water from their natal streams. To get to the ocean young anadromous species can rely on downstream currents in the rivers and increasing salinity in the estuary to guide them. The greatly altered channels, gates, flows, diversions, exports, and repelled salinity of the Delta provide a multitude of barriers to successful spawning migration of adults and outmigration of young native salmon, steelhead, sturgeon and lampreys.

Because it is a tidal environment, water in Delta channels flows both landward and seaward twice each day. The flow volumes of freshwater from the rivers entering the Delta are generally two or three orders of magnitude less than tidal flows. However, DWR can export as much as 10,000 cfs and Reclamation can export as much as 5,000 cfs out of the south Delta channels. These facilities usually export much more water than the median flow on the San Joaquin River, thus, most of the exported water must move from the Sacramento River and up Old and Middle rivers to Clifton Court Forebay and the Jones Pumping Plant. Movement of Sacramento River Water from the central Delta reduces the duration and volume of water flowing down the channels of Old and Middle Rivers and results in net negative flows in those channels.

These flow modifications can affect salmonid migration and estuarine transport of pelagic species through alteration of circulation patterns which leads to adverse transport flows, changes in water quality, changes to Delta habitats, and entrainment of fish and other aquatic organisms. The preferred flow circulation pattern for achieving a variable, more complex estuary is one that produces an east to west salinity gradient (Moyle et al. 2010). The east to west salinity gradient and water circulation pattern has been altered due to operation of the Delta Cross Channel and the SWP and CVP export facilities.

Reverse flows in the southern Delta are associated with increased entrainment of some fish species (Grimaldo et al. 2009) and disruption of migration cues for migratory fish. Reverse and otherwise altered flows, the constraints of artificially connected Delta channels, plus water exports affect Delta habitat largely through effects on water residence time, water temperature, and the transport of sediment, nutrients, organic matter, and salinity (Monsen et al. 2007). Long-term water diversions also have contributed to reductions in the phytoplankton and zooplankton populations in the Delta itself as well as alterations in nutrient cycling within the Delta ecosystem (NMFS 2009).

San Joaquin River flows, outside of flood conditions or regulatory action, are often entirely drawn to the SWP and CVP pumps. During these times, almost no water from the San Joaquin River reaches the confluence with the Sacramento River. Instead, water from the Sacramento River and its tributaries fills most of the Delta, obscuring and confusing the chemical and flow cues that adult salmon and other migratory fish depend on to reach the ocean and natal streams.

Entrainment occurs when fish and other aquatic life are drawn into a water diversion intake and are unable to escape. In the Delta, entrainment occurs primarily at the CVP facilities (Tracy Fish Facility and the nearby Delta-Mendota Canal) and the SWP facilities (including Clifton Court Forebay and the Skinner Fish Facility), as well as other smaller Delta intakes. Some of the entrained fish are "salvaged," meaning they are caught in facilities at the pumps and then trucked and released to an area beyond the pumps' influence. The salvage can increase survival of salmon smolts relative to their passage through the Delta when flows are low and temperatures are high. Unfortunately, many fish, including Delta smelt, are not able to survive the collection, handling, transport, and release. Also, high mortality rates in front of the fish screens mean that the number of fish salvaged is a small portion of the fish entrained. In addition to high rates of predation that occur at the fish screens, much "indirect" mortality is thought to occur before fish enter the facilities at all, in the sloughs and channels leading to the export facilities. Small fish drawn into this part of the Delta, or which migrate in inappropriate directions to changes in channel flows have a very low chance of survival. Juvenile salmon from the Sacramento River, including listed winter and spring run salmon, steelhead, and green sturgeon enter the central Delta through the Delta Cross Channel or Georgiana Slough and have a lower chance of survival than fish staying in the Sacramento River's mainstem. (ERP 2014).

3.3 Species-Specific Analyses

The remainder of the chapter examines the science regarding flow needs of a suite of native Bay-Delta aquatic species which are representative of existing beneficial uses of water to be protected under the Clean Water Act and Porter-Cologne Water Quality Act, including Estuarine Habitat, Cold Freshwater Habitat, Migration of Aquatic Organisms, Spawning, Reproduction and/or Early Development, and Rare, Threatened, or Endangered Species. The species selected for evaluation focus on native species that can serve as indicators of the overall health of the estuary and species for which there is adequate information on flow relationships including species listed under the federal and state Endangered Species Acts species of commercial, recreational and ecological importance, and recommendations from CDFW (2010) as part of the Delta Flow Criteria Report Proceeding. The species includes all four races of Chinook salmon, Central Valley steelhead, and multiple estuarine dependent species. The estuarine-dependent species are Sacramento splittail, Longfin smelt, Delta smelt, California bay shrimp, Starry flounder, White and Green sturgeon and several zooplankton species. The list of species is similar to that used in the 2010 Delta Flow Criteria Report except that it includes white and green sturgeon. For each species, its life history, population abundance, and functional flow-abundance relationships are summarized.

3.3.1 Updated Quantitative Analysis

In addition to discussion of the life history, population abundance, and flow-abundance relationships of each species published in the existing scientific literature, the sections that follow contain updated quantitative analyses performed by State Water Board staff to document abundance trends, flow-abundance relationships, and to estimate ranges of flow predicted to be protective of individual species. Staff obtained abundance index data on predominantly estuarine species from the CDFW fall midwater trawl (FMWT; CDFW 2016) and San Francisco Bay Study (Bay Study) otter trawl (Hieb 2015) surveys. Staff relied primarily on the published literature for analysis of the effects of flow on salmonid populations, although the flow-abundance relationship for unmarked Chinook salmon (Brandes and McLain 2001) was updated using Chipps Island trawl data from the Delta Juvenile Fish Monitoring Program (DJFMP 2016a, 2016b). In all cases, staff used flow data from Dayflow (DWR 2016). Analyses were conducted using the R statistical computing language (R Core Team 2015).

Staff estimated abundance trends by fitting a linear regression to each annual abundance index as a function of year (e.g., log (FMWT) = a * Year + b). In data sets that included abundance indices of zero, the response variable was the logarithm of the abundance index plus one (e.g., log (FMWT + 1) = a * Year + b), since the logarithm of zero is undefined.

For negative slopes that differed significantly from zero (two-tailed t-test, $p<0.05$), staff concluded that the population was declining over the time period in question.

Staff estimated flows likely to be protective of estuarine species using three general methods summarized below, all of which require an abundance goal and some prior knowledge of the season (e.g., January–June) during which Delta outflow is likely to affect the success of each species. Staff used abundance goals previously identified in the Delta flow criteria report (SWRCB 2010). Information on seasons that should be used for the analyses was taken from the scientific literature and the Delta Flow Criteria Report (Jassby et al. 1995; Kimmerer 2002; CDFW 2010; SWRCB 2010). Staff performed analyses as follows:

1. Flow-abundance relationships: following the general methodology of Jassby et al. (1995) and Kimmerer (2002), staff estimated the relationship between the logarithm of seasonal average Delta outflow and the respective species abundance indices using the most recent data available. Following the methods of Kimmerer (2002), staff omitted zero values from the abundance indices for the purposes of this analysis and included a step change for species that experienced a substantial decline immediately following the introduction of *Corbula*. The regression was then used to predict the flow associated with the abundance goal. Staff did not use this method if the predicted flow fell outside of the range of the observed flow data.
2. Cumulative frequency distributions of flow: if staff could identify a period of years during which the abundance goal was attained and the population was not in decline, the median of the seasonal average flows over that period was used as an indicator of the flow that would be protective of the species.
3. Logistic regression estimates of the probability of population growth: for species that spawn predominantly at a single age, logistic regression was used to estimate the response of generation-over-generation population growth to seasonal average flow (TBI/NRDC 2010a). For a given population index N, the growth rates were estimated as N(t)/N(t-L), where L is the age of reproduction. These rates were converted to a binary variable (1=growth, 0=decline) and regressed on the logarithm of average seasonal outflow using a general linear model with a logit link function. Staff interpreted the flow that predicted a fifty percent probability of population growth as a threshold flow that would benefit the species.

The flows found in the scientific literature or estimated using the above methods should not be taken to represent absolute flow needs that must be met at all times or in all years to support native species. Rather, they serve as indicators of conditions that favor native species, and constitute a set of quantifiable metrics that can be used to assess the relative protection afforded by a range of flow regimes. The scientific information supporting modifications to existing flow requirements is broader than these quantitative relationships, and includes knowledge of life history, ecology, and the conditions under which native species evolved. Generally, higher flows and lower X2 values in winter and spring confer the greatest benefits for native species and the ecosystem, provided adequate supplies are maintained for cold water and flows at other times.

3.4 Chinook Salmon (*Oncorhynchus tshawytscha*) and Central Valley Steelhead (*Oncorhynchus mykiss*)

3.4.1 Overview

A combined species evaluation has been prepared for all four runs of Chinook salmon and Central Valley steelhead. Less information is available for steelhead than for salmon. Because salmon and steelhead share similar life history strategies, factors which benefit salmon will likely do the same for steelhead. The evaluation provides information on life histories of the species, population abundance trends through time, population restoration goals, and where available, information on the functional flow needed by each race to successfully emigrate from upstream tributaries in the Phase II area through the Delta to the Pacific Ocean. Because inflows from the San Joaquin River above the Delta are addressed in Phase I of the update to the Bay-Delta Plan, those inflows are not discussed below. However, issues below the San Joaquin River at Vernalis are discussed as are issues related to the eastside Delta tributaries that flow into the downstream portions of the San Joaquin River in the Delta.

The following evaluation shows that adult and juvenile salmon benefit from an increase in a more natural flow pattern in Central Valley tributaries. Increased tributary flow aids adult upstream spawning migration, juvenile rearing in tributary watersheds and emigration to the Delta. Juvenile fall and winter run salmon are expected to benefit from additional spring inflow in the lower Sacramento River while emigrating past Chipps Island. Flows greater than 20,000 cfs at Rio Vista between February and June are expected to improve juvenile salmon survival during outmigration. In addition, juvenile salmon emigrating from both the Sacramento and San Joaquin Rivers through the Delta have better survival if smolts remain in main stem river channels and do not migrate through the interior Delta.

3.4.2 Life History

3.4.2.1 Chinook Salmon

Chinook salmon are anadromous with adults returning to their natal streams to spawn and die. The different Chinook salmon-runs have developed a broad array of different life history characteristics. These include the timing of adult migration, degree of sexual maturation at the time of river entry, and time of spawning. Juveniles of each run also display differences in the duration of freshwater residency and the timing of outmigration. This diversity in life history traits reflects adaptations to both the natural flow regimes and physical attributes of their natal streams, and the broad diversity in regional and seasonal flow patterns in the Central Valley.

Chinook salmon are an important ecological, cultural, subsistence, recreational and commercial fish species in California (Figure 3.4-1). Historically, 5 million to 6 million salmon may have returned annually to California waterways with Native American consumption and trade estimated as high as 125-million pounds per year (Gresh et al. 2000). Ecologically, the large salmon runs were an important energy and nutrient source for invertebrates and small fish in oligotrophic mountain streams and riparian areas (Nakajima and Ito 2003; Bilby et al. 1996, 1998 and 2001). The commercial and recreational catch from 1975 to 2014 now averages about half a million fish per year (Azat 2015). Most of the catch during this 40-year time period was taken in the marine commercial fishery and is from hatchery production.

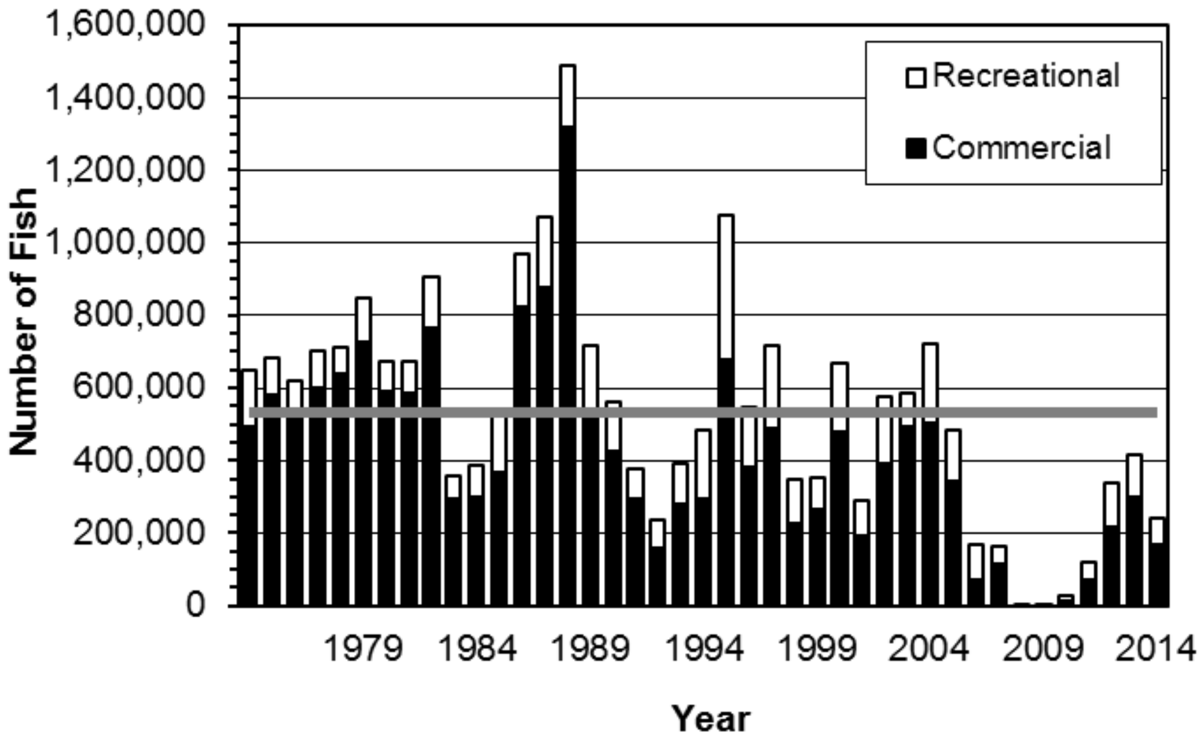


Figure 3.4-1. California Commercial and Recreational Chinook Salmon Ocean Catch, 1975 to 2014. The gray line shows the 40 year mean. (Source Azat 2015)

Four Chinook salmon-runs are present in the Sacramento River mainstem and tributaries and Delta eastside tributaries and are named for the timing of adult upstream migration: fall-run, late fall-run, winter-run, and spring-run (Table 3.4-1).

Table 3.4-1. General Timing of Important Life Stages of Sacramento and San Joaquin River Basin Chinook Salmon and California Central Valley Steelhead

	Adult Migration period	Adult Peak Migration	Adult Spawning Period	Adult Peak Spawning Period	Juvenile Emergence Period	Juvenile Stream Residency (Months)
Sacramento Basin						
Winter-run	Dec-Jul	Mar	Late Apr-early Jul	May-Jun	July-Oct	5-10
Spring-run	Mar-Sept	May-Jun	Late Aug-Nov	Oct-Nov	Dec-Mar	1-7
Late fall-run	Oct-Apr	Dec-Jan	Early Jan-Apr	Feb-Mar	Apr-Jun	7-13
Fall-run	Jun-Dec	Nov	Late Sep-Jan	Nov	Dec-Apr	1-5
San Joaquin Basin						
Fall-run	Sept-Dec	Nov	Nov-Jan	Nov-Dec	Dec-Mar	2-5
Steelhead (Both Basins)	July-Mar	Sep-Oct	Nov-Apr	Dec-Apr	Jan-May	12-36

Source: Modified from Yoshiyama et al. (1998) and NMFS (2014)

Chinook salmon exhibit two general freshwater life history strategies (Healey 1991). Adult "stream-type" Chinook salmon enter fresh water several months before spawning and juveniles reside in fresh water for a year or more. In contrast, "ocean-type" Chinook salmon runs enter freshwater at maturity, rapidly move upstream to their natal streams, spawn, and die, with juveniles generally emigrating within months of emergence (Healey 1991). Winter and spring-run Chinook salmon display a stream-type strategy as adults, migrating far upriver and delaying spawning for several months until sexually mature (Healey 1991; Moyle 2002). As juveniles, winter-run display an intermediate strategy, residing in the upper Sacramento River for 5–10 months, and rearing in the estuary for an indeterminate period (Moyle 2002). Spring-run show a more typical stream-type life history, although some juveniles may remain in fresh water for less than a year (Moyle 2002). Late fall-run Chinook display a predominantly stream-type life history, holding for a few months before spawning, and emigrating as yearlings (Moyle 2002). Fall-run Chinook have an unambiguous ocean-type life history (Moyle 2002).

For successful upstream migration, adult salmon require adequate flow to provide olfactory cues to locate their natal streams. Sufficient flow is also needed for adult passage to upstream holding and spawning habitat. Adult salmon require water depths greater than 0.8 feet and water velocities less than 8 feet per second for successful upstream migration (Thompson 1972). Adult salmon migrating upstream mostly use pool and mid-channel habitat (Stillwater Sciences 2004) and are thought to be primarily active during twilight hours. The preferred temperature range for upstream migration is 38° Fahrenheit (F) to 56°F (Bell 1991; CDFW 1998). Boles (1988) recommended water temperatures below 65°F for adult salmon upstream migration and Lindley et al. (2004) reported that adult migration is blocked when temperature reaches 70°F.

Spawning Chinook salmon require clean, loose gravel in swift, relatively shallow riffles or along the margins of deeper runs, and suitable water temperatures, depths and velocities for redd (nest) construction and adequate oxygenation of incubating eggs. Chinook salmon typically spawn in gravel beds that are located at the end of holding pools (USFWS 1995). Chinook salmon will spawn in a wide range of water depths and velocities. Moyle (2002) reported that water velocities for salmon spawning range from 1.0 to 2.6 feet per second at a depth of a few inches to several feet. In contrast, USFWS (2003) reported that winter-run prefer water velocities from 1.5 to 4.1 feet per second at a depth of 1.4 to 10 feet. The preferred upper ambient water temperature range for Chinook salmon spawning is 55°F to 57°F (Bjornn and Reiser 1991; Snider 2001).

Studies of Chinook salmon egg survival indicate that about 85-percent of the fry will successfully emerge from redds when there is adequate subsurface gravel flow (Shelton and Koenings 1995). The optimal water temperature for egg incubation ranges from 41°F to 56°F (Moyle 2002). A significant reduction in egg viability occurs above 57.5°F and total mortality can occur at temperatures above 62°F (NMFS 2014). The lower and upper thermal range causing 50 percent pre-hatch mortality is 37°F and 61°F, respectively. Finally, as water temperature increases the rate of embryo malformations and susceptibility to fungal and bacterial infestation also increases.

Development time for Chinook salmon embryos is dependent on ambient water temperatures. Colder temperatures result in slower development rates and a longer development time. Within the optimal thermal range, embryos hatch in 40 to 60 days. Alevins remain in the gravel for an additional 4 to 6 weeks metabolizing their yolk sac for nourishment. When the yolk sac is depleted, the fry emerge from the gravel to begin external feeding.

Upon emergence, fry disperse to the margins of their natal stream, seeking shallow water with slower velocity and begin feeding on zooplankton, small insects, and other micro crustaceans. Some fry take up residence in their natal stream for up to a year while others are displaced downstream by the current. Once downstream migration begins, fry may continue to the estuary and rear there or take up residence in intermediate upstream river reaches for up to a year (Healey 1991).

When juvenile Chinook salmon reach a length of 2 to 2.25 inches in length, they move into deeper water with greater current velocities, but still seek shelter in quiescent areas to conserve energy (Healey 1991). In the Sacramento River near West Sacramento larger bodied juveniles were located in the main channel while smaller fry were found along the river margin (USFWS 1997 as reported in CDFW 2010). When channel depth is greater than 9-10 feet, juveniles tend to remain near the surface (Healey 1982). An increase in turbidity from storm runoff, increased flows or changes in day length trigger outmigration of juveniles from the upper Sacramento River Basin (Kjelson et al. 1982; Brandes and McLain 2001). Juvenile salmon migration rates vary considerably depending on the physiological stage of the individual and ambient hydrologic conditions. Chinook salmon fry can travel as fast as 12 mile per day in the Sacramento River (Kjelson et al. 1982). Sommer et al. (2001) measured travel rates as low as 0.5 to more than 6.0 miles per day in the Yolo Bypass.

Juveniles begin to emigrate once they start to undergo smoltification. Smoltification is the physiological process that increases salinity tolerance and enables salmonids to transition from fresh to saltwater. Smoltification usually starts when juveniles are 3 to 4 inches in length (CDFW 2010). Environmental factors such as increased stream flow and changes in water temperature and photoperiod can also affect the onset of smoltification (Rich and Loudermilk 1991). After smoltification begins, salmon often rear further downstream where ambient salinities are higher (Healey 1980; Levy and Northcote 1981).

The majority of Sacramento River juvenile Chinook salmon enter the Delta between October and May (Table 3.4-2). However, there are run-specific differences. Fall-run mostly enter between January and May and Spring-run mostly in March and April. Winter-run has a more prolonged migration pattern and enter between November and March. The different migration patterns reflect the differences in life history characteristics of the runs.

Table 3.4-2 Timing of Juvenile Chinook Salmon and California Central Valley Steelhead Entry into the Delta from the Sacramento River Basin by Month

Month	Sacramento River Total[1,2] (%)	Fall-run (%)	Spring-run (%)	Winter-run (%)	Sacramento Steelhead[3] (%)
January	12	14	3	17	5
February	9	13	0	19	32
March	26	23	53	37	60
April	9	6	43	1	0
May	12	26	1	0	0
June	0	0	0	0	0
July	0	0	0	0	0
August	4	1	0	0	0
September	4	0	0	0	1
October	6	9	0	0	0
November	9	8	0	3	1
December	11	0	0	24	1
Total	100	100	100	100	100

[1] Midwater trawl data
[2] All runs combined
[3] Rotary screw trap data from Knights Landing
Source: NMFS 2009 RPA with 2011 amendments

In the Delta, juvenile Chinook salmon tend to forage in shallow areas with protective cover, such as intertidal and subtidal mudflats, marshes, channels, and sloughs (McDonald 1960; Dunford 1975; Healey 1980). This foraging behavior is likely advantageous because shallow habitats are more productive than main channels, and support faster growth because of higher food availability and more favorable ambient water temperatures (Sommer et al. 2001). Cladocerans, copepods, amphipods and larval dipterans are common prey items (Kjelson et al. 1982; Sommer et al. 2001; MacFarland and Norton 2002). Optimal water temperatures for the growth of juvenile Chinook salmon is between 54°F and 64°F (Brett 1952), though the range is different for particular runs of Chinook (Moyle 2002). In Suisun and San Pablo Bays, water temperatures reach 54°F by February. In the central and southern Delta, ambient water temperatures can reach 70°F by February in dry years but typically most of the Delta stays cooler until after spring runoff has ended (Meng and Matern 2001; Mesick 2001).

Juvenile Chinook salmon movements are controlled by the tides in the Delta. Juveniles move into shallow water habitat on the rising limb of the tide and return to main channels when the tide recedes (Ley and Northcote 1981; Healey 1991). In Suisun Marsh Chinook salmon fry tend to remain close to the bank under vegetative cover and in dead end tidal sloughs. Kjelson et al. (1982) reported that juvenile salmon follow a diel migration pattern, orienting themselves to nearshore cover during the day but moving into more open, offshore habitat at night. The fish also distribute themselves vertically in the water column in relation to light. During night, juveniles are distributed randomly through the water column, but school up during the day in the upper 10 feet of the water column. Catch data indicate that juvenile Chinook salmon use Suisun Marsh both as a migration corridor and as rearing habitat as they emigrate out of the estuary and into the Pacific Ocean (Kjelson et al. 1982; O'Rear and Moyle 2008).

Juvenile Chinook salmon were found to spend about 40 days migrating through the Delta to San Francisco Bay and grew little until they reached the Gulf of the Farallones (MacFarlane and Norton 2002). Based mostly upon observations with fall run salmon, MacFarlane and Norton (2002) concluded that Central Valley Chinook salmon did not appear to benefit from estuarine residency, and might even benefit from a rapid transit through the Delta to the Pacific Ocean. Juveniles of other runs also appear to pass through the estuary rapidly under existing conditions, although it is unclear whether this reflects historical patterns or is a response to degraded conditions in the estuary (Moyle 2002).

3.4.2.2 Central Valley Steelhead

California Central Valley steelhead may exhibit either an anadromous or a resident life history strategy. Resident steelhead are commonly known as rainbow trout. Zimmerman et al. (2008) demonstrated that resident rainbow trout can produce anadromous offspring and anadromous adults can produce resident rainbow trout in the Central Valley.

Central Valley migratory steelhead are "winter steelhead." The naming convention refers to the timing of upstream adult migration. Winter steelhead adults migrate from the ocean as sexually mature individuals and are ready to spawn when they arrive on their breeding grounds (Moyle 2002; McEwan and Jackson 1996). Adult upstream migration from the ocean occurs throughout the year but peaks in the Sacramento River in September and October (McEwan and Jackson 1996). Migration in the San Joaquin River begins as early as July and continues through April with a peak in upstream migration between October and February (USDOI 2008). Adult Central Valley steelhead mostly uses the Sacramento and San Joaquin River channels as a migration corridor to reach upstream natal streams (Moyle 2002).

Steelhead historically spawned in foothill streams. However, water development now confines most spawning to areas below dams (NMFS 2014). Peak spawning generally occurs between January and March in both the Sacramento and San Joaquin watershed (Hallock et al. 1961; McEwan 2001). Female steelhead are benthic pair spawners; they select a site, excavate a redd in the gravel and deposit eggs. A waiting male fertilizes them without parental guarding behavior (Moyle 2002). The time required for egg development is approximately four weeks, but is temperature dependent (McEwan and Jackson 1996). Optimal egg development occurs at temperatures between 48°F and 52°F. After hatching, the yolk sac alevin remain in the gravel for an additional four to six weeks before emerging (McEwan and Jackson 1996). Upon emerging, fry move to shallow protected stream margins. Older, larger individuals use riffles and pools. Young steelhead feed on immature aquatic and terrestrial insects (Moyle 2002; Benigno and Summer 2008; Weber 2009; Kammerer and Heppell 2012).

Juvenile steelheads migrate to the ocean after spending one to two years in fresh water (McEwan and Jackson 1996). Steelhead from the Sacramento watershed are caught in the Knights Landing rotary screw trap from November to March (Table 3.4-2). However, peak catch occurs in February and March. San Joaquin River steelheads begin their downstream migration between late December and July with a peak in March and April (USDOI 2008). Emigrating juvenile steelhead fish are larger and have a greater swimming ability than do juvenile emigrating Chinook salmon. This is because of their longer freshwater rearing period (1 to 2 years). The longer freshwater residency resulting in a larger body size and better swimming ability may confer some migratory advantages and a decrease in mortality during downstream emigration. Juvenile steelhead salvaged at the State and Federal pumping facilities indicate that most steelhead are moving through the Delta from November through June with a peak emigration period between February and May (NMFS 2009).

3.4.3 Life History, Distribution and Abundance Trends Over-Time

3.4.3.1 Population Abundance Goals and Species Declines

The Central Valley Project Improvement Act (CVPIA) was enacted in 1992 and has mandated changes in the management of the Central Valley Project, particularly for the protection, restoration and enhancement of fish and wildlife. The CVPIA established the Anadromous Fish Restoration Project (AFRP) to "*implement a program which makes all reasonable efforts to ensure that, by the year 2002, natural production of anadromous fish in Central Valley Rivers and streams will be sustainable, on a long term basis, at levels not less than twice the average levels attained during the period of 1967-1991.*" This mandate included doubling the natural production for each Chinook salmon run (Table 3.4-3). The Salmon Protection Objective in the Bay-Delta Plan and D-1641 is similar, and provides that "*water quality conditions shall be maintained together with other measures in the watershed sufficient to achieve a doubling of natural production of Chinook salmon from average production of 1967-1991, consistent with the provisions of State and Federal law*." Table 3.4-3 shows significant declines in the natural production of species notwithstanding the population abundance goals.

Table 3.4-3. Summary of the Natural Production of All Four Runs of Chinook Salmon in the Sacramento and San Joaquin River Basins between the Anadromous Fish Restoration Program (AFRP) Baseline Period of 1967-1991 and 1992-2011 Indicating that the Natural Abundance of All Races Has Declined between the Two Time Periods

	Natural production annual average baseline (1967-1991) period	Natural production annual average for 1992-2011 period	Change in average natural production between 1967-1991 and 1992-2011
Sacramento Winter run	54,439	6,320	-88 percent
Sacramento Spring run	34,374	13,654	-60 percent
Sacramento Late fall run	34,192	17,835	-48 percent
Sacramento Fall-run	115,371	72,595	-37 percent
San Joaquin Fall-run	38,388	18,703	-51 percent

3.4.3.2 Winter-Run Chinook Salmon

Adult Winter-run Chinook salmon enter the Sacramento River between December-July and spawn between late April and mid-August (Table 3.4-1). Most adults are 3 years old and are sexually immature when re-entering fresh water (Moyle 2002). Immature adults must hold in fresh water for several months before they are capable of reproducing. Winter-run are unique because they finish sexual development and spawn during summer when air temperature in the Central Valley approaches an annual maximum. As a result, winter-run require cold water to protect their developing eggs and young from the ambient warm air and water conditions typical of the Central Valley in summer. Historically, winter-run only spawned in the upper Sacramento River, including the Pit, McCloud, Fall and Little Sacramento Rivers (Yoshiyama et al. 1998). Construction of Shasta and Keswick dams eliminated passage to the upper Sacramento River basin and restricted spawning to between Keswick Dam and the Red Bluff Diversion Dam (RBDD). Winter-run survive now mainly because of the release of cold water from Shasta Dam (Good et al. 2005). Temperature control is achieved by managing reservoir storage levels and operating a temperature control device, which was installed at Shasta Dam in 1998 (NMFS 2009). Maintaining cold water in the Sacramento River below Keswick Reservoir can also benefits spring and fall-run Chinook salmon and green sturgeon.

Winter-run fry emerge, generally at night, from the gravel between mid-June and mid-October and occupy nearshore shallow habitat with slow water velocity (NMFS 2014). Outmigration begins as early as mid-July with most emigrants passing the RBDD in September and October (Vogel and Marine 1991; NMFS 2009). Rearing occurs in the Delta and in the Sacramento River below the RBDD from November through April (Table 3.4-2; Williams 2006). Timing of migration to nursery locations is variable and is dependent upon flow, dam operations, and water temperature. Rearing generally occurs for 5 to 10 months before smoltification and outmigration to the ocean. Marine outmigration usually begins in the fall and continues through the spring with outbound smolts passing inbound spawners (Moyle 2002). Winter-run Chinook salmon reside in coastal marine waters between San Francisco and Monterey for 2–4 years before migrating inland to spawn and complete their life cycle (Moyle 2002; Myers et al. 1998).

The Sacramento River winter-run Chinook salmon population is supported by hatchery production from the Livingston Stone National Fish Hatchery (LSNFH) located downstream of Shasta Dam (NMFS 2014). The LSNFH releases between about 30,000 and 250,000 pre-smolts[1] annually each winter (NMFS 2014). Hatchery fish are marked with a coded wire tag (CWT) and a clipped adipose fin to allow fishery managers to differentiate between wild and hatchery produced fish. Winter-run hatchery fish have made up more than 5 percent of escapement[2] of winter-run fish since 2001. In 2005 the contribution from the hatchery exceeded 18 percent of total in-river spawners (Lindley et al. 2007).

The abundance of winter-run Chinook salmon has declined significantly. Escapement in the 1960s was near 100,000 fish (Good et al. 2005). Figure 3.4-2 presents escapement for both natural and hatchery production between 1975 and 2014. Escapement was as high as 35,000 fish in 1976 and has now declined to a few thousand individuals (Azat 2015). The average 2000–2014 population estimate is about half of the 40-year average. Natural juvenile production and adult escapement to in-river spawning locations has also declined relative to the 1967–1991 baseline CVPIA value (Figure 3.4-3). Natural production was 88 percent less in 1992–2011 than in 1967–1991 (Table 3.4-3).

[1] Mean annual release has been about 167,000 fish.

[2] Number of adult fish returning to spawn.

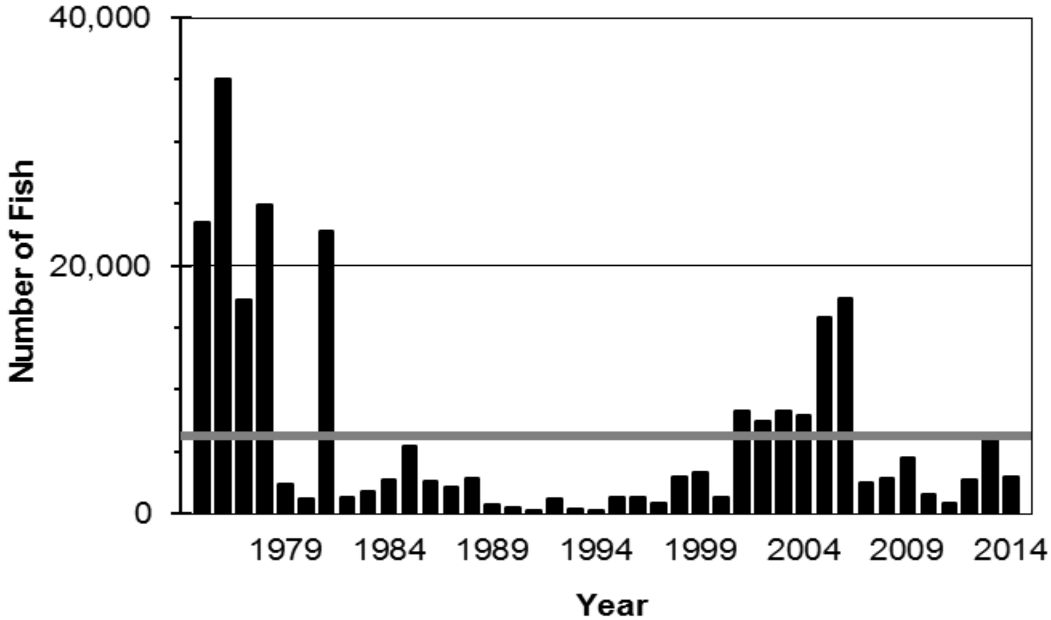


Figure 3.4-2. Annual Winter-run Chinook Salmon Escapement from the Sacramento River Basin from 1975 to 2014 and the 40 Year Mean Population Size (gray line) (Source Azat 2015).

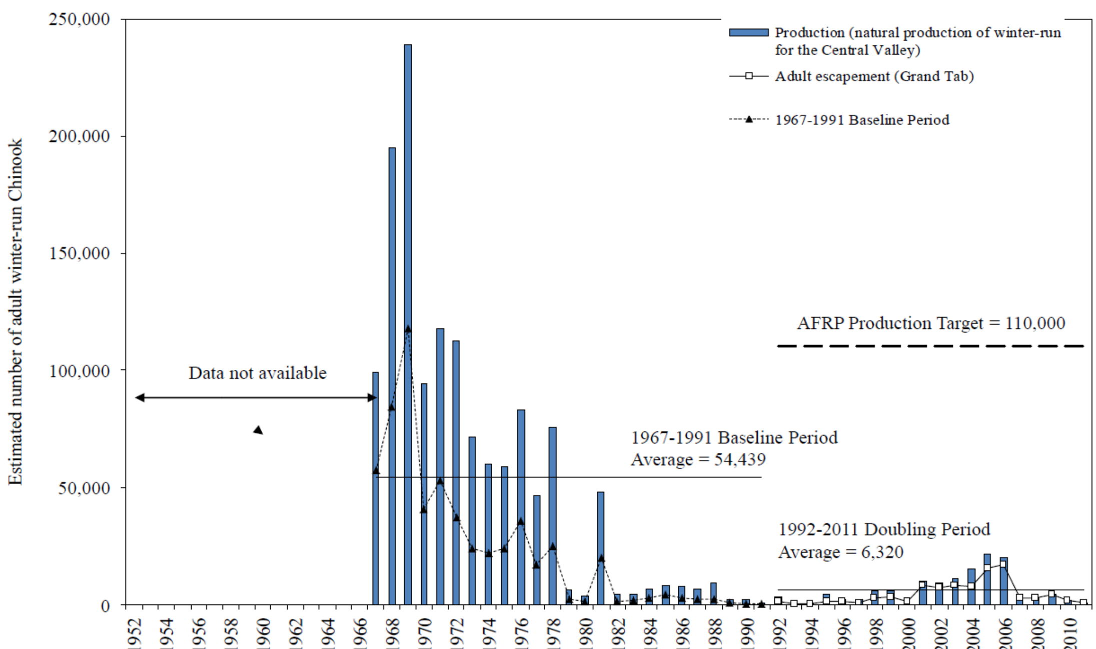


Figure 3.4-3. Estimated Yearly Adult Natural Production and in-River Adult Escapement of Winter-run Chinook Salmon in Central Valley Rivers and Streams. 1992-2011 numbers are from CDFG Grand Tab (Apr 24, 2012). 1967-1991 baseline period numbers are from Mills and Fisher (CDFG 1994)[3]

[3] Figure from http://www.fws.gov/lodi/afrp/Documents/Doubling_goal_graphs_020113.pdf.

The Sacramento River winter-run Chinook salmon evolutionary significant unit (ESU)[4] was originally listed as endangered under the federal ESA in 1994 (59 FR 440). The listing was reaffirmed in 2005 (70 FR 37160) and in 2011 (76 FR 50447). The listing includes both naturally occurring and artificially propagated stock (70 FR 37160). The ESU was listed as endangered under the California ESA in 1989.

3.4.3.3 Spring-Run Chinook Salmon

Historically, Central Valley spring-run Chinook salmon were likely the most abundant salmon run in the Central Valley. Spring-run used the headwaters of all the major rivers to spawn and rear (NMFS 2014). The run enters fresh water as immature adults and requires cool fresh water to mature over summer. In the Central Valley ambient summer water temperatures are only suitable above 500-1,500 feet elevation and most of this habitat is now upstream of impassable dams (NMFS 2005 as cited in NMFS 2014). As a result, spring-run have suffered the most severe decline of all the four runs of Chinook salmon in the Sacramento River Basin (Fisher 1994).

Habitat requirements for spring-run are similar to those previously described for winter-run. The main life history differences between the two runs are the duration and the time of year that the life stages utilize Central Valley habitat (Table 3.4-1). Spring-run Chinook enter the Sacramento River basin between March-September, primarily in May-June (Yoshiyama et al. 1998). Spring-run generally enter as sexually immature adults and must hold in fresh water for several months to mature (Moyle 2002). While maturing, adults need access to deep pools with cold water. Spawning occurs between late-August and November with a peak in September (Moyle 2002).

The development of embryos and emergence from the gravel is dependent on ambient water temperatures. Water temperatures must be between 41°F and 55°F for optimal embryo survival (Moyle 2002). Embryos hatch in 40–60 days under these conditions and the alevins remain in the gravel for an additional 4 to 6 weeks before emerging as fry (Moyle 2002). Fry leave the gravel between December and March (Table 3.4-1). Juveniles typically may remain in fresh water for 12–16 months, but some individuals migrate downstream to the ocean as young of the year in winter or early spring (NMFS 2014).

The Feather River Fish hatchery (FRFH) is responsible for replacing the loss of natural production of spring-run that previously occurred in the Feather River watershed above Oroville Dam (USFWS 2014). The production goal is two-million smolts per year. The proportion of hatchery fish in the returning population has steadily increased since the 1970s. Hatchery origin fish may comprise between 20 and 50 percent of total escapement in recent years (estimated from Figure 2-7 in NMFS 2014).

Spawning habitat for Central Valley spring-run Chinook salmon also includes the main stem of the Sacramento (between Keswick Dam and RBDD), Feather, Yuba, and Calaveras Rivers and Cottonwood, Antelope, Thomes, Big Chico, Battle, Butte, Deer and Mill Creeks (NMFS 2014). Self-sustaining populations occur on Mill, Deer, and Butte Creeks, while other streams are dominated by strays from hatchery stocks that have undergone hybridization with fall-run Chinook (NMFS 2014).

[4] NMFS uses the term "ESU" to identify a DPS as specified in the Endangered Species Act. The Endangered Species Act does not define DPS. The DPS and ESU are smaller evolutionary units than a species.

The Central Valley is estimated to have produced spring-run Chinook salmon runs as large as 600,000 fish between 1880 and 1940 (CDFW 1998). More than half a million spring run salmon are believed to have been caught in the commercial fishery in 1883 (Yoshiyama et al. 1998). Escapement is now much smaller with a 40-year average of about 14,500 fish (Figure 3.4-4). Natural production of spring run has also declined (Figure 3.4-5). Production in the AFRP baseline period of 1967-1991 was estimated at 34,374 fish. Average production in 1992-2011 decreased to 13,654 fish. This represents a 60 percent decline over the baseline period (Table 3.4-3) and is only 20 percent of the AFRP doubling goal.

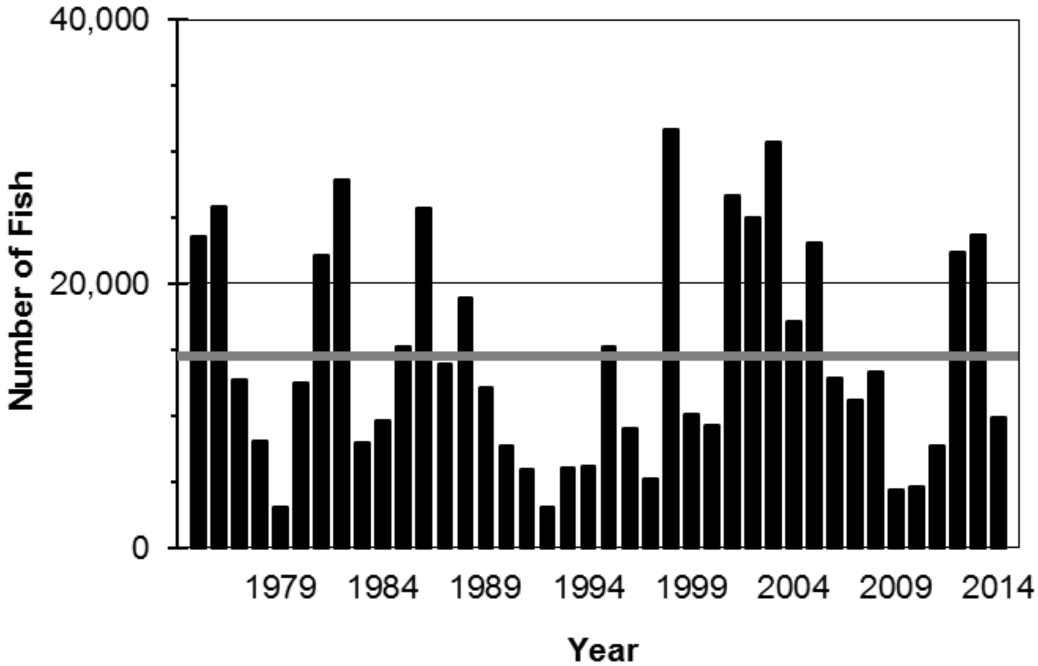


Figure 3.4-4. Annual Spring-run Chinook Salmon Escapement to Sacramento River Tributaries from 1975 to 2014 and the 40 Year Mean (gray line) (Source Azat 2015).

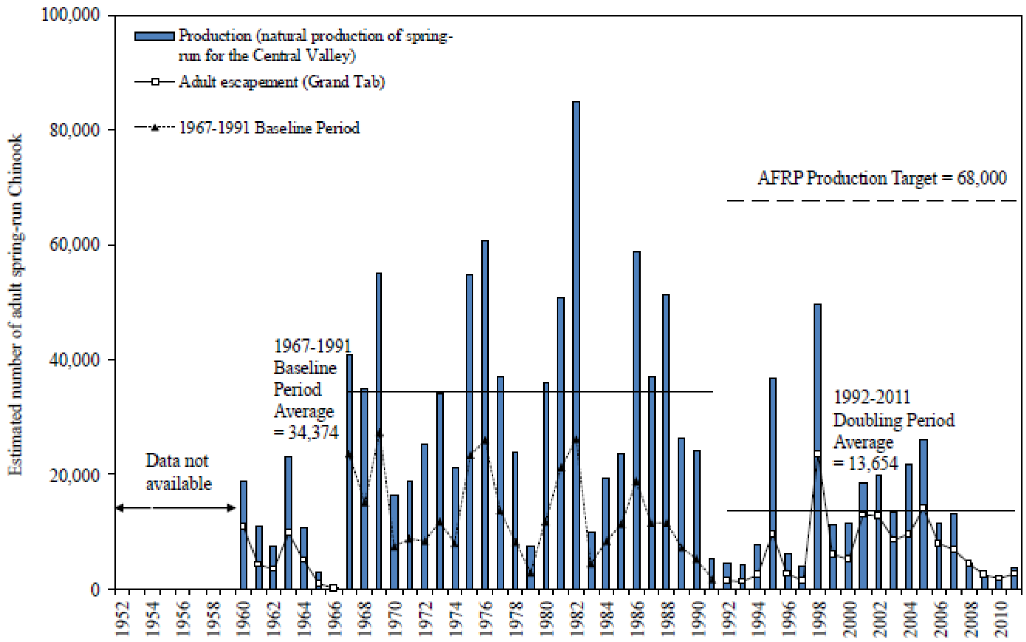


Figure 3.4-5. Estimated Yearly Adult Natural Production and in-River Adult Escapement of Spring-run Chinook Salmon in the Central Valley Rivers and Streams. 1992-2011 numbers are from CDFG Grand Tab (Apr 24, 2012). 1967-1991 baseline period numbers are from Mills and Fisher (CDFG 1994)[5]

The Central Valley spring-run Chinook salmon ESU was listed as threatened under the federal ESA in 1999 (64 FR 50394). The listing was reaffirmed in 2005 and expanded to include the Feather River hatchery stock (70 FR 37160). The ESU was listed as threatened in 1999 under the California ESA. Hatcheries that propagate Central Valley spring-run Chinook salmon are the Trinity River and Feather River Fish Hatcheries (CDFW 2016).

3.4.3.4 Late Fall-Run Chinook Salmon

Late fall-run Chinook salmon have the largest body size of the four runs and can weigh 20 pounds or more (Moyle 2002). Their large size makes them a sought after recreational trophy sport fish.

The historical abundance and distribution of the late fall-run is not known because the run was only recognized as distinct after construction of the RBDD in 1966 (Yoshiyama et al. 2001). The late fall-run probably spawned above Shasta Reservoir in the upper Sacramento River and its tributaries (Yoshiyama et al. 2001). The primary spawning habitat for late fall-run is now in the Sacramento River above the RBDD. Some spawning has also been observed in Clear, Mill, Cottonwood, Salt, Battle and Craig Creeks and in the Yuba and Feather rivers. Annual production from these watersheds is thought to only constitute a minor fraction of total population abundance.

Late fall-run Chinook salmon migrate upstream in December and January as mature fish, although some upstream migration has been documented as early as October and as late as April (Table 3.4-1, Williams 2006). Spawning occurs in late December and January as fish arrive on the spawning

[5] Figure from http://www.fws.gov/lodi/afrp/Documents/Doubling_goal_graphs_020113.pdf.

grounds, although it may extend into April in some years (Williams 2006). Fry begin to emerge from the gravel in April with emergence complete by early June. Juveniles may hold in the River for 7-13 months before migrating downstream to the ocean (Moyle 2002). Peak downstream migration is in October, although some individuals may leave at an earlier age and a smaller body size (Williams 2006).

Construction of Shasta and Keswick Dams in the 1940s blocked late fall-run Chinook salmon access to upstream spawning areas where snow melt and spring water originating from Mt. Shasta kept ambient water temperature cool enough for successful spawning, egg incubation and survival of juvenile salmon year round. Late fall-run Chinook salmon are now dependent on cold water release from Shasta Reservoir. Reservoir releases and installation of a temperature control device at Shasta Dam has provided cooler water temperatures during summer for winter-run Chinook salmon which likely also benefits late fall-run.

As previously mentioned, the historic abundance of late fall run Chinook salmon is not known because the race was not recognized as distinct from fall-run until after construction of the RBDD in 1966. AFRP estimates of natural production demonstrate a long term decline (Figure 3.4-6). Natural production between 1992 and 2011 was only 48 percent of the production during the base period of 1967-1991 (Table 3.4-3). The average number of returning adults during the past 40 years (1976-2014) is about 12,000 fish (Figure 3.4-7). Late fall-run Chinook salmon are produced at the Coleman National Fish Hatchery on Battle Creek. The target is one million fish per year. Juvenile fish are released in December at or near the hatchery (California Hatchery Scientific Review Group 2012).

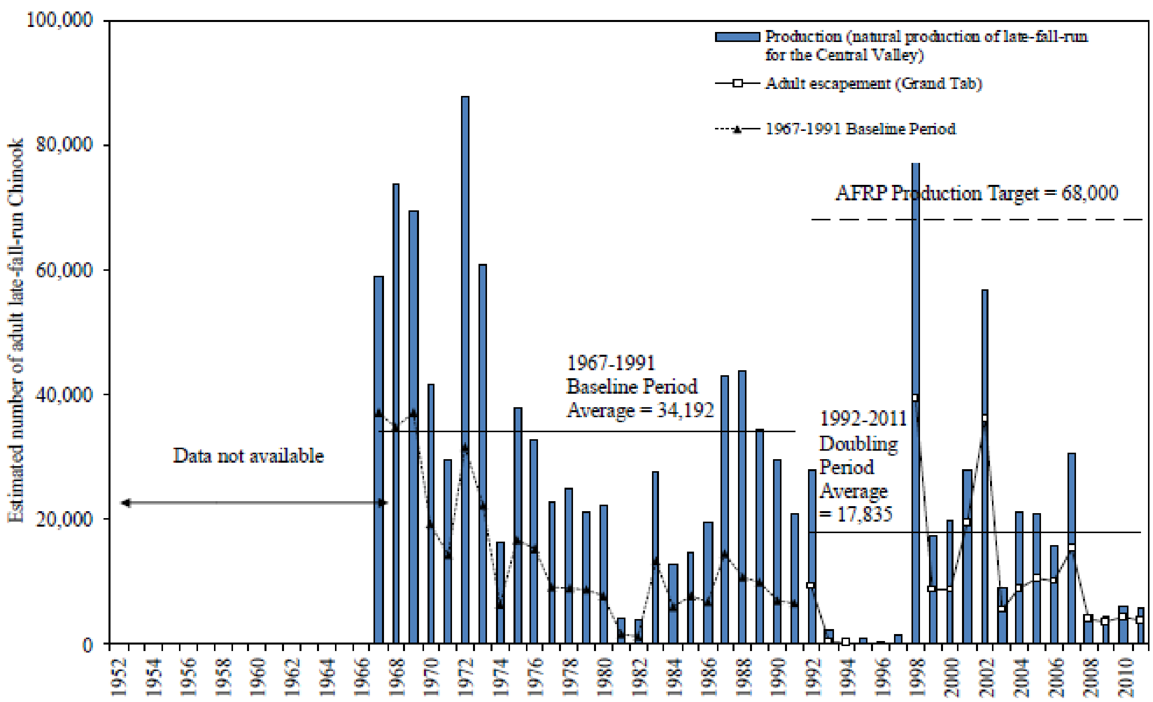


Figure 3.4-6. Estimated Yearly Adult Natural Production and in-River Adult Escapement of Late Fall-run Chinook Salmon in Central Valley Rivers and Streams. 1992-2011 numbers are from CDFG Grand Tab (Apr 24, 2012). 1967-1991 baseline period numbers are from Mills and Fisher (CDFG 1994).[6]

[6] Figure from http://www.fws.gov/lodi/afrp/Documents/Doubling_goal_graphs_020113.pdf.

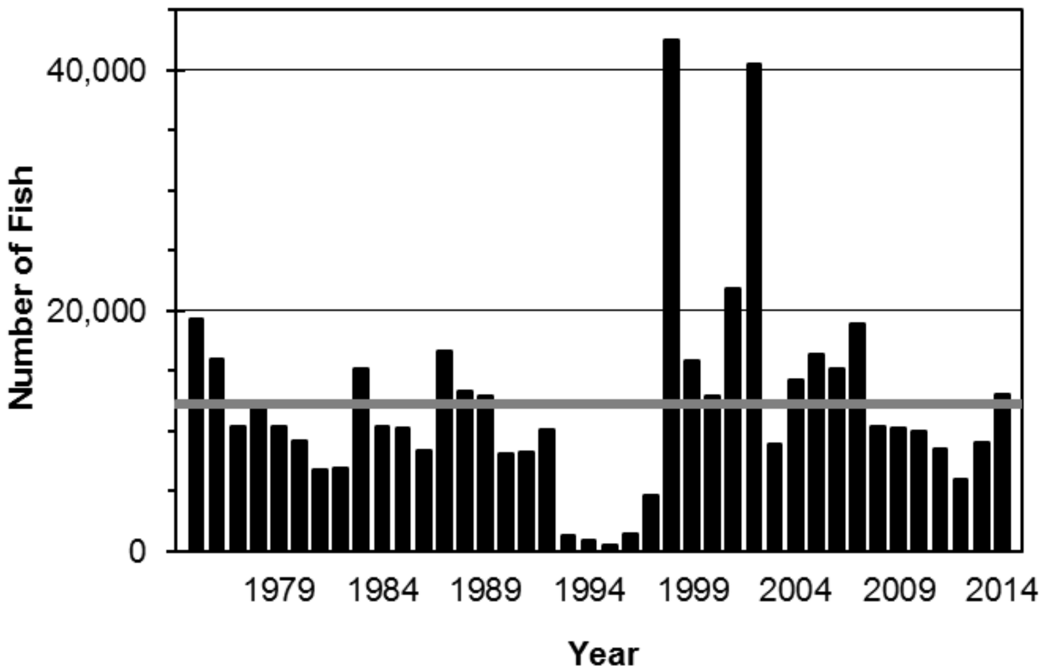


Figure 3.4-7. Annual Late Fall-run Chinook Salmon Escapement to the Sacramento River Watershed from 1975 to 2014 and 40 Year Mean (gray line). (Source Azat 2015)

3.4.3.5 Fall-Run Chinook Salmon

Historically, fall-run Chinook salmon likely occurred in all Central Valley streams with adequate flow during the fall (Yoshiyama et al. 2001). Fall-run spawned in valley floor streams and lower foothill water courses and were limited in their upstream spawning migration because of a deteriorating body condition (Yoshiyama et al. 2001). The cue for upstream migration appears to be an increase in flow. Adults often move on the rising limb of the hydrograph (USDOI 2010). Adults are sexually mature and upon arrival in their natal stream start to select spawning sites and construct redds.

Sacramento fall- run spawn from late September through January and larval hatching occurs about two months later (Table 3.4-1). Egg incubation is temperature dependent and lasts 40 to 60 days. Upon hatching, the alevins remain in the gravel for 4 to 6 weeks until their yolk sac has been absorbed (Moyle 2002). The young emerge from redds and migrate to the ocean primarily between April and June (Stevens and Miller 1983). In wet years with high runoff smaller individuals have been observed to enter the estuary a few days after emerging (Kjelson et al. 1981).

Life history characteristics of the San Joaquin fall run population are similar, but with small differences, to that previously described for fall run from the Sacramento basin. Adult San Joaquin River fall run Chinook salmon migrate through the Delta to their natal streams from late September to early December. Peak migration occurs in November (Table 3.4-1). Spawning can occur at any time between October and December in the Merced, Tuolumne and Stanislaus Rivers, but typically happens in November (McBain and Trush 2002; CDFW 1993). Fry emerge from the gravel between February and March (McBain and Trush 2002). Some individuals immediately migrate downstream to the main stem San Joaquin River and the Delta while others linger in their natal stream and emigrate in April and May. Peak outmigration past Mossdale occurs between mid-April and the end of May (Figure 3.4-10). Juvenile salmon can rear in the Delta downstream of Mossdale for an additional one to three months before moving to San Francisco Bay and the Pacific Ocean (Williams 2006).

Fall-run Chinook salmon are the most abundant of all Central Valley salmon runs. The life history strategy of adult Chinook salmon spawning upon entry into the watershed and juveniles leaving shortly after emerging from redds makes them suitable for culture in production hatcheries. Fall-run salmon fry are raised at six hatcheries[7] which together release more than 32 million smolts each year (CDFW 2016). Hatchery production contributes to a large commercial and recreational ocean fishery and a popular freshwater sport fishery. In 2007 and 2008 there was a large decline in escapement (Figure 3.4-8). The NMFS (2009) concluded that the decline was likely due primarily to poor ocean conditions in 2005 and 2006. The number of returning adults has since recovered and is now about at the 40-year average (Figure 3.4-8). Like other salmon runs, the natural production of Sacramento and San Joaquin River Basin fall-run have declined since the AFRP baseline years of 1967-1991 (Figure 3.4-9 and 3.4-11). Average natural production of San Joaquin and Sacramento runs between 1992 and 2011 were about 50 and 60 percent of the baseline period, respectively (Table 3.4-3).

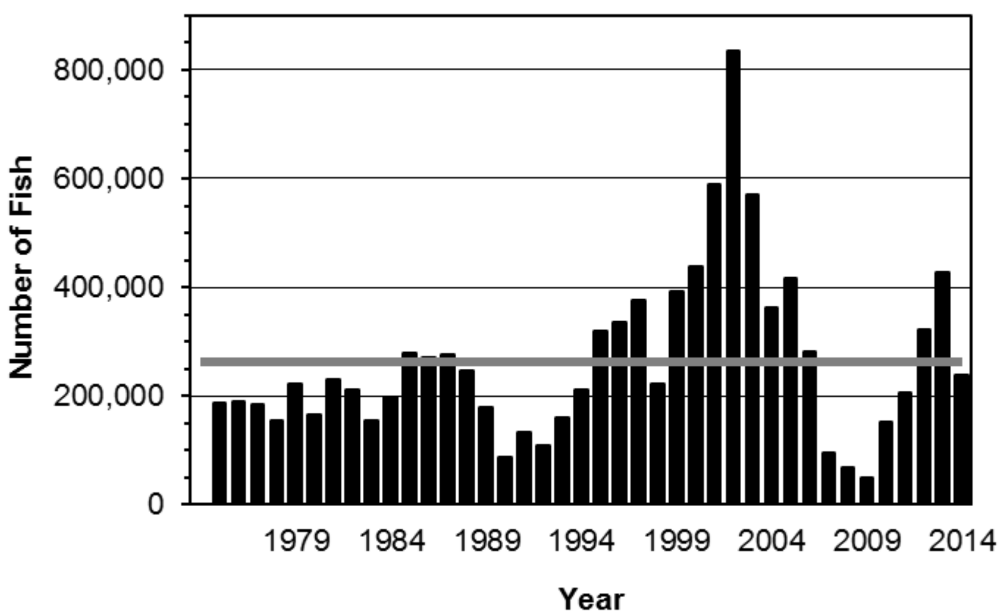


Figure 3.4-8. Annual Fall-run Chinook Salmon Escapement to the Sacramento River Watershed from 1975 to 2014 and 40 Year Mean (gray line). (Source Azat 2015).

[7] American, Feather, Trinity, Merced, Mokelumne, and Klamath River hatcheries

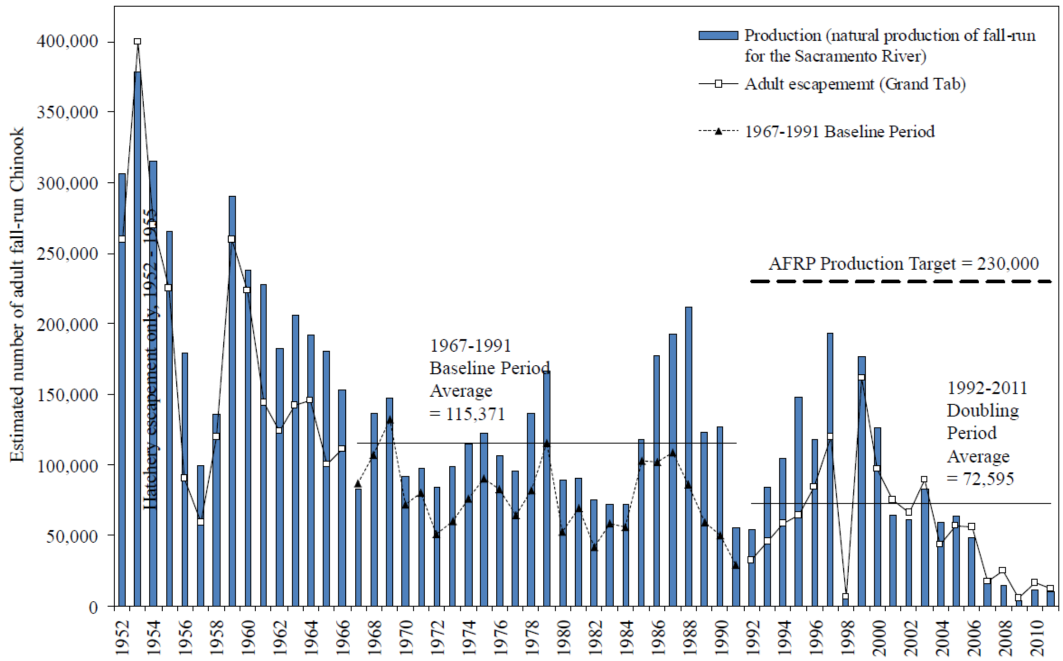


Figure 3.4-9. Estimated Yearly Adult Natural Production and in-River Adult Escapement of Fall-run Chinook Salmon in the Main Stem Sacramento River Basin. 1952-1966 and 1992-2011 numbers are from CDFG Grand Tab (Apr 24, 2012). 1967-1991 baseline period numbers are from Mills and Fisher (CDFG 1994)[8]

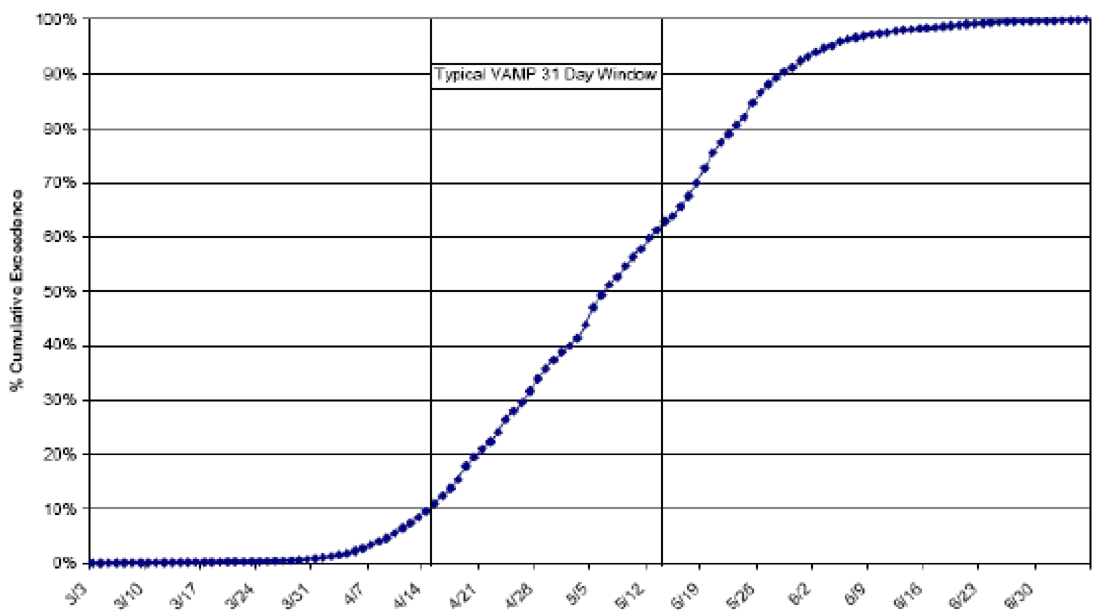


Figure 3.4-10. Mossdale Smolt Outmigration Pattern 1988-2004. (From CDFW 2005)

[8] Figure from http://www.fws.gov/lodi/afrp/Documents/Doubling_goal_graphs_020113.pdf.

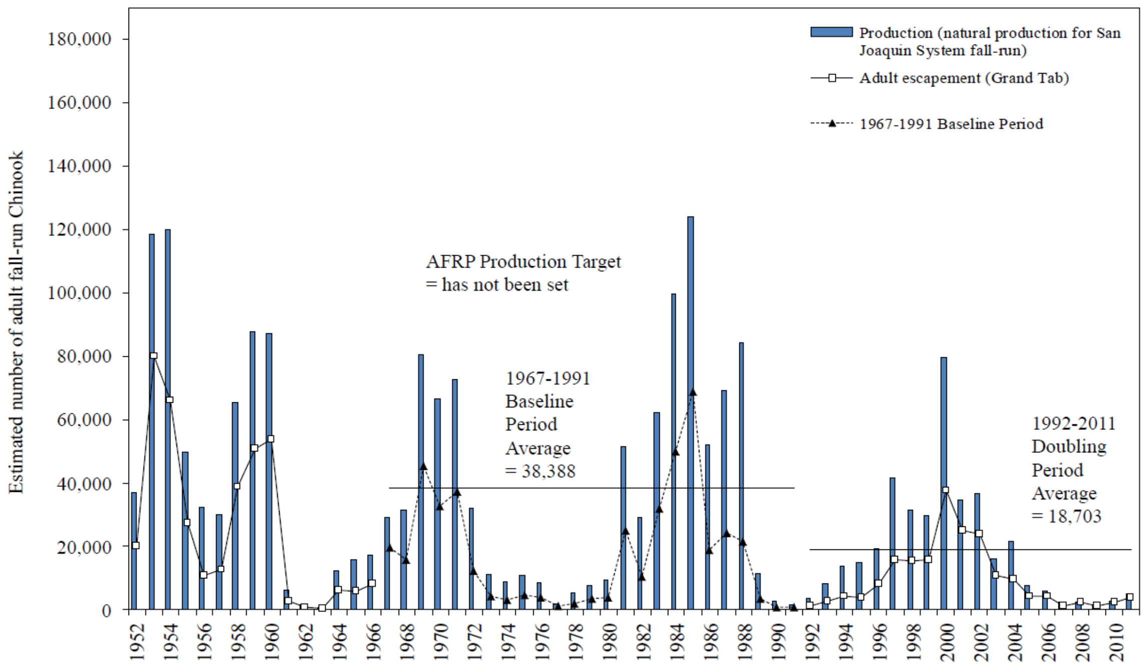


Figure 3.4.-11. Estimated Yearly Natural Production and Instream Escapement of San Joaquin Adult Fall-run Chinook Salmon. The San Joaquin system is the sum of the Stanislaus, Tuolumne and Merced Rivers. 1952-1966 and 1992-2011 numbers are from CDFG grand tab. 1967-1996 baseline period numbers are from Mills and Fischer (CDFG 1994)[9]

NMFS groups Sacramento fall and late fall-run Chinook salmon in a single ESU, which is currently listed as a federal Species of Concern (69 FR 19975). CDFW distinguishes between Sacramento fall and late fall-runs, and both are identified as California Species of Special Concern (Moyle et al. 2015).

The San Joaquin fall-run Chinook salmon population is not listed as either threatened or endangered under California or Federal ESA. CDFW includes San Joaquin fall-run Chinook in the Central Valley fall-run ESU, which is identified as a California Species of Special Concern (Moyle et al. 2015).

3.4.3.6 Central Valley Steelhead

Historically, Central Valley adult steelhead were widely distributed throughout the Sacramento and San Joaquin watersheds prior to dam and reservoir construction (NMFS 1996; McEwan 2001). Their distribution in the upper Sacramento River basin likely included the upper Sacramento and Pitt Rivers, Sacramento River tributaries on both the east and west side of the River and as far south as the Kings River in the San Joaquin basin (Yoshiyama et al. 1996; Lindley et al. 2006). Lindley et al. estimated that historically there may have been as many as 81 distinct steelhead populations distributed throughout the Central Valley.

[9] Figure from http://www.fws.gov/lodi/afrp/Documents/Doubling_goal_graphs_020113.pdf.

Existing wild steelhead populations now occur in the Sacramento, Yuba, Feather, and American Rivers and in Cottonwood, Deer, Mill, Antelope, Clear and Battle Creeks in the Sacramento Basin (NMFS 2014). On the eastside of the Delta, returning adult steelhead have been observed in the Mokelumne and Calaveras Rivers. In the San Joaquin River Basin, adult steelhead have been reported on the Stanislaus, Tuolumne, and Merced rivers (NMFS 2014).

Available data indicate a long-term decline in escapement of steelhead from the Sacramento and San Joaquin River basins (McEwan 2001). It is estimated that there were 1 million to 2 million spawners in the mid-1880s; abundance declined to 40,000 in the 1960s and further decreased to about 3,600 individuals between 1998 and 2000 (Good et al. 2005).

Four hatcheries in the Central Valley produce steelhead including the Battle Creek, Feather, American, and Mokelumne River Fish hatcheries. Together the hatcheries produce about 1.6 million fish each year (NMFS 2014).

The relative abundance of naturally spawned and hatchery reared steelhead in the Central Valley have been estimated in counts from the Chipps Island Spring Kodiak Trawl (SKT) data (USDOI 2008). Since 1998 all hatchery reared steelhead have had their adipose fin clipped for identification. The SKT results indicate that 60 to 80 percent of juvenile steelhead leaving the Delta were reared in a hatchery.

The life history characteristics and needs of Chinook salmon have been more intensively studied than those of California Central Valley steelhead. The CDFG (1992) and NMFS (2009) recommend, because of the similarity of both life histories, that actions to benefit salmon should also help steelhead.

The California Central Valley (CCV) steelhead DPS was listed as threatened in March, 1998 (63 FR 13347). This DPS includes all natural populations from the Delta, the Sacramento River and tributaries, and the San Joaquin River and tributaries. In January 2006 the Central Valley steelhead status as threatened was retained and the Coleman National Fish Hatchery and the Feather River Hatchery were included in the DPS (71 FR 834; Good et al. 2005). The risk of extinction for Central Valley steelhead was determined to have increased since 2005 (NMFS 2009; 76 FR 50447; Good et al. 2005). Critical habitat was designated in September 2005. It includes the Sacramento, Feather, and Yuba Rivers; Deer Mill, Battle and Antelope Creeks; the San Joaquin River and tributaries and the Delta (70 FR 52488).

3.4.4 Flow Effects on Salmonids

Protection of Chinook salmon and steelhead in the Central Valley and Bay-Delta Estuary requires appropriate flow conditions for each life stage in both fresh and estuarine water. Adult fish require flow of sufficient magnitude, timing and continuity to provide the olfactory cues, water quality and passage conditions to successfully migrate from the estuary to tributary spawning areas. Similarly, juveniles are adapted to the natural hydrologic patterns that provide suitable water temperatures and food resources for larval growth and development, trigger and facilitate downstream migration to the estuary, and provide seasonal access to productive rearing habitats such as floodplains and side-channels (Raymond 1979; Bunn and Arthington 2002; Connor et al. 2003; Sykes et al. 2011). Finally, outmigrating juvenile fish need spring Delta outflow of sufficient magnitude to ensure successful passage through the Delta to San Francisco Bay and on to the Pacific Ocean (USFWS 1987; Brandes and McLain 2001). The discussion that follows is organized by life stage, starting with adult migration, spawning and incubation and then juvenile rearing and outmigration.

3.4.4.1 Adult Migration, Spawning and Incubation

At least one run of salmon or steelhead is migrating through the Delta or holding in the upper watershed during each month of the year (Table 3.4-4). The year-round upstream migration of different runs of salmon requires that tributary inflows occur throughout the year to guide successful migration to natal streams and to provide appropriate water quality and flow conditions to support holding adult fish awaiting spawning and egg incubation.

Typically, salmon delay their spawning migration until water temperatures start to decline and flow increases before attempting migration through a tributary. During upstream migration, adult salmon and steelhead require flows of sufficient magnitude and continuity to provide olfactory cues needed to successfully find their natal stream (Moyle 2002; Groves et al. 1968). Peak or rising flows associated with natural precipitation events serve as important triggers for upstream migration of fall-run Chinook salmon (Moyle 2002). Continuous flows from natal tributaries through the Delta may be more important for other runs (CDFW 2010). Absence of a consistent pattern of chemical signals increases the likelihood of straying and a loss of genetic integrity and life history diversity (NMFS 2014). At the same time, a lack of appropriate adult holding conditions due to a lack of flows and elevated ambient water temperatures can reduce the fecundity of fish awaiting spawning (NMFS 2014) and is a common problem in the Bay-Delta watershed.

Larger and more variable tributary outflows benefit salmon by increasing the connectivity between the main stem and tributaries and by improving conditions for adult spawning. Low flows, typically associated with higher ambient water temperature, have been reported to delay upstream adult migration to spawning areas throughout the range of anadromous salmonids (Bjornn and Reiser 1991). NMFS (2014, Appendix A) found in an assessment of salmonid stressors in Central Valley tributaries that warm water and low flows resulted in a reduction in adult attraction and migration cues, a delay in immigration and spawning and a reduction in the viability of incubating embryos. State Water Board staff analyzed the frequency with which different impairments occurred and found that flow and warm water temperatures negatively affected adult salmon reproduction and the viability of their incubating embryos in 54 and 73 percent of the tributaries evaluated by NMFS (Table 3.4-5). The lack of flow was attributed to insufficient releases from upstream reservoirs and the presence of agricultural and municipal diversions on the valley floor (NMFS 2014). Elevated water temperature is caused by agricultural and municipal water diversions that reduce instream flow, elevated air temperature, lack of riparian forest cover for shade, and the presence of irrigation return flows (ERP 2014; NMFS 2014).

Adult salmonids that migrate through the Bay-Delta to return to their natal streams also encounter altered flow pathways resulting from SWP and CVP southern Delta export operations that cause flows to move toward the export facilities rather than out toward the ocean. These alterations to flow pathways largely affect fish returning to the San Joaquin and the Mokelumne River basins. Adult fall-run San Joaquin Chinook salmon migrate upstream through the Delta primarily during October when San Joaquin River flows are typically low (Hallock et al. 1970; Mesick 2001; Marston et al. 2012). As a result, if exports are high, little if any flow from the San Joaquin basin may make it out to the ocean to help guide San Joaquin River basin salmon back to spawn (Hallock et al. 1970; Mesick 2001; Marston et al. 2012). Analyses indicate that increased straying occurs when exports are greater than 400% of the flow of the San Joaquin River at Vernalis, while straying rates decreased when export rates were less than 300% of Vernalis flow (Mesick 2001).

Table 3.4-4. Timing of Adult Chinook Salmon and Steelhead Migrations through the Delta to Upstream Sacramento and San Joaquin River Spawning Tributaries.

	Months[1/]											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
Fall-run Chinook Salmon							■	■	■	■	■	
Spring-run Chinook Salmon			■	■	■	■	■					
Winter-run Chinook Salmon	■	■	■	■	■	■						■
Late Fall-run Chinook Salmon	■	■								■	■	■
Central Valley Steelhead	■	■	■				■	■	■	■	■	■

[1] Adapted from Herbold et al 1992 and USFWS 2014.

Table 3.4-5. State Water Board Staff Analysis of the Frequency of Common Flow related Stressors for Spring-run Chinook Salmon and Central Valley Steelhead in Twenty-two Salmon Bearing Tributaries of the Sacramento River. Information is from Appendix A in NMFS (2014).

Watersheds Affected (%)	Water-related Stress
73	Warm water temperatures negatively affect adult immigration, holding, spawning or embryo incubation
54	Low flows resulting in reduced adult attraction and migration cues, immigration, holding or spawning
50	Riparian habitat and instream cover affecting juvenile rearing and outmigration
40	Warm water temperatures negatively affecting juvenile rearing and outmigration.
32	Low flow negatively affecting juvenile rearing and outmigration

More recent analyses by Marston et al. (2012) found that straying rates estimated from CWT data from 1979 through 2007 decreased significantly with increasing San Joaquin River flows ($p=0.05$) and increased with increasing exports, although the decrease associated with reductions in exports was not statistically significant ($p=0.1$). Marston et al. (2012) also found that stray rates for San Joaquin fish were greater than those observed in the Sacramento River Basin (18% vs. less than 1%, on average). Taken together, this information suggests that pulse flows and exports jointly affect straying rates in the San Joaquin River basin (Monismith et al. 2014).

Recent studies have shown that pulse flows from the Mokelumne River in combination with closure of the DCC Gates during October increases the number of returning Chinook salmon and reduces straying of Mokelumne River fish to the American River (EBMUD 2013; CDFW 2012, Table 3.4-6). CDFW (2012) recommended that the DCC Gates be closed for up to 14 days in October in combination with experimental pulse flows from the Mokelumne River to increase adult salmon returns and reduce adult salmon straying.

Table 3.4-6. Salmon Returns on the Mokelumne River (from CDFW 2012)

Escapement Year	Number of Fall-run Returning	Estimated Stray Rate to American River	Pulse Flow	DCC Closure
2008	412	75%	No	No
2009	2,232	54%	Yes	No
2010	7,196	25%	Yes	Yes (2 day)
2011	18,462	7%	Yes	Yes (10 day)

3.4.4.2 Juvenile Rearing and Outmigration

During their freshwater rearing and emigration periods, juvenile Chinook salmon and steelhead require flows of sufficient magnitude to trigger and facilitate downstream migration to the estuary, provide seasonal access to productive rearing habitats (floodplains) and provide suitable food resources for growth and development (Raymond 1979; Connor et al. 2003; Smith et al. 2003; Sykes et al. 2011). Central Valley Chinook salmon and steelhead exhibit a broad range of juvenile rearing and migration strategies that likely reflect adaptations to natural hydrologic patterns and the spatial and temporal distribution of habitat extending from their natal tributaries to the estuary. Some salmon and steelhead juveniles rear for extended periods of time in natal streams or in main stem rivers above the Delta. The majority of salmon exhibit an ocean-type life history in which large numbers of juveniles move rapidly to the lower reaches of the system within the year after emergence. The dominance of this life history strategy is thought to be linked in part to the high productivity of formerly extensive floodplain, wetland, and estuarine habitat that favored rapid growth and survival of juveniles prior to seaward migration (Healey 1991). A common problem in salmon bearing tributaries in the Bay-Delta watershed appears to be a lack juvenile rearing habitat and a lack of connectivity between tributaries and the river due to lack of flow and elevated ambient water temperatures (NMFS 2014 Appendix A, Table 3.4-5). Below is a discussion of the needs for flows throughout the salmonid migratory corridor from natal tributaries and floodplains, through the main stem rivers, and then through the Delta for juvenile salmon.

Tributary Habitat

Natal streams are important initial rearing habitat for newly hatched larvae. The NMFS (2014, Appendix A) developed a watershed profile for salmon bearing streams in the Sacramento River Basin and tributaries draining to the Eastern Delta. Common stressors for juvenile salmon in the tributary streams were "*low flow negatively affecting juvenile rearing and outmigration*" and "*warm water temperature negatively affecting juvenile salmon rearing and outmigration".* An analysis by State Water Board staff determined that these two impairments occurred in 32 and 40 percent of the tributaries, respectively (Table 3.4-5). Agricultural diversions and dams were reported to occur in many of the same watersheds and likely contributed to the impairment (NMFS 2014, Appendix A).

Riparian Habitat

Riparian forest vegetation is important to juvenile salmonids for several reasons. Newly hatched larvae move to shallow protected areas associated with stream margins to feed (Royal 1972; Fausch 1984). Juveniles are reported to select sites with overhead cover (Fausch 1993) and appear to favor stream positions with low ambient light levels (Shirvell 1990). Riparian forests also provide shade and reduce ambient water temperature (NMFS 2014). Loss of riparian vegetation destabilizes banks and increases erosion which degrades the quality of spawning gravels. Finally, absence of riparian forests reduces the amount of large woody instream debris that would add spatial complexity and provide refuge from predators (NMFS 2014).

Analysis of information in the NMFS (2014 Appendix A) shows that 45 percent of the northern California watersheds that were assessed (Table 3.4-5) lacked appropriate riparian habitat and instream cover for juvenile salmonid rearing and outmigration. Watersheds with reduced riparian forest cover included Dry Creek, Auburn Ravine, Butte, Cow, Putah and Cottonwood Creeks, though success has been shown with rehabilitation of habitat in Putah Creek (Kiernan et al. 2012). The lower American, Feather and Cosumnes Rivers were also reported to lack sufficient riparian cover.

CDFW (2012) found that a key limiting factor for reestablishment of cottonwood and other native riparian trees along the Sacramento River and its tributaries was a drop in the water table as a result of water management and a reduction in the magnitude and frequency of winter overbank flows needed for successful germination and reestablishment of riparian forests. CDFW (2012) recommended a more variable and natural flow pattern with periodic large winter storms that overtop channel banks to saturate the soil profile to encourage seed germination and reestablishment of riparian habitat.

Floodplain Rearing

Restoring floodplain habitat and connectivity to the main river channels has been identified as a key objective of current ecosystem restoration and recovery efforts for Chinook salmon and other native fishes in the Central Valley (Moyle et al. 2008). Historically, the Central Valley contained extensive areas of seasonal floodplains and wetlands that flooded nearly every winter and spring. These habitats supported significant production of native fish species and may have contributed substantially to overall biological productivity of the river and estuary (Ahearn et al. 2006).

Lateral connectivity of the main river channels to floodplains can greatly expand the amount of rearing habitat for young salmon during seasonal inundation periods. The main stem rivers on the valley floor now flow mostly in confined channels with steep banks, but remnants of this formerly extensive habitat remain in engineered flood basins of the Sacramento River (Butte Sink, Sutter and Yolo Bypass) and along reached of the Cosumnes River where levees were breached. Studies of juvenile rearing in the Yolo Bypass and Cosumnes River floodplain following connection of high winter and spring flows show that juveniles grow rapidly in response to high prey abundance in the shallow, low velocity habitat created by floodplain inundation (Benigno and Sommer 2008; Jeffres et al. 2008; Sommer et al. 2001). The benefits of floodplain habitat likely increase with increased duration of floodplain inundation, although juveniles may benefit from even short periods of flooding (Jeffres et al. 2008). The ephemeral nature of seasonal inundated floodplain habitat creates higher risk of stranding, thermal stress, and low dissolved oxygen. However, the quality of rearing habitat appears to be significantly better than main stem river habitats, potentially resulting in greater survival of floodplain juveniles relative to those that stay in the main stem channels (Sommer et al. 2001). Faster growth and associated higher levels of smolt quality have been shown to be associated with higher marine survival in other west coast Chinook salmon populations (Beckman et al. 1999).

In the Yolo Bypass, the preferred timing of floodplain inundation is based on a combination of natural emigration timing, and hydrologic conditions that promote floodplain connection and activation (Opperman 2008). Maximum floodplain rearing opportunities for Chinook salmon generally occur from late November through April based on long-term juvenile outmigration monitoring at Knights Landing and the timing of flows of sufficient magnitude and duration to overtop the Fremont Weir, trigger major downstream movement of juveniles, and maximize the availability of floodplain habitat in the Yolo Bypass.

The NMFS BO requires actions to restore floodplain rearing habitat for juvenile winter-run, spring-run and California Central Valley steelhead in the lower Sacramento River to compensate for unavoidable adverse effects of CVP and SWP operations (NMFS 2009, pp. 608-610). This may be achieved in the Yolo Bypass or through actions in other suitable areas of the lower Sacramento River. The action recommends an initial size of 17,000 to 20,000 acres with an appropriate frequency and duration of flooding.[10]

[10] The NMFS BO required Reclamation and DWR to provide NMFS an Implementation Plan by December 2011. In 2013 Reclamation and DWR submitted their Implementation Plan to NMFS. A draft environmental document for the project is scheduled for completion in the spring of 2017 with design and construction to begin in the winter of 2017 or the spring of 2018.

Juvenile Outmigration

All Central Valley Chinook salmon and steelhead must migrate through the Delta as juveniles. In addition, many Central Valley Chinook salmonids also rear in the Delta for a period of time (USDOI 2010, p. 53). Studies indicate that higher flows during these periods are protective of outmigrating juveniles increasing both the abundance and survival of emigrants out of the Delta. Studies also show that survival is better if emigrants remain in the main stem river channels and other higher survival routes rather than entering the interior Delta where survival is known to be lower. Following is a discussion of the science regarding inflows, outflows and interior Delta flow conditions needed to protect emigrating salmonids.

Winter-run Chinook salmon enter the Delta from the Sacramento River between November and April (Table 3.4-2). Juvenile spring-run Chinook salmon enter the Delta from the Sacramento Valley approximately between January and April as yearlings and from January through June as young of the year. Juvenile fall-run Chinook salmon from the San Joaquin, Sacramento, and Mokelumne River systems migrate into the Delta between October and May (Table 3.4-2). The emigration of wild and hatchery steelhead is spread over an approximate five month period between November and March but with peak emigration in February and March. Thus, the outmigration of Central Valley salmonids spans the period from October to June, with the largest fraction of each population in the Delta from November to June (see also Vogel and Marine 1991).

Rain induced pulse flow events stimulate outmigration of juvenile salmon from the upper Sacramento River Basin tributaries to the Delta. The first autumn pulse flow exceeding 15,000 to 20,000 cfs on the Sacramento River at Wilkins Slough[11] has been shown to trigger outmigration of about half the annual catch of juvenile winter-run Chinook salmon at Knights Landing about four days later (del Rosario et al. 2010). The remaining upstream population continues to emigrate to the Delta during subsequent precipitation induced pulse flow events. Loss of or decrease in the magnitude of a pulse flow event because it was captured by diversions or upstream reservoirs may block outmigration of winter-run and other salmonids to the Delta and increase the risk of predation while juvenile fish are in the upper basin.

Fall-run Chinook salmon smolt survival through the Delta is positively correlated with Delta outflow (USFWS 1987). Kjelson and Brandes (1989) reported that the survival of tagged smolt through the Delta from the City of Sacramento to Suisun Bay was positively related to mean daily Sacramento River flow at Rio Vista during May or June. Survival of fall run smolts increased with an increase in flows from 7,000 to 25,000 cfs. Insufficient data exists to determine the relationship with confidence above 25,000 cfs.

Brandes and McLain (2001) also reported a positive relationship between abundance of unmarked outmigrating Chinook salmon and April–June flow at Rio Vista flow (Figure 3.4-12 (plot a)). Catch appeared independent of flow between about 5,000 and 15,000 cfs, suggesting that there might be a lower threshold effect. Catch increased in a linear fashion between 20,000 and 50,000 cfs. However, the small number of observations above 30,000 cfs makes the shape of the catch-flow relationship difficult to ascertain with confidence at the highest flows. State Water Board staff extended this analysis using Dayflow (DWR 2016) and Delta Juvenile Fish Monitoring Program data (DJFMP 2016). The results of the updated analysis are substantially similar to the previously published analysis (Figure 3.4-12 (plot b)).

[11] Wilkins Slough is near Knights Landing and is about 35 miles upstream of the Delta.

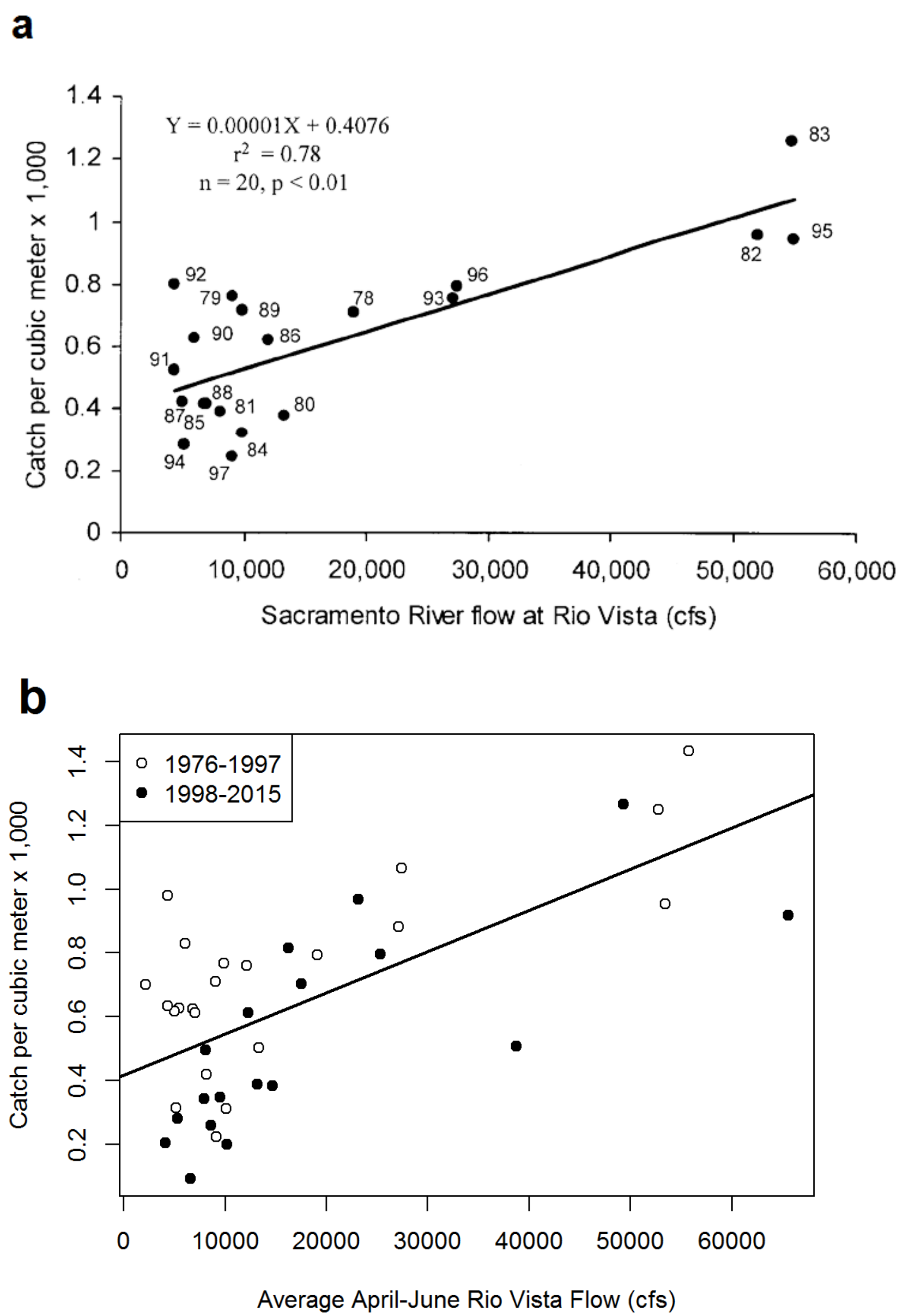


Figure 3.4-12. Mean Catch of Unmarked Chinook Salmon Smolt per Cubic Meter (x 1,000) in the Midwater Trawl at Chipps Island between April and June from (a) 1978 through 1997 versus Mean Daily Sacramento River Flow (cfs) at Rio Vista between April and June (from Brandes and McLain, 2001), and (b) 1976-2015 (updated analysis by State Water Board staff). The updated analysis shows the same pattern, with somewhat lower predictive power associated with flow (y = 0.0000129 x + 0.417; R2 = 0.438; p < 0.01).

Del Rosario and Redler (2010) reported that the migration of winter-run Chinook salmon smolts past Chipps Island begins after pulse flows exceed 20,000 cfs at Freeport. Most of the outmigration of winter-run occurs between February and April with about half the run passing Chipps Island in March (NMFS 2014; Del Rosario and Redler 2010). The cumulative catch per unit effort of smolt at Chipps Island was a positive function of the volume of water passing Freeport between November and April. In summary, flows greater than 20,000 cfs are expected to improve the abundance of fall and winter-run salmon smolt migrating past Chipps Island between February and June (Table 3.4-7). These higher flows may be protective because they result in lower water temperatures, a lower proportion of flow diverted into the Central Delta, and reduced entrainment at agricultural pumps and export facilities in the South Delta (USDOI 2010).

No similar flow abundance information is available for spring-run or for steelhead that have not been as widely studied. However, these fish have similar life history characteristics as fall- and winter-run and it is likely that a similar magnitude of flow would also be beneficial for them. Peak out migration of juvenile spring-run Chinook salmon past Chipps Island is between February and May (NMFS 2014). Steelhead catch at this station peaks between March and April (NMFS 2014). Therefore, spring-run and steelhead are also expected to benefit from flows as high as 20,000 to 30,000 cfs at Rio Vista between February and May.

Delta Cross Channel Gate Operations and Georgiana Slough

Juvenile salmonids originating in the Sacramento River and its tributaries may enter the interior Delta via the DCC when the DCC Gates are open or through Georgiana Slough (USFWS 1987; Low et al. 2006; Perry 2010). Juvenile salmonids migrating through the interior Delta experience lower survival rates to Chipps Island, often as low as half the survival rates of fish that migrate via the mainstem of the Sacramento River and northern Delta routes (Kjelson and Brandes 1989; Brandes and McLain 2001; Vogel 2004, 2008; Newman 2008; Newman and Brandes 2010; Perry 2010; Perry et al. 2013). Lower survival in the interior Delta has been ascribed to a longer migration route where fish are exposed to increased predation, higher water temperatures, and entrainment at CVP and SWP export facilities (Brandes and McLain 2001; NMFS 2009; Newman and Brandes 2010; Perry 2010).

Information suggested that juvenile salmonids "go with the flow" and thus either stay in the Sacramento River or enter the interior Delta through the DCC Gates or Georgiana Slough in proportion to the flow split at each junction (Schaffter 1980, as cited in Low et al. 2006; Burau 2004). Information specifically indicates that proportional losses of winter-run Chinook increase with the proportion of flow entering the interior Delta during December and January (Figures 3.4-13 and 3.4-14; Low et al. 2006). During the November-June outmigration period of Central Valley salmonids, approximately 40–50 percent of Sacramento River flow enters the interior Delta through the DCC Gates and Georgiana Slough when the DCC Gates are open, whereas only 15–20 percent of the flow enters through Georgiana Slough when the DCC Gates are closed (Low et al. 2006). In addition to eliminating entry to the interior Delta through the DCC Gates when they are closed, closure of the DCC Gates has also been show to redirect the migration route of a portion of juvenile Sacramento River basin fish through Sutter and Steamboat Sloughs in the north Delta, reducing the fraction of fish exposed to entrainment at Georgiana Slough (Perry 2010; Perry et al. 2013).

Recent modeling results have suggested that diurnal operations of DCC with gate closures at night may be nearly as effective at reducing entrainment to the interior Delta as seasonal closures (Perry et al. 2015).

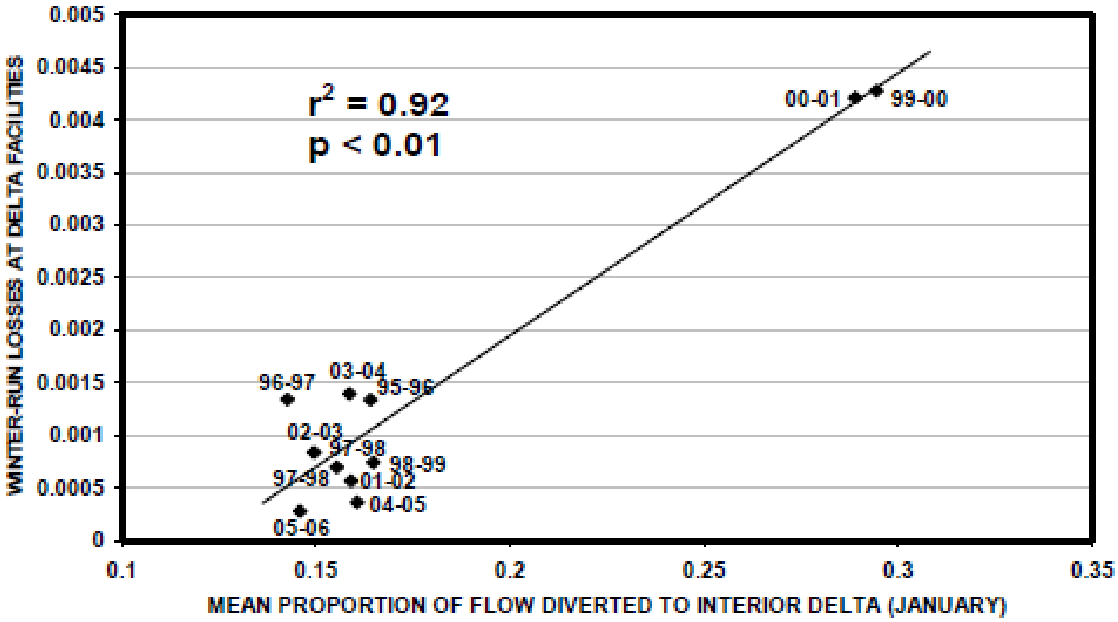


Figure 3.4-13. Relationship between the Mean Proportion of Flow Diverted into the Interior Delta in January and the Proportion of Juvenile Winter-run Lost at the CVP and SWP Pumping Facilities (loses divided by the juvenile production index) October 1 through May 31, 1996-2006 (from Low and White, 2006).

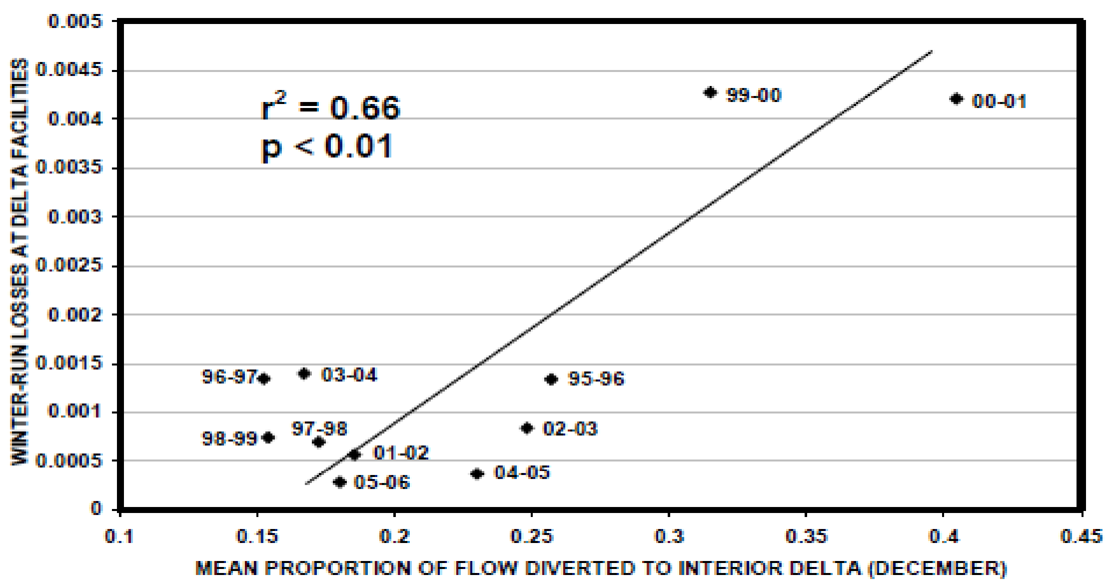


Figure 3.4-14. Relationship between the Mean Proportion of Flow Diverted into the Interior Delta in December and the Proportion of Juvenile Winter-run Chinook Salmon Lost at the CVP and SWP Pumping Facilities (loses divided by the juvenile production index) October 1 through May 31, 1995-2006. (From Low and White, 2006)

More recent studies involving mark-recapture experiments and detailed hydrodynamic analysis have shown that entrainment to the interior Delta via the DCC and Georgiana Slough depends more directly on instantaneous channel velocities than daily or tidally averaged flows (Burau 2004; Steel et al. 2013; Burau 2014). However, these velocities arise from the interaction of inflow from upstream and tidal flow, so entrainment can be minimized if inflows are sufficient to prevent tidal reversals at DCC and Georgiana Slough (Burau 2014; Perry 2010; Perry et al. 2015). Flows of 17,000 (USDOI 2010) to 20,000 cfs (Perry et al. 2015) at Freeport are sufficient to prevent these reversals and expected to minimize entrainment of migrating Sacramento Valley juvenile salmonids to the interior Delta (Table 3.4-7).

USGS has recently conducted pilot studies to evaluate the effectiveness of non-physical barriers including a bio-acoustic fish fence (BAFF) that makes use of light, sound, and bubbles, and a floating fish guidance structure (FFGS) comprised of a floating boom. Initial results have shown that the BAFF is marginally effective, reducing entrainment to Georgiana Slough from 22.3 percent to 7.7 percent in an experiment conducted over a range of flow conditions (Perry et al. 2014). A pilot study using only a floating boom FFGS showed no effect on entrainment to Georgiana Slough, although similar structures have been effective in the Columbia River system and additional studies are ongoing (Perry et al. 2014a).

Interior Delta Flows

Delta exports affect salmon migrating through and rearing in the Delta by modifying tidally dominated flows in the channels. It is, however, difficult to quantitatively evaluate the direct and indirect effects of these hydrodynamic changes. Delta exports can cause a false attraction flow drawing emigrating fish to the export facilities where direct mortality from entrainment may occur (USDOI 2010, p. 29; Monismith et al. 2014). More important than direct entrainment effects, however, may be the indirect effects caused by export operations increasing the amount of time salmon spend in channelized habitats where predation is high (USDOI 2010, p. 29). Steady flows during drier periods (as opposed to pulse flows that occur during wetter periods) may increase these residence time effects (USDOI 2010, p. 30).

Direct mortality from entrainment at the south Delta export facilities is most important for salmon and steelhead from the San Joaquin River and eastside tributaries (USDOI 2010, p. 29). Juvenile salmonids emigrate downstream on the San Joaquin River during the winter and spring (Table 3.4-1). San Joaquin salmonids are at risk of entrainment at the export facilities first at the head of Old River, where a rock barrier (Head of Old River Barrier, HORB) is typically installed in late spring (Chapter 2). The HORB directs the majority of the flow down the main stem of the San Joaquin River and prevents entrainment to upper Old River, a direct route to the Project export facilities. Tagging studies and modeling demonstrate that installation of the HORB improves the survival of outmigrating juvenile Chinook salmon from the San Joaquin Basin in spring (SJRGA 2008; Brandes and McLain 2001; Newman 2008).

Salmonids from the Calaveras River basin and the Mokelumne River basin also use the lower San Joaquin River as a migration corridor. This lower reach of the San Joaquin River between the Port of Stockton and Jersey Point has several side channels leading toward the export facilities that draw water through the channels to the export pumps (NMFS 2009, p. 651). Particle tracking model (PTM) simulations and acoustic tagging studies indicate that migrating fish may be diverted into these channels (Vogel 2004; SJRGA 2006, p. 68; SJRGA 2007, pp. 76-77; NMFS 2009, p. 651). Analyses indicate that tagged fish may be more likely to choose to migrate south toward the export facilities during periods of elevated diversions than when exports are reduced (Vogel 2004).

Table 3.4-7. Specific Sacramento River and Interior Delta flows Indicated to Increase the Abundance and Survival of Chinook Salmon Populations. Listed flows (cfs) are the monthly average of net daily outflow at Rio Vista unless noted otherwise. Though not specifically identified below in the summary of survival and abundance relationships, tributary flows are also needed to provide for connectivity, rearing and passage.

<table>
<tr><th rowspan="2"></th><th colspan="12">Months</th></tr>
<tr><th>Jan</th><th>Feb</th><th>Mar</th><th>Apr</th><th>May</th><th>Jun</th><th>Jul</th><th>Aug</th><th>Sept</th><th>Oct</th><th>Nov</th><th>Dec</th></tr>
<tr><td>Outmigration flows for juvenile fall-run[1,6]</td><td></td><td></td><td></td><td colspan="3">>20,000</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Outmigration flows for juvenile winter-run[1,2]</td><td></td><td colspan="3">>20,000</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Georgiana Slough[2]</td><td colspan="5">17,000-20,000</td><td></td><td></td><td></td><td></td><td></td><td colspan="2"></td></tr>
<tr><td>San Joaquin at Jersey Point[3]</td><td colspan="6">Positive Flow</td><td></td><td></td><td></td><td colspan="3">Positive Flow</td></tr>
<tr><td>OMR reverse flow[4]</td><td colspan="6">-2,500 to -5,000</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>San Joaquin River export constraint[5]</td><td></td><td colspan="5">1:1 - 4:1</td><td></td><td></td><td></td><td>>0.3</td><td></td><td></td></tr>
</table>

1 The flow may also aid juvenile spring-run and steelhead. Both species emigrate out of the Delta between February and May.
2 Flow at Freeport.
3 Five day tidally averaged net flow; when salmon are present.
4 14-day running average of tidally filtered flow at Old and Middle Rivers.
5 San Joaquin at Vernalis to the sum of CVP and SWP exports when salmon are present.
6 Flow at Rio Vista.

Statistical analyses have also shown that salvage of juvenile salmonids at CVP/SWP facilities increases with water exports (Kimmerer 2008; NMFS 2009, pp. 368-371; Zeug and Cavallo 2014). Many additional uncounted fish are lost each year because of pre-screen mortality and salvage making it is difficult to evaluate the population-level direct effects of exports (Kimmerer 2008; NMFS 2009, pp. 341-352; Zeug and Cavallo 2014)

Similarly, salmon that enter the San Joaquin River through the DCC or Georgiana Slough from the Sacramento River may also be vulnerable to export effects (NMFS 2009, p. 652). While fish may eventually find their way out of the Delta, migratory paths through the Central Delta channels increase the length and time that fish take to migrate to the ocean increasing their exposure to predation, increased temperatures, contaminants, and unscreened diversions (NMFS 2009, pp. 651-652).

Regression and PTM analyses have been used to determine the risk of salvage to juvenile salmon and steelhead and to establish Old and Middle River (OMR) reverse flow rates that minimize the risk of entrainment and loss. DWR regressed the monthly loss of juvenile salmon against average monthly OMR reverse flow rates between December and April, showing that loss of juvenile fish at the CVP and SWP pumping facilities increased exponentially with increasing OMR reverse flows (Figures 3.4-15 and 3.4-16; NMFS 2009, pp. 361-362). Both facilities show a substantial increase in loss around -5,000 cfs in most months (NMFS 2009, pp. 361-362). The loss of fish is almost linear at flows below this level but increases rapidly at more negative flows. PTM analyses indicate that as net reverse flows in Old and Middle rivers increase from -2,500 cfs to -3,500 cfs, entrainment of particles inserted at the confluence of the Mokelumne and San Joaquin Rivers increase from 10% to 20% and then again to 40% when flows are -5,000 cfs (NMFS 2009, pp. 651-652). Based on these findings, the NMFS's BO includes requirements that exports be reduced to limit negative net Old and Middle river flows of -2,500 cfs to -5,000 cfs depending on the presence of salmonids from January 1 through June 15 (NMFS 2009, p. 648). While fish are not neutral particles they often respond to flow and velocity fields that direct their migration, especially at the earliest life stages (Kimmerer and Nobriga 2008). PTM results provide a valuable approximation of hydrodynamic effects on route selection.

In addition to effects of net reverse flows in Old and Middle rivers, analyses concerning the effects of net reverse flows in the San Joaquin River at Jersey Point were also conducted and documented in the USFWS, 1995 Working Paper on Restoration Needs, Habitat Restoration Actions to Double the Natural Production of Anadromous Fish in the Central Valley California (1995 Working Paper, USFWS 1995). These analyses show that net reverse flows at Jersey Point decrease the survival of smolts migrating through the lower San Joaquin River (Figure 3.4-17; USFWS 1992). Net reverse flows on the lower San Joaquin River and diversions into the central Delta may also result in reduced survival for Sacramento River fall-run Chinook salmon (USFWS 1995, p. 3Xe-19). Based on these factors, net positive flow at Jersey Point between October and June is expected to improve the survival of emigrating juvenile Chinook salmon (Table 3.4-7).

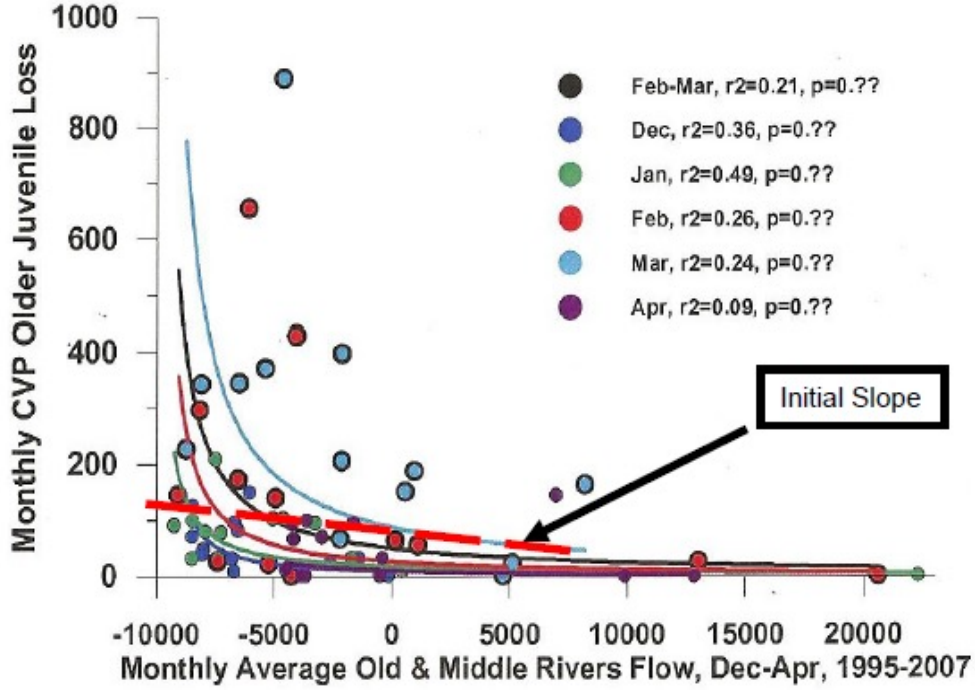


Figure 3.4-15. Relationship between OMR Reverse Flows and Entrainment at the Federal Pumping Facility, 1995-2007. (From NMFS, 2009)

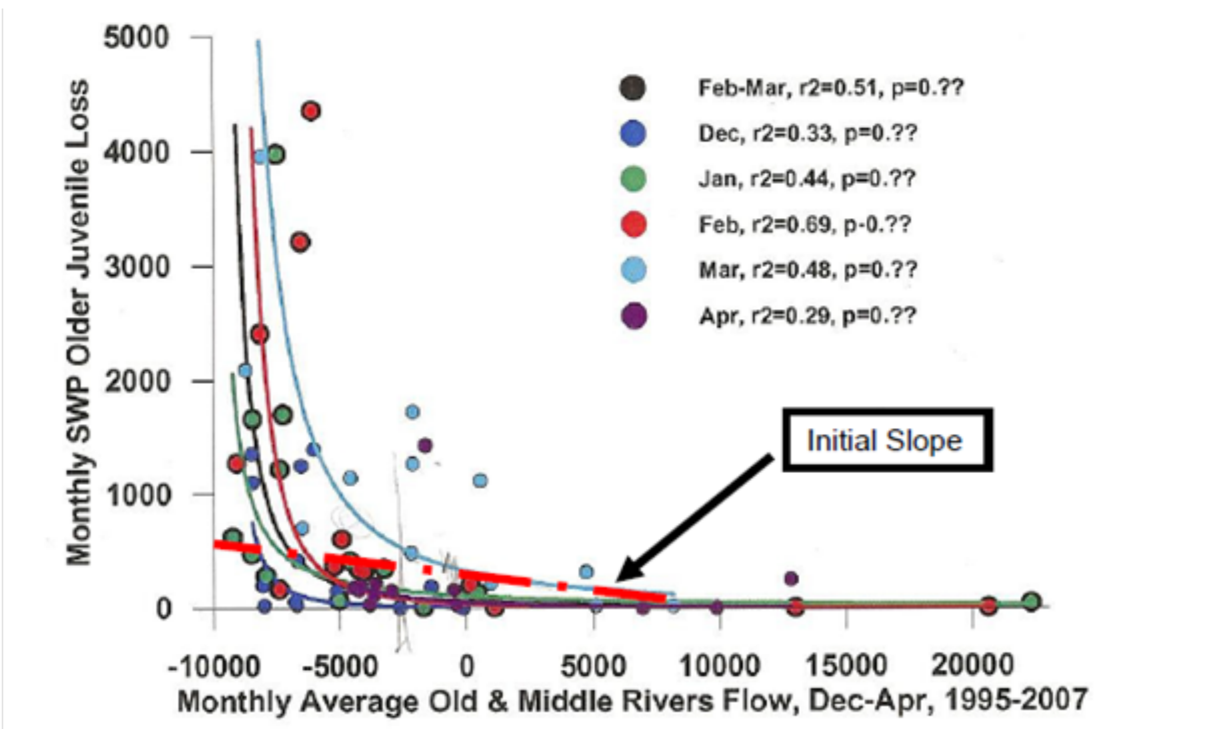


Figure 3.4-16. Relationship between OMR Reverse Flow and Entrainment at the State Pumping Facility 1995-2007. (From NMFS 2009)

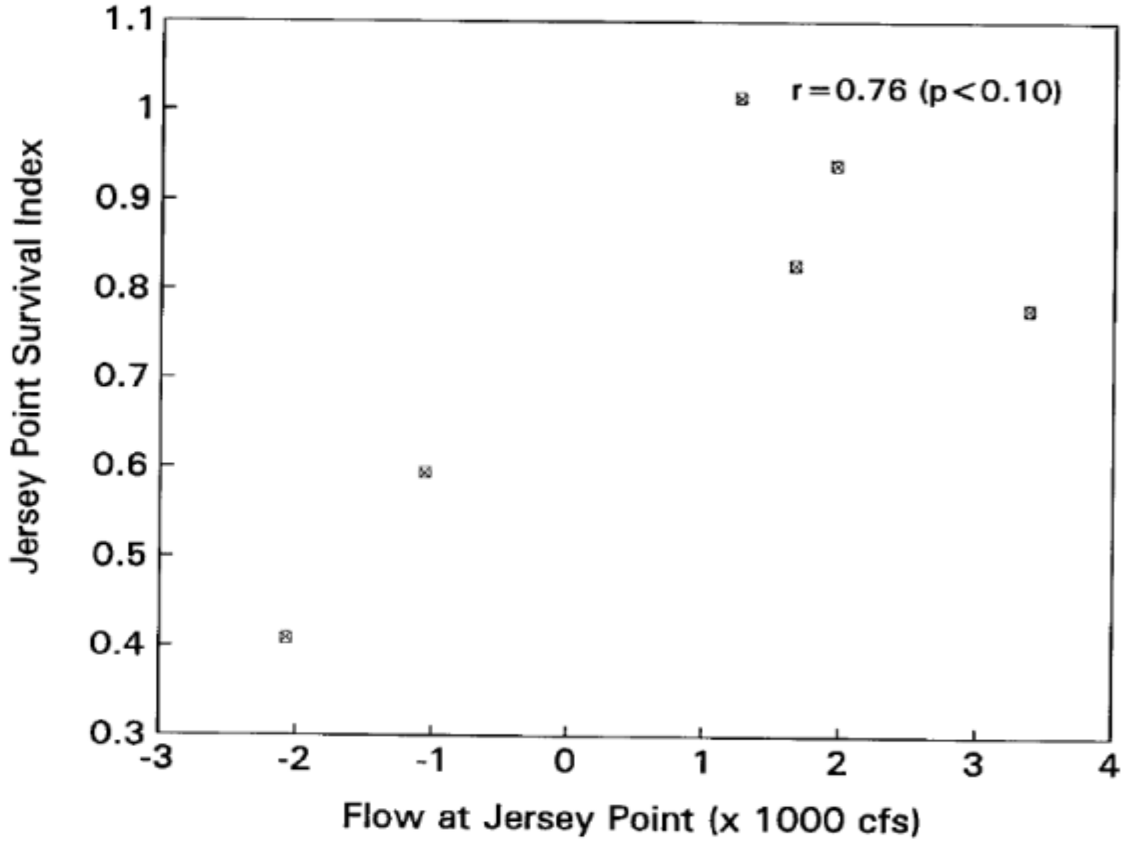


Figure 3.4-17. Temperature Corrected (to 610F) Survival Indices for CWT Salmon Smolt Released at Jersey Point and Recovered at Chipps Island between 1989 and 1991. Flow estimates were the 5-day mean value starting on the release date (from USFWS 1992)

Flows on the San Joaquin River versus exports also appear to be an important factor in protecting San Joaquin River Chinook salmon. Various studies show that, in general, juvenile salmon released downstream of the effects of the export facilities (Jersey Point) have higher survival out of the Delta than those released closer to the export facilities (NMFS 2009a, p. 74). Studies also indicate that San Joaquin River basin Chinook salmon production increases when the ratio of spring flows at Vernalis to exports increases (DFG 2005; SJRGA 2007 as cited in NMFS 2009a, p. 74). However, it should be noted that the flow at Vernalis is the more significant of the two factors. Increased flows in the San Joaquin River may also benefit Sacramento basin salmon by reducing the amount of Sacramento River water that is pulled into the central Delta and increasing the amount of Sacramento River water that flows out to the Bay (NMFS 2009a, p. 74-75). Based on these findings, the NMFS BO calls for export restrictions from April 1 through May 31 with San Joaquin River at Vernalis flows to export ratios ranging from 1.0 to 4.0 based on water year type, with unrestricted exports above flows of 21,750 cfs at Vernalis, in addition to other provisions for health and safety requirements (NMFS 2009a, p.73-74). The NMFS BO also requires a six year acoustic tagging study of steelhead survival in the south Delta to inform future management (NMFS 2009, pp. 645-648). Additional collaborative investigations of steelhead and Chinook survival in the south Delta are ongoing through the Collaborative Adaptive Management Team

(CAMT) and its Salmonid Scoping Team (SST) (CAMT 2014, 2016). SST is expected to release a report containing preliminary findings and recommendations for future adaptive management actions (J. Israel, personal communication).

Juvenile salmonids migrate out of the San Joaquin basin during February through June (SWRCB 2012), and may need protection from export-related mortality at any time during this period in order to preserve life history diversity. Although peak outmigration occurs in April and May, recent research has shown that individuals leaving their natal tributaries as fry in February and March can make up a substantial fraction of individuals that ultimately return to spawn (Sturrock et al. 2015).

3.5 Longfin Smelt (*Spirinchus thaleichthys*)

3.5.1 Overview

Longfin smelt were once a common species in the San Francisco Estuary but the population has declined and is now about a tenth of one percent of its abundance when sampling began 50-years ago. The abundance of juvenile longfin smelt in the fall is positively correlated with Delta outflow during the previous spawning season. Average daily outflows of 41,900 and 29,200-cfs in January-March and April-May are associated with positive population growth in half of all years. Adult and juvenile longfin smelt are vulnerable to entrainment at the CVP and SWP pumping facilities when the population migrates into the central Delta during the spawning season. OMR reverse flows between -1,250 to -5,000-cfs when fish are present in the central Delta are expected to reduce smelt salvage at the two pumping facilities.

3.5.2 Life History

Longfin smelt are a native semi-anadromous, open water fish moving between fresh and salt water (CDFW 2009; Wang 2007). Longin smelt generally live two years with females reproducing in their second year (Moyle 2002; CDFW 2009). Adults spend time in San Francisco Bay and may go outside the Golden Gate (Rosenfield and Baxter 2007; Wang 2007). Adults aggregate in Suisun Bay and the western Delta in late fall and migrate upstream to spawn in freshwater as water temperatures drop below 18°C. (CDFW 2009; Wang 2007; Baxter et al. 2009). Spawning habitat in the Delta is between the confluence of the Sacramento and San Joaquin rivers (around Point Sacramento) to Rio Vista on the Sacramento side and Medford Island on the San Joaquin River (Moyle 2002; Wang 2007). Reproductive activity appears to decrease with distance from the low salinity zone, so the location of X2 influences how far spawning migrations extend into the Delta. (Baxter et al. 2009). Spawning takes place between November and April with peak reproduction in January to as late as April when water temperature is between 8 and up to 14.5^{O}C (Emmett et al. 1991; CDFW 2009; Wang 1986, 2007). Eggs are deposited on the bottom (Martin and Swiderski 2001; CDFW 2010) and hatch between December and May into buoyant larvae with a peak hatch in February (CDFW 2010; Bennett 2002). Net Delta outflow transports the larvae and juvenile fish back downstream to higher salinity habitats. Both juveniles and adults feed on zooplankton (Slater 2008).

3.5.3 Population Abundance Trends Over Time

Longfin smelt population abundance in the Bay-Delta has declined significantly since the 1980s (Moyle 2002; Rosenfield and Baxter 2007; Baxter et al. 2010). Thomson et al. (2010) examined trends in abundance using long term data sets from the FMWT and the San Francisco Bay midwater and otter trawl studies and found a statistically significant decrease in longfin smelt abundance over time. State Water Board staff reexamined the inter-annual trend in the FMWT index using data collected through 2015 and found that the index has continued to decline and is now about one tenth of one percent of the 1967 level[12] (Figure 3.5-1, P<0.001).

The 2015 FMWT index is four percent of the 2000 value[13](P<0.05) indicating that the population has continued to decline since revised Delta outflow requirements were last implemented in D-1641. The last three years of the trend occurred during a drought which undoubtedly contributed to the decline, however, there have been 16 years since 2000 and these have included both wet and dry periods. As discussed in Chapter 4, multiple stressors, including inadequate flow, may be responsible for the decline (Sommer et al. 2007).

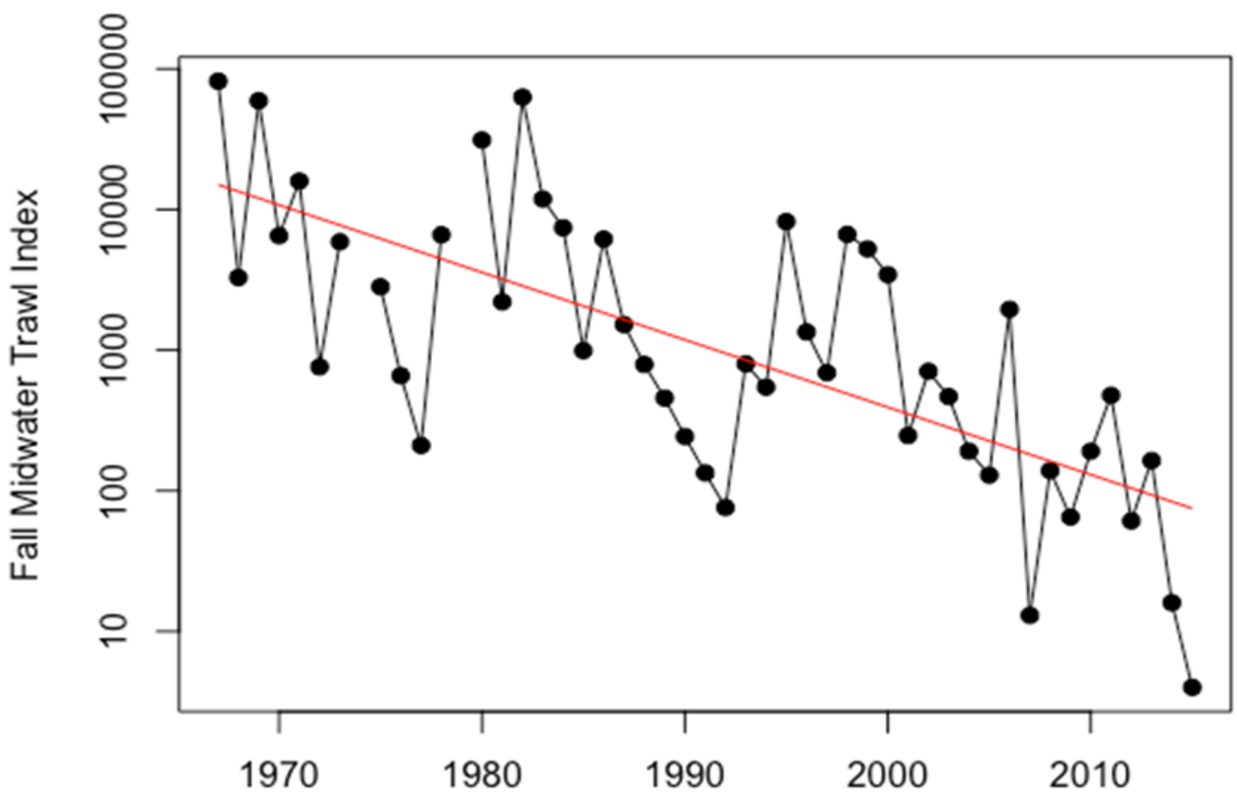


Figure 3.5-1. Inter-Annual Trend in the FMWT Index for Longfin Smelt (1967 to 2015). The decrease in the logarithm of the index is statistically significant [R^2=0.49; P<0.001].

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[12] The decrease was estimated from the average of the first three (1967–1970) and the last three (2012–2015) annual FMWT index values to account for inter-annual variability.

[13] The decrease was also calculated from the average of the first three FMWT index values after implementation of D1641 (2000–2003) and the most recent three years (2012–2015).

In their recovery plan for longfin smelt, the USFWS (1995) indicates that, "*longfin smelt will be considered restored when its population dynamics and distribution pattern within the Estuary are similar to those that existed in the 1967–1984 period.*" The 2010 Delta Flow Criteria Report also relies on this definition. The USFWS recommended that the FMWT index be used to determine compliance with their recovery goal. The median longfin smelt FMWT index value for the seventeen year period between 1967 and 1984 was 6,500.

The Bay-Delta distinct population segment (Bay-Delta DPS) of longfin smelt is currently a candidate for listing under the Federal Endangered Species Act (74 FR 16169). In 2012 the USFWS determined that listing the Bay-Delta DPS of longfin smelt was warranted but precluded by higher priority actions at the time of publication (77 FR 19755). In 2009 the Fish and Game Commission listed longfin smelt as threatened under CESA (CDFG 2009)

3.5.4 Flow Effects on Longfin Smelt

3.5.4.1 Delta Outflow

The population abundance of juvenile longfin smelt in fall is positively correlated to Delta outflow during the previous winter and spring reproduction period (Jassby et al. 1995; Rosenfield and Baxter 2007; Kimmerer 2002a; Thomson et al. 2010; Maunder et al. 2015; Stevens and Miller 1983; Nobriga and Rosenfield 2016). Statistically, the strongest correlation is with outflow between January and June. These months correspond to when adults migrate into the Delta to spawn and their larvae hatch, rear and are carried back downstream to more saline water.

The longfin smelt flow abundance relationship changed after 1987. The intercept for that relationship decreased with fewer smelt being produced for any given outflow (Kimmerer 2002). This decline has been attributed to the invasion by the overbite clam, *Corbula,* and its impact on the aquatic food web (Kimmerer 2002).

State Water Board staff conducted an analysis using the most recent FMWT survey data to determine whether Longfin smelt abundance is still correlated with Delta outflow and found that a positive relationship continues to exists between average daily outflow since the *Corbula* invasion (1988–2015) and the annual FMWT index for longfin smelt ($P<0.01$, Figure 3.5-2). Higher outflow in winter and spring is associated with more smelt in fall. The analysis indicates that flows in excess of 100,000 cfs are needed since the *Corbula* invasion to meet the USFWS recovery goal of 6,500. In comparison, before the *Corbula* invasion, flows of 50,000 and 30,000 cfs would have been sufficient to meet the goal in January–March and March–May, respectively. The new flows required to achieve the USFWS recovery goal are very large and suggest that the goal may no longer be attainable.

The recent pattern of wet and dry years confirms the importance of Delta outflows on changes in longfin smelt population size (Figure 3.5-1). The 2011 water year was wet with high Delta outflow in the winter and spring time period. The following four years were classified as below normal to critically dry. Longfin smelt abundance increased in 2011 and declined in three of the four following years (Figure 3.5-1). The population response indicates that longfin smelt is still able to respond positively to favorable environmental conditions.

State Water Board staff conducted a logistic regression analysis to estimate the magnitude of flow required to grow the longfin smelt population using data from 1967 to 2015 (Figure 3.5-3). A similar approach was used by The Bay Institute (TBI) (2010) in analyses submitted for the 2010 Flow Criteria Report with data from 1988-2007 (SWRCB 2010). The flow required to achieve a 50 percent

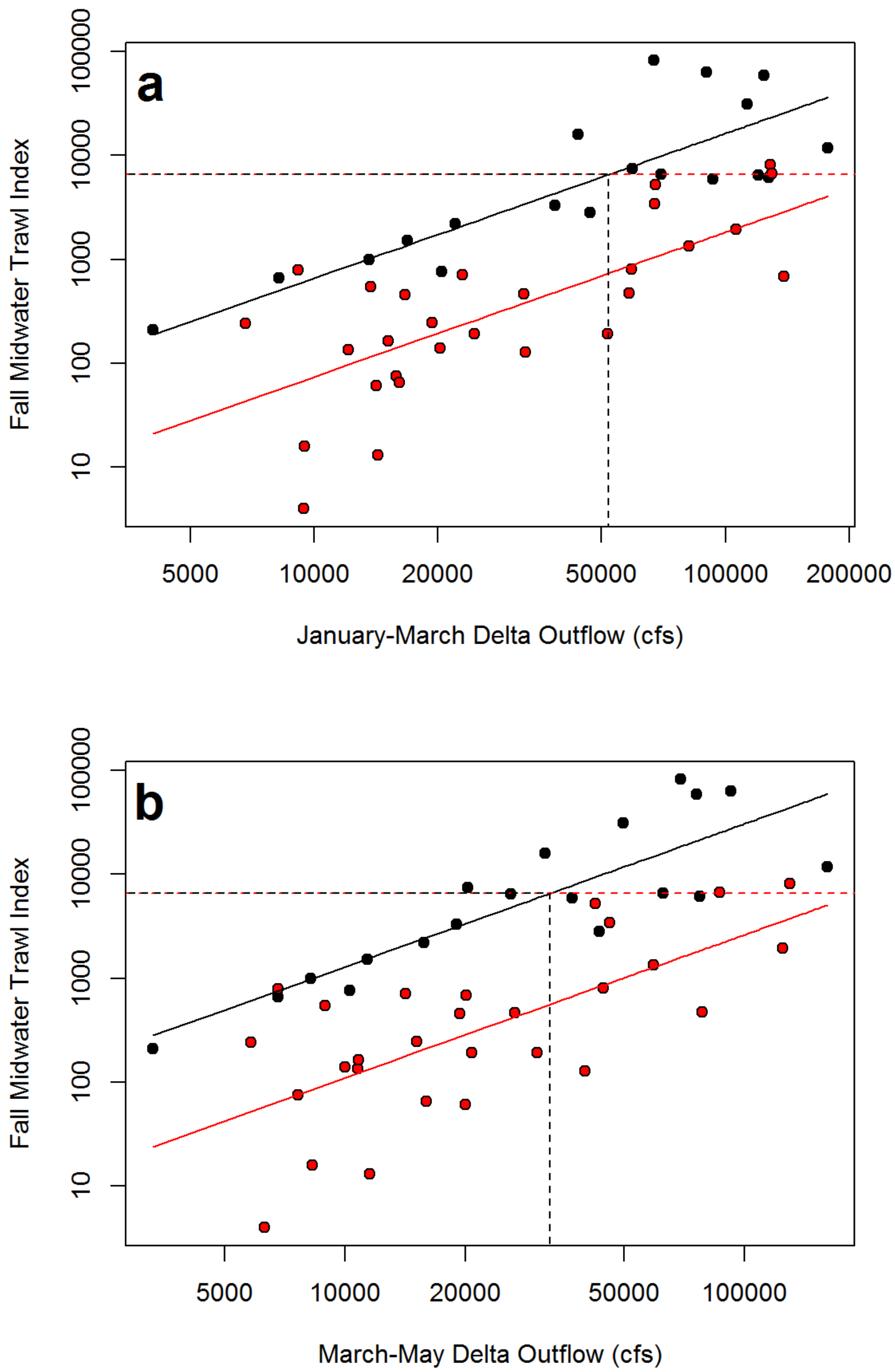

Figure 3.5-2. FMWT Index Values for Longfin Smelt Regressed against Average Daily Delta Outflow for 1967–2015 (Black and red points and lines are for years before and after the invasion of Corbula in 1987, respectively). The slope of both regressions are statistically significant (P<0.001)

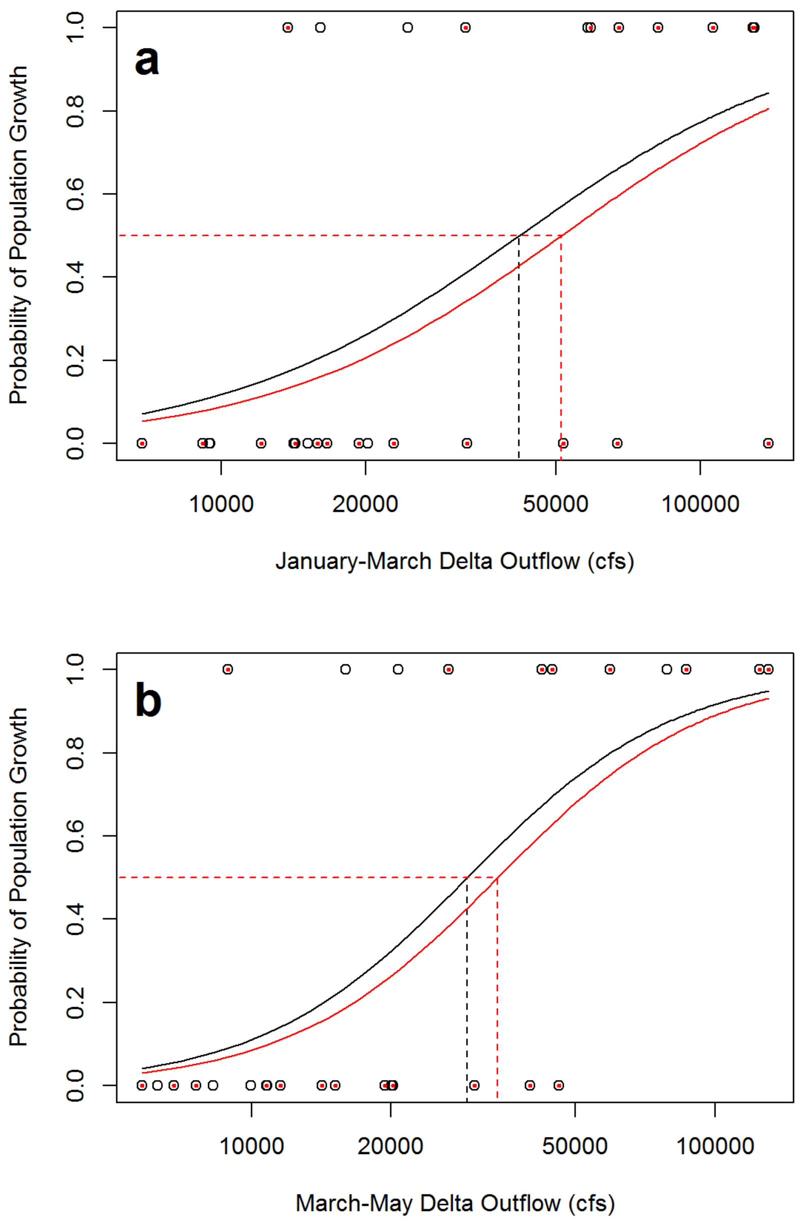

Figure 3.5-3. Probability of Positive Longfin Smelt Population Growth as a Function of Delta Outflow (black lines and open symbols are for years 1988 through 2015 while red lines and symbols are for 1988 through 2007 and are from TBI (2010)). [a] Probability of population growth as a function of average daily outflow during January through March. [b] Probability of population growth as a function of average daily outflow during March through May. Dashed lines indicate the flow that is predicted to produce positive population growth in 50 percent of years. All regressions are significant at P<0.05

probability of positive population growth was less with current data (1988–2015) than with the information used by TBI for the earlier period (1988–2007, Figure 3.5-3). For example, the flows associated with 50 percent probability of positive population growth in January through March declined from 51,000 to 41,900 cfs (Figure 3.5-3a). A similar analysis was also conducted for March to May (Figure 3.5-3b). The flow needed to achieve positive population growth in half of all years decreased from 35,000 to 29,200 cfs. These differences are likely a result of our inability to precisely measure the responses of longfin smelt and other species to changes in Delta outflows, but are indicative of the general relationship of longfin smelt and other species to increased Delta outflows. Delta outflows predicted to increase the longfin smelt population are summarized in Table 3.5-1.

3.5.4.2 Interior Delta Flows

Export pumping at the State and Federal facilities that causes OMR reverse flows, may draw large numbers of fish, including Longfin smelt, into the interior Delta and results in their entrainment (USFWS 2008; NMFS 2009). Grimaldo et al. (2009) reported that 122,747 Longfin smelt were salvaged at the CVP and SWP facilities between 1992 and 2005. However, the loss of fish, including Longfin smelt, as a result of OMR reverse flow, is difficult to quantify (Baxter et al. 2009). Estimates of losses do not account for indirect mortality as individuals move down the rip-rapped channels toward the pumping facilities, counting inefficiencies at the salvage facilities, loss of fish smaller than 20 millimeters (mm) that pass through the louvers without being counted, and mortalities from handling, transport, and release back into the Delta after salvage (Baxter et al. 2009). Counts of fish entrained and salvaged at the CVP and SWP pumping facilities potentially represent only a small part of the overall loss (Baxter et al. 2009). Because of the imprecise loss estimates, it is difficult to know whether export pumping has a negative population level effect on longfin smelt and no statistical evidence for one currently exists (Thomson et al. 2010; Mauder and Deriso 2015). However, the lack of evidence may, at least in part, result from the need to use salvage data which is an imprecise measure of population loss.

Baxter et al. (2009) conducted an analysis of CVP and SWP export pumping for the CDFW Longfin smelt Incidental Take Permit No. 2081-2009-001-03 and determined that adult Longfin smelt became vulnerable to entrainment and salvage between December and March as adults moved onto the spawning grounds. Adult salvage was found to have an inverse logarithmic relationship to net OMR reverse flow (Figure 3.5-4). The OMR salvage relationship has an inflection point around -5,000 cfs with salvage often increasing rapidly at more negative reverse flows. The inflection point is used as justification for not allowing OMR reverse flow to become more negative than -5,000-cfs when adult longfin smelt are present.

Baxter et al. also determined that juvenile longfin smelt were at risk of entrainment between April and June (Figure 3.5-5; Baxter et al. 2009). Like adult smelt, salvage of juvenile smelt increases exponentially with increased negative OMR reverse flows. Grimaldo et al. (2009) found a similar negative relationship between juvenile longfin smelt salvage and the magnitude of OMR reverse flow. The lowest salvage rates occurred in the Baxter et al. (2008) data at 1,250 cfs, the lowest OMR reverse flows measured (Figure 3.5-5).

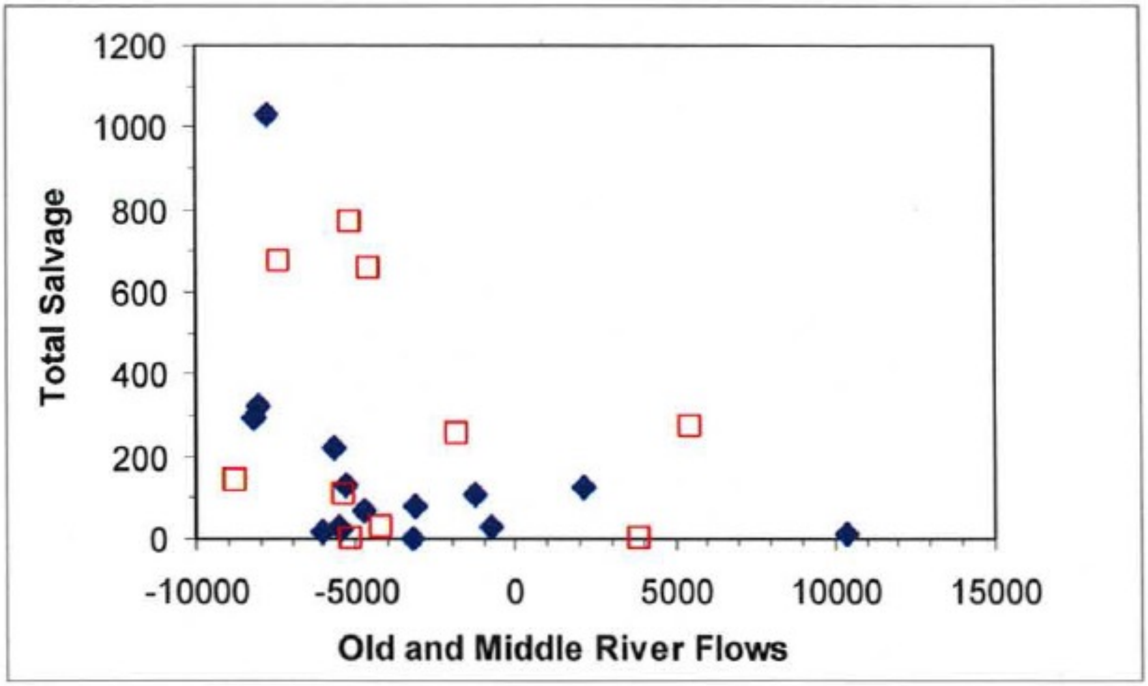

Figure 3.5-4. Total Salvage of Longfin Smelt between December and March as a Function of Average Old and Middle River (OMR) Flows during the Same Period for Water Years 1982–1992 (squares) and 1993–2007 (diamonds). OMR estimates for 1982–1992 were based upon calculations conducted by Lenny Grimaldo; those for 1993–2007 were from measured flows by the USGS. A single data point with an OMR reverse flow of -7,744-cfs and a salvage value of 20,962 individuals was not included. (Source: Baxter et al. 2009).

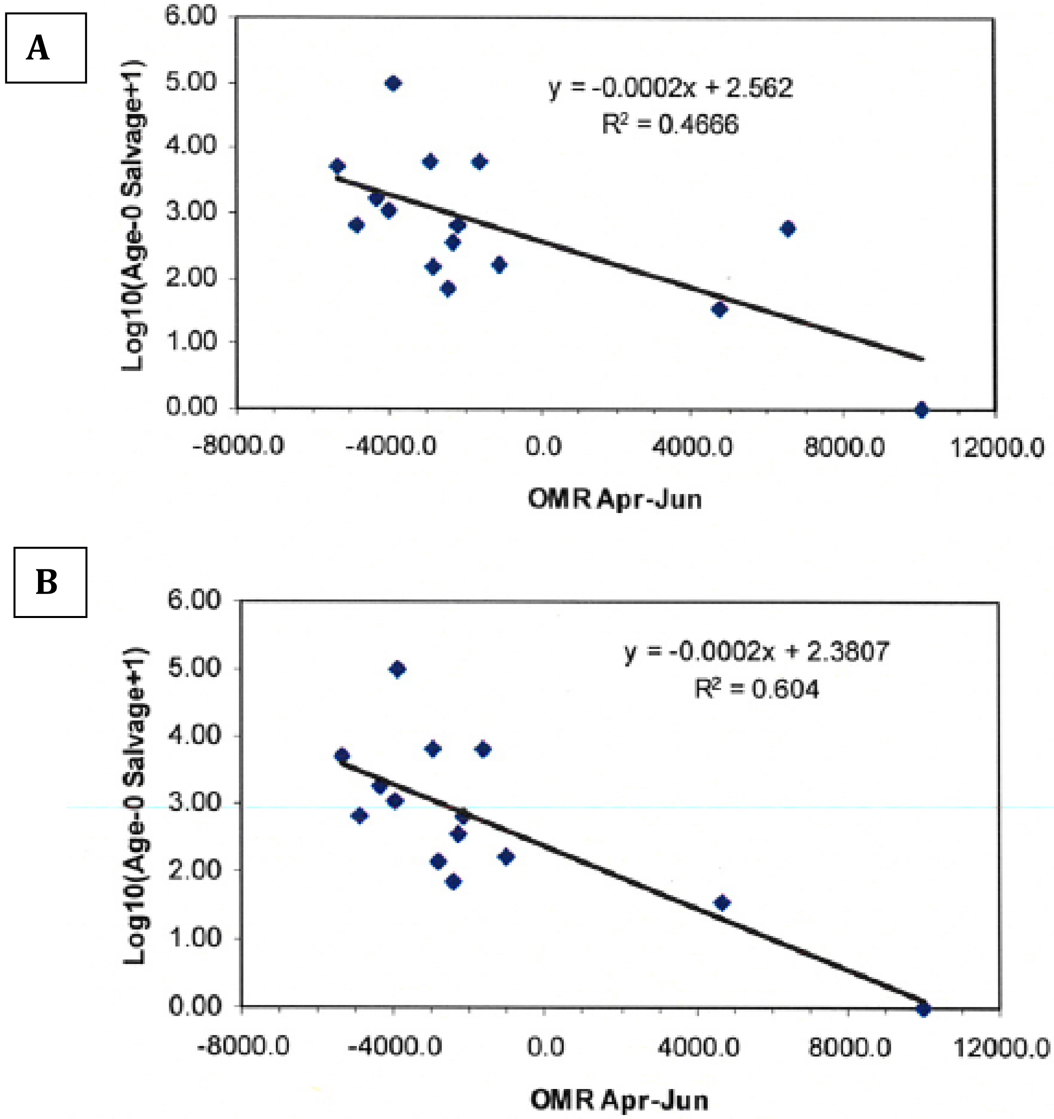

Figure 3.5-5. (A) Relationship between Average OMR Reverse Flows in April to June and the Sum of SWP and CVP Juvenile (age-0) Longfin Smelt Salvage during the Same Time Period, 1993–2007. (B) Presents the sme regression as in (A) excluding 1998 when a protracted SWP export shutdown allowed longfin smelt larvae to grow to salvageable size in Clifton Court before pumping resumed and fish salvage re-commenced. In other years these fish would have passed through the system as larvae without being counted in the salvage record [from Baxter et al. 2009].

Baxter et al. also found that juvenile longfin smelt salvage was positively correlated with the location of X2 and negatively associated with Delta outflow between January and June (Figure 3.5-6, Baxter et al. 2008). Salvage increased exponentially with increasing X2 or decreasing Delta outflow. The lowest salvage rate occurred at an X2 of less than 60 km (Figure 3.5-6) which corresponds to a location near Roe Island (Port Chicago) and a net Delta outflow of around 55,000 cfs. The Delta outflow salvage relationship is used to justify suspending the OMR reverse flow requirements when outflow exceeds 55,000 cfs.

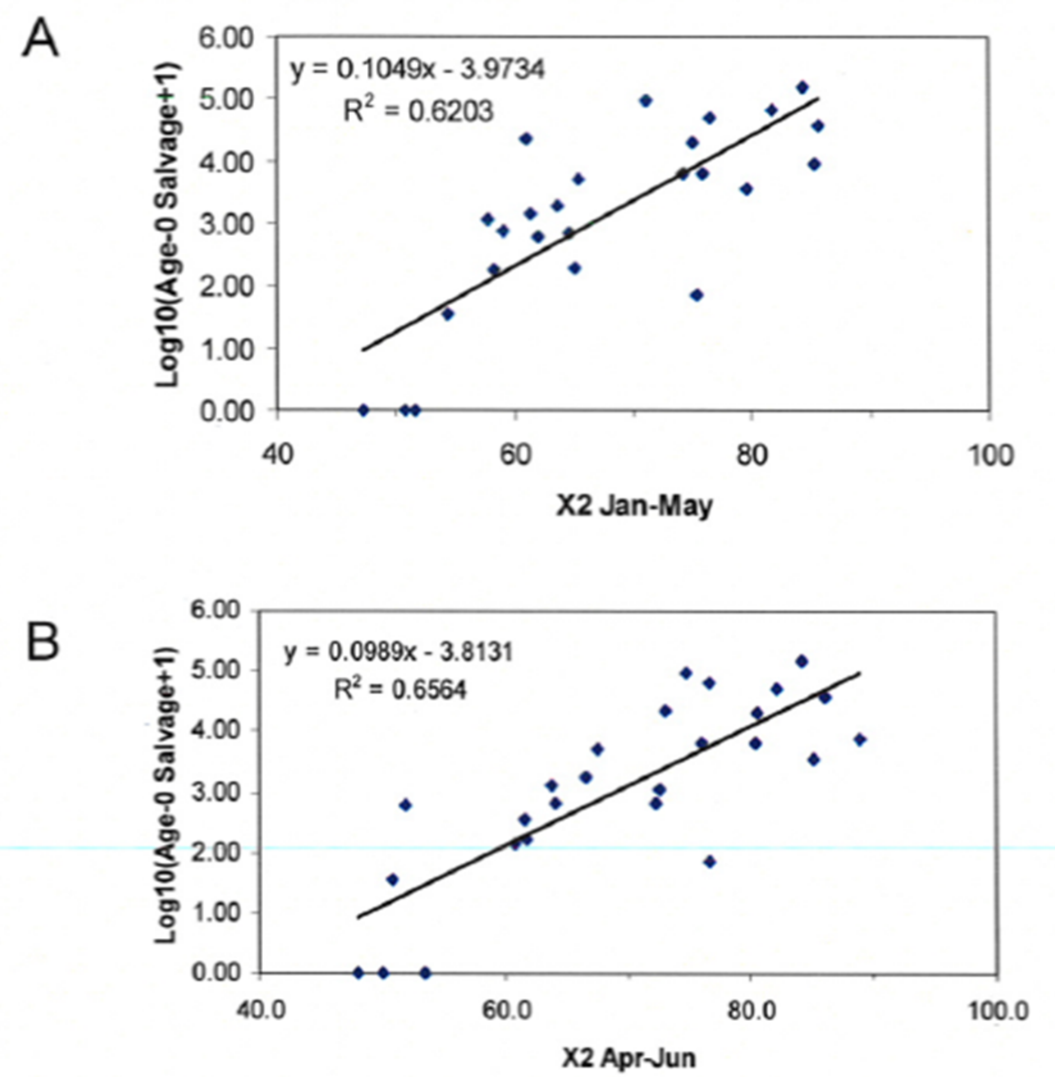

Figure 3.5-6. (A) Relationship between the Average Location of X2 between January and May and the Sum of Juvenile (age-0) Longfin Smelt Salvage between March and July at the SWP and CVP. (B) Relationship between the average location of X2 in April and June and the sum of juvenile (age-0) longfin smelt salvage for April to June at the SWP and CVP. Salvage was incremented by one and log 10 transformed [from Baxter et al. 2009].

In summary, the salvage export pattern is consistent with what is known about the spawning migration habits of longfin smelt (Dege and Brown 2004; Rosenfield and Baxter 2007; Baxter et al. 2009). Adults are known to travel farther into the Delta in low flow years to reproduce and this increases the vulnerability of their offspring to entrainment from OMR reverse flow (Figure 3.5-6). For adult longfin smelt, an OMR reverse flow inflection point occurs around -5,000cfs (Figure 3.5-6). Increased salvage happens at OMR reverse flows more negative than -5,000 cfs (Figure 3.5-4). Juvenile salvage also has an exponential relationship to negative OMR flows (Figure 3.5-5). The lowest salvage rate was measured at an OMR reverse flow of -1,250 cfs which was considered a "safe" value (Figure 3.5-5). Ranges of OMR reverse flows to benefit adult and juvenile Longfin smelt by reducing entrainment at the CVP and SWP are summarized in Table 3.5-1.

Table 3.5-1. Delta Outflow and OMR Reverse Flows Indicated to Be Protective of Longfin Smelt. Delta outflows (cfs) are the monthly averages of net daily outflow as calculated by Dayflow.

	Months											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Delta Outflow	41,900			29,200								
OMR	-1,250 to -5,000											

3.6 Green Sturgeon (*Acipenser medirostris)* and White Sturgeon (*Acipenser transmontanus*)

3.6.1 Overview

Green and White sturgeon are anadromous, long-lived, iteroparous, native species. Green sturgeon is listed as threatened under the federal ESA. Recruitment of both species has been episodic in the San Francisco Estuary. Years with high precipitation and large Delta outflows in winter and spring are associated with higher recruitment. Long life and high fecundity make it possible for sturgeon to maintain a stable population with infrequent high outflow years. The Green sturgeon population size has always been much smaller than White sturgeon and this has made Green sturgeon difficult to study. Functional flow requirements for White sturgeon are assumed to be similar to those of Green sturgeon. Average Delta outflow of 37,000 cfs or larger between March and July appears to be needed to consistently produce strong White sturgeon recruitment. It is assumed that Green sturgeon recruitment has a similar relationship to flow.

3.6.2 Life History

3.6.2.1 Green Sturgeon

Green sturgeon is an anadromous, long-lived, iteroparous, native species. Females become sexually mature at about 17 years of age and males at about 15 years (Van Eenennaam et al. 2006; Cech et al. 2000). Adults migrate upstream to spawn every 3 to 5 years (NMFS 2005; NMFS 2010) selecting river reaches with small to large sized gravel and turbulent high velocity currents for reproduction (Poytress et al. 2015; CDFW 2002, Hueblein et al. 2009). Adhesive eggs are broadcast spawned, externally fertilized and sink to the bottom into pores in the gravel where they develop (Emmett et al. 1991). Females produce between 60,000 and 240,000 eggs per year (Adams et al. 2002; Van Eenennaam et al. 2001; 2006; Moyle 2002) and may live for up to 70 years, returning repeatedly to their natal river to spawn (Van Eenennamm et al., 2006; Moyle 2002). Studies demonstrate that successful recruitment is episodic. Years with high precipitation and large Delta outflow are associated with higher recruitment (Klimley, et al. 2015; Fish 2010).

Spawning is believed to have historically occurred on the Sacramento River above Shasta Dam and possibly on the upper Feather River (USFWS 1996; Lindley et al. 2004). Construction of Shasta and Oroville Dams blocked upstream spawning access above the dams (USFWS 1996; Beamesderfer et al. 2004, CDFW 2002). Green sturgeon move upstream from San Francisco Bay passing the Knights Landing rotary screw trap on the Sacramento River in April (Heublein et al. 2006). Peak spawning activity occurs in May and June (Emmett et al. 1991, CDFW 2002; Poytress et al. 2015). Spawning habitat on the Sacramento River is between the RBDD and about 15 miles upstream (Poytress et al. 2015) and is the primary remaining spawning habitat for Green sturgeon in the Central Valley (NMFS 2005). Cooler temperatures on the upstream Sacramento River may limit the extent of upstream spawning habitat for Green sturgeon as laboratory studies indicate a reduction in hatching rates and smaller embryos at temperatures as cool as 11°C (Van Eenennaam et al. 2005). Average river temperature between April and June are less than or equal to 11°C above the confluence of Clear Creek[14] in most years (Poytress et al. 2015).

Young sturgeons remain in the upper Sacramento River between the RBDD and Hamilton City for the first several months before beginning a slow downstream migration (CDFW 2002). Larval Green sturgeons are often found in the rotary screw trap at the RBDD and at the Glen Colusa Canal in June and July (Beamesderfer et al. 2004; CDFG 2002). Juveniles spend their first several years in the Delta before emigrating to salt water (CDFG 2002). Upon entering the ocean, sub-adults remain in coastal waters but may travel great distances. Tagged individuals from San Pablo Bay, California, have been recovered in summer from as far south as Monterey Bay, California, and as far north as Vancouver Island, Canada, before returning the following spring to the California outer coast (Lindley et al. 2008).

The southern DPS of Green sturgeon is restricted to spawning in the Sacramento River Basin (Lindley et al. 2011; Israel et al. 2004). This population segment was listed as threatened in 2009 (71 FR 17757), with critical habitat designated in 2009 (74 FR 52300) and take prohibitions established in 2010 (75 FR 30714).

3.6.2.2 White Sturgeon

White sturgeon are also a long-lived, late maturing, iteroparous species (Moyle 2002). Males and females become sexually mature at around 10 and 12–16 years of age, respectively (Moyle 2002). Spawning occurs every two to four years for females and every one to two years for males (Chapman et al*.* 1996). White sturgeon begin their upstream spawning migration in late fall and early winter triggered by increased outflow (Miller 1972, Kohlhorst et al*.* 1991; Fish 2010; Schaffter 1997). Spawning occurs from mid-February through June with peak spawning activity in March and May (Kohlhorst 1976; Schaffter 1997). After hatching, undeveloped larvae disperse downstream. In laboratory studies, the downstream dispersal stage may last for up to six days before larvae seek cover for about 10 days to complete absorption of their egg sac (Deng et al. 2002). After the egg sac is adsorbed, larvae resume their downstream migration and begin to feed at night (Kynard et al. 2005). Outflow distributes the larvae to rearing habitats throughout the lower Sacramento River and the Delta (McCabe and Tracey 1994; Kynard et al. 2005). High spring outflow is correlated with increased juvenile recruitment (Fish 2010; Kolhurst et al. 1991).

The Sacramento River between Knights Landing and Colusa is the primary spawning habitat for White sturgeon (Kohlhorst 1976) although, some spawning has been observed in the San Joaquin River (Gruber et al. 2012; Jackson and Van Eenennaam 2013). Historically, spawning may also have occurred in both the upper Feather and Sacramento River basins but these areas are now inaccessible because of the construction of Shasta and Oroville Dams (Kohlhorst 1976).

[14] About 15 miles upstream of the upper limit of present spawning habitat

The diet of sturgeon larvae is varied. The larvae are bottom feeders that forage on whatever benthic prey are available (Moyle 2002). Laboratory studies suggest that larvae consume periphyton, insect larvae, and zooplankton (Buddington and Christofferson 1985). Juveniles eat amphipods, mysids, and larval and juvenile midges (Schreiber 1962; Radtke 1966) but also consume opossum shrimp and other small invertebrates such as crabs, clams, and shrimp (Moyle 2002). As sturgeon mature, they become more piscivorous, consuming herring and their eggs, anchovies, American shad, starry flounder and gobies (Radtke 1966; McKechnie and Fenner 1971). The invasive overbite clam, *Corbula*, has recently become a major component of the diet of white sturgeon (Kogut 2008).

3.6.3 Population Abundance Trends Over-Time

3.6.3.1 Green Sturgeon

Abundance information for Green sturgeon comes from tagging and genetic studies, CDFW (2002) has estimated from tagging studies that the size of the adult Green sturgeon population in the Bay-Delta Estuary has ranged from a low of 175 to more than 8,400 adults between 1951 and 2001 with a median size of about 1,500 adults. The change in population size between 1951 and 2001 was not statistically significant (CDFW 2002). Genetic analysis has indicated that the size of mating populations above the RBDD has ranged from 32 to 124 mating pairs between 2002 and 2006 (Israel 2006 as cited in NMFS 2009) with an average of 71 pairs per year. These genetic studies suggest that the size of the reproductively active population was between 200 and 1,250 individuals, assuming that adults return every 3 to 5 years to spawn (NMFS 2009). The USFWS (1996) Native Fish Recovery Plan includes a restoration goal of at least 1,000 fish in the Sacramento River and Delta during spawning season.

A decline in Green sturgeon population abundance has been inferred from reductions in the average number of juveniles salvaged annually at the SWP and CVP pumping facilities. The mean number of sturgeon taken per year at the SWP was 732 individuals between 1968 and 1986 and declined to 47 between 1987 and 2001. Similarly, the mean number of sturgeon salvaged at the CVP was 889 individuals per year between 1980 and 1986 and declined to 32 individuals between 1987 and 2001 (Adams et al. 2002). Similar declines are evident when salvage is normalized by the amount of water exported (70 FR 17386). Salvage estimates have continued to be low since 2001 (NMFS 2009).

3.6.4 Flow Effects on Green and White Sturgeon

3.6.4.1 Delta Outflow

Because the size of the Green sturgeon population is so small much less information exists on the flow needs of Green sturgeon but the assumption is that this species needs flows of a similar magnitude as white sturgeon (USFWS 1996). Accordingly, the remainder of this discussion focuses on white sturgeon.

White sturgeon is sampled in the Bay Study. Trends in abundance show large annual variations in recruitment. A few years of good recruitment are followed by multiple years with negligible production (Figure 3.6-1). Strong recruitment events typically occur in wet years, although not all wet years produce good recruitment (example 1984 to 1986 and 1999). Little to no recruitment occurs in dry and critically dry water years. Long life and high fecundity make it possible for sturgeon to maintain a stable population with infrequent high outflow years.

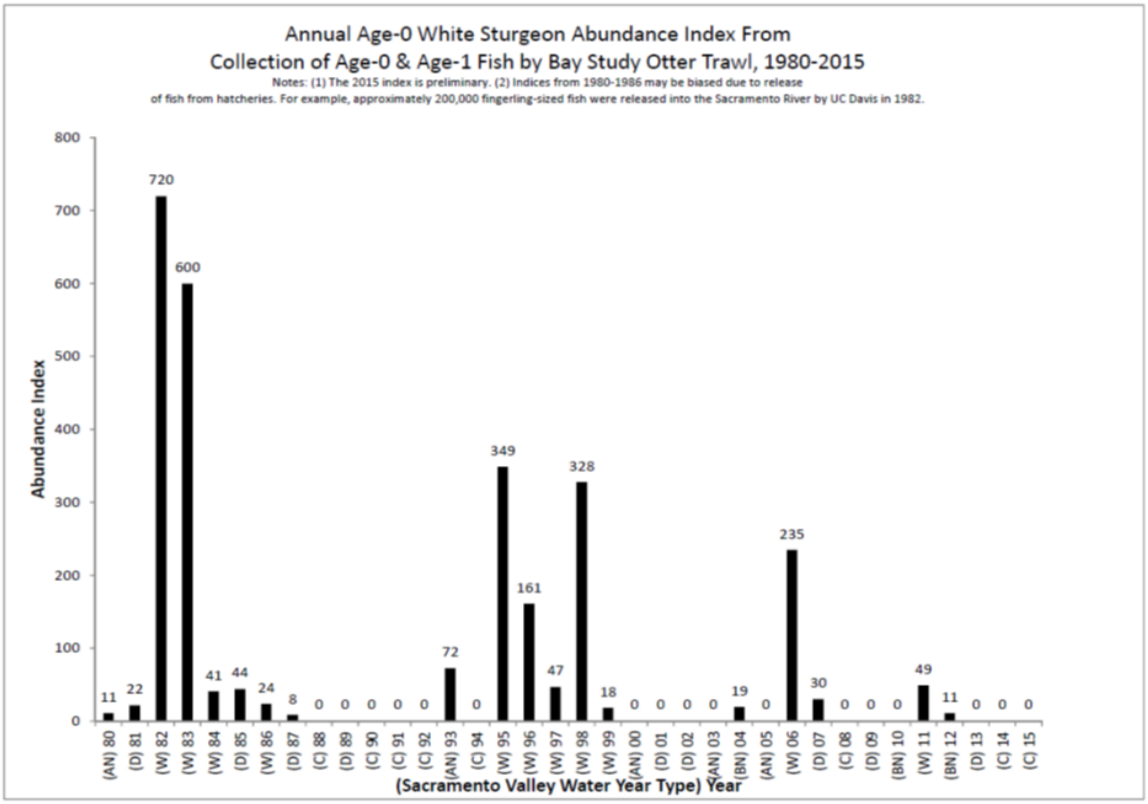

Figure 3.6-1. White Sturgeon Year Class Indices for San Francisco Bay from 1980 through 2015

The CDFW (1992) constructed an index of White sturgeon year class strength using Bay Study survey data for 1975 to 1990. The strongest relationship was with outflow between April and July. The largest year classes occurred at Delta outflows greater than 60,000 cfs. The CDFW (1992) study also evaluated SWP salvage data from 1968 to 1987. The strongest correlations were with outflow between April and May. No recruitment occurred at average Delta outflows less than 20,000 cfs.

Gingras and others (2014) reanalyzed the impact of recreational fishing and water operations on White sturgeon population recruitment and confirmed a positive relationship between Delta outflow in winter and spring with recruitment. Average Delta outflows of less than 30,000 cfs had a small probability of producing strong year classes and outflows of 37,000 cfs or larger between March and July had a 50 percent probability of producing a good year class. The analysis also provided evidence for a stock-recruitment effect. As the number of spawning adults increased, the importance of net Delta outflow declined. The presence of a stock recruitment effect suggests that Delta outflow greater than 37,000 cfs may not be necessary if the size of the adult breeding population can be increased. Gingras and others (2014) also implicated recreational fishing as a factor affecting recruitment.

Fish (2010) analyzed White sturgeon year class data from Bay Study catch data for 1980 through 2006. The study found statistically significant positive correlations between catch and mean daily Delta outflow for November–February and for March–July (Figures 3.6-2 and 3.6-3). Fish (2010) concluded that White sturgeon year class strength was a function of both attraction flows between

November–February that stimulated adult upstream migration and March–July flows that triggered spawning and downstream transport of juvenile fish. Both flow abundance relationships exhibited threshold values around 32,000 cfs (log (4.5)). Above the threshold, recruitment was always positive (Figures 3.6-2 and 3.6-3), consistent with conclusions from Gingras et al. (2014). Fish (2010) observed that the March–July relationship appeared to be the more critical of the two flow events as all years with high spring outflow produced large sturgeon year classes regardless of the magnitude of the attraction flows that preceded them in November–February (Table 3.6-1).

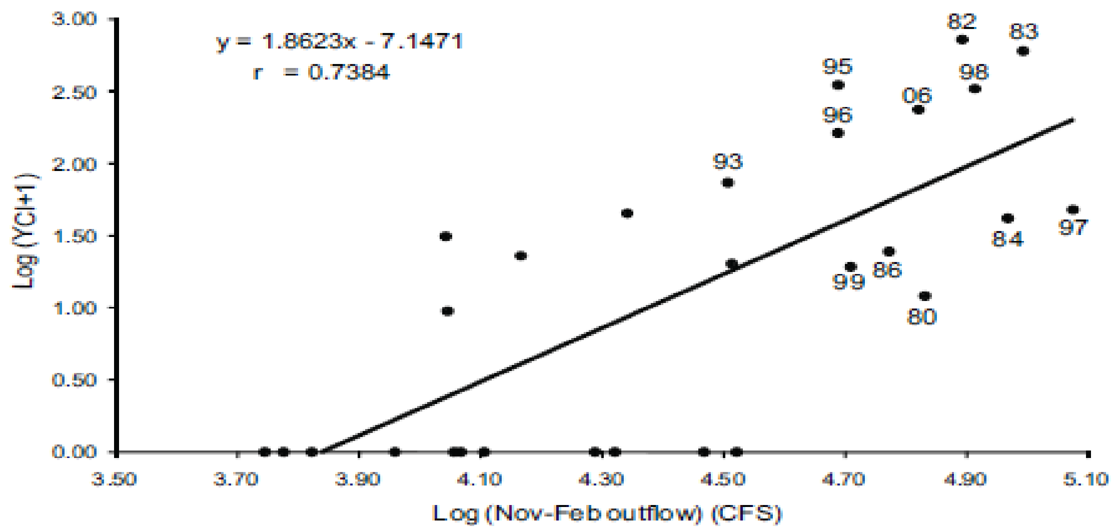

Figure 3.6-2. White Sturgeon Year Class Index (YCI) from San Francisco Bay Study Otter Trawl Catch versus Mean Daily Delta Outflow from November through February (numbers adjacent to points designate year classes [from Fish 2010])

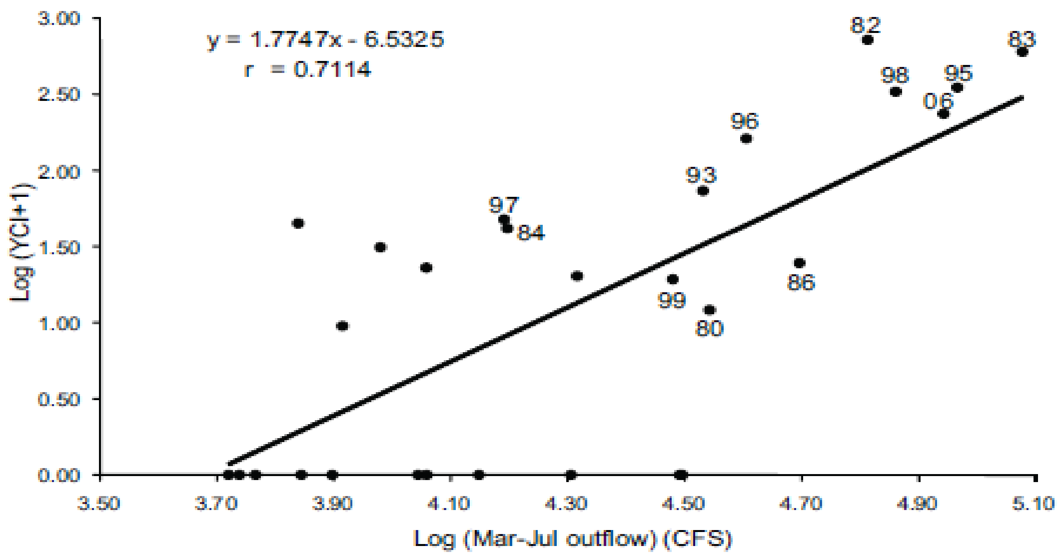

Figure 3.6-3. White Sturgeon YCI from San Francisco Bay Study Otter Trawl Catches versus Mean Daily Delta Outflow for March through July (Numbers adjacent to points designate select year classes. Log (4.7) is equivalent to a flow rate of 50,000 cfs [from Fish 2010]).

Table 3.6-1. Delta Outflow (cfs) Indicated to Be Protective of White and Green Sturgeon. Outflows are monthly averages.

	Months											
	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
Delta Outflow			>37,000									

3.6.4.2 Interior Delta Flow

Green and White sturgeon have been salvaged at the CVP and SWP pumping facilities during all months of the year (NMFS 2009). The presence of both species in salvage at CVP and SWP pumping facilities indicates that the species are vulnerable to entrainment from exports. However, no statistical evidence exist that exports affect White sturgeon population abundance (CDFW 1992; 2002) and there are currently no other OMR restrictions for Green sturgeon included in biological opinions or ITPs.

3.7 Sacramento Splittail (*Pogonichthys macrolepidotus*)

3.7.1 Overview

Sacramento splittail is a native species that has decreased in abundance and is now about 3 percent of its population size when sampling began in 1967. Splittail spawn on flooded vegetation in spring. Large recruitment has only been observed in years when the Yolo Bypass has flooded for more than 30 days. The size of the juvenile splittail population in fall is positively correlated with Delta outflow during the previous spring. Studies indicate that Delta outflows of 38,000 to 47,000 cfs are needed between February and May to improve splittail populations. These are among the largest flows needed by any Bay-Delta estuarine fish species. The magnitude of these flows might be reduced if the Fremont Weir had an operable gate and the Yolo Bypass was able to be flooded at a lower Sacramento River flow.

3.7.2 Life History

Sacramento splittail is a native cyprinid minnow. Their distribution is mostly in the Central Valley and Bay-Delta Estuary although some fish have been collected in the Napa and Petaluma Rivers (Caywood 1974; Moyle 2002). Splittail were historically fished by both commercial and Native Americans and are now part of a small recreational fishery (Moyle 2002; Moyle et al. 2004).

Adult splittail live seven to nine years and become sexually mature in their second year (Moyle 2002; Daniels and Moyle 1983). Adults are mostly observed in Suisun Bay and Marsh and in the western Delta during summer and fall. Mature splittail typically migrate upstream for spawning between November and March (Caywood 1974; Moyle et al. 2004). Seasonally inundated floodplains are preferentially used by adults for spawning and foraging, although vegetated channel margins and perennial marshes may also be used when floodplain habitat is unavailable (Caywood 1974; Daniels and Moyle 1983; Feyrer et al. 2005; Moyle et al. 2004). Eggs are adhesive and are laid on submerged vegetation and hatch in three to seven days depending upon temperature (Wang 1986;

Moyle 2002; Moyle et al. 2004). Some juveniles remain upstream during their first year but most migrate downstream in spring and summer either passively carried by high flows or actively swimming because of warming water temperature (Baxter 1999; Baxter et al. 1996; Sommer et al. 2002; Moyle et al. 2004). After spawning, adult splittail generally migrate downstream (Moyle et al. 2004).

Large splittail recruitment events only occur when sufficient flow exists to flood the Yolo and Sutter Bypasses for extended periods of time (Meng and Moyle 1995; Feyrer et al. 2006a; Sommer et al. 1997). Two factors appear important for successful floodplain recruitment (Feyrer et al. 2006a). First, it is necessary to have inundating flows in January and February to stimulate and attract reproductively active adults to floodplains. Second, the floodplain must remain underwater long enough to allow eggs to hatch and larvae to mature into competent swimmers (Moyle et al. 2004). Very large splittail recruitment has only been observed in years with 30 or more days of floodplain inundation (Meng and Moyle 1995; Feyrer et al. 2006a). The largest recruitment occurred when the Bypass was flooded for more than 50 days (Meng and Moyle 1995). Floodplain inundation during the months of March, April and May appears to be most beneficial for the recruitment of a large year class (Wang 1986; Moyle 2002).

3.7.3 Population Abundance Trends Over Time

Sacramento splittail abundance has declined since the first FMWT survey and is now 3 percent of its initial 1967 value[15] (Figure 3.7-1; $P<0.01$). Abundance has also decreased by 91 percent since implementation of D-1641 in 2000, and is almost statistically significant ($P<0.1$).

The 2010 Flow Criteria Report (SWRCB 2010) recommended an immediate goal to stabilize the Sacramento splittail population, as measured by the FMWT index, and to begin to grow the population with a long-term goal to maintain the population abundance index as measured by FMWT in half of all years above the long term population index value The median FMWT index value between 1967 and 2014 is 10 and is the recovery goal evaluated for this Report. The average FMWT index for the last three years is 1 and has not been above 10 for the past thirteen years (Figure 3.7-1).

Sacramento splittail was listed as threatened under the federal ESA in 1999 but removed from the list in 2003 (64 FR 5963; 68 FR 55139). In 2010 the USFWS reevaluated the status of the species and concluded that listing was not warranted (75 FR 62070).

3.7.4 Flow Effects on Sacramento Splittail

3.7.4.1 Delta Outflow

The FMWT survey index of Sacramento splittail is positively correlated with both Delta outflow between February and May and with days of Yolo Bypass floodplain inundation (Meng and Moyle 1995; Sommer et al. 1997; Kimmerer 2002a; CDFW, 1992). No change in the flow abundance relationship was observed after the invasion of *Corbula* (Kimmerer 2002a).

[15] The decline was estimated from the average of the first three (1967-1970) and the last three (2012-2014) years of the FMWT index to account for inter-annual variability.

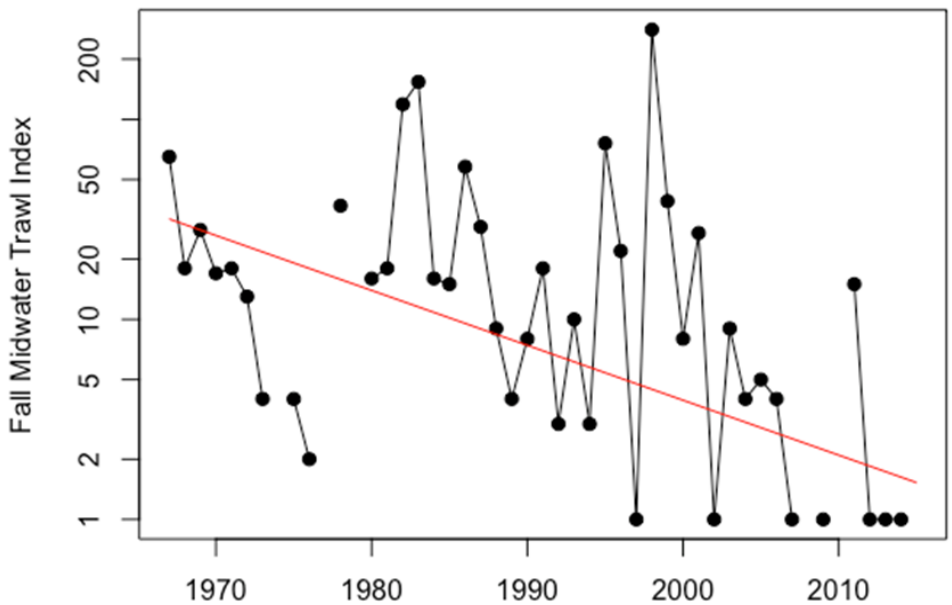

Figure 3.7-1. Sacramento Splittail Population Abundance as Measured in the FMWT Survey (1967–2014).

State Water Board staff reassessed the flow abundance relationship with new data collected through 2014 (Figure 3.7-2). The current relationship is still significant ($P<0.001$). More spring outflow is associated with a higher FMWT index later in the year. This is a long standing flow abundance relationship and has existed since sampling began in 1967 (Kimmerer 2002). Increased outflow between February and May coincides with the timing of adult spawning and larval rearing in the Delta (Moyle et al. 2004; Meng and Matern 2001). Increased flow increases both the amount of flooded habitat along vegetated channel margins and the acreage of inundated floodplain in the Central Valley (Moyle et al. 2004).

Two methods were used to determine the flow required to meet the population abundance goal identified above. First, a regression analysis was conducted with Delta outflow and splittail abundance during the February through May time frame to determine that 38,000 cfs was correlated with the abundance goal (Figure 3.7-2). Second, the USFWS (1996) recommended that Sacramento Splittail be considered fully recovered if population abundance returned to values measured between 1967 and 1983. The median flow during this 16-year period was 47,000 cfs (Figure 3.7-3). These analyses suggest that an average daily Delta outflow of 38,000 to 47,000 cfs is needed between February and May to meet the abundance goal (Table 3.7-1) absent other measures.

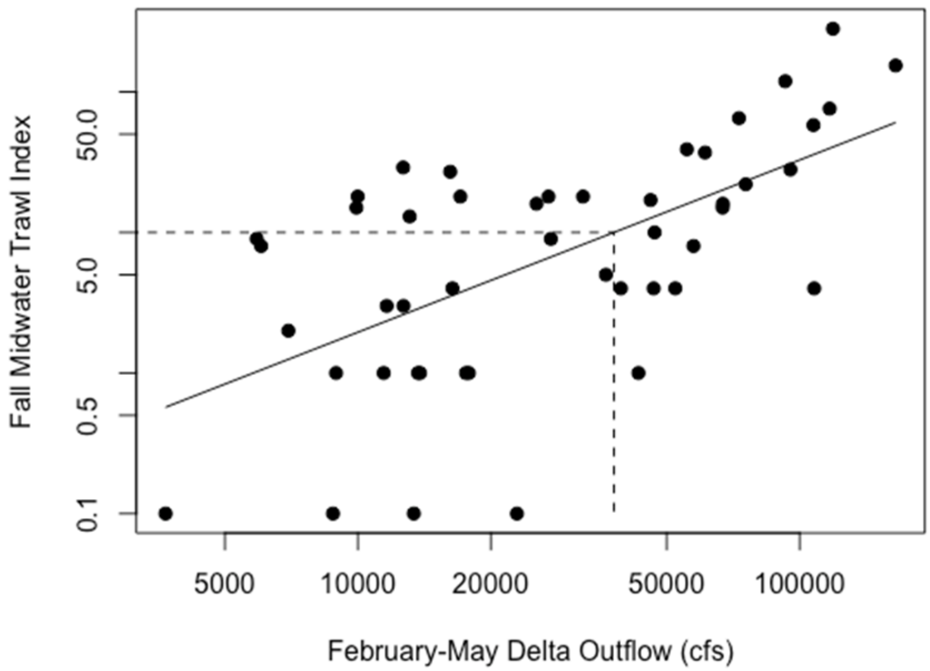

Figure 3.7-2. Correlation between the Sacramento Splittail FMWT Index (1967–2014) and Average Daily Outflow (cfs) between February and May. The flow abundance relationship is statistically significant [P<0.001, R2=0.37]. The dotted line indicates that a flow rate of 38,000 cfs is correlated with the recommended abundance index of 10.

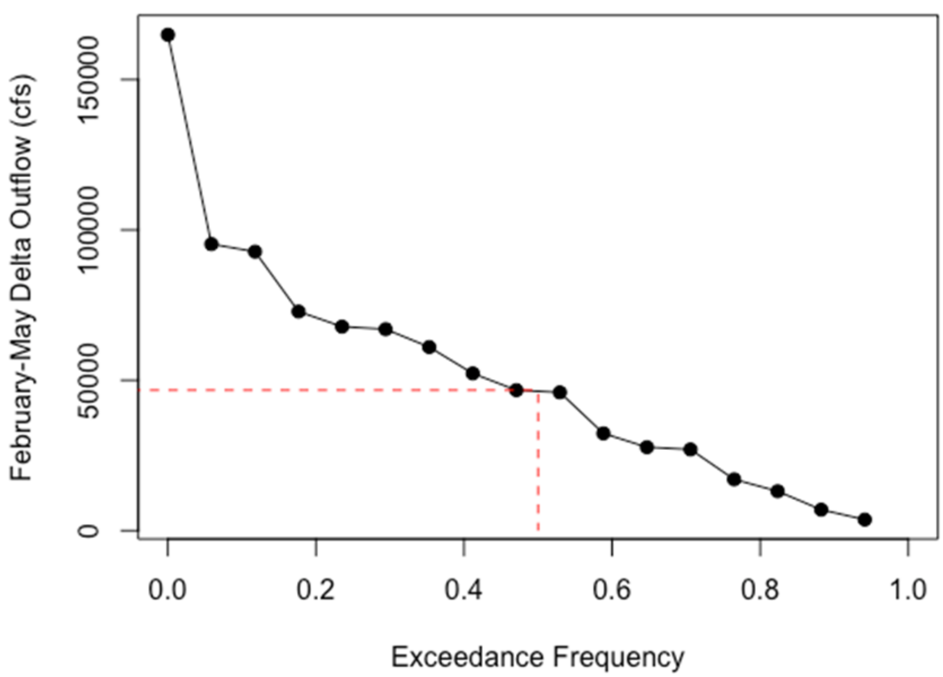

Figure 3.7-3. Cumulative Frequency Distribution of Average Daily Outflow between February and May for 1967 to 1983. The dotted line is the daily average outflow (47,000 cfs) that occurred in half of all years.

Table 3.7-1. Delta Outflow Indicated to Be Protective of Sacramento Splittail. Outflows are monthly averages [cfs]

	Months											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Delta Outflow		38,000–47,000										

3.7.4.2 Interior Delta Flow

Sacramento splittail have been salvaged at the CVP and SWP pumping facilities in many years. The risk of splittail entrainment appears greatest during adult upstream spawning migrations and juvenile emigration from the Delta in spring and early summer (Sommer *et al*. 1997; Moyle et al 2004). In 1998 over three million juvenile splittail were taken at the export facilities in early summer, representing a quarter of all the fish salvaged that year (Arnold 1999; Moyle et al. 2004).

Sommer et al. (1997) evaluated salvage and population abundance indices to determine the effect of the CVP and SWP operations on the Sacramento splittail population size. They found that salvage was highest in wet years when population levels were greatest and losses were typically low in dry years. Sommer et al. (1997) concluded that, while entrainment at CVP and SWP export facilities was large in some years, it did not have a measurable effect on inter-annual splittail population size.

3.8 Delta Smelt (*Hypomesus transpacificus*)

3.8.1 Overview

Delta smelt were once a common native species in the Bay-Delta Estuary. Most individuals live one year with adults moving into the Delta to spawn and die and their offspring migrating back to rear in Suisun Bay. Indices of Delta smelt population abundance have declined and the size of the population is now about 2 percent of what it was 50 years ago. The species is listed as threatened by the USFWS and as endangered by the CDFW. The population abundance of larval Delta smelt in spring is positively correlated with the magnitude of Delta outflow during the previous winter-spring and fall periods. Delta smelt are entrained and lost at the CVP and SWP pumping facilities when adults migrate into the Delta in winter and early spring to spawn and again when the larvae are tidally transported back to Suisun Bay in early summer.

3.8.2 Life History

Delta smelt are endemic to the Delta and upper estuary. The species has an annual, one-year life cycle although some females may live to reproduce in their second year (Bennett 2005). Delta smelt were once a common pelagic fish species in the upper Bay-Delta Estuary (USFWS 1996).

Adult Delta smelt undergo a slow upstream spawning migration from the low salinity zone (LSZ) to freshwater (Grimaldo et al. 2009), though there is also evidence of freshwater resident smelt in the Sacramento River Deepwater Ship Channel (Hobbs et al. 2007; IEP 2015). Spawning migrations occur between late December and February, typically during "first flush" periods when inflow and turbidity increase on the Sacramento and San Joaquin Rivers because of snowmelt and upstream precipitation (Grimaldo et al. 2009; Sommer et al. 2011). Catches of adult Delta smelt in the USFWS

Chipps Island Survey and in salvage at the CVP and SWP pumping facilities during first flush events are characterized by sharp unimodal peaks, suggesting that rapid changes in environmental conditions trigger population-level migrations (Grimaldo et al. 2009; Sommer et al. 2011). Pre-spawning adults move furthest upstream during low outflow years. If the run migrates into the lower San Joaquin River and the Central Delta, then the risk of entrainment at the CVP and SWP pumping facilities is high, and less if the migration is into the lower Sacramento River and the Cache Slough complex (Kimmerer and Nobriga 2008).

Adult Delta smelt spawn during the late winter and early spring, with most reproduction occurring in April through mid-May (Moyle 2002). Spawning habitat in the Delta includes the lower Sacramento, San Joaquin, and Mokelumne Rivers and the western and southern Delta (Wang 2007: Hobbs et al*.* 2006). Eggs are negatively buoyant and adhesive with larvae hatching in about 13 days (Wang 1986; 2007). The initial distribution of Delta smelt larvae is similar to that of their parents because larvae emerge near where the parents laid eggs. Upon hatching the larvae are semi-buoyant, staying near the bottom. Within a few weeks, larvae develop swim bladders and become pelagic utilizing vertical tidal migrations to maintain their preferred location in the Delta (Bennett et al. 2002). Dege and Brown (2004) found that larvae smaller than 20 mm reared 3–12 miles upstream of X2. As larvae grow and water temperature increases in the Delta, larval distributions shift downstream towards the low salinity zone (Dege and Brown 2004; Nobriga et al. 2008).

Delta outflow during late spring and early summer affects the distribution of larval and juvenile smelt by actively transporting them seaward toward the LSZ (Dege and Brown 2004). Low outflow increases Delta smelt residence time in the Delta, probably leading to increased exposure to higher water temperatures and increased risk of entrainment at the CVP and SWP pumping facilities (Moyle 2002). Once larvae develop into juveniles, they become capable of exploiting tidal flows to move to new preferred habitat (Bennett 2002). Monitoring in June–August showed that suitable habitat shifted west in the Delta toward the confluence of the Sacramento and San Joaquin Rivers and Suisun Bay (Nobriga et al*.* 2008). Preferred juvenile habitat in summer was defined by a combination of turbidity, low salinity and a more optimal water temperature. By fall the distribution of juvenile and sub-adult Delta smelt is tightly coupled with X2 (Sommer et al. 2011; Sommer and Mejia 2013). As X2 moves either up or down the estuary in fall so does the distribution of Delta smelt (Jassby et al. 1995).

Larval and juvenile Delta smelt primarily consume calanoid copepods, particularly *Eurytemora affinis* and *Pseudodiaptomus forbesi*, (Nobriga 2002; Slater and Baxter 2014). *E. affinis* is abundant only during winter and spring whereas *P. forbesi* is common in summer and fall (Durand 2010; Winder and Jassby 2011). The transition between the high abundance of the two copepods has been hypothesized to create a “food gap” during spring and early summer. Kimmerer (2008) and IEP (2015) found that Delta smelt abundance and survival from summer to fall was positively correlated with calanoid copepod biomass in the low salinity zone. The diets of sub-adult Delta smelt are broader and include a higher frequency of amphipods and mysids along with *P. forbesi* (IEP 2015).

3.8.3 Population Abundance Trends Over-Time

The abundance of larval, juvenile and sub adult Delta smelt Delta smelt is measured in the 20-mm Survey (March–July), the Summer Townet Survey (STN) (June-August) and the FMWT Survey (September–December) , respectively (Kimmerer et al. 2009). All three surveys indicate that the Delta smelt population has declined significantly and is at a record low level (Messineo et al*.* 2010).

State Water Board staff reexamined the inter-annual trend in the FMWT index with data collected through 2015 to determine whether the index has continued to decline (Figure 3.8-1). The updated analysis demonstrates that the FMWT smelt index continues to decrease and as of 2015 was about 2 percent of the 1967 value[16] (P<0.001) and 2 percent of the 2000 value (P<0.01) when D-1641 was implemented. The two lowest values ever recorded were in the recent drought years of 2014 and 2015.

In the wet year of 2011 when high outflows occurred throughout the year (including winter, early spring and fall) the Delta Smelt FMWT index rebounded (Figure 3.8-1) demonstrating that despite significant declines, recently Delta smelt appeared to still have the ability to respond favorably to improved environmental conditions.

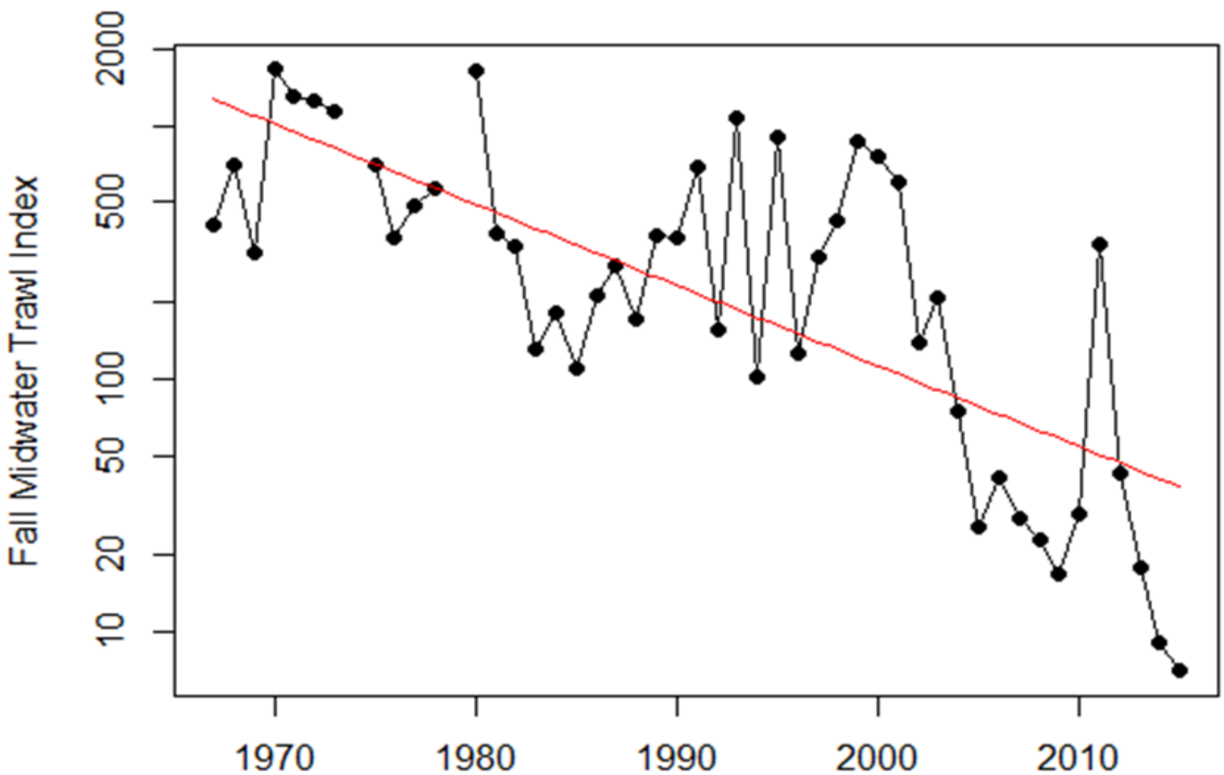

Figure 3.8-1. Inter-annual Trend in the FMWT INDEX for Delta Smelt (1967-2015). The decrease in the logarithm of the index is statistically significant [P<0.001, R2=0.53]

Delta smelt was listed as threatened under the federal ESA in 1993 (58 FR 12863). In 2010, USFWS determined that Delta smelt should be listed as endangered but has not yet reclassified the species because of higher priority listing actions (75 FR 17667).

Delta smelt was listed as threatened under CESA in 1993 (CDFW 2016) and as endangered in 2009 (CDFW 2016). Critical habitat was designated in 1994 (59 FR 65256). The critical habitat includes Suisun, Grizzly, and Honker Bays, Mallard and Montezuma sloughs and contiguous waters of the legal Delta (59 FR 65256).

16 The decrease was estimated from the average of the first three (1967–1970) and the last three (2013–2015) annual FMWT index values to account for inter annual variation in population abundance.

3.8.4 Flow Effects on Delta Smelt

Much research has been devoted to investigating the factors responsible for the decline in Delta smelt abundance (Bennett 2005; Kimmerer 2008; Thomson et al 2010; Maunder and Deriso 2011; Miller et al 2012;). Several factors have been implicated in the decline including exports (Kimmerer 2008, 2011; Maunder and Deriso 2011; Rose et al 2013), food (Maunder and Deriso, 2011; Hammock et al. 2015) and predators (Maunder and Deriso 2011). Emerging evidence also suggests that spring outflow may be more critical for the production of larvae and the maintenance of the adult population than was previously realized (IEP 2015). In the fall, outflow may also be important for providing critical habitat for Delta smelt (Feyrer et al. 2007; IEP 2015).

3.8.4.1 Winter and Spring Delta Outflow

Historically, a weak negative relationship existed between Delta smelt abundance, as measured in the STN survey June–August), and Delta outflow the previous February to June (Jassby *et al*. 1995; Kimmerer *et al*. 2009). The historical relationship suggested that high winter spring outflow was moderately detrimental to the size of the Delta smelt population and that smelt population abundance benefitted from a lower outflow and a more upstream LSZ in late winter and spring. The negative flow abundance relationship disappeared after 2001 (IEP 2015).

Multivariate statistical modelling was used to explore relationships between spring and fall Delta outflow and juvenile abundance as measured by the 20 mm index[17] similar to the approach used by Jassby et al. (1995) to describe the initial relationship between Delta outflow and the abundance of estuarine dependent species (IEP 2015). The analyses identified a unimodal relationship between X2 or outflow (February to June) and the 20 mm index of larval Delta smelt after 2003. The Delta outflow abundance relationship became statistically stronger when the 20 mm index was standardized by either the number of sub adult smelt in the previous year's FMWT index[18] or by the number of spawning adults in the SKT survey[19] several months earlier (Figure 3.8-2). The standardization suggests that both the number of available spawners (stock-recruitment effect) and the magnitude of spring outflow are important for determining larval abundance. More spawning adults result in more larvae, if outflow is favorable during the spawning season. The spring outflow and the stock-recruitment relationships together explained 59 to 65 percent of the variation in the 20mm index for the 11 years between 2003 and 2013 ($P<0.006$, IEP 2015). However, the IEP (2015) report recommended that conclusions based upon the relationship between spring outflow and Delta smelt population abundance be considered preliminary until additional data, analyses and review were conducted to confirm the robustness of the results.

The presence of a stock-recruitment relationship suggests that elevated flows may only be required until the abundance of the adult spawning population has been rebuilt. Once the size of the breeding population has recovered, then a lower, but as yet undetermined, flow may be sufficient to maintain a robust population.

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[17] The 20 mm survey is conducted between March and July and measures the abundance of larval smelt greater than 20 mm.

[18] The FMWT index is conducted between September and December and is a measure of the abundance of sub adult smelt

[19] The SKT survey is conducted between January and March and is a measure of the abundance of adults available to spawn.

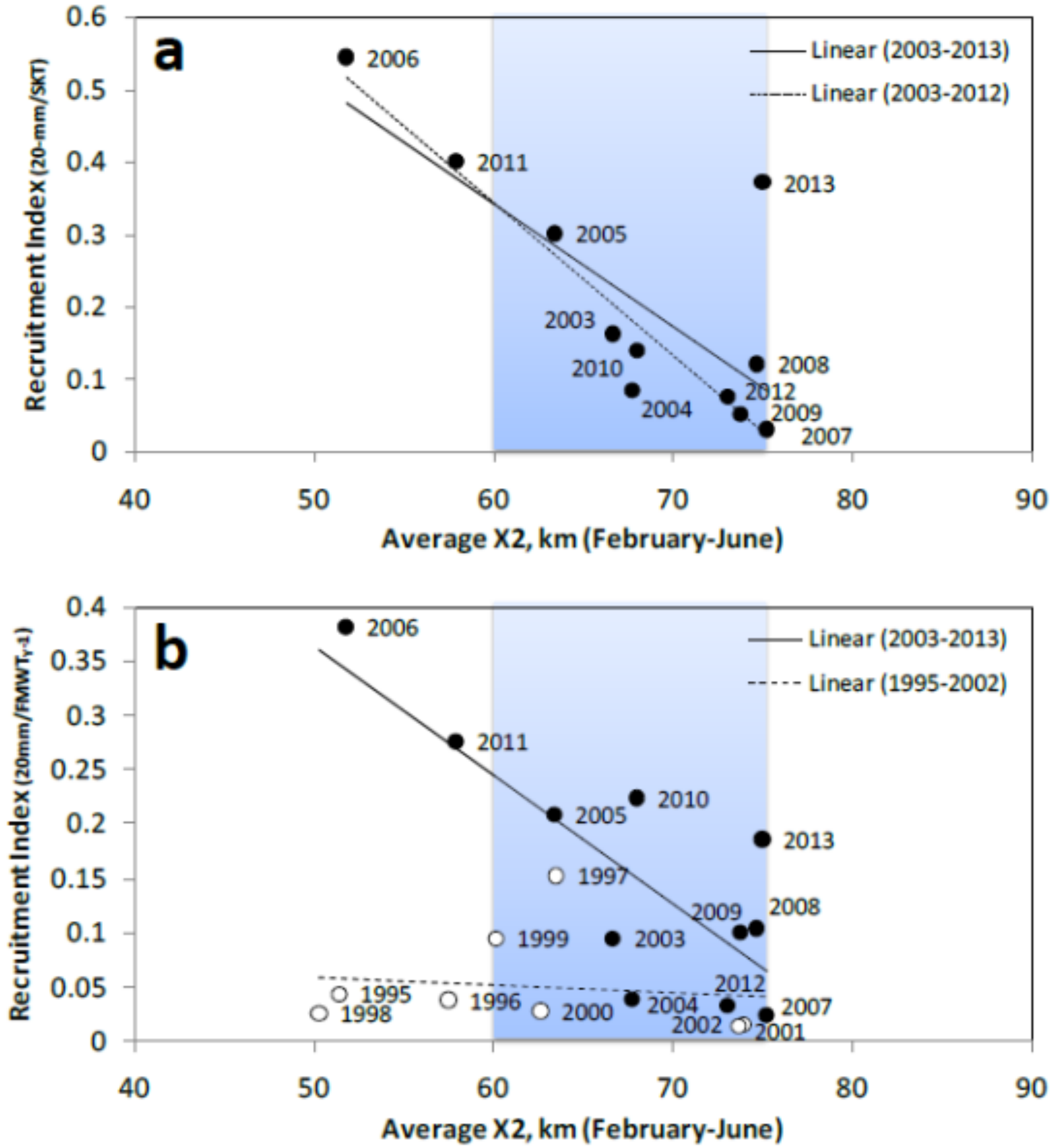

Figure 3.8-2. Adult (panel a, SKT) and Sub-adult (panel b, FMWT from previous year) to Larval (20 mm survey) Recruitment Indices as a Function of Spring X2 (February–June) (For the 20 mm/SKT panel, a linear regression was calculated with and without 2013, which appears to be an outlier. For the 20 mm/FMWT panel, the period before the POD [1995–2002] and the 2002–2013 period are plotted [figure reproduced from the 2015 IEP report]).

3.8.4.2 Summer Outflow

Emerging scientific evidence suggests that Delta smelt abundance in the fall is positively related to Delta outflow in the prior summer. The science indicates that when X2 was greater than 80-km (flows ≤7,500 cfs) between June and August, then the population experienced a year-over-year decrease in the FMWT index (CDFW 2016). In addition, survival of Delta smelt in summer, as measured by FMWT and STN[20], was a positive function of Delta outflow (CDFW 2016). More flow in July, August and September resulted in statistically greater survival from the juvenile to sub adult stages (Figure 3.8-3). Both relationships only appeared after 2002, the start of the pelagic organism decline. The two relationships may result from an increase in the quantity and quality of available food, a decrease in the magnitude and frequency of toxic cyanobacterial blooms, a reduction in ambient water temperature and a reduction in the risk of predation with an increase in summer flow (CDFW 2016). Further evaluation of this relationship is needed.

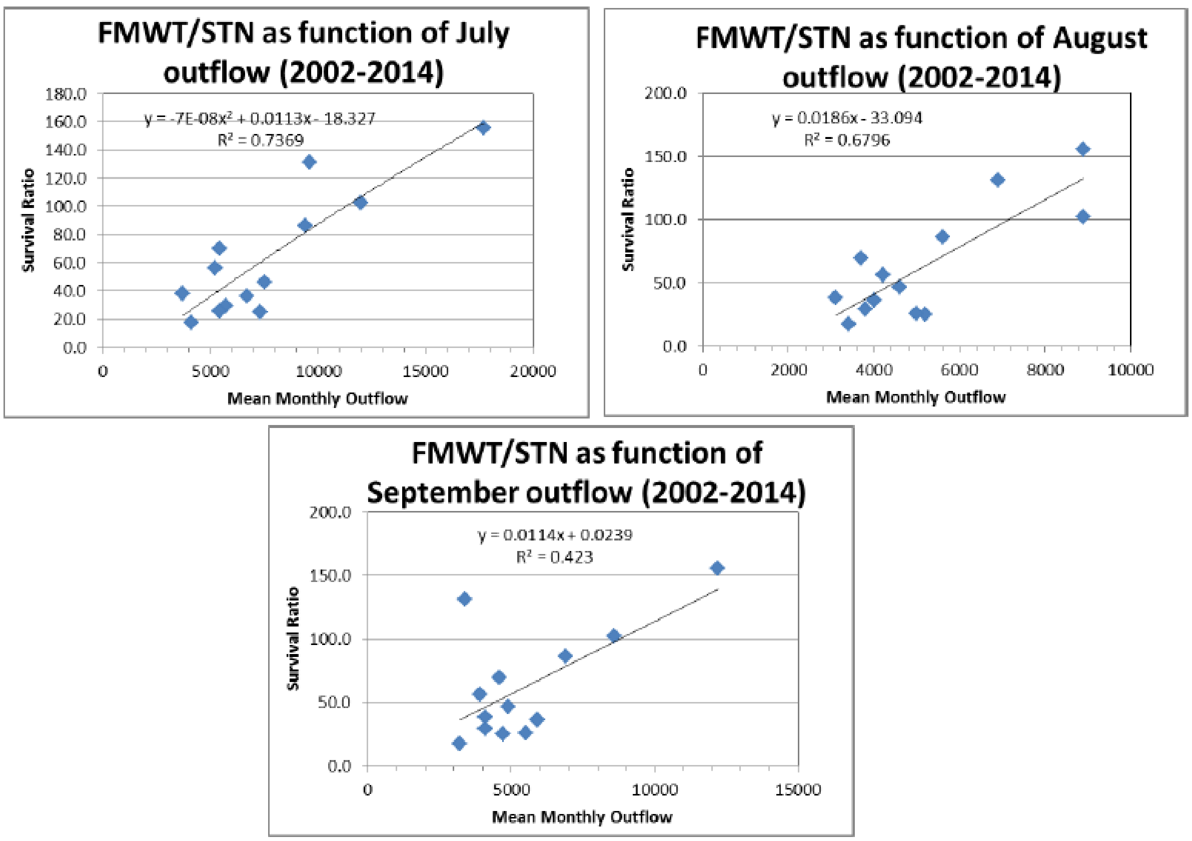

Figure 3.8-3. Delta Smelt Survival in Fallas a Function of Monthly Mean Delta Outflow (cfs), for July (top left), August (top right) and September (bottom). Survival is estimated as the quotient of the FMWT index divided by the STN index. All three relationships are statistically significant. (From CDFW 2016).

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20 The STN and FMWT indices result from sampling between June–August and September–December, respectively.

3.8.4.3 Fall Outflow

Feyrer et al. (2007) and Nobriga et al. (2008) used the abundance and distribution of Delta smelt from the FMWT survey to determine the environmental characteristics of preferred Delta smelt habitat in fall and used this to develop an abiotic habitat index. The index quantifies the acreage of preferred habitat in terms of salinity and water clarity. The analysis found that if X2 was at 74 km or smaller then there was about 12,000 acres of high quality habitat located in Suisun Bay. If X2 was 85 km or larger, then the amount of favorable habitat was about half as large and was located above the confluence of the Sacramento and San Joaquin Rivers. Intermediate X2 values had intermediate amounts of suitable habitat (USFWS 2008). Historically, fall X2 was often located in Suisun Bay in wet and above normal water years. Increased CVP and SWP exports combined with declining inflows since 2000 in fall have reduced outflows and decreased the abiotic habitat index for smelt by moving X2 upstream into the Sacramento and San Joaquin Rivers and away from Suisun Bay (IEP 2015). The decrease in fall outflow and reduction in preferred habitat is hypothesized to be one factor contributing to the decrease in Delta smelt population abundance. Consistent with this hypothesis is the observation that the abundance of juvenile smelt in summer is a function of the location of X2 during the previous fall (USFWS 2008). Based on this science, the USFWS BO requires that Delta outflow in September and October be managed so that X2 is no greater than 74 km[21] and 81 km[22] in wet and above normal water year types, respectively (Table 3-8-1, USFWS 2008). In addition, the USFWS BO requires that all flow into CVP and SWP reservoirs in November during both water year types be released to increase Delta outflow and move X2 further downstream.

[21] This X2 value is roughly equivalent to 11,400 cfs

[22] This X2 value is roughly equivalent to 7,100 cfs.

Table 3.8-1. Delta Outflow and OMR Flows Indicated to Be Protective of Delta Smelt. Outflows are monthly averages [cfs]

	Water Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Fall X2	AN									7,100		[1]	
Fall X2	W									11,400		[1]	
OMR	All	-1,250 to -5,000[2]											
Summer	All							X2≤80 Km[3]					

[1] Release November inflow to Sacramento Basin CVP and SWP reservoirs to increase Delta outflow

[2] 14-day running average in cfs

[3] Outflow ≥ 7,500 cfs

The IEP (2015) report evaluated the effect of the location of fall X2 on larval Delta smelt abundance as measured by the 20 mm index. The analysis found an inverse relationship between the location of X2 during the previous fall and the abundance of larval smelt in the next spring (Figure 3.8-4). The relationship was statistically significant (P<0.001) and explained 48 percent of the variation in the 20 mm index. The relationship improved when the index was divided by the FMWT index value for the previous year. For example, the location of the previous fall's X2 value and the FMWT index together explained 62 percent of the variation in the 20 mm index for the 19-year period between 1995 and 2013. More outfall in fall resulted in a higher 20 mm index for larval Delta smelt the next year. The fall X2 results also support the importance of a stock recruitment relationship, more breeding adults lead to more offspring. An important difference between the Feyrer et al. (2007) and IEP (2015) results are that Feyrer et al. recommended increasing fall outflow between September and October while the IEP analysis was based upon data between September and December.

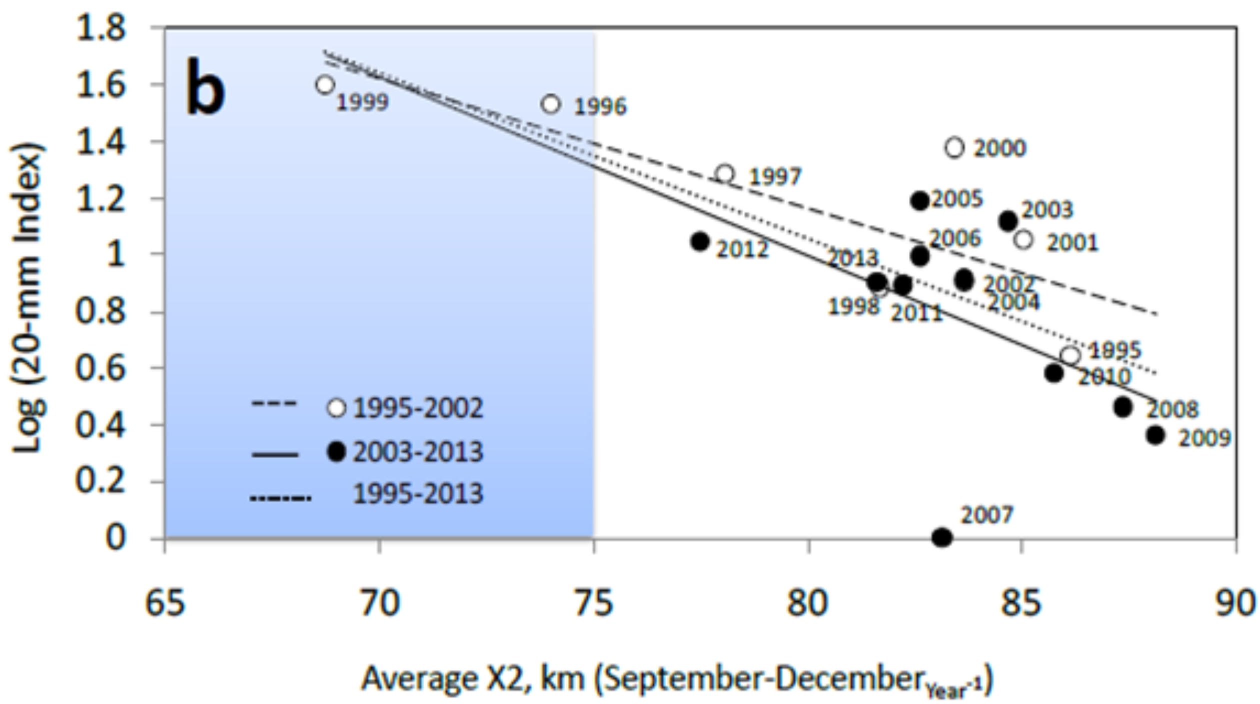

Figure 3.8-4. Plot of the Delta Smelt 20 mm Survey Abundance Index as a Function of the Location of the Previous Year's Fall X2 (Figure from IEP (2015)

3.8.4.4 Interior Delta Flow

Adult Delta smelt are vulnerable to entrainment when they migrate upstream from Suisun Bay and enter the Delta to spawn (IEP 2015; Grimaldo et al 2009). Juvenile fish are at risk when rearing in the Delta or when migrating back down to Suisun Bay. The location of adult spawning determines the distribution of eggs and larvae. In some years, a large fraction of the adult spawning population move into the Sacramento River and the north Delta. In other years, adults migrate into the San Joaquin and Mokelumne Rivers and the central and south Delta (USFWS 2008). The risk of entrainment for Delta smelt adults and larvae are substantially less when individuals are located in the northern Delta than when spawning occurs near the pumps in the south and central Delta (Kimmerer and Nobriga 2008; USFWS 2008).

Pre- spawning adults are taken in salvage as they migrate into the Delta between December and March (Figure 3.8-5, USFWS 2008). The peak spawning migration is in January and February, although a few adults are salvaged as early as December (Figure 3.8-5). The cue for mass upstream migration appears to be an increase in both outflow and turbidity from upstream precipitation events (Figure 3.8-6; Grimaldo et al 2009). Flows and turbidity of 20,000 to 25,000 cfs and 10 to 12 Nephelometric Turbidity Units (NTU) initiate upstream migration (Figure 3.8-5).

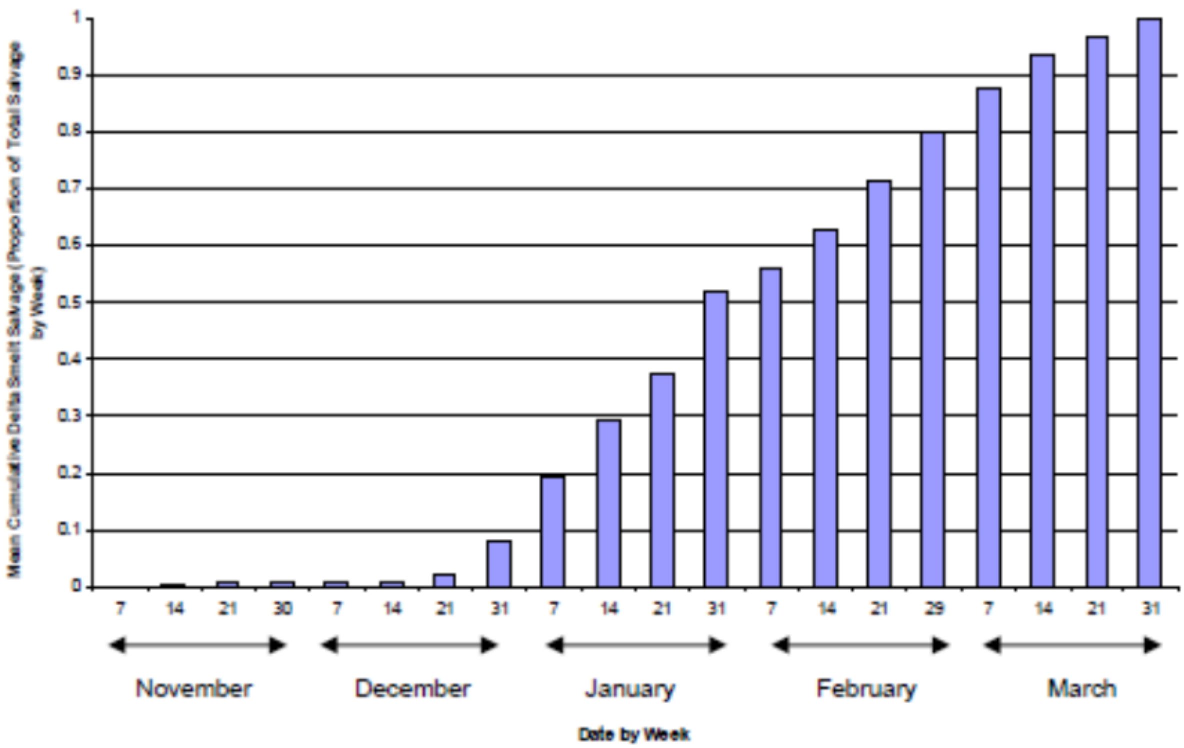

Figure 3.8-5. Cumulative Porportional Adult Delta Smelt Salvage by Week for 1993 to 2006 (From USFWS 2008)

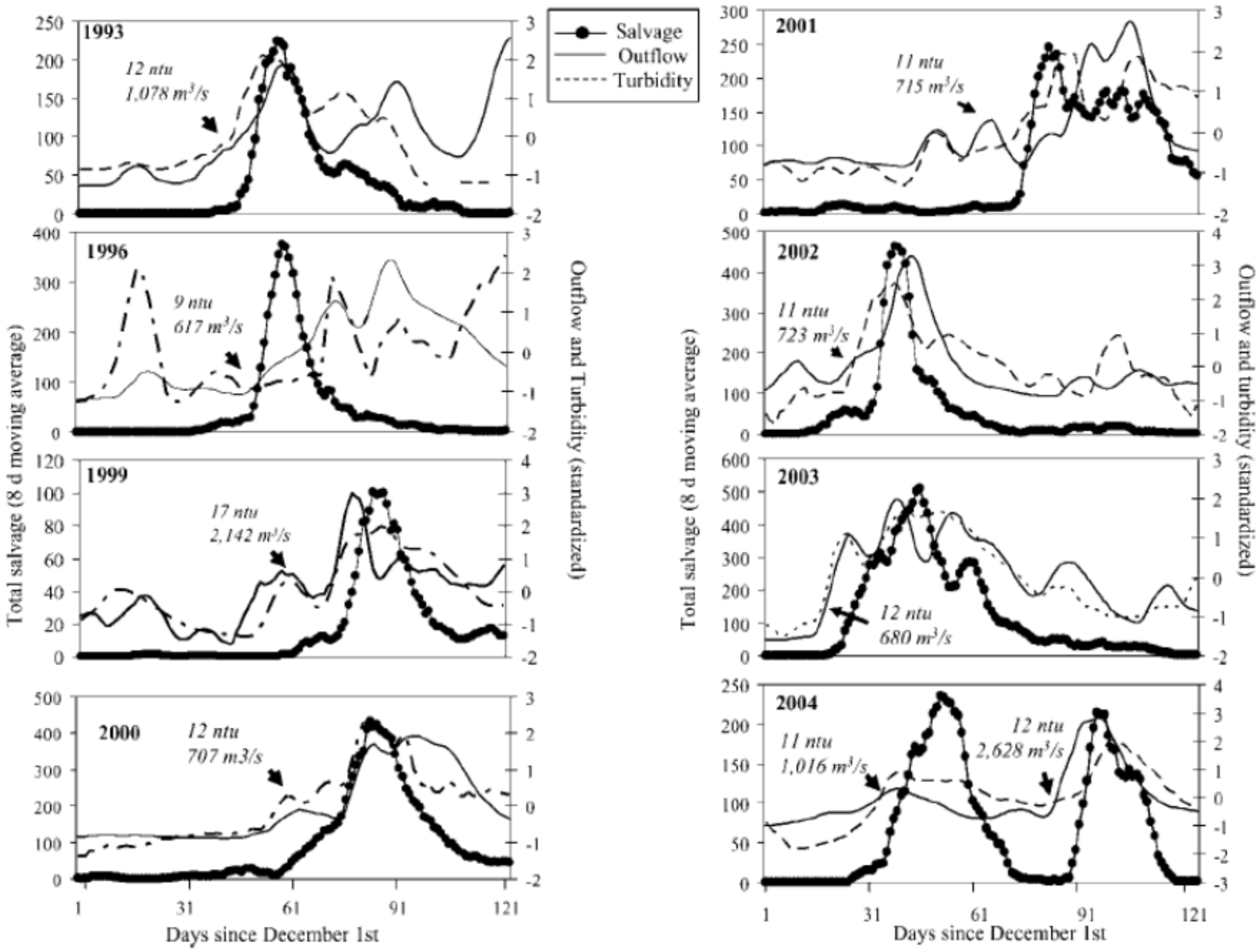

Figure 3.8-6. Eight-day Running Averages of Adult Delta Smelt Salvage, Total Outflow (m^3/s), Turbidity (NTU) for the Eight Most Abundant Delta Smelt Salvage Years between December 1992 and April 2005 at the SWP and CVP (total Delta outflow and turbidity were standardized to a mean of zero [from Grimaldo et al. 2009].)

Most of the information about early stage larval Delta smelt is inferred from the collection of spent adult females in the SKT survey and larval fish in the 20 mm survey. The center of the distribution of early stage larval smelt is downstream of the location where spent female Delta smelt are caught but upstream of X2 in spring (Dege and Brown 2004).

The risk of salvage and entrainment depends on the location of larval and adult Delta Smelt relative to the export facilities and the magnitude of OMR reverse flow (USFWS 2008). The USFWS (2008) evaluated adult salvage by regressing average OMR between December and March against adult Delta smelt salvage for 1984–2007 (Figure 3.8-7). The USFWS found that salvage increased exponentially with increasingly negative OMR reverse flow. An inflection point occurred in the USFWS salvage data with higher salvage rates at more negative OMR flows than -5,000 cfs. The USFWS (2008) used a piecewise polynomial regression analysis to establish a break point in the

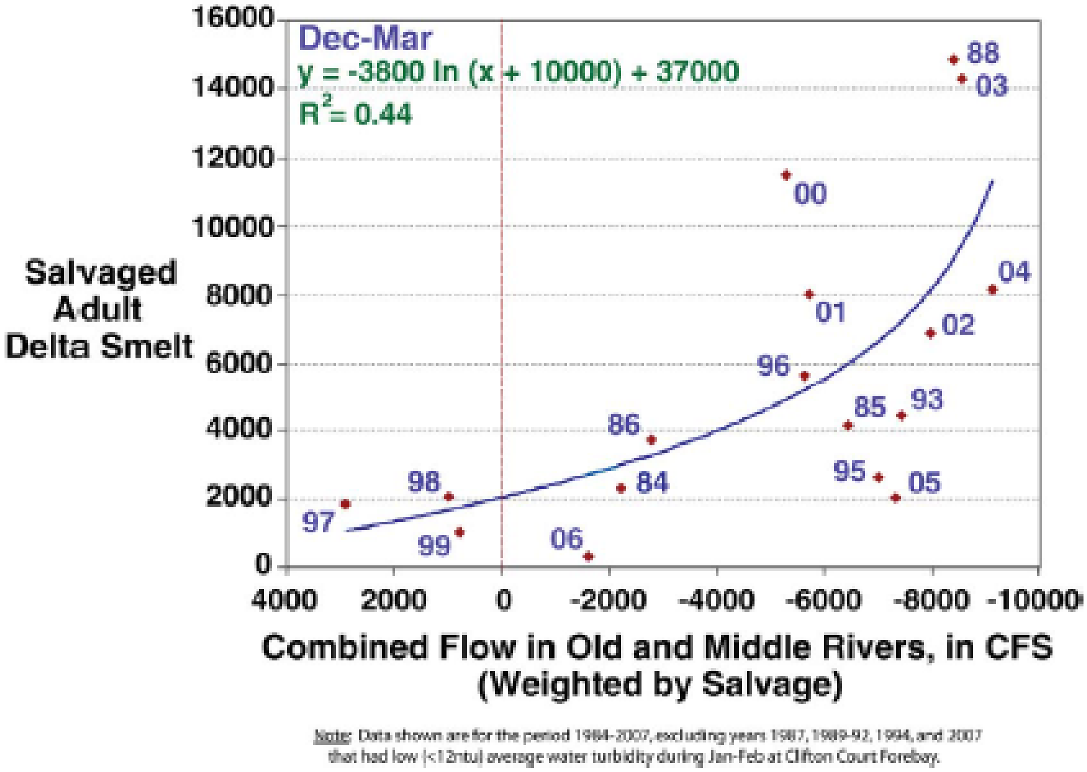

Figure 3.8-7. Salvage of Adult Delta Smelt as a Function of OMR Reverse Flows for December through March (from USFWS 2008)

dataset and determined the OMR reverse flow where smelt salvage first began to increase. The analysis indicated that this occurred at about -1,250 cfs suggesting a relatively constant amount of entrainment at OMR reverse flows more positive than -1,250 cfs. The conclusions from analyses of the salvage data are consistent with Grimaldo et al. (2009) and USFWS PTM results. The PTM analysis confirmed that the probability of entrainment was a function of the location of the Delta smelt population and the magnitude of OMR reverse flow (USFWS 2008). Together the analyses indicates that OMR reverse flows should be maintained between -1,250 and -5,000 cfs depending upon the presence of Delta smelt and other physical and biological factors known to influence entrainment (Table 3.8-1).

3.9 Starry Flounder (*Platichthys stellatus*)

3.9.1 Overview

Starry flounder is a native species that spawns outside of the Golden Gate and whose young are transported into brackish freshwater habitat in the Delta on gravitational bottom currents. Young Starry flounder rear for several years in the Delta before returning to the ocean. Indices of population size are positively correlated with Delta outflow in spring. An average Delta outflow of 21,000 cfs is needed between March and June to improve population abundance.

3.9.2 Life History

Adults are primarily a marine fish with a geographic distribution from Santa Barbara, California, to the Canadian Arctic (Moyle 2002; Miller and Lea 1972). Starry flounder are a minor part of the California commercial fishery but an important part of the recreational fishery (Wang 1986; Haugen 1992, Moyle 2002). The San Francisco Estuary serves as rearing habitat for this pelagic species (Moyle 2002).

Starry flounder spawn in shallow coastal marine waters adjacent to sources of freshwater between November and February (Orcutt 1950). The pelagic eggs and larvae are buoyant and are found mostly in the upper water column (Orcutt 1950; Wang 1986). After about two months the larvae settle to the bottom and are transported by tidal currents into nearby fresh and brackish water, like San Francisco Bay between March and June (Baxter 1999). The larvae spend the next several years in fresh and estuarine waters (Haertel and Osterberg 1967; Bottom et al. 1984; Wang 1986; Baxter 1999). Starry flounder are common in San Pablo Bay and Suisun Bay and Marsh and can be found upstream of here in low flow years (Haertel and Osterberg 1967; Bottom et al. 1984; Wang 1986). The abundance and distribution of Starry flounder is not affected by entrainment at the CVP and SWP exports as their distribution is downstream of the influence of the two pumping facilities (Jassby et al. 1995). Starry flounder distribution is affected by temperatures with fish most often found at temperatures of 10–20°C (Wang 1986; Moyle 2002).

Starry flounder feed on a variety of invertebrates. Pelagic larvae primarily consume marine planktonic algae and small crustaceans. Benthic flounder eat small crustacea, barnacle larvae, polychaete worms, and molluscs (Orcutt 1950; Wang 1986). The diet in brackish and marine water is similar (Porter 1964; Ganssle 1966; Moyle 2002)

3.9.3 Population Abundance and Trends Over Time

The population abundance of young of the year and of one year old Starry flounder in the Bay-Delta Estuary has been measured by the San Francisco Bay Study since 1980 and is reported as an annual index (Figure 3.9-1). While there has been considerable inter annual variability, no statistical trend in abundance of one-year old Starry flounder has occurred since sampling began in 1980 (P=0.08) or since implementation of D-1641 in 2000. The large drop in population abundance in 2014 coincides with the drought. Similar decreases in abundance occurred in earlier droughts and were followed by a rebound in the population in succeeding years.

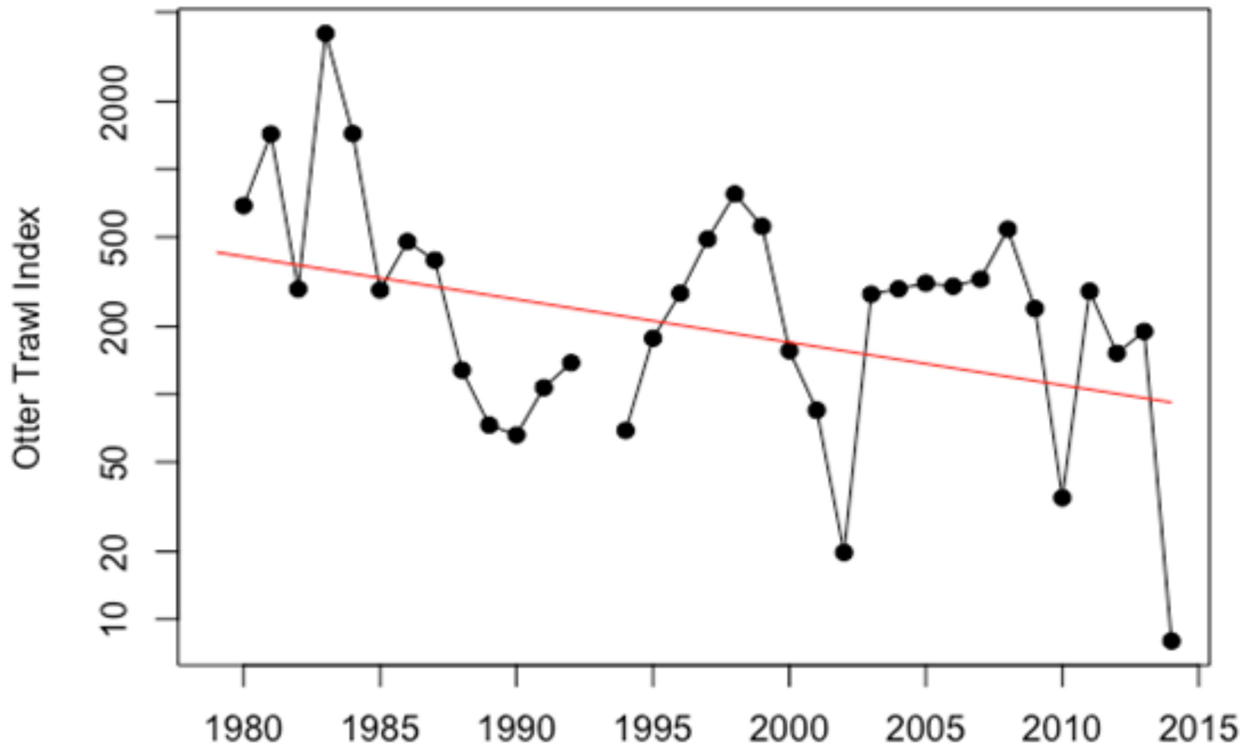

Figure 3.9-1. Population Abundance of 1-year-old Starry Flounder as Measured in the San Francisco Bay Study (1980–2014)

3.9.4 Population Abundance and Relationship to Flow

Age-one Starry flounder abundance is positively correlated with Delta outflow between March and June (CDFG 1992; Jassby et al. 1995, Kimmerer 2002a). A statistically significant reduction in the abundance of Starry flounder per unit outflow occurred after the invasion of *Corbula* in 1987 (Kimmerer 2002).

State Water Board staff reassessed the relationship with new data collected through 2014. The current analysis was restricted to the period between 1988 and 2014 to reflect future conditions in the presence of the clam. The relationship was still statistically significant (R^2=0.26, P<0.01). More Delta outflow results in a higher Bay Study index for age-one Starry flounder the following year.

CDFW (2010) suggests that there may be at least four possible mechanisms for the positive Starry flounder flow abundance relationship. First, increasing Delta outflow may provide stronger chemical cues to aid larvae and juvenile flounder locating estuarine nursery habitat. Second, higher Delta outflows generate stronger upstream directed gravitational bottom currents that may assist larval immigration into the Bay. Third, higher flow may increase the volume of low salinity habitat needed for rearing. Finally, Delta outflow is positively correlated with the abundance of the bay shrimp (*Crangon franciscorum*), another benthic species that is an important food resource for young Starry flounder (please see Bay shrimp sections for more information).

A cumulative frequency distribution was calculated for average daily Delta outflow between March and June of 1994 to 2014 to determine Delta outflow needs of Starry flounder (Figure 3.9-2). This 20 year period was selected because the years represent a period when the median annual Bay Study index of age-1 Starry flounder (280) was close to the population abundance goal in the 2010 Flow Criteria Report of 293. The median outflow during the 20 year period was 21,000 cfs.

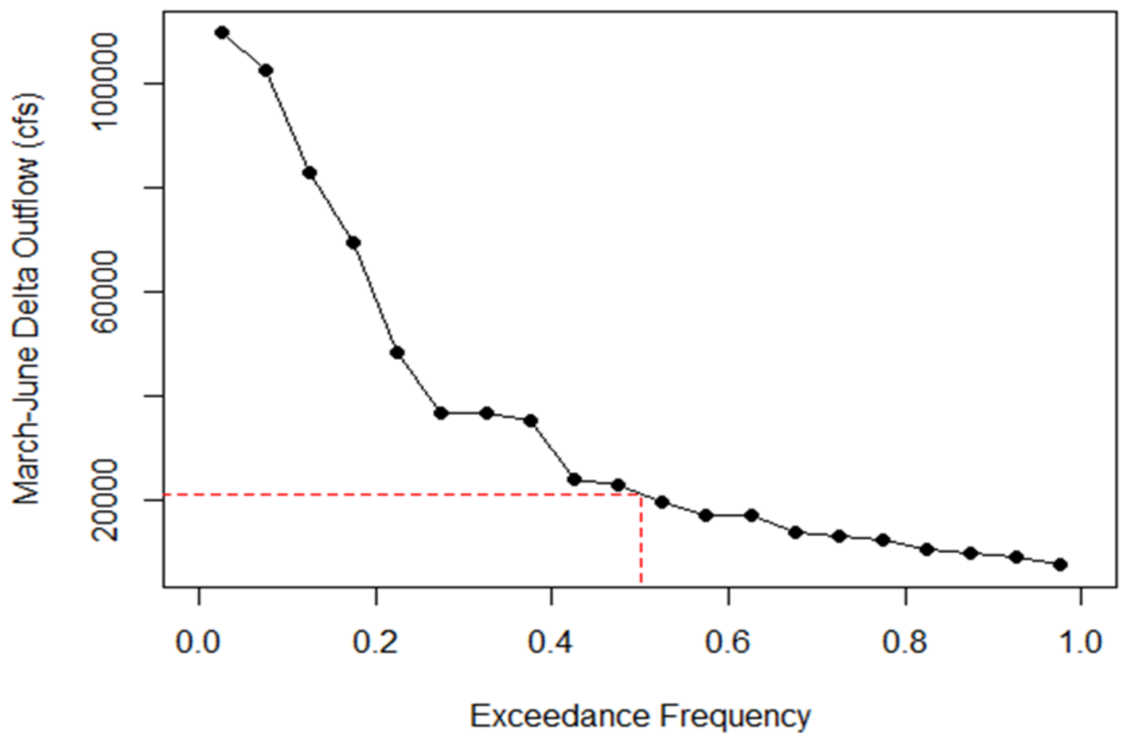

Figure 3.9-2. Cumulative Frequency Distribution of Monthly Average Daily Delta Outflow for March through June (1994–2013). The dotted line is the average daily outflow of 21,000 cfs that occurred in half of all years

Table 3.9-1. Delta Outflow Indicated to Be Protective of Starry Flounder. Outflows are monthly averages [cfs]

Starry Flounder	Months											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
			21,000									

3.10 California Bay Shrimp (*Crangon franciscorum*)

3.10.1 Overview

The California bay shrimp is a native species. Planktonic larvae hatch from eggs released in San Francisco Bay or offshore and are carried into the Delta on bottom gravitational currents. *Crangon* is important in the diet of several recreationally important fish species in the San Francisco Estuary. A positive correlation exists between indices of population abundance for one year old shrimp and Delta outflow in spring. An average Delta outflow between March and May of 19,000 to 26,000 cfs is needed to improve shrimp population abundance.

3.10.2 Life History

There are three native species of *Crangon* shrimp in the Bay-Delta Estuary--*Crangon franciscorum*, *C. nigricauda*, and *C. nigromaculata* (Heib 1999). This report refers to *C. franciscorum*. Bay shrimp are widely distributed along the Pacific Coast of North America from San Diego to Southeastern Alaska (Rathbun 1904; Hieb 1999). The shrimp is common in bays on mud and sand bottoms and offshore in deeper water (Siegfried 1989).

Bay shrimp have been fished commercially in San Francisco Bay since the 1860s. Historically, fresh shrimp were eaten locally and dried shrimp exported to Asia (Siegfried 1989). The annual San Francisco Bay catch exceeded 720 ton per year in the 1920s and 1930s, but the fishery gradually evolved into supplying bait for recreational fishermen and landings decreased to about 32 tons per year between 2000 and 2008 (CDFW 1987; Siegfried 1989; Reilly *et al*. 2001).

Crangon spp. is a major component in the aquatic food web of West Coast estuaries (Siegfried 1989). In the Bay-Delta, the shrimp has been reported in the diet of juvenile and adult striped bass, starry flounder, white and green sturgeon, American shad, white catfish, Pacific tomcod, brown smooth-hound, and staghorn sculpin (Johnson and Calhoun 1952; Heubach et al. 1963; Granssle1966; McKechnie and Fenner 1971; Reilly et al. 2001). A change in shrimp abundance could affect the population size of predator fish consuming *Crangon*.

Female Bay shrimp are reproductively active throughout much of the year (Krygier and Horton 1975). Bay shrimp mature in one year and may live for two years (Hatfield 1985). Females hatch multiple broods during the breeding season (Siegfried *et al*. 1989) with larval abundance peaking in winter and early spring in California (CDFW 1987). Larval development is believed to require 30-40 days (Hatfield 1985). Early stage larvae are found in near surface water while later stages are located closer to the bottom (Siegfried 1989). The bottom orientation of late larval stages may facilitate passive onshore and estuarine migration to the low salinity zone in bottom gravitational currents (Hatfield 1985). Upstream migration primarily occurs between April and June (CDFW 2010). Juveniles seek shallow brackish to freshwater nursery habitats, remaining there for up to six months before commencing a slow migration back down the estuary (Hatfield 1985). Small juvenile shrimp are common in San Pablo and Suisun Bay during years with high Delta outflow (CDFW 1992; Hieb 1999) while the population shifts further upstream to Honker Bay and the confluence of the Sacramento and San Joaquin Rivers during low flow years. In fall, adults migrate back down the estuary to repeat the cycle (Hatfield 1985). The larvae are located too far west in the estuary for significant entrainment to occur at the CVP and SWP pumping facilities.

Larvae prey on small zooplankton, such as copepods (Reilly et al. 2001) and have been maintained in the laboratory on a diet of *Artemia* nauplii (Siegfried 1989). Juvenile and adult Bay shrimp are predators (Siegfried 1982; Wahle 1985). In San Francisco Bay *Crangon* feed on crustaceans, polychaetes, molluscs, and plant matter (Wahle 1985). In the Delta the most important food resource for Bay shrimp in the past was the mysid shrimp, *Neomysis mercedis* (Siegfried1982) but the diet may have changed since the invasion of *Corbula* and the decline in *Neomysis* abundance (Kimmerer 2002a; Hennessy 2009). Recently, *Pseudodiaptomus forbesi* has been observed in the guts of Bay shrimp (Wahle 1985).

3.10.3 Population Abundance Trends Over-Time

The population abundance of juvenile Bay shrimp in the Bay-Delta Estuary has been measured by the San Francisco Bay Otter Trawl survey since 1980. Abundance estimates between May and October are reported as an annual index. Trend analysis demonstrates inter-annual variation in abundance but no long term change in population size (Figure 3.10-1). There has also not been a change in abundance since implementation of D-1641 in 2000.

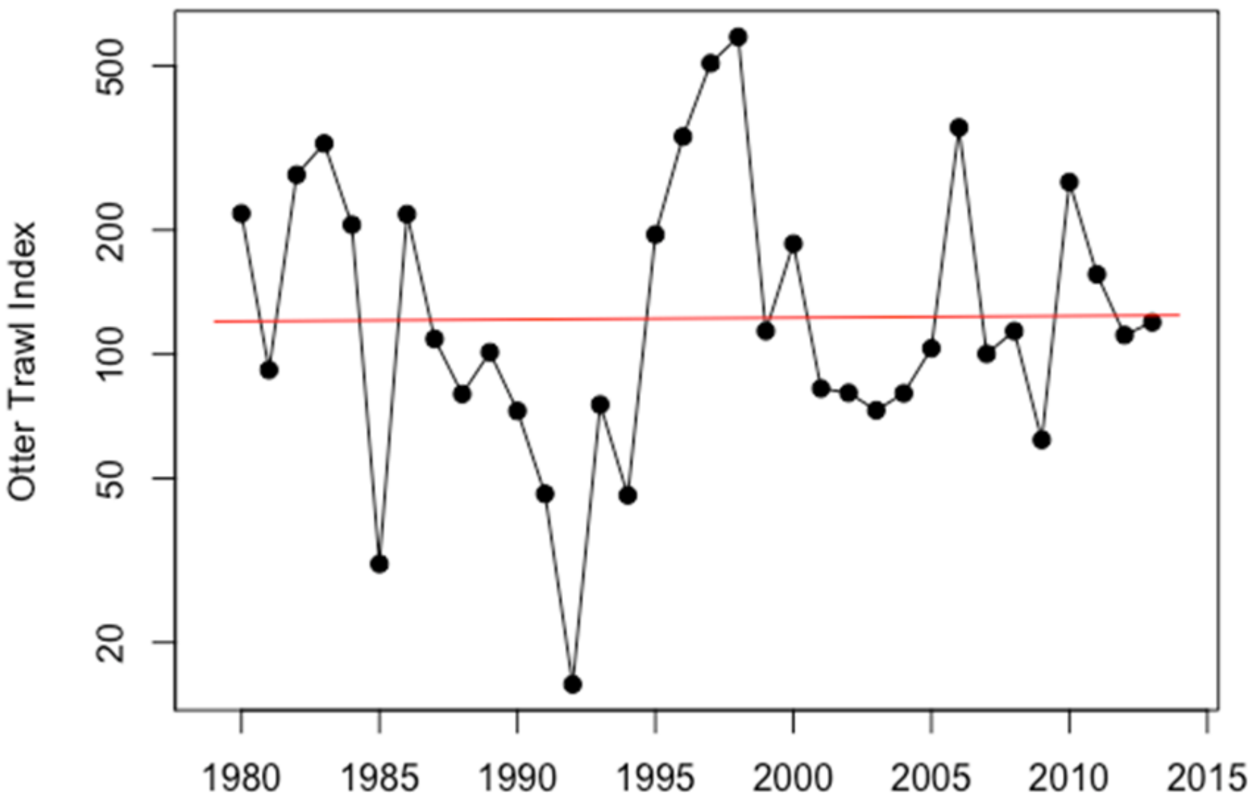

Figure 3.10-1. Index of Juvenile *Crangon franciscorum* Abundance as Measured in the San Francisco Bay Otter Trawl Survey (1980–2013). The dotted line is an estimate of the trend in population abundance over time; no trend is apparent since sampling began in 1980 [P>0.05]

3.10.4 Flow Effects on Bay Shrimp

A positive correlation has been reported between abundance of 1-year old Bay shrimp and Delta outflow from March to May of the same year (Hatfield 1985; CDFW 1992; Jassby et al. 1995; Kimmerer 2002a; Hieb 2008; Kimmerer et al. 2009). The flow abundance relationship did not change with the invasion of *Corbula* (Kimmerer 2002a).

State Water Board staff reassessed the March to May Delta outflow relationship with data collected through 2014 (Figure 3.10-2). The relationship is still significant (P<0.001). More Delta outflow is correlated with higher Bay Study index values for juvenile Bay shrimp (P<0.001).

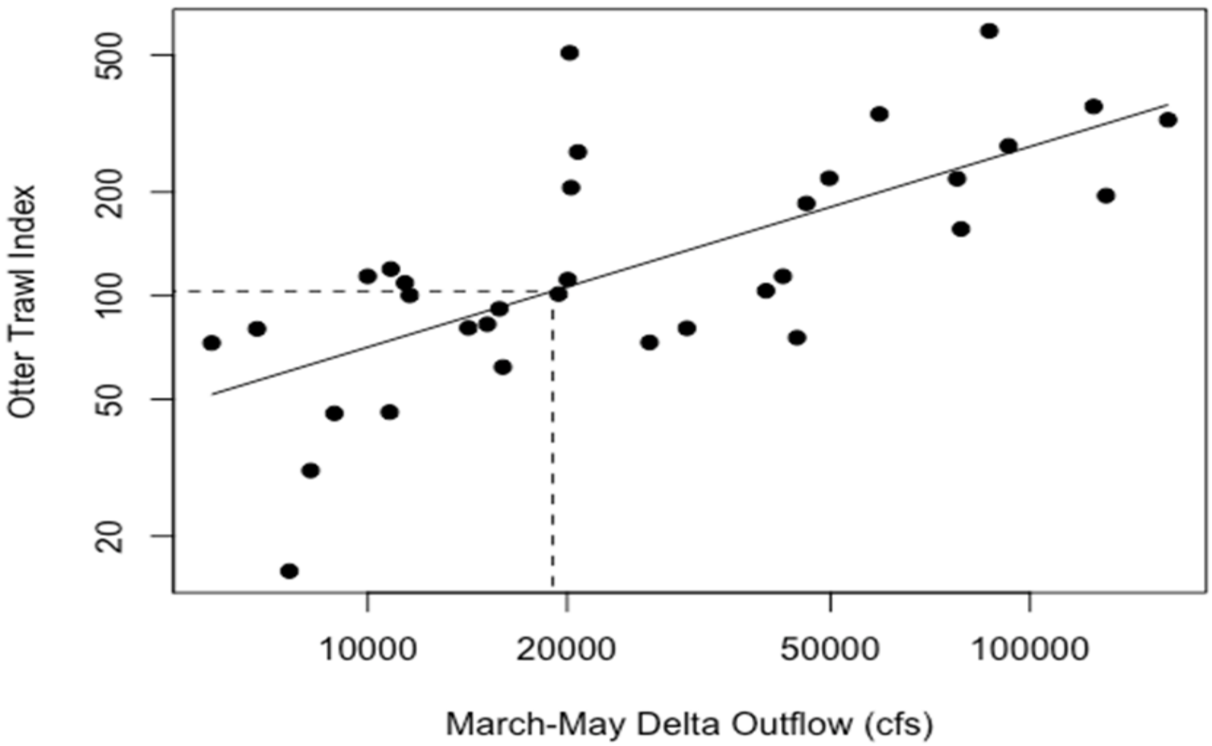

Figure 3.10-2. Relationship between Juvenile Bay Shrimp Abundance, as Measured by the San Francisco Bay Otter Trawl Survey (1980–2013), and Average Daily Outflow (cfs) between March and May of the Same Year. The flow-abundance relationship is significant (P<0.001, R^2=0.49). The dotted line indicates that a flow of 19,000 cfs is predicted to produce the recommended population abundance goal

Mechanisms for why increased outflow may increase population abundance are that outflow increases gravitational bottom currents and passive transport of juvenile bay shrimp from marine to brackish water in the Delta (Siegfried et al. 1979; Moyle 2002; Kimmerer et al. 2009). A second mechanism is that the size of brackish nursery habitat favored by juvenile bay shrimp increases with increasing flow (CDFW 2010; Reilly et al. 2001). The increase in habitat size may reduce intra- and inter-specific competition for food and other resources.

3.10.4.1 Delta Outflow

Three methods were used to determine a flow that would benefit Bay shrimp. First, a regression of flow and abundance was used to predict the outflow associated with the recommended 2010 Flow Criteria Report abundance goal. The regression predicted that an average outflow of 19,000-cfs between March and May would achieve the goal (Figure 3.10-2). Second, a cumulative frequency distribution was calculated for the average daily outflow between March and May of 1980 to 2013[23]. The median flow was 20,000 cfs (Figure 3.10-3).

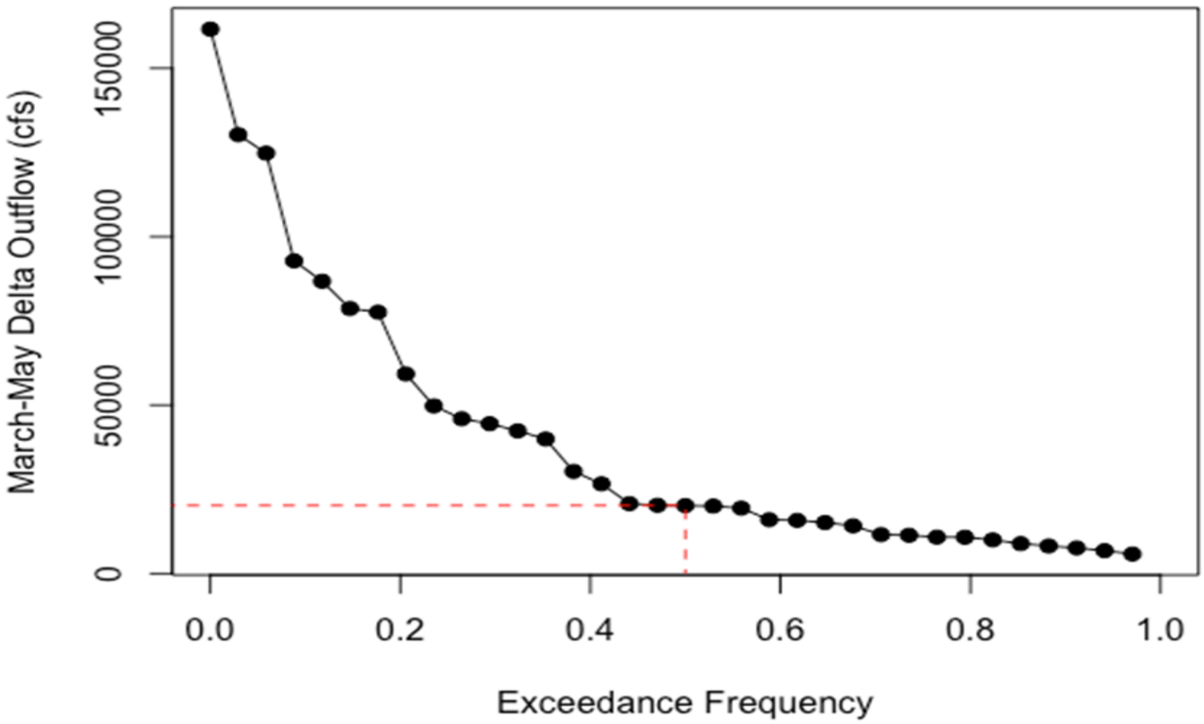

Figure 3.10-3. Cumulative Frequency Distribution of Average Daily Outflow for March to May (1980–2013). The dotted line is the average daily outflow of 20,000 cfs that occurred in half of the years

Third, logistic regression analysis predicted that 26,000 cfs would produce positive population growth in 50 percent of years using Bay Study data for 1980–2013 (Figure 3.10-4). The estimate is similar to that of TBI/NRDC (2010), who employed the same approach for data from 1980–2007and estimated positive growth would occur in 50 percent of years at 27,600 cfs (SWRCB 2010).

In summary, the three analytical methods provide an indication of the magnitude of Delta outflow needed to maintain the present population size of *C. franciscorum* in the Bay-Delta Estuary (Table 3.10-1). The methods indicate that a median outflow of 19,000 to 26,000 cfs between March and May should be sufficient to maintain the present population size (Table 3.10-1).

[23] These years were selected for analysis as the median value for the 34 year period (110) is near the 2010 Flow Criteria goal of 103.

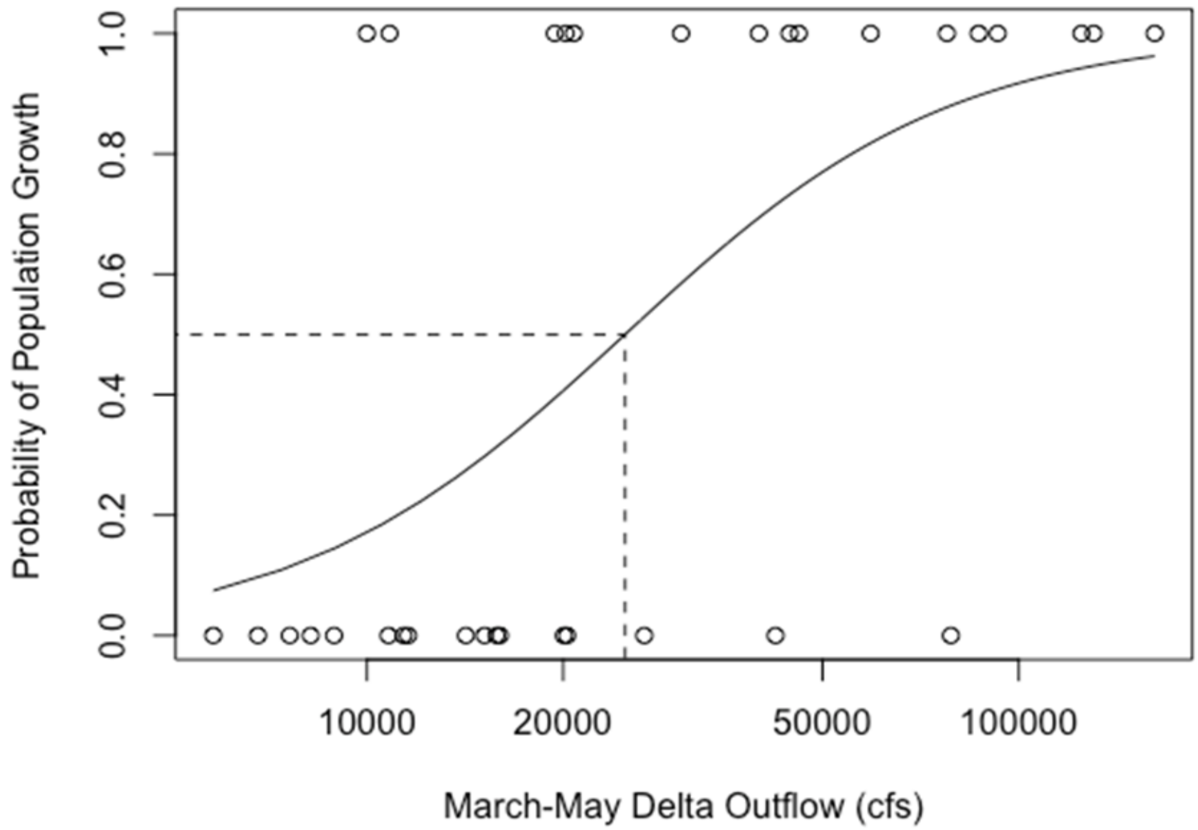

Figure 3.10-4. Probability of Juvenile Bay Shrimp Population Growth as a Function of Delta Outflow from a Logistic Regression Analysis (P<0.01). The dotted line indicates that an average daily outflow of 26,000 cfs between March and May would result in a 50 percent probability of population growth

Table 3.10-1. Delta Outflows Indicated to Be Protective of Bay Shrimp. Outflows are monthly averages [cfs]

	Months											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bay shrimp			19,000 to 26,000									

3.11 Zooplankton (*Neomysis mercedis* and *Eurytemora affinis*)

3.11.1 Overview

Zooplankton are an important food resource for juvenile fish and for small, pelagic adult fish, such as Delta smelt and Longfin smelt. Two upper estuary zooplankton species that have exhibited flow-abundance relationship are *Neomysis mercedis* and *Eurytemora affinis*. The population size of both species has declined since the invasion of the overbite clam, *Corbula.* Both species have been replaced by a group of alien copepod taxa from East Asia that are smaller and may be less nutritious for planktivorous fish. The CDFW recommends a Delta outflow of 11,400 to 29,200 cfs between February and June for the benefit of the zooplankton community.

3.11.2 Life History

Zooplankton is a general term for small, planktonic invertebrates that constitute an essential food resource for fish, especially young fish and all stages of pelagic fishes that mature at a small size, such as Longfin and Delta smelt (CDFW 1987; Kimmerer et al. 1998; Bennett et al. 2002; Bennett 2005). Two upper estuary zooplankton species that have exhibited flow-abundance relationships in the past and are important food resources for pelagic fish are *Neomysis mercedis* and *Eurytemora affinis* (SWRCB 2010).

3.11.2.1 Neomysis mercedis

The mysid shrimp, *Neomysis mercedis,* is euryhaline and in California has been found in salinities from 0.5 to 32.0 parts per thousand (ppt) (Orsi and Knutson 1979) but is most abundant in the low salinity zone (Orsi and Mecum 1996). The mysid shrimp has an upper thermal limit of 22^{0}C in San Francisco Bay (Orsi and Knuston 1979) with reproduction occurring in winter and spring (Durand 2015). *N. mercedis* is omnivorous and feeds on diatoms, copepods, and rotifers (Siegfried and Kopache 1980).

The range of *N. mercedis* is from Alaska to San Francisco Bay (Orsi and Knutson 1979).The shrimp is found throughout the Delta and San Francisco Bay but is most abundant in the low salinity zone in Suisun Bay (Orsi and Knutson 1979; Hennessy 2009; Hennessy and Enderlein 2013; Durand 2015).

3.11.2.2 Eurytemora affinis

In San Francisco Bay the calanoid copepod, *Eurytemora affinis,* has been observed from the low salinity zone to freshwater in the Sacramento and San Joaquin Rivers (Orsi and Mecum 1996, Durand 2010). The copepod is omnivorous and feeds on diatoms, particulate organic matter, detritus, nanophytoplankton, protozoa, microplankton, and ciliates (Siegfried and Kopache 1980; Durand 2015).

E. affinis can live for up to 73 days with females producing several clutches of up to 18 eggs during its lifetime (Durand 2010; Kipp 2013). In the Delta, egg production is highest in the spring at locations with salinities from 0.5–2.0 ppt (Durand 2010). *E. affinis* is an important food for most small fishes, particularly those with winter and early spring larvae, such as Longfin smelt, Delta smelt, and striped bass (Lott 1998; Bennett 2005).

3.11.3 Population Abundance and Trends Over Time

3.11.3.1 Neomysis mercedis

Mean spring and summer abundance of *N. mercedis* was high prior to 1988, but has now declined to low levels (Kimmerer 2002; Hennessy 2009; CDFW 2010). The decline may be due to competition for food with the invasive clam, *Corbula,* and other benthic grazers (Orsi and Mecum 1996; Winder et al. 2011; Hennessy and Enderlein 2013; Durand 2015). The mysid shrimp was an important food resource for many fish in the upper Estuary prior to its decline in the late 1980s (Feyrer et al. 2003; Bennet 2005)

3.11.3.2 Eurytemora affinis

The calanoid copepod *E. affinis* used to be abundant in the San Francisco Bay year around but currently is moderately abundant in winter and spring and rare in summer and fall (Durand 2010; 2015). The abundance of *E. affinis* began to decline in the 1970's but exhibited a steep decrease in spring and summer after 1987, coincident with the invasion and establishment of *Corbula* and another invasive calanoid copepod *Pseudodiaptomus forbesi* (Kimmerer and Orsi 1996; Orsi and Mecum 1996; Bennett 2005; Winder and Jassby 2011; Hennessy and Enderlein 2013). The decline in copepod abundance after 1987 may have been due to both competition for food and predation by *Corbula* (Kimmerer 2006). Zooplankton compete with benthic filterfeeders for phytoplankton (Winder and Jassby 2011) and the nauplii larval stage of *E. affinis* is ingested by *Corbula* (Kimmerer et al 1994). Grazing rates by *Corbula* are low in winter and spring but increase in summer and fall and may, in part, explain the seasonal abundance pattern of *E. affinis* (Durand 2010; Hennessy and Enderlein 2013). The effects of contaminants may have also played a role in the decline (Kimmerer 2004; Teh et al. 2013).

3.11.4 Flow Effects on Zooplankton

3.11.4.1 Neomysis mercedis

Prior to 1987 the abundance of *N. mercedis* in summer increased as X2 moved downstream with higher Delta outflow (Kimmerer 2002). After 1987 there was an inverse relationship: abundance showed a positive relationship with X2, low Delta outflows correlated with higher numbers of mysid shrimp (Kimmerer 2002). The species prefers cold-brackish water with higher concentrations of phytoplankton food (Orsi and Mecum 1996).

3.11.4.2 Eurytemora affinis

Historically*, E. affinis* abundance in summer was not correlated with X2 (Kimmerer 2002). After 1987, *E. affinis* abundance in spring became positively related to Delta outflow; higher abundances are now associated with more outflow (Kimmerer 2002). As flows decrease in late spring, copepod abundance declines to low levels throughout the Estuary (Hennessy 2009).

3.11.4.3 Non-native Zooplankton

Reduced flows because of the extended drought between 1987and 1994 and changes in benthic and zooplankton community composition have contributed to the decline of common zooplankton species and facilitated the invasion of more salinity tolerant non-native copepod and mysid shrimp species (Orsi and Ohtsuka 1999; Winder and Jassby 2011; Kratina et al. 2014) Currently, the Bay-Delta zooplankton community is dominated by invasive copepod species from East Asia which are smaller than native copepods and may provide less nutritional value to planktivorous fish such as Delta and Longfin smelt (Winder and Jassby 2011).

The CDFW provided Delta outflow recommendations for *E. affinis* and *N. mercedis* at the 2010 Informational Proceeding (SWRCB 2010,)and recommended maintaining X2 between 75 and 64 km, corresponding to a net Delta outflow of approximately 11,400 and 29,200 cfs, respectively, between February and June (Table 3.11-1).

Table 3.11-1. Delta Outflow Indicated to Be Protective of Zooplankton Species. Delta outflows are monthly averages (cfs)

	Months											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Zooplankton		11,400 to 29,200										

3.12 Non-Native Species

American shad and Striped bass are popular non-native sport fish. Both species exhibit positive flow-abundance relationships in the Bay-Delta Estuary. More Delta outflow in spring results in more juvenile recruitment for both species.

American shad (Alosa sapidissima) was introduced to the Pacific West Coast from the Atlantic seaboard between 1871 and 1881 (MacKenzie et al. 1985; Skinner 1962). American shad historically supported a large commercial gill net fishery in California but this was banned in 1957 to protect the recreational Striped bass fishery (Moyle 2002; Dill and Cordone 1997). Shad are now a popular sport fish in the Central Valley, especially on the Feather and American Rivers (Wang 1986).

Three to five year old American shad return from the ocean and migrate into freshwater between March and May to spawn (Stevens et al. 1987). The peak of the spawning migration occurs in May with adults reproducing from May through early July in large river channels (Urquhart 1987; Stevens et al. 1987). The FMWT index for American shad is positively correlated with Delta outflow during the previous February to May spawning season (Kimmerer 2002a; Kimmerer et al. 2009). The slope of the flow abundance relationship has remained positive since FMWT sampling began in 1967, although recruitment of juvenile shad in fall has increased for any given spring Delta outflow value (intercept of the regression line) since the *Corbula* invasion (Kimmerer 2002a; Kimmerer et al. 2009).

Striped bass (*Morone saxatilis*) was first introduced to the Bay-Delta estuary in 1879 and within 10 years had become a commercial fishery (Herbold et al. 1992). Commercial fishing for Striped bass was banned in 1935 but the species has continued to support the most important recreational fishery in the Bay-Delta Estuary (Moyle 2002). Adult bass migrate to brackish or marine water in summer and return to freshwater in fall and winter to spawn. Spawning begins on the Sacramento River above the confluence of the Feather River in April with peak spawning activity in May and early June. Eggs are semi buoyant and require flow to keep them suspended and carry them and newly hatched larvae downstream to low salinity rearing habitat in the Delta and Suisun Bay (Moyle 2002).

A positive correlation exists between the survival of Striped bass eggs through their first summer and Delta outflow between April and June (Kimmerer 2002a; Kimmerer et al. 2009). Positive correlations also exist between Delta outflow in spring and population abundance indices from the TNS, FMWT, Bay midwater trawl and Otter trawl indices (Kimmerer et al. 2009). In each case higher Delta outflows in spring result in larger index values. The size of the Striped bass population has undergone a long-term decline since the 1970s and is one of the four POD species that underwent a further decrease in population size around 2000 (Herbold et al. 1992; Sommer et al. 2007). An increase in Delta outflow in spring is predicted to increase the population abundance of Striped bass and American shad, two important sport fish in the Bay-Delta Estuary.

3.13 Conclusion

The species evaluations indicate that multiple aquatic species in the Bay-Delta Estuary are in crisis. Recovery of native species will require both habitat restoration and increased flow in Central Valley tributaries and the Delta. Successful recovery of native species is not possible without parallel investment in both efforts. The focus of analysis here has been to determine the magnitude and timing of flow needed to restore salmonids and the estuarine dependent fish and invertebrate community. The State Water Board will address the need for non-flow measures to protect fish and wildlife beneficial uses in the program of implementation for the revised Bay-Delta Plan.

Indices of population abundance for all of the estuarine species are at all-time low levels, except for Bay shrimp (Table 3.13-1; Figure 3.13-1). The population abundance of Sacramento splittail, Delta smelt and Longfin smelt have declined by 97, 98 and 99 percent since sampling began in 1967. The decrease in abundance of these three species is also statistically significant since implementation of D-1641 in 2000 ($P<0.05$, Table 3.13-1). Several of these species are protected under CESA and ESA (Table 3.13-1). The population abundance of the California bay shrimp is an exception and has remained near its long-term median abundance since monitoring began in 1980.

Table 3.13-1. Estuarine-dependent Species Listed under the California (CESA) and Federal Endangered Species (FESA) Acts and Changes in Indices of Their Population Abundance in the San Francisco Estuary

Species	Listing		Statistically Significant Long term Decline since sampling began?	Statistically Significant decline since adoption of D-1641 in 2000?	Present abundance[3]
	CESA	FESA			
Starry Flounder			No[1]	No	Lowest on record
Sacramento Splittail	Species of concern		Yes[2] (-97%)[4]	Yes (-91%)	Lowest on record
Longfin smelt	Threatened	Candidate	Yes[2] (-99%)	Yes (-97%)	Lowest on record
Delta Smelt	Endangered	Threatened	Yes[2] (-98%)	Yes (-98%)	Lowest on record
Bay Shrimp			No[1]	No	Near median value

1 San Francisco Bay study (1980–present)
2 Fall mid water trawl Index (1967–present)
3 2014/2015
4 The percent decrease was estimated from the average of the first three and last three years of index values to account for inter-annual variability.

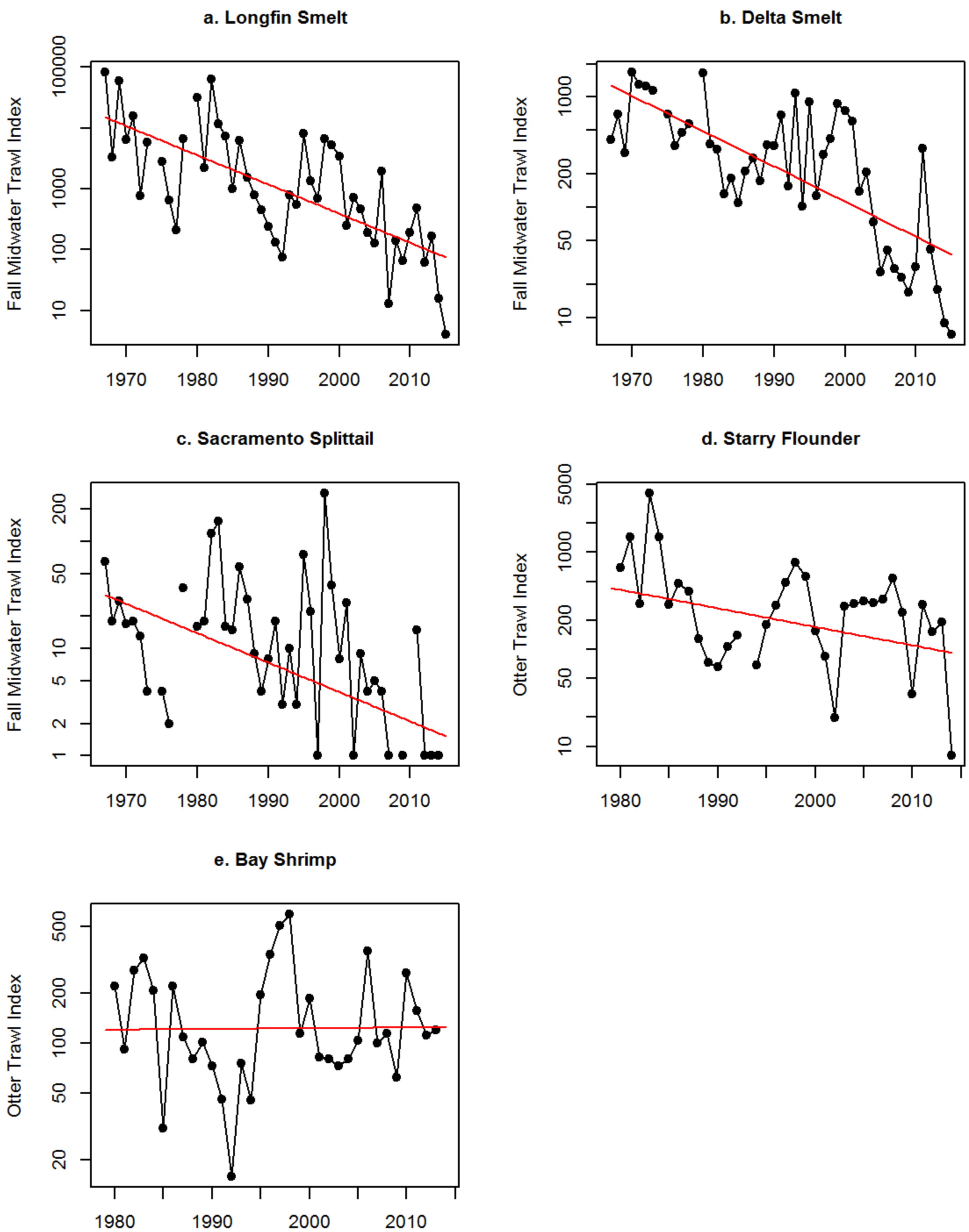

Figure 3.13-1. Trends Over Time in Indices of Abundance for Native Fish and Invertebrate Species from the San Francisco Estuary

Population abundance increases for all the native estuarine species and non-native American shad and Striped bass with increasing Delta outflow in winter and spring. The slope of the flow-abundance relationship has changed for some species during the last half century of monitoring but has always remained positive. More Delta outflow in winter and spring has consistently been associated with a higher abundance of fish in fall. The relationship demonstrates that one option for increasing population abundance of these species is to increase Delta outflow in winter and spring.

Population abundance goals were previously identified in the Delta Flow Criteria Report for restoring some estuarine species. The species evaluations contain an analysis of the Delta outflow needed to achieve these restoration goals and/or a 50 percent probability of positive population growth. These flows are summarized in Table 3.13-2. When possible, multiple methods were used to estimate flows predicted to increase the population size of each species and this has resulted in a range of Delta outflows for some taxa. The range emphasizes that there is no single "correct" outflow for any species. Likewise, other restoration goals may be proposed in the future and similar analytical methods may be used to estimate the new flows predicted to achieve these goals. Nonetheless, the present analyses provide an estimate of the range of flows that are expected to benefit each species. Together, the flows in Table 3.13-2 provide an indication of the magnitude, duration, and seasonality of flow that may be required to support a healthy aquatic estuarine community.

The analyses indicate that multiple species benefit from a similar magnitude and timing of Delta outflow (Table 3.13-2). For example, flow from February through May for Longfin smelt will also meet the flows predicted to support the populations of Starry flounder, California bay shrimp, and zooplankton during the same months. Sacramento splittail and Sturgeon respond to higher flows after March than do Longfin smelt. The flows predicted to benefit Sacramento splittail might be reduced if the Yolo Bypass was able to be flooded at a lower Sacramento River flow. The long life and high fecundity rate of sturgeon make this species less dependent on frequent high Delta outflow than other species. Spring recruitment of Delta smelt in the 20 mm index increases if X2 was located in the previous fall in the low salinity zone (Figure 3.8-2). The USFWS (2008) BO requires that the location of X2 in September and October of wet and above normal water years be further west than 74 and 81 km[24], respectively (Table 3.13-2). In addition, recent scientific findings suggest that the abundance of Delta smelt in fall is positively related to Delta outflow in summer, more flow in July, August and September results in greater survival in summer (Table 3.13-2).

Biological mechanisms that may account for the statistically significant relationships between Delta outflow and the population abundance of estuarine dependent species are listed in Table 3.13-3. Most of the functional flows provide mechanisms to increase reproductive output and survival of young. The mechanisms include adult attraction flows, transport flows to carry weakly swimming larvae to rearing habitats, and higher flows to create spawning and rearing floodplain habitat in the Central Valley, and low salinity rearing habitat in Suisun Bay and Marsh.

Historically, the Delta received higher outflow in winter and spring than in recent years, placing X2 further downstream under these conditions (Chapter 2). The highest outflows identified for estuarine species were 41,900 cfs in January for Longfin smelt, 38,000–47,000 cfs between February and May for Sacramento splittail, and greater than 37,000 cfs for White sturgeon in June and July (Table 3.13-2). The median unimpaired Delta outflow between January and May is greater than 50,000 cfs (Chapter 2). Median unimpaired flows in June are less than 50,000 cfs but still greater

[24] An X2 of 74 and 81-km is equivalent to an average Delta outflow of 11,400 and 7,100-cfs, respectively.

than the 37,000 cfs needed by Sturgeon demonstrating that native fish evolved under a regime of higher Delta outflows than occurs now. Loss of functional flows in winter and spring reduce potential recruitment opportunities and the viability of the estuarine dependent community.

The natural production of all four runs of Chinook salmon and Central Valley steelhead is also in decline. Natural production of winter, spring, late fall and fall-run Chinook salmon have decreased from the annual average baseline in 1967-1991 by 88, 60, 48, and 37 percent, respectively (Table 3.2-3). Natural production of steelhead has declined by 90 percent from 1960 to 1998–2000. Hatcheries now provide the majority of the salmon and steelhead caught in the commercial and recreational fisheries.

Adult and juvenile salmonids benefit from an increased, more natural flow pattern in Central Valley tributaries. At least one salmonid run is migrating through the Delta or holding in the upper Sacramento Basin each month of the year necessitating near year around tributary inflows (Table 3.4-4). Adult salmonids require continuous tributary flows of sufficient magnitude to provide the olfactory cues to find, enter, hold, and spawn in their natal stream. NMFS (2014, Appendix A) determined that warm water and low flow resulted in a reduction in adult attraction and migration cues, and a delay in immigration and spawning which appear to negatively affected adult salmon in 54 and 73 percent of the tributaries evaluated (Table 3.4-5). The seasonal decrease in flow that now occurs for tributaries is illustrated in Chapter 2 for Antelope, Mill and Deer Creeks. The combined flow for the three creeks is lower between April and October than in unimpaired conditions with the greatest impairment happening in May through September of drier years when the Creeks sometimes go dry.

Juvenile salmonids require flows of sufficient magnitude to trigger and facilitate downstream migration and provide seasonal access to productive floodplains. A problem in Sacramento tributaries for juvenile salmonids is a lack of rearing habitat and connectivity between tributaries and the Sacramento River because of a lack of flow and elevated water temperature which negatively affect juvenile salmonid rearing and outmigration in 32 and 40 percent of the tributaries evaluated by the NMFS in a recent study (Table 3.4-5). Studies of juvenile salmon rearing in the Yolo Bypass and Cosumnes River floodplain found that fish grow faster on floodplains than in adjoining river channels. Faster growth and higher quality smolt have been associated with higher marine survival in other west coast Chinook salmon populations.

The survival of juvenile salmon migrating down the Sacramento River to Chipps Island is twice that of fish exiting through the Central Delta. Juvenile salmon in the Sacramento River enter the Central Delta through the DCC or Georgiana Slough. The 2006 Bay-Delta Plan and the NMFS (2009) BO have DCC gate closure requirements to prevent juvenile salmonids from entering the Central Delta which should be maintained. Entrainment of juvenile salmon into Georgiana Slough can be reduced if tidal reverse flows do not occur on the Sacramento River at Georgiana Slough. Reverse flows cease if the flow rate of the Sacramento River at Freeport is greater than 17,000 to 20,000 (Table 3.4-7).

The abundance and survival of juvenile fall and winter run Chinook salmon emigrating past Chipps Island increase when Sacramento River flow is greater than 20,000 cfs between February and June (Table 3.4-7). Flows of this magnitude may also aid emigration of juvenile spring-run and steelhead. The Sacramento River is the main source of water for Delta outflow. Current Sacramento River flow is less than the unimpaired flow at Freeport between February and June (Chapter 2). The median flow is now 70 percent of unimpaired flow between January and June, with median April and May flows below 50 percent of the unimpaired flow rate. If higher outflow for Longfin smelt and other estuarine dependent species is provided in winter and spring (Table 3.13-2), then this flow will also assist salmon to emigrate past Chipps Island (Table 3.4-7). The survival of emigrating juvenile salmonids from the San Joaquin Basin increases when flow at Jersey Point is positive (Figure 3.4-17). The USFWS (1995) recommends positive flows for Jersey Point from October 1 through June 30 to improve survival of salmonids migrating through and rearing in the Delta and to provide attraction flow for returning adults (Table 3.4-7).

Export pumping at the CVP and SWP facilities cause OMR reverse flows and draw large numbers of fish into the interior Delta resulting in their entrainment and salvage. The risk of entrainment depends upon the location of the fish relative to the export facilities and the magnitude of OMR reverse flows. Juvenile salmonids emigrating from the San Joaquin Basin and Eastside tributaries are at risk of entrainment when migrating through the Central Delta. Sacramento River salmon are vulnerable if they migrate into the Central Delta through the DCC gates or Georgiana Slough. Delta smelt and Longfin smelt are vulnerable if adults migrate into the Central Delta to spawn. Salvage data and PTM results for all these species demonstrate that salvage increases exponentially with increasingly negative OMR reverse flows (Figure 3.4-15, 3.4-16, 3.5-4 and 3.8-7). An inflection point occurs for all species at about -5,000 cfs with much higher salvage rates at more negative OMR reverse flows. The lowest salvage rates are measured for smelt at an OMR reverse flow of -1,250 cfs or more positive flow rates. Fishery Agencies recommend that CVP and SWP exports be managed to maintain OMR reverse flows between -1,250 and -5,000 cfs from January to June with flows adaptively managed based upon the abundance and distribution of salmonids and smelt and other physical and biological factors known to affect entrainment (Table 3.13-4).

The production of San Joaquin basin Chinook salmon increase when the ratio of spring flow at Vernalis to exports increase. The NMFS (2009) BO requires export restrictions from April 1 through May 31[25]. Juvenile salmonids migrate out of the San Joaquin Basin from February to June and may need protection from export related mortality during this entire period (Table 3.13-4).

.

[25] San Joaquin River at Vernalis flows to export ratios ranging from 1.0 to 4.0 based on water year type.

Table 3.13-2. Magnitude and Timing of Delta Outflows Indicated to Be Protective of Estuarine-dependent Species. Flows (cfs) are monthly averages

<table>
<tr><th></th><th colspan="12">Months</th></tr>
<tr><th>Species or Purpose</th><th>Jan</th><th>Feb</th><th>Mar</th><th>Apr</th><th>May</th><th>Jun</th><th>Jul</th><th>Aug</th><th>Sept</th><th>Oct</th><th>Nov</th><th>Dec</th></tr>
<tr><td>Estuarine Habitat</td><td colspan="6">7,100-29,200</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Longfin smelt</td><td colspan="3">41,900</td><td colspan="2">29,200</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Starry flounder</td><td></td><td></td><td colspan="4">>21,000</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>California Bay Shrimp</td><td></td><td></td><td colspan="3">19,000-26,000</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Sacramento Splittail</td><td></td><td colspan="4">38,000-47,000</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>White sturgeon</td><td></td><td></td><td colspan="5">>37,000</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Delta Smelt</td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="2">X2≤80 km[2]</td><td colspan="2">Fall X2[1,2]</td><td></td><td></td></tr>
<tr><td>Zooplankton</td><td></td><td colspan="5">11,400-29,200</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

1 Wet water year >11,400 cfs; above normal water year >7,100 cfs

2 July, August, and September of all years; flow ≥ 7,500 cfs

Table 3.13-3. Functional Flow Needs for Estuarine-dependent Species[1]

Species			Months[2]											
Name	**Life stage**	**Mechanism(s)**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Longfin smelt	Eggs	Freshwater, brackist habitat	••	••	•	•								•
Longfin smelt	Larvae	Freshwater-brackish habitat, transport, turbidity	•	••	••	••	••							•
White sturgeon	Adults	Attraction	•	•									•	•
White sturgeon	Adults, larvae	Spawning, downstream larval transport			•	•	•	•	•					
Green sturgeon	Adults	Attraction			•	•								
Green sturgeon	Adults, larvae	Spawning, downstream larval transport					•	•	•					
Sacramento splittail	Adults	Flood plain inundation, spawning (can be short)	•	•	•	•								
Sacramento splittail	Eggs, larvae	Flood plain habitat rearing	•	•	••	••	••							
Delta smelt	preadult	Transport, habitat			•	••	••	•	•	•	•	•	•	
Starry flounder	Settled juveniles, juvenile 2-year olds	Estuary attraction, habitat		•	•	•	•							
Bay shrimp	Late stage larvae & small juveniles	Transport		•	•	••	••	••						
Bay shrimp	juveniles	Nursery habitat				••	••	••						
Neomysis mercedis (zooplankton)	All	Habitat			•	•	•	•	•	•	•	•	•	
Eurytemora affinis (zooplankton)	All	Habitat			••	••	••							

1 Adapted from SWRCB (2010) and CDFW (2010)
2 •=Flow timing important during this month, ••=Flow timing very important during this month.

Table 3.13-4. Summary of Interior Delta Flows Indicated to Be Protective of Salmonids and Estuarine-dependent Fish Species

	Months											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
NMFS Biological Opinion for OMR flow[1,4]	-2,500 to -5,000											
USFWS Biological Opinion for OMR flow[2,4]	-1,250 to -5,000											
CDFW Incidental Take Permit for OMR flow[3,4]	-1,250 to -5,000											
Georgiana Slough[5]	17,000-20,000											
San Joaquin River @ Jersey Point[6]	Positive flow											
San Joaquin River Export Constraint[7]		1:1 - 4:1								>0.3[8]		

1 When Chinook salmon or steelhead are present
2 When adult and juvenile Delta smelt are present.
3 When Longfin smelt are present.
4 14-day running average of tidally filtered flow at Old and Middle Rivers.
5 To minimize reverse tidal flow when salmonids are present.
6 When salmonids are present.
7 San Joaquin River at Vernalis to sum of CVP and SWP exports.
8 Minimize adult straying.

Chapter 4
Other Aquatic Ecosystem Stressors

4.1 Introduction

The factors that harm native species are broadly referred to as “stressors.” Stressors affect populations by altering the growth, reproduction and mortality rate of individual organisms. Stressors may also interact with each other in an additive or synergistic fashion (Sommer et al. 2007). These stressors occur both within the Delta and upstream in the greater watershed and are unfavorable and unnatural attributes of the ecosystem, leading ultimately to diminished populations and, in the worst case, extinction of native species (Mount et al. 2012).

While this Report focuses largely on addressing flow-related stressors, the State Water Board recognizes that ecosystem recovery in the Delta depends on more than just adequate flows. Many scientific studies have identified the involvement of other aquatic ecosystem stressors, such as reduced habitat, pollutants, nonnative invasive and predatory species, and abiotic factors as contributing factors in species declines (Sommer et al. 2007; Moyle et al. 2012; Mount et al. 2012). Projects and programs to address these other stressors are often referenced generically as “non-flow actions.” However, that term is something of a misnomer as it fails to capture both how inadequate flows have contributed to the pervasiveness and severity of other stressors and the need for adequate flows to successfully implement many “non-flow” measures. The benefits of flows are enhanced when implemented in concert with habitat restoration, control of waste discharges, control of invasive species, fisheries management, and other ongoing efforts. A multifaceted approach is needed to address Delta concerns and reconcile an altered ecosystem (Sommer et al. 2007; Moyle et al. 2012).

This chapter organizes other aquatic ecosystem stressors into six categories: physical habitat loss or alteration, water quality, nonnative species, fisheries management, and climate change. No one category is independent of the others, and significant interactions can amplify or suppress the negative effects each has on the aquatic ecosystem. The following subsections describe generally how stressors negatively affect the aquatic ecosystem, and the interactions between stressors. This chapter also describes how flow management interacts with other stressors, indicating the need for including flow considerations in strategies for reducing the effects of stressors as a whole.

4.2 Physical Habitat Loss or Alteration

For fish, flow is habitat. The hydraulic structural conditions (depth, velocity, substrate or cover) define the actual living space of the organism (USFWS 2010). However, in the Delta watershed, there has also been a dramatic loss in other aspects of physical habitat suitable for native fish species. Dredging and other construction-related activities in the watershed have modified aquatic habitat, including increased sedimentation, simplified streambank and riparian habitat, reduced connectivity to floodplain habitat, and modified hydrology. For example, the channels of the Delta have been modified by the raising of levees and armoring of the levee banks with stone riprap. This reduces habitat complexity by reducing the incorporation of woody debris and vegetative material into the nearshore area, minimizing and reducing local variations in water depth and velocities, and simplifying the community structure of the nearshore environment (NMFS 2009).

The habitat within the Delta can be divided into distinct segments that include freshwater tidal marsh habitat in the north and south Delta and Suisun Marsh, riparian habitat and open channels throughout the Delta, and floodplain and wetland habitat in the north and south Delta and its tributaries.

4.2.1 Freshwater Tidal Marsh Habitat

Tidal marshes historically supported multiple species, creating habitat which has changed dramatically over the past 100 years, largely due to population increases and filling, leveeing, and conversion from open water bays to tidal marsh or away from tidal marsh altogether (Figure 4.2-1; Atwater et al. 1979; Moyle 2002; Whipple et al. 2012). Not only does tidal marsh encapsulate multiple plant species, it houses multiple fauna within the complexity of habitat (Atwater et al. 1979). These include networks of sloughs that provide refuge and structure for feeding, and production and retention of nutrients and with it connectivity between these spaces. The refuge function of these water bodies may also include cooling during summer heat spells (Mount et al. 2012). The Delta currently supports less than 10,000 acres of tidal wetland, all of which is small and fragmented (USFWS 2008). With the loss of this habitat, the loss of these functions goes with it (Whipple et al. 2012).

An example of how freshwater and estuarine flows have been altered can be illustrated with Suisun Marsh. It is the largest expanse of marsh in the San Francisco Bay-Delta and is the largest remaining brackish wetland in western North America (O'Rear and Moyle 2009). The Marsh provides important habitat for many bird, mammal, and reptile species, and more than 40 fish species (USBR 2013; O'Rear and Moyle 2009). It also provides important tidal rearing areas for juvenile salmonid fish. Suisun Marsh currently consists of a variety of habitats, including managed diked wetlands, unmanaged seasonal wetlands, tidal wetlands, sloughs and upland grasslands. The Marsh encompasses more than ten percent of California's remaining natural wetlands (SWRCB 1978; Whipple et al. 2012). The conversion of tidal wetlands due to the creation of dikes resulted in a loss of habitat for many species, including those now listed as threatened or endangered, and estuarine habitat in general has shrunken over recent years and with it suitable habitat for primarily estuarine species, like Delta and Longfin smelt. Because much of the freshwater transition zone has decreased (Feyrer et al. 2011), the effects of increased salinity in water used in managed wetlands in Suisun Marsh also include reduced wetland diversity and food-plant productivity that in turn decreases the primary productivity of the habitat (USBR 2013).

The environmental challenges that are changing Suisun Marsh include 1) sea level rise, which leads to overtopping and erosion of levees; 2) subsidence of land inside dikes due to management actions; 3) reduced sediment supply from upstream sources, which exacerbates the subsidence problems, and 4) reduced tidal energy that results from larger areas being submerged (Mount and Twiss 2005). As Moyle et al. (2013) describes, reduced tidal energy leads to reduced sediment and nutrient transport. Ultimately, Moyle et al. (2013) project that Suisun Marsh will become increasingly intertidal due to increased sea level rise as a result of climate change and subsidence and difficult to sustain as diked and managed wetlands.

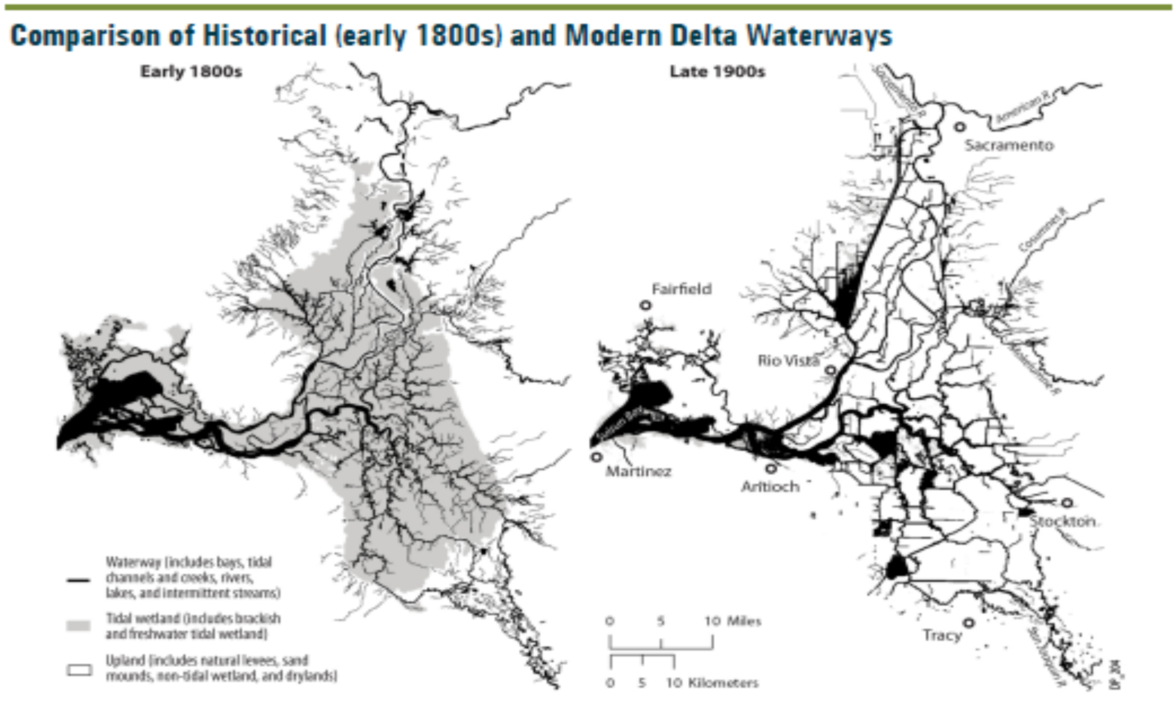

Figure 4.2-1. Comparison of Historical and Modern Delta Waterways, Tidal Wetland, and Upland Areas (Whipple et al. 2012)

4.2.2 Riparian Habitat and Open Channels

Historically, oak and other deciduous as well as coniferous trees were prevalent in the Sacramento River system and surrounding tributaries (Whipple et al. 2012; Roberts et al. 1980). Another common species was cottonwood (Rood et al. 2003). The habitat also included vines, shrubs, and grasses that sprung up when fluvial and alluvial sediments and their associated flows were more prevalent (Roberts et al. 1980). The vegetation provided habitat, harboring species and providing shade and habitat structure, through root systems, for fish in rivers and channels

The Sacramento River has gone from 800,000 acres of riparian vegetation in 1848 down to only 12,000 in 1972. Most of California's riparian ecosystems were destroyed or degraded due to the conversion of forests to orchard and field crops, logging, streambank stabilization, channelization, and reduction of water flow by dams and irrigation. The rate of destruction is comparable to that of the tropical forests of the equatorial region (Golet et al. 2006).

The channelized, leveed, and riprapped river reaches and sloughs that are common in the Sacramento River system are degraded, and typically have low habitat complexity, low abundance of food organisms, and offer little protection from either fish or avian predators. However, some complex, productive habitats with floodplains remain in the system [e.g., Sacramento River reaches with setback levees (primarily located upstream of the City of Colusa)] and flood bypasses (Yolo and Sutter bypasses). Juvenile life stages of salmonids are dependent on the function of this habitat for successful survival and recruitment (NMFS 2009).

4.2.3 Floodplain and Wetland Habitat

A natural floodplain, in the absence of levees, is an important component of rivers and estuaries that allows many essential ecological functions to occur. Healthy floodplains are morphologically complex. They include backwaters, wetlands, sloughs, and connected channels that carry and store floodwater. Floodplain areas can constitute islands of biodiversity within semi-arid landscapes, especially during dry seasons and extended droughts (ERP 2014). Floodplains have abundant food sources, lower flows (Jeffres et al. 2008; Sommer et al. 2001), and increased shading (Li et al. 1994).

Floodplain habitat in California has frequently been lost through the channelization of rivers, including construction of levees and channel straightening, deepening, and lining (Mount 1995). Impacts of hydraulic mining, especially in the Yuba and Feather rivers, caused changes in sediment deposition within channels and floodplains, loss of channel capacity, and aggradation of river courses (Mount 1995). A variety of activities, including water storage, conveyance, flood management, and navigation enhancements, have contributed to river modification and impaired natural floodplain inundation. Recent modeling studies have indicated that these factors can also affect habitats integral to the floodplain as well as their fisheries (Feyrer et al. 2006). Jeffres et al. (2008) demonstrated in a Consumnes River study that fish grew much larger when rearing in floodplain habitat with vegetation because the zooplankton biomass was found to be 10–100 times more than open river habitat.

4.3 Water Quality

Water quality conditions, including contaminants, low dissolved oxygen (DO), increased temperature and reduced turbidity can adversely affect native fish and other aquatic organisms in the Bay-Delta watershed. In addition to impacting aquatic organisms, various contaminants may impact terrestrial wildlife, including birds, and may bioaccummulate in edible fish tissue to become a human health concern. While also related to water quality, flow management and associated salinity management is addressed in a separate section, and in detail throughout this Report. DO concentrations, turbidity, and temperatures are also parameters directly influenced by flow management that are discussed individually below and in the context of flow elsewhere in this Report. Contaminants are also affected by flows but are primarily discussed in this chapter.

4.3.1 Contaminants

Contaminants are introduced into Bay-Delta waterways by wastewater treatment works, agricultural and industrial discharges and urban storm water runoff. Herbicides and insecticides are also applied directly to Bay-Delta waterways for aquatic plant and mosquito control. Other contaminants already exist in the environment naturally or are legacy contaminants that are no longer in use but still present in the environment. Many of these contaminants can affect the survival and fitness of organisms and alter food webs and ecosystem dynamics. Some contaminants may also enter public drinking water sources and bioaccumulate in edible fish tissue to become a human health concern (Davis et al. 2013). Other trace metals and organic compounds bind strongly with sediment making the movement of sediment a mechanism for their transport (Schoellhamer et al. 2007). The Central Valley and San Francisco Bay Regional Water Quality Control Boards and State Water Board have various efforts underway to address these and other contaminants. These efforts are complimentary to the State Water Board's efforts to update the Bay-Delta Plan.

In general, contaminant effects vary based on the magnitude and duration of exposure and species-specific sensitivity, with insecticides and heavy metals being more likely to affect zooplankton and other small bodied invertebrates.) At higher trophic levels, toxic effects from these contaminants are less likely to be lethal (i.e. no kill fish), but sublethal effects may reduce ecological fitness through impaired growth, reproduction, or behavior, or increase the organism's susceptibility to disease (Davis et al. 2013). Moreover, the consequences of sublethal pollutant effects on keystone species that play a disproportionate role in controlling ecosystem function may manifest itself throughout the entire ecosystem (Clements and Rohr 2009).

The level and degree to which a species is exposed to different contaminants varies based on a number of factors including the species' life cycle, geographic range of that species, contaminant loading and other factors. Reduced freshwater inflow from the Sacramento-San Joaquin River system may also reduce the estuary's capacity to dilute, transform, or flush contaminants (Nichols 1986). Aquatic organisms may be simultaneously exposed to contaminants present in water, sediment, and/or food depending on the species, life stage, life history, trophic level, and feeding strategy. For example, early life stages of many Delta fish species inhabit the system during late winter and spring, a time when storm water runoff from agricultural and urban areas can transport contaminants, such as dormant spray pesticides and metals, into the Delta. Early life stages are generally far more sensitive to contaminants than adults and the toxic effects of these contaminants may be far more serious seasonally for that reason (Werner et al. 2010b; Weston et al. 2014). Bottom-feeding fish or sediment-dwelling invertebrates may also be more likely to be exposed to sediment-associated contaminants (via diet and interstitial water), while pelagic (meaning "open water") organisms are mostly exposed to dissolved and suspended particle-associated contaminants in the water column.

4.3.1.1 Pesticides and Other Pollutants

Recent water quality sampling surveys from 2011 and 2012 indicate widespread occurrence of a number of agricultural pesticides including insecticides, herbicides, and fungicides throughout the Delta (Orlando et al. 2013). The toxicity of these new pesticides to aquatic life is not known (SWRCB, SFRWQCB, and CVRWQCB 2014). Pesticide transport is influenced by the timing of pesticide applications and by rainfall, runoff, and streamflow conditions.

Pesticide toxicity has been suggested as one potential factor contributing to the decline in the population of Delta smelt and other pelagic fishes (Sommer et al. 2007). Exposure to pesticides is more likely to occur in the rainy season due to stormwater runoff, which increases pesticide loading in streams and rivers. A study by Kuivila and Moon (2004) examined the co-occurrence of Delta smelt and pesticide concentrations at sampling locations in the central and south Delta from 1998-2000. For some locations, peak pesticide concentrations coincided with the highest population densities of Delta smelt (Bennett 2005) although no evidence of toxicity was determined.

In recent years, pyrethroid insecticides have been detected in sediment samples collected from water bodies draining agricultural areas in the Central Valley (Weston et al. 2004). Many of these samples were toxic to aquatic insects in bioassays (Werner et al. 2010a; Weston and Lydy 2010). Urban runoff samples collected in Sacramento, Stockton and Vacaville have been found to contain pyrethroid insecticides and caused death or reduced swimming ability to the amphipod *Hyalella azteca* in bioassays (Werner et al. 2010a). Wastewater effluent samples were also found to contain quantifiable concentrations of pyrethroids, suggesting that significant loading of pyrethroids may occur from wastewater treatment facilities (Weston and Lydy 2010). A pyrethroid pesticide control program for Central Valley Rivers and the Delta is being developed by the California Regional Water Quality Control Board, Central Valley Region.

Mosquito and Vector Control Districts use Integrated Pest Management (IPM) to control mosquito populations in Counties surrounding the Delta (Sacramento-Yolo Mosquito & Vector Control District 2014). IPM includes biological, physical and, as a last resort, chemical/microbial control. The chemical and microbial agents used are organophosphate and pyrethroid insecticides, *Bacillus thuringensis* and *B. sphaericus*, two bacterial extracts, and the insect growth regulator methoprene. Chemical applications include direct applications on stagnant surface water including seasonally flooded wetlands.

There are several legacy contaminants that are no longer used but are still present in the Bay-Delta Watershed. Organochlorine (OC) pesticides like dichlorodiphenyltrichloroethane (DDT), chlordane, and dieldrin have been banned, but were used extensively in agriculture in the Central Valley half a century ago. Presence of these pesticides in fish tissue collected from Central Valley rivers and the Delta resulted in issuance of advisories recommending limited human consumption of some fish species (De Vlaming 2008). OC pesticide concentrations have declined and were significantly lower in fish caught in 2005 than during the 1970s although some individual fish still had concentrations above levels of concern for human health (De Vlaming 2008). Connors et al. (2007) reports that legacy pesticides enter San Francisco Bay from a variety of sources, including runoff from the Central Valley and from dredging and disposal of dredged material.

Polychlorinated biphenyls (PCB) are legacy industrial contaminants which persist in the environment. PCBs were banned in the late 1970s. Like OC pesticides, PCB contamination was widespread and fish advisories were released for multiple Central Valley Rivers and the Delta (De Vlaming 2008). PCB fish tissue concentrations have declined and in 2005 were less than in earlier periods, however, some fish still had concentrations of concern for human health (De Vlaming 2008).

PCB concentrations in some San Francisco Bay sport fish today are more than ten times higher than the threshold of concern for human health and three San Francisco Bay monitoring stations have also shown to have PCB concentrations more than ten times higher than 2006 water quality objectives for fish and wildlife (Davis et al. 2007). PCB contamination is generally associated with industrial areas, especially near port facilities and areas along shorelines, and urban runoff in local watersheds throughout the San Francisco Bay area. The San Francisco Bay Regional Water Quality Control Board adopted a PCB control program in 2007 (SFBRWQCB 2007).

4.3.1.2 Endocrine Disruptors

Endocrine disruptors are contaminants from pharmaceuticals and personal care products, and industrial chemicals. Endocrine disrupting chemicals can interfere with the hormonal systems in fish and wildlife, and act at low concentrations resulting in negative effects on reproduction and development. Exposure of fish populations to low concentrations of such compounds can have dramatic effects. For example, Brander et al. (2013) found that the reproductive health of *Menidia audens* (Mississippi silverside), a small pelagic fish introduced to the Delta, was negatively impacted by endocrine disrupting chemicals in samples from two locations in Suisun Marsh. The State and Regional Water Boards have various monitoring programs and special studies in its drinking water and recycled water programs for constituents of emerging concern, including endocrine disruptors.

4.3.1.3 Ammonia/Ammonium

Ammonia exists in two forms in water: un-ionized ammonia (NH3) and ammonium (NH4). The equilibrium between NH3 and NH4 depends primarily on pH and to a lesser extent on temperature and salinity (USEPA 2013). Both NH3 and NH4 are present in effluent from municipal wastewater treatment plants and confined animal facilities. Additional sources of NH4 to the Delta include agricultural and urban runoff, atmospheric deposition and internal nutrient cycling (Novick and Senn 2013). NH3 is the more toxic of the two forms. In acute and chronic toxicity tests freshwater mussels were the most sensitive aquatic organisms. Juvenile salmonids were the most sensitive cold water fish species (USEPA 2013).

Recent work has shown that elevated NH4 levels reduce diatom growth rates in water samples collected from Suisun Bay and from the Delta by suppressing nitrate uptake (Wilkerson et al. 2006; Dugdale et al. 2007; Parker et al. 2010). High filtration rates by the overbite clam, *Corbula*, and high turbidity levels are additional factors that may be responsible for reducing diatom production and standing algal biomass in Suisun Bay. Elevated NH4 levels may contribute to the observed shift in algal species composition from diatoms to blue-greens and flagellates (Glibert et al. 2011; Brown 2010). These latter algal forms are less sensitive to elevated NH4 concentrations (Glibert et al. 2011) and are believed to be less nutritious to secondary consumers, like zooplankton (Lehman 1998; Glibert et al. 2011). The San Francisco Bay and Central Valley Regional Water Quality Control Boards are planning a joint workshop to evaluate the role that NH4 and other nutrients and nutrient ratios may play in algal growth and species composition in the San Francisco Estuary. The results of the workshop will inform the development of a nutrient research plan and potential future nutrient control efforts.

4.3.1.4 Cyanobacteria

Cyanobacteria blooms have occurred in the Delta almost every year since 1999 (Lehman 2005). *Microcystis aeruginosa* is the most common cyanobacteria species although *Anabaena* and *Aphanizomenon* have also been seen (Berg and Sutula 2015). All three blue green algal species secrete hepatotoxins which can be toxic to people, wildlife and livestock if ingested (Lehman 2008; Berg and Sutula 2015). Sublethal toxic concentrations of microcystin have been measured in fish in the Delta. Striped bass and Mississippi silversides from the Delta have been collected with liver lesions consistent with sublethal exposure to microcystin (Lehman et al. 2010). Dissolved microcystin concentrations in the Delta have also occasionally exceeded both the Office of Environmental Health and Hazzard Assessment Action level for human health and the World Health Organization recreational use guideline (Berg and Sutula 2015).

M. aeruginosa blooms tend to occur during the summer and fall in the Central Delta associated with water temperature above 20°C, long water residence time, high irradiance and elevated nutrient concentrations (Jacoby et al. 2000; Berg and Sutula 2015). These factors are more common during drought years which may, at least partially, explain the recent increase in cyanobacteria blooms in the Delta. Salinities greater than 10 parts per thousand (ppt) suppress *M. aeroguinosa* growth (Berg and Sutula 2015).

The Central Valley Regional Water Quality Control Board is developing a research plan to determine whether nutrient control will reduce the magnitude and frequency of cyanobacteria blooms and toxin formation in the Delta. To help guide this effort Berg and Sutula (2015) have written a white paper on the factors affecting the growth of Cyanobacteria in the Sacramento-San Joaquin Delta. Results of the research will inform future nutrient control planning.

4.3.1.5 Selenium

Selenium is an essential micronutrient at low levels but toxic at higher concentrations (Chapman et al. 2009). The most lethal forms of selenium are selenomethionine and selenocysteine (Chapman et al. 2009). Organic forms of selenium are produced by microorganisms and biomagnify in aquatic food chains with diet being the primary route of exposure (Lemly 1985; Chapman et al. 2009). At high concentrations, selenium is a reproductive toxicant (Chapman et al. 2009). The primary controllable sources of selenium to the San Francisco estuary are subsurface agricultural drainage from the west side of the San Joaquin Valley and discharge of oil processing waste from refineries in the North Bay (USEPA 2016). Total maximum daily loads (TMDLs) were adopted for the control of loads from both sources. TMDLs have reduced agricultural and refinery loads, but ambient concentrations may still be above levels of concern in some parts of the Estuary (USEPA 2016) with bottom feeding species, such as white sturgeon and diving ducks, being at risk of toxicity from elevated selenium concentrations (Baginska 2015).

4.3.1.6 Mercury

Mercury was mined in the California Coast range and used in gold mining in the Sierra Nevada Mountains (Churchill 2000). The mining resulted in widespread inorganic mercury contamination in water courses in the Coast range, valley floor and Sierra Nevada Mountains. Methyl mercury is the most toxic form of the element and is produced by sulfate reducing bacteria in anaerobic sediment (Compeau and Bartha 1985; Gilmour et al. 1992). River bottoms and seasonal wetlands are primary sources of methyl mercury production in Northern California (Wood et al. 2009). Like selenium, methyl mercury bioaccumulates in the aquatic food chain with the primary route of exposure being consumption of mercury contaminated fish (USEPA 1997). At greatest risk are human and wildlife fetuses and young (NRC 2000). Fish advisories have been issued recommending limited human consumption of several fish species caught in the Sacramento and San Joaquin Rivers and in the Bay-Delta Estuary (OEHHA 2009). The San Francisco Bay and Central Valley Regional Water Quality Control Boards adopted mercury TMDL control programs for San Francisco Bay and the Delta.

4.3.2 Low Dissolved Oxygen

DO is critical to the health and survival of aquatic species. DO concentrations in waterways are affected by temperatures, flows, channel characteristics, waste discharges, mixing, oxygen demanding organisms, and substances in the channel. DO concentrations typically are lowest during the summer with low river flows and warmer river temperatures (Spence et al. 1996; Newcomb et al. 2010). Warm water holds less DO and higher water temperatures increase the metabolic rate and associated oxygen consumption rate of aquatic organisms (Myrick and Cech 2000). The occurrence of decomposing aquatic vegetation, poor channel geometry, poor mixing of water with the atmosphere, and the presence of oxygen-depleting substances (e.g., sewage, animal waste, ammonia, organic nitrogen, and algae) can also contribute to diminished DO conditions, though tidal cycle and stream flow may be strong factors that impact all the others (USFWS 2001; O'Rear and Moyle 2008; Nobriga 2008).

The occurrence of locations with low DO concentrations in the Delta may have negative impacts on aquatic organisms, as many species are unable to tolerate low DO conditions (Moyle 2002; Moyle and Cech 2004). Fish generally avoid low DO situations, but sensitivity varies by species. Fish also often show a threshold response to low DO such that a fish may show no response to decreasing oxygen to a certain point, then show substantial effects when DO concentrations are further reduced (Cech et al. 1990).

Low DO concentrations are a particular concern for salmonid species that migrate up to or out of upper watersheds to or from the ocean. Low DO can both reduce the suitability of areas for spawning or rearing and block or delay passage to suitable habitat for spawning and rearing both in the Delta and tributaries where fish travel (Newcomb et al. 2010; Scholz et al. 2011). Low DO and a lack of attraction flows may also delay or block the upstream migration of Chinook salmon and lead to straying (NMFS 2014; USFWS 2001; Marston et al. 2012).

Seven creeks and sloughs in the southern and eastern Delta; and the lower Calaveras, Middle, Mokelumne and Old Rivers are on the Clean Water Act (CWA) Section 303(d) list as impaired because of low DO. Low DO also occurs in low flow channels and dead-end sloughs particularly in Suisun Marsh (O'Rear and Moyle 2009). Fish kill events have been observed when managed wetlands are flooded and subsequently drained, which releases high loads of organic carbon and low DO water into adjacent channels (Tetratech 2013; O'Rear and Moyle 2009). The San Francisco Bay Regional Water Quality Control Board is in the process of developing a TMDL control program to correct the low DO impairment in Suisun Marsh. Low DO can also interact with contaminants by increasing their toxicity to fish (Lloyd 1961; Evans and Claiborne 2006) and impairing swimming ability (Shingles et al. 2001).

4.3.3 Sediments and Turbidity

Turbidity is a measure of water clarity and is important for some estuarine species (Bennett 2005; USFWS 2001). Reductions in turbidity are associated with declines in estuarine habitat for Delta smelt, striped bass, and threadfin shad. These fish are found in high abundance near X2, an area of optimal turbidity for some native fishes (Hasenbein et al. 2012). Laboratory studies have shown that Delta smelt require turbidity for successful feeding (Baskerville et al. 2004).

Delta turbidity occurs when suspended material such as silts, clays, and organic matter come from the major tributary rivers during high flow events, are deposited in river channels and mudflats and periodically resuspended by wind (Schoellhamer et al. 2007; Schoellhamer 2011). Turbidity in the Delta has decreased through time. In rivers, dams reduce the supply of sediment that would be deposited on the valley floor or in upstream channels in the watershed because reservoirs trap sediment and release water containing little or no sediment. This can lead to net erosion of the channel downstream of dams (Wright and Schoellhamer 2004) where salmonids spawn, reducing the quality and quantity of appropriate spawning habitat (Moyle 2002). Likewise, reservoir releases are less variable than natural flows, i.e., peak flows are stored in the reservoir for flood control, irrigation, and water supply. Because the majority of sediment transport occurs during high flows, reducing the magnitude of these flows reduces the total sediment load transported downstream. Other factors that have likely reduced sediment yield include bank protection measures, such as riprap, that have been implemented to minimize the risk of levee and bridge failures in many locations (Wright and Schoellhamer 2004).

4.3.4 Temperature

Water temperature is a key factor in habitat suitability for aquatic organisms. High water temperature is a stressor for many aquatic organisms (Kammerer and Heppell 2012), particularly for fish because warm water contains less of the DO that is needed to support metabolic functions (Salinger and Anderson 2006; Evans and Claiborne 2006). Higher water temperatures also increase growth and distribution of many nonnative species, thus increasing their predation on, and competition for food and habitat with native species (Kiernan et al. 2012; Moyle 2002). Major factors that increase water temperature and negatively impact the health of the Delta are disruption of historical streamflow patterns, loss of riparian vegetation, reduced flows, discharges from agricultural drains and climate change (USFWS 2001).

Exposure of Chinook salmon and steelhead populations to elevated water temperatures is a major factor contributing to the decline of Chinook salmon and steelhead populations (Myrick and Cech 2001). Elevated temperatures have also been shown to have lethal effects on other native species like Delta smelt who are affected between 25-28°C, depending on life stage (Swanson et al. 2000; Komoroske et al. 2014). Temperatures in the Delta can get very high (≥28°C), especially when water is shallow such as in sloughs and canals (Meng and Matern 2001; O'Rear and Moyle 2009). This restricts native species habitat as they cannot persist at high temperatures.

4.4 Nonnative Species

The Sacramento River, Bay-Delta and major tributaries to both Suisun Bay and Suisun Marsh are home to a diverse assemblage of native and nonnative species. While native species evolved and adapted to the unique hydrology of the area, nonnatives were introduced over time deliberately and accidentally by government agencies and others, ship ballast water releases and other vessel introductions, releases of aquarium species, and bait bucket releases (Kimmerer 2004). Species were deliberately introduced for several reasons including: 1) improving fishing and aquaculture, 2) providing bait for anglers, and 3) providing biological control of aquatic pests or disease vectors (Moyle 2002). There are over 250 introduced species, including fish, invertebrates and plants, in the Bay-Delta (Cohen and Carlton 1995; USFWS 2004).

When nonnative species are introduced to an ecosystem, they can have direct and indirect effects on native species and affect ecosystem processes. Nonnatives can reduce ecosystem biodiversity by placing additional stress on native species through 1) competition, 2) predation, 3) hybridization, 4) habitat interference, and 5) disease (Moyle 2002; Mount et al. 2012). Regions in the Bay-Delta watershed with the greatest alteration in flow are most dominated by non-native species (Brown and May 2006; Brown and Michniuk 2007). The altered hydrology creates more competitively favorable conditions for spawning and rearing of non-natives than natives (Brown and Bauer 2009).

The Bay-Delta alone has roughly 51 nonnative freshwater fish species that have become part of the ecosystem (Moyle 2002). It has been acknowledged by the scientific community that the Bay-Delta Estuary has become a novel ecosystem given all the nonnative introductions (Moyle et al. 2012). Many are considered to be recreationally or commercially important such as striped bass, largemouth bass, and threadfin shad, all of which interact with native species but some of which are also in decline (Sommer et al. 2007; Moyle et al. 2012).

NMFS considers predation by nonnative species an important factor affecting Sacramento River winter-run Chinook salmon (*Oncorhynchus tshawytscha*), Central Valley spring-run Chinook salmon (*O. tshawytscha*), Central Valley fall- and late fall-run Chinook salmon, and Central Valley steelhead (*O. mykiss*) (CDFW 2011). Native predators of salmon and steelhead include pikeminnow (*Ptychocheilus grandis*), several avian species (BPA 2010) in the Delta, along with the occasional marine mammal (CDFW 2011a; Grossman et al. 2013). Invasive fishes may either eat or compete with smelts and other natives for food (Sommer et al. 2007; Moyle 2002), most notably centrarchids such as bass species, the major ones discussed here (DSC 2013). As discussed below, centrarchids interfere with native species through predation and competition (Grossman et al. 2013).

4.4.1 Fishes

4.4.1.1 Threadfin Shad

Threadfin shad were intentionally introduced to the Bay-Delta in 1959 to provide forage for game fish. From these transplants, they have become established in the Sacramento-San Joaquin Delta. Juveniles form dense schools and are found in shallow water of all salinities, although they are most abundant in fresh water (Moyle 2002). Shad are an important food resource for striped bass and other piscivorous or “fish-eating” fish in the Delta although their overall role in the aquatic food web is unknown (Moyle 2002). Threadfin shad abundance declined substantially in the early 2000’s and has remained low (Sommer et al. 2007).

4.4.1.2 Catfish

Catfish, introduced in the 1800s, are bottom feeders that prefer low flow areas and back-end sloughs. Catfish tend to associate with other alien species that favor highly altered environments (Moyle 2002). They can live in many temperatures but seem to be most common at 20-33°C. Thus, low flow, turbid areas favor these fish. White catfish, for example, like slow-current areas like Frank’s Tract and the south Delta. Catfish are omnivorous and feed by angling mouth barbels just above the substrate to suck up insects and larvae, eating whatever organism is most available including small fish. As benthic or bottom feeders, they may compete for habitat with native benthic feeding fish such as sturgeon. They spawn May through July, and are able to adapt to a wide range of salinities. They are important as a recreational fish (Moyle 2002).

4.4.1.3 Striped Bass

Striped bass were introduced to the Bay-Delta in 1879 from the Atlantic Coast to establish a commercial fishery on the West Coast (Dill and Cordone 1997). Within 10 years of their introduction, the striped bass fishery supported one of California’s largest commercial and recreational fisheries, though their numbers have declined since the 1930s (Moyle 2002).

Striped bass is a euryhaline pelagic fish, meaning it can adapt to a wide range of salinities and lives in open water. Striped bass are widespread in the Bay-Delta Estuary. Adults spend the majority of their life in saltwater and return in fall to freshwater to spawn (Baxter et al. 2008). Striped Bass populations are usually located in San Pablo Bay, San Francisco Bay; however, the species can also be found in the larger river systems downstream of impassible dams (Baxter et al. 2008). Approximately one half to two thirds of the striped bass population spawns in the Sacramento River Basin while the remainder spawns in the lower San Joaquin River. Striped bass can withstand a wide range of environmental conditions including high water temperatures, low DO, high turbidity, and rapid temperature changes that native species of the Bay and in particular, the Delta, cannot (Moyle 2002). Their adaptability often lead them to outcompete and prey on native fish species that are at a disadvantage due to degraded ecosystem conditions (Ferrari et al. 2013; Loboschefsky et al. 2012; Sabal et al. 2016). Striped bass are opportunistic and feed on whatever prey is most abundant, from invertebrates to their own young to salmon smolts and shad (Nobriga et al. 2013; Grossman et al. 2013). The population level effect of striped bass predation on salmonid population abundance is not known (Grossman et al. 2013).

4.4.1.4 Largemouth Bass

Largemouth Bass was first introduced to the Bay-Delta in 1891 for mosquito and algal control (Dill and Cordone 1997; Moyle 2002). Within ten years of their introduction, the largemouth bass fishery flourished, and is still a large recreational fishery. They have many similarities to striped bass and are also predators of native species and competitors with natives (Moyle 2002).

Many California reservoirs and farm ponds support an abundance of largemouth bass for fishing. Like striped bass, largemouth bass are more tolerant than native species to environmental stressors, such as changes in water levels, temperature, and DO levels (Schindler et al. 1997; Moyle 2002).

4.4.1.5 Inland Silversides

Silversides (*Menidia*), also called Mississippi silversides or Inland silversides, were introduced into the Bay-Delta in 1960's, and are now the most abundant fish in many shallow-water areas of the estuary (Chernoff et al. 1981; Kramer et al. 1987; Moyle 2002). Silversides school in large numbers near sand or gravelly bottom habitat and occur in a range of temperatures up to 34°C. They are commonly found in estuarine salinities (10–15 ppt) that overlap with many native species (Moyle 2002). In particular, silversides may outcompete Delta smelt and other small estuarine species like juvenile salmonids, splittail, and other fish of shallow habitat areas that may spawn and rear there. Silversides are voracious predators on fish larvae and are abundant in the shallow areas where Delta smelt spawn, especially during low flow years (Moyle 2002). The introduction of silversides coincided with and may have contributed to the crash of Delta smelt populations, and their continued abundance may inhibit recovery (Moyle 2002).

4.4.1.6 Wakasagi Smelt

Wakasagi smelt are native to Japan and were first detected in the American River, where they were likely introduced as a result of a recreational aquarium release. Wakasagi live 1–2 years, are anadromous, and have a temperature tolerance of 27–29°C maximum (Swanson and Cech 2000). Their spawning period is April to May, and they deposit eggs in sand or gravel, much like Delta smelt (Wang et al. 2007). Wakasagi may compete with native Delta and longfin smelts for food and habitat and may also eat their eggs (Moyle 2002).

In addition to competing with and preying upon Delta smelt, Wakasagi may breed with Delta smelt resulting in hybridization and introgression. Hybrids of Delta smelt and Wakasagi have already been detected. This hybridization and introgression can compromise the distinct character of a native species, reduce its reproductive fitness and jeopardize its continued existence (Moyle 2002; Wang 2007; Swanson and Cech 2000; Fisch et al. 2014).

4.4.2 Invertebrate Species

The value of the Bay-Delta estuary as a nursery area for native species has been compromised by the invasions of nonnative invertebrates including copepods, amphipods, shrimp, crabs and clams which now dominate both the benthic and planktonic environments of the estuary and disrupt the base of the food web in the estuary (Mount et al. 2012; Sommer et al. 2007; Jassby et al. 2002).

Well-documented long-term declines in phytoplankton biomass (chlorophyll-a) and primary productivity in Suisun Bay and other locations in the Delta is apparent from 1975-2005 (Jassby et al. 2002; Jassby 2008), attributable in part to the introduction of invasive bivalves. *Potamocorbula* *amurensis* or *Corbula amurensis*, (hereafter referred to as"*Corbula*") is native to Asia and was first observed in the Bay-Delta in 1986 (Carlton et al. 1990; Jassby 2008). *Corbicula fluminea*, is native to southeastern and eastern Asia and Africa and was first reported in the Bay-Delta in 1945 (Cohen and Carlton 1995). As filter feeders, clams consume large quantities of phytoplankton, bacterioplankton, and small zooplankton such as rotifers and copepod nauplii (Greene et al. 2011), decreasing availability of food for larger zooplankton and mysids that serve as food for fish species in the Delta (Mount et al. 2012). When *Corbula* invaded, there was a large decline in the carrying capacity of the estuary for Delta and longfin smelt (Bennett 2005; Moyle et al. 2016). Today *Corbula* dominates the entire brackish transition zone of the estuary and its grazing influence extends well into the Delta and *C. fluminea* is widely dispersed as the most abundant bivalve species in the freshwater portion of the Bay-Delta (Lucas et al. 2002). Because of the widespread and overlapping distribution of these two invasive clam species, there are very few locations in the estuary where phytoplankton assemblages can persist without the effects of clam grazing and the capacity of the system to produce food for fish and other consumers is now limited.

Between the early 1960s to mid-1990s, eight East Asian pelagic copepods are known to have been introduced to the Bay-Delta estuary where they have replaced native species and disrupted the food chain for native species. Those species include: *Acartiella sinensis*, *Limnoithona sinensis*, *Limnoithona tetraspina*, *Oithona davisae*, *Pseudiodiaptomus forbesi*, *Pseudodiaptomus marinus*, *Sinocalanaus doerri*, and *Tortanus dextrilobatus* (Orsi and Ohtsuka 1999). During the late 1980s and early 1990s, the nonnative copepod *P. forbesi* largely replaced the native *Eurytemora affinis* as *Corbula* became abundant in the low-salinity reaches of the estuary (Winder and Jassby 2011). *E. affinis* still achieves high population levels during spring, but is replaced by *P. forbesi* in late spring and early summer. While small native fish such as smelts can switch between both prey species, *P. forbesi* is a faster swimmer than *E. affinis*, and may not be as cost-efficient a prey type to consume (Morgan et al. 1997; Slater and Baxter 2014; Moyle et al. 2016).

Some of these nonnative copepods are also generally less nutritious for native fish. *Psuedodiaptomus forbesi*, *Acartiella* spp. and *Limnoithona*, are smaller than native copepods such as *Eurytemora* spp. and *Acartia* spp and take more energy to capture while providing less nutritional value than natives (Winder and Jassby 2011; Mount et al. 2012). *P. forbesi* species also tend to consume ciliates, which have lower nutritional quality, instead of higher quality diatoms.

In addition to the above, mysid populations, including *N. mercedis* and several species of *Crangonid* shrimp in the Delta, have also been impacted by invasive species. Native mysid populations, which are the preferred and more nutritious prey for both juvenile and adult native fish species, have declined (Winder and Jassby 2011). Natives have been replaced by nonnatives including *Gammarus daiberi* (Kimmerer 2004) and the grass shrimp, a commercial bait species. Rotifers, another important food source for larval fish, have also declined.

At the same time, two species of jellyfish, believed to be native to the Black and Caspian Seas, are now established in Suisun Bay. There is concern regarding the potential of these predatory jellyfish to alter zooplankton communities and feed directly on larvae and early juveniles of native and nonnative fish, although the extent to which this has occurred remains undocumented (Rees and Gershwin 2000).

Complex trophic interactions can make it hard to predict the outcome of the observed changes in zooplankton and micro-zooplankton species composition and abundance (York et al. 2013). However, the changes that have been observed in the Bay-Delta suggest a shift has occurred in energy flow from a phytoplankton-based pelagic food web to a detritus-based benthic food web (Winder and Jassby 2011).

4.4.3 Plants

Nonnative plant species have the ability to spread rapidly under the right types of environmental conditions, displacing native species, clogging waterways, altering turbidity, and negatively affecting other aquatic species. In the Bay-Delta there are several nonnative plant species that cause harm to native species including Brazilian waterweed, water hyacinth, water primrose, curly leaf pondweed, milfoils (e.g., Eurasian Watermilfoil), and Giant Reed. (Ferrari et al. 2012; CDBW 2014; DSC 2013; Boyer and Sutula, 2015). However, the two most problematic nonnative aquatic plant species in the Delta are the Brazilian waterweed and water hyacinth. These species are often considered "ecosystem engineers" (Mount et al. 2012) because they have the ability to create, significantly modify, maintain, or destroy habitat.

Brazilian waterweed, or *Egeria densa*, is native to South America and was introduced to the United States in 1893, and became established in shallow littoral areas of the upper Bay-Delta during the mid-1980s. From 2004 to 2006, the distribution of Brazilian waterweed increased by more than ten percent per year and has become rampant during the recent drought. Brazilian waterweed has many detrimental effects on the Bay-Delta ecosystem. It traps suspended sediment in the water column, inducing deposition and a change in the texture and organic content of underlying shallow-water sediments (Ferrari et al. 2013; Conrad 2016). Water circulation is impeded in areas of dense waterweed growth, and local increases in water temperature, and decreases in DO may occur. This increase in water clarity reduces habitat suitability for native fish such as the Delta smelt, and simultaneously enhances habitat suitability for nonnative species, notably centrarchids (Brown and Michniuk 2007). Small prey species which use turbidity as a refuge from predation are also at an increased risk in a system with increased water clarity (Ferrari et al. 2013).

Water hyacinth, or *Eichhornia crassipes*, is native to South America and was introduced to the United States in 1884 (DSC 2013). Water hyacinth is an invasive nonnative species, and since its introduction has proliferated to such an extent that eradication is next to impossible (CDBW 2012). The main issue created with hyacinth is that it covers the entire water surface of many sloughs, blocking light available to phytoplankton and other submersed autotrophic plants, decreasing DO, creating barriers, both physical and in the form of changing turbidities in the water column, affecting fish feeding and passage (Villamagna and Murphy 2010), much like *Egeria* (Ferrari et al. 2013).

A number of control options are being evaluated. The Central Valley Regional Water Quality Control Board has assembled a Science Work Group and is developing a research plan to determine whether nutrient control will reduce the abundance and distribution of invasive macrophytes in the Delta (CVRWQCB 2014). As part of this effort, Boyer and Sutula (2015) have written a white paper on the factors that control submerged and aquatic macrophytes in the Sacramento-San Joaquin Delta estuary to inform future nutrient research and, if needed a nutrient research plan. The U.S. Department of Agricultural Research Services and the California Department of Food and Agriculture are investigating the potential introduction of biological control agents for control of aquatic weeds (Boyer and Sutula, 2015). The California Department of Boating and Waterways now applies chemical herbicides to control the spread of both E. densa and E. crassipes and have experimented with mechanical shredding (Boyer and Sutula, 2015; CDBW 2006).

4.5 Fisheries Management

This section focuses on the effects of fisheries management activities on the aquatic ecosystem in the Delta and its tributaries such as harvest and hatchery operations.

4.5.1 Harvest

The Delta and its tributaries currently support a commercial salmonid ocean fishery and a recreational and subsistence marine and freshwater fishery for striped bass, largemouth bass, black bass, white sturgeon, Chinook salmon, steelhead, catfish, and American shad (DFW 2012). The only commercial fisheries in the Delta are for threadfin shad and crayfish. (Water Science and Technology Board et al. 2012). These activities may impact native fish species.

Some fishermen in the Delta rely on fishing for primarily resident alien centarchids and catfish, but also native salmonids and sturgeon for subsistence. This practice has been increasing with the growth of ethnic groups that have the tradition of harvesting local fish (Moyle 2002; Mount et al. 2012). Poaching represents an illegal form of harvest, and has been a problem in the Delta specifically for sturgeon, whose roe are used as caviar (Mount et al. 2012). In addition, green sturgeon can be caught incidentally while fishing for white sturgeon, and must be released. Hooking mortality may occur due to incidental catches (ICF International 2012).

Commercial, recreational, and tribal fisheries represent a potential stressor for the Chinook salmon population. The commercial and recreational ocean and recreational inland fisheries for Chinook salmon are for a mixed stock of wild and hatchery-produced fish. Because the stock of wild salmon is small, their populations are less able to withstand high harvest rates than hatchery-based populations. Harvest has the potential to result in detrimental effects on the wild stock by altering the abundance, distribution, and demographics of the population (Moyle 2002; Knight and Cole 1991). The recreational freshwater fishery has a lower impact than the commercial ocean harvest because less fish are taken (ICF International 2012).

The primary effect of the commercial ocean harvest of salmon is the decline in abundance of four-year-old fish. The loss of a multiple-aged population causes salmon runs to be more vulnerable to natural disasters. In addition, four-year-old female salmon dig deeper redds that protect eggs from bed scour during high flows. Four-year-old females also produce more eggs than do three-year-olds and the reduction in numbers of four-year olds has reduced the overall fecundity of the wild population (Mesick 2001).

4.5.2 Boating

Fishing activities within the Delta and its tributaries can contribute to other stressors. Boats, other watercraft, and trailers used to transport them are primary sources of aquatic nonnative species. Nonnative species such as mussels can become attached to the hulls and engines of watercraft or various parts of trailers, or be transported in standing bilge water or live bait tanks (ICF International 2012; DSC 2013). Fragmentation (from operating watercraft) of invasive water plants such as *Egeria densa* may also occur, increasing the spread of the species (NMFS 2014).

Boats and other watercraft can create wave action in the water channel that may degrade riparian and wetland habitat by eroding channel banks and mid-channel islands, thereby causing an increase in siltation and turbidity. Wakes and propeller wash also churn up benthic sediments thereby potentially re-suspending contaminated sediments (USDOI 2008; NMFS 2014). Resuspension, in turn, reduces habitat quality for the benthic invertebrates that may serve as a forage base for juvenile salmonids and green sturgeon moving through the system. These physical habitat effects can smother sessile organisms, prolong hatching times, reduce fish growth rates, lessen feeding efficiency, impair schooling ability, and impair the growth of bottom vegetation as a result of reduced light penetration (Lindegarth 2001; Bishop and Chapman 2004).

Marina facilities, including boat launching ramps, can impact aquatic resource through boat wake-induced shore erosion, re-suspension of bottom sediments and the release of highly toxic anti-fouling coatings from boat hulls and treated timbers, hydrocarbon spills associated with boat refueling, discharge of sewage from vessels, toxic runoff from boat repair and maintenance areas, and other impacts associated with impervious surfaces (URS 2007). Marina facilities and operations also have the potential to affect water quality via accidental spills of contaminants (e.g., sewage, storm drainage, and fish waste), and with it fish rearing or migration routes, submerged aquatic vegetation, tidal marshes, and other important vegetative and aquatic habitat (ICF International 2012). Additionally, building structures that support boating activities such as bridges, piers, and wharves provide conditions that disorient juvenile salmonids and attract predators (NMFS 2014).

Boating activities could result in illegal dumping of domestic and industrial garbage, oil, and other contaminants into the waterway which may also degrade habitat quality. These contaminants may injure or kill salmonids and other fish species by affecting food availability, growth rate, susceptibility to disease, or other physiological processes necessary for survival (USDOI 2008).

4.5.3 Hatcheries

Large-scale releases of hatchery Chinook salmon have supported commercial, tribal, and sportfishing activities for many years (ICF International 2012). Hatchery management has been identified as a factor in the listing of steelhead (NMFS 2014) and is a recognized threat for spring and winter salmonid runs (NMFS 2014). The practice of hatchery production may have negative effects on naturally produced salmon and steelhead through disease transmission, competition from hatchery introductions, and genetic introgression or mixing (USDOI 2008). Another concern is that the use of antibiotics to treat disease in hatcheries increases resistance to diseases known to cause population crashes to native stock (Nichols and Foott 2002). One example is Bacterial Kidney Disease, *Ceratomyxa shasta*, a myxosporean parasite present in the Central Valley (Nichols and Foott 2002; NMFS 2014). Whirling disease and furunculosis are other prevalent diseases affecting hatchery salmonids (Austin et al 1983; Sarker et al. 2015; CPW 2015) and warm temperatures in particular increase the life cycles of parasites and bacteria commonly affecting salmonids. One particularly serious disease for Delta fishes is mycobacterium, which can negatively affect swimming ability (Swanson et al. 2002). Another negative effect of hatcheries is that their discharges, though regulated, can become a problem especially with the introduction of net pens (Brager et al. 2015) such as in the Yolo Bypass (SJRRP 2015).

4.6 Climate Change

Climate change can exacerbate stressors, particularly through increased water temperatures, changing patterns of runoff, and salinity intrusion (Knowles and Cayan 2002; 2004). Following is a discussion of the effects of climate change on those factors and associated effects on fish and wildlife.

The trend of increasing temperature through the 20th century has decreased the controllable water supply, raised flood risk, and contributed to the severity of recent droughts (Roos 2005; DWR 2013). Since 1900, the global average temperature has risen by 1.5° F and may increase an additional 2.5–10.4° F by the end of the century (IPCC 2001; Mirchi et al. 2013). Future temperature increases of 1 to 3 degrees are expected to decrease the magnitude of the snowpack and cause up to 40 percent more of the winter precipitation to fall as rain (Knowles and Cayan 2002; 2004; DSC 2013). The shift in precipitation from snow to rain may result in larger runoff prior to April and less snowmelt-driven runoff in later months. This shift may also lead to higher flooding risks in spring (Knowles and Cayan 2004; Knowles et al. 2006) and lower Sacramento River runoff later in the year (Figure 4.6-1). Reduced snowfall will also diminish the volume of water held in the snowpack and the inter-annual water carry-over capacity of the system, negatively affecting the state's water supply reliability (DSC 2013; Mirchi et al. 2013).

Warmer water temperature because of less runoff from snow melt in spring and summer may directly affect the life cycle of many fish species. Elevated ambient water temperatures can also stimulate growth of nuisance aquatic plants and blooms of harmful algae, which can lead to decreases in DO and increases in organic carbon (DSC 2013). Higher evaporation rates from warmer temperatures, particularly during the hot summer months, contribute to reduced stream flows that lead to drier soils, reduced groundwater infiltration, higher evaporative losses of water from surface reservoirs, increased urban and agricultural demand for irrigation water, and less water available for ecosystem and habitat protection (DWR 2008). Increased water temperature will negatively affect cold water dependent fish species, including salmonids and smelt species, and will likely increase the range of invasive species (Healey et al. 2008; Villamanga and Murphy 2010). The projected effects of climate change are particularly problematic for species like Delta smelt because of their low temperature tolerances (Wagner et al. 2011).

Sea level rise, predicted to increase by as much as 55 inches by 2100 (OPC 2011; DSC 2013), is already occurring in San Francisco Bay (Grenier et al. 2015). Sea level rise will create greater salinity intrusion into the interior Delta, which can impair water quality for agricultural and municipal uses, and has already changed habitat for fish species (Feyrer et al. 2011; Moyle et al. 2010; Grenier et al. 2015). Rising sea level also increases the risk of levee failure and disruption of water exports, particularly in the interior Delta where substantial Delta island subsidence has already occurred (Mount and Twiss 2005; DWR 2008). Rising sea level inundates freshwater marshes and other freshwater aquatic habitats with brackish water, reducing habitat for native plants and wildlife and shifting intertidal to subtidal habitat, and low lying upland areas to intertidal habitat (Mount and Twiss 2005; Whipple et al. 2012; DSC 2013). Additionally, adjacent higher elevation habitat will be necessary for wildlife to escape flooding (ERP 2104; Grenier et al. 2015).

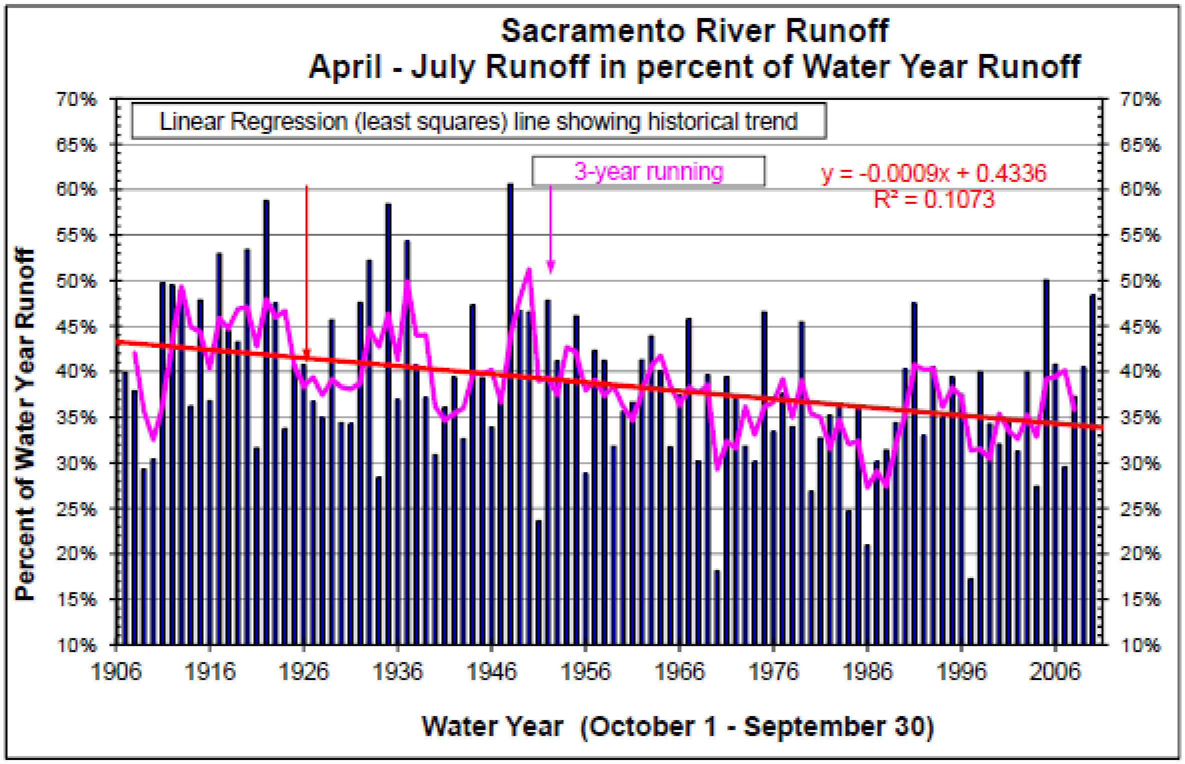

Figure 4.6-1. Declining Trend in April–July Contribution to Total Water Year Runoff in the Sacramento River System, 1907–2010 (from Roos 2012)

4.7 Summary

As stated previously, the State Water Board recognizes that ecosystem recovery in the Delta depends on more than just flow, and a multi-faceted approach is needed to address Delta concerns and reconcile an altered ecosystem. The benefits of flows are enhanced when implemented in concert with other efforts and with consideration of other aquatic ecosystem stressors and climate change. Other stressors are addressed in the context of flow when appropriate (e.g., floodplain restoration could reduce flow demands for splittail), and will also be addressed in the program of implementation.

Chapter 5
Recommended New and Revised Flow Requirements

5.1 Introduction

This chapter describes potential new and revised flow requirements for the Bay-Delta Plan in four general categories, including new inflow requirements for the Sacramento River, its tributaries, and eastside tributaries to the Delta;[1] modified Delta outflow requirements; new cold water habitat requirements; and modified interior Delta flow requirements. The new and revised requirements are being developed to ensure the reasonable protection of fish and wildlife beneficial uses and to address the significant species declines and ecosystem collapse that has occurred since the Bay-Delta Plan was last updated and implemented. The scientific evidence summarized in the preceding chapters indicates that the current Bay-Delta Plan requirements are inadequate to protect the ecosystem and its native fish and wildlife and that a comprehensive regulatory approach is needed that protects the ecosystem and Bay-Delta fish and wildlife throughout their migratory range that integrates inflows, outflows, and Project operational requirements throughout the year in a coordinated manner to the extent possible. Timely and meaningful action is critical given the status of the ecosystem so that improvements can occur before the various imperiled species in the watershed are no longer able to be restored. Because the science is ever evolving and the actions needed to protect the Bay-Delta ecosystem will take significant cooperation, flexibility and coordination with other planning, science and regulatory efforts is also important.

Currently, the Bay-Delta Plan does not include adequate flow and Project operational requirements to provide for critical functions to protect beneficial uses within tributaries and in the Delta including appropriate migration, holding, spawning and rearing conditions. Inadequate or nonexistent requirements may lead to insufficient flows to protect fish and wildlife, drainage of cold water for water supply and instream flow purposes, redirected impacts to times of year when flow requirements are less strict or do not apply and overreliance on one tributary to meet flow and water quality requirements. While there are additional flow and operational requirements included in ESA and CESA requirements to avoid jeopardy of listed species, the State Water Board has an independent and distinct obligation to reasonably protect fish and wildlife that may extend beyond the ESA and CESA requirements.

Chapters 2, 3 and 4 on hydrology, biology, and other stressors include strong scientific evidence to support development of new and revised requirements to address the issues discussed above in an adaptive management framework with other nonflow measures. Additional analyses are presented in this chapter to synthesize the information in prior chapters and to develop the conceptual bases for the recommended changes to the Bay-Delta Plan that will be further developed in the final Report, SED and associated documents. The conceptual bases for all of the requirements are supported by the best available scientific information on functional flow needs of individual species and the ecosystem as well as statistical and other correlation relationships between flows and

[1] Mokelumne, Calaveras, and Cosumnes Rivers.

species needs. Because the Bay-Delta ecosystem is exceedingly complex it is likely not possible to identify every function that drives a correlation relationship with certainty, particularly since it may change to some extent given different circumstances (e.g., temperature relationships may change as a result of availability of food). Nevertheless, the relationships themselves are strong information given their endurance through time and the relatively strong statistical significance for a biologically based relationship. Estimates of specific flow needs to protect fish and wildlife beneficial uses are also imprecise given the various complicating factors between abiotic and biotic factors in this ecosystem. These issues can be addressed through monitoring and adaptive implementation management.

Chapter 2 provides information to demonstrate how altered the current hydrology is in the Sacramento River, its tributaries and the eastside Delta tributaries and the Delta compared to unimpaired conditions. While unimpaired conditions are not natural conditions, they are similar to natural conditions and when compared to impaired conditions serve as an indication of the amount of water that has been removed from the system and the shift in timing of flows that has occurred over the years. Natural channel and other habitat conditions have not existed in the Bay-Delta watershed for more than a hundred years. Nevertheless, many of the native fish and wildlife species were able to maintain healthy populations until relatively recently when water development intensified. When combined with other habitat modifications, the flow alterations have significantly impacted fish and wildlife. In some streams, at certain times, flows are completely eliminated or significantly reduced. At other times, flows are increased, but then exported before contributing to Delta outflows. At the same time, the dams that impound that water block access to upstream habitat and may cause significant warming of flows.

Scientific evidence presented in Chapter 3 shows that native fish and other aquatic species require more flow of a more natural pattern than is currently required under the Bay-Delta Plan to support specific functions for anadromous and estuarine species that provide appropriate habitat quantity and quality. Given the dynamic and variable environment to which fish and wildlife adapted, and our imperfect understanding of these factors, developing precise numeric prescriptive flow requirements that will provide absolute certainty with regard to protection of fish and wildlife beneficial uses is not possible. However, the science indicates that more natural flows that closely mimic the shape of the unimpaired hydrograph including the general seasonality, magnitude, and duration of flows generally provide those functions. Due to the altered nature of the watershed, it may also be necessary to consider flows and cold water habitat preservation requirements that do not mimic the natural hydrograph, but nonetheless produce more natural temperature, salinity, or other water quality conditions for fish in locations where these fish now have access to them. This is the case to some extent in the summer and fall when it may be necessary to provide additional colder reservoir release flows for salmonids due to lack of access to historic upstream cooler spawning and rearing habitat after construction of dams. It may also be the case for pelagic species in the summer and fall that require more Delta outflow to position X2 in a hospitable habitat location where temperatures, food resources and other conditions are appropriate since these conditions are no longer appropriate much of the time within the Delta. It is possible that flow needs could be reduced by addressing habitat and other aquatic ecosystem stressors that are discussed in Chapter 4, but these interact with flow and as such, adequate flows are critical.

5.1.1 Use of Percent Unimpaired Flow

Similar to the draft Phase I San Joaquin River flow requirements, this Report recommends the use of unimpaired flows to develop proposed Sacramento River and Delta tributary inflow requirements. This Report also recommends continued use of an index of unimpaired flows that is currently used for Delta outflow requirements in the Bay-Delta Plan and D-1641. Unimpaired flow represents the total amount of water available at a specific location and time, a percentage of which can be allocated to beneficial uses and the environmental functions supporting those uses. As discussed above, while unimpaired flow is not the same as natural flow, it is generally reflective of the frequency, timing, magnitude, and duration of the natural flows to which fish and wildlife have adapted. A flow requirement based on unimpaired flows is intended to restore a specific percent of these flows for the reasonable protection of the fish and wildlife beneficial use. Adaptive management provisions are then proposed to provide for any necessary sculpting of that flow to maximize the protection of flows by providing for specific functional fish and wildlife needs.

As discussed in Chapter 3, the flow regime has widespread effects on physical and biological processes in both the riverine and tidal portions of the Bay-Delta Watershed. The long-term physical characteristics of flow variability have strong ecological consequences at local to regional scales, and at time intervals ranging from days (ecological effects) to millennia (evolutionary effects) (Lytle and Poff 2004). Nearly every other habitat factor that affects community structure, from temperature to water chemistry to physical habitat complexity, is influenced by flow (Moyle et al. 2011). Consequently, using a river's unaltered hydrographic condition as a foundation for determining ecosystem flow requirements is well supported by the current scientific literature (Poff et al. 1997; Tennant 1976; Orth and Maughan 1981; Marchetti and Moyle 2001; Mazvimavi et al. 2007; Moyle et al. 2011; Kiernan et al. 2012). As an example, regulatory programs in Texas, Florida, Australia and South Africa have developed flow prescriptions based on unimpaired hydrographic conditions in order to enhance or protect aquatic ecosystems (Arthington et al. 1992; Arthington et al. 2004; NRDC 2005; Florida Administrative Code 2010), and the World Bank now uses a framework for ecosystem flows based on the unaltered quality, quantity, and timing of water flows (Hirji and Davis 2009). Researchers involved in developing ecologically protective flow prescriptions concur that mimicking the unimpaired hydrographic conditions of a river is essential for protecting populations of native aquatic species and promoting natural ecological functions (Sparks 1995; Walker et al. 1995; Richter et al. 1996; Poff et al. 1997; Tharme and King 1998; Bunn and Arthington 2002; Richter et al. 2003; Tharme 2003; Poff et al. 2006; Poff et al. 2007; Brown and Bauer 2009). In their report describing methods for deriving flows needed to protect the Bay-Delta and watershed, Fleenor et al. (2010) suggest that while using unimpaired flows may not indicate precise, or optimal, flow requirements for fish under current conditions, it would provide the general seasonality, magnitude, and duration of flows important for native species (see also Lund et al. 2010).

Unimpaired flow is not a fixed quantity, but varies with local and seasonal hydrology, so it is more reflective of the conditions to which the species being protected are adapted (SWRCB 2010) and to the availability of water for all purposes. The percent of unimpaired flow approach encourages the diversity of flow needed for ecosystem functions described in Chapter 3. Specifically, information indicates that salmonids respond to variations in flow and need continuity of flow between natal streams and the Delta for transport and homing fidelity. Healthy salmonid populations also require healthy subpopulations in different streams with different life history strategies to maintain genetic diversity and distribute risk to the population that may occur from ecological disturbances. The historic practice of developing fixed monthly flow criteria to be met from a few sources is not optimal for providing these functions while unimpaired flow requirements from different tributaries are. At the same time, however, given the impediments to fish passage into historic spawning and rearing areas, there are also needs within some tributaries to diverge from the natural hydrograph at certain times of the year to provide more flow than might have naturally occurred or less flow to ensure that sufficient water is available at other times of year to mitigate for loss of access to appropriate habitat, particularly during summer and fall.

In addition to the scientific basis for the unimpaired flow approach, the approach affords public transparency as to the allocation of water between fish and wildlife and other beneficial uses. The percent of unimpaired flow approach identifies the allocation of a seasonally and annually variable quantity of water for the reasonable protection of fish and wildlife and other beneficial uses. In contrast, a table of different flow requirements to protect fish and wildlife in different seasons and under different hydrologic conditions provides no indication of the allocation that has occurred between beneficial uses of the water. The use of a percent of unimpaired flow approach assigns a percent of the available water to fish and wildlife, and leaves the remainder for other uses.

Based on the above, this Report recommends the continued use of the unimpaired flow approach for inflows and an index of unimpaired flows for outflows, along with appropriate measures for adaptive management to provide for specific functional flows, adaptive management experiments and to respond to new information and changing circumstances. To assist the State Water Board in determining the amount of water that should be provided to reasonably protect fish and wildlife beneficial uses in the Sacramento basin and Delta, a range of percent of unimpaired flow is analyzed in this Report. The Report analyzes a range from 35 to 75 percent of unimpaired flow from the Sacramento River and eastside tributaries to determine the frequency of achieving flows protective of specific species identified in Chapter 3 and the potential for increasing native fish abundance as a function of increasing the percent unimpaired flow provided to fish and wildlife. While specific flow versus species abundance relationships are evaluated in this chapter, there are also benefits that occur at lower and higher flows that are identified in the tables and figures included in Chapter 3. Generally, the higher the flows up to 100 percent of unimpaired flow (and higher in the summer and fall), the greater the benefits are for native species and the ecosystem provided adequate supplies are maintained for cold water and flows at other times.

These initial analyses compare modeled existing conditions with a range of potential percent of unimpaired Delta inflow and Delta outflow scenarios. This range will be refined with modeling to develop alternatives for additional analysis that consider the needs for cold water storage and other uses. Specifically, data from SVUFM (Appendix A) are combined with results from a recent CalSim II planning study (DWR 2015) to compare the flow that would occur under a range of unimpaired flows to the modeled CalSim II flows. For the analysis of Delta outflow, modeled values of minimum required Delta outflow (MRDO) pursuant to the requirements of the 2006 Bay-Delta Plan/D-1641 and the USFWS) BO are provided for comparison as well. The comparison between MRDO and existing conditions indicates that required flows are much lower than existing conditions. This is due to a combination of uncontrollable flows and the operation of other flow requirements and physical limitations, such as maximum diversion rates. However, without adequate regulatory requirements, future flows may be reduced relative to existing conditions as a result of additional diversions. The analysis of MRDO and existing conditions helps to illustrate the magnitude of existing Delta outflow that is not currently required and as such could be reduced over time. Because there are only very limited existing Bay-Delta Plan/D-1641 and BO requirements on tributaries, only existing conditions are provided for inflows.

Like MRDO, the percent unimpaired inflow and outflow scenarios below do not fully account for other uncontrolled (e.g., storm events and other uncaptured flows) and controlled flows (e.g., flood control and power generation releases) that are not included in the 2006 Bay-Delta Plan and D-1641 and that would be expected occur in the real world that would increase the flows provided under the scenarios at some times. The State Water Board's hydrologic planning model, SacWAM, will be used to develop estimates of expected flows under different scenarios that account for other controlled and uncontrolled flows. In the interim, the analysis provided below provides a conservative estimate.

The range presented in this chapter does not necessarily represent the numeric range that will be evaluated in the environmental and other review processes. The range will be further refined with modeling to evaluate needs to reserve cold water in storage and other considerations. The 35 to 75 percent range encompasses flows that are generally close to lower baseline flow conditions at 35 percent and more optimal flows for fish species at 75 percent that were identified in the 2010 Delta Flow Criteria Report. As described in the Chapter 2, baseline flows between tributaries and water years can vary significantly and flows on many tributaries in many months are currently well below 35% while other tributaries are above 35%. Given the poor status of many native species, which have been impacted by reduced flows, the State Water Board generally does not plan to consider flows that are lower than drier baseline conditions. As will be shown below, the upper range of 75% continues to be supported using the updated flow and species abundance relationships. It is used to provide an upper range for evaluating water supply effects of potential flow requirements (SWRCB 2010).

5.2 Tributary Inflow Requirements

5.2.1 Introduction

This Report recommends new inflow requirements for anadromous fish-bearing tributaries in the Sacramento River basin and Delta eastside tributaries (see map in Figure 1.3-1).[2] Year-round inflows are needed to protect anadromous and other fish and wildlife species that inhabit the Bay-Delta and its tributaries throughout the year as juveniles or adults. Specifically, inflows are needed to provide appropriate habitat conditions for migration, spawning and rearing of anadromous fish species (primarily Chinook salmon and steelhead) that inhabit the Delta and its tributaries. These flows are also needed to contribute to Delta outflows needed to support migrating, spawning, and rearing

[2] An exception to the general approach is currently being considered for Cache Creek, which does not support anadromous fish but discharges to the Yolo Bypass (see Chapter 2). Increased flows from Cache Creek would cause localized flooding in the Yolo Bypass (YBWA Management Plan, 2008, p. 3.4-19), increasing the acreage of floodplain inundation, and enhancing spawning and rearing opportunities for Sacramento splittail and rearing habitat for juvenile Chinook salmon in winter and spring while also contributing to Delta outflow (see also discussion of floodplain rearing in Section 3.4.4.2).

estuarine species. This Report recommends a year round inflow requirement based on a percent of unimpaired flow for the Sacramento River and its tributaries and eastside tributaries to the Delta that allows for adaptive management to provide for specific functional instream flow needs, scientifically based experiments, and coordination with other measures. This Report also recommends preservation of high flow levels that are already being provided in some less impaired tributaries where they are providing important functions to ensure that those flows are not reduced (e.g., maintain existing protective conditions).

5.2.1.1 Current Bay-Delta Plan and D-1641 Requirements

The only inflow requirements in the Phase II area of the Bay-Delta Plan are for minimum monthly average flows on the Sacramento River at Rio Vista for the months of September through December. These flow requirements range from 3,000 to 3,500 cfs during critical water years, and from 3,000 to 4,500 cfs for other water year types. There is an additional requirement that the 7-day running average flow during this period not be less than 1,000 cfs below the monthly objective. This objective is intended to provide minimum flows to attract adult fall-run Chinook salmon to the Sacramento River.

DWR and Reclamation are solely responsible for providing the flows needed to comply with the flow requirements on the Sacramento River at Rio Vista. There are currently no other instream flow requirements for the Sacramento River Basin and Delta eastside tributaries in the Bay-Delta Plan. However, numerous other agreements and various regulatory requirements exist that apply some flow requirements to specific tributaries, some of which are discussed in the cold water habitat section.

There are also requirements in D-1641 assigning responsibility for meeting Bay-Delta Plan flow objectives from the Mokelumne River system. For the protection of fall-run Chinook salmon, releases from Camanche Reservoir are required to comply with a flow schedule based on water year type consistent with provisions of a Joint Settlement Agreement. From July through September, releases are required to be at least 100 cfs for all water year types. For all other months of the year, releases are required to be at least 100 to 325 cfs, depending upon water year type.

5.2.2 Discussion

Currently, inflows to the Delta are largely controlled by upstream water withdrawals and releases for water supply, power production, and flood control. As a result, inflows from tributaries do not provide habitat or contribute flow to the Delta in the same proportions as they would have naturally. At the same time, historic usptream habitat for salmonids and other species on many tributaries is blocked by dams. As discussed in Chapter 2, construction of upstream dams and increased in-basin water demand has resulted in a decrease in net annual inflow to the Delta and a seasonal shift in inflows from winter-spring to summer-fall. Peak runoff from winter rainstorms and spring snowmelt is now captured in the upstream reservoirs and released later for downstream use. The result of water development in the Sacramento Basin is a river system with less seasonal and annual variability and a smaller total outflow, with median flows reduced by more than 50 percent during April and May. Other regulated (reservoir controlled) tributaries to the Sacramento River show similar altered seasonal and annual flow patterns with flow significantly reduced in some of the tributaries by more than 70 percent.

Water development has also altered the hydrology of unregulated tributaries to the Sacramento River (NMFS 2014). These smaller waterways do not have large water storage facilities in their upper basin but often have small dams and other diversion structures on the valley floor above the confluence with the Sacramento River. The diversions reduce much, and at times all, of downstream channel flow during spring and summer, with the greatest impairments occurring in June through September of drier years when flows may be reduced by over 90 percent in drier years on some streams.

As discussed in Chapter 3, at least one salmonid run is migrating through the Delta or holding in the upper Sacramento Basin each month of the year necessitating year-round tributary inflows. Adult salmonids require continuous tributary flows of sufficient magnitude to provide the olfactory cues to find, enter, hold, and spawn in their natal streams (Moyle 2002). Juvenile salmon also require continuous tributary flows for rearing and successful emigration. A lack of tributary flow affects both hydrologic connectivity between tributaries and the main stem Sacramento River and a lack of juvenile rearing habitat.

As discussed in Chapter 3, there is specific flow versus survival and abundance information for juvenile fall- and winter-run Chinook salmon that indicates that flows greater than 20,000 cfs from February through June on the lower Sacramento River increase survival and abundance of these species. Flows of this magnitude are also expected to aid emigration of juvenile spring-run and steelhead. Modeling demonstrates that in half of all years flow in April and May is less than 50 percent of what would occur in unimpaired conditions in the lower Sacramento River and that these reductions in flows significantly reduce the occurrence of flows of 20,000 cfs or more in the lower Sacramento River.

The exceedance plots in Figures 5.2-1 and 5.2-2 show the distributions of average lower Sacramento River flows under modeled existing conditions (CalSim II; DWR 2015) and 35% to 75% of unimpaired flow (SVUFM; Appendix A) during April-June and February-April, respectively. As previously discussed, the representations of 35% to 75% of unimpaired flows shown below do not fully account for storm flows, other uncontrolled flows and other regulatory requirements for flows. When accounting for those flows, flows at certain times would be much higher than indicated below. This is generally the case for the wettest and driest years in the period of record examined. Additional analyses will be provided in the future that account for these additional flows. The dashed horizontal lines indicate flows of 20,000 cfs to support outmigration of juvenile Chinook salmon, and their intersections with the exceedance curves provide an estimate of how frequently these flows would be observed under this range of conditions. Even without accounting for controlled and uncontrolled flows, flows greater than 50% of unimpaired increase the frequency of average April-June and February through June flows exceeding 20,000 cfs relative to existing conditions (Figure 5.2-1 and 5.2-2).

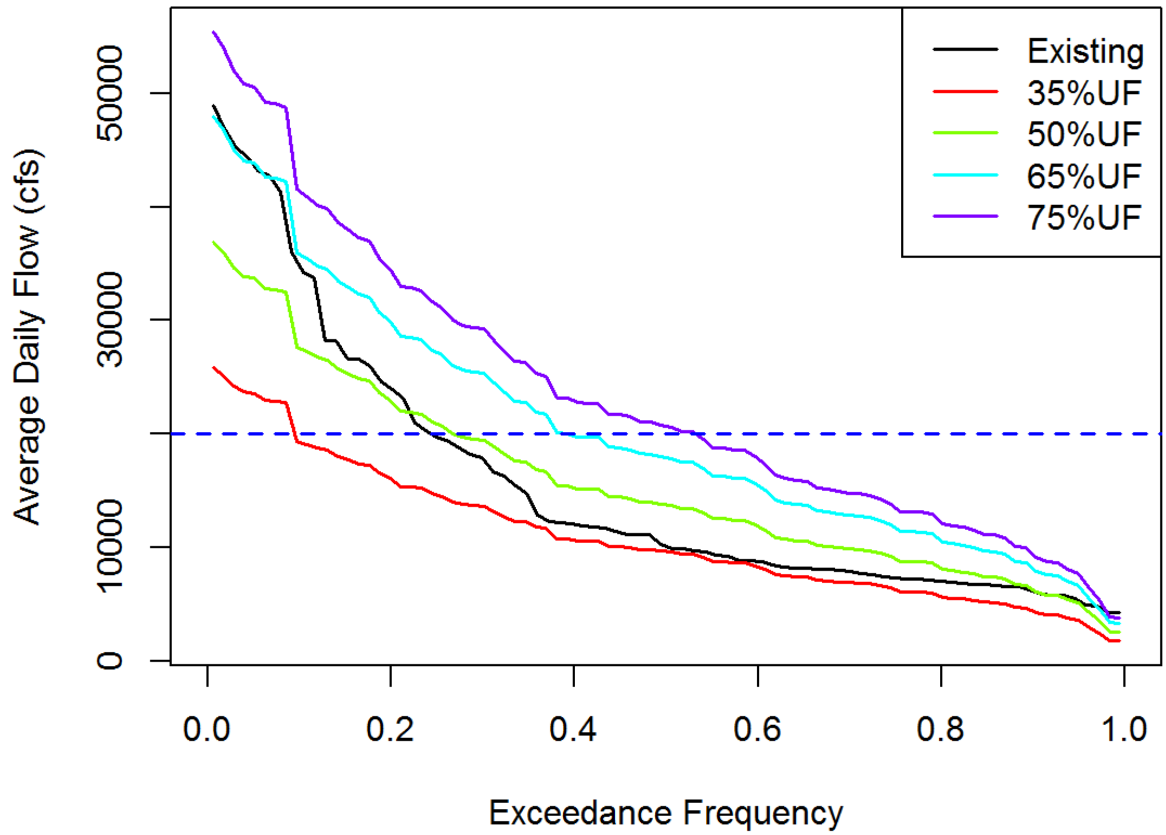

Figure 5.2-1. Frequency of Meeting April-June Sacramento River at Rio Vista Flows of 20,000 cfs for Existing Conditions as Modeled by CalSim II, and 35% to 75% of Unimpaired Flow at Rio Vista.

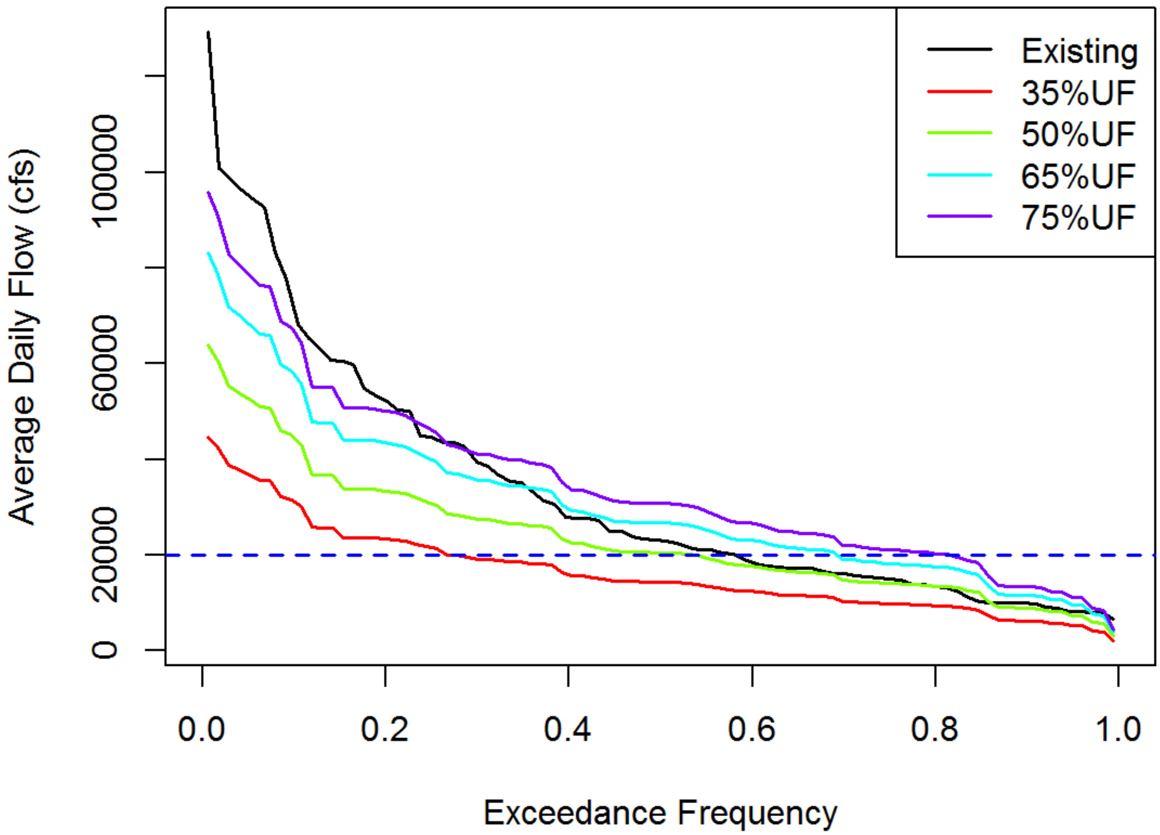

Figure 5.2-2. Frequency of Meeting February-April Sacramento River at Rio Vista Flows of 20,000 cfs for Existing Conditions as Modeled by CalSim II, and 35% to 75% of Unimpaired Flow at Rio Vista.

Chapter 3 also identifies flows exceeding 17,000-20,000 cfs at Freeport as sufficient to prevent flow reversal at Georgiana Slough, thus decreasing the likelihood of entrainment of Sacramento River basin salmonids to the interior Delta, where survival is lower. Figure 5.2-3 shows the exceedance frequency distributions of monthly Freeport flows during November through May for existing conditions and the range of 35% to 75% of unimpaired flow. Similar to the pattern seen for Rio Vista flows, higher percentages of unimpaired flow provide conditions more often that prevent flow reversals in late fall and winter. Again, actual flows under a percent of unimpaired flow requirement would be higher when accounting for storm flows, other uncontrolled flows, and other regulatory flows, particularly for the lower percent unimpaired requirements and the wettest and driest hydrologies. However, even without accounting for these other flows, in April and May flows of 17,000 cfs would be achieved more often at flows of 65% and higher.

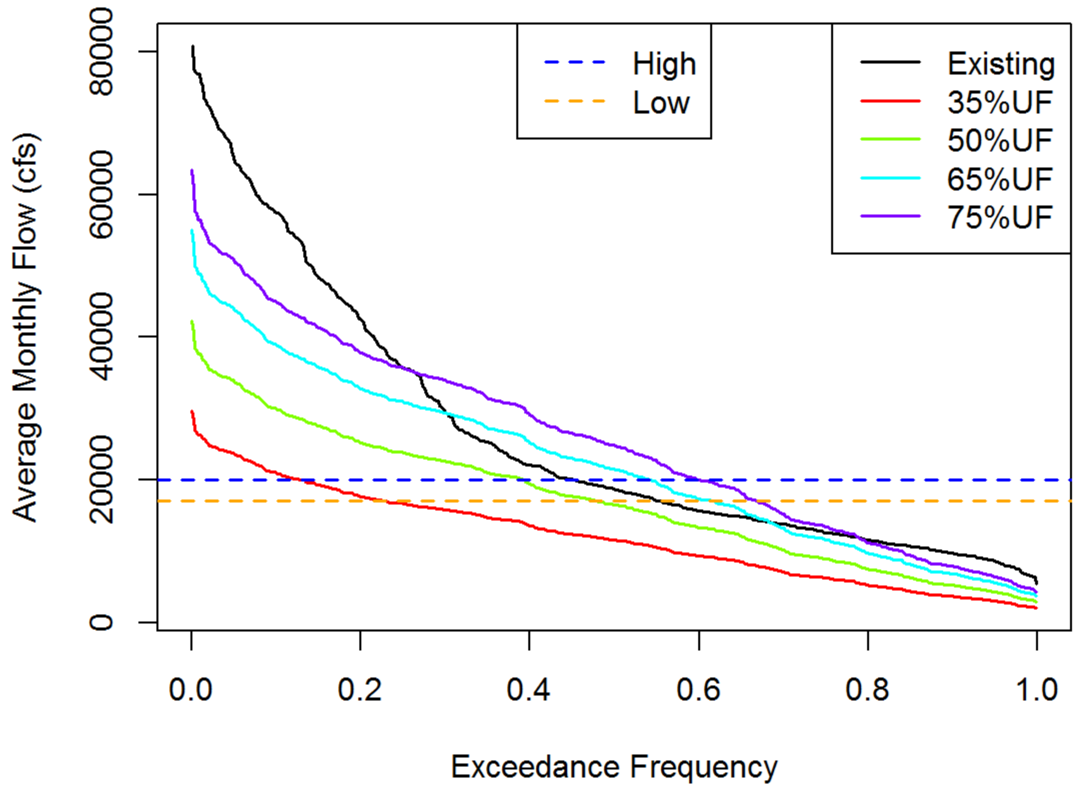

Figure 5.2-3. Exceedance Frequency of Monthly Flow at Freeport on the Sacramento River for November-May under Existing Conditions as Modeled by CalSim II, and 35% to 75% of Unimpaired Flow. Flows greater than 17,000 (orange line) to 20,000 cfs (blue line) prevent tidal reversal at Georgiana Slough.

No similar specific numbers are provided for other tributaries or for the Sacramento River at other times of the year, however, there are flow needs year round for salmon migration and rearing and to contribute to Delta outflow. As discussed in Chapter 3, a lack of hydrologic connection between tributaries and the Sacramento River was identified as the most common stressor for both adult and juvenile salmon. The loss of connectivity commonly results from water temperatures that are too elevated and flows that are too low for salmonid wellbeing in summer. As discussed above, some tributaries have no requirements at all or only minimal requirements that are not adequate to protect fish and wildlife. While conditions may currently be protective of fish and wildlife in some of these tributaries, flow requirements are needed to ensure that the current conditions are not degraded over time as the result of new or modified diversions. In addition, some of these tributaries may dry up at times of year due to the lack of regulatory flow requirements and others may have inadequate flow and water quality conditions to protect fishery resources.

Tributary inflows contribute to Delta outflows that are critical for both salmonids and estuarine dependent species. From January through June, the needs for tributary inflows and Delta outflow overlap and both inflow and outflow benefit salmonid and estuarine species. Information was assembled for several estuarine species chosen as indicators of ecosystem health and is summarized in Table 3.13-2.

5.2.3 Conclusion

The scientific information supports the conclusion that year round inflow requirements should be established for the Sacramento River, its tributaries and the Delta eastside tributaries to ensure the reasonable protection of fish and wildlife beneficial uses, including the natural production of viable native fish populations rearing in and migrating to and from tributaries and the Delta. Indicators of viability include abundance, spatial extent or distribution, genetic and life history diversity, migratory pathways, and productivity. Specifically, the purpose of year-round inflows is to contribute to increasing Delta outflow and, in salmon bearing tributaries, to improve adult salmonid immigration and holding and juvenile rearing and outmigration. Increased tributary flow will also increase the frequency of large flows on the Sacramento River for sturgeon spawning and increase flooding in the Yolo Bypass for splittail spawning and rearing and salmon rearing.

In some tributaries where flows are currently significantly impaired, inflow requirements are needed to improve conditions for fish and wildlife in those tributaries and to provide for connectivity and contribution of flow to the Delta. In other tributaries where flows are less impaired, inflow requirements are needed to ensure that those flows do not become impaired to the detriment of fish and wildlife. The science supports establishment of a flow regime that more closely mimics the biotic and abiotic functions provided by the natural flow regime. A percent of unimpaired flow is recommended as a regulatory framework to provide for those functions in an adaptive management context. While unimpaired flows are not natural flows, they are similar to natural tributary flows and provide similar variability and the general magnitude, spatial and temporal attributes of natural flows in tributaries to which native species adapted. As indicated by the science presented in this Report, higher more natural quantities of flows provide for more abundant species populations. At the same time, more variable flows provide for genetic and life history diversity needed for resilient ecosystems.

A range for the unimpaired inflow requirements is recommended such that, as appropriate, changing information and the unique conditions of tributaries can be accommodated to provide for specific functions while at the same time providing minimal and generally similar quantities of flow for outflow purposes from all tributaries. The numeric range would also accommodate for the cold water management needs and integration with other nonflow measures as appropriate.

Adaptive management is recommended within a range that allows for sculpting of flows to maximize the effectiveness of flow measures to provide specific functions and to respond to additional science and changing conditions. Biological goals are proposed to inform whether and how adaptive management is conducted. The biological goals are proposed to incorporate “SMART” -specific, measurable, achievable, relevant, and time bound- principles and will be tied to controllable factors within specific watersheds. The parameters for use of unimpaired flows, adaptive management, and biological goals will be provided in the proposed Phase II water quality objectives and program of implementation language included with the final Report.

While the existing Sacramento River at Rio Vista flow requirements are minimal, they could help to ensure that existing minimally protective flows are maintained. Accordingly, at this time, no changes to these requirements are specifically recommended.

5.3 Delta Outflow

5.3.1 Introduction

This Report recommends increased Delta outflow requirements to stabilize and enhance the abundance and distribution of native aquatic species. Specifically, Delta outflows are needed throughout the year to support and maintain the natural production of viable native fish populations residing in, rearing in, or migrating through the estuary. Flow conditions that reasonably contribute toward maintaining viable native estuarine fish populations include, but may not be limited to, flows that connect low salinity pelagic waters to productive tidal wetlands, produce salinity distributions that mimic the natural conditions to which native fish species are adapted, including the relative magnitude, duration, timing, and spatial extent of flows as they would naturally occur. Indicators of viability include abundance, spatial extent or distribution, genetic and life history diversity, migratory pathways, productivity, spawning and rearing habitat quantity and quality, and productivity of the food web supporting native fishes.

This Report recommends increased Delta outflows from January through June to support migration and recruitment of estuarine species, outmigration of salmonid smolts and other estuarine functions. The Report recommends an approach based on the construct for the current Delta outflow requirements during this time that relies on an index of unimpaired flows (the Eight River Index [ERI][3] or similar index) to determine additional Delta outflow requirements. To better integrate the inflow and outflow requirements during this time period, use of the current month's ERI is recommended rather than the prior month. The State Water Board is specifically requesting input on this approach. The range of Delta outflows under consideration is consistent with the range for inflows discussed above.

An analysis is provided to compare the Delta outflows to benefit multiple species identified in Chapter 3 to existing MRDO, modeled existing flows and a range of Delta outflow scenarios within the range of inflows discussed above. As previously discussed, the scenarios do not yet account for other regulated and unregulated flows. , and predicted flows would be higher at times as is the case between MRDO and existing conditions. While a complete analysis of this issue will include predicted flows under the scenarios that accounts for other flows, the analysis is still useful for several reasons. First, the analysis indicates that MRDO is inadequate to ensure the current level of Delta outflow protection. While MRDO requirements do not control operations much of the time, with increasing water diversions, adequate minimum requirements will be critical as is

[3] The ERI refers to the sum of the unimpaired runoff as published in the DWR Bulletin 120 for the following locations: Sacramento River flow at Bend Bridge, near Red Bluff; Feather River, total inflow to Oroville Reservoir; Yuba River flow at Smartville; American River, total inflow to Folsom Reservoir; Stanislaus River, total inflow to New Melones Reservoir; Tuolumne River, total inflow to Don Pedro Reservoir; Merced River, total inflow to Exchequer Reservoir; and San Joaquin River, total inflow to Millerton Lake.

demonstrated in Chapter 2. Second, the analysis is useful to evaluate in a relative sense the magnitudes of difference between MRDO and the scenarios and the magnitude of difference between MRDO and existing conditions that help to illustrate the increased outflows that would be provided if the scenarios were implemented. Additional analyses will be provided in the future to further evaluate this issue.

In addition to modifications to winter and spring Delta outflow requirements, a fall X2 requirement consistent with the USFWS BO is recommended. Recommendations for changes to summer Delta outflows, including adaptive management experiments, may be provided in the final Report based on evolving science. This is another issue that the State Water Board is specifically seeking feedback on. Existing Delta outflow requirements in summer and fall are recommended to be maintained to ensure that existing baseline protection provided by those flows is not diminished. As with inflows, adaptive management provisions are proposed to provide for specific flow functions and ecosystem processes for the new or modified Delta outflow requirements.

Delta outflow requirements largely control flow conditions in Suisun Marsh and modified Delta outflow requirements are expected to reasonably protect fish and wildlife in Suisun Marsh. As such, substantive changes to existing Suisun Marsh requirements are not anticipated at this time. Potential non-substantive changes to requirements may be addressed in the draft Phase II changes to the Bay-Delta Plan that will be provided at a later date.

5.3.2 Current Bay-Delta Plan, D-1641 and Biological Opinion Requirements

Existing year round Delta outflow requirements are set forth in Tables 3 and 4 of the Bay-Delta Plan and D-1641, and vary depending on water year type and season. Requirements are expressed by a specific numeric flow or by the location of X2, the distance of the near-bottom 2 psu isohaline in kilometers from the Golden Gate Bridge.

The Delta outflow requirements are expressed in Bay-Delta Plan Table 3 as an NDOI. The NDOI is a calculated flow expressed as Delta inflow, minus net Delta consumptive use, minus Delta exports (Bay-Delta Plan Figure 4). An EC measurement of 2.64 mmhos/cm at Collinsville station C2 can be substituted for the NDOI during February through June. Bay-Delta Plan Table 4 specifies the number of days that X2 is required to be maintained downstream of Chipps Island or Port Chicago as a function of the previous month's ERI. The ERI is based on measurements of unimpaired flows from eight major tributaries (Bay-Delta Plan Table 3, Footnote 10).

- For January, the minimum Delta outflow is 4,500 cfs, and is raised to 6,000 cfs if the previous month's ERI is greater than 800 thousand acre feet.
- For February through June, the Delta outflow requirement may be met using three day average flows, daily salinity (EC), or 14-day running average EC based on the previous month's ERI:
    - Minimum flow of 7,100 cfs or meet Collinsville salinity requirements (all days).
    - Flows of 11,400 cfs or meet Chipps Island salinity requirements.

  - Flows of 29,200 cfs or meet Port Chicago salinity requirements.
  - The requirements include off ramps for dry conditions.
- For July through December, the minimum Delta outflow varies within the range of 3,500 cfs to 8,000 cfs based on month and water year type.

DWR and Reclamation have additional obligations under the USFWS BO for meeting Delta outflow requirements to improve fall habitat for Delta smelt during the months of September through November following wet and above normal years. The USFWS BO requires Delta outflows sufficient to maintain average X2 for September and October no greater than 74 km (approximately 11,400 cfs) in the fall following wet years and 81 km (approximately 7,100 cfs) in the fall following above normal years. In November, the inflow to CVP and SWP reservoirs in the Sacramento River Basin is required to be added to reservoir releases to provide an added increment of Delta inflow and to augment Delta outflow up to the fall target. The action is subject to evaluation through adaptive management and may be modified or terminated as determined by the USFWS (Action 4, p. 369).

5.3.3 Discussion

The effects of the flow regime on the ecosystem of the Bay-Delta Estuary and several estuarine dependent species are documented in Chapter 3. The distribution and abundance of a diverse array of estuarine species at all levels of the food web respond positively to increased Delta outflow. Several scientifically based mechanisms generally related to reproduction and recruitment have been identified to explain these relationships. Although definitive understanding of these mechanisms is not available, the available scientific information supports the conclusion that greater quantities of Delta outflow are needed during the winter and spring to support estuarine processes, habitat, and the species that depend upon them. Additional information supports the conclusion that Delta smelt benefit from flows that place the low salinity zone downstream of the confluence of the Sacramento and San Joaquin rivers during summer and fall.

The discussion that follows synthesizes the specific ranges of flow identified to support estuarine habitat and species summarized in Chapter 3 and hydrologic models of unimpaired flows to help to determine the benefit that more Delta outflow might provide individual species. As discussed above, these initial analyses do not account for storm flows, uncontrolled flows, and other required flows that would actually add to outflows. . More operationally realistic flows that may result under different scenarios will be evaluated using SacWAM and will be provided in subsequent analyses. In the interim, the analysis provided below provides a conservative estimate.

The sections that follow describe the analytical approach used for evaluating a range of potential winter-spring Delta outflow requirements designed to couple required Delta outflows to a percent of unimpaired inflow from the Sacramento Basin and eastside tributaries to the Delta. The approach presented is similar to the existing February-June objective for Delta outflow, which is based on the previous month's ERI. The one-month time lag is removed to better reflect the availability of water when monthly inflows are managed according to a percent of unimpaired flow. First is a description of how a range of Delta outflow is derived, followed by an assessment of the frequency that flows to support estuarine resources are met, and predicted changes to abundances of various species under a range of flows between 35% and 75% of unimpaired Delta inflow from the Sacramento River basin and eastside tributaries to the Delta. The purpose of this exercise is to assist the State Water Board and the public in evaluating a range of outflows and the biological benefits associated with those flows for multiple species.

5.3.3.1 Estimating Delta Outflow

The quantity of Delta outflows reflects the availability of water from the three major regions tributary to the Delta: the Sacramento River basin, the eastside tributaries to the Delta, and the San Joaquin River basin. The three regions differ in the timing of peak contributions to Delta inflow (see Chapter 2). Flow contributions from the San Joaquin River upstream of Vernalis, which are currently heavily impaired, are being addressed through the separate Phase I process to amend the Bay-Delta Plan. Because revised San Joaquin River flow objectives have not yet been adopted by the State Water Board, for purposes of developing the illustrative example presented here, staff assumed that San Joaquin River contributions would continue to reflect existing conditions as modeled in CalSim II (DWR 2015). With the Phase I changes to the Bay-Delta Plan, these contributions would potentially increase. The potential Delta outflows are derived as follows:

1. Fit a multiple linear regression independently for each month to predict unimpaired Delta outflow for January to June as a function of unimpaired inflows from the Sacramento River basin, Eastside tributaries to the Delta, and San Joaquin River basin (Table 5.3-1).
2. Using the linear model obtained in (1), predict the Delta outflow that would result from unimpaired Sacramento and Eastside tributary flows and existing conditions for San Joaquin inflows at Vernalis (Figure 5.3-1).
3. Fit a monthly linear regression that predicts the monthly Delta outflows obtained in (2) as functions of monthly ERI (Figure 5.3-2).
4. Scale the values obtained in (3) by the percent of unimpaired inflow being provided from the Sacramento River basin tributaries and Eastside tributaries.
5. Substitute any flows lower than current monthly minimum flows specified in Bay-Delta Plan Table 3 with those monthly minimums. For the purpose of this illustrative example, minimum February to June flows are taken to be 7,100 cfs, and drought relaxations included in footnote 11 to Bay-Delta Plan Table 3 are not included.

This procedure ultimately produces a prediction of monthly outflows as a function of monthly ERI. Staff applied this simple model to the historical ERI time series for water years 1922-2003 to obtain time series of January to June flows corresponding to a range from 35% to 75% of unimpaired inflow from the Sacramento Basin and Eastside tributaries to the Delta. To complete the time series, CalSim II estimates of MRDO[4] are included for July to December to produce time series that reflect minimum year-round outflows over the modeled range of inflows.

[4] MRDO is defined as the minimum Delta outflow needed to meet the Delta outflow and X2 requirements in Bay-Delta Plan Tables 3 and 4, salinity control for the protection of agricultural and municipal beneficial uses in Bay-Delta Plan Tables 1 and 2, and USFWS Opinion RPA 4 (Fall X2). The values used in this chapter are those modeled by CalSim II (DWR 2015), and are obtained by summing the arcs D407 and C407_ANN.

Table 5.3-1. Monthly Multiple Regression Parameters for Predicting Unimpaired Delta Outflow as a Function of Unimpaired Inflows

	Jan	Feb	Mar	Apr	May	Jun
(Intercept) (cfs)	119.7	-994.1	-927.3	-535.4	-354.4	-311.3
Sacramento	1.035	1.032	1.016	1.005	1.006	1.005
Eastside	1.042	0.9986	1.123	1.171	0.9496	0.9473
San Joaquin	1.032	1.098	1.017	0.9811	1.003	1.004

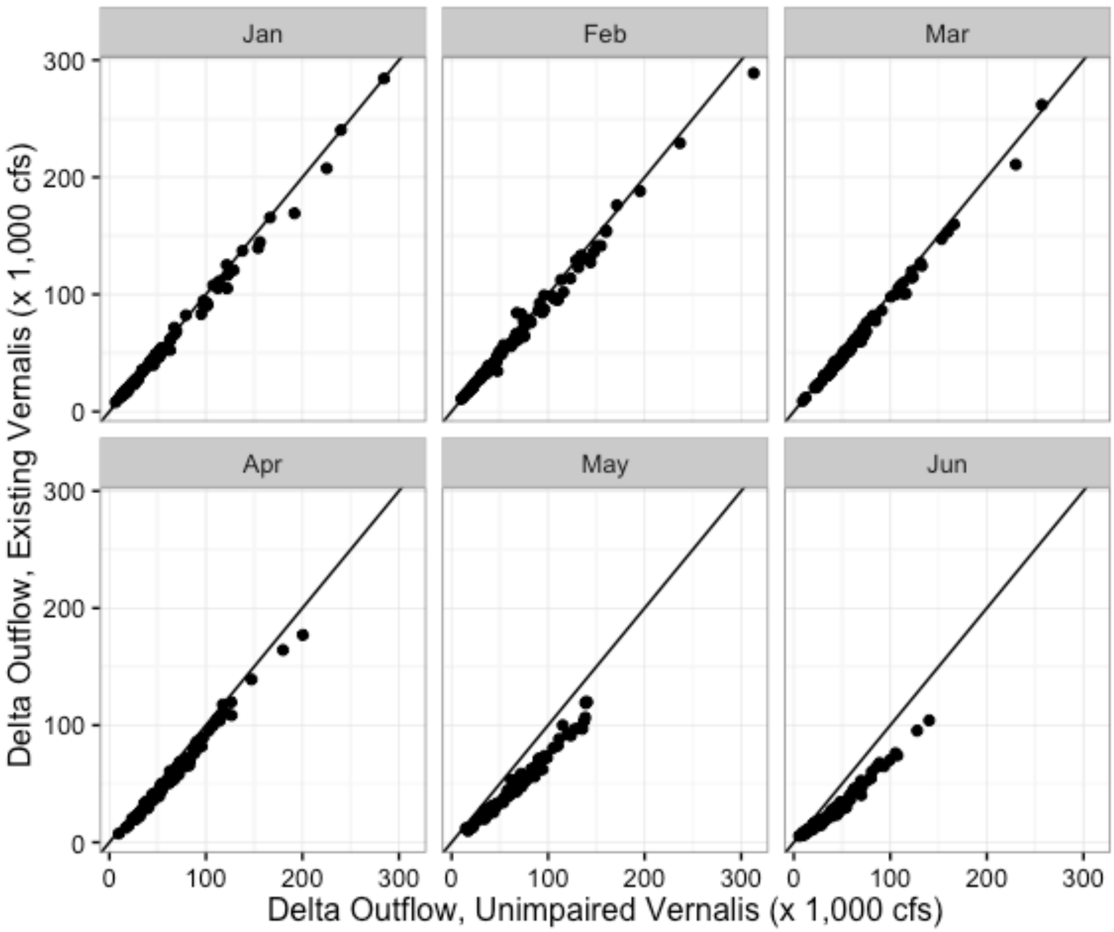

Figure 5.3-1. Delta Outflow Predicted from the Linear Model Shown in Table 5.3-1 with Existing Condition Flows at Vernalis as a Function of Unimpaired Delta Outflow. May and June flows fall below the one-to-one line, reflecting the effect of impaired Vernalis flows under existing conditions.

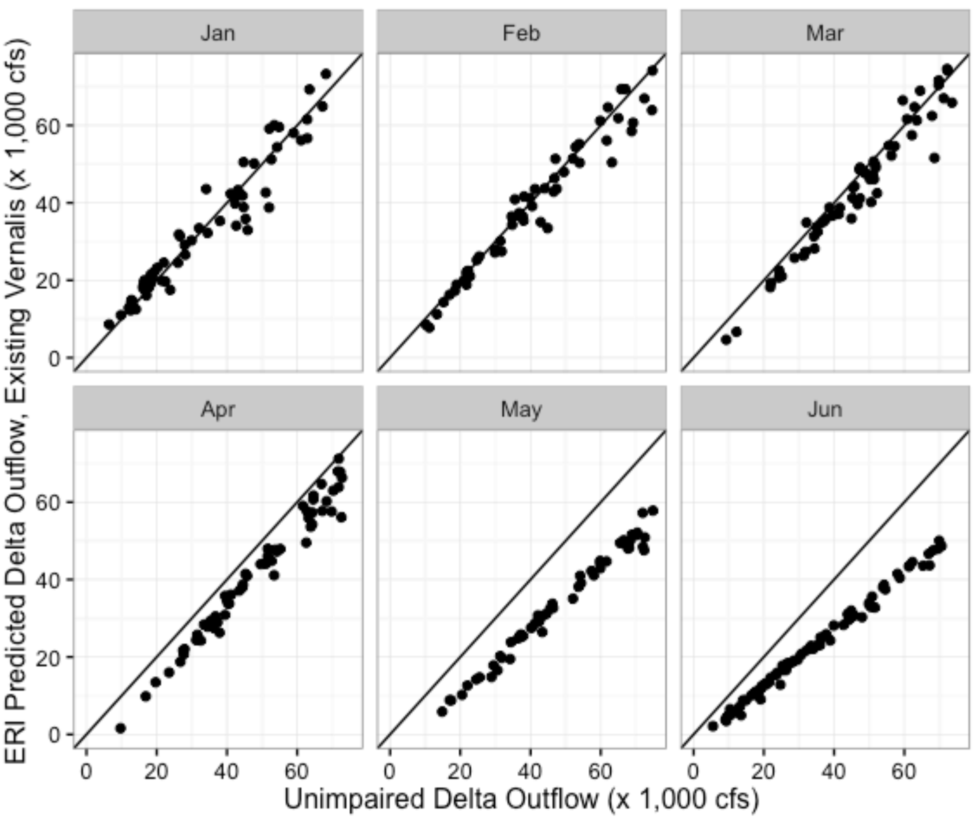

Figure 5.3-2. Predicted Delta Outflow as a Function of ERI, Assuming Existing Condition Flows at Vernalis. April-June flows generally fall below the one-to-one line due to the impairment of Vernalis flows.

5.3.3.2 Winter-Spring Existing Conditions

Figure 5.3-3 shows seasonal comparisons of MRDO pursuant to Bay-Delta Plan and D-1641 requirements and the USFWS BO with CalSim II modeled flows under existing regulatory conditions (DWR 2015) and observed Delta outflows (DWR 2016) prior to and subsequent to the adoption of D-1641. Modeled flows are most similar to regulatory minimums during the dry season of July-October, but deviate substantially during wetter months (Figure 5.3-3). Differences between observed and modeled flows reflect differences in intensity of water development, the regulatory environment, and underlying hydrology. For example, the lower outflow observed in fall during 2000-2015 reflects increased water development relative to 1956-1999, dry hydrology relative to both 1956-1999 and the 1921-2003 CalSim II record, and the absence of a fall X2 requirement in the first half of the period. Although a portion of the wet season difference is due to other regulatory constraints such as the export to inflow ratio and limitations on OMR reverse flows, much of the "surplus" Delta outflow modeled and observed under existing conditions results from the inability to capture valley floor runoff. The most striking difference between required and observed flows is seen during winter and spring of wetter years, when both modeled and observed flows greatly exceed regulatory minimums. These flows may be reduced by future water development, so additional flow requirements may be needed to maintain the existing level of protection of estuarine-dependent fish and wildlife.

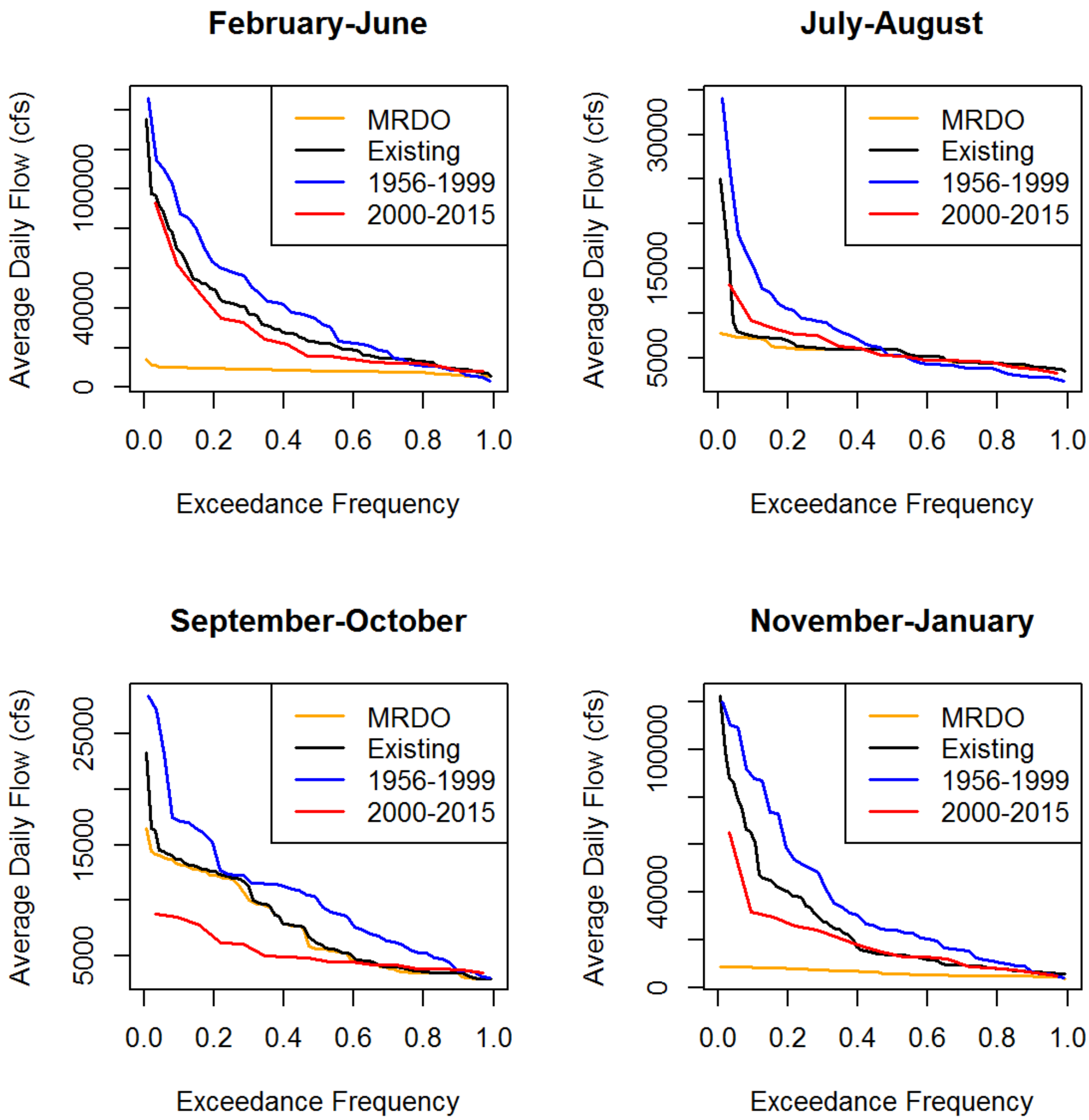

Figure 5.3-3. Comparison of Minimum Required Delta Outflow ("MRDO", orange line), CalSim II Modeled Delta Outflow ("Existing", black line), and Observed Delta Outflow for 1956-1999 (blue) and 2000-2015 (red) (Dayflow data, DWR 2016).

A comparison of the flows identified in Chapter 3 to support estuarine habitat and species (Table 3.13-2) and MRDO shows that the existing Delta outflow objectives for winter and spring do not generally achieve the species specific flow levels. Existing flows generally exceed minimum D-1641 Delta outflow objectives for February through June, which means that over time with increasing water development, existing outflows will likely diminish with additional diversions without additional regulatory requirements. This also indicates that the 2006 Bay-Delta Plan and D-1641 do not provide sufficient flow during dry water years for any of the species in Table 3.13-2. Likewise, the flows shown in Table 3.13-2 to support longfin smelt, Sacramento splittail, and White sturgeon are larger than the maximum flow requirement in D-1641 of 29,200 cfs. Thus, minimum D-1641 outflows are not at the flow levels indicated to be protective of these three species under any hydrologic condition. This conclusion is consistent with the 2010 Delta Flow Criteria report that stated "…the best available science suggests that current flows are insufficient to protect public trust resources." It is important to note however that while Sacramento splittail and sturgeon need higher flows after March than do longfin smelt, the flows needed for Sacramento splittail might be reduced if the Yolo Bypass was able to be flooded at a lower Sacramento River flow. Also, the long life and high fecundity rate of sturgeon make this species less dependent on frequent high Delta outflow events. Nonetheless, the science indicates that increased flows will help to protect the species.

5.3.3.3 Potential Benefits of Increased Winter-Spring Delta Outflow

The flows found in the scientific literature or estimated using the methods in Chapter 3 should not be taken to represent absolute flow needs that must be met at all times or in all years to support species. Rather, they serve as indicators of conditions that favor native species, and constitute a set of quantifiable metrics that can be used to assess the relative protection afforded by a range of flow regimes. The scientific information supporting modifications to existing flow requirements is broader than these quantitative relationships, and includes knowledge of life history, ecology, and the conditions under which native species evolved. The analysis below shows how frequently the flows identified in Chapter 3 that are expected to achieve specified species population levels or population growth rates (for ease of reference "species flow") would be realized under the range of percent unimpaired flows developed above. However, benefits to species and the estuary are also expected at lower flows that exceed existing flows. Generally, the higher the flows up to 100 percent of unimpaired flow (and higher in the summer and fall) and the lower the X2 value, the greater the benefits are for native species and the ecosystem provided adequate supplies are maintained for cold water and flows at other times. The following analysis as it is updated in the final Report will help the State Water Board to evaluate the benefits of different flow levels such that these can be considered when evaluating against other effects on beneficial uses. However, the identified species flow levels should not be interpreted to be the only levels at which benefits to species or the ecosystem occur.

The exceedance plots in Figures 5.3-4 through 5.3-9 show the distributions of average Delta outflows over each of the multi-month periods in Table 3.13-2, with dashed horizontal lines indicating each of the flows over that period identified to achieve species population levels identified in Chapter 3. The intersections of the horizontal lines with the exceedance curves provide an estimate of how frequently each species flow would occur in each percent unimpaired flow scenario. The more frequently a species flow is met, the more favorable conditions are to support the beneficial use. The results of this analysis are summarized in Table 5.3-2. As discussed above, caution should be used in interpreting the results for 35% and 50% UF scenarios. The frequencies shown for some species flows are lower than existing conditions, particularly for higher flows. This reflects the fact that the 35% to 75% UF scenarios represent a bare requirement, rather than a modeled flow that considers other requirements and physical constraints on diversions. Future modeling analysis will factor in these operational considerations, and the 35% and 50% scenarios are expected to resemble existing conditions for these higher flows.

The frequency of meeting the flows to support estuarine beneficial uses increases with each increase in percent of unimpaired inflow (Table 5.3-2). For example, flows that correspond to an average X2 position downstream of Port Chicago occur 44 percent of the time under existing conditions but are estimated to occur 65 percent of the time at 75% UF (Figure 5.3-4). Also, the probability of achieving a species flow target varies among species. Targets requiring lower flow are met more frequently than those needing high flow. For example, the low flow target of 19,000 cfs for Bay shrimp is met 57 percent of the time under existing conditions and increased to 90 percent of the time at 75% UF (Figure 5.3-6). In contrast, the high flow target of 47,000 cfs for Sacramento splittail is met 29 percent of the time under existing conditions and only increases to 41 percent of the time at 75% UF (Table 5.3-2, Figure 5.3-8). None of the species-specific flows is met 100 percent of the time, even at 75% UF.

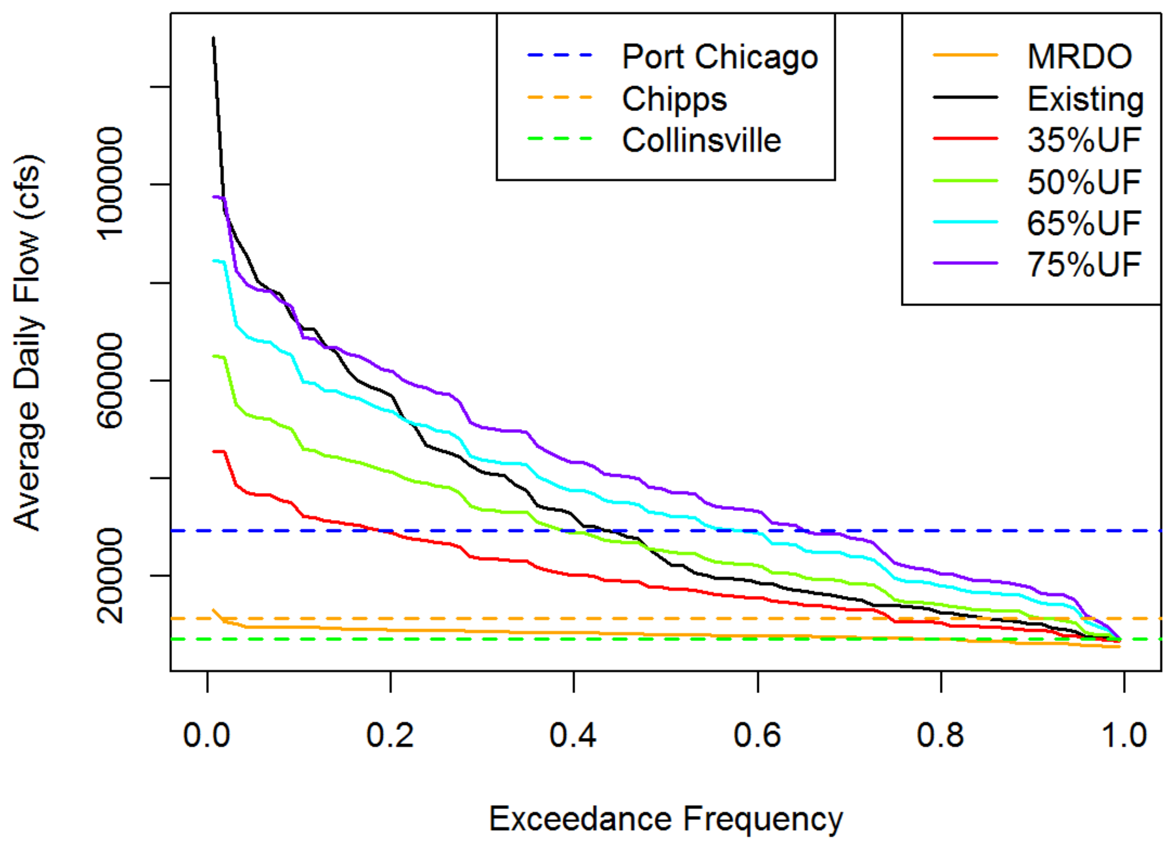

Figure 5.3-4. Frequency of Meeting January-June Delta Outflows to Benefit Estuarine Low Salinity Zone Habitat for Minimum Required Delta Outflow (MRDO), Existing Conditions as Modeled by CalSim II, and Delta Outflows Resulting from 35% to 75% of Unimpaired Delta Inflow.

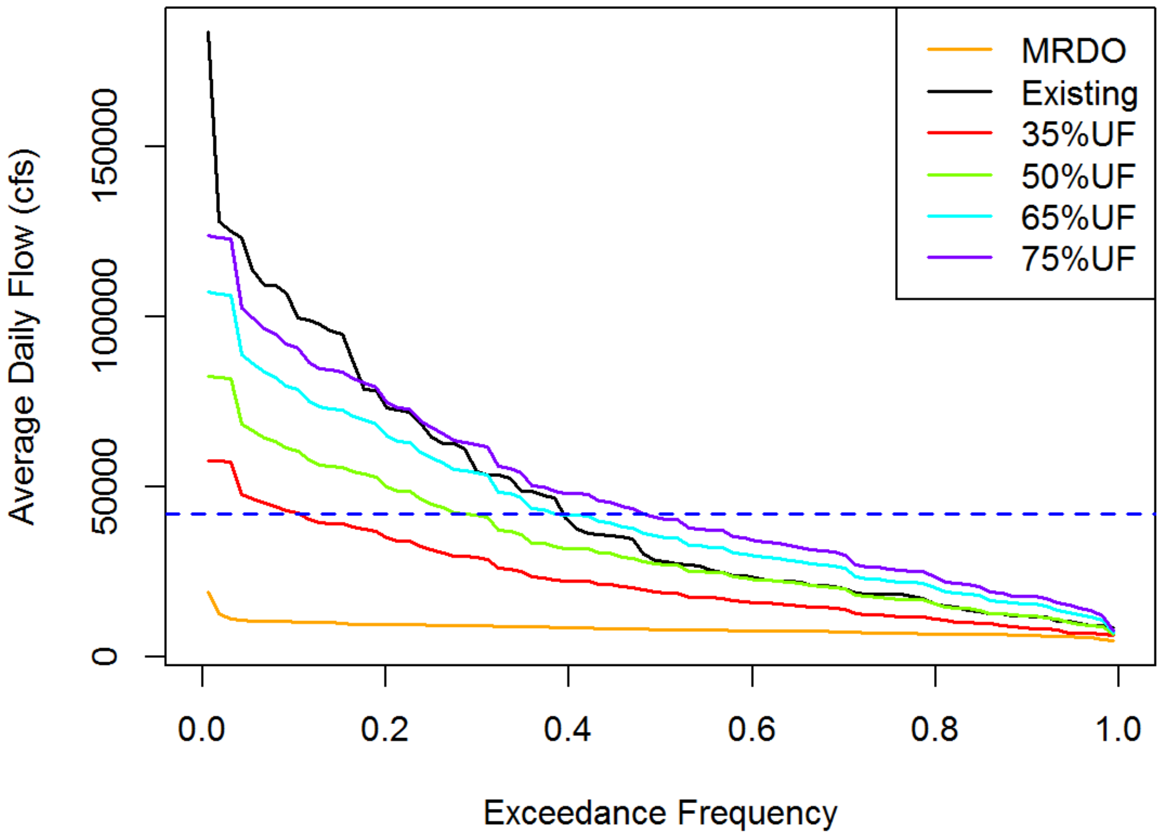

Figure 5.3-5. Frequency of Meeting January-March Delta Outflows to Benefit Adult Longfin Smelt for Minimum Required Delta Outflow (MRDO), Existing Conditions as Modeled by CalSim II, and Delta Outflows Resulting from 35% to 75% of Unimpaired Delta Inflow.

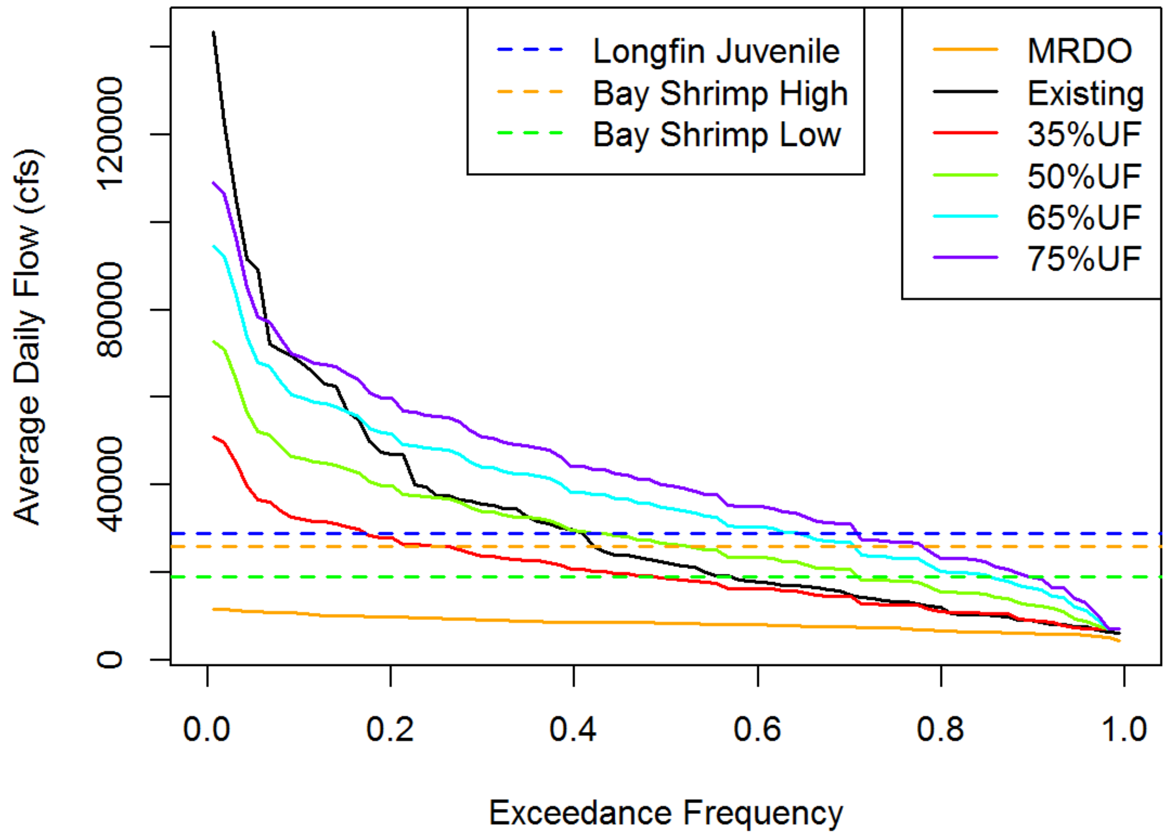

Figure 5.3-6. Frequency of Meeting March-May Delta Outflows to Benefit Juvenile Longfin Smelt and California Bay Shrimp for Minimum Required Delta Outflow (MRDO), Existing Conditions as Modeled by CalSim II, and Delta Outflows Resulting from 35% to 75% of Unimpaired Delta Inflow.

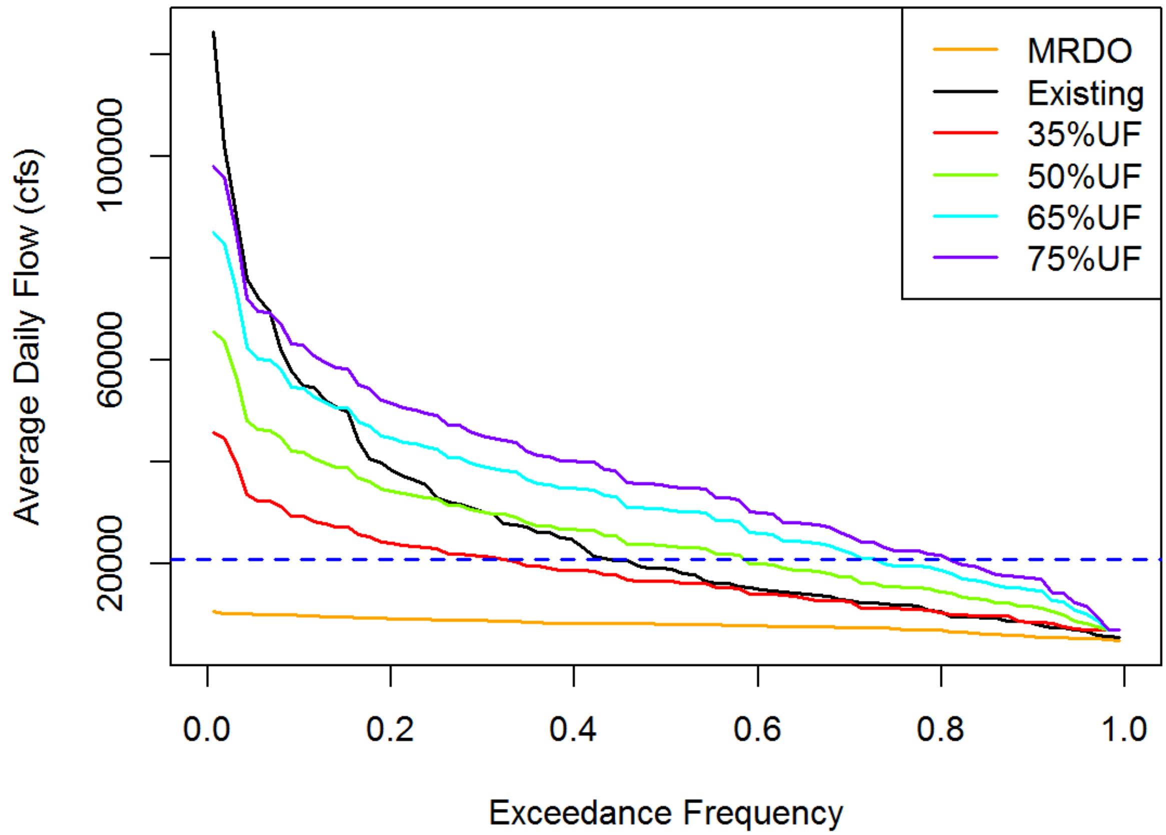

Figure 5.3-7. Frequency of Meeting March-June Delta Outflows to Benefit Starry Flounder for Minimum Required Delta Outflow (MRDO), Existing Conditions as Modeled by CalSim II, and Delta Outflows Resulting from 35% to 75% of Unimpaired Delta Inflow.

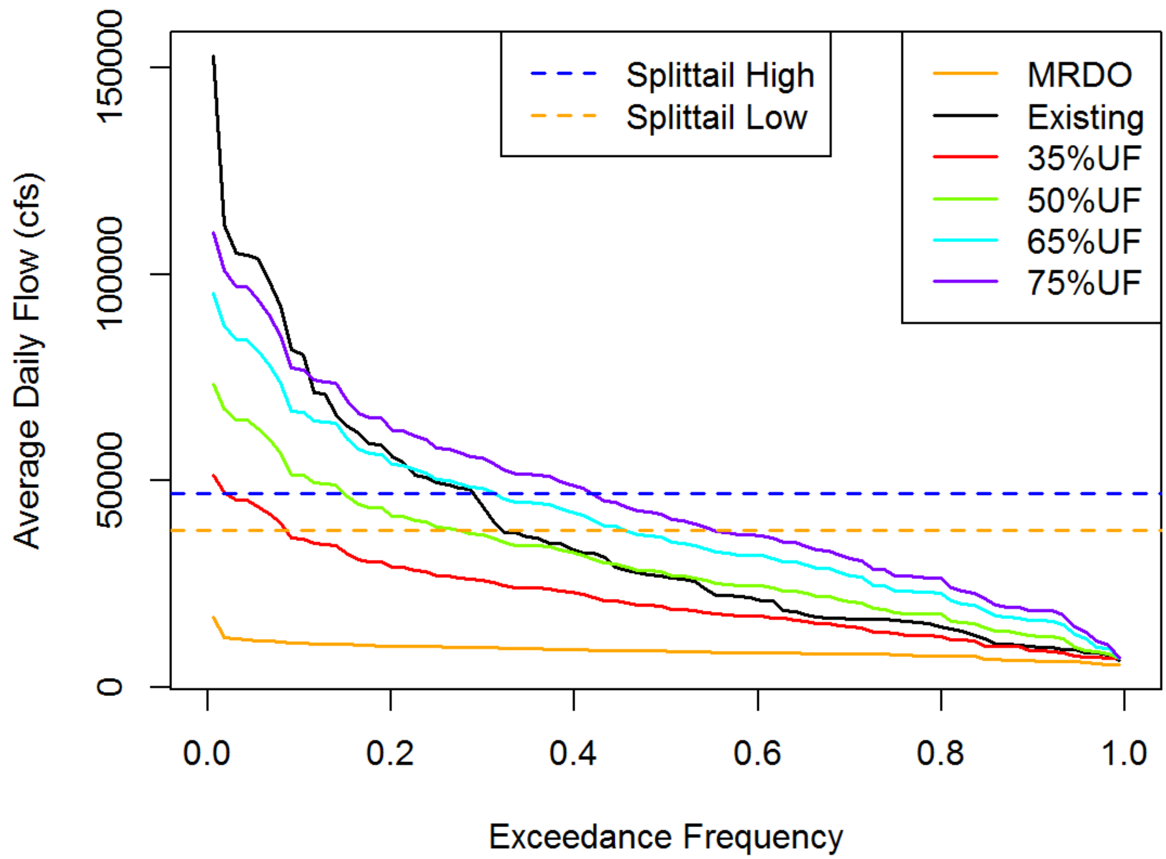

Figure 5.3-8. Frequency of Meeting February-May Delta Outflows to Benefit Sacramento Splittail for Minimum Required Delta Outflow (MRDO), Existing Conditions as Modeled by CalSim II, and Delta Outflows Resulting from 35% to 75% of Unimpaired Delta Inflow.

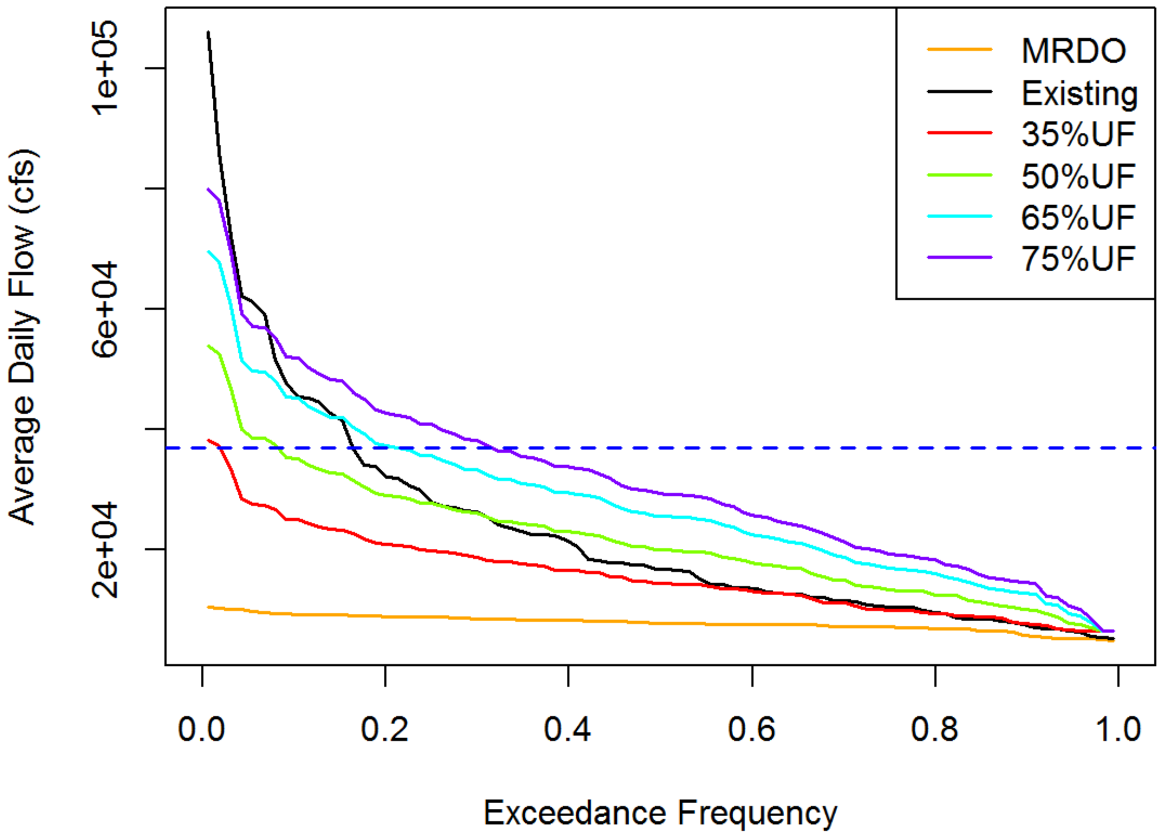

Figure 5.3-9. Frequency of Meeting March-July Delta Outflows to Benefit White and Green Sturgeon for Minimum Required Delta Outflow (MRDO), Existing Conditions as Modeled by CalSim II, and Delta Outflows Resulting from 35% to 75% of Unimpaired Delta Inflow.

Table 5.3-2. Summary of Frequency of Meeting Winter-Spring Delta Outflows to Benefit Estuarine Habitat and Species. As discussed above, these frequencies would be much higher for the unimpaired scenarios when accounting for unregulated flows, other regulatory flows, etc. Existing conditions reflects MRDO flows plus the other regulated and unregulated flows.

Species	MRDO	Existing	35%UF	50%UF	65%UF	75%UF
Port Chicago[5]	0	44	18	39	59	65
Chipps Island	1	84	74	90	95	96
Collinsville	79	99	95	99	100	100
Longfin Smelt Adult	0	39	11	29	39	48
Longfin Smelt Juvenile	0	40	17	44	65	71
Bay Shrimp (High)	0	43	24	52	71	78
Bay Shrimp (Low)	0	57	49	71	85	90
Starry Flounder	0	44	32	59	73	80
Sacramento Splittail (High)	0	29	2	15	32	41
Sacramento Splittail (Low)	0	32	9	27	45	55
Green and White Sturgeon	0	16	2	9	21	32

The flow frequency distributions suggest that population abundance of native species will increase with increasing percent of unimpaired flow because net Delta outflow also increases. However, the population recovery rate may vary among species because the flow needs of the different species vary substantially and this changes the frequency with which the species-specific flows are likely to be met. The potential increase in population abundance was estimated for several species using the flow-abundance relationships in Chapter 3. For each flow scenario a distribution of expected abundance indices was generated by applying the flow-abundance regression formula to the distribution of modeled flows. The percent increase in the median of each abundance index was calculated relative to the median abundance index for the existing conditions scenario (Table 5.3-3). This calculation is meant to give a general sense of the relative benefit each species may realize for a given flow scenario, and should not be interpreted as a prediction of future population abundances. No attempt was made to quantify the statistical uncertainty in these values. According to this analysis, estuarine species would be expected to derive little to no benefit from the 35% unimpaired scenario, modest benefit from the 50% scenario, and more substantial benefits from 65% and 75% scenarios when compared to existing conditions. As discussed above, this analysis does not consider other uncontrolled and regulatory flows which would significantly increase the flows and assumed benefits in some years. These effects will be assessed in forthcoming analyses.

[5] While the 2006 Bay-Delta Plan and D-1641 include requirements for Port Chicago days, because of the limited amount of time they apply and the several month averaging done for this analysis, they do not appear in the results.

Table 5.3-3. Potential Percent Increase in Median Abundance Indices Relative to CalSim II Modeled Flows for Existing Regulatory Conditions Assuming no Additional Unregulated or Regulated Flows.

Species	35%UF	50%UF	65%UF	75%UF
Longfin Smelt	0	13	66	104
Bay Shrimp	0	11	29	41
Starry Flounder	0	10	26	36
Sacramento Splittail	0	3	31	49

5.3.3.4 Summer and Fall

The USFWS BO requires Delta outflow to be managed in September and October so that X2 is no greater than 74 km or 81 km following wet and above normal water years, respectively. The purpose of this action is to increase the quantity and quality of Delta smelt habitat in fall by locating X2 in Suisun Bay. As summarized in Chapter 3, the findings from the Interagency Ecological Program MAST (Baxter et al. 2015) have confirmed the importance of the location of X2 in fall for Delta smelt larval recruitment. Baxter et al. (2015) found an inverse relationship between the location of X2 in fall and larval smelt abundance the following spring (Figure 3.8-4). The relationship was improved by the addition of a FMWT index value suggesting that both habitat quantity and quality and the number of breeding adults were important in determining recruitment (Baxter et al. 2015). Based upon these findings, this Report recommends a fall X2 requirement that includes adaptive management consistent with the USFWS BO in wet and above normal water years to increase Delta smelt recruitment.

Summer habitat for Delta Smelt has also been degraded with increased water development. Recent information developed by CDFW and USFWS indicates that placing X2 downstream of the confluence of the Sacramento and San Joaquin Rivers increases the survival of juvenile Delta smelt to the sub-adult stage (Figure 3.8-3). These conclusions are based largely on recent work that has not yet been subjected to peer review. Based on further development of the science on this matter, the final Report may include additional recommended summer Delta outflow requirements or specific adaptive management provisions.

5.3.3.5 Additional Considerations

In addition to protecting estuarine species, year round Delta outflow also protects estuarine habitat for anadromous fish. Delta outflows affect migration patterns of anadromous species and the availability of habitat. Freshwater flow is an important cue for upstream spawning migration of adult salmon and other estuarine-dependent species, and is a factor in the survival of salmon smolts moving downstream through the Delta. As discussed in more detail above for freshwater inflows, salmonids need year-round flows (Section 5.2). Year-round Delta outflow is also important for the survival of Chinook salmon and steelhead. Thus, the State Water Board will also consider the adoption of a year-round outflow narrative objective. The State Water Board may also need to revisit numeric outflow objectives outside of the winter-spring period if protective flows are not provided through the adaptive management provisions.

Suisun Marsh is the largest contiguous brackish wetland in the western United States, situated between the fresh water Delta ecosystem and the saline ecosystem of San Francisco Bay. Delta inflow from Sacramento River tributaries and outflow through the Delta are the primary factor governing salinity in the Marsh, along with some regulation by salinity control gates. A variety of environmental stressors previously discussed also affect Suisun Marsh in addition to flow. Suisun Marsh wetlands provide many important ecological functions, including wintering and nesting area for waterfowl and water birds of the Pacific Flyway, nursery habitat for native fish, and essential habitat for other fish, wildlife, and plants (smelts in particular).

The Bay-Delta Plan already includes a narrative objective for the brackish tidal marshes of Suisun Bay which is implemented in part by the Suisun Marsh Habitat Management Preservation, and Restoration Plan (SMP). The SMP addresses habitats and ecological process, public and private land use, levee system integrity, and water quality through tidal restoration and managed wetland activities. The SMP is intended to guide near-term and future actions over the next 30 years related to restoration of tidal wetlands and managed wetland activities in the Marsh.

Implementation of any new inflow and Delta outflow requirements will support habitat which has become essential to smelts in particular, which will also implement the narrative objective for the brackish tidal marshes of Suisun Bay. Increased flow has documented successes with decreased predation and increased native fish abundance with the re-introduction of more natural flows in other areas of the Bay-Delta. The State Water Board is not considering any changes to the narrative objective at this time. Potential non-substantive changes to requirements may be addressed in the draft Phase II changes to the Bay-Delta Plan that will be provided at a later date.

5.3.4 Conclusion

Greater quantities of Delta outflow requirements are needed during the winter and spring to support estuarine processes, habitat, and the species that depend upon them. In addition, Delta smelt appear to benefit from flows that place the low salinity zone downstream of the confluence of the Sacramento and San Joaquin Rivers during summer and fall. Populations of several estuarine-dependent species of fish and shrimp vary positively with flow as do other measures of the health of the estuarine ecosystem. Freshwater inflow also has chemical and biological consequences through its effects on loading of nutrients and organic matter, pollutant concentrations, and residence time. More outflow in spring results in higher recruitment in the fall for each species. Native estuarine species evolved to take advantage of elevated winter-spring flows for reproduction. This Report recommends increases in outflow, particularly in spring, for the update to the Bay-Delta Plan to provide reasonable protection of fish and wildlife beneficial uses to stabilize and enhance the distribution and abundance of aquatic resources. The beneficial uses that would be protected include Warm and Cold Water Habitat, Migration of Aquatic Organisms, Spawning, Reproduction and/or Early Development, Estuarine Habitat and Rare, Threatened or Endangered Species.

An increase in juvenile recruitment is an essential step for increasing population abundance. However it is impossible, without robust life cycle models, to predict how much recruitment is needed over how many generations to recover the populations. The State Water Board will consider outflows that encompass a range of flows coupled with a robust monitoring and science program. The requirements may need to be adaptively managed either by increasing or decreasing the numeric flow requirement within the defined range as monitoring indicates whether population abundance is increasing at a satisfactory rate.

The new winter and spring numeric Delta outflow requirement is recommended to be structured similarly to the existing Delta outflow objectives, which require a certain amount of outflow based on a measure of unimpaired inflows (the ERI) for the previous month. The requirement would be modified to use the current month's index to be compatible with the inflow requirements discussed above, and to better allow management in a variable system. Minimum flow requirements in the existing Bay-Delta Plan and D-1641 are recommended to remain in place including the minimum January requirement for NDOI of at least 4,500 cfs, and February through June 3-day average NDOI of at least 7,100 cfs. It is recommended that the X2 requirement in Bay-Delta Plan Table 4 be replaced with a new monthly requirement that is at least as protective as the existing requirements. The removal or modification of the existing Delta outflow objectives for July through December would remain in place to provide minimum protections.

Consistent with potential modifications to freshwater inflow requirements, provisions that allow for Delta outflow to be managed adaptively, with shaping and shifting of flows within the range permitted by the numeric requirement are recommended to maximize the protection of fish and wildlife and achieve specific flow functions. A fall X2 requirement consistent with the USFWS BO is also recommended in above normal and wet years. Additional summer outflows requirements or adaptive management provisions will be considered based on evolving science on this matter.

5.3.4.1 January to June Requirements

The precise formulation of modifications to the January through June Table 4 Delta outflow requirements has not been determined. The initial recommended formulation of the requirement is presented in Table 5.3-4, and is based on the flows developed in Section 5.3.3. The requirement should be consistent with a numeric inflow requirement based on a percent of unimpaired flow that is also subject to adaptive management. Thus, implementation will require the development of water accounting procedures to accommodate shifting of flow within the January-June period, with some portion potentially available to be shifted outside of this period. Compliance could be determined by a calculated index of net Delta outflow similar to the existing NDOI, by the number of days meeting a salinity requirement at a number of compliance locations, or by a combination of both approaches, as is currently implemented by Bay-Delta Plan and D-1641 Tables 3 and 4. A more fully developed recommended structure for the requirements will be included in a draft revised Bay-Delta Plan and program of implementation that will be informed by modeling, a recently completed Delta Science Program review of a DWR report on methods for calculating net Delta outflow (DWR 2016a), and by input from agencies, including ISB, and the public.

Table 5.3-4. Illustrative Example Delta Outflow Associated with 65 percent Unimpaired Inflow. The monthly average net Delta outflows in cfs is determined by the current month's ERI in TAF.

ERI (TAF)	Jan	Feb	Mar	Apr	May	Jun
500	7,510	7,100	7,100	7,100	7,100	7,100
1,000	14,900	14,300	9,670	7,100	7,100	7,100
1,500	22,300	22,700	17,000	12,500	9,880	11,200
2,000	29,600	31,100	24,300	19,600	15,000	15,900
2,500	37,000	39,500	31,600	26,700	20,100	20,500
3,000	44,400	47,800	38,900	33,700	25,200	25,200
4,000	59,100	64,600	53,500	47,900	35,400	34,600
5,000	65,000	65,000	65,000	62,000	45,600	43,900

5.3.4.2 Fall X2 Requirements

The Report recommends inclusion in the Bay-Delta Plan of a new fall X2 requirement that places X2 in September and October following wet and above normal water years at 74 and 81-km,[6] respectively, for the protection of Delta smelt. In November the inflow to Sacramento CVP and SWP reservoirs would be added to reservoir releases to provide additional delta inflow and augment Delta outflow up to the fall target.

The recommended fall X2 requirement may be implemented as part of an adaptive management program to encourage additional scientific information to inform future management of fall X2 or to provide additional flow after scientific studies have determined the magnitude and duration of fall outflow needed to protect Delta smelt resources.

5.3.4.3 Summer Requirements

Based on additional scientific information, the State Water Board will consider a summer Delta outflow requirement for increased Delta outflow to benefit Delta smelt. The anticipated range for such a requirement would be from 7,100 to 11,400 cfs during July and August. Summer outflows may also be part of an adaptive management program.

5.3.4.4 Adaptive Management

As with inflows, adaptive management provisions are proposed to provide for specific flow functions and ecosystem processes for the new or modified Delta outflow requirements. The January-June numeric Delta outflow requirements may include a block of water that can be adaptively shifted within or outside the winter-spring time period. The purpose of adaptively managing a portion of Delta Outflow would be to provide water for experimental studies and for augmenting flows when scientific information and real time circumstances indicate that additional flow is needed to achieve the narrative objective. A water mass balance accounting procedure should be developed to track the volume of water used and the amount remaining for environmental purposes.

[6] This corresponds to about 11,400 and 7,100-cfs, respectively.

5.3.4.5 Suisun Marsh

Delta outflow requirements largely control flow conditions in Suisun Marsh and modified Delta outflow requirements are expected to reasonably protect fish and wildlife in Suisun Marsh. As such, substantive changes to existing Suisun Marsh requirements are not anticipated at this time.

5.4 Cold Water Habitat Below Reservoirs

5.4.1 Introduction

As discussed above, salmonids require adequate cold water and flow conditions through their spawning and rearing period. Historically before construction of reservoirs and other habitat alterations, salmonids generally had access to cold water habitat in higher altitudes year round. Since construction of dams and other habitat alterations, access for salmonids to cold water habitat is extremely limited at times of year. Climate change will further limit this access. This Report recommends a new cold water habitat requirement to ensure that salmonids have access to cold water habitat at critical times and to ensure that adequate water is available for minimum instream flow purposes downstream of reservoirs. Specific provisions needed for different tributaries will differ depending on the conditions in that tributary and the options available for providing cold water habitat. As such, this Report does not recommend specific requirements but instead recommends a narrative requirement. Depending on the specific conditions of a tributary, the narrative may be implemented through cold water storage requirements, temperature control devices, flow provisions, passage to cold water habitat, or other measures.

5.4.2 Discussion

Since construction of onstream dams in the Central Valley for consumptive uses and hydropower production, access for salmonids to much of their historic upstream cooler spawning and rearing habitat has been blocked. Due to these dams and reservoirs, fish that would otherwise be able to migrate to upstream habitat are now dependent on maintenance of suitable conditions downstream. The release of stored water from reservoirs helps provide downstream conditions that serve to replace, in part, the fishery habitat that would otherwise be available upstream. During the summer and fall when air temperatures exert a strong influence on river temperatures, the water temperature requirements of these species can be met by withdrawing and releasing water from upstream reservoirs. The downstream extent of suitable water temperatures depends on release temperatures (a function of reservoir storage and outlet depth), discharge, and meteorological conditions.

In addition to impacts from reservoir operations, diversions on uncontrolled and controlled streams may also decrease flows and cause temperature impacts, as well as dewatering and stranding impacts, particularly during the summer and fall when inflows are limited and diversions are being made for agricultural and other purposes. Warmer return flows from agricultural and other activities may also cause temperature impacts.

The upper preferred water temperature for spawning Chinook salmon is 55°F to 57°F (Chambers 1956, Smith 1973, Bjornn and Reiser 1991, and Snider 2001). Estimates for optimal water temperatures for Chinook salmon egg incubation range from 41°F to 56°F [44°F to 54°F (Rich 1997), 46°F to 56°F (NMFS 1997), and 41°F to 56°F (Moyle 2002)]. A significant reduction in egg viability occurs at water temperatures above 57.5°F and total embryo mortality can occur at temperatures above 62°F (NMFS 1997). As water temperatures increase, the rate of embryo malformation also increases, as well as susceptibility to fungal and bacterial infestations. Warmer rearing temperatures (46.5 to 770F) provide for optimal growth if food is readily available. However, temperatures that exceed these optimal levels can lead to decreased food availability and salmonid growth rates, and reduce the amount of suitable habitat for rearing (McCullough 1999, Myrick and Cech, Jr. 2001). The preferred temperature range for upstream migration of adult salmonids is 38°F to 56°F (Bell 1991, CDFG 1998). Boles (1988) recommends water temperatures below 65°°F for adult Chinook salmon migration, and Lindley et al. (2004) report that adult migration is blocked when temperatures reach 70°°F, and that fish can become stressed as temperatures approach 70°°F.

The optimal temperature range for spawning Central Valley steelhead is 39°F to 52°F (USDOI 2008). Steelhead egg mortality begins to occur at 56°F (USDOI 2008). Steelhead eggs hatch in three to four weeks at 50°F to 59°F, and fry emerge from the gravel four to six weeks later (Shapovalov and Taft 1954, as cited in NMFS 2014). Juvenile steelhead can be found where daytime water temperatures range from 45°F to 81° (USDOI 2008). Optimal temperatures range during migration is unknown for Central Valley steelhead. Based on northern stocks, the optimal temperature range is 46°F to 52°F (USDOI 2008).

In addition to temperature effects, changes in reservoir flow releases (ramping rate) and diversions of water on tributaries can also cause river flow fluctuations that result in stranding of fish and dewatering of redds. Redds may become dewatered when flows drop as a result of diversions or due to changes in reservoir releases. Juvenile salmonids may also become stranded when side channels become disconnected from the main channel due to rapid flow reductions, or in extreme dewatering events when pools go dry (Bradford 1997, Hunter 1992). Entrapments, another form of stranding, can occur when flows drop and isolated pools of water are created, trapping fish in shallow water where they can be easy targets for predators or suffer from the effects of temperature shock, and/or oxygen depletion. (Hunter 1992).

5.4.2.1 Bay-Delta Watershed Reservoir Storage Management

Maintaining suitable cold water habitat in Delta tributaries requires careful planning because of the need to consider multiple factors, such as current year biological flow needs in the tributaries and in the Delta, biological flow needs for the next year, water deliveries, forecasted hydrology, reservoir storage limitations, and available coldwater pool (NMFS 2009).

Temperature control management below reservoirs is dependent on ambient air temperatures, reservoir storage levels, reservoir releases and the presence and sophistication of temperature control devices and how they are operated if they are in place. Generally, higher reservoir levels help to maintain stratification of reservoirs longer and the volume of cold water in the reservoir that is available for use through the summer and fall. For the protection of salmonids, reservoir releases must be managed to provide minimum flows while at the same time preserving supplies for sustained cold water management throughout the season. Flows must also be managed to avoid fluctuations that cause stranding and dewatering. In reservoirs where temperature control devices are present, they assist with temperature management by allowing for selective withdrawal of releases from varying depths within reservoirs which provides access to cold water deep within reservoirs and allows for cold water pool resources to be metered out over time.

Annual temperature management plans that are adjusted throughout the season and regular monitoring and evaluation of fish distribution and timing, reservoir and flow temperatures, predicted and actual inflows and other factors are also important components for temperature management.

As discussed below, some reservoirs currently include cold water management requirements. However, comprehensive requirements do not exist for all regulated tributaries or for unregulated tributaries and the Bay-Delta Plan does not include any such requirements. Requirements are needed to ensure that flows and storage levels are maintained to provide for cold water habitat, particularly with new flow requirements and climate change that may place greater demands on available supplies. The flow requirements and cold water habitat requirements discussed in this Report will need to be coordinated to ensure the reasonable protection of fish and wildlife.

5.4.2.2 Existing Cold Water Habitat Requirements

The current Bay-Delta Plan does not include explicit requirements that protect cold water habitat downstream of reservoirs; however, there are existing regulations that are applicable to protecting cold water habitat in the Delta. General requirements include the California Fish and Game Code section 5937 which requires that "[t]he owner of any dam shall allow sufficient water at all times to pass through a fishway, or in the absence of a fishway, allow sufficient water to pass over, around, or through the dam to keep in good condition any fish that may be planted or exist below the dam." In addition, the Central Valley Regional Water Quality Control Board's Basin Plan specifies that controllable factors in the Sacramento River from Shasta Dam to the I Street Bridge shall not cause temperatures to "be elevated above 56°F in the reach from Keswick Dam to Hamilton City nor above 68°F in the reach from Hamilton City to the I Street Bridge during periods when temperature increases will be detrimental to the fishery." Specific requirements include those described below.

Upper Sacramento River

The Sacramento River downstream of Shasta Reservoir is the only remaining habitat for endangered winter-run Chinooks salmon with winter-run entirely dependent on adequate cold water releases below Shasta Reservoir for their survival. Spring-run and fall-run also inhabit the upper Sacramento River and are affected by Shasta Reservoir operations. To address significant temperature related mortality to winter-run Chinook salmon on the Sacramento River, the State Water Board adopted Order 90-5 in 1990. The Order required Reclamation to install a temperature control device on Shasta Reservoir to provide for better temperature control and also requires Reclamation to operate Keswick and Shasta dams to meet a daily average temperature of 56°F at the RBDD during periods when higher temperatures will be detrimental to the fishery. The Order allows the temperature compliance point to be moved upstream if factors beyond Reclamation's reasonable control prevent maintenance of 56°F at the RBDD, and upon submittal of a strategy for meeting the temperature requirement at the new compliance point. Factors beyond the reasonable control of Reclamation are not specified nor are explicit carryover storage and other requirements to ensure effective implementation of temperature requirements. The NMFS BO (2009) also includes requirements that Reclamation manage Shasta reservoir storage to reduce adverse effects on winter-run Chinook salmon egg incubation in summer months, and on spring-run during fall months. The emphasis on management of Shasta Reservoir during the summer and early fall is on winter-run Chinook salmon because of their endangered status and very limited range. However, fall-run and spring-run also require consideration and protection from flow fluctuations and temperature effects.

The Delta Science Program conducted an Independent Review Panel (IRP) to assess the effectiveness of the NMFS (and USFWS) BO Shasta Reservoir temperature management actions in 2013, 2014, and 2015. In particular, the IRP reviewed the recommendation by NMFS to use a 55°F 7-day average of daily maximum (7DADM) water temperature requirement for the Sacramento River instead of the 56°F daily average recommended by EPA (2003) to avoid sub-lethal effects on salmonid life history stages (spawning, egg incubation, and fry emergence). The 7DADM was proposed to better protect against impacts from diurnal temperature changes and daily maximum temperatures that have cumulative impacts to developing salmonids. These impacts become more severe based on the duration and severity of exposure with longer exposures reducing changes for long-term survival. Sub-lethal effects from high water temperature can also lead to reduced fry and smolt sizes from sub-optimal growth that can lead to later mortality. These temperature effects could result in reduced productivity of a stock and reduced population size (Anderson et al. 2013).

In its review, the IRP indicated that there is evidence that the 7DADM may better protect salmon early life stages from negative effects of temperature spikes than does an average daily temperature requirement, but also indicated that the question of changing temperature compliance points (TCP) from a daily average temperature to a 7DADM needs to be evaluated in the context of how it affects the location of the TCP as well as survival of salmonid early life stages (Anderson et al. 2013). The IRP encouraged improvements in temperature modeling approaches, including development of a reservoir stratification model, incorporation of biological data into retrospective analysis of modeling and water flows, increased spatial distribution of temperature monitoring in the reservoir, and incorporation of limnological parameters (Anderson et al. 2015). The IRP also suggested that instead of requiring temperature compliance at specific river mile locations, during critically dry conditions, action could be based on protecting areas known to be used for spawning rather than areas that have potential to support spawning but has never been used (Anderson et al. 2015).

After very high temperature related mortality in 2014 and 2015 of winter-run eggs, use by NMFS and the State Water Board of the 55°F 7DADM with some of the recommendations from the IRP was attempted in 2016 to better ensure that significant mortality did not occur for a third year. This issue and needed actions to ensure temperature control on the Sacramento River should be further evaluated in the context of an updated Bay-Delta Plan and new flow requirements to ensure the protection of salmonids on the Sacramento River.

Lower American River

The State Water Board adopted Decision 893 (D-893) in 1958, establishing very minimal instream flow requirements on the American River in Reclamation's water rights for Folsom Reservoir. D-893 is outdated and does not control operations. Instead the NMFS BO (2009) largely controls operations for salmonid protection. The BO incorporates the 2000 Water Forum Agreement which includes new recommended minimum flow requirements, water temperature goals, and monitoring and evaluation to inform cold water temperature management and flow management for spawning and rearing of salmon and steelhead, including avoidance of dewatering and stranding (American River Water Forum 2003; 2004). The Water Forum Agreement has not been reviewed, approved, or incorporated into any water right permit or license by the State Water Board.

Monitoring of juvenile steelhead by CDFW in the American River has shown evidence of visible thermal stress which increased in frequency as the duration of exposure to water temperatures over 65° F increased (NMFS BO 2009). Maintaining suitable water temperatures for all life history stages of steelhead in the American River is a chronic issue because of reduced storage caused by use of Folsom Reservoir for water quality and water supply purposes and because of the limited cold water resources in Folsom Reservoir (NMFS 2009). Only in wetter hydrologic conditions is the volume of cold water pool available sufficient to meet all water temperature goals. Annual operation strategies are developed to manage the available cold water pool in consideration of other water demands and tradeoffs (NMFS 2009), although in practice, water temperature goals have not been met, as a the overall CVP and SWP operation strategy is to increase releases from Oroville or Folsom before increasing releases from the Shasta system in order to meet NMFS BO RPA requirements for end of September Shasta storage, Delta outflow, X2, and other legal requirements (Sacramento River Temperature Task Group 2014, 2015).

In addition to temperature issues, flow fluctuations in the lower American River have also been reported to result in steelhead redd dewatering and isolation (Hannon et al. 2003, Water Forum 2005, Hannon and Deason 2008). Impacts associated with flow fluctuations are expected to continue to occur without additional management for this issue (NMFS 2009). This issue and needed actions to ensure temperature control on the American River should be further evaluated in the context of an updated Bay-Delta Plan and new flow requirements to ensure the protection of salmonids on the American River.

Feather River

The existing hydroelectric power license issued by the FERC for the Oroville facilities expired in 2007, and DWR is currently seeking a new license. The State Water Board's water quality certification for the facilities was issued in 2010 (Order WQ 2010-0016). At the time of the water quality certification, the facilities were found not to adequately protect downstream coldwater beneficial uses. DWR's studies showed that water temperatures in the Low Flow Channel and the High Flow Channel were contributing to adverse conditions for anadromous salmonids. Studies have shown it is unlikely that adult Chinook salmon can use the Feather River below the Thermalito Afterbay Outlet (High Flow Channel) except as a migration corridor. Water temperature monitoring in 2002 and 2003 showed that the temperature of water released from Thermalito Afterbay was as much as 11.3°F higher than that of incoming water. DWR concluded that increased incidence of disease, developmental abnormalities, increased in-vivo egg mortality, and temporary cessation of migration could occur due to elevated water temperatures in some areas of the lower Feather River. The water quality certification states that the water temperatures specified in the 2006 Settlement Agreement are necessary for the protection of cold freshwater, spawning, and migration beneficial uses of the Feather River.

Among other requirements, the facilities currently operate to a Settlement Agreement signed in 2006, which contains water temperature requirements at the Feather River Fish Hatchery and in the Low Flow Channel while conserving the coldwater pool in Lake Oroville (NMFS 2009). As part of the settlement agreement, DWR is required to develop a Feasibility Study and Implementation Plan for Facility Modification(s) to improve temperature conditions for spawning, egg incubation, rearing and holding habitat for anadromous fish in the Low Flow Channel and the High Flow Channel within three years of FERC license issuance. The water quality certification includes temperature requirements for the Feather River Fish Hatchery to provide cooler temperatures to aid in managing disease outbreaks. The Board's water quality certification includes interim and final deadlines for completing the documents and any required facility modifications to meet interim and final temperature requirements in the Low Flow Channel, High Flow Channel, and at the Feather River Fish Hatchery. This matter should be reassessed in the context of an updated Bay-Delta Plan and new flow requirements to ensure the protection of salmonids on the Feather River.

Lower Yuba River

State Water Board Decision 1644 (D-1644), adopted in 2003, contains revised instream flow requirements for the lower Yuba River, defined as the 24-mile section of the river between Englebright Dam and the confluence with the Feather River south of Marysville, flow fluctuation (ramping) requirements, and specific actions to provide suitable water temperatures for all life stages of Chinook salmon and steelhead, and to reduce fish losses at water diversion facilities. D-1644 finds that compliance with CDFW and NMFS recommendations for lower Yuba River temperature was not feasible prior to the construction of additional facilities at New Bullards Bar Reservoir. The Board retained continuing authority to establish water temperature requirements for the lower Yuba River, and required YCWA to make reasonable efforts to operate the Yuba River Development Project to maintain suitable water temperatures in the lower Yuba River for fall-, late-fall, and spring-run Chinook salmon and steelhead.

Water Right Order 2008-0014 amended YWCA's water right permits to include the Yuba Accord's flow schedules and other specified terms and conditions of the Accord's Fisheries Agreement. It included the Accord's provisions for the River Management Team to determine the operation of the upper and lower outlets at New Bullards Reservoir and any temperature control devices that might be built at Englebright Dam. The Order included the Yuba Accord's temperature planning methods that included the input of fisheries agencies and State Water Board approval of recommended actions. The Order noted that YCWA reported data indicating that operation under the Yuba Accord flows does not meet CDFG and NMFS' maximum water temperature requirements for anadromous fish in the months of May through September, even in a wet year. In addition, wet year Yuba Accord flows did not meet the index temperature of 60° F in August and September. This issue and needed actions to ensure temperature control on the Yuba River should be further evaluated in the context of an updated Bay-Delta Plan and new flow requirements to ensure the protection of salmonids on the Yuba River.

Mokelumne River

EBMUD's facilities on the Mokelumne River include two reservoirs, Pardee and Camanche, as well as the Mokelumne Aqueducts which conveys water from Pardee Reservoir to the East Bay, and hydroelectric generation facilities at the base of Pardee and Camanche Dams. In 1998, EBMUD, USFWS, and CDFW entered into a Joint Settlement Agreement (JSA) which specifies minimum flow releases from Camanche Dam, ramping rates and reservoir coldwater pool goals. The JSA allows for modification of releases as long as the total volume released during the year would not be less than that specified in the JSA for the water year type. The JSA's flow release requirements are included in D-1641 and the 1998 amended FERC license for the facilities. EBMUD operates Camanche Reservoir and Pardee Reservoir in an integrated manner for temperature control informed by monitoring, modeling, and forecasting However, EBMUD has reported that historical water temperatures have often exceeded salmonid life stage EPA criteria based on JSA water year type (EBMUD 2013).

Hydropower Facilities

In addition to the above, there are a number of smaller hydroelectric projects within the Bay-Delta watershed that are licensed by FERC for between 30 and 50 years. Licenses issued by FERC are subject to section 401 of the 1972 Clean Water Act. Section 401 requires that any person applying for a federal permit or license, which may result in a discharge of pollutants into waters of the United States, must obtain a state water quality certification that the activity complies with all applicable water quality standards, limitations, and restrictions. These include beneficial uses, defined as the uses of water necessary for the survival or wellbeing of man, plants, and wildlife. Examples include agricultural supply, water contact recreation, and cold freshwater habitat.

Water quality certifications issued by the State Water Board for new and renewed FERC licenses contain various terms and conditions for the facilities to meet water quality standards in applicable State Water Board and Regional Water Quality Control Board Basin Plans. Biological, scientific, and legal conditions have changed since original licenses were issued. Recent water quality certifications have included terms and conditions such as water temperature requirements, ramping criteria, development of plans for managing the coldwater pool in the reservoir to minimize exceedances of downstream temperature requirements, and development of plans for facility modifications if facilities cannot meet specified water temperature requirements. However, older FERC licenses may lack any measures for the protection of cold water species.

5.4.3 Potential Modification to Bay-Delta Plan

With the increased demands that new inflow and outflow requirements may present and existing concerns with protection of cold water for salmonids, it is important that requirements protecting coldwater habitat and storage be developed to assure protection of fisheries resources in the tributaries of the Delta, particularly given potential climate change concerns. This Report recommends a narrative requirement be included in the Bay-Delta Plan, to provide reasonable protection of coldwater habitat below reservoir. Such an approach will allow for development and implementation of tributary specific cold water management approaches that take into consideration the unique design and hydrological characteristics of the many tributaries in the Phase II project area.

5.5 Interior Delta Flows

5.5.1 Introduction

This Report recommends new and modified interior Delta flow requirements to protect native migratory and estuarine species from entrainment effects in the southern Delta associated with CVP and SWP diversion activities. Recommended new and modified requirements include: additional DCC gate closure requirements in October, new limitations on Old and Middle River reverse flows, and additional constraints on spring and fall exports associated with San Joaquin River flows. At this time, no changes to the Delta inflow to export ratio requirements are proposed. However, this is an issue the State Water Board is specifically seeking input on. Some of the proposed interior Delta flow requirements are identical or consistent with biological opinions requirements and are intended to be implemented adaptively in collaboration with the various agencies and workgroups involved.

5.5.2 Discussion

Flow management, including the operation of the CVP and SWP Projects in the Delta affects salmonids, pelagic and other species through alteration of circulation patterns which leads to adverse transport flows, changes in water quality, changes to Delta habitat, and entrainment of fish and other aquatic organisms. The preferred flow pattern for fish and wildlife is one that produces a natural east to west flow and salinity gradient (Moyle et al. 2010). This pattern has been altered due to operation of the DCC and operations of the SWP and CVP diversion facilities (as well as other diversions).

The DCC is opened to bring fresh Sacramento River water directly into the interior Delta to support CVP and SWP diversions and to meet southern Delta water quality requirements. The DCC preserves the quality of water diverted from the Sacramento River by conveying it to southern Delta pumping plants through eastern Delta channels rather than allowing it to flow through more saline western Delta channels. With a capacity of 3,500 cfs, the DCC can divert a significant portion of the Sacramento River flows into the eastern Delta, particularly in the fall. Juvenile salmon drawn into the central Delta through the DCC or Georgiana Slough have a lower chance of survival than fish staying in the Sacramento River's mainstem.

Locations near the CVP and SWP export pumps, including parts of Old River and Middle River in the south Delta, experience net "reverse" flows when export pumping by the Projects exceeds these channels' downstream flows. The average flow in these channels actually runs backward at times, which affects the Delta's aquatic ecosystems both directly and indirectly. Reverse flow in the southern Delta is associated with increased entrainment of some fish species (Grimaldo et al. 2009) and disruption of migration cues for migratory fish. Reverse flows, in combination with altered flows caused by upstream reservoir operations, the constraints of artificially connected Delta channels, plus water exports, affect Delta habitat largely through effects on water residence time, water temperature, and the transport of sediment, nutrients, organic matter, and salinity (Monsen et al. 2007). These reverse flows could, in turn, affect the behavior of migrating fish, and habitat suitability for resident and migratory fish and other species.

5.5.3 Delta Cross Channel Gate Closure Requirements

The existing Bay-Delta Plan includes DCC gate closure requirements that help to minimize risk of entrainment of juvenile Sacramento River salmon at the export pumps by preventing their migration into the central Delta. The Bay-Delta Plan currently requires the DCC gates to be closed: for a total of up to 45 days for the November through January period ,from February through May 20, and for a total of 14 days for the May 21 through June 15 period to prevent juvenile Sacramento River salmon from migrating into the central Delta. During the November-January and May 21-June 15 periods, the timing and duration of gate closure is based on the need to protect fish. Reclamation is required to determine the timing and duration of gate closures after consultation with the fisheries agencies.

As described in Chapter 3, when the DCC gates are open, the probability of entraining outmigrating Sacramento River juvenile salmon and steelhead into the Central Delta is increased. The survival of juvenile salmon migrating through the Central Delta to Chipps Island is about half the survival rate of fish remaining in the Sacramento River channel (Kjelson and Brandes 1989, Brandes and McLain 2001). Closing the DCC gates reduces the number of salmonids diverted into the Central Delta and improves survival to Chipps Island. Closure also redirects a portion of emigrating juvenile salmon into Sutter and Steamboat Sloughs and reduces entrainment at Georgiana Slough (Perry 2010, Perry et al 2013).

As described in Chapter 3, recent literature indicates that the DCC gate closure period should include the month of October. The 2009 NMFS BO includes a DCC gate closure requirement for the interval of October 1 through November 30 to reduce loss of Sacramento River salmonids into Georgiana Slough and the interior Delta that is based on early entry of juvenile salmonids into the Delta. On the Mokelumne River, adult fall-run salmon return to spawn in October. Recent studies have shown that pulse flows from the Mokelumne River in combination with closure of the DCC gates in October increases the number of returning Chinook salmon and reduces straying to the American River (EBMUD 2013, CDFW 2012). CDFW (2012) has recommended that the DCC gates be closed for up to 14 days in October in combination with experimental pulse flows from the Mokelumne River to increase salmonid returns and reduce straying.

Diurnal operations of the DCC gates has also been proposed to minimize the water quality impacts of gate closures. However, Reclamation has indicated that it is not clear whether water quality benefits can be achieved through diurnal operations and it is not clear whether the gates can be opened and closed repeatedly for diurnal operations due to their age, condition, and design. The DSP's LOBO Review Report (December 2014) indicated that potential improvements in the operational effectiveness of the DCC gates should be examined, including opening the gates on ebb tides during the day and closing at other times.

The information above and in Chapter 3 supports the addition of the month of October to the Bay-Delta Plan's existing suite of DCC gate closure requirements. Specifically, additional potential closure days are recommended during October based on fish presence and in coordination with the fisheries agencies. Adaptive management provisions are also proposed for DCC gate closure requirements to consider diurnal operations and other real time measures to improve the efficiency and effectiveness of DCC gate closures.

5.5.4 Old and Middle River Reverse Flow Limitations

SWP and CVP exports have been identified as a contributing factor in the decline of Delta smelt and other pelagic species (Chapter 3). Diversions in the southern Delta, particularly the large SWP and CVP export facilities, can cause the net flow in nearby reaches of Old and Middle Rivers to reverse from the natural northward direction and flow south towards the SWP and CVP pumps. These reverse flows can draw fish, especially the smaller larval and juvenile forms of pelagic species, into the SWP and CVP export facilities where they can experience significant mortality.

Net OMR reverse flow restrictions are included in the USFWS 2008 BO (Actions 1 through 3), the NMFS BO (Action IV.2.3), and the CDFW Incidental Take Permit (Conditions 5.1 and 5.2) for the protection of Delta smelt, salmonids, and longfin smelt, respectively. (NMFS 2009. p. 648; USFWS 2008, CDFW 2009.) This Report recommends a similar numeric range for net OMR reverse flows.

OMR reverse flows are harmful to fish and wildlife throughout the year, but especially in winter and spring when larval and juvenile estuarine species may be present near the export facilities and juvenile anadromous Chinook salmon, steelhead, and green sturgeon are migrating through the Delta to the ocean. The magnitude and frequency of OMR reverse flows has increased over time as CVP and SWP exports and other diversions have increased. Figure 4.4-3 shows that during pre-development years (1925-2000), negative OMR flow was estimated to have occurred about 15 percent of the time. In contrast, between 1986 and 2005, OMR reverse flows have increased in frequency to more than 90 percent of the time.

As described in Chapter 3, high net OMR reverse flows have negative ecological consequences. First, net reverse flow draws fish, especially the smaller larval and juvenile forms, into the export facilities where they can experience high mortality (NMFS 2009, Bennett 2005). Second, net OMR reverse flow reduces the size of the spawning and rearing habitat available for fish in the Delta. Third, net OMR reverse flow leads to a confusing environment for juvenile salmon emigrating from the San Joaquin River basin. Through-Delta exports reduce salinity in the central and southern Delta and as a result juvenile salmon migrate from higher salinity in the San Joaquin River to lower salinity in the southern Delta, contrary to the natural historical conditions and their inherited migratory cues. Finally, net OMR reverse flow reduces the natural variability in the Delta by homogenizing the system similar to the water quality in the Sacramento River (Moyle et al 2010).

OMR reverse flows within a specified range would help to reduce the risk of salvage and entrainment. Chapter 3 indicates that salvage export patterns appear to be consistent with known migration habits; and that the risk of salvage and entrainment of fish depends on the location of juvenile and adult individuals relative to the export facilities and the magnitude of OMR reverse flows. The following summarizes time periods and OMR reverse flows associated with increased risk of entrainment.

- Between December and April, a step increase in juvenile salmonid entrainment is estimated to occur when OMR reverse flows become more negative than -2,500 cfs. Another larger step increase in entrainment occurs when OMR reverse flows become more negative than -5,000 cfs.

- Delta smelt spawning and rearing in the Delta occur between December and June. Higher adult salvage rates statistically begin to happen at OMR reverse flows more negative than -5,000 cfs. Lower adult salvage rates occur at OMR reverse flows less negative than -1,250 cfs.
- Between December and March, increased adult longfin smelt salvage begins to occur at OMR reverse flows more negative than -5,000 cfs. Between April and June, the lowest juvenile salvage rates occur at an OMR reverse flows less negative than -1,250 cfs.
- Green and white sturgeon are vulnerable to entrainment from exports year-round.
- Entrainment of American shad at the export facilities is highest between July and August and again between October and December, although some salvage occurs each month of the year.
- The risk of Sacramento splittail entrainment appears greatest in spring (adult upstream spawning migration) and early summer (juvenile emigration).

Based on the above, new OMR reverse flow requirements from December through June are recommended. The suggested flow range is from -1,250 cfs to -5,000 cfs, which would be managed based on the presence of Delta smelt, longfin smelt, and salmonids in an adaptive management framework informed by real-time monitoring of fish species abundance and distribution, and in consultation with the fisheries agencies.

5.5.5 Export Limit Modifications

The existing export limits contained in the Bay-Delta Plan are intended to protect fish and wildlife beneficial uses, including the habitat of estuarine-dependent species, in part by reducing the entrainment of various life stages by the Projects' export pumps in the southern Delta. In addition to reducing entrainment, the existing export limits are intended to provide general protection of the Delta ecosystem and a variety of fish and wildlife beneficial uses by limiting the portion of freshwater that may be diverted by the SWP and CVP export facilities. Additional ecosystem benefits beyond reduced entrainment may include reduction in losses of nutrients and other materials important for the base of the food web, food organisms, habitat suitability, and more natural flow and salinity patterns.

The Bay-Delta Plan limits exports in two ways. One is based on the combined amount of water that may be exported from the Delta by the SWP and CVP water project facilities in the southern Delta relative to total Delta inflow. The limit is 35 to 45 percent of Delta inflow for February (depending on total inflow conditions during January), 35 percent from March through June, and 65 percent of Delta inflow from July through January.

The second is based the ratio of San Joaquin River flow at Vernalis to the combined amount of water exported. Limits of 1,500 cfs or 100 percent of San Joaquin River flow apply from April 15 through May 15 (spring pulse flow period). These spring flow limits may be adjusted upon the agreement of the fishery agencies and upon notice to the Executive Director of the State Water Board. The spring flow limit specifies that the variations in the maximum export rate are intended to result in no net annual loss of water supply within the water quality and operational requirements of the plan.

Chapter 3 highlights the need to improve in-Delta survival of fish originating from the San Joaquin River and Delta eastside tributaries, especially in consideration of the improvements in tributary flows contemplated through the Phase I update of the Bay-Delta Plan anticipated to establish increased San Joaquin River tributary flow requirements. Delta exports can cause a false attraction flows that draws emigrating fish to the South Delta export facilities where direct mortality from entrainment may occur, especially for fish from the San Joaquin River and Delta eastside tributaries. The following recommended modifications to the Bay-Delta Plan would help reduce straying and entrainment of San Joaquin River and Delta eastside tributary migratory fish as they migrate through the central Delta.

5.5.5.1 Modifications to the Ratio of San Joaquin Flow to Export Rate

The April 15 to May 15 export limits in the Bay-Delta Plan restrict the combined pumping at the SWP and CVP south Delta pumping facilities to 1,500 cfs or the measured flow of the San Joaquin River at Vernalis, whichever is greater. This requirement, in tandem with the Bay-Delta Plan's San Joaquin River spring pulse flow requirement, is intended to improve survival of downstream migrating juvenile salmon originating in the San Joaquin River and its tributaries by improving net downstream flows past the export facilities.

Information suggests that fish species, particularly San Joaquin River and Delta eastside fish species, could benefit from additional restrictions on export pumping as a function of San Joaquin River flows to provide for more natural flow patterns to the ocean. In particular, additional flows provided through the Phase I update of the Bay-Delta Plan's San Joaquin River flow requirements should not be subject to export to ensure that fish outmigrating with those flows are protected and that those flows contribute to Delta outflows as intended.

During the April to May peak outmigration period for San Joaquin Basin steelhead, the NMFS BO (NMFS 2009) restricts the ratio of San Joaquin inflow (at Vernalis) to south Delta exports (I:E) to between 1:1 and 4:1 based on water year type or 1,500 cfs, whichever is greater. When Vernalis flows exceed 21,750 cfs, export rates are not restricted. The Bay-Delta Plan currently includes less restrictive export rates than the NMFS BO. Specifically, the maximum export rate during April and May is 1,500 cfs, or 100% of the 3-day running average of San Joaquin River flow at Vernalis, whichever is greater. The minimum 1,500 cfs export amount has historically been identified as the minimal amount of export needed for CVP and SWP health and safety purposes. Recent information from drought operations indicates that this amount may be as low as 800 cfs or lower.

Chapter 3 supports an expanded window of limited maximum export rates to protect juvenile salmonids migrating from the San Joaquin basin, including consideration of a lower minimum export rate, as low as 800 cfs. Juvenile salmonids migrate out of the San Joaquin River basin during February through June (SWRCB 2012), and may need protection from export-related mortality at any time during this period to minimize mortality and preserve life history diversity. As such, this Report recommends consideration of additional export restrictions during the February through June time period based on fish presence and in coordination with the fishery agencies within the range of 1:1 to 4:1 San Joaquin River flows to exports (consistent with the NMFS BO) with minimal exports as low as 800 cfs. The range recommended for consideration is illustrated in Figure 5.5-1.

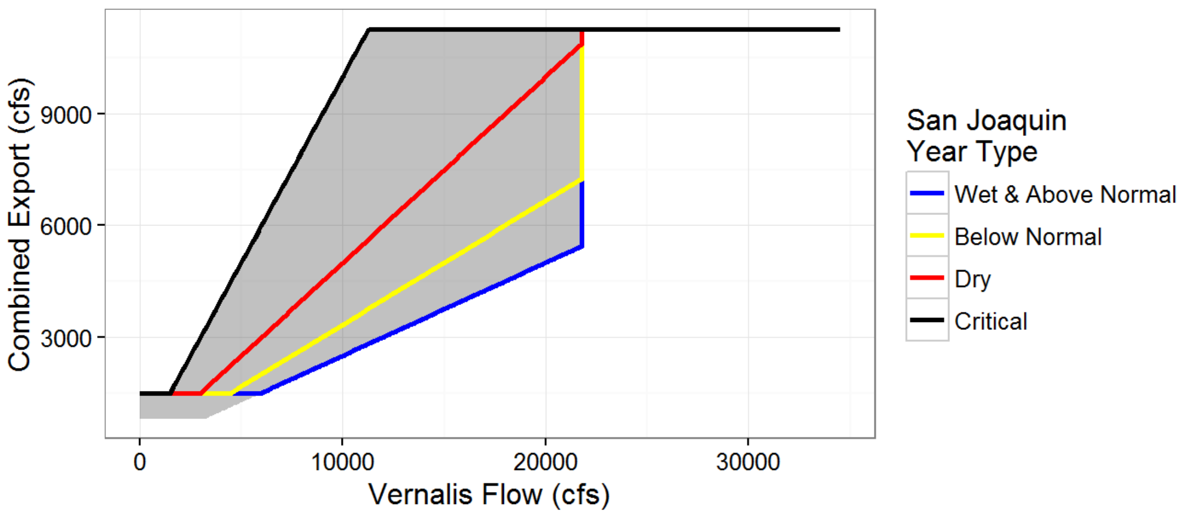

Figure 5.5-1. Potential Adaptive Range for Combined CVP and SWP South Delta Exports as a Function of Delta Inflow from the San Joaquin River at Vernalis (shaded area). The black, red, yellow, and blue lines represent the existing NMFS BO export constraints for critical, dry, below normal, and wet/above normal years, respectively. The grey shaded area represents the range of export constraints recommended for consideration.

5.5.5.2 New Limits on South Delta Exports During the San Joaquin River October Pulse Flow Period

Chapter 3 shows that Vernalis flow to export ratios appear to be important during the fall period to provide improved migration conditions for adult San Joaquin River fall-run Chinook salmon. A combination of higher Vernalis flows and lower export rates help to reduce the straying rates of adult San Joaquin River fall run Chinook salmon during their spawning migration in October (Marston et al. 2012, Monismith et al. 2014). When exports are high, little if any flow from the San Joaquin basin may make it out to the ocean to help guide San Joaquin basin salmon back to the basin to spawn (AFRP 2005). Adult fall run Chinook salmon straying rates decrease when export rates are less than 300% of Vernalis flow (Mesick 2001). The existing Bay-Delta Plan includes October pulse flow requirements at Vernalis to help attract adult spawning fall-run Chinook salmon to the SJR basin and to provide incidental benefits to Central Valley steelhead. Limiting south Delta exports to no more than 300% of Vernalis flow during any October pulse flow would help to reduce straying of San Joaquin Chinook salmon during their spawning migration.

5.5.6 Conclusion

New and modified interior Delta flow requirements are recommended to protect resident and migratory species from entrainment and related effects including: additional DCC gate closure days in October, new Old and Middle River flow limitations, and additional constraints on spring and fall exports as a function of San Joaquin River flows. Several of the proposed interior Delta flow requirements are identical or consistent with biological opinion requirements and are intended to be implemented adaptively in collaboration with the various agencies and workgroups involved.

Adaptive management provisions are proposed for all of the interior Delta flow requirements such that the requirements can adapt to new scientific knowledge as it becomes available, through the Delta Science Program, CSAMP, CAMT, and other efforts.

Chapter 6
References Cited

6.1 Chapter 1, Overview

Delta Stewardship Council (DSC). 2013. *The Delta Plan: Ensuring a Reliable Water Supply for California, a Health Delta Ecosystem, and a Place of Enduring Value*. May. Sacramento, CA. Available: http://deltacouncil.ca.gov/delta-plan-0.

Grossman, G. D., T. Essington, B. Johnson, J. Miller, N. E. Monsen, and T. N. Pearsons. 2013. *Effects of Fish Predation on Salmonids in the Sacramento River–San Joaquin Delta and Associated Ecosystems*. Available: http://deltacouncil.ca.gov/sites/default/files/documents/files/Fish_Predation_Final_Report_9_30_13.pdf.

ICF International (ICF). 2013. *Comprehensive (Phase 2) Review and Update to the Bay-Delta Plan: Final Bay-Delta Plan Workshops Summary Report*. June. Sacramento, CA. Available: http://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/bay_delta_plan/docs/bdwrkshprpt070813.pdf.

Jassby, A. D., W. J. Kimmerer, S. G. Monismith, C. Armor, J. E. Cloern, T. M. Powell, J. R. Schubel, and T. J. Vendlinski. 1995. Isohaline position as a habitat indicator for estuarine populations. *Ecological Applications* 5:272–289.

Kimmerer, W. J., E. S. Gross, and M. L. MacWilliams. 2009. Is the response of estuarine nekton to freshwater flow in the San Francisco Estuary explained by variation in habitat volume? *Estuaries and Coasts* 32:375–389.

Monismith, S., M. Fabrizio, M. Healey, J. Nestler, K. Rose, and J. Van Sickle. 2014. *Workshop on the Interior Delta Flows and Related Stressors Panel Summary Report. Delta Stewardship Council, Delta Science Program*. July. Sacramento, CA. Available: http://deltacouncil.ca.gov/sites/default/files/documents/files/Int-Flows-and-Related-Stressors-Report.pdf.

National Marine Fisheries Service (NMFS). 2014. *Recovery Plan for the Evolutionarily Significant Units of Sacramento River Winter-Run Chinook Salmon and Central Valley Spring-Run Chinook Salmon and the Distinct Population Segment of California Central Valley Steelhead*. West Coast Region, Sacramento, CA.

Reed, D., J. T. Hollibaugh, J. Korman, E. Peebles, K. Rose, P. Smith, and P. Montagna. 2014. *Workshop on Delta Outflows and Related Stressors Panel Summary Report. Delta Stewardship Council, Delta Science Program*. May 5. Sacramento, CA. Available: http://deltacouncil.ca.gov/sites/default/files/documents/files/Delta-Outflows-Report-Final-2014-05-05.pdf.

Rozengurt, M., M. Herz, and S. Feld. 1987. *The Role of Water Diversions in the Decline of Fisheries of the Delta–San Francisco Bay and other Estuaries*. Technical Report 87-8 to State Water Resources Control Board 1987 Bay-Delta Hearings.

6.2 Chapter 2, Hydrology

Adams, Frank. 1920. *Rice Irrigation Measurements and Experiments in Sacramento Valley, 1914–1919.* Bulletin 325. Berkeley, CA: University of California Agricultural Experiment Station.

Ahearn, D. S., R. W. Sheibley, and R. A. Dahlgren. 2005. Effects of river regulation on water quality in the lower Mokelumne River, California. *River Research Applications* 21:651–670.

Ahearn, D. S., R. W. Sheibley, R. A. Dahlgren, and K. E. Keller. 2004. Temporal dynamics of stream water chemistry in the last free-flowing river draining the western Sierra Nevada, California. *Journal of Hydrology* 295:47–63.

Armentrout, S., H. Brown, S. Chappell, M. Everett-Brown, J. Fites, J. Forbes, M. McFarland, J. Riley, K. Roby, A. Villalobos, R. Walden, D. Watts, and M. R. Williams. 1998. *Watershed Analysis for Mill, Deer, and Antelope Creeks.* Prepared for the Almanor Ranger District, Lassen National Forest.

Baker, F. G., and H. F. Pavlik. 1990. Characterization of aquifer heterogeneity in a complex fluvial hydrogeologic system to evaluate migration in ground water. In G. Moltyaner, G. (ed.). *Environmental Sciences* (B3150), pp. 775–794. Atomic Energy of Canada Ltd. International conference and workshop on transport and mass exchange processes in sand and gravel aquifers. Ottawa, Canada. October 1–4, 1990.

Barnett, T. P., D. W. Pierce, H. G. Hidalgo, C. Bonsfils, B. D. Santer, T. Das, G. Bala, A. W. Wood, T. Nozawa, A. A. Mirin, D. R. Cayan, and M. D. Dettinger. . 2008. Human-induced changes in the hydrology of the western United States. Science 319:1080–1083.

Big Chico Creek Watershed Alliance. 2007. *Big Chico Creek Watershed Alliance: Project Description and History of the Alliance*. Available: http://www.bigchicocreek.org/nodes/library/ecr/projectdesc_and_history.htm. Accessed: December 10, 2014.

Blair, T. C., F. G. Baker, and J. B. Turner. 1992. Cenozoic Fluvial-Facies Architecture and Aquifer Heterogeneity, Oroville, California, Superfund Site and Vicinity. In Society for Sedimentary Geology. *The Three-Dimensional Facies Architecture of Terrigenous Clastic Sediments and it Implications for Hydrocarbon Discovery and Recovery*, pp. 147–159. Tulsa, OK: American Association of Petroleum Geologists.

Blodgett, J. C., J. R. Walters, and J. W. Borchers. 1992. *Streamflow Gains and Losses and Selected Flow Characteristics of Cottonwood Creek, North-Central California, 1982–1985*. U.S. Geological Survey Water-Resources Investigations Report 02-4009.

Booth, E. G., J. F. Mount, and J. H. Viers. 2006. *Hydrologic Variability of the Cosumnes River Floodplain*. *San Francisco Estuary & Watershed Science* 4(2).

Bourez, W. 2012. Sacramento Valley Water Users [PowerPoint slides]. Presented to the State Water Resources Control Board, Bay-Delta Water Quality Control Plan Workshop, September 6. Available: http://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/docs/wrkshop1/walterbourez.pdf.

Brown and Caldwell. 2013a. *Aquifer Performance Test Report*. Report prepared for Butte County, Department of Water and Resource Conservation. April 26. Available: https://www.buttecounty.net/Portals/26/Tuscan/FinalAquiferTestsReport_ReportBody.pdf.

Brown, R. T., and A. Huber. 2015. *Relationships between Measured X2 and Equivalent Outflow (cfs) and Salinity (EC) during Low-Flow Conditions*. Available: http://baydeltaoffice.water.ca.gov/modeling/deltamodeling/DSM2UsersGroup/ICF_2014%20salinity%20intrusion_Feb%202015%20DSM2%20User%20Group.pdf.

Brush, C. F., E. C. Dogrul, and T. N. Kadir. 2013. *Development and Calibration of California Central Valley Groundwater Surface Water Simulation Model (C2VSim), Version 3.02-CG*. California Department of Water Resources Technical Memorandum. June.

Bryan, K. 1923. *Geology and Ground-Water Resources of Sacramento Valley, California*. U.S. Geological Survey Water-Supply Paper 495.

Bureau of Reclamation. 2008. *Central Valley Project and State Water Project, Operations Criteria and Plan, Biological Assessment.* U.S. Department of the Interior, Bureau of Reclamation, Mid-Pacific Region. Sacramento, CA. May. Available: http://www.usbr.gov/mp/cvo/OCAP/docs/OCAP_BA_2008.pdf.

Bureau of Reclamation. 2009. *Delta-Mendota Canal/California Aqueduct Intertie.* Central Valley Project, California. Final Environmental Impact Statement. Volume I: Main Report. U.S. Department of the Interior, Bureau of Reclamation, Mid-Pacific Region. Sacramento, CA. November. Available: http://www.usbr.gov/mp/intertie/docs/FEIS%20Webfiles/DMC-CA-Intertie_FinalEIS_Vol_I_MainReport_Nov2009.pdf.

Busacca, A. J., M. J. Singer, and K. L. Verosub. 1989. *Late Cenozoic Stratigraphy of the Feather and Yuba Rivers Area, California, with a Section on Soil Development in Mixed Alluvium at Honcut Creek*. U.S. Geological Survey Bulletin 1590-G.

Butte Creek Watershed Project. 1998. *Butte Creek Watershed Project: Existing Conditions Report*. California State University, Chico.

Cain, J. R., R. P. Walkling, S. Beamish, E. Cheng, E. Cutter, and M. Wickland. 2003. *San Joaquin Basin Ecological Flow Analysis*. August. Prepared for The Bay Institute by the Natural Heritage Institute, Berkeley, CA.

California Department of Engineering. 1914. *Fourth Biennial Report, December 1, 1912 to November 30, 1914*.

California Data Exchange Center (CDEC). 2016. Available: http://cdec.water.ca.gov.

California Department of Fish and Game (CDFG). 2008. *Yolo Bypass Wildlife Area Land Management Plan*. June. Available: https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=84924&inline.

California Department of Fish and Wildlife (CDFW). 2014. Study Plan Passage Assessment for Adult and Juvenile Chinook Salmon and Steelhead Trout in Mill Creek, Tehama County. California Department of Fish and Wildlife Instream Flow Program. July.

California Department of Public Works. 1923. *Bulletin 6, Irrigation Requirements of California Lands*. Appendix B. Division of Engineering and Irrigation.

California Department of Water Resources (DWR). 1931. *Variation and Control of Salinity in Sacramento–San Joaquin Delta and Upper San Francisco Bay*. Bulletin 27.

California Department of Water Resources (DWR). 1964. *Colusa Basin Investigation*. Bulletin 109.

California Department of Water Resources (DWR). 1974. *Evaluation of Ground Water Resources: Sacramento County*. Bulletin 118-3. July.

California Department of Water Resources (DWR). 1984. *Eastern Shasta County Water Study*. Report, Northern District. June.

California Department of Water Resources (DWR). 1994. *Sacramento River Bank Erosion Investigation*. September 23, 1962.

California Department of Water Resources (DWR). 1995. *Sacramento River Gravel Study - Keswick Dam to Cottonwood Creek*. October 20.

California Department of Water Resources (DWR) 2004. *Stony Creek Groundwater Recharge Investigation, 2003, Glenn County, California*. December.

California Department of Water Resources (DWR). 2007. *Draft Environmental Impact Report, Oroville Facilities Relicensing FERC Project 2100*. May. [NOTE: This was in the footnotes: "Department of Water Resources. 2007. *California Central Valley Unimpaired Flow Data.* Fourth edition." Is the DWR 2007 citation referring to the DEIR or the footnote?]

California Department of Water Resources (DWR) 2009a. *Deer Creek Flow Enhancement Program, Tehama County Permit Application to Extract Groundwater for Off Parcel Use*. April.

California Department of Water Resources (DWR). 2010a. *Central Valley Flood Management Planning Program, State Plan of Flood Control Descriptive Document*. November.

California Department of Water Resources (DWR). 2010b. *Fact Sheet: Sacramento River Flood Control Project Weirs and Flood Relief Structures*. December.

California Department of Water Resources (DWR). 2012. *2012 Central Valley Flood Protection Plan Consolidated Final Program Environmental Impact Report*.

California Department of Water Resources (DWR). 2013. *North-of-the-Delta Offstream Storage Project EIR/EIS Preliminary Administrative Draft*. December.

California Department of Water Resources (DWR). 2013a. *Development and Calibration of the California Central Valley Groundwater Surface Water Simulation Model (C2VSim), Version 3.02-CG*. Technical Memorandum. Bay-Delta Office. June.

California Department of Water Resources (DWR). 2014a. *Geology of the Northern Sacramento Valley, California*. Summary Report. September 22.

California Department of Water Resources (DWR). 2015. *State Water Project Delivery Capability Report 2015*. Available: https://msb.water.ca.gov/documents/86800/144575dd-0be1-4d2d-aeff-8d7a2a7b21e4.

California Department of Water Resources. 2016a. *Estimates of Natural and Unimpaired Flows for the Central Valley of California: Water Years 1922–2014*. Bay-Delta Office. March. Available: https://msb.water.ca.gov/documents/86728/a702a57f-ae7a-41a3-8bff-722e144059d6.

California Department of Water Resources. 2016b. *Fish Passage Improvement Program—Yuba River*. Available: http://www.water.ca.gov/fishpassage/projects/yuba.cfm.

California Department of Water Resources. 2016c. *On Estimating Net Delta Outflow (NDO): Approaches to estimating NDO in the Sacramento–San Joaquin Delta*. Bay-Delta Office. March.

California Department of Water Resouces. 2016d. *Chonological Reconstructed Sacramento and San Joaquin Valley Water Year Hydrologic Classification Indices*. Available: http://cdec.water.ca.gov/cgi-progs/iodir/wsihist. Accessed July 6, 2016.

Carpenter, E. J., A. T. Strahorn, T. W. Glassey, and R. E. Storie. 1926. *Soil Survey of the Oroville Area, California.* Washington, D.C.: U.S. Department of Agriculture.

CDM. 2008. *Butte Basin Groundwater Model Update: Base Case and Water Management Scenario Simulations.* Technical Memorandum. Submitted to Butte County Department of Water and Resource Conservation. April. Available: https://www.buttecounty.net/Portals/26/Modeling/TM3BaseCaseScenario20080424.pdf.

CH2M Hill. 2002. *Cottonwood Creek Watershed Assessment*. Report for the CALFED Ecosystem Restoration Program. August. Available: http://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb5399938.pdf.

Clear Creek Technical Team. 2013. *2013 Clear Creek Technical Team Report for the Coordinated Long-term Operation Biological Opinions Integrated Annual Review*. September 17. Available: http://deltacouncil.ca.gov/sites/default/files/documents/files/2013CCTT_Annual_Report.pdf.

Clynne, M. A., and L. J. Patrick Muffler. 2010. *Geologic Map of Lassen Volcanic National Park and Vicinity, California*. Pamphlet and U.S. Geological Survey Scientific Investigations Map 2899.

Contra Costa Water District (CCWD). 2012. *Use of an Index for Old and Middle River Flow Objectives*. Submitted to State Water Resources Control Board September 14, 2012, for Workshop II, Comprehensive Update of the Bay-Delta Water Quality Control Plan. Available: http://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/docs/cmnt091412/leah_orloff.pdf.

Crain, P. K., K. Whitener, and P. B. Moyle. 2004. Use of a restored central California floodplain by larvae of native and alien fish. *American Fisheries Society Symposium* 39:125–140.

Dettinger, M. D. 2005. *A Long-Term (~50-YR) Historical Perspective on Flood-Generating Winter Storms in the American River Basin*. Proceedings, 2005 California Extreme Precipitation Symposium, April 22. La Jolla, CA: Scripps Institution of Oceanography.

Drexler, J. Z., C. S. De Fontaine, and S. J. Deverel. 2009b. The legacy of wetland drainage on the remaining peat in the Sacramento–San Joaquin Delta, California, USA. *Wetlands* 29:372–386.

Delta Stewardship Council (DSC). 2012. *Final Draft Delta Plan*. Available: http://deltacouncil.ca.gov/sites/default/files/documents/files/FinalDraft_DeltaPlan_Chapters_combined2%201.pdf.

Dunshee, C. F. 1928. *Rice experiments in Sacramento Valley 1922–1927*. Bulletin 454. May. Berkeley, CA: University of California Agricultural Experiment Station.

East Bay Municipal Utility District (East Bay MUD). 1996.

East Bay Municipal Utility District, California Department of Fish and Game, and U.S. Fish and Wildlife Service (East Bay MUD, CDFW, and USFWS). 1996. *Lower Mokelumne River Project*. FERC Project 2916-004. Joint Settlement Agreement.

East Bay Municipal Utility District, California Department of Fish and Game, U.S. Fish and Wildlife Service (East Bay MUD, CDFG, and USFWS). 2008. *Lower Mokelumne River Project Joint Settlement Agreement Ten-Year Review*. September. Available: http://www.ebmud.com/recreation/protecting-natural-habitat/fisheries-and-wildlife-division-reports/.

ECORP. 2003. *Dry Creek Watershed Coordinated Resource Management Plan*. December 31.

EDAW. 2005. *Lower Putah Creek Watershed Management Action Plan. Phase I – Resource Assessments*. Report for the Lower Putah Creek Coordinating Committee. December.

Enplan. 2006. *Bear Creek Watershed Assessment*. Report to the Western Shasta Resource Conservation District. January.

Enright, C. 2008. *Suisun Marsh Salinity Control Gate: Purpose, Operation, and Hydrodynamics/Salinity Transport Effect*. PowerPoint slides. Presented at California Water and Environmental Modeling Forum, February 28. Available: http://www.cwemf.org/Asilomar/ChrisEnright.pdf.

Enright, C. 2014. Physical processes and geomorphic features. In P. B. Moyle, A. D. Manfree, and P. L. Fiedler (eds.). *Suisun Marsh, Ecological History and Possible Futures*. Pp. 45–64. Berkeley, CA: University of California Press.

Entrix, Inc. 2003. *Stakeholder Review Draft Daguerre Point Dam Fish Passage Improvement Project 2002 Water Resources Studies*. Report submitted to Department Of Water Resources and U.S. Army Corps of Engineers. July.

Epke, G. A. 2011. *Spring Snowmelt Recession in Rivers of the Western Sierra Nevada Mountains*. M.S. thesis. University of California. Davis, CA.

Federal Energy Regulatory Commission (FERC). 2008. *Final Environmental Impact Statement for Hydropower License Upper American River Hydroelectric Project—FERC Project 2101-084—California Chili Bar Hydroelectric Project—FERC Project 2155-024—California*. March.

Feyrer, F., T. Sommer, and W. Harrell. 2006a. Importance of flood dynamics versus intrinsic physical habitat in structuring fish communities: Evidence from two adjacent engineered floodplains on the Sacramento River, California. *North American Journal of Fisheries Management* 26:408–417.

Feyrer, F., T. Sommer, and W. Harrell. 2006b. Managing floodplain inundation for native fish: Production dynamics of age-0 splittail (*Pogonichthys macrolepidotus*) in California's Yolo Bypass. *Hydrobiologia*. 573:213–226.

Fleckenstein, J. H, R. G Niswonger, and G. E. Fogg. 2006. River-Aquifer Interactions, Geologic Heterogeneity, and Low-Flow Management. *Ground Water* 44(6):837-852.

Fleenor, W., W. Bennett, P. Moyle, and J. Lund. 2010. *On Developing Prescriptions for Freshwater Flows To Sustain Desirable Fishes in the Sacramento–San Joaquin Delta*. Submitted to the State Water Resources Control Board regarding flow criteria for the Delta necessary to protect public trust resources.

Garone, P. 2011. *The Fall and Rise of the Wetlands of California's Great Central Valley*. Berkeley, CA: University of California Press.

George, H., D. Lile, C. Childers, C. Noble, A. Oilar, K. Haworth, K. Schmidt, and G. Miller. 2007. *Upper Feather River Watershed (UFRW) Irrigation Discharge Management Program. Irrigated Agricultural Practices in UFRW*. SWRCB Agreement 04-317-555-0. Regents of the University of California. Final. March.

Graham Matthews and Associates. 2003b. *Hydrology, Geomorphology, and Historic Channel Changes of Lower Cottonwood Creek, Shasta And Tehama Counties, California*. Report to the National Fish and Wildlife Foundation. November.

Graymer, D. L., D. L. Jones, and E. E. Brabb. 2002. *Geologic map and map database of northeastern San Francisco Bay Region, California*. Misc. Field Studies Map MF-2403 version 1.0. USGS.

Greater Battle Creek Watershed Working Group. 2016. *Battle Creek Salmon and Steelhead Restoration Project Update*. January. Available: http://www.battle-creek.net/.

HDR and SWRI. 2007.

Helley, E. J., D. S, Harwood, J. A. Barker, and E. A. Griffen. 1981. Geologic map of the Battle Creek fault zone and adjacent parts of the Northern Sacramento Valley, California. USGS Miscellaneous Field Studies Map MF-1298.

Herbold, B., and P. B. Moyle. 1989. *The Ecology of the Sacramento–San Joaquin Delta: A Community Profile*. U.S. Fish and Wildlife Service. Biological Report. 85(7.22).

Holmes, L. C., and J. W. Nelson. 1913. *Field Operations of the Bureau of Soils, 1913*. Fifteenth Report.

H. T. Harvey and Associates. 2007b. *Stony Creek Watershed Assessment Volume 2. Existing Conditions Report*. Prepared for the Glen County Resource Conservation District. February 23.

Jackson, W. T. and A. M. Patterson. 1977. *The Sacramento–San Joaquin Delta: The Evolution and Implementation of Water Policy: An Historical Perspective*. Technical Completion Report, Contribution 163. June. California Water Resources Center, Davis, CA.

James, L. A. 1989. Sustained storage and transport of hydraulic gold mining sediment in the Bear River, California. *Annals of the Association of American Geographers* 79:570–592.

James, L. A. 1995. Diversion of the upper Bear River: Glacial diffluence and Quaternary erosion. Sierra Nevada, California. *Geomorphology* 14:131–148.

James, L. A. 2003. Glacial erosion and geomorphology in the northwest Sierra Nevada, CA. *Geomorphology* 55:283–303.

James, L. A., and M. B. Singer. 2008. Development of the lower Sacramento Valley flood-control system: Historical perspective. *Natural Hazards Review* 9:125–135.

James, L. A., J. Harbor, D. Febel, D. Dahms, and D. Elmore. 2002. Late Pleistocene Glaciations in the Northwestern Sierra Nevada, California. *Quaternary Research* 57:409–419.

Jassby, A. D. 2005. Phytoplankton Regulation in a Eutrophic Tidal River (San Joaquin River, California). *San Francisco Estuary and Watershed Science* 3(1).

Jassby, A. D., Kimmerer, W. J., Monismith, S. G., Armor, C. Cloern, J. E., Powell, T. M., Schubel, J. R., Vendlinski, T. J. 1995. *Isohaline Position as an Indicator for Estuarine Populations*. Available: http://www.fws.gov/stockton/afrp/SWRCB/Jassby_et%20al_1995.pdf.

Jones & Stokes. 2001. *A Framework for the Future: Yolo Bypass Management Strategy*. Final report prepared for the CALFED Bay-Delta Program. August. Sacramento, CA.

Jones & Stokes. 2005. *Battle Creek Salmon and Steelhead Restoration Project Final Environmental Impact Statement/Environmental Impact Report*. *Volume I*. July. (J&S 03035.03.) Sacramento, CA.

Jones & Stokes Associates, Inc., and EDAW, Inc. 1975. *Fish and Wildlife Element, Suisun Marsh Protection Plan* December. Sacramento, CA.

Jones, B. L., N. L. Hawley, and J. J. Crippen. 1972. *Sediment Transport in the Western Tributaries of the Sacramento River, California*. U.S. Geological Survey Water-Supply paper 1798-J.

Kelley, R. 1989. *Battling the Inland Sea*. Berkeley, CA: University of California Press.

Kimmerer, W. J. 2002a. Effects of freshwater flow on abundance of estuarine organisms: Physical effects or trophic linkages? *Marine Ecology Progress Series* 243:39–55.

Kimmerer, W. J. 2002b. Physical, biological and management responses to variable freshwater flow into the San Francisco Estuary. *Estuaries* 25(6B):1275–1290.

Kimmerer, W. J. 2004. Open water processes of the San Francisco Estuary: From physical forcing to biological responses. *San Francisco Estuary and Watershed Science* 2(1).

Kimmerer, W. J., and Nobriga, M. L. 2008. Investigating Particle Transport and Fate in the Sacramento–San Joaquin Delta Using a Particle Tracking Model. *San Francisco Estuary and Watershed Science* 6(1).

Koczot, K. M., A. E. Jeton, B. J. McGurk, and M. D. Dettinger. 2005. Precipitation-runoff processes in the Feather River Basin, Northeastern California, with prospects for streamflow predictability, water years 1971–97. In *U.S. Geological Survey Scientific Investigations Report*, pp. 2004–5202.

Kondolf, G., M., M. Smeltzer, J. G. Williams, and N. Lassettre. 2001. *Fluvial Geomorphic Study of Mill Creek Tehama County, California*. July 31. Final report submitted to U.S. Fish and Wildlife Service. Stockton, CA.

Kondolf, G. M., K. Podolak, and T. E. Grantham. 2012. Restoring Mediterranean-climate rivers. *Hydrobiologia* 719:527–545.

Larsen, E., E. Anderson, E. Avery, and K. Dole. 2002. *The Controls on and Evolution of Channel Morphology of the Sacramento River: A Case Study of River Miles 201–185*. Report to the Nature Conservancy.

LA Times. 1989. *A River Banks on a Bailout*. Available: http://articles.latimes.com/1989-11-23/local/me-34_1_sacramento-river.

Low, A. F., J. White, and E. Chappel. 2006. *Relationship of Delta Cross Channel Gate Operations to loss of Juvenile Winter-Run Chinook Salmon at the CVP/SWP Delta Facilities*. California Department of Fish and Game. November. Available: http://science.calwater.ca.gov/pdf/ewa/EWA_delta_cross_channel_clo sures_06_111406.pdf.

MacWilliams. M. L., A. J. Bever, E. G. Gross, G. S. Ketefian, and W. J. Kimmerer. 2015. Three-Dimensional Modeling of Hydrodynamics and Salinity in the San Francisco Estuary: An Evaluation of Model Accuracy, X2, and the Low–Salinity Zone. *San Francisco Estuary & Watershed Science* 13(1).Malamud-Roam, K. P. 2000. *Tidal Regimes and Tide Marsh* hydroperiod *in the San Francisco Estuary: Theory and Implications for Ecological Restoration*. PhD dissertation. University of California, Berkeley.

Mann, C. W., J. F. Warner, H. L. Westover, and J. E. Ferguson. 1911. *Soil Survey of the Woodland Area, California*. U.S. Department of Agriculture.

McComish, C. D., and R. T. Lambert. 1918. *History of Colusa and Glenn Counties, California*. Los Angeles, CA: History Record Company.

Meirovitz, C. D. 2010. *Influence of the American River Incised Valley Fill on Sacramento County Hydrology*. M.S. thesis. University of California, Davis.

Milly, P. C. D., J. Betancourt, M. Falkenmark, R. M. Hirsch, Z. W. Kundzewicz, D. P. Lettenmaier, and R. J. Stouffer. 2008. Stationarity is dead: Whither water management? *Science* 319:573–574.

Monismith, S. G., W. J. Kimmerer, J. R. Burau, and M. T. Stacey. 2002. Structure and flow-induced variability of the subtidal salinity field in northern San Francisco Bay. *Journal of Physical Oceanography* 32:3003–3019.

Moran, J. E., G. B. Hudson, G. F. Eaton, and R. Leif. 2005. *California GAMA Program: Groundwater Ambient Monitoring and Assessment Results for the Sacramento Valley and Volcanic Provinces of Northern California*. January. Report prepared for the California State Water Resources Control Board. Available: http://www.swrcb.ca.gov/gama/docs/cas_llnl_no_sacval_volcanics.pdf.

Mount, J., and R. Twiss. 2005. Subsidence, sea level rise, seismicity in the Sacramento–San Joaquin Delta. *San Francisco Estuary and Watershed Science* 3(1).

Mount, J., G. E. Fogg, L. Kavvas, J. Fleckenstein, M. Anderson, Z. Q. Chen, and E. Suzuki. 2001. *Linked Surface Water-Groundwater Model for the Cosumnes River Watershed: Hydrologic Evaluation of Management Options to Restore Fall Flows*. Report to the U.S. Fish and Wildlife Service Anadromous Fish Restoration Program. September.

Moyle, P. B., P. K. Crain, K. Whitener, and J. F. Mount. 2003. Alien fishes in natural streams: Fish distribution, assemblage structure, and conservation in the Cosumnes River, California, USA. *Environmental Biology of Fishes* 68:143–162.

Mueller-Solger, A. 2012. *Notes on Estimating X2, the Distance from the Golden Gate to 2 ppt Salinity (km).* U.S. Environmental Protection Agency. Available: https://www.epa.gov/sites/production/files/documents/notes-on-estimating-x2-with-dayflow.pdf.

Muffler, L., J. Pattrick, and M. A. Clynne. 2015. *Geologic Field-Trip Guide to the Lassen Volcanic National Park and Vicinity, California*. U.S. Geological Survey Scientific Investigations Report 2015-5067.

Myers, T. 2012. *Cumulative Watershed Effects of Timber Harvest and Other Activities, Battle Creek Watershed, Northern California*. Final report for the Battle Creek Alliance. July.

National Marine Fisheries Service (NMFS). 2009. *Biological Opinion and Conference Opinion on the Long-Term Operations of the Central Valley Project and State Water Project*. June 4.Southwest Region.

National Marine Fisheries Service (NMFS). 2012. *Summary of the Expected Benefits to Salmonid Survival of a Rock Barrier at the Head of Old River & Preferential Use of the Central Valley Project Export Facility*. Southwest Region. Available: http://swr.nmfs.noaa.gov/pdf/Summary_Expected_benefits_to_Salmonid_survival.pdf.

National Marine Fisheries Service (NMFS). 2014. *Recovery Plan for the Evolutionarily Significant Units of Sacramento River Winter-Run Chinook Salmon and Central Valley Spring-Run Chinook Salmon and the Distinct Population Segment of California Central Valley Steelhead*. Appendix A, Central Valley watershed profiles. California Central Valley area office. July.

National Oceanic and Atmospheric Administration (NOAA). 2016. *Heavy Precipitation Event, Southwest Oregon, Northern California, and Western Nevada, December 26, 1996 – January 3, 1997*. California Nevada River Forecast Center. Available: http://www.cnrfc.noaa.gov/storm_summaries/jan1997storms.php. Accessed: April 6, 1997.

Neiman, P. J., F. M. Ralph, B. J. Moore, and R. J. Zamora. 2014. The regional influence of an intense Sierra barrier jet and landfalling atmospheric river on orographic precipitation in Northern California: A case study. *Journal of Hydrometerology* 15:1419–1439.

Nevada Irrigation District (NID). 2008. Figure 6.1-1. Yuba-Bear hydroelectric project. PG&E's Drum-Spaulding Project. FERC Projects 2266, 2301, and 2784.

Nevada Irrigation District (NID). 2010. Modeling schematic of projects. Yuba-Bear hydroelectric project. PG&E's Drum-Spaulding Project. FERC Projects 2266, 2301, and 2784.

Nevada Irrigation District (NID). 2011. *Application for new license major project—existing dam volume II: Exhibit E*. Yuba-Bear hydroelectric project FERC Project 2266-096. Drum-Spaulding Project FERC Project 2310-173. April.

Northwest Hydraulic Consultants (NHC). 2012. *Yolo Bypass MIKE-21 Model Review: Strengths, Limitations and Recommendations for Refinement*. September.

Null, S. E., J. H. Viers, and J. F. Mount. 2010. *Hydrologic Response and Watershed Sensitivity to Climate Warming in California's Sierra Nevada*. Available: http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0009932.

Null, S. E., and J. H. Viers. 2013. In bad waters: Water year classification in nonstationary climates. *Water Resources Research* 49(2):1137–1148.

Olmsted, F. E., and G. H. Davis. 1961. *Geologic Features and Ground-Water Storage Capacity of the Sacramento Valley California*. U.S. Geology Survey Water-Supply Paper 1497.

Pasternack, G. B. 2009. *SHIRA-Based River Analysis and Field-Based Manipulative Sediment Transport Experiments to Balance Habitat and Geomorphic Goals on the Lower Yuba River*. Report For Cooperative Ecosystems Studies Unit. Revised. January 29.

Piper, A. M., H. S. Gale, H. E. Thomas, and T. W. Robinson. 1939. *Geology and Ground-Water Hydrology of the Mokelumne Area, California*. U.S. Geological Survey Water-Supply Paper 780.

Placer County Water Agency (PCWA). 2007. Middle Fork American River project. Map 3-1. Topography in the Middle Fork American River watershed.

Redmond. 2000.

Resource Management Associates (RMA). 2009. *Numerical Modeling in Support of Suisun Marsh Preliminary Environmental Impact Report/Environmental Impact Statement—Technical Appendix*. September.

Resource Management Associates (RMC). 2007. *Upper Mokelumne River Watershed Assessment and Planning Project*. Prepared for the Upper Mokelumne River Watershed Authority. December.

Resource Management Associates (RMC). 2006. *Mokelumne/Amador/Calaveras Integrated Regional Water Management Plan*. November.

Robertson, R. D. 1917. *Irrigation of Rice in California*. Bulletin 279. Berkeley, CA: University of California Agricultural Experiment Station.

Robertson-Bryan, Inc. 2006a. *Lower Cosumnes River Watershed Assessment*. Report for Cosumnes River Preserve. December.

Robertson-Bryan, Inc. 2006b. *Cosumnes River Flow Augmentation Project*. Report for Southeast Sacramento County Agricultural Water Authority. April.

Roos, M. 2006. Flood management practice in northern California. *Irrigation and Drainage* 55:S93–S99.

Sacramento River Watershed Program. 2010. *The Sacramento River Basin, a Roadmap to Watershed Management. Feather River Subregion, Lower Feather River Watershed*. October. Available: http://www.sacriver.org/aboutwatershed/roadmap/.

San Francisco Bay Regional Water Quality Control Board (San Francisco Bay Regional Water Board). 2009. *San Francisco Bay Region Order No. R2-2009-0039, NPDS No. CA0038024. Fairfield-Suisun Sewer District Wastewater Treatment Plant*. April 8. Available: http://www.waterboards.ca.gov/rwqcb2/board_decisions/adopted_orders/2009/R2-2009-0039.pdf.

San Francisco Bay Regional Water Quality Control Board (San Fransciso Bay Regional Water Board). 2014. *San Francisco Bay Region Order No. R2-2009-0039, NPDS No. CA0038024. Waste Discharge Requirements for Nutrients from Municipal Wastewater Discharges to San Francisco Bay, Fairfield-Suisun Sewer District*. 2011–2014.

Schumm, S. A., J. F. Dumont, and J. M. Holbrook. 2000. *Active Tectonics and Alluvial Rivers*. Cambridge, UK: Cambridge University Press.

Shelmon et al. 2000.

Shlemon, R., J. 1971. The Quaternary deltaic and channel system in the Great Central Valley, California. *Annals of the Association of American Geographers* 61:427–440.

SHN. 2001. *Cow Creek Watershed Assessment*. Report for the Western Shasta Resource Conservation District. November.

Siegel, S., C. Enright, C. Toms, C. Enos, and J. Sutherland. 2010. *Suisun Marsh Tidal Marsh and Aquatic Habitats Conceptual Model,* Chapter 1: *Physical Processes*. Final review draft. September 15.

Singer, M. B., and R. Aalto. 2009. Floodplain development in an engineered setting. *Surface Processes and Landforms* 34:291–304.

Singer, M. B., R. Aalto, and L. A. James. 2008. Status of the lower Sacramento Valley flood control system within the context of its natural geomorphic setting. *Natural Hazards Review* 9:104–115.

Sommer, T., B. Harrell, M. Nobriga, R. Brown, P. Moyle, W. Kimmerer, and L. Schemel. 2001b. California's Yolo Bypass: Evidence that flood control can be compatible with fisheries, wetlands, wildlife, and agriculture. *Fisheries* 26(8):6–16.

Sommer, T. R., W. C. Harrell, and M. L. Nobriega. 2005. Habitat use and stranding risk of juvenile Chinook salmon on a seasonal floodplain. *North American Journal of Fisheries Management* 25:1493–1504.

Sommer, T. R., W. C. Harrell, F. Feyrer. 2014. Large-bodied fish migration and residency in a flood basin of the Sacramento River, California, USA. *Ecology of Freshwater Fish* 23:414–423.

Springhorn, S. T. 2008. Stratigraphic analysis and hydrogeologic characterization of Cenozoic strata in the Sacramento Valley near the Sutter Buttes. MS thesis. California State University, Chico.

State Water Commission of California. 1917. *Water and Rice Culture*. Report of the State Water Commission.

Stillwater Sciences. 2011. *Assessment of Hydrology and Geomorphology Related to Fish Passage in Lower Antelope Creek*. Report submitted to U.S. Fish and Wildlife Service. February.

Stillwater Sciences. 2015. *Fish Passage in Lower Antelope Creek*. Report submitted to U.S. Fish and Wildlife Service. January.

Strahorn, A. T., W. W. Mackie, H. L. Westover, L. C. Holmes, and C. Van Duyne. 1911. *Soil Survey of the Marysville Area, California*. U.S. Department of Agriculture.

Swenson, R. O., K. Whitener, and M. Eaton. 2003. Restoring floods to floodplains: Riparian and floodplain restoration at the Cosumnes River Preserve. In P. M. Faber (ed.). *California Riparian Systems: Processes and Floodplain Management, Ecology, and Restoration*. 2001 Riparian habitats and floodplains conference proceedings. pp. 224–229. Riparian Habitat Joint Venture, California.

State Water Resources Control Board (State Water Board). 1955. *Placer County Investigation*. Bulletin 10. June.

State Water Resources Control Board (State Water Board). 2010. *Development of Flow Criteria for the Sacramento–San Joaquin Delta Ecosystem*. Available: http://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/deltaflow/docs/final_rpt080310.pdf.

Ta, J. 2015. *Decision Support Tool for Water Management and Environmental Flows: Mill Creek Case Study*. M.S. thesis. University of California, Davis.

Tehama County Flood Control and Water Conservation District. 2012. *Coordinated AB 3030 Groundwater Management Plan 2012*. Available: http://www.tehamacountypublicworks.ca.gov/Flood/groundwater/gwmp.pdf.

Tehama County Resource Conservation District. 2010a. *Tehama East Watershed Assessment*. Report to California Department of Water Resources. April. Red Bluff, CA.

Tehama County Resource Conservation District. 2010b. *Tehama East Watershed Assessment Atlas*. Report to California Department of Water Resources. April. Red Bluff, CA.

Tehama Environmental Solutions. 2015. *Biological Assessment, Mill Creek Fish Passage Restoration Project, Ward Dam, Tehama County, California*. Report prepared for Northwest Hydraulic Consultants. February.

Tetra Tech, Inc. 1998. *Upper Clear Creek Watershed Analysis, Shasta County, California*. Report for Western Shasta Resource Conservation District. November.

The Bay Institute (TBI). 1998. *From the Sierra to the Sea: The Ecological History of the San Francisco Bay-Delta Watershed*. Novato, CA: The Bay Institute of San Francisco. Available: http://www.bay.org/sierra_to_the_sea.htm.

The Bay Institute (TBI). 2003. *San Francisco Bay Freshwater Flow Index: Indicator Analysis and Evaluation.* Available: http://thebayinstitute.blob.core.windows.net/assets/Freshwater_Inflow.pdf.

Thomasson, H. G. Jr., F. H. Olmstead, and E. F. LeRoux. 1960. *Geology, Water Resources and Usable Ground-Water Storage Capacity of Part of Solano, County, California*. Geological Survey Water-Supply Paper 1464.

Tompkins, M. R., and G. M. Kondolf. 2007. *Lower Deer Creek Ecosystem Restoration and Flood Management: Feasibility Study and Conceptual Design*. *Existing Conditions: Hydrology and Geomorphology Technical Memorandum.* Report to Deer Creek Watershed Conservancy CalFed Ecosystem Restoration Program. June.

U.S. Army Corps of Engineers (USACE). 1981. *USACE Public Notice 5820-A*. October 13.

U.S. Army Corps of Engineers (USACE). 2013. *Biological Assessment for the U.S. Army Corps of Engineers Authorized Operations and Maintenance of Existing Fish Passage Facilities at Daguerre Point Dam on the Lower Yuba River*. October.

U.S. Army Corps of Engineers (USACE). 2014. *Voluntary Conservation Measures— Habitat Enhancement on the Lower Yuba River, Yuba County, California*. Draft Environmental Assessment. July.

U.S. Bureau of Reclamation (USBR). 2001. *Hydrology of North and South Fork Battle Creeks*. April.

U.S. Bureau of Reclamation (USBR). 2016. *Environmental Assessment, Upper Sacramento River Anadromous Fish Habitat Restoration Program*. January.

U.S. Bureau of Reclamation (USBR). 2006. *Delta Cross Channel*. September. Agailable: https://portals.icfi.com/eet/StateWaterBoard/05%20Technical%20Appendix/5.%20References/USBR%202006%20Delta%20Cross%20Channel.pdf.

U.S. Bureau of Reclamation (USBR). 2014. *Implementation of Old and Middle River Index Demonstration Project*. Available: http://www.usbr.gov/mp/BayDeltaOffice/Documents/Current_Implementation/OMR_Index_Demonstration_Project/Letter_to_NMFS_on_OMR_Index_Demonstration_Project_02202014.pdf.

U.S. Department of the Interior (USDOI). 2008. *Central Valley Project and State Water Project Operations Criteria and Plan Biological Assessment.*

U.S. Fish and Wildlife Service (USFWS). 1995. *Habitat Restoration Actions to Double Natural Production of Anadromous Fish in the Central Valley of California, Volume 2*. May 9.

U.S. Fish and Wildlife Service (USFWS). 2011. *Fall Outflow Adaptive Management Plan, Milestone Draft: Adaptive Management of Fall Outflow for Delta Smelt Protection and Water Supply*. Available: https://www.fws.gov/sfbaydelta/documents/ Adaptive%20Management%20of%20Fall%20Outflow%20for%20Delta%20Smelt%20Protection%20and%20Water%20Supply%20Reliability.pdf.

USFWS. 2014.

U.S. Geological Survey (USGS). 1908. *Courtland Qudrangle*.

U.S. Geological Survey (USGS). 1910b. *Bruceville Quadrangle*.

U.S. Geological Survey (USGS). 1910c. *Galt Quadrangle*.

U.S. Geological Survey (USGS). 1912a. *Biggs Quadrangle.*

U.S. Geological Survey (USGS). 1913.

U.S. Geological Survey (USGS). 2013. *Water-resources data for the United States, water year 2012*. U.S. Geological Survey Water-Data Report WDR-US-2012, site 11406800. Available: http://wdr.water.usgs.gov/wy2012/pdfs/11406800.2012.pdf on 04/18/2016.

U.S. Geological Survey (USGS). 1999. *Floods in Northern California, January 1997*. U.S. Geological Survey Fact Sheet FS-073-99. April.

Upper Yuba River Studies Program Study Team (UYRSPST). 2007. *Upper Yuba River Watershed Chinook Salmon and Steelhead Habitat Assessment*. Report submitted to California Department of Water Resources. November.

VESTRA Resources. 2006. *Tehama West Watershed Assessment.* Report for the Tehama County Resource Conservation District. April.

VESTRA Resources. 2007. *Cow Creek Irrigation Efficiency and Instream Flow Augmentation Feasibility Report*. Report prepared for the Bureau of land Management. January 1996.

Water Engineering and Technology, Inc. (WET). 1998. *Geomorphic Analysis of Sacramento River*. Draft, Phase II. Report submitted to the U.S. Army Corps of Engineers. March.

Water Resources Association of Yolo County (WRAYC). 2005. *Yolo County IRWMP Background Date and Information Appendix*. Available: http://www.yolowra.org/irwmp_documents_prop50.html.

Water Resources Association of Yolo County (WRAYC). 2007. *Integrated Regional Water Management Plan*. Appendix A. April.

Weissmann, G. S., G. L. Bennett, and A. L. Lansdale. 2005. Factors controlling sequence development on Quaternary fluvial fans, San Joaquin Basin, California, USA. In A. M. Harvey, A. E. Mather, and M. Stokes (eds.). Alluvial Fans: Geomorphology, Sedimentology, Dynamics. *Special Publications* 251:169–186. London: Geological Society.

Western Shasta Resource Conservation District. 1996. *Lower Clear Creek Watershed Analysis*. Report to the U.S. Fish and Wildlife Service. March 2005.

Western Shasta Resource Conservation District. 2005.

Whipple, A., R. Grossinger, D. R., B. Stanford, and R. Askevold. 2012. *Sacramento–San Joaquin Delta Historical Ecology Investigation: Exploring Pattern and Process*. Report prepared by San Francisco Estuary Institute-Aquatic Science Center. August.

Williams, John G., G. M. Kondolf, and E. Ginney. 2002. *Geomorphic Assessment of Butte Creek, Butte County, California*. Report prepared for Chico State University Research Foundation. February.

Wood Rodgers, Inc. 2012. *Sutter County Groundwater Management Plan*. Submitted to Sutter County. March 19.

Yarnell, S. M., R. A. Peek, D. E. Rheinheimer, A. J. Lind, and J. H. Viers. 2013. *Management of the Spring Snowmelt Recession: An Integrated Analysis of Empirical, Hydrodynamic and Hydropower Modeling Applications*. July. Prepared for the California Energy Commission. Available: https://watershed.ucdavis.edu/files/biblio/CEC_Recsn_Limb_Draft_Final_Report.pdf.

Yarnell, S. M., J. H. Viers, and J. F. Mount. 2010. Ecology and Management of the Spring Snowmelt Recession. *sBioScience* 60:114–127.

Yolo County. 2006. *Cache Creek Status Report and Trend Analysis 1996–2006*. July.

6.3 Chapter 3, Scientific Knowledge to Inform Fish and Wildlife Flow Recommendations

6.3.1 Flow and the Ecosystem

Abrantes, K. G., A. Barnett, R. Baker, and M. Sheaves. 2015. Habitat-specific food webs and trophic interactions supporting coastal-dependent fishery species: an Australian case study. Reviews in Fish Biology and Fisheries 25(2):337–363.

Barbier, E. B., S. D. Hacker, C. Kennedy, E. W. Koch, A. C. Stier, and B. R. Silliman. 2011. The value of estuarine and coastal ecosystem services. *Ecological Monographs* 81: 169–193.

Bartholow, J., R.B. Hanna, L. Saito, D. Lieberman, and M. Horn. 2001. Simulated Limnological Effects of the Shasta Lake Temperature Control Device. *Environmental Management* 27: 609-626.

Baxter, R., R. Breuer, L. Brown, M. Chotkowski, F. Feyrer, M. Gingras, B. Herbold, A. Mueller-Solger, M. Nobriga, T. Sommer and K. Souza. 2008. Pelagic organism decline progress report: 2007 synthesis of results. Interagency Ecological Program for the San Francisco Estuary. http://www/science.calwater.ca.gov/pdf/workshops/POD/IEP_POD_2007_synthesis_report_031408.pdfBarbier et al. 2011.

Baxter, R., R. Breuer, L. Brown, L. Conrad, F. Feyrer, S. Fong, K. Gehrts, L. Grimaldo, B. Herbold, P. Hrodey, A. Mueller-Solger, T. Sommer, and K. Souza. 2010. *Interagency Ecological Program 2010 Pelagic Organism Decline Work Plan and Synthesis of Results*. Interagency Ecological Program for the San Francisco Estuary. 259 p. Available: http://www.water.ca.gov/iep/docs/FinalPOD2010Workplan12610.pdf.

Baxter, R., L. R. Brown, G. Castillo, L. Conrad, S. Culberson, M. Dekar, M. Dekar, F. Feyrer, T. Hunt, K. Jones, J. Kirsch, A. Mueller-Solger, M. Nobriga, S. B. Slater, T. Sommer, and K. Souza. 2015. *An updated conceptual model of Delta Smelt biology: our evolving understanding of an estuarine fish. Interagency Ecological Program: Management, Analysis, and Synthesis.* Team Technical Report 90.

Bennett, W.A. and J.R. Burau. 2015. Riders on the Storm: Selective Tidal Movements Facilitate the Spawning Migration of Threatened Delta Smelt in the San Francisco Estuary. *Estuaries and Coasts.* 38(3):826-835.

Bever, A. J., M. L. MacWilliams, B. Herbold, L. R. Brown, and F. V. Feyrer. 2016. Linking Hydrodynamic Complexity to Delta Smelt (*Hypomesus transpacificus*) Distribution in the San Francisco Estuary, USA. *San Francisco Estuary & Watershed Science* 14(1).

Brown, L. R., and M. L. Bauer. 2009. Effects of hydrologic infrastructure on flow regimes of California's Central Valley rivers: Implications for fish populations. *River Research and Applications* 26(6):751–765.

Brown, L. R. and J. T. May. 2006. Variation in Spring Nearshore Resident Fish Species Composition and Life Histories in the Lower Sacramento-San Joaquin Watershed and Delta. San Francisco Estuary Watershed and Science 4(2).

Brown, L. R., and D. Michniuk. 2007. Littoral fish assemblages of the alien-dominated Sacramento–San Joaquin Delta, California, 1980–1983 and 2001–2003. *Estuaries and Coasts* 30(1):186–200.

Bunn, S. E., and A. H. Arthington. 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental Management* 30:492–507.

Carlisle, D. M., D. M. Wolock, and M. R. Meador. 2011. Alteration of Streamflow Magnitudes and Potential Ecological Consequences: A Multiregional Assessment. 9(5): 264-270.

Carlson, S. M. and W.H. Satterthwaite. 2011. Weakened Portfolio Effect in a Collapsed Salmon Population Complex. Canadian Journal of Fisheries and Aquatic Sciences 68: 1579-1589.

Cloern, J. E. and A.D. Jassby, 2012. Drivers of change in estuarine-coastal ecosystems: discoveries from four decades of study in San Francisco Bay. Reviews of Geophysics 50:1-33.

Correigh M., K. Greene J. Nohner, A. Candelmo, and D. Nelson. 2015. A National Assessment of Stressors to Estuarine Fish Habitats in the Contiguous USA. *Estuaries and Coasts* 38(3).

Dance M. A. and J. R. Rooker. 2015. Habitat- and bay-scale connectivity of sympatric fishes in an estuarine nursery. *Estuarine, Coastal and Shelf Science* 167(2).

Deas, M. L. and C. L. Lowney. 2000. Water Temperature Modeling Review: Central Valley. *Bay Delta Modeling Forum*.

Delta Environmental Flows Group (DEFG). 2010. Key Points on Delta Environmental Flows for the State Water Resources Control Board. http://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/deltaflow/docs/intro_key_points_on_flows_9.pdf.

Del Rosario, R., and Y. Redler. 2010. *Residence of Winter-Run Chinook Salmon in the Sacramento–San Joaquin Delta: The Role of Sacramento River Hydrology in Driving Juvenile Abundance and Migration Patterns in the Delta*. NMFS Exhibit 7. Submitted for the Informational Proceeding to Develop Flow Criteria for the Delta Ecosystem Necessary to Protect Public Trust Resources.

De Robertis, A., C. H. Ryer, A. Veloza, and R. D. Brodeur. 2003. Differential effects of turbidity on prey consumption of piscivorous and planktivorous fish. *Canadian Journal of Fisheries and Aquatic Sciences* 60(12):1517–1526.

Drinkwater, K.F. and K.T. Frank. 1994. Effects of river regulation and diversion on marine fish and invertebrates. Aquatic Conservation: Freshwater and Marine Ecosystems. 4:135-151.

Ecosystem Restoration Program (ERP). 2014. Conservation Strategy for Restoration of the Sacramento-San Joaquin Delta, Sacramento Valley and San Joaquin Valley Regions.

Feyrer, F. 2004. Ecological segregation of native and alien larval fish assemblages in the southern Sacramento-San Joaquin Delta. American Fisheries Society Symposium. 39:67-80.

Feyrer, F. and M.P. Healey. 2003. Fish Community Structure and Environmental Correlates in the Highly Altered Southern Sacramento-San Joaquin Delta. Environmental Biology of Fishes 66: 123-132.

Feyrer, F, M.L. Nobriga, and T.R. Sommer. 2007. Multi-decadal trends for three declining fish species: habitat patterns and mechanisms in the San Francisco Estuary, California, USA. Canadian Journal of Fisheries and Aquatic Sciences. 64:723–734.

Fleenor, W., W. Bennett, P. B. Moyle, and J. Lund. 2010. On Developing Prescriptions for Freshwater Flows to Sustain Desirable Fishes in the Sacramento-San Joaquin Delta. Submitted to the State Water Resources Control Board Regarding Flow Criteria for the Delta Necessary to Protect Public Trust Resources. 43 pages.

Freeman, M. C., Z.H. Bowen, K. D. Bovee, and E. R. Irwin. 2001. Flow and Habitat Effects on Juvenile Fish Abundance in Natural and Altered Flow Regimes. Ecological Applications 11(1).

Gido, K. B. and J. H. Brown. 1999. Invasion of North American Drainages by Alien Fish Species. Freshwater Biology 42: 387-399.

Grant, G. E. 1997b. Chapter 7: A Geomorphic Basis for Interpreting the Hydrologic Behavior of Large River Basins. Pages 105-116 In: A. Laenen and K.A. Dunnette, editors, River Quality: Dynamics and Restoration. Boca Raton: CRC/Lewis.

Gregory, R. S. 1993. The Effect of Turbidity on the Predator Avoidance Behavior of Juvenile Chinook Salmon (Oncorhynchus tshawytscha). Canadian Journal of Fisheries and Aquatic Sciences 50: 241–246.

Gregory, R. S. and C. D. Levings. 1998. Turbidity Reduces Predation on Migrating Juvenile Pacific Salmon. Transactions of the American Fisheries Society 127: 275–285.

Grimaldo, L., F. Feyrer, J. Burns, and D. Maniscalco. 2014. Sampling Uncharted Waters: Examining Longfin Smelt and Delta Smelt Rearing Habitat in Fringe Marshes of the Low Salinity Zone. Oral presentation, 2014 Bay-Delta Science Conference. October 28, 2014. Sacramento, CA.

Grimaldo, L. F., T. Sommer, N. Van Ark, G. Jones, E. Holland, P. Moyle, P. Smith, and B. Herbold. 2009. Factors affecting fish entrainment into massive water diversions in a freshwater tidal estuary: can fish losses be managed? *North American Journal of Fisheries Management* 29:1253–1270.

Grimaldo, L. F. 2016. Rearing habitat of larval and juvenile longfin smelt in the San Francisco Estuary: A case to move into uncharted waters. Oral presentation. UC Davis Center for Coastal Ocean Issues and Delta Science Program Symposium: Delta & Longfin Smelt: Is Extinction Inevitable? March 29, 2016. Davis, CA.Harrell, W.C. and T.R. Sommer. 2003. Patterns of adult fish use on California's Yolo Bypass floodplain. Pages 88-93 in Faber, PM (ed), California riparian systems: processes and floodplain management, ecology, and restoration. Riparian Joint Venture, Sacramento, CA.

Herbold, B., A. D. Jassby, and P. B. Moyle. 1992. Status and Trends Report on Aquatic Resources in the San Francisco Estuary. San Francisco Estuary Project. March, 1992.

Hughes, R. M., J. N. Rinne, and B. Calamusso. 2005. Historical changes in large river fish assemblages of the Americas: a synthesis. American Fisheries Society Symposium. 45:603-612.

Jager, H. I. and K. A. Rose. 2003. Designing Optimal Flow Patterns for Fall Chinook Salmon in a Central Valley, California River. North American Journal of Fisheries Management 23: 1-21.

Jassby, A. D., W. J. Kimmerer, S. G. Monismith, C. Armor, J. E. Cloern, T. M. Powell, J. R. Schubel, and T. J. Vendlinkski. 1995. Isohaline position as a habitat indicator for estuarine populations. Ecological Applications. 5(1):272-289.

Jeffres, C.A., J.J. Opperman, and P.B. Moyle. 2008. Ephemeral Floodplain Habitats Provide Best Growth Conditions for Juvenile Chinook Salmon in a California River. Environmental Biology of Fishes 83: 449-458.

Jones and Stokes. 2010. Final Hatchery and Stocking Program Environmental Impact Report/Environmental Impact Statement. January 2010.

Junk, W.J., P.B., Bayley, and R.E. Sparks. 1989. The Flood Pulse Concept in River-Floodplain Systems. Special publication. Canadian Journal of Fisheries and Aquatic Science 106:110–127.

Kiernan, J. D., P. B. Moyle, and P. K. Crain. 2012. Restoring native fish assemblages to a regulated California stream using the natural flow regime concept. Ecological Applications. 22(5):1472-1482.

Kimmerer, W.J. 2002. Effects of freshwater flow on abundance of estuarine organisms: Physical effects or trophic linkages? Marine Ecology Progress Series. 243:39-55.

Kimmerer, W.J. 2002a. Physical, Biological, and Management Responses to Variable Freshwater Flow into the San Francisco Estuary. Estuaries. 25(6B):1275-1290.

Kimmerer, W. 2004. Open Water Processes of the San Francisco Estuary: From Physical Forcing to Biological Responses. San Francisco Estuary and Watershed Science Volume 2 Issue 1.

Kimmerer, W. and M. Nobriga. 2008. Investigating Particle Transport and Fate in the Sacramento-San Joaquin Delta using a Particle Tracking Model. San Francisco Estuary and Watershed Science 6(1): Article 4.

Kimmerer, W. J., E. S. Gross, and M. L. MacWilliams. 2009. Is the Response of Estuarine Nekton to Freshwater Flow in the San Francisco Estuary Explained by Variation in Habitat Volume? Estuaries and Coasts. 32:375-389.

Kimmerer, W.J., E.S. Gross, and M.L. MacWilliams. 2014. Tidal migration and retention of estuarine zooplankton investigated using a particle-tracking model. Limnology and Oceanography. 59(3):901-916.

Kimmerer, W.J, M.L. MacWilliams, and E.S. Gross. 2013. Variation of Fish Habitat and Extent of the Low-Salinity Zone with Freshwater Flow in the San Francisco Estuary. San Francisco Estuary and Watershed Science. 11(4). https://escholarship.org/uc/item/3pz7x1x8.

King, A. J., P.Humphries, and P. S. Lake. 2003. Fish Recruitment on Floodplains: the Roles of Patterns of Flooding and Life History Characteristics. Canadian Journal of Fisheries and Aquatic Sciences 60: 773-786.

Knowles, N. and D. R. Cayan. 2002. Potential effects of global warming on the Sacramento/San Joaquin watershed and the San Francisco estuary. Geophysical Research Letters. 29(38):1-4.

Knowles N. and D. R. Cayan. 2004. Elevational dependence of projected hydrologic changes in the San Francisco Estuary and Watershed. Climate Change. 62:319–336.

Kondolf, G. M., A. J. Boulton, S. O'Daniel, G. C. Poole, F. J. Rahel, E. H. Stanley, E. Wohl, A. Bang, J. Carlstrom, C. Cristoni, H. Huber, S. Koljone, P. Louh, K. Nakamura. 2006. Process-Based River Restoration: Visualizing Three-Dimensional Connectivity and Dynamic Vectors to Recover Lost Linkages. Ecology and Society 11(2): 5.

Lindley, S. T., C. B. Grimes, M. S. Mohr, W. Peterson, J. Stein, J. T. Anderson, L. W. Botsford, D. L. Buttom, C.A. Busack, T.K. Collier, J. Ferguson, J.C. Garza, A.M. Grover, D.G. Hankin, R.G. Kope, P.W. Lawson, A. Low, R. B. MacFarlane, K. Moore, M. Palmer-Zwahlen, F.B. Schwing, J. Smith, C. Tracy, R. Webb, B. K. Wells, and T.H. Williams. 2009. What Caused the Sacramento River Fall Chinook Stock Collapse? Pacific Fishery Management Council. March 18, 2009.

Lund, J, E. Hanak, W. Fleenor, R. Howitt, J. Mount, and P. Moyle. 2007. Envisioning futures for the Sacramento-San Joaquin Delta. Public Policy Institute of California. (www.ppic.org)

Lytle, D.A. and N.L. Poff. 2004. Adaptation to Natural Flow Regimes. Trends in Ecology and Evolution 19: 94-100.

Matern, S. A. and P. B. Moyle. 2002. Native and Alien Fishes in a California Estuarine Marsh: Twenty-One Years of Changing Assemblages. Transactions of the American Fisheries Society. 131:797-816.

McCullough, D.A. 1999. A Review and Synthesis of Effects of Alterations to the Water Temperature Regime on Freshwater Life Stages of Salmonids with Special Reference to Chinook Salmon. 279 pages.

McElhany, P., M. Ruckelshaus, M.J. Ford, T.C.Wainwright, and E.P. Bjorkstedt. 2000. Viable Salmonid Populations and the Recovery of Evolutionarily Significant Units. U.S. Dept. of Commerce. NOAA Tech. Memo. NMFS-NWFSC-42,156 pages.

Meng, L, P.B. Moyle, and B. Herbold. 1994. Changes in abundance and distribution of native and introduced fishes of Suisun Marsh. Transactions of the American Fisheries Society. 123:498-507.

Montagna, P. A., T. A. Palmer, and J. Beseres Pollack. 2013. Hydrological Changes and Estuarine Dynamics. Springer Briefs in Environmental Science. DOI: 10.1007/978-1-4614-5833-3

Monsen N. E., J.E. Cloern, J.R. Burau. 2007. Effects of flow diversion on water and habitat quality: Examples from California's highly manipulated Sacramento-San Joaquin Delta. San Francisco Estuary and Watershed Science 5(3):1–15.

Moore, J.W., M. McClure, L.A. Rogers, and D.E. Schindler. 2010. Synchronization and Portfolio Performance of Threatened Salmon. Conservation Letters 3: 340-348.

Moyle, P.B. 2002. Inland Fishes of California, 2nd Edition. University of California Press, Berkeley, California. 502 pages.

Moyle, P.B., P.K. Crain, and K. Whitener. 2007. Patterns in the Use of a Restored California Floodplain by Native and Alien fishes. San Francisco Estuary and Watershed Science 5:1–27. http://repositories.cdlib.org/jmie/sfews/vol5/iss3/art1

Moyle, P.B. and J.F. Mount. 2007. Homogenous Rivers, Homogenous Faunas. Proceedings of the National Academy of Science. 104: 5711-5712.

Moyle, P. B., J. R. Lund, W. A. Bennett, and W. E. Fleenor. 2010. Habitat Variability and Complexity in the Upper San Francisco Estuary. *San Francisco Estuary and Watershed Science* 8(3). Available: http://escholarship.org/uc/item/0kf0d32x.

Moyle, P. B., Williams, J. G., and Kiernan, J. D. 2011. Improving Environmental Flow Methods Used in California FERC Licensing. California Energy Commission, PIER. CEC-500-XXXX-XXX.

Myrick, C. A., and Cech, J. J., Jr. 2001. *Temperature effects on Chinook salmon and steelhead: A review focusing on California's Central Valley populations*. Bay-Delta Modeling Forum Technical Publication 01-1:1–57. Available: http://www.sfei.org/modelingforum/.

National Marine Fisheries Service (NMFS). 2009. Endangered Species Act Section 7 Consultation. Biological Opinion and Conference Opinion on the Long-Term Operations of the Central Valley Project and State Water Project. June 2009.

National Marine Fisheries Service (NMFS) 2014. Recovery plan for the evolutionarily significant units of Sacramento River winter-run Chinook salmon and Central Valley spring-run Chinook salmon and the Distinct Population segment of California Central Valley Steelhead. National Marine Fisheries Service, West Coast Region, Sacramento, California.

Newman, K.B. 2003. Modelling paired release-recovery data in the presence of survival and capture heterogeneity with application to marked juvenile salmon. Statistical Modelling. 3:157-177.

Nobriga, M.L., F. Feyrer, and R.D. Baxter. 2006. Aspects of Sacramento pikeminnow biology in nearshore habitats of the Sacramento-San Joaquin Delta, California. Western North American Naturalist. 66:106-114.

Nobriga, M. L., F. Feyrer, R. D. Baxter, and M. Chotkowski. 2005. Fish Community Ecology in an Altered River Delta: Spatial Patterns in Species Composition, Life History Strategies, and Biomass. Estuaries. 28(5):776-785.

Peterson, M.S. 2003. A Conceptual View of Environment-Habitat-Production Linkages in Tidal River Estuaries. Reviews in Fisheries Science. 11(4):291-313.

Petts, G.E. 2009. Instream Flow Science for Sustainable River Management. Journal of the American Water Resources Association 45: 1071-1086.

Poff, N.L., J.K. Allan, M.B. Bain, J.R. Karr, K.L Prestegaard, B.D. Richter, R.E. Sparks, and J.C. Stromberg. 1997. The Natural Flow Regime. Bioscience 47: 769-784.

Poff, N.L., J.D. Olden, D.M. Merritt, and D.M. Pepin. 2007. Homogenization of Regional River Dynamics by Dams and Global Biodiversity Implications. Proceedings of the National Academy of Sciences 104: 5732-5737.

Pringle, C.M., M.C. Freeman, and B.J. Freeman. 2000. Regional Effects of Hydrologic Alterations on Riverine Macrobiota in the New World; Tropical-Temperate Comparisons. American Institute of Biological Sciences. 50: 807-823.

Reed, D., J.T. Hollibaugh, J. Korman, E. Peebles, K. Rose, P. Smith, and P. Montagna. 2014. Workshop on Delta Outflows and Related Stressors Panel Summary Report. Delta Stewardship Council Delta Science Program. May 5, 2014.

Richter, B.D. and G.A. Thomas. 2007. Restoring Environmental Flows by Modifying Dam Operations. Ecology and Society 12(1).

Sommer, T, R. Baxter, and B. Herbold. 1997. Resilience of splittail in the Sacramento-San Joaquin Estuary. Transactions of the American Fisheries Society. 126:961-976.

Sommer, T.R., M.L. Nobriga, W.C. Harrel, W. Batham, and W.J. Kimmerer. 2001. Floodplain Rearing of Juvenile Chinook Salmon; Evidence of Enhanced Growth and Survival. Canadian Journal of Fisheries and Aquatic Sciences 58: 325-333.

Sparks, R.E. 1995. Need for Ecosystem Management of Large Rivers and Their Floodplains. Bioscience 45: 168-182.

State Water Resources Control Board (State Water Board). 2010. Development of Flow Criteria for the Sacramento-San Joaquin Delta Ecosystem. August 3, 2010.

Tasto, R.N. 1983. Juvenile Dungeness crab, *Cancer magister*, studies in the San Francisco Bay area. In: Life History, Environment and Mariculture Studies of the Dungeness Crab, Cancer magister, with Emphasis on the Central California Fishery Resource, P.W. Wild and R.N. Tasto, (Eds.). Fish Bull. No. 172, California Department of Fish and Game. pp 135-154.

The Bay Institute (TBI). 1998. From the Sierra to the Sea: The Ecological History of the San Francisco Bay-Delta Watershed.

The Bay Institute (TBI) and Natural Resources Defense Council (NRDC). 2010a. Exhibit 1 - Written Testimony of Jonathan Rosenfield. Ph.D., Christina Swanson, Ph.D., John Cain, and Carson Cox Regarding General Analytical Framework.

The Bay Institute (TBI) and Natural Resources Defense Council (NRDC). 2010b. Exhibit 2 - Written Testimony of Jonathan Rosenfield, Ph.D., and Christina Swanson, Ph.D., Regarding Delta Outflows.

The Bay Institute (TBI) and Natural Resources Defense Council (NRDC). 2010c. Exhibit 3 - Written Testimony of Christina Swanson, Ph.D., John Cain, Jeff Opperman, Ph.D., and Mark Tompkins, Ph.D. Regarding Delta Inflows.

Thompson, L. C. and R. Larsen. 2002. Fish Habitat in Freshwater Streams. ANR Publication 8112: 12.

U.S. Army Corps of Engineers (USACE). 1987. Distribution Restriction Statement. Engineering and Design: Reservoir Water Quality Analysis. Engineer Manual 1110-2-1201.

U.S. Environmental Protection Agency (USEPA). 2001. Issue Paper 1. Salmonid Behavior and Water Temperature. Prepared as part of EPA Region 10 Temperature Water Quality Criteria Guidance Development Project.

Whipple, A.A., R.M. Grossinger, D. Rankink, B. Stanford, and R.A. Askevold. 2012. Sacramento-San Joaquin Delta Historical Ecology Investigation: Exploring Pattern and Process. Prepared for the CDFW and Ecosytem Program. A Report of the SFEI-ASC's Historical Ecology Program, SFEI-ASC Publication #672, San Francisco Estuary Institute-Aquatic Science Center, Richmond, CA.

Williams, J.G. 2006. Central Valley Salmon: A Perspective on Chinook and Steelhead in the Central Valley of California. San Francisco Estuary and Watershed Science, 4.

Yarnell, S. M., G. E. Petts, J. C. Schmidt, A. A. Whipple, E. E. Beller, C. N. Dahm, P. Goodwin, and J. H. Viers. 2015. Functional Flows in Modified Riverscapes: Hydrographs, Habitats and Opportunities. BioScience 65 (10): 963-972. DOI: 10.1093/biosci/biv102

6.3.2 Species-Specific Analyses

Brandes, P. L., and J. S. McLain. 2001. Juvenile Chinook salmon abundance, distribution, and survival in the Sacramento–San Joaquin Estuary. In R. L. Brown (ed.). Contributions to the Biology of Central Valley Salmonids. *Fish Bulletin* 179.

California Department of Fish and Game (CDFG). 2010 Quanitifiable Biological Objectives and Flow Criteria for Aquatic and Terrestrial Species of Concern Dependent on the Delta. November 23. Available: https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=25987. Accessed: October 5, 2016.

California Department of Fish and Wildlife (CDFW) 2016. Fall midwater trawl monthly abundance indices. Available: http://www.dfg.ca.gov/delta/data/fmwt/indices.asp. Accessed: April 15, 2016.

California Department of Water Resources (DWR). 2016. *Dayflow Data through Water Year 2015*. Available: http://www.water.ca.gov/dayflow/output/Output.cfm. Accessed: March 18, 2016.

Delta Juvenile Fish Monitoring Program (DJFMP). 2016a. *Chipps Island Trawls CHN-POD Species 1976–2011*. Monitoring Data. Available: http://www.fws.gov/lodi/juvenile_fish_monitoring_program/jfmp_index.htm. Accessed: March18, 2016.

Delta Juvenile Fish Monitoring Program (DJFMP). 2016b. *Chipps Island Trawls CHN-POD Species 2012–2016*. Monitoring Data. Available: http://www.fws.gov/lodi/juvenile_fish_monitoring_program/jfmp_index.htm. Accessed: May 18, 2016.

Hieb. 2015. Excel spreadsheet containing San Francisco Bay Study Indices, 1980–2014. Personal Communication.

Jassby, A. D., W. J. Kimmerer, S. G. Monismith, C. Armor, J. E. Cloern, T. M. Powell, J. R. Schubel, and T. J. Vendlinski. 1995. Isohaline position as a habitat indicator for estuarine populations. *Ecological Applications* 5(1):272–289.

Kimmerer, W. J. 2002. Effects of freshwater flow on abundance of estuarine organisms: Physical effects or trophic linkages? *Marine Ecology Progress Series* 243:39–55.

R Core Team. 2015. R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria. Available: http://www.R-project.org/.

State Water Resources Control Board (State Water Board). 2010. *Development of Flow Criteria for the Sacramento–San Joaquin Delta Ecosystem*. Prepared pursuant to the Sacramento–San Joaquin Delta Reform Act of 2009.

The Bay Institute (TBI) and Natural Resources Defense Council (NRDC). 2010b. Exhibit 2-Written testimony of Jonathan Rosenfield, Ph.D. and Christina Swanson, Ph.D. Regarding flow criteria for the Delta necessary to protect public trust Resources: Delta Outflows.

U.S. Fish and Wildlife Service (USFWS). 2008. *Formal Endangered Species Act Consultation on the Proposed Coordinated Operations of the Central Valley Project (CVP) and State Water Project (SWP)*. Sacramento, CA.

6.3.3 Chinook Salmon and Central Valley Steelhead

Ahearn, D., J. Viers, J. Mount, and R. Dahlgren. 2006. Priming the productivity pump: flood pulse driven trends in suspended algal biomass distribution across restored floodplain. *Freshwater Biology* 51:1417–1433.

Azat, J. 2015. Central Valley Chinook salmon harvest and escapement: 1975–2014. *IEP Newsletter* 28(2):12–16.

Beckman, B. R., W. W. Dickhoff, W. S. Zaugg, C. Sharpe, S. Hirtzel, R. Schrock, D. A. Larsen, R. D. Ewing, A. Palmisano, C. B. Schreck, and C. V. W. Mahnken. 1999. Growth, smoltification, and smolt-to-adult return of spring Chinook salmon from hatcheries on the Deschutes River, Oregon. *Transactions of the American Fisheries Society* 128:1125–1150.

Bell, M. 1991. *Fisheries Handbook of Engineering Requirements and Biological Criteria*. 3rd Edition. U.S. Army Corp of Engineers. North Pacific Division. Fish Passage and Evaluation Program. Portland, OR.

Benigno, G. M., and T. R. Sommer. 2008. Just add water: Sources of chironomid drift in a large river floodplain. *Hydrobiologia.*

Benigno, G. M., and T. R. Sommer. 2008. Just add water: Sources of chironomid drift in a large river floodplain. *Hydrobiologia 600:297–305*

Bilby, R., B. Fransen, and P. Bisson. 1996. Incorporation of nitrogen and carbon from spawning coho salmon into the trophic system of small streams: evidence from stable isotopes. *Canadian Journal of Fisheries and Aquatic Sciences* 53:164–173.

Bilby, R., B. Fransen, P. Bisson and J. Walter. 1998. Response of juvenile coho salmon (Oncorhynchus kisutch) and steelhead (Oncorhynchus mykiss) to the addition of salmon carcasses to two streams in southwestern Washington, USA. *Canadian Journal of Fisheries and Aquatic Sciences* 55:1909–1918.

Bilby, R., B. Fransen, J. Walter, C. Cederholm, and W. Scarlett. 2001. Preliminary evaluation of the use of nitrogen stable isotope ratios to establish escapement levels for Pacific salmon. *Fisheries* 26(1):6–14.

Bjornn, T. C., and D. W. Reiser. 1991. Habitat requirements of salmonids in streams. *American Fisheries Society Special Publication* 19:83–138.

Boles, G. 1988. *Water Temperature Effects on Chinook Salmon (*Onchorhycchus tshawytscha*) with Emphasis on the Sacramento River: A Literature Review*. Report to the California Department of Water Resources. Northern District. 43 p.

Brandes, P. L., and J. S. McLain. 2001. Juvenile Chinook salmon abundance, distribution, and survival in the Sacramento–San Joaquin Estuary. In R. L. Brown (ed.). Contributions to the Biology of Central Valley Salmonids. *Fish Bulletin* 179.

Brett, J. R. 1952. Temperature tolerance in our Pacific salmon, genus *Oncorhynchus*. *Journal of the Fisheries Research Board of Canada* 9(6):265–285.

Bunn, S. E., and A. H. Arthington. 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental Management* 30:492–507.

Burau, J. R. 2004. *Summary of Delta Cross Channel Studies*. Exhibit DOI-08 to the 2006 Bay-Delta Water Quality Control Plan Update. Available: http://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/wq_control_plans/2006wqcp/exhibits/append2/doi/doi-08.pdf.

Burau, J. R. 2014. *Understanding Juvenile Salmon Entrainment at Junctions*. Presentation. Delta Science Workshop on the Interior Delta Flows and Related Stressors. April 16. Available: https://www.youtube.com/watch?v=RNldBDqL3rc&index=7&list=PLqTHCliW1HhrNF3c81L_k9Ml7VLcoJ4j2.

California Department of Fish and Game (CDFG). 1992a. *Estuary Dependent Species*. State Water Resources Control Board 1992 Water Quality/Water Rights Proceedings on the San Francisco Bay/Sacramento–San Joaquin Delta. WRINT-DFG-Exhibit 6.

California Department of Fish and Game (CDFG). 1993. *Restoring Central Valley Stream: A Plan for Action*. November 10. Report for public distribution. Inland Fisheries Division. Compiled by F. L. Reynolds, T. J. Mills, R. Benthin, and A. Low. Sacramento CA.

California Department of Fish and Game (CDFG). 1994.

California Department of Fish and Game (CDFG). 1998. *A Status Review of the Spring Run Chinook Salmon in the Sacramento River Drainage*. Candidate Species Status Report 98-1. June. Report to the Fish and Game Commission. Sacramento, CA. 394 p.

California Department of Fish and Game (CDFG). 2005. Final draft 11-28-05 San Joaquin River Fall-run chinook salmon population model.

California Department of Fish and Game (CDFG). 2010a. *Quanitifiable Biological Objectives and Flow Criteria for Aquatic and Terrestrial Species of Concern Dependent on the Delta*. November 23. Available: https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=25987. Accessed: October 5, 2016.

California Department of Fish and Game (CDFG). 2012. *Written Information Responsive to the Workshop Questions for the Bay-Delta Workshop-2*. September 20. Bay-Delta Fishery Resources. Ecosystem Conservation Division/Water Branch. Sacramento, CA.

California Department of Fish and Wildlife (CDFW). 2016a. *CDFW Fish Hatcheries*. Available: https://www.wildlife.ca.gov/Fishing/Hatcheries.

California Hatchery Review Project (CHRP). 2012. *Livingston Stone National Fish Hatchery Winter Chinook Program Report*. Appendix VIII.

California Hatchery Scientific Review Group (California HSRG). 2012. *California Hatchery Review Report*. Prepared for the U.S. Fish and Wildlife Service and Pacific States Marine Fisheries Commission. June. 100 p.

Collaborative Adaptive Management Team (CAMT). 2014. *Progress Report to the Collaborative Science Policy Group*. February 14. 89 p. Available: http://deltacouncil.ca.gov/sites/default/files/documents/files/Item_7_Attach_1_CAMT%20Progress%20Report%20Version%206_0%20140207_0.pdf.

Collaborative Adaptive Management Team (CAMT). 2016. *Calendar Year 2015 Annual Progress Report to the Collaborative Science Policy Group*. March 15.

Connor, W. P., H. L. Burge, J. R. Yearsley, and T. C. Bjornn. 2003. Influence of flow and temperature on survival of wild subyearling fall Chinook salmon in the Snake River. *North American Journal of Fisheries Management* 23:362–375.

Del Rosario, R., and Y. Redler. 2010. *Residence of Winter-Run Chinook Salmon in the Sacramento–San Joaquin Delta: The Role of Sacramento River Hydrology in Driving Juvenile Abundance and Migration Patterns in the Delta*. NMFS Exhibit 7. Submitted for the Informational Proceeding to Develop Flow Criteria for the Delta Ecosystem Necessary to Protect Public Trust Resources.

Del Rosario, R. B., Y. J. Redler, K. Newman, P. L. Brandes, T. Sommer, K. Reece, and R. Vincik. 2013. Migration patterns of juvenile winter-run-sized Chinook salmon (*Oncorhynchus tshawytscha*) through the Sacramento–San Joaquin Delta. *San Francisco Estuary and Watershed Science* 11(1):1–22.

Delta Juvenile Fish Monitoring Program (DJFMP). 2016. Chipps Island Trawls CHN-POD Species 1976–2011 and 2012–2016. Monitoring Data. Available: http://www.fws.gov/lodi/juvenile_fish_monitoring_program/jfmp_index.htm. Accessed: May 18, 2016.

Department of Water Resources (DWR). 2016. Dayflow Data through Water Year 2015. Accessed: http://www.water.ca.gov/dayflow/output/Output.cfm. Accessed: March 18, 2016.

Dunford, W. 1975. *Space and Food Utilization by Salmonids in Marsh Habitats of Fraser River Estuary*. M.S. thesis. University of British Columbia, Vancouver, BC, Canada. 81 p.

Ecosystem Restoration Program (ERP). 2014. *Conservation Strategy for Restoration of the Sacramento–San Joaquin Delta, Sacramento Valley and San Joaquin Valley Regions.* 218 p. May. Available: https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=31232.

Fausch, K. 1984. Profitable stream positions for salmonids: Relating specific growth rates to net energy gain. *Canadian Journal of Zoology* 62:441–451.

Fausch, K. 1993. Experimental analysis of microhabitat selection by juvenile steelhead (*Oncorhynchus mykiss*) and coho salmon (*O. kisutch*) in a British Columbia stream. C*anadian Journal of Fisheries and Aquatic Sciences* 50:1198–1207.

Fisher, F. W. 1994. Past and present status of Central Valley Chinook salmon. *Conservation Biology* 8:870–873.

Good, T. P., R. S. Waples, and P. Adams (eds.). 2005. *Updated Status of Federally Listed ESUs of West Coast Salmon and Steelhead*. NOAA Technical Memorandum NMFS-NWFSC-66. U.S. Department of Commerce. 598 p.

Groves, A., G. Collins, and P. Trefethen. 1968. Roles of olfaction and vision in choice of spawning site by homing adult Chinook salmon. *Journal of the Fisheries Research Board of Canada* 25:867–76.

Hallock, R. J., W. F. Van Woert, and L. Shapovalov. 1961. An evaluation of stocking hatchery reared steelhead rainbow (*Salmo gairdnerii gairdnerii*) in the Sacramento River System. *California Department of Fish and Game Bulletin* 114.

Hallock, R. J., R. F. Elwell, and D. H. Fry, Jr. 1970. Migrations of adult king salmon, *Oncorhynchus tshawytscha*, in the San Joaquin Delta. *California Fish and Game* 151:1–92.

Healey, M. C. 1980. Utilization of the Nanaimo River Estuary by juvenile Chinook salmon, *Oncorhynchus tshawytscha. U.S. Fisheries Bulletin* 77:653–668.

Healey, M. C. 1982. Juvenile Pacific Salmon in Estuaries: The Life Support System. In V. S. Kennedy (ed). *Estuarine Comparisons*. New York, NY: Academic Press. Pages 315–342.

Healey, M. C. 1991. Life History of Chinook Salmon (*Oncorhynchus tshawytscha*). In C. Groot and L. Margolis (eds.). *Pacific Salmon Life-Histories*. Vancouver, BC, Canada: UBC Press. Pages 313–393.

Jeffres, C. A., J. J. Opperman, and P. B. Moyle. 2008. Ephemeral floodplain habitats provide best growth conditions for juvenile Chinook salmon in a California river. *Environmental Biology of Fishes* 83:449–458.

Kammerer, B., and S. A. Heppell. 2012. Individual condition indicators of thermal habitat quality in field populations of redband trout (*O. mykiss gairdneri*). *Environmental Biology of Fishes* 96:823–835.

Kiernan, J. D. 2012. Restoring native fish assemblages to a regulated California stream using the natural flow regime concept. *Ecological Applications* 22(5):1472–1482.

Kjelson, M. A., and P. L. Brandes. 1989. The use of smolt survival estimates to quantify the effects of habitat changes on salmonid stocks in the Sacramento–San Joaquin River, California. In C. D. Levings, L. B. Holtby, and M. A. Henderson (eds.). Proceedings of the National Workshop on the Effects of Habitat Alteration on Salmonid Stocks. *Canadian Journal of Fisheries and Aquatic Sciences* 105:100–115.

Kjelson, M. A., P. F. Raquel, and F. W. Fisher. 1981. Influences of freshwater inflow on Chinook salmon (*Oncorhynchus tshawytscha*) in the Sacramento–San Joaquin Estuary. In P. D. Cross and D. L. Williams (eds.). *Proceedings of the National Symposium on Freshwater Inflow to Estuaries*. FWS/OBS-81-04. U.S. Fish and Wildlife Service. Pages 88–108.

Levy, D. A., and T. G. Northcote. 1981. *The Distribution and Abundance of Juvenile Salmon in Marsh Habitats of the Fraser River Estuary*. Technical Report 25. Westwater Research Centre, University of British Columbia, Vancouver, BC, Canada.

Lindley, S. T., R. Schick, E. Mora, P. B. Adams, J. J. Anderson, S. Greene, C. Hanson, B. P. May, D. R. McEwan, R. B. MacFarlane, C. Swanson, and J. G. Williams. 2007. Framework for assessing viability of threatened and endangered Chinook salmon and steelhead in the Sacramento–San Joaquin Basin. *San Francisco Estuary and Watershed Science* [online serial] 5(1).

Lindley, S. T., R. Schick, A. Agrawal, M. Goslin, T. E. Pearson, E. Mora, J. J. Anderson, B. May, S. Greene, C. Hanson, A. Low, D. McEwan, R. B. MacFarlane, C. Swanson, and J. G. Williams. 2006. Historical population structure of Central Valley steelhead and its alteration by dams. *San Francisco Estuary and Watershed Science* [online serial] 4(2).

Lindley, S. T., R. Schick, B. P. May, J. J. Anderson, S. Greene, C. Hanson, A. Low, D. McEwan, R. B. MacFarlane, C. Swanson, and J. G. Williams. 2004. *Population Structure of Threatened and Endangered Chinook Salmon ESUs in California's Central Valley Basin*. NOAA Technical Memorandum NOAA-TM-NMFS-SWFSC-360. April.

Low, A. F., J. White, and E. Chappell. 2006. *Relationship of Delta Cross Channel Gate operations to loss of juvenile winter-run Chinook salmon at the CVP/SWP Delta facilities*. Available: http://www.science.calwater.ca.gov/pdf/ewa/EWA_delta_cross_channel_closures_06_111406.pdf.

MacFarlane, B. R., and E. C. Norton. 2002. Physiological ecology of juvenile Chinook salmon (*Oncorhynchus tshawytscha*) at the southern end of their distribution, the San Francisco Estuary and Gulf of the Farallones, California. *Fisheries Bulletin* 100:244–257.

Marston, D., C. Mesick, A. Hubbard, D. Stanton, S. Fortmann-Roe, S. Tsao, and T. Heyne. 2012. Delta Flow Factors Influencing Stray Rate of Escaping Adult San Joaquin River Fall-Run Chinook Salmon (*Oncorhynchus tshawytscha*). *San Francisco Estuary and Watershed Science* 10(4).

McBain & Trush (eds.). 2002. *San Joaquin River Restoration Study Background Report*. December. Prepared for Friant Water Users Authority, Lindsay, CA, and the Natural Resources Defense Council, San Francisco CA. Arcata, CA.

McDonald, J. 1960. The behavior of pacific salmonfry during their downstream migration to freshwater and saltwater nursery areas. *Journal of the Fisheries Research Board of Canada* 17(5):655–676.

McEwan, D. R., and T. Jackson. 1996. *Steelhead Restoration and Management Plan for California.* February. California Department of Fish and Game.

McEwan, D. R. 2001. Central Valley steelhead. In R. Brown (ed.). Contributions to the biology of Central Valley salmonids. California Department of Fish and Game. *Fish Bulletin* 179.

Meng, L., and S. Matern. 2001. Native and introduced larval fishes of Suisun Marsh, California: Effects of freshwater flow. *Transactions of the American Fisheries Society* 130:750–765.

Mesick, C. 2001. The effects of San Joaquin River flows and Delta export rates during October on the number of adult San Joaquin Chinook salmon that stray. In R. L. Brown (ed.). Contributions to the biology of Central Valley salmonids. Volume 2. California Department of Fish and Game. *Fish Bulletin* 179:139–161.

Monismith, S., M. Fabrizio, M. Healey, J. Nestler, K. Rose, and J. Van Sickle. 2014. *Workshop on the Interior Delta Flows and Related Stressors Panel Summary Report*. July. Delta Science Program.Sacramento, CA. Available: http://deltacouncil.ca.gov/sites/default/files/documents/files/Int-Flows-and-Related-Stressors-Report.pdf.

Moyle, P. B. 2002. *Inland Fishes of California*. 2nd Edition. Berkeley, CA: University of California Press. 502 p.

Moyle, P. B., J. A. Israel, and S. E. Purdy. 2008. *Salmon, Steelhead, and Trout in California: Status of an Emblematic Fauna*. Commissioned by California Trout.

Moyle, P. B., R. M. Quiñones, J. V. Katz, and J. Weaver. 2015. *Fish Species of Special Concern in California*. Third edition. California Department of Fish and Wildlife. Sacramento, CA.

Myers, J. M., R. G. Kope, G. J. Bryant, D. Teel, L. J. Lierheimer, T. C. Wainwright, W. S. Grant, F. W. Waknitz, K. Neely, S. T. Lindley, and R. S. Waples. 1998. *Status Review of Chinook Salmon from Washington, Idaho, Oregon, and California*. Report NMFS-NWFSC-35. NOAA Technical Memorandum. U.S. Department of Commerce.

National Marine Fisheries Service (NMFS). 2009. *Public Draft Recovery Plan for the Evolutionarily Significant Units of Sacramento River Winter-Run Chinook Salmon and Central Valley Spring-Run Chinook Salmon and the Distinct Population Segment of Central Valley Steelhead*. Sacramento Protected Resources Division.

National Marine Fisheries Service (NMFS). 2010. *Species of Concern: Chinook Salmon* Oncorhynchus tshawytscha*, Central Valley Fall, Late-Fall Run ESU*. Available: http://www.nmfs.noaa.gov/pr/pdfs/species/chinooksalmon_highlights.pdf .

National Marine Fisheries Service (NMFS). 2014. *Recovery Plan for the Evolutionarily Significant Units of Sacramento River Winter-Run Chinook Salmon and Central Valley Spring-Run Chinook Salmon and the Distinct Population Segment of California Central Valley Steelhead*. West Coast Region, Sacramento, CA.

National Marine Fisheries Service (NMFS). 1997. *Proposed Recovery Plan for the Sacramento River Winter-Run Chinook Salmon*. Southwest Region, Long Beach, CA.

National Marine Fisheries Service (NMFS). 2009a. *Biological Opinion and Conference Opinion on the Long-Term Operations of the Central Valley Project and State Water Project*. June. Endangered Species Act Section 7 Consultation.

National Marine Fisheries Service (NMFS). 2009b. *Technical Memorandum Regarding the San Joaquin River "4:1 Flow to Export ratio" Reasonable and Prudent Alternative (RPA) for the Formal Section 7 Consultation Regarding the Long-Term Operations of the Central Valley Project and State Water Project*. June 2.

National Oceanic and Atmospheric Association Fisheries (NOAA Fisheries). 2016. *Species in the Spotlight, Priority Actions: 2016–2020, Sacramento River Winter-Run Chinook Salmon*. Available: http://www.nmfs.noaa.gov/stories/2016/02/docs/sacramento_winter_run_chinook_salmon_spotlight_species_5_year_action_plan_final_web.pdf. Accessed: October 6, 2016.

Newman, K. B. 2008. *An Evaluation of Four Sacramento–San Joaquin River Delta Juvenile Salmon Survival Studies*. Project SCI-06-G06-299. U.S. Fish and Wildlife Service, Stockton, CA.

Newman, K. B., and P. L. Brandes. 2010. Hierarchical modeling of juvenile Chinook salmon survival as a function of Sacramento–San Joaquin Delta water exports. *North American Journal of Fisheries Management* 30(1):157–169.

Opperman, J. 2008. *Floodplain Conceptual Model*. Delta Regional Ecosystem Restoration Implementation Plan. Sacramento, CA. Available: http://www.cwemf.org/ModelingClearinghouse/DRERIP_FloodplainConceptualModel_2007final012208.pdf. Accessed: October 6, 2016.

O'rear, T., and P. B. Moyle. 2008. *Trends in Fish Populations of Suisun Marsh*. Annual report for DWR contract SAP 4600001965.

Perry, R. W. 2010. *Survival and Migration Dynamics of Juvenile Chinook Salmon (*Oncorhynchus tshawytscha*) in the Sacramento–San Joaquin River Delta*. Ph.D. dissertation. University of Washington.

Perry, R. W., P. L. Brandes, J. R. Burau, A. P. Klimley, B. MacFarlane, C. Michel, and J. R. Skalski. 2013. Sensitivity of survival to migration routes used by juvenile Chinook salmon to negotiate the Sacramento–San Joaquin River Delta. *Environmental Biology of Fishes* 96:381–392.

Perry, R. W., J. G. Romine, N. S. Adams, A. R. Blake, J. R. Burau, S. V. Johnston, and T. L. Liedtke. 2014. Using a non-physical behavioural barrier to alter migration routing of juvenile Chinook salmon in the Sacramento–San Joaquin River Delta. *River Research and Applications* 30(2):192–203.

Perry, R. W., J. G. Romine, A. C. Pope, N. S. Adams, A. Blake, J. R. Burau, S. Johns, and T. Liedtke. 2014a. *Effect of a Floating Fish Guidance Structure on Entrainment of Juvenile Salmon into Georgina Slough*. Bay-Delta Science Conference 2014. Sacramento, CA.

Perry, R. W., P. L. Brandes, J. R. Burau, P. T. Sandstrom, and J. R. Skalski. 2015. Effect of tides, river flow, and gate operations on entrainment of juvenile salmon into the interior Sacramento–San Joaquin River Delta. *Transactions of the American Fisheries Society* 144:445–455.

Raymond, H. L. 1979. Effects of dams and impoundments on migrations of juvenile chinook salmon and steelhead from the Snake River, 1966 to 1975. *Transactions of the American Fisheries Society* 108:505–529.

Rich, A., and W. E. Loudermilk. 1991. *Preliminary Evaluation of Chinook Salmon Smolt Quality in the San Joaquin Drainage*. CDFG and Federal Aid Sport Fish Restoration Program.

Royal, L. 1972. *An Examination of the Anadromous Trout Program in the Washington State Game Department*. 1 May 2000 (Exhibit S-DFG-39).

Rueth, J. 2008. *Livingstone Stone National Fish Hatchery: Conservation Programs for Endangered Winter Chinook salmon* Oncorhynchus tshawytscha *and Threatened Delta Smelt* Hypomesus transpacificus. Presentation. U.S. Fish and Wildlife Service. 21 p.

Shelton, J., and J. Koenings. 1995. Marine factors in the production of salmon: Their significance to the pacific salmon treaty. *Alaska Fishery Research Bulletin* 2(2):156–163.

Shirvell, C. 1990. Role of instream rootwads as juvenile coho salmon (*Oncorhynchus kisutch*) and steelhead trout (*O. mykiss*) cover habitat under varying stream flows. *Canadian Journal of Fisheries and Aquatic Sciences* 47:852–861.

San Joaquin River Group Authority (SJRGA). 2006. *2005 Annual Technical Report on Implementation and Monitoring of the San Joaquin River Agreement and the Vernalis Adaptive Management Plan*. Prepared for the California Water Resources Control Board in compliance with D-1641.

San Joaquin River Group Authority (SJRGA). 2007. *2006 Annual Technical Report on Implementation and Monitoring of the San Joaquin River Agreement and the Vernalis Adaptive Management Plan*. Prepared for the California Water Resources Control Board in compliance with D-1641.

San Joaquin River Group Authority (SJRGA). 2008. *Summary Report of the Vernalis Adaptive Management Plan (VAMP) for 2000–2008*. Prepared by San Joaquin River Technical Committee. Prepared for the Advisory Panel Review Conducted by the Delta Science Program. 84 p.

Steel, A. E., P. T. Sandstron, P. L. Brandes, and A. P. Klimley. 2013. Migration Route Selection of Juvenile Chinook Salmon at the Delta Cross Channel, and the Role of Water Velocity and Individual Movement Patterns. *Environmental Biology of Fishes* 96:215–224.

Stillwater Sciences. 2004. *Lower Calaveras River Chinook salmon and Steelhead Limiting Factors Analysis*. First Year Report (Revised). Prepared for the Fishery Foundation of California.

Sturrock, A. M., J. D. Wikert, T. Heyne, C. Mesick, A. E. Hubbard, T. M. Hinkelman, P. K. Weber, G. E. Whitman, J. J. Glessner, and R. C. Johnson. 2015. Juvenile salmon life history diversity and survival. *PLOS One* 1–23.

Smith, S. G., W. D. Muir, E. E. Hockersmith, R. W. Zabel, R. J., Graves, C. V. Ross, W. P. Connor, and B. D. Arnsberg. 2003. Influence of river conditions on the survival and travel time of Snake River subyearling fall Chinook salmon. *North American Journal of Fisheries Management* 23(3):939–961.

Snider, B. 2001. *Evaluation of Effects of Flow Fluctuations on the Anadromous Fish Populations in the Lower American River*. Technical Reports 1 and 2 with Appendices 1–3. California Department of Fish and Game, Habitat Conservation Division. Stream Evaluation Program. Sacramento, CA.

Sommer, T. R., M. L. Nobriga, W. C. Harrell, W. Batham, and W. Kimmerer. 2001a. Floodplain rearing of juvenile Chinook salmon: Evidence of enhanced growth and survival. *Canadian Journal of Fisheries and Aquatic Sciences* 58:325–333.

State Water Resources Control Board (State Water Board). 2010. *Development of Flow Criteria for the Sacramento–San Joaquin Delta Ecosystem*. Prepared pursuant to the Sacramento–San Joaquin Delta Reform Act of 2009.

State Water Resources Control Board (State Water Board). 2012. *Technical Report on the Scientific Basis for Alternative San Joaquin River Flow and Southern Delta Salinity Objectives.*

Stevens, D. E., and L. W. Miller. 1983. Effects of river flow on abundance of young Chinook salmon, American shad, longfin smelt, and delta smelt in the Sacramento–San Joaquin river system. *North American Journal of Fisheries Management* 3:425–437.

Sykes, G. E., C. J. Johnson, and J. M. Shrimpton. 2009. Temperature and flow effects on migration timing of Chinook salmon smolts. *Transactions of the American Fisheries Society* 138:1252–1265.

Thompson, K. 1972. *Determining Stream Flow for Fish Life*. Pacific Northwest River Basins Commission. Instream Flow Requirements Workshop. March 15–16.

Titus, R. G., M. Volkoff, and W. M. Snider. 2004. Use of otolith microstructure to estimate growth rates of juvenile chinook salmon from a Central Valley California stock. In F. Feyrer, l. Brown, R. L., J. J. Orsi (eds.). *Early Life History of Fishes in the San Francisco Estuary and Watershed*. American Fisheries Society Symposium 39. Bethesda Maryland American Fisheries Society. Pages 181–202.

U.S. Department of the Interior. 2008. *Biological Assessment on the Continued Long-Term Operation of the CVP and SWP*. Bureau of Reclamation.

U.S. Department of the Interior. 2010. *Comments Regarding the California SWRCB Notice of Public Information Proceedings to Develop Delta Flow Criteria for the Delta Ecosystem Necessary to Protect Public Trust Resources (Exhibit 1)*.

U.S. Fish and Wildlife Service (USFWS). 1987. *Exhibit 31: The Needs of Chinook Salmon, Oncorhyncus tshawytscha, in the Sacramento–San Joaquin Estuary*. Entered by the U.S. Fish and Wildlife Service for the State Water Resources Control Board, 1987 Water Quality/Water Rights Proceedings on the San Francisco Bay/Sacramento–San Joaquin Delta.

U.S. Fish and Wildlife Service (USFWS). 1992. *Expert Testimony of United States Fish and Wildlife Service on Chinook Salmon Technical Information for State Water Resources Control Board Water Rights Phase of the Bay/Delta Estuary Proceedings*. July 6. WRINT-USFWS-7.

U.S. Fish and Wildlife Service (USFWS). 1995. *Working Paper on Restoration Needs: Habitat Restoration Actions to Double Natural Production of Anadromous Fish in the Central Valley of California*. Volume 2. May 9. Prepared for the U.S. Fish and Wildlife Service under the direction of the Anadromous Fish Restoration Program Core Group. Stockton, CA.

U.S. Fish and Wildlife Service (USFWS). 2001. *Final Restoration Plan for the Anadromous Fish Restoration Program: A plan to Increase Natural Production of Anadromous Fish in the Central Valley of California*.

U.S. Fish and Wildlife Service (USFWS). 2003. *Flow-Habitat Relationships for Steelhead and Fall, Late-Fall and Winter-Run Chinook Salmon Spawning in the Sacramento River between Keswick Dam and Battle Creek*. Sacramento Fish and Wildlife Office Energy Planning and Instream Flow Branch. Sacramento, CA.

U.S. Fish and Wildlife Service (USFWS). 2008. *Livingstone Stone National Fish Hatchery*.

U.S. Fish and Wildlife Service (USFWS). 2008. *Biological Opinion on Coordinated Operations of the Central Valley Project and State Water Project*. :

U.S. Fish and Wildlife Service (USFWS). 2015. *Colman National Fish Hatchery*. Available: https://www.fws.gov/coleman/index.html. Accessed: October 6, 2016.

Vogel, D. A. 2004. *Juvenile Chinook Salmon Radio-Telemetry Studies in the Northern and Central Sacramento–San Joaquin Delta, 2002–2003*. January. Report to the National Fish and Wildlife Foundation, Southwest Region. 44 p.

Vogel, D. A. 2008. *Pilot Study to Evaluate Acoustic-Tagged Juvenile Chinook Salmon Smolt Migration in the Northern Sacramento–San Joaquin Delta 2006–2007*. Prepared for California Department of Water Resources Bay/Delta Office. Prepared by Natural Resource Scientists. Red Bluff, CA.

Vogel, D. A., and K. R. Marine. 1991. *Guide to Upper Sacramento River Chinook Salmon Life History.* July. Prepared for the Bureau of Reclamation, Central Valley Project.

Weber, N. 2009. *Evaluation of Macroinvertebrates as a Food Resource in the Assessment of Lotic Salmonid Habitat*. M.S. thesis. Utah State University. Pages 1–126.

Williams, J. G. 2006. Central Valley salmon. A perspective on Chinook and steelhead in the Central Valley of California. *San Francisco Estuary and Watershed Science* 4(3)2:1–398.

Yoshiyama, R. M., Gerstung, E. R., Fisher, F. W., and P. B. Moyle. 1996. Historical and present distribution of Chinook salmon in the Central Valley drainage of California. In *Sierra Nevada Ecosystem Project: Final Report to Congress, Vol. III—Assessments, Commissioned Reports, and Background Information*. Centers for Water and Wildland Resources, University of California, Davis. Pages 309–362.

Yoshiyama, R. M., F. W. Fisher, and P. B. Moyle. 1998. Historical abundance and decline of Chinook salmon in the Central Valley region of California. *North American Journal of Fisheries Management* 18:487–521.

Yoshiyama, R. M., E. R. Gerstung, F. W. Fisher, and P. B. Moyle. 2001. Historical and present distribution of Chinook salmon in the Central Valley drainage of California. In R. L. Brown (ed.). Contributions to the biology of Central Valley salmonids. *Fish Bulletin* 179(1):71–176.

Zeug, S. C., and B. J. Cavallo. 2014. Controls on the entrainment of juvenile Chinook salmon (*Oncorhynchus tshawytscha*) into large water diversions and estimates of population-level loss. *Plos One* 9:e101479.

Zimmerman, C. E., G. W. Edwards, and K. Perry. 2008. *Maternal Origin and Migratory History of* Oncorhynchus mykiss *Captured in Rivers of the Central Valley, California.* Final Report. Contract P0385300. Prepared for the California Department of Fish and Game.

6.3.3.1 Federal Register Notices

(59 FR 440). 1994. Final Rule: Endangered and Threatened Species; Status of Sacramento River Winter-Run Chinook Salmon. 59:440.

(63 FR 13347). 1998. *Final Rule; Notice of Determination: Endangered and Threatened Species: Threatened Status for Two ESUs of Steelhead in Washington, Oregon, and California*. 63:13347.

(64 FR 50394). 1999. *Final Rule; Notice of Determination: Endangered and Threatened Species; Threatened Status for Two Chinook salmon Evolutionarily Significant Units (ESUs) in California*. 64:50394.

(70 FR 37160). 2005. *Final Rule: Endangered and Threatened Species: 1 Final Listing Determinations for 16 ESUs of West Coast Salmon, and Final 4(d) Protective Regulations for Threatened Salmonid ESUs*. 70:37160.

(70 FR 52488). 2005. *Final Rule: Endangered and Threatened Species; Designation of Critical Habitat for Seven Evolutionarily Significant Units of Pacific Salmon and Steelhead in California*. 70:52488.

(71 FR 834). 2006. *Final Rule: Endangered and Threatened Species: Final Listing Determinations for 10 Distinct Population Segments of West Coast Steelhead*. 71:834.

(76 FR 50447). 2011. *Endangered and Threatened Species; 5-Year Reviews for 5 Evolutionarily Significant Units of Pacific Salmon and 1 Distinct Population Segment of Steelhead in California*. 76:50447.

6.3.4 Longfin Smelt

Baxter, R., R. Breuer, L. Brown, M. Chotkowski, F. Feyrer, M. Gingras, B. Herbold, A. Mueller- Solger, M. Nobriga, T. Sommer, and K. Souza. 2008. Pelagic organism decline progress report: 2007 synthesis of results. Interagency Ecological Program for the San Francisco Estuary, Technical Report 227, 86 p. Available: http://www.water.ca.gov/iep/docs/pod/synthesis_report_031408.pdf.

Baxter, R., R. Breuer, L. Brown, L. Conrad, F. Feyrer, S. Fong, K. Gehrts, L. Grimaldo, B. Herbold, P. Hrodey, A. Mueller-Solger, T. Sommer, and K. Souza. 2010. *Interagency Ecological Program 2010 Pelagic Organism Decline Work Plan and Synthesis of Results*. Interagency Ecological Program for the San Francisco Estuary. 259 p. Available: http://www.water.ca.gov/iep/docs/FinalPOD2010Workplan12610.pdf.

Baxter, R., M. Nobriga, S. Slater, and R. Fujimura. 2009. *Effects Analysis: State Water Project Effects on Longfin Smelt*. California Department of Fish and Game.

Bennett, W. A., W. J. Kimmerer, and J. R. Burau. 2002. Plasticity in vertical migration by native and exotic estuarine fishes in a dynamic low-salinity zone. *Limnology and Oceanography* 47(5):1496–1507.

California Department of Fish and Game (CDFG) 2009. *Report to the Fish and Game Commission: A Status Review of the Longfin Smelt (*Spirinchus thaleichthys*) in California*. January 23. Available: http://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=10263.

California Department of Fish and Game (CDFG). 2010b. *Effects of Delta Inflow and Outflow on Several Native, Recreational, and Commercial Species*. Prepared for the Informational Proceeding to Develop Flow Criteria for the Delta Ecosystem Necessary to Protect Public Trust Resources Before the State Water Resources Control Board. Sacramento, CA.

Dege, M., and L. Brown. 2004. Effect of outflow on spring and summertime distribution and abundance of larval and juvenile fishes in the upper San Francisco Bay. In F. Freyer, L. Brown, R. Brown, and J. Orsi (eds.). *Early life history of fishes in the San Francisco Estuary and Watershed*. American Fisheries Society. Symposium 39, Bethesda, MD. Pages 49–66.

Emmett, R., S. Hinton, S. Stone, and M. Monaco. 1991. *Distribution and Abundance of Fishes and Invertebrates in West Coast Estuaries*. Volume II: Species Life History Summaries. ELMR Report 8. NOAA/NOS Strategic Environmental Assessments Division, Rockville, MD. 329 p.

Grimaldo, L. F., T. Sommer, N. Van Ark, G. Jones, E. Holland, P. Moyle, B. Herbold, and P. Smith. 2009. Factors affecting fish entrainment into massive water diversions in a tidal freshwater estuary: Can fish losses be managed? *North American Journal of Fisheries Management* 29:1253–1270.

Jassby, A. D., W. J. Kimmerer, S. G. Monismith, C. Armor, J. E. Cloern, T. M. Powell, J. R. Schubel, and T. J. Vendlinski. 1995. Isohaline position as a habitat indicator for estuarine populations. *Ecological Applications* 5(1):272–289.

Kimmerer, W., and M. Nobriga. 2008. Investigating particle transport and fate in the Sacramento–San Joaquin Delta using a particle tracking model. *San Francisco Estuary and Watershed* 6(1):1–26.

Kimmerer, W. J. 2002a. Effects of freshwater flow on abundance of estuarine organisms: Physical effects or trophic linkages? *Marine Ecology Progress Series* 243:39–55.

Martin, K. L. and D. L. Swiderski. 2001. Beach spawning in fishes: Phylogenetic test of hypotheses. *American Zoology* 41:526–537.

Maunder, M., R. Deriso, and C. Hanson. 2015. Use of state space population dynamics models in hypothesis testing: Advantages over simple log linear regressions for modeling survival, illustrated with application to longfin smelt (*Spirinchus thaleichthys*). *Fisheries Research* 164:102–111.

Moyle, P. B. 2002. *Inland Fishes of California*. Berkeley, CA: University of California Press.

Nobriga, M., and J. Rosenfield. 2016. Population dynamics of longfin smelt in the San Francisco Estuary. Disaggregation forces driving long term decline of an estuarine forage fish. *Transactions of the American Fisheries Society* 145(1):44–58.

Rosenfield, J. A., and R. D. Baxter. 2007. Population dynamics and distribution patterns of longfin smelt in the San Francisco Estuary. *Transactions of the American Fisheries Society* 136(6):1577–1592.

Slater, S. B. 2008. *Feeding Habits of Longfin Smelt in the Upper San Francisco Estuary*. Presented at the 5th Biennial CALFED Science Conference 2008. October 22–24. Sacramento Convention Center, Sacramento, CA.

Sommer, T., C. Armor, R. Baxter, R. Breuer, L. Brown, M. Chotkowski, S. Culberson, F. Feyrer, M. Gingras, B. Herbold, W. Kimmmerer, A. Mueller-Solger, M. Nobriga, and K. Souza. 2007. The collapse of pelagic fishes in the upper San Francisco Estuary. *Fisheries Research* 32(6):270–277.

Stevens, D., and L. Miller. 1983. Effects of river flow on abundance of young Chinook salmon, American shad, longfin smelt, and delta smelt in the Sacramento–San Joaquin River system. *North American Journal of fish Management* 3:425–437.

The Bay Institute (TBI). 2010a. *Exhibit 2—Written testimony of Jonathan Rosenfield, Ph.D., and Christina Swanson, Ph.D., Regarding Flow Criteria for the Delta Necessary to Protect Public Trust Resources: Delta Outflows*.

The Bay Institute (TBI). 2010b. *Exhibit 4—Written testimony of Christina Swanson, Ph.D., Regarding Flow Criteria for the Delta Necessary to Protect Public Trust Resources: Delta Hydrodynamics*.

Thompson, J., W. Kimmerer, L. Brown, K. Newman, R. Mac Nally, W. Bennett, F. Freyer, and E. Fleishmann. 2010. Bayesian change point analysis of abundance trends for pelagic fishes in the upper San Francisco Estuary. *Ecological Applications* 20:1431–1448.

State Water Resources Control Board (State Water Board). 2010. *Development of flow criteria for the Sacramento–San Joaquin Delta Estuary*. Prepared pursuant to the Sacramento–San Joaquin Delta Reform Act of 2009.

U.S. Fish and Wildlife Service (USFWS). 1995. *1995 Recovery Plan for the Sacramento–San Joaquin Native Fishes*. Portland, OR.

Wang, J. 1986. *Fishes of the Sacramento–San Joaquin Estuary and Adjacent Waters, California: A Guide to the Early Life Histories*. Interagency Ecological Program Technical Report 9.

Wang, J. 2007. *Spawning, early life stages, and early life histories of the Osmerids found in the Sacramento–San Joaquin Delta of California*. Volume 38. U.S. Department of the Interior, U.S. Bureau of Reclamation.

6.3.4.1 Federal Register Notices

(74 FR 16169). 2009. *Endangered and Threatened Wildlife and Plants; 12-Month Finding on a Petition to List the San Francisco Bay-Delta Population of the Longfin Smelt (*Spirinchus thaleichthys*) as Endangered*. 74:16169.

(77 FR 19755). 2012. *Endangered and Threatened Wildlife and Plants; 12-Month Finding on a Petition to List the San Francisco Bay–Delta Population of the Longfin Smelt as Endangered or Threatened*. 77:19755.

6.3.5 Green Sturgeon and White Sturgeon

Adams, P. B., C. B. Grimes, J. E. Hightower, S. T. Lindley, and M. L. Moser. 2002. *Status Review for the North American Green Sturgeon*. June. Santa Cruz, CA: National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Southwest Fisheries Science Center.

Beamesderfer, R., M. Simpson, G. Kopp, J. Inman, A. Fuller, and D. Demko. 2004. *Historical and Current Information on Green Sturgeon Occurrence in the Sacramento and San Joaquin Rivers and Tributaries*. August. Sacramento, CA. Prepared by S.P. Cramer & Associates, Inc., Oakdale, CA.

Buddington, R. K., and J. P. Christofferson. 1985. Digestive and Feeding Characteristics of the Chondrosteans. In F. P. Binkowski and S. I. Doroshov (eds.). *North American Sturgeons: Biology and Aquacultural Potential*. Dordrecht, Netherlands: Dr. W. Junk Publishers.

California Department of Fish and Game (CDFG). 1992b. Sturgeon in relation to water development in the Sacramento San Joaquin Estuary. State Water Resources Control Board 1992 Water Rights Phase of the Bay-Delta Estuary Proceedings. WRINT-DFG-Exhibit 28.

California Department of Fish and Game (CDFG). 2002. California Department of Fish and Game Comments to NMFS Regarding Green Sturgeon Listing.

Cech, J. J., S. I. Doroshov, G. P. Moberg, B. P. May, R. G. Schaffter, and D. M. Kohlhorst. 2000. *Biological Assessment of Green Sturgeon in the Sacramento-San Joaquin Watershed (Phase 1)*. Final. October. Davis, CA, and Stockton, CA. Prepared for CALFED Bay-Delta Program.

Chapman, F. A., J. P. Van Eenennaam, and S. I. Doroshov. 1996. The reproductive condition of white sturgeon, *Acipenser transmontanus*, in San Francisco Bay, California. *Fishery Bulletin* 94:628–634.

Deng, X., J. P. Van Eenennaam, and S. I. Doroshov. 2002. Comparison of early life stages and growth of green and white sturgeon. In W. Van Winkle, P. Anders, D. Secor, and D. Dixon (eds.). *Biology, Management, and Protection of North American Sturgeon*. Bethesda, MD: American Fisheries Society.

DuBois, J., and M. Gringras. 2011. Using harvest rate and harvest to estimate white sturgeon abundance. *Interagency Ecological Program for the Sacramento-San Joaquin Estuary Newsletter* 24(3):23–26.

DuBois, J., M. Gringras, and G. Aasen. 2011. Status and trends of San Francisco Estuary white sturgeon. *Interagency Ecological Program for the Sacramento-San Joaquin Estuary Newsletter* 24(2):50–55.

Emmett, R. L., S. A. Hinton, S. L. Stone, and M. E. Monaco. 1991. Distribution and Abundance of Fishes and Invertebrates in West Coast Estuaries, Volume II: Species Life History Summaries. August. ELMR Report 8. Prepared by National Oceanic and Atmospheric Administration, National Ocean Service, Strategic Environmental Assessments Division, Rockville, MD.

Fish, M. A. 2010. White sturgeon year-class index for the San Francisco Estuary and its relation to Delta outflow. *Interagency Ecological Program for the Sacramento-San Joaquin Estuary Newsletter* 23(2):80–84.

Gingras, M., J. DuBois, and M. Fish. 2014. "Impact of Water Operations and Overfishing on White Sturgeon." Presentation with annotations at the Interagency Ecological Program Annual Workshop, Folsom, CA. February 27, 2014.

Gruber, J. J., S. J. Jackson, and J. P. Van Eenennaam. 2012. *2011 San Joaquin River Sturgeon Spawning Survey*. Final Annual Report. May. Lodi, CA: U.S. Fish and Wildlife Service, Stockton Fish and Wildlife Office, Anadromous Fish Restoration Program.

Heublein, J. C. 2006. *Migration of Green Sturgeon,* Acipenser medirostris*, in the Sacramento River*. M.S. thesis. San Francisco State University. San Francisco, CA.

Heublein, J. C., J. T. Kelly, C. E. Crocker, A. P. Klimley, and S. T. Lindley. 2009. Migration of green sturgeon *Acipenser medirostris* in the Sacramento River. *Environmental Biology of Fishes* 84(3):245–258.

Israel, J. A., J. F. Cordes, M. A. Blumberg, and B. Mays. 2004. Geographic patterns of genetic differentiation among collections of green sturgeon. *North American Journal of Fisheries Management* 24:922–931

Jackson, Z. J and J. P. Van Eenennaam. 2013. 2012 San Joaquin River Sturgeon Spawning Survey. Final Annual Report. March. Lodi, CA: U.S. Fish and Wildlife Service, Stockton Fish and Wildlife Office, Anadromous Fish Restoration Program.

Klimley, A., E. Chapman, J. Cech, D. Cocherell, N. Fangue, M. Gingras, Z. Jackson, E. Miller, E. Mora, J. Poletto, A. Schreier, A. Seesholtz, K. Sulak, M. Thomas, D. Woodbury, and M. Wyman. 2015. Sturgeon in the Sacramento-San Joaquin Watershed: New insights to support conservation and management. *San Francisco Estuary and Watershed Science* 13(4): Article 1.

Kogut, N. 2008. Overbite clams, *Corbula amurensis*, defecated alive by white sturgeon, *Acipenser transmontanus*. *California Fish and Game* 94:143–149.

Kohlhorst, D. W., L. W. Botsford, J. S. Brennand, and G. M. Caillet. 1991. Aspects of the Structure and Dynamics of an Exploited Central California Population of White Sturgeon (*Acipenser transmontanus*). In P. Williott (ed.). *Acipenser*. Bordeaux, France: Cemagref Publishers.

Kohlhorst, D. W. 1976. Sturgeon spawning in the Sacramento River in 1973, as determined by distribution of larvae. *California Fish and Game* 62:32–40.

Kynard, B., E. Parker, and T. Parker. 2005. Behavior of early life intervals of Klamath River green sturgeon, *Acipenser medirostris*, with note on body color. *Environmental Biology of Fishes* 72:85–97.

Lindley, S. T., M. M. Moser, D. L. Erickson, M. Belchik, D. W. Welch, E. Rechisky, A. P. Klimley, J. T. Kelly, and J. Heublein. 2008. Marine migration of North American green sturgeon. *Transactions of the American Fisheries Society* 137:182–194.

Lindley, S. T., D. L. Erickson, M. L. Moser, G. Williams, O. Langness, B. W. McCovey, M. Belchik, D. Vogel, W. Pinnix, J. T. Kelly, J. C. Heublein, and A. P. Klimley. 2011. Electronic tagging of green sturgeon reveals population structure and movement among estuaries. *Transactions of the American Fisheries Society* 140:108–122.

Lindley, S. T., R. Schick, B. May, J. Anderson, S. Greene, C. Hanson, A. Low, D. McEwan, R. MacFarland, C. Swanson, and J. Williams. 2004. *Population Structure of Threatened and Endangered Chinook Salmon ESUs in California's Central Valley Basin*. April. NOAA-TM-NMFS-SWFSC-360. La Jolla, CA: National Oceanic and Atmospheric, National Marine Fisheries Service, Southwest Fisheries Science Center.

McCabe, G. T., and C. A. Tracy. 1994. Spawning and early life history of white sturgeon, *Acipenser transmontanus*, in the lower Columbia River. *Fishery Bulletin* 92:760–772.

Mckechnie, R. J., and R. B. Fenner. 1971. Food habits of white sturgeon, *Acipenser transmontanus*, in San Pablo and Suisun Bays, California. *California Fish and Game* 57 (3):209–212.

Miller, L. W. 1972. Migrations of sturgeon tagged in the Sacramento San Joaquin Estuary. *California Fish and Game* 58:102–10.

Moyle, P. B. 2002. *Inland Fishes of California*. Berkeley, CA: University of California Press.

Moyle, P. B., R. M. Quinones, J. V. Katz, and J. Weaver. 2015. Northern Green Sturgeon. Fish Species of Special Concern in California. Third edition. July. Sacramento, CA: California Department of Fish and Wildlife.

National Marine Fisheries Service (NMFS). 2005. Green Sturgeon (Acipenser medirostris) Status Review Update. February. Santa Cruz, CA: Biological Review Team, Santa Cruz Laboratory, Southwest Fisheries Science Center.

National Marine Fisheries Service (NMFS). 2009. *Biological Opinion and Conference Opinion on the Long-Term Operations of the Central Valley Project and State Water Project*. Endangered Species Act Section 7 Consultation. June 4. Southwest Region.

Poytress, W. R., J. J., Gruber, J. P. Van Eenennaam, and M. Gard. 2015. Spatial and temporal distribution of spawning events and habitat characteristics of Sacramento River Green sturgeon. *Transactions of the American Fisheries Society* 144:1129–1142.

Radtke, L. D. 1966. Distribution of smelt, juvenile sturgeon, and starry flounder in the Sacramento-San Joaquin Delta with observations on food of sturgeon. In J. L. Turner and D. W. Kelley (eds.), *Ecological Studies of the Sacramento-San Joaquin Delta, Part II: Fishes of the Delta*. *Fish Bulletin* 136.

Schaffter, R. 1997. White sturgeon spawning migrations and location of spawning habitat in the Sacramento River, California. *California Department of Fish and Game* 83:1–20.

Schreiber, M. R. 1962. *Observations on the food habits of juvenile white sturgeon*. California Fish and Game 48:79–80.

U.S. Department of the Interior. 2008. *Biological Assessment on the Continued Long-Term operation of the Central Valley Project and the State Water Project*. August. Bureau of Reclamation.

U.S. Fish and Wildlife Service (USFWS). 1996. *Working Paper on Restoration Needs: Habitat Restoration Actions to Double Natural Production of Anadromous Fish in the Central Valley of California*. Volume 2. May 9. Prepared for the U.S. Fish and Wildlife Service under the direction of the Anadromous Fish Restoration Program Core Group. Stockton, CA.

U.S. Fish and Wildlife Service (USFWS). 2001. *Final restoration plan for the Anadromous Fish Restoration Program: A plan to increase natural production of anadromous fish in the Central Valley of California*. Prepared for the Secretary of the Interior by the U.S. Fish and Wildlife Service with the assistance of the Anadromous Fish Restoration Program Core Group. Stockton, CA.

Van Eenennaam, J. P., M. A. H. Webb, X. Deng, and S. I. Doroshov. 2001. Artificial spawning and larval rearing of Klamath River green sturgeon. *Transactions of the American Fisheries Society* 130:159–165.

Van Eenennaam, J. P., J. Linares-Casenave, X. Deng and S. I. Doroshov. 2005. Effect of incubation temperature on green sturgeon embryos, *Acipenser medirostris*. *Environmental Biology of Fishes* 72:145–154.

Van Eenennaam, J. P., J. Linares, S. I. Doroshov, D. C. Hillemeier, T. E. Willson, and A. A. Nova. 2006. Reproductive conditions of the Klamath River green sturgeon. *Transactions of the American Fisheries Society* 135(1):151–163.

6.3.5.1 Federal Register Notices

(70 FR 17386) U.S. Fish and Wildlife Service. 2005. *Endangered and Threatened Wildlife and Plants: Proposed Threatened Status for Southern Distinct Population Segment of North American Green Sturgeon*. 70(65):17386–17401.

(73 FR 52084) U.S. Fish and Wildlife Service. 2008. *Endangered and Threatened Wildlife and Plants: Proposed Rulemaking to Designate Critical Habitat for the Threatened Southern Distinct Population Segment of North American Green Sturgeon*. 73(174):52084–52110.

(71 FR 17757) U.S. Fish and Wildlife Service. 2006. *Endangered and Threatened Wildlife and Plants: Threatened Status for Southern Distinct Population Segment of North American Green Sturgeon*. 71(67):17757–17766.

(74 FR 52300) U.S. Fish and Wildlife Service. 2009. *Endangered and Threatened Wildlife and Plants: Final Rulemaking to Designate Critical Habitat for the Threatened Distinct Population Segment of North American Green Sturgeon.* 74(195):52300–52351.

(75 FR 30714) U.S. Fish and Wildlife Service. 2010. *Endangered and Threatened Wildlife and Plants: Final Rulemaking to Establish Take Prohibitions for the Threatened Southern Distinct Population Segment of North American Green Sturgeon.* 75(105):30714–30730.

6.3.6 Sacramento Splittail

Arnold, J. 1999. Fish salvage at SWP and CVP facilities. *Interagency Ecological Program for the San Francisco Estuary Newsletter* 12(2):45–48.

Baxter, R. D. 1999a. Status of splittail in California. *California Fish and Game* 85(1):28–30.

Baxter, R., W. Harrell, and L. Grimaldo. 1996. 1995 Splittail spawning investigations. *Interagency Ecological Program for the San Francisco Estuary Newsletter* 9(4):27–31.

Caywood, M. L. 1974. *Contributions to the Life History of the Splittail,* Pogonichthys acrolepidotus *(Ayers)*. M.S. thesis. California State University. Sacramento, CA.

Center for Biological Diversity. 2009. *Complaint for Declaratory and Injunctive Relief*. Case filed in the United State District Court for the Northern District of California. Available: http://www.biologicaldiversity.org/species/fish/Sacramento_splittail/pdfs/Sacramento_Splittail_complaint.pdf.

Daniels, R. A., and P. B. Moyle. 1983. Life history of splittail (Cyprinidae: *Pogonichthys macrolepidotus*) in the Sacramento-San Joaquin Estuary. *Fishery Bulletin* 81(3):647–654.

Dill, W. A., and A. J. Cordone. 1997. History and status of introduced fishes in California, 1871–1996. *Fish Bulletin* 178.

Feyrer, F., T. Sommer, and W. Harrell. 2006. Managing floodplain inundation for native fish: Production dynamics of Age-0 splittail (*Pogonichtys macrolepidotus*) in California's Yolo Bypass. *Hydrobiologia* 573:213–226.

Feyrer, F., T. Sommer, and R. D. Baxter. 2005. Spatial-temporal distribution and habitat associations of Age-0 splittail in the Lower San Francisco Watershed. *Copeia* 2005(1):159–168.

Kimmerer, W. J. 2002. Effects of freshwater flow on abundance of estuarine organisms: Physical effects or trophic linkages? *Marine Ecology Progress Series* 243:39–55.

Meng, L., and S. Matern. 2001. Native and introduced larval fishes of Suisun Marsh, California: the effects of freshwater flow. *Transactions of the American Fisheries Society* 130(5):750–765.

Meng, L., and P. B. Moyle. 1995. Status of splittail in the Sacramento-San Joaquin Estuary. *Transactions of the American Fisheries Society* 124(4):538–549.

Moyle, P. B. 2002. *Inland Fishes of California*. Berkeley, CA: University of California Press.Moyle, P. B., R. D. Baxter, T. Sommer, T. C. Foin, and S. A. Matern. 2004. Biology and population dynamics of Sacramento splittail (*Pogonichthys macrolepidotus*) in the San Francisco Estuary: A review. *San Francisco Estuary and Watershed Science* 2(2):Article 3.

Sommer, T. R., R. Baxter, and B. Herbold. 1997. Resilience of splittail in the Sacramento-San Joaquin Estuary. *Transactions of the American Fisheries Society* 126(6):961–976.

Sommer, T. R., L. Conrad, G. O'Leary, F. Feyrer, and W. C. Harrell. 2002. Spawning and rearing of splittail in a model floodplain wetland. *Transactions of the American Fisheries Society* 131(5):966–974.

State Water Resources Control Board (State Water Board). 2010. *Development of Flow Criteria for the Sacramento–San Joaquin Delta Estuary*. Final. August 3. Sacramento, CA.

U. S. Fish and Wildlife Service (USFWS). 1996. *Sacramento–San Joaquin Delta Native Fishes Recovery Plan*. Portland, OR: U.S. Fish and Wildlife Service, Oregon Fish and Wildlife Office.

Wang, J. C. S. 1986. *Fishes of the Sacramento–San Joaquin Estuary and Adjacent Waters, California: A Guide to the Early Life Histories*. Technical Report 9. January. Prepared for Interagency Ecological Study Program for the Sacramento–San Joaquin Estuary.

6.3.6.1 Federal Register Notices

(64 FR 5963) U.S. Fish and Wildlife Service. 1999. *Endangered and Threatened Species; Determination of Threatened Status for the Sacramento Splittail*. 64(25): 5963–5981.

(68 FR 55139) U.S. Fish and Wildlife Service. 2003. *Endangered and Threatened Species; Notice of Remanded Determination of Status for the Sacramento Splittail (*Pogonichthys macrolepidotus*)*. 68(183): 55139–55166.

(75 FR 62070) U.S. Fish and Wildlife Service. 2010. *Endangered and Threatened Wildlife and Plants; 12-Month Finding on a Petition to List the Sacramento Splittail as Endangered or Threatened*. 75(194):62070–62095.

6.3.7 Delta Smelt

Bennett, W. A. 2005. Critical assessment of the delta smelt population in the San Francisco Estuary, California. *San Francisco Estuary and Watershed Science* [online serial] 3(2).

Bennett, W. A., W. J. Kimmerer, and J. R. Burau. 2002. Plasticity in vertical migration by native and exotic estuarine fishes in a dynamic low-salinity zone. *Limnology and Oceanography* 47:1496–1507.

California Department of Fish and Wildlife (CDFW). 2016b. State and Federally Listed Endangered and Threatened Animals of California. Biogeographical Data Branch. California Natural Diversity Database.

California Department of Fish and Wildlife (CDFW). 2016. *CDFW Rationale for Summer Delta Flow Augmentation for Improving Delta Smelt Survival*. July 8.

Dege, M., and L. R. Brown. 2004. Effect of outflow on spring and 1 summertime distribution and abundance of larval and juvenile fishes in the upper San Francisco Estuary. In F. Feyrer, L. R. Brown, R. L. Brown, and J. J. Orsi (eds.). Early life history of fishes in the San Francisco Estuary and Watershed. *American Fisheries Society Symposium* 39:49–66.

Durand, J. R. 2010. *Determinants of Seasonal Abundance of Key Zooplankton of the San Francisco Estuary*. M.S. thesis. San Francisco State University, San Francisco, CA. 55 p.

Feyrer, F., M. L. Nobriga, and T. R. Sommer. 2007. Multi-decadal trends for three declining fish species: Habitat patterns and mechanisms in the San Francisco Estuary, California, USA. *Canadian Journal of Fisheries and Aquatic Science* 64:723–734.

Fisch, K. M., J. M. Henderson, R. S. Burton, and B. May. 2011. Population genetics and conservation implications for the endangered delta smelt in the San Francisco Bay–Delta. *Conservation Genetics* 12:1421–1434.

Grimaldo, L. F., T. Sommer, N. Van Ark, G. Jones, E. Holland, P. B. Moyle, P. Smith, and B. Herbold. 2009. Factors affecting fish entrainment into massive water diversion in a tidal freshwater estuary: Can fish losses be managed? *North America Journal of Fisheries Management* 29:1253–1270.

Hammock, B., J. Hobbs, S. Slater, S. Acuna, and S. Teh. 2015. Contaminant and food limitation stress in an endangered estuarine fish. *Science of the Total Environment* 532:316–326.

Hobbs, J. A., W. A. Bennett, and J. E. Burton. 2006. Assessing nursery habitat for native smelts (*Osmeridae*) in the low-salinity zone of the San Francisco Estuary. *Journal of Fish Biology* 69:907–922.

Hobbs, J. A., W. Bennett, J. Burton, and M. Gras. 2007. Classification of larval and adult delta smelt to nursery areas by use of trace elemental finger printing. *Transactions of the American Fisheries Society* 136:518–527.

Interagency Ecological Program (IEP). 2015. *An Updated Conceptual Model of Delta Smelt biology: Our Evolving Understanding of an Estuarine Fish*. Technical Report 90. 206 p.

Jassby, A. D., W. J. Kimmerer, S. G. Monismith, C. Armor, J. E. Cloern, T. M. Powell, J. R. Schubel, and T. J. Vendlinski. 1995. Isohaline position as a habitat indicator for estuarine populations. *Ecological Applications* 5:272–289.

Kimmerer, W. J. 2008. Losses of Sacramento River Chinook salmon and delta smelt to entrainment in water diversions in the Sacramento–San Joaquin Delta. *San Francisco Estuary and Watershed Science* 6(2).

Kimmerer, W. 2011. Modeling delta smelt losses at the south delta facilities. *San Francisco Estuary and Watershed Sciences* 9(1).

Kimmerer, W. J., and M. L. Nobriga. 2008. Investigating particle transport and fate in the Sacramento–San Joaquin Delta using particle tracking model. *San Francisco Estuary and Watershed Science* 6(1).

Kimmerer, W. J., E. S. Gross, and M. L. MacWilliams. 2009. Is the response of estuarine nekton to freshwater flow in the San Francisco Estuary explained by variation in habitat volume? *Estuaries and Coasts* 32:375–389.

Maunder, M., and R. Deriso. 2011. A state space multi stage life cycle model to evaluate population inpacts in the presence of density dependence: Illustrated with application to delta smelt (*Hypomesus transpacificus*). *Canadian Journal of Fisheries and Aquatic Sciences* 68:1285–1306.

Messineo, J., M. Fish, D. Contreras, K. Hieb, and V. Afentoulis. 2010. 2009 fishes annual status and trends report for the San Francisco Estuary. *Interagency Ecological Program for the Sacramento–San Joaquin Estuary Newsletter* 23(2):49–72.

Miller, W. J., B. F. J. Manly, D. D. Murphy, D. Fullerton, and R. R. Ramey. 2012. An investigation of factors affecting the decline of delta smelt (*Hypomesus transpacificus*) in the Sacramento–San Joaquin Estuary. *Reviews in Fisheries Science* 20:1–19.

Moyle, P. B. 2002. *Inland Fishes of California*. Revised and expanded. Berkeley, CA: University of California Press.

Nobriga, M. L., T. R. Sommer, F. Feyrer, and D. Fleming. 2008. Long-Term trends in summertime habitat suitability for delta smelt (*Hypomesus transpacificus*). *San Francisco Estuary and Watershed Science* 6(1):1–13.

Rose, K., W. Kimmerer, K. Edwards, and W. Bennett. 2013. Individual based modeling of delta smelt population dynamics in the upper San Francisco Estuary II: Alternative baselines and good versus bad years. *Transactions of the American Fisheries Society* 142:1260–1272.

Slater, S. B., and R. D. Baxter, 2014. Diet, prey selection and body condition of age-0 delta smelt, *Hypomesus transpacificus*, in the upper San Francisco Estuary. *San Francisco Estuary and Watershed Science* 12(3)23.

Sommer, T., F. Mejia, M. Nobriga, F. Feyrer, and L. Grimaldo. 2011. The spawning migration of delta smelt in the upper San Francisco Estuary. *San Francisco Estuary and Watershed Science* 9(2):1–16.

Sommer, T., and F. Mejia. 2013. A place to call home: A synthesis of delta smelt habitat in the upper San Francisco Estuary. *San Francisco Estuary and Watershed Science* 11(2).

Thomson, J., W. Kimmerer, L. Brown, K. Newman, R. MacNally, W. Bennett, F. Freyer, and E. Fleishman. 2010. Bayesian change point analysis of abundance trends for pelagic fishes in the upper San Francisco Estuary. *Ecological Applications* 20:1431–1448.

U.S. Fish and Wildlife Service (USFWS). 1996. *Recovery Plan for the Sacramento–San Joaquin Delta Native Fishes*. Portland, OR.

U.S. Fish and Wildlife Service (USFWS). 2008. *Formal Endangered Species Act Consultation on the Proposed Coordinated Operations of the Central Valley Project (CVP) and State Water Project (SWP)*. Sacramento, CA.

Wang, J. 1986. *Fishes of the Sacramento–San Joaquin Estuary and Adjacent Waters, California: A guide to the Early Life Stages*. Interagency Ecological Studies Program Technical Report 9. Sacramento, CA.

Wang, J. C. S. 2007. *Spawning, Early Life Stages, and Early Life Histories of the Osmerids Found in the Sacramento–San Joaquin Delta of California*. Tracy Fish Facilities Studies California Volume 38. U.S. Bureau of Reclamation, Mid-Pacific Region.

6.3.7.1 Federal Register Notices

(58 FR 12863). 1993. *Endangered and Threatened Wildlife and Plants; Determination of Threatened Status for the Delta Smelt*. 58:12854.

(59 FR 65256). 1994. *Endangered and Threatened Wildlife and Plants; Critical Habitat Determination for the Delta Smelt*. 59:65256.

(75 FR 17667). 2010. *Endangered and Threatened Wildlife and Plants; 12-Month Finding on a Petition to Reclassify the Delta Smelt From Threatened to Endangered Throughout Its Range*. 75:17667.

6.3.8 Starry Flounder

Baxter, R. D. 1999b. Pleuronectiformes. In J. Orsi (ed.). *Report on the 1980–1995 Fish, Shrimp, and Crab Sampling in the San Francisco Estuary, California*. Technical Report 63. Prepared for the Interagency Ecological Study Program for the Sacramento–San Joaquin Estuary.

Bottom, D. L., K. K. Jones, and M. J. Herring. 1984. *Fishes of the Columbia River Estuary*. Final report on the Fish Work Unit of the Columbia River Estuary Data Development Program. June. Portland, OR: Oregon Department of Fish and Wildlife.

California Department of Fish and Game (CDFG). 1992a. *Estuary Dependent Species*. State Water Resources Control Board 1992 Water Quality/Water Rights Proceedings on the San Francisco Bay/Sacramento–San Joaquin Delta. WRINT-DFG-Exhibit 6.

California Department of Fish and Game (CDFG). 2010. *Effects of Delta Inflow and Outflow on Several Native, Recreational, and Commercial Species*. February. Stockton, CA, and Sacramento, CA. Prepared for the Informational Proceeding to Develop Flow Criteria for the Delta Ecosystem Necessary to Protect Public Trust Resources before the State Water Resources Control Board. Sacramento, CA.

Emmett, R. L., S. L. Stone, S. A. Hinton, and M. E. Monaco. 1991. *Distribution and abundance of fishes and invertebrates in west coast estuaries*. Volume II: Species life history summaries. ELMR Report. 8. NOAA/NOS Strategic Environmental Assessments Division, Rockville, MD.

Granssle, D. 1966. Fishes and Decapods of San Pablo and Suisun Bays. In D. W. Kelley (ed.). *Ecological Studies of the Sacramento–San Joaquin Estuary, Part I: Zooplankton, Zoobenthos, and Fishes of San Pablo and Suisun Bays, Zooplankton and Zoobenthos of the Delta*. *Fish Bulletin* 133.

Haertel, L., and C. Osterberg. 1967. Ecology of zooplankton, benthos and fishes in the Columbia River Estuary. *Ecology* 48(3):459–472.

Haugen, C. W. 1992. Starry Flounder. In W. S. Leet, C. D. Dewees, and C. W. Haugen (eds.). *California's Living Marine Resources and Their Utilization*. Davis, CA: Sea Grant Extension Program, Department of Wildlife and Fisheries Biology, University of California.

Jassby, A. D., W. J. Kimmerer, S. G. Monismith, C. Armor, J. E. Cloern, T. M. Powell, J. R. Schubel, and T. J. Vendlinski. 1995. Isohaline position as a habitat indicator for estuarine populations. *Ecological Applications* 5(1):272–289.

Kimmerer, W. J. 2002. Effects of freshwater flow on abundance of estuarine organisms: Physical effects or trophic linkages? *Marine Ecology Progress Series* 243:39–55.

Miller, D. J., and R. N. Lea. 1972. Guide to the coastal marine fishes of California. *Fish Bulletin* 157.

Moyle, P. B. 2002. *Inland Fishes of California*. Berkeley, CA: University of California Press.

Orcutt, H. G. 1950. The life history of the starry flounder, *Platichthys stellatus* (Pallas). *Fish Bulletin* 78:64.

Porter, R. 1964. *Food and Feeding of Staghorn Sculpin (*Leptocottus armatus *Girard) and Starry Flounders (*Platiohthus stellatus *Pallas) in Euryhaline Environments*. M.S. thesis. Humboldt State College.

Radke, L. 1966. Distribution of smelt, juvenile sturgeon, and starry flounder in the Sacramento–San Joaquin Delta with observations on food of sturgeon. In J. L. Turner and D. W. Kelley (eds.). Ecological studies of the Sacramento–San Joaquin Delta, part II: fishes of the delta. *Fish Bulletin* 136.

State Water Resources Control Board (State Water Board) 2010. Development of Flow Criteria for the Sacramento–San Joaquin Delta Ecosystem. Final. August 3. Sacramento, CA. http://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/deltaflow/docs/final_rpt080310.pdf

Wang, J. C. S. 1986. *Fishes of the Sacramento–San Joaquin Estuary and Adjacent Waters, California: A Guide to the Early Life Histories*. Technical Report 9. January. Prepared for the Interagency Ecological Study Program for the Sacramento–San Joaquin Estuary.

6.3.9 California Bay Shrimp

California Department of Fish and Game (CDFG). 1987. *Delta Outflow Effects on the Abundance and Distribution of San Francisco Bay Fish and Invertebrates, 1980–1985*. State Water Resources Control Board 1987 Water Quality and Water Rights Proceedings on the San Francisco Bay and Sacramento–San Joaquin Delta. WRINT-DFG-Exhibit 60.

California Department of Fish and Game (CDFG). 1992a. *Estuary Dependent Species*. State Water Resources Control Board 1992 Water Quality/Water Rights Proceedings on the San Francisco Bay/Sacramento–San Joaquin Delta. WRINT-DFG-Exhibit 6. 97 pp. http://www.swrcb.ca.gov/waterrights/water_issues/programs/bay_delta/ deltaflow/dfg_spprt_docs1992.shtml.

California Department of Fish and Game (CDFG). 2010. *Effects of Delta Inflow and Outflow on Several Native, Recreational, and Commercial Species*. February. Stockton, CA and Sacramento, CA. Prepared for the Informational Proceeding to Develop Flow Criteria for the Delta Ecosystem

Necessary to Protect Public Trust Resources before the State Water Resources Control Board. Sacramento, CA.

Granssle, D. 1966. Fishes and Decapods of San Pablo and Suisun Bays. In D. W. Kelley (ed.). *Ecological Studies of the Sacramento–San Joaquin Estuary, Part I: Zooplankton, Zoobenthos, and Fishes of San Pablo and Suisun Bays, Zooplankton and Zoobenthos of the Delta*. *Fish Bulletin* 133.

Hatfield, S. 1985. Seasonal and interannual variation in distribution and population abundance of the shrimp *Crangon franciscorum* in San Francisco Bay. *Hydrobiologia* 129:199–210.

Hennessy, A. 2009. Zooplankton monitoring 2008. *Interagency Ecological Program for the Sacramento–San Joaquin Estuary Newsletter* 22(2):10–16.

Hieb, K. 1999. Caridean Shrimp. In J. Orsi (ed.). *Report on the 1980–1995 Fish, Shrimp, and Crab Sampling in the San Francisco Estuary, California*. Technical Report 63. Prepared for the Interagency Ecological Study Program for the Sacramento–San Joaquin Estuary.

Hieb, K. 2008. 2007 Shrimp annual status and trends report for the San Francisco Estuary. *Interagency Ecological Program for the Sacramento–San Joaquin Estuary Newsletter* 21(2):22–26.

Heubach, W., R. Toth, and A. McCready. 1963. Food of young of the year striped bass (*Roccus saxatilis*) in the Sacramento–San Joaquin River system. *California Department of Fish and Game* 49:224–239.

Jassby, A. D., W. J. Kimmerer, S. G. Monismith, C. Armor, J. E. Cloern, T. M. Powell, J. R. Schubel, and T. J. Vendlinski. 1995. Isohaline position as a habitat indicator for estuarine populations. *Ecological Applications* 5(1):272–289.

Johnson, W. C., and A. J. Calhoun. 1952. Food habits of California striped bass. *California Department of Fish and Game* 38:531–533.

Kimmerer, W. J. 2002. Effects of freshwater flow on abundance of estuarine organisms: Physical effects or trophic linkages? *Marine Ecology Progress Series* 243:39–55.

Kimmerer, W. J., E. S. Gross, and M. L. MacWilliams. 2009. Is the response of estuarine nekton to freshwater flow in the San Francisco Estuary explained by variation in habitat volume? *Estuaries and Coasts* 32:375–389.

Krygier, E. E., and H. F. Horton. 1975. Distribution, reproduction and growth of *Crangon nigricauda* and *Crangon franciscorum* in Yaquina Bay, Oregon. *Northwest Science* 49:216–240.

McKechnie, R. J., and R. B. Fenner. 1971. Food habits of white sturgeon, *Acipenser transmontanus*, in San Pablo and Suisun Bays, California. *California Department of Fish and Game* 57:209–212.

Moyle, P. B. 2002. *Inland Fishes of California*. Berkeley, CA: University of California Press.

Rathbun, M. J. 1904. Decapod crustaceans of the northwest coast of North America. *Harriman Alaska Expedition* 10:1–190.

Reilly, P., K. Walters, and D. Richardson. 2001. Bay Shrimp. In W. S. Leet, C. M. Dewees, R. Klingbeil, and E. J. Larson (eds.). *California's Living Marine Resources: A Status Report*. Richmond, CA: University of California Press.

Siegfried, C. A. 1982. Trophic relations of *Crangon franciscorum* Stimpson and *Palaemon macrodactylus* Rathubun: Predation on the opossum shrimp *Neomysis mercedis* Holmes. *Hydrobiologia* 89:129–139.

Siegfried, C. A. 1989. *Species Profiles: Life Histories and Environmental Requirements of Coastal Fishes and Invertebrates (Pacific Southwest), Crangonid Shrimp*. Biological Report. December. Slidell, LA: U.S. Fish and Wildlife Service, National Wetlands Research Center.

Siegfried, C. A., M. E. Kopache, and A. W. Knight. 1979. The distribution and abundance of *Neomysis mercedis* in relation to the entrapment zone in the western Sacramento–San Joaquin Delta. *Transactions of the American Fisheries Society* 108:262–270.

State Water Resources Control Board (State Water Board) 2010. Development of Flow Criteria for the Sacramento–San Joaquin Delta Ecosystem. Final. August 3. Sacramento, CA. http://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/deltaflow/docs/final_rpt080310.pdf

The Bay Institute. 2010. Written testimony of Jonathan Rosenfield, Ph.D., and Christina Swanson, Ph.D. Regarding flow criteria for the Delta necessary to protect public trust resources: Delta outflows. Exhibit TBI-2.

Wahle, R. A. 1985. The feeding ecology of *Crangon franciscorum* and *Crangon nigricauda* in San Francisco Bay, California. *Journal of Crustacean Biology* 5(2):311–326.

6.3.10 Zooplankton

Bennett, W., W. Kimmerer, and J. Burau. 2002. Plasticity in vertical migration by native and exotic estuarine fishes in a dynamic low-salinity zone. *Limnology and Oceanography* 47(5):1496–1507.

Bennett, W. 2005. Critical assessment of the delta smelt population in the San Francisco Estuary, California. *San Francisco Estuary and Watershed Science* 3(2):1–71.

California Department of Fish and Game (CDFG). 1987. Long-term trends in zooplankton distribution and abundance in the Sacramento–San Joaquin Estuary. State Water Resources Control Board 1987 Water Quality and Water Rights Proceedings on the San Francisco Bay and Sacramento–San Joaquin Delta. WRINT-DFG-EXHIBIT 28.

California Department of Fish and Game (CDFG). 2010. *Quantifiable Biological Objectives and Flow Criteria for Aquatic and Terrestrial Species of Concern Dependent on the Delta*. Draft. September 21. Sacramento, CA: California Department of Fish and Game, Water Branch.

Durand, J. R. 2010. *Determinants of Seasonal Abundance in Key Zooplankton of the San Francisco Estuary*. M.S. thesis. San Francisco State University. San Francisco, CA.

Durand, J. R. 2015. A conceptual model of the aquatic food web of the Upper San Francisco Estuary. *San Francisco Estuary and Watershed Science* 13(3): Article 5.

Feyrer, F., B. Herbold, S. A. Matern, and P. B. Moyle. 2003. Dietary shifts in a stressed fish assemblage: Consequences of a bivalve invasion in the San Francisco Estuary. *Environmental Biology of Fishes* 67(3):277–288.

Hennessy, A. 2009. Zooplankton monitoring 2008. *Interagency Ecological Program for the Sacramento–San Joaquin Estuary Newsletter* 22(2):10–16. http://www.water.ca.gov/iep/products/newsletterPrevious.cfm.

Hennessy, A., and T. Enderlein. 2013. Zooplankton monitoring 2011. *Interagency Ecological Program for the Sacramento–San Joaquin Estuary Newsletter* 26(4):16–30.

Kimmerer, W. J. 2002. Effects of freshwater flow on abundance of estuarine organisms: Physical effects or trophic linkages? *Marine Ecology Progress Series* 243:39–55.

Kimmerer, W. J. 2004. Open water processes of the San Francisco Estuary: From physical forcing to biological responses. *San Francisco Estuary and Watershed Science* 2(1):Article 1. http://repositories.cdlib.org/jmie/sfews/vol2/iss1/art1

Kimmerer, W. J. 2006. Response of anchovies dampens effects of the invasive bivalve *Corbula amurensis* on the San Francisco Estuary foodweb. *Marine Ecology Progress Series* 324:207–218.

Kimmerer, W. J., J. R. Burau, and W. A. Bennett. 1998. Tidally oriented vertical migration and position maintenance of zooplankton in a temperate estuary. *Limnology and Oceanography* 43(7): 1697–1709.

Kipp, R. M., A. J. Benson, J. Larson, T. H. Makled, and A. Fusaro. 2013. *Eurytemora affinis*. Nonindigenous Aquatic Species Database. U.S. Geological Survey. Last revised: June 20, 2013. Available: http://nas.er.usgs.gov/queries/factsheet.aspx?SpeciesID=178.

Kratina, P., R. Mac Nally, W. J. Kimmerer, J. R. Thomson, and M. Winder. 2014. Human-induced biotic invasions and changes in plankton interaction networks. *Journal of Applied Ecology* 51(4):1066–1074.

Lott, J. 1998. Feeding habits of juvenile and adult delta smelt from the Sacramento–San Joaquin River Estuary. *Interagency Ecological Program for the Sacramento–San Joaquin Estuary Newsletter* 11(1):14–19.

Orsi, J. J., and A. C. Knutson. 1979. An extension of the known range of *Neomysis mercedis*, the opossum shrimp. *California Fish and Game* 65:127–130.

Orsi, J. J., and W. L. Mecum. 1996. Food Limitation as the Probable Cause of a Longterm Decline in the Abundance of *Neomysis mercedis* the Opossum Shrimp in the Sacramento–San Joaquin Estuary. In J. T. Hollibaugh (ed.). *San Francisco Bay: The Ecosystem*. San Francisco, CA: American Association for the Advancement of Science.

Orsi, J. J., and S. Ohtsuka. 1999. Introduction of the Asian copepods *Acartiella sinensis*, *Tortanus dextrilobatus* (Copepoda: Calanoida), and *Limnoithona tetraspina* (Copepoda: Cyclopoida) to the San Francisco Estuary, California, USA. *Plankton Biology and Ecology* 46(2):128–131.

Siegfried, C. A., and M. E. Kopache. 1980. Feeding of *Neomysis mercedis* (Holmes). *Biological Bulletin* 159:193–205.

Teh, S., S. Lesmeister, and B. G. Hammock. 2013. The Acute and Chronic Effects of Pesticides on the Calanoid copepods, *Eurytemora affinis* and *Pseudodiaptomus forbesi*, of the San Francisco Estuary. Final. June 30. Davis, CA. Prepared for California Department of Pesticide Regulation, Sacramento, CA.

Winder, M., and A. D. Jassby. 2011. Shifts in zooplankton community structure: Implications for food web processes in the Upper San Francisco Estuary. *Estuaries and Coasts* 34:675–690.

Winder, M., A. D. Jassby, and R. Mac Nally. 2011. Synergies between climate anomalies and hydrological modifications facilitate estuarine biotic invasions. Ecology Letters 14(8):749–757.

6.3.11 Non-Native Species

Dill, W. A., and A. J. Cordone. 1997. History and Status of Introduced Fishes in California, 1871–1996. *Fish Bulletin* 178.

Herbold, B., A. D. Jassby, and P. B. Moyle. 1992. *Status and Trends Report on Aquatic Resources in the San Francisco Estuary*. San Francisco Estuary Project. March.

Kimmerer, W. J. 2002. Effects of freshwater flow on abundance of estuarine organisms: Physical effects or trophic linkages? *Marine Ecology Progress Series* 243:39–55.

Kimmerer, W. J., E. S. Gross, and M. L. MacWilliams. 2009. Is the response of estuarine nekton to freshwater flow in the San Francisco Estuary explained by variation in habitat volume? *Estuaries and Coasts* 32:375–389.

MacKenzie, C., L. S. Weiss-GLanz, and J. R. Moring. 1985. *Species Profiles: Life Histories and Environmental Requirements of Coastal Fishes and Invertebrates (Mid-Atlantic). American Shad*. Biological Report 82(1137). April. Lafayette, LA: U.S. Fish and Wildlife Service, National Wetlands Research Center. Prepared for the U.S. Fish and Wildlife Service and Coastal Ecology Group Waterways Experiment Station.

Moyle, P. B. 2002. *Inland Fishes of California, Revised and Expanded*. Berkeley: University of California Press.

Skinner, J. E. 1962. *A Historical Review of the Fish and Wildlife Resources of the San Francisco Bay Area*. Water Projects Branch Report No. 1. June. Prepared for the California Department of Fish and Game, Water Projects Branch.

Sommer, T., C. Armor, R. Baxter, R. Breuer, L. Brown, M. Chotkowski, S. Culberson, F. Feyrer, M. Gingras, B. Herbold, W. Kimmerer, A. Mueller-Solger, M. Nobriga, and K. Souza. 2007. The collapse of pelagic fishes in the upper San Francisco Estuary. *Fisheries* 32(6):270–277.

Stevens, D. E., H. K. Chadwick, and R. E. Painter. 1987. American shad and striped bass in California's Sacramento–San Joaquin River System. In M. J. Dadswell, R. J. Klauda, C. M. Moffitt, R. L. Saunders, R. A. Rulifson, and J. E. Cooper (eds.). *Common Strategies of Anadromous and Catadromous Fish*. Bethesda, MD: American Fisheries Society.

Urquhart, K. 1987. Association between Factors and the Abundance and Distribution of Resident Fisheries in the Sacramento–San Joaquin Delta. CDFG Exhibit 24. SWRCB 1987 Water Quality/Water Rights Proceedings for the San Francisco Bay/Sacramento–San Joaquin Delta. Sacramento, CA.

Wang, J. 1986. *Fishes of the Sacramento–San Joaquin Estuary and Adjacent Waters, California: A Guide to the Early Life Histories*. Interagency Ecological Program Technical Report 9.

6.3.12 Conclusion

California Department of Fish and Wildlife. (CDFW). 2010.

National Marine Fisheries Service (NMFS). 2009. *Biological Opinion and Conference Opinion on the Long-Term Operations of the Central Valley Project and State Water Project*. June 4. Endangered Species Act Section 7 Consultation. Southwest Region.

National Marine Fisheries Service (NMFS). 2014. *Recovery Plan for the Evolutionarily Significant Units of Sacramento River Winter-Run Chinook Salmon and Central Valley Spring-Run Chinook Salmon and the Distinct Population Segment of California Central Valley Steelhead*. Appendix A, Central Valley watershed profiles. California Central Valley area office. July.

State Water Resources Control Board (State Water Board). 2010. *Development of Flow Criteria for the Sacramento-San Joaquin Delta Ecosystem*. August 3, 2010.

U.S. Fish and Wildlife Service (USFWS). 1995.

U.S. Fish and Wildlife Service (USFWS). 2008. *Formal Endangered Species Act Consultation on the Proposed Coordinated Operations of the Central Valley Project (CVP) and State Water Project (SWP)*. Sacramento, CA.

6.4 Chapter 4, Other Aquatic Ecosystem Stressors

Atwater, B. F., S. F. Conrad, J. N. Dowden, C. W. Hedel, R. L. MacDonald, and W. Savage. 1979. History, landforms, and vegetation of the estuary's tidal marshes. In T. J. Conomos (ed.). *San Francisco (CA): San Francisco Bay, the Urbanized Estuary*. American Association for the Advancement of Science. pp. 347–385.

Austin, B., J. Rayment, and D. J. Alderman. 1983. Control of furunculosis by oxolinic acid. *Aquaculture* 31:101–108.

Baginska, B. 2015. *Total Maximum Daily Load of Selenium in North San Francisco Bay*. Staff report for Proposed Basin Plan Amendment for the California Regional Water Quality Control Board, San Francisco Bay Region. November 18. Oakland, CA.

Baskerville-Bridges, B., J. Lindberg, and S. I. Doroshov. 2004. The effect of light intensity, alga concentration, and prey density on the feeding behavior of delta smelt larvae. *American Fisheries Society Symposium* 39:219–227.

Baxter, R., R. Breuer, L. Brown, M. Chotkowski, F. Feyrer, M. Gingras, B. Herbold, A. Mueller-Solger, M. Nobriga, T. Sommer, and K. Souza. 2008. *Pelagic Organism Decline Progress Report: 2007 Synthesis of Results.* January 15.

Baxter, R., M. L. Nobriga, S. B. Slater, and R. W. Fujimura. 2009. *Effects Analysis: State Water Project Effects on Longfin Smelt*. California Department of Fish and Game report. February.

Bennett, W. A. 2005. The population ecology of delta smelt in the San Francisco estuary. *San Francisco Estuary and Watershed Science* 3(2):1–71.

Berg, M., and M. Sutula. 2015. *Factors Affecting the Growth of Cyanobacteria with Special Emphasis on the Sacramento–San Joaquin Delta*. Southern California Coastal Water Research Project. Technical Report 869. August.

Bishop, M. J., and M. G. Chapman. 2004. Managerial decisions as experiments: An opportunity to determine the ecological impact of boat-generated waves on macrobenthic in fauna. *Estuarine, Coastal and Shelf Science* 61(4):613–622.

Bonneville Power Administration (BPA). 2010. *Predator Control Helps Salmon*. DOE/BP-4172. September.

Bouley, P., and W. J. Kimmerer. 2006. Ecology of a highly abundant, introduced cyclopoid in a temperate estuary. *Marine Ecology Progress Series* 324:219–228.

Boyer, K., and M. Sutula. 2015. *Factors controlling submersed and floating macrophytes in the Sacramento–San Joaquin Delta*. Southern California Coastal Water Research Project. Technical Report 870. Costa Mesa, CA.

Brager, L. M., P. J. Cranford, J. Grant, and S. M. C. Robinson. 2015. Spatial distribution of suspended particulate wastes at open-water Atlantic salmon and sablefish aquaculture farms in Canada. *Agriculture Environment Interactions* 6:135–149.

Brander, S. M., R. E. Connon, G. He, J. A. Hobbs, K. L. Smalling, S. J. Teh, J. W. White, I. Werner, M. S. Denison, and G. N. Cherr. 2013. From 'Omics to Otoliths: Responses of an estuarine fish to endocrine disrupting compounds across biological scales. PLoS ONE 8(9):e74251.

Brown, L. R. and M. L. Bauer. 2009. Effects of hydrologic infrastructure on flow regimes of California's central Valley rivers: implications for fish populations. *River Research and Applications*. 26(6):751–765.

Brown, L.R. and J.T. May. 2006. Variation in Spring Nearshore Resident Fish Species Composition and Life Histories in the Lower Sacramento-San Joaquin Watershed and Delta. San Francisco Estuary Watershed and Science 4(2).

Brown, L. R., and D. Michniuk. 2007. Littoral fish assemblages of the alien-dominated Sacramento–San Joaquin Delta, California, 1980–1983 and 2001–2003. *Estuaries and Coasts* 30(1):186–200.

Brown, T. 2010. Phytoplankton community composition: The rise of the flagellates. *IEP Newsletter* 23(2):9–13

Busby, S., R. Grant, R. Iwamoto C. Kope, G. Mahnken, J. Matthews, P. Myers, M. Roni, D. Schiewe, T. Teel, F. W. Wainwright, R. Waknitz, J. Waples, G. Williams, C. Bryant, S. Wingert, P. Lindley, A. Adams, R. Wertheimer, and R. Reisenbichler. 1998. *Review of the status of Chinook salmon (O. tshawytscha) from Washington, Oregon, California, and Idaho under the U.S. Endangered Species Act.* West Coast Salmon Biological Review Team report, joint National Marine Fisheries Service Northwest, Southwest, and Alaska Fisheries Science Centers. December 17.

California Department of Boating and Waterways (CDWB). 2006. Egeria densa *Control Program: Second Addendum to 2001 Environmental Impact Report with Five-Year Program Review and Future Operations Plan*. December 8. Sacramento, CA.

California Department of Fish and Game (CDFG). 2011. *A Report to the California Fish and Game Commission on Stressors Impacting Delta Related Organisms*.

California Department of Fish and Wildlife (CDFW). 2016. *2016–2017 California Freshwater Sport Fishing Regulations.*

California Department of Parks and Recreation, Division of Boating and Waterways (CDBW). 2014. *Frequently Asked Questions: Water Hyacinth* Available: http://dbw.ca.gov/PDF/WHCP/FAQ_Water_Hyacinth_2014-12-08-14_FINAL.pdf.

California Department of Water Resources (DWR). . 2008. *Managing an Uncertain Future: Climate Change Adaptation Strategies for California's Water*. Sacramento, CA.

California Department of Water Resources (DWR). 2013. *California Water Plan Update 2013*. Available: http://www.water.ca.gov/waterplan/cwpu2013/final/index.cfm.

California Department of Water Resources (DWR). 2016. *Suisun Marsh Program*. Available: http://www.water.ca.gov/suisun/facilities.cfm.

Carlton, J. T., J. K. Thompson, L. E. Schemel, and F. H. Nichols. 1990. Remarkable invasion of San Francisco Bay (California, USA) by the Asian clam *Potamocorbula amurensis*. Displacement of a former community. *Marine Ecology Progress Series* 66:81–94.

Central Valley Regional Water Quality Control Board (CVRWQCB). 2014. *Charge to Macrophyte Science Work Group*. Available:http://www.waterboards.ca.gov/centralvalley/water_issues/delta_water_quality/delta_nutrient_research_plan/science_work_groups/macro_swg_charge.pdf.

Chapman, P., W. Adams, M. Brooks, C. Delos, S. Luoma, W. Haher, H. Ohlendorf, T. Presser, and D. Shaw. 2009. *Ecological Assessment of Selenium in the Aquatic Environment.* Summary of a SETAC Pellston Workshop. 22–28 February. Pensacola, Florida..

Chernoff, B. J., J. V. Conner, and C. F. Bryan. 1981. Systematics of *Menidia beryllina* complex (*Pisces: Atherinidae*) from the Gulf of Mexico and its tributaries. *Copeia* 1981:319–335.

Churchill, R. 2000. *Contributions of mercury to California's environment from mercury and goldmining activities— Insights from the historical record*. Manuscript and slides for oral conference presentation at: Assessing and Managing Mercury from Historic and Current Mining Activities, November 28–30. San Francisco, CA. Sponsored by the U.S. Environmental Protection Agency, Office of Research and Development.

Clements, W. H., and J. R. Rohr. 2009. Community Responses to Contaminants: Using Basic Ecological Principles to Predict Ecotoxicological Effects. *Environmental Toxicology and Chemistry* 28(9):1789–1800.

Cohen, A. N., and J. T. Carlton. 1995. *Nonindiginous Aquatic Species in a United States Estuary: A Case Study of the Biological Invasions of the San Francisco Bay and Delta*. A report for the United States Fish and Wildlife Service, Washington, D.C., and the National Sea Grant College Program Connecticut Sea Grant. December. Available: http://nsgl.gso.uri.edu/conn/connt95002/connt95002main.pdf.

Colorado Parks and Wildlife. 2015. *Whirling Disease and Trout*. Available: http://cpw.state.co.us/learn/Pages/WhirlingDisease.aspx.

Connor, M. S., J. A. Davis, J. Leatherbarrow, B. K. Greenfield, A. Gunther, D. Hardin, T. Mumley, J. J. Orama, and C. Werme. 2007. The slow recovery of San Francisco Bay from the legacy of organochlorine pesticides. *Environmental Research* 105:87–100.

Conrad, J. L., E. Wells, R. Baxter, A. Bever, L. Brown, G. Castillo, S. Culberson, M. Dekar, M. Eakin, G. Erickson, J. Hobbs, K. Jones, S. Lesmeister, M. MacWilliams, S. Slater, T. Sommer, S. Tharratt. 2016. *Does the Delta have a "Drought Syndrom?" Synthesizing a Picture of Drought from 14 IEP Datasets*. Interagency Ecological Program presentation.

Cowen, L., N. Trouton, and R. E. Bailey. 2007. Effects of Angling on Chinook Salmon for the Nicola River, British Columbia, 1996–2002. *North American Journal of Fisheries Management* 27:256–267.

Davis, J. A., F. Hetzel, J. J. Oram, L. J. McKee. 2007. Polychlorinated biphenyls (PCBs) in San Francisco Bay. *Environmental Research* 105(1):67–86.

Davis, J. A., J. R. M. Ross, S. N. Bezalel, J. A. Hunt, G. Ichikawa, A. Bonnema, W. A. Heim, D. Crane, S. Swenson, and C. Lamerdin. 2013. *Contaminants in Fish from California Rivers and Streams, 2011*. A Report of the Surface Water Ambient Monitoring Program (SWAMP). California State Water Resources Control Board, Sacramento, CA.

Delta Stewardship Council (DSC). 2013. The Delta Plan: Ensuring a reliable water supply for California, a healthy Delta ecosystem, and a place of enduring value. Sacramento, CA. Available: http://deltacouncil.ca.gov/delta-plan-0.

De Vlaming, V. 2008. *Organochlorine Pesticides and Polychlorinated Biphenyls (PCB) concentrations in muscle tissue of fish collected from the San Joaquin River and Sacramento River Watersheds and Delta during 2005*. Prepared for the Regional Water Quality Control Board, Central Valley Region.

Dill, W. A., and A. J. Cordone. 1997. History and Status of Introduced Fishes in California, 1871–1996. *Fish Bulletin* 178.

Dugdale, R. C., F. P. Wilkerson, V. E. Hogue, A. Marchi. 2007. The role of ammonium and nitrate in spring bloom development in San Francisco Bay. *Estuarine, Coastal and Shelf Science* 73:17–29.

Ecosystem Restoration Program (ERP). 2014. *Conservation Strategy for Restoration of the Sacramento–San Joaquin Delta, Sacramento Valley and San Joaquin Valley Regions*. May. Available: https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=31232.

Emmett, R. L., S. L. Stone, S. A. Hinton, and M. E. Monaco. 1991. *Distribution and abundance of fishes and invertebrates in west coast estuaries*. Volume II: Species life history summaries. ELMR Report 8. NOAA/NOS Strategic Environmental Assessments Division, Rockville, MD.

Evans, D. H., and J. B. Claiborne. 2006. *Physiology of Fishes.* Third Edition. Boca Raton, FL: Taylor and Francis Group, LLC.

Fausch, K. D., C. E. Torgersen, C. V. Baxter, and H. Li. 2002. Landscapes to riverscapes: Bridging the gap between research and conservation of stream fishes. *Bioscience* 52(6):483–498.

Ferrari, M. C. O., L. Ranaker, K. L. Weinersmith, M. J. Young, A. Sih, and J. L. Conrad. 2013. Effects of turbidity and an invasive waterweed on predation by introduced largemouth bass. *Environmental Biology of Fishes* 97(1):79–90.

Feyrer, F., B. Herbold, S. A. Matern, and P. B. Moyle. 2003. Dietary shifts in a stressed fish assemblage: Consequences of a bivalve invasion in the San Francisco Estuary. *Environmental Biology of Fishes* 67(3):277–288.

Feyrer, F., K. Newman, M. Nobriga, and T. Sommer. 2011. Modeling the effects of future outflow on the abiotic habitat of an imperiled estuarine fish. *Estuaries Coasts* 34(1):120–128.

Feyrer, F., M. L. Nobriga, and T. R. Sommer. 2007. Multi-Decadal Trends for Three Declining Fish Species: Habitat Patterns and Mechanisms in the San Francisco Estuary, California, USA. *Canadian Journal of Fisheries and Aquatic Science* 64:723–734.

Fisch, K. M., B. Mahardja, R. S. Burton, and B. May. 2014. Hybridization between delta smelt and two other species within the family *Osmeridae* in the San Francisco Bay-Delta. *Conservation Genetics* 15(2):489–494.

Gehrke, P. C. 1991. Implications of water quality for larval fish metabolism, activity and growth in extensive rearing conditions. *Bureau of Rural Resources Proceedings* 15:84–87.

Glibert, P., D. Fullerton, J. Burkholder, J. Cornwell, and T. Kana. 2011. Ecological stoichiometry, biogeochemical cycling, invasive species and aquatic food webs: San Francisco Estuary and comparative systems. *Reviews in Fisheries Science* 19(4):358–417.

Golet, G. H., M. D. Roberts, R. A. Luster, G. Werner, E. W. Larsen, R. Unger, G. G. White. 2006. Environmental Assessment: Assessing Societal Impacts when planning restoration of large Alluvia Rivers: A case study of the Sacramento River Project, CA*. Environmental Management* 37(6):862–879.

Greene, V. E., L. J. Sullivan, J. K. Thompson, W. J. Kimmerer. 2011. Grazing Impact of the Invasive Clam *Corbula amurensis* on the microplankton assemblage of the Northern San Francisco Estuary. *Marine Ecology Progress Series* 431:183–193.

Grenier, L., A. Gunther, L. Grenier, A. Robinson, J. Lowe, J. Bourgeois, W. Kimmerer, M. Latta, J. Collins, D. Ball, N. Nur, B. Herbold, J. Callaway, S. Crooks. 2015. *The Baylands and* C*limate Change: What We Can Do*. California State Coastal Conservancy: Baylands Ecosystem Habitat Project Goals Science Update. Available: http://baylandsgoals.org/.

Grimaldo, L. F., T. Sommer, N. V. Ark, G. Jones, E. Holland, P. B. Moyle, B. Herbold, and P. Smith. 2009. Factors affecting fish entrainment into massive water diversions in a tidal freshwater estuary: Can fish losses be managed? *North American Journal of Fisheries Management* 29:1253–1270.

Grossman, G. D., T. Essington, B. Johnson, J. Miller, N. E. Monsen, and T. N. Pearsons. 2013. *Effects of fish predation on salmonids in the Sacramento River–San Joaquin Delta and associated ecosystems*. September 25. Available: https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=73874.

Hallock, R. J., R. F. Elwell, D. H. Fry, Jr. 1970. Migrations of adult king salmon *Oncorhynchus tshawytscha* in the San Joaquin Delta as demonstrated by the use of sonic tags. *Fish Bulletin* 151:1–42.

Hasenbein, M., L. M. Komoroske, R. E. Connon, J. Geist, and N. Fangue. 2012. Turbidity and salinity affect feeding performance and physiological stress in the endangered delta smelt. *Integrative and Comparative Biology* 53(4):620–634.

Healey, M, M. Dettinger, R. Norgaard, D. Jones, and R. Ullrey. 2008. *The State of Bay-Delta Science 2008 Summary for Policymakers and the Public November 2007*. CALFED Science Program report. Available: http://science.calwater.ca.gov/pdf/publications/sbds/sbds_2008_summary_011808.pdf.

Hooff, R. C., and S. M. Bollens. 2004. Functional response and potential predatory impact of *Tortanus dextrilobatus*, a carnivorous copepod recently introduced to the San Francisco Estuary. *Marine Ecology Progress Series* 277:167–179.

ICF International. 2012. *Administrative Draft Environmental Impact Report/Environmental Impact Statement for the Bay Delta Conservation Plan (BDCP).* February. Prepared for California Department of Water Resources and U.S. Bureau of Reclamation. Sacramento, CA. Available: http://baydeltaconservationplan.com/Library/ArchivedDocuments/EIREISDocuments_2012Draft.asp.

Intergovernmental Panel on Climate Change (IPCC). 2001. *Climate change 2001: Scientific basis*. In B. Metz B et al. (eds.). *Contribution of working group III to the third assessment report of the Intergovernmental Panel on Climate Change*. Cambridge: University Press.

Jacoby, J. M., D. C. Collier, E. B. Welch, F. J. Hardy, and M. Crayton. 2000. Environmental factors associated with a toxic bloom of *Microcystis aeruginosa*. *Canadian Journal of Fisheries and Aquatic Science* 57:231–240.

Jassby, A. D. 2008. Phytoplankton in the upper San Francisco Estuary: Recent biomass trends, their causes and their trophic significance. *San Francisco Estuary and Watershed Science* 6(1).

Jassby, A. D., J. E. Cloern, and B. E. Cole. 2002. Annual primary production: Patterns and mechanisms of change in a nutrient-rich tidalecosystem. *Limnology and Oceanography* 47(3):698–712.

Jassby, A. D., W. J. Kimmerer, S. G. Monismith, C. Armor, J. E. Cloern, T. M. Powell, J. R. Schubel, and T. J. Vendlinski. 1995. Isohaline position as a habitat indicator for estuarine application. *Ecological Applications* 5:272–289.

Jassby, A. D., A. B. Mueller-Solger, and M. Vaysierres. 2005. Subregions of the Sacramento–San Joaquin Delta: Identification and use. Interagency Ecological Program Newsletter 18(2):45–56.

Jeffres, C. A., J. J. Opperman, and P. B. Moyle. 2008. Ephemeral floodplain habitats provide best growth conditions for juvenile Chinook salmon in a California river. *Environmental Biology of Fishes* 83:449–458.

Kammerer, B. D., and S. A. Heppell. 2012. Individual condition indicators of thermal habitat quality in field populations of redband trout (*Oncorhynchus mykiss* gairdneri). *Environmental Biology Fishes* 96:823–835.

Kiernan, J. D. 2012. Restoring native fish assemblages to a regulated California stream using the natural flow regime concept. *Ecological Applications* 22(5):1472–1482.

Kimmerer, W. 1992. *An evaluation of existing data in the entrapment zone of the San Francisco Bay Estuary*. Technical Report 33, Interagency Ecological Studies Program for the Sacramento–San Joaquin Estuary, California Department of Water Resources, Sacramento, CA.

Kimmerer, W. J. 2004. Open Water Processes of the San Francisco Estuary: From Physical Forcing to Biological Responses. *San Francisco Estuary and Watershed Science* 2(1).

Kimmerer, W. J., J. R. Burau, and W. A. Bennett. 1998. Tidally oriented vertical migration and position maintenance of zooplankton in a temperate estuary. *Limnology and Oceanography 43*(7):1697–1709.

Kimmerer, W. J., E. S. Gross, and M. L. MacWilliams. 2009. Is the response of estuarine nekton to freshwater flow in the San Francisco Estuary explained by variation in habitat volume? *Estuaries and Coasts* 32:375–389.

Knight, R. L., and D. N., Cole. 1991. Effects of Recreational Activity on Wildlife. *Transactions of the 56th North American Wildlife and Natural Resources Conference*. pp. 238–247.

Knowles, N., and D. R. Cayan. 2002. Potential effects of global warming on the Sacramento/San Joaquin watershed and the San Francisco estuary. *Geophysical Research Letters* (29)18:38-1–38-4.

Knowles, N., and D. R. Cayan. 2004. Elevational dependence of projected hydrologic changes in the San Francisco Estuary and Watershed. *Climate Change* 62:319–336.

Knowles, N., M. D. Dettinger, and D. R. Cayan. 2006. Trends in snowfall vs. rainfall in the Western United States. *Journal of Climate* (19):4545–4559.

Komoroske, L. M., R. E. Connon, J. Lindberg, B. S. Cheng, G. Castillo, M. Hasenbein, and N. A. Fangue. 2014. Ontogeny influences sensitivity to climate change stressors in an endangered fish. Conservation Physiology 2(1).

Kramer, V. L., R. Garcia, and A. E. Colwell. 1987. An evaluation of the mosquitofish, *Gambusiz affinis,* and the inland silverside, *Menidia beryllina*, as mosquito control agents in California wild rice fields. *Journal of the American Mosquito Control Association* 3(4):626–632.

Kuivila, K. M., and G. E. Moon. 2004. Potential exposure of larval and juvenile delta smelt to dissolved pesticides in the Sacramento–San Joaquin Delta, California. *American Fisheries Society Symposium* 39:229–241.

Lehman, P. 1998. *Phytoplankton species composition, size structure and biomass and their possible effect on copepod food availability in the low salinity zone of the San Francisco Bay/Delta and Suisun Bay*. IEP Technical Report 62. August. Prepared for the Interagency Ecological Program for the San Francisco Bay/Delta Estuary. Sacramento, CA.

Lehman, P. W., G. Boyer, C. Hall, S. Waller, and K. Gehrts. 2005. Distribution and toxicity of a new colonial *Microcystis aeruginosa* bloom in the San Francisco Bay Estuary, California. *Hydrobiologia* 541:87–99

Lehman, P. W., S. J. Teh, G. L. Boyer, M. L. Nobriga, E. Bass, and C. Hogle. 2010. Initial impacts of *Microcystis aeruginosa* blooms on the aquatic food web in the San Francisco Estuary. *Hydrobiologia* 637:229–248.

Lemly, A. 1985. Toxicology of selenium in a freshwater reservoir: Implications for environmental hazard evaluation and safety. *Ecotoxicology and Environmental Safety* 10:314–338.

Li, H., G. A. Lamberti, T. N. Pearsons, C. K. Tait, and J. L. Li. 1994. Cumulative effects of the riparian disturbances along high desert trout streams of the John Day Basin, Oregon. *Transactions of the American Fisheries Society* 123:627–640.

Lindegarth, M. 2001. Assemblages of animals around urban structures: Testing hypotheses of patterns in sediments under boat-mooring pontoons. *Marine Environmental Research* 51(4):289–300.

Lindley, S. T., R. S. Schick, E. Mora, P. B. Adams, J. J. Anderson, S. Greene, C. Hanson, B. P. May, D. R. McEwan, R. B. MacFarlane, C. Swanson, and J. G. Williams. 2007. Framework for assessing viability of threatened and endangered Chinook salmon and steelhead in the Sacramento–San Joaquin Basin. *San Francisco Estuary and Watershed Science* 5(1).

Lloyd, R. 1961. Effect of dissolved oxygen concentrations on the toxicity of several poisons to rainbow trout (*Salmo gairdnerii* Richardson). *Journal of Experimental Biology* 38:447–455.

Loboschefsky, E., G. Benigno, T. Sommer, K. Rose, T. Ginn, A. Massoudieh, and F. Loge. 2012. Individual-level and population-level historical prey demand of San Francisco Estuary striped bass using a bioenergetics model. *San Francisco Estuary and Watershed Science* 10(1):3–23.

Lucas, L. V., J. E. Cloern, J. K. Thompson, and N. E. Monsen. 2002. Functional Variability of Habitats within the Sacramento–San Joaquin Delta: Restoration Implications. *Ecological Applications* 12(5):1528–1547.

Marston, D., C. Mesick, A. Hubbard, D. Stanton, S. Fortmann-Roe, S. Tsao, and T. Heyne. 2012. Delta flow factors influencing stray rate of escaping adult San Joaquin River fall-run Chinook salmon (*O. mykiss*). *San Francisco Estuary and Watershed Science* 10(4).

Meng, L., and S. A. Matern. 2001. Native and introduced larval fishes of Suisun Marsh, California: The effects of freshwater flow. *Transactions of the American Fisheries Society* 130(5):750–765.

Meng, L., and J. J. Orsi. 1991. Selective predation by larval striped bass on native and introduced copepods. *Transactions of the American Fisheries Society* 120(2):187–192.

Mesick, C. F. 2001. *Factors that potentially limit the populations of fall-run Chinook salmon in the San Joaquin tributaries*. Stanislaus Fish Group, Stockton, CA.

Mirchi, A., K. Madani, M. Roos, and D. W. Watkins. 2013. Climate change impacts on California's water resources. In *Drought in Arid and Semi-Arid Regions*. Chapter 17, pp. 301–319.

Morgan, C. A., J. R. Cordell, and C. A., Simenstad. 1997. Sink or swim? Copepod population maintenance in the Columbia River estuarine turbidity-maxima region. *Marine Biology* 129:309–317.

Mount, J. F. 1995. *California Rivers and Streams: The Conflict between Fluvial Process and Land Use*. Berkeley: University of California Press. Available: https://www.amazon.com/California-Rivers-Streams-Conflict-Between/dp/0520202503#reader_0520202503.

Mount, J., W. Bennett, J. Durand, W. Fleenor, E. Hanak, J. Lund, and P. Moyle. 2012. *Aquatic Ecosystem Stressors in the Sacramento–San Joaquin Delta*. San Francisco: Public Policy Institute of California. pp. 1–22.

Mount, J., and R. Twiss. 2005. Subsidence, sea level rise, and seismicity in the Sacramento–San Joaquin Delta. San Francisco. *Estuary and Watershed Science* 3(1).

Moyle, P. B. 2002. *Inland Fishes of California, Revised and Expanded*. Berkeley: University of California Press.

Moyle, P. B., W. Bennett, J. Durand, W. Fleenor, B. Gray, E. Hanak, J. Lund, and J. Mount. 2012. *Where the wild things aren't: Making the Delta a better place for native species*. San Francisco: Public Policy Institute of California.

Moyle, P. B., W. Bennett, W. Fleenor, and J. Lund. 2010. Habitat variability and complexity in the Upper San Francisco Estuary. *San Francisco Estuary and Watershed Science* 8(3).

Moyle, P. B., and J. J. Cech, Jr. 2004. Fishes: An Introduction to Ichthyology. Fifth Edition. New York: Pearson Education.

Moyle, P., D. Manfree, and P. L. Fiedler. 2013. The future of Suisun Marsh: Balancing policy with change. *San Francisco Estuary and Watershed Science* 11(3):1–7.

Moyle, P. B. L. R. Brown, and J. A. Hobbs. 2016. Delta smelt: Life history and decline of a once-abundant species in the San Francisco Estuary. *San Francisco Estuary and Watershed Science* 14(2).

Myrick, C. A., and J. J. Cech, Jr. 2000.Temperature influences on California rainbow trout physiological performance. *Fish Physiology and Biochemistry* 22:245–254.

Myrick, C. A., and Cech, J. J., Jr. 2001. *Temperature effects on Chinook salmon and steelhead: A review focusing on California's Central Valley populations*. Bay-Delta Modeling Forum Technical Publication 01-1:1–57. Available: http://www.sfei.org/modelingforum/.

National Marine Fisheries Service (NMFS). 2009. *Biological Opinion and Conference Opinion on the Long-Term Operations of the Central Valley Project and State Water Project*. June 4. Endangered Species Act Section 7 Consultation. Southwest Region.

National Marine Fisheries Service (NMFS). 2014. Recovery plan for the evolutionarily significant units of Sacramento River winter-run Chinook salmon and Central Valley spring-run Chinook salmon and the distinct population segment of California Central Valley steelhead. West Coast Region, Sacramento, CA.

National Research Council (NRC). 2012. *Sustainable Water and Environmental Management in the California Bay-Delta*. Washington, D.C.: National Academy Press. Available: http://www.nap.edu/.

Newcomb, J., L. Pierce, and H. Spanglet. 2010. *Low Dissolved Oxygen Levels in the Stockton Deep Water Shipping Channel: Adverse Effects on Salmon and Steelhead and Potential Beneficial Effects of Raising Dissolved Oxygen Levels with the Aeration Facility*. October. Fish Passage Improvement Program and Flood Safe Environmental Stewardship and Statewide Resources Office, California Department of Water Resources.

Nichols, K., and J. S. Foot. 2002. Health monitoring of hatchery and natural fall-fun Chinook salmon juveniles in the San Joaquin River and tributaries, April–June 2001. U.S. Fish and Wildlife Service California-Nevada Fish Health Center, FY 2001 Investigational Report.

Nobriga, M. L., F. Feyrer, R. D. Baxter, and M. Chokowski. 2005. Fish community ecology in an altered river delta: Spatial patterns in species composition, Life history strategies, and biomass. *Estuaries* 28(5):776–785.

Nobriga, M. L., T. R. Sommer, F. Feyrer, and K. Fleming. 2008. Long-term trends in summertime habitat suitability for Delta Smelt (*Hypomesus transpacificus*). *San Francisco Estuary and Watershed Science* 6(1).

Novick, E., and D. Senn. 2013. *External nutrient loads to San Francisco Bay*. Draft. April 9. Prepared by the San Francisco Estuary Institute for the California Regional Water Quality Control Board, San Francisco Bay Region.

California Ocean Protection Council (OPC). 2011. *Resolution of the California Ocean Protection Council on Sea-Level Rise*. March. Available: http://www.opc.ca.gov/webmaster/ftp/pdf/docs/OPC_SeaLevelRise_Resolution_Adopted031111.pdf.

Office of Environmental Health Hazard Assessment (OEHHA). 2009. *Update of California Sport Fish Advisories*. California Environmental Protection Agency. March. Available: http://www.oehha.ca.gov/fish/so_cal/index.html.

Orsi, J. J., and S. Ohtsuka. 1999. Introduction to the Asian copepods *Acartiella sinensis*, *Tortanus dextrilobatus* (Copepoda: Calanoida), and *Limnoithona tetraspina* (Copepoda: Cyclopoidia) to the San Francisco Estuary, California, USA. *Plankton Biology and Ecology* 46(2):128–131.

O'Rear, T. A., and P. B. Moyle. 2009. Trends in Fish Populations of Suisun Marsh, Jan. 2008–Dec. 2008. California Department of Water Resources, Annual Report SAP 4600001965.

Parker, A, A. Marchi, J. Davidson-Drexel, R. Dugdale, and F. Wilkerson. 2010. *Effect of Ammonium and Wastewater Effluent on Riverine Phytoplankton in the Sacramento River, CA*. Final Report. Prepared for the California State Water Resources Control Board. Romberg Tiburon Center for Environmental Studies. San Francisco State University.

Quinn, T. P. 2005. The Behavior and Ecology of Pacific Salmon and Trout. American Fisheries Society. Bethesda, MD.

Rees, J. T., and L. A. Gershwin. 2000. Non-indigenous hydromedusae in California's upper San Francisco Estuary: Life cycles, distribution, and potential environmental impacts. *Science Marina* 64:73–86.

Roberts, W. G., J. G. Howe, and J. Major. 1980. A survey of riparian forest flora and fauna in California. In Sands, A. (ed). *Riparian Forests in California: Their Ecology and Conservation*. University of California, Davis Press, Institute of Ecology.

Rood, S. B., C. R. Gourley, E. M. Ammon, L. G. Heki, J. R. Klotz, M. L. Morrison, D. Mosley, G. G. Scoppetone, S. Swanson, and P. L. Wagner. 2003. Flows for floodplain forests: A successful riparian restoration. *Bioscience* 53(7):647–656.

Roos, M. 2005. Accounting for Climate Change. In *California Water Plan Update 2005 Volume 4, Reference Guide*: *Global Climate Change*. Sacramento, CA: Department of Water Resources.

Roos, M. 2012. *Snowpack and Snowmelt Changes*. January 3. Available: http://www.water.ca.gov/climatechange/docs/CP-Jan3-2012.pdf.

Sacramento-Yolo Mosquito and Vector Control District. 2014. *2014 Annual Report*. Elk Grove and Woodland, CA. Available: http://www.fightthebite.net/download/annualreport/AnnualReport2014.pdf.

Salinger, D. H., and J. J. Anderson. 2006. Effects of water temperature and flow on adult salmon migration swim speed and delay. *Transactions of the American Fisheries Society* 135:188–199.

San Francisco Regional Water Quality Control Board (SFRWQB). 2007. *Proposed amendment to the water quality control plan (Basin Plan) to establish a total maximum daily load (TMDL) for polychlorinated biphenyls (PCBs) in San Francisco Bay*. California Reporting, LLC. Board hearing transcripts. Available: http://www.waterboards.ca.gov/sanfranciscobay/board_decisions/adopted_orders/2008/R2-2008-0012.pdf.

San Joaquin River Restoration Program (SJRRP). 2015. *Floodplain production study*. Final 2015 Monitoring and Analysis Plan. January. Available: http://www.restoresjr.net/download/map/MAP_AppD_35_Floodpln-Prodctn_2015.0109.pdf.

Sarker, S., D. M. Kallert, R. P. Hedrick, and M. El-Matbouli. 2015. Whirling diseases revisited: Pathogenesis, parasite biology, and disease intervention. *Diseases of Aquatic Organisms* 114:155–175.

Schindler, D. E., J. R. Hodgson, and J. F. Kitchell. 1997. Density-dependent changes in individual foraging specialization of largemouth bass. *Oecologia* 110(4):592–600.

Schoellhamer, D. H. 2011. Sudden clearing of estuarine waters upon crossing the threshold from transport to supply regulation of sediment transport as an erodible sediment pool is depleted: San Francisco Bay, 1999. *Estuaries and Coasts* 34:885–899.

Schoellhamer, D. H., T. E. Mumley, and J. E. Leatherborrow. 2007. Suspended sediments and sediment-associated contaminants in San Francisco Bay. *Environmental Research* 105:119–131.

Scholz, N. L., M. S. Myers, S. G. McCarthy, J. S. Labenia, J. K. McIntyre, G. M. Ylitalo, L. D. Rhodes, C. A. Laetz, C. M. Stehr, B. L. French, B. McMillan,D. Wilson, L. Reed, K. D. Lynch, S. Damm, J. W. Davis, and T. K. Collier. 2011. Recurrent die-offs of adult coho salmon returning to spawn in Puget Sound lowland urban streams. *PLoS ONE* 6(12):e28013 (1–12).

Shingles, A., D. J. McKenzie, E. W. Taylor, A. Moretti, P. G. Butler, and S. Ceradini. 2001. Effects of sublethal ammonia exposure on swimming performance in rainbow trout (*Oncorhynchus mykiss*). *Journal of Experimental Biology* 204:2691–2698.

Singer, M. B. 2007. The influence of major dams on hydrology through the drainage network of the Sacramento River basin, California. *River Research and Applications* 23:55–72.

Slater, S., and R. Baxter. 2014. Diet, prey selection, and body conditions of age-0 delta smelt, *Hypomesus transpacificus*, in the upper San Francisco Estuary. *San Francisco Estuary and Watershed Science* 12(3).

Sommer, T., C. Armor, R. Baxter, R. Breuer, L. Brown, M. Chotkowski, S. Culberson, F. Feyrer, M. Gingras, B. Herbold, W. Kimmerer, A. Mueller-Solger, M. Nobriga, and K. Souza. 2007. The collapse of pelagic fishes in the upper San Francisco Estuary. *Fisheries* 32(6):270–277.

Spence, B. C, G. A. Lomnicky, R. M. Hughes, and R. P. Novitski. 1996. *An ecosystem approach to salmonid conservation*. TR-4501-96-6057. Corvalis, OR: ManTech Corp. Funded by National Marine Fisheries Service, U.S. Fish and Wildlife Service and the U.S. Environmental Protection Agency. Available: http://www.nwr.noaa.gov/1habcon/habweb/ManTech/front.htm#TOC.

State Water Resources Control Board (State Water Board). 1978. *Draft Environmental Impact Report for the Water Quality Control Plan for the Sacramento–San Joaquin Delta and Suisun Marsh*. Sacramento, CA.

State Water Resources Control Board (State Water Board). 2006. *Water Quality Control Plan for the San Francisco Bay/Sacramento–San Joaquin Delta Estuary*. December 13. Sacramento, CA. Available: http://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/wq_control_plans/2006wqcp/docs/2006_plan_final.pdf.

State Water Resources Control Board, San Francisco Regional Water Quality Control Board, and Central Valley Regional Water Quality Control Board (State Water Board, San Francisco Regional Water Board, and Central Valley Regional Water Board). 2014. *Delta Strategic Work Plan: Strategic Work Plan prepared for the California Regional Water Quality Control Board, Central Valley Region*. Available: http://www.waterboards.ca.gov/centralvalley/water_issues/delta_water_quality/strategic_workplan_baydelta/2014_delta_strategic_workplan.pdf.

Swanson, C., T. Reid,·P. S. Young, and J. J. Cech Jr. 2000. Comparative environmental tolerances of threatened delta smelt (*Hypomesus transpacificus*) and introduced wakasagi (*H. nipponensis*) in an altered California estuary. *Oecologia* 123:384–390.

Swanson, C., D. Baxa, P. S. Young, J. J. Cech, Jr., and R. P. Hedrick. 2002. Reduced swimming performance in delta smelt infected with Mycobacterium spp. *Journal of Fish Biology* 61(4):1012–1020.

Tetratech, Inc., and Wetlands and Water Resources. 2013. *Suisun Marsh Conceptual Model—Impairment Assessment Report for Organic Enrichment, Dissolved Oxygen, Mercury, Salinity and Nutrients*. November 26. Prepared for the San Francisco Bay Regional Water Quality Control Board.

Tucker, M. E., C. M. Williams, and R. R. Johnson. 1998. *Abundance, Food Habits and Life History Aspects of Sacramento Squawfish and Striped Bass at the Redd Bluff Diversion Complex, Including the Research Pumping Plant, Sacramento River, California, 1994–1996*. Red Bluff Research Pumping Plan Report Series, Volume 4. U.S. Fish and Wildlife Service, Red Bluff, CA.

U. S. Environmental Protection Agency (USEPA). 1997. *Mercury Study Report to Congress Vol. 7: Characterization of Human Health and Wildlife Risks from Mercury Exposure in the United States*. Office of Air Quality Planning and Standards and Office of Research and Development.

United Research Services Corporation (URS). 2007. Status and Trends of Delta-Suisun Services. May. Prepared for California Department of Water Resources. . Available: http://www.water.ca.gov/floodmgmt/dsmo/sab/drmsp/docs/Status_and_Trends-PRD.pdf.

U.S. Environmental Protection Agency (USEPA). 2013. Aquatic Life Ambient Water Quality Criteria for Ammonia–Freshwater. April. Office of Water, Office of Science and Technology: Washington, D.C.

U.S. Fish and Wildlife Service (USFWS). 1999. *Effects of temperature on early-life survival of Sacramento River fall and winter-run Chinook salmon*. Final report. Northern Central Valley Fish and Wildlife Office, Red Bluff, CA.

U.S. Fish and Wildlife Service (USFWS). 2001. *Final restoration plan for the Anadromous Fish Restoration Program: A plan to increase natural production of anadromous fish in the Central Valley of California*. Prepared for the Secretary of the Interior by the US Fish and Wildlife Services with the assistance of the Anadromous Fish Restoration Program Core Group. Stockton, CA.

U.S. Fish and Wildlife Service (USFWS). 2004. *Fish and Wildlife Office Mission*. Available: http://www.fws.gov/help/about_us.html.

USFWS. 2010.

Villamagna, A. M., and B. R. Murphy. 2010. Ecological and socio-economic impacts of invasive water hyacinth (*Eichhornia crassipes*): A review. *Freshwater Biology* 55(2):282–298.

Vogel, D. A., and K. R. Marine. 1991. *U.S. Bureau of Reclamation Central Valley Project: Guide to Upper Sacramento River Chinook Salmon Life History*. Prepared by CH2M Hill, Sacramento, CA.

Wagner, R. W., M. Stacey, L. R. Brown, and M. Dettinger. 2011. Statistical models of temperature in the Sacramento–San Joaquin Delta under climate-change scenarios and ecological Implications. *Estuaries and Coasts* 34:544–556.

Wang, J. C .S. 2007. Spawning, early life stages, and early life histories of the Osmerids found in the Sacramento–San Joaquin Delta of California. October. In *Tracy Fish Facility Studies*, Volume 38. U.S. Department of the Interior and U.S. Bureau of Reclamation Mid-Pacific Region Technical Service Center, Byron, CA.

Water Science and Technology Board, Ocean Studies Board, Division on Earth and Life Studies, and National Research Council. 2012. *Sustainable Water and Environmental Management in the California Bay-Delta*. Available: https://www.nap.edu/catalog/13394/sustainable-water-and-environmental-management-in-the-california-bay-delta.

Werner, I., L. A. Deanovic, D. Markiewicz, J. Khamphanh, C. K. Reece, M. Stillway, and C. Reece. 2010a. Monitoring acute and chronic water column toxicity in the northern Sacramento–San Joaquin Estuary, California, USA, using the euryhaline amphipod, *Hyalella azteca*: 2006–2007. *Environmental Toxicology and Chemistry* 29:2190–2199.

Werner, I., D. Markiewicz, L. Deanovic, R. Connon, S. Beggel, S. Teh, M. Stillway, C. Reece. 2010b. *Pelagic Organism Decline (POD): Acute and chronic invertebrate and fish toxicity testing in the Sacramento–San Joaquin Delta 2008–2010*. Final Report. University of California, Davis–Aquatic Toxicology Laboratory, Davis, CA.

Weston, D. P., A. M. Asbell, S. A. Lesmeister, S. J. Teh, and M. J. Lydy. 2014. Urban and agricultural pesticide inputs to a critical habitat for the threatened delta smelt (*Hypomesus transpacificus*). *Environmental Toxicology and Chemistry* 33(4):920–929.

Weston, D. P., and M. J. Lydy. 2010. Urban and agricultural sources of pyrethroid insecticides to the Sacramento–San Joaquin Delta of California. *Environmental Science and Technology* 44(5):1833–1840.

Whipple, A. A., R. M. Grossinger, D. Rankink, B. Stanford, and R. A. Askevold. 2012. *Sacramento–San Joaquin Delta Historical Ecology Investigation: Exploring Pattern and Process*. Prepared for the California Department of Fish and Game and Ecosystem Program. A Report of the SFEI-ASC's

Historical Ecology Program, SFEI-ASC Publication #672. San Francisco Estuary Institute-Aquatic Science Center, Richmond, CA.

Wilkerson, F., R. Dugdale, A. Parker, S. B. Blaser, and A. Pimenta. 2015. Nutrient uptake and primary productivity in an urban estuary: using rate measurements to evaluate phytoplankton response to different hydrological and nutrient conditions. *Aquatic Ecology 49(2):211–233.*

Winder, M., and A. D. Jassby. 2011. Shifts in zooplankton community structure: Implications for food web processes in the upper San Francisco estuary. *Estuaries and Coasts* 34:675–690.

Wood, M., C. Foe, J. Cooke, and S. Louie. 2010. *Sacramento–San Joaquin Delta Estuary TMDL for Methylmercury*. Available: http://www.waterboards.ca.gov/centralvalley/water_issues/tmdl/central_valley_projects/delta_hg/april_2010_hg_tmdl_hearing/apr2010_tmdl_staffrpt_final.pdf.

Wright, S. A., and D. H. Schoellhamer. 2004. Trends in the sediment yield of the Sacramento River, California, 1957–2001. *San Francisco Estuary and Watershed Science* 2(2).

York, J. K., G. B. McManus, W. J. Kimmerer, A. M. Slaughter, and T. R. Ignoffo. 2013. Trophic links in the plankton in the low salinity zone of a large temperate estuary: Top-down effects of introduced copepods. *Estuaries and Coasts* 37(3):576–588.

Yoshiyama, R. M., E. R. Gerstung, F. W. Fisher, and P. B. Moyle. 2001. Historical and present distribution of Chinook salmon in the Central Valley Drainage of California. *Fish Bulletin* 179(1):71–176.

6.4.1.1 Federal Register Notices

(81 FR 46030, 460033) U.S. Environmental Protection Agency. 2016. *Water Quality Standards; Establishment of Revised Numeric Criteria for Selenium for the San Francisco Bay and Delta, State of California*. 81(136): 46030–46042.

6.5 Chapter 5, Recommended New and Revised Flow Requirements

Anadromous Fish Restoration Program (AFRP). 2005.

American River Water Forum. 2003.

American River Water Forum. 2004.

Anderson, James J., J. A. Gore, R. T. Kneib, J. M. Nestler, and J. Van Sickle. 2013. *Report of the 2013 Independent Review Panel (IRP) on the Long-term Operations Biological Opinions (LOBO) Annual Review*. Prepared for the Delta Science Program. December 7.

Anderson, James J., J. Gore, R. Knei b, N. Monsen, G. Schladow, and J. Van Sickle. 2015. *Independent Review Panel (IRP) Report for the 2015 Long-term Operations Biological Opinions (LOBO) Annual Science Review.* A report to the Delta Science Program. December.

Arthington et al. 1992.

Arthington et al. 2004.

Baxter, R., L. R. Brown, G. Castillo, L. Conrad, S. Culberson, M. Dekar, M. Dekar, F. Feyrer, T. Hunt, K. Jones, J. Kirsch, A. Mueller-Solger, M. Nobriga, S. B. Slater, T. Sommer, and K. Souza. 2015. *An updated conceptual model of Delta Smelt biology: our evolving understanding of an estuarine fish. Interagency Ecological Program: Management, Analysis, and Synthesis.* Team Technical Report 90.

Bell, M. 1991. *Fisheries Handbook of Engineering Requirements and Biological Criteria*. 3rd Edition. U.S. Army Corp of Engineers. North Pacific Division. Fish Passage and Evaluation Program. Portland, OR.

Bennett, W. A. 2005. The population ecology of delta smelt in the San Francisco Estuary. *San Francisco Estuary and Watershed Science* 3(2):1–71.

Bjornn, T. C., and D. W. Reiser. 1991. Habitat requirements of salmonids in streams. *American Fisheries Society Special Publication* 19:83–138.

Boles, G. 1988. *Water Temperature Effects on Chinook Salmon (*Onchorhycchus tshawytscha*) with Emphasis on the Sacramento River: A Literature Review*. Report to the California Department of Water Resources. Northern District. 43 p.

Bradford. 1997.

Brandes, P. L. and J. S. McLain. 2001. Juvenile Chinook salmon Abundance, Distribution, and Survival in the Sacramento-San Joaquin Estuary. In: Brown, R. L., (ed.). Contributions to the Biology of Central Valley Salmonids. *Fish Bulletin* 179.

Brown, L. R., and M. L. Bauer. 2009. Effects of hydrologic infrastructure on flow regimes of California's Central Valley rivers: Implications for fish populations. *River Research and Applications* 26(6):751–765.

Bunn, S. E. and A. H. Arthington. 2002. Basic Principles and Ecological Consequences of Altered Flow Regimes for Aquatic Biodiversity. *Environmental Management* 30(4): 492–507.

California Department of Fish and Game (CDFG). 1988.

California Department of Fish and Wildlife (CDFW). 2009. *Endangered Species Act Incidental Take Permit No. 2081-2009-001-03*. Bay Delta Region. Yountville, CA.

California Department of Fish and Wildlife (CDFW). 2012. *Written information responsive to the workshop questions for the Bay-Delta Workshop-2. Bay-Delta Fishery Resources, September 20, 2012*. California Department of Fish and Wildlife Ecosystem Conservation Division/Water Branch. Sacramento, CA.

California Department of Water Resources (DWR) 2016. *Dayflow Data*.

California Department of Water Resources (DWR). 2016. Suisun Marsh Program. Available: http://www.water.ca.gov/suisun/facilities.cfm

East Bay Municipal Utility District (East Bay MUD). 2013. *Permit 10478 Time Extension Project Draft Environmental Impact Report.* September.

Fleenor, W. E., W. A. Bennett, P. B. Moyle, and J. R. Lund. 2010. *On Developing Prescriptions for Freshwater Flows to Sustain Desirable Fishes in the Sacramento–San Joaquin Delta*. Delta Solutions, Center for Watershed Sciences, University of California, Davis. pp. 1–46.

Grimaldo, L.F., T. Sommer, N. Van Ark, G. Jones, E. Holland, P. Moyle, P. Smith, and B. Herbold. 2009. Factors affecting fish entrainment into massive water diversions in a freshwater tidal estuary: can fish losses be managed? *North American Journal of Fisheries Management* 29:1253–1270.

Hannon et al. 2003.

Hannon and Deason. 2008.

Hirji and Davis. 2009.

Hunter. 1992.

Jassby, A. D., W. J. Kimmerer, S. G. Monismith, C. Armor, J. E. Cloern, T. M. Powell, J. R. Schubel, and T. J. Vendlinski. 1995. Isohaline position as a habitat indicator for estuarine populations. *Ecological Applications* 5:272–289.

Kjelson, M. A, and P. L. Brandes. 1989. The Use of Smolt Survival Estimates to Quantify the Effects of Habitat Changes on Salmonid Stocks in the Sacramento-San Joaquin River, California. In CLevings, C.D., L. B. Holtby, and M. A. Henderson (eds.). *Proceedings of the National Workshop on the Effects of Habitat Alteration on Salmonid Stocks. Canadian Journal of Fisheries and Aquatic Sciences* 105:100–115.

Lindley, S. T., R. Schick, B. P. May, J. J. Anderson, S. Greene, C. Hanson, A. Low, D. McEwan, R. B. MacFarlane, C. Swanson, and J. G. Williams. 2004. *Population Structure of Threatened and Endangered Chinook Salmon ESUs in California's Central Valley Basin*. NOAA Technical Memorandum NOAA-TM-NMFS-SWFSC-360. April.

Lund, J., E. Hanak, W. Fleenor, W. Bennett, R. Howitt, J. Mount, and P. Moyle. 2010. *Comparing Futures for the Sacramento–San Joaquin Delta*. Berkeley, CA: University of California Press.

Lytle, D.A. and N.L. Poff. 2004. Adaptation to Natural Flow Regimes. *Trends in Ecology and Evolution* 19: 94-100.

Marchetti and Moyle. 2001.

Marston, D., C. Mesick, A. Hubbard, D. Stanton, S. Fortmann-Roe, S. Tsao, and T. Heyne. 2012. Delta Flow Factors Influencing Stray Rate of Escaping Adult San Joaquin River Fall-Run Chinook Salmon (*Oncorhynchus tshawytscha*). *San Francisco Estuary and Watershed Science* 10(4).

Mazvimavi et al. 2007.

McCullough, D.A. 1999. A Review and Synthesis of Effects of Alterations to the Water Temperature Regime on Freshwater Life Stages of Salmonids with Special Reference to Chinook Salmon. 279 pages.

Mesick, C. 2001. The effects of San Joaquin River flows and Delta export rates during October on the number of adult San Joaquin Chinook salmon that stray. In R. L. Brown (ed.). Contributions to the biology of Central Valley salmonids. Volume 2. California Department of Fish and Game. *Fish Bulletin* 179:139–161.

Monismith, S, M. Fabrizio, M. Healey, J. Nestler, K. Rose, and J. Van Sickle. 2014. *Workshop on the Interior Delta Flows and Related Stressors Panel Summary Report*. Prepared for the Delta Stewardship Council. Delta Science Program. July. Sacramento, CA. Available: http://deltacouncil.ca.gov/sites/default/files/documents/files/Int-Flows-and-Related-Stressors-Report.pdf.

Monsen N. E., J.E. Cloern, J.R. Burau. 2007. Effects of flow diversion on water and habitat quality: Examples from California's highly manipulated Sacramento-San Joaquin Delta. San Francisco Estuary and Watershed Science 5(3):1–15.

Moyle, P. B., J. R. Lund, W. A. Bennett, and W. E. Fleenor. 2010. Habitat Variability and Complexity in the Upper San Francisco Estuary. *San Francisco Estuary and Watershed Science* 8(3). Available: http://escholarship.org/uc/item/0kf0d32x.

Moyle, P. B., Williams, J. G., and Kiernan, J. D. 2011. *Improving Environmental Flow Methods.* Used in California FERC Licensing. California Energy Commission, Preliminary Environmental Impact Report.

Moyle, P. B. 2002. *Inland Fishes of California, Second Edition*. Berkeley, CA: University of California Press.

Myrick, C. A., and Cech, J. J., Jr. 2001. *Temperature effects on Chinook salmon and steelhead: A review focusing on California's Central Valley populations*. Bay-Delta Modeling Forum Technical Publication 01-1:1–57. Available: http://www.sfei.org/modelingforum/.

National Marine Fisheries Service (NMFS). 1997. *Proposed Recovery Plan for the Sacramento River Winter-Run Chinook Salmon*. Southwest Region, Long Beach, CA.

National Marine Fisheries Service (NMFS). 2009. *Biological Opinion and Conference Opinion on the Long-Term Operations of the Central Valley Project and State Water Project*. June 4. Endangered Species Act Section 7 Consultation.

National Marine Fisheries Service (NMFS). 2014. *Recovery Plan for the Evolutionarily Significant Units of Sacramento River Winter-Run Chinook Salmon and Central Valley Spring-Run Chinook Salmon and the Distinct Population Segment of California Central Valley Steelhead*. West Coast Region, Sacramento, CA.

NRDC. 2005.

Orth and Maughan. 1981.

Perry, R. W. 2010. *Survival and Migration Dynamics of Juvenile Chinook Salmon (*o. Tshawytscha*) in the Sacramento–San Joaquin River Delta*. PhD. dissertation. University of Washington. Seattle, WA.

Perry, R. W., P. L. Brandes, J. R. Burau, A. P. Klimley, B. MacFarlane, C. Michel, and J. R. Skalski. 2013. Sensitivity of survival to migration routes used by juvenile Chinook salmon to negotiate the Sacramento–San Joaquin River Delta. *Environmental Biology of Fishes* 96:381–392.

Poff, N. L., J. D. Allan, M. B. Bain, J. R. Karr, K. L. Prestegaard, B. D. Richter, R. E. Sparks, and J. C. Stromberg. 1997. The Natural Flow Regime. *BioScience* 47 (11):769-784.

Poff et al. 2006.

Poff, N. L., J. D. Olden, D. M. Merritt, and D. M. Pepin. 2007. Homogenization of Regional River Dynamics by Dams and Global Biodiversity Implications. *Proceedings of the National Academy of Sciences* 104: 5732-5737.

Rich. 1997.

Richter et al. 1996.

Richter et al. 2003.

Sacramento River Temperature Task Group. 2014.

Sacramento River Temperature Task Group. 2015.

Smith. 1973.

Snider, B. 2001. *Evaluation of Effects of Flow Fluctuations on the Anadromous Fish Populations in the Lower American River*. Technical Reports 1 and 2 with Appendices 1–3. California Department of Fish and Game, Habitat Conservation Division. Stream Evaluation Program. Sacramento, CA.

Sparks, R.E. 1995. Need for Ecosystem Management of Large Rivers and Their Floodplains. *Bioscience* 45:168–182.

State Water Resources Control Board (State Water Board). 2006. *Water Quality Control Plan for the San Francisco Bay/Sacramento–San Joaquin Delta Estuary*. December 13. Sacramento, CA. Available: http://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/wq_control_plans/2006wqcp/docs/2006_plan_final.pdf.

State Water Resources Control Board (State Water Board). 2010. *Development of Flow Criteria for the Sacramento San Joaquin Delta Ecosystem*. Prepared pursuant to the Sacramento–San Joaquin Delta Reform Act of 2009. Available: http://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/deltaflow/docs/final_rpt080310.pdf.

State Water Resources Control Board (State Water Board). 2012. *Technical Report on the Scientific Basis for Alternative San Joaquin River Flow and Southern Delta Salinity Objectives*.

Tennant. 1976.

Tharme. 2003.

Tharme and King. 1998.

U.S. Department of the Interior. 2008. *Central Valley Project and State Water Project Operations Criteria and Plan Biological Assessment.*

U.S. Fish and Wildlife Service (USFWS). 2008. *Biological Opinion on Coordinated Operations of the Central Valley Project and State Water Project*. Available: http://www.fws.gov/sacramento/es/documents/swp-cvp_ops_bo_12-5_final_ocr.pdf. Accessed: October 6, 2016.

Walker et al. 1995.

Water Forum. 2005.

YBWA Management Plan. 2008.

Appendix A Draft Modeling Approaches Used to Develop Unimpaired Watershed Hydrologies

Attachment A: Sacramento Valley Unimpaired Flow Model Schematic

Appendix A
Draft Modeling Approaches Used to Develop Unimpaired Watershed Hydrologies

A.1 Background

The State Water Resources Control Board (State Water Board) is considering the use of unimpaired flows in its Phase II comprehensive update to the Water Quality Control Plan for the San Francisco Bay-Sacramento/San Joaquin Delta Estuary (Bay-Delta Plan) for Sacramento River mainstem and major tributary inflow and Delta eastside tributary inflow (including the Calaveras, Cosumnes and Mokelumne rivers) requirements. The State Water Board is also considering the use of unimpaired flows as part of the Phase I update to the Bay-Delta Plan for San Joaquin River inflow requirements as part of a separate process that is not addressed in this document. Unimpaired hydrology or "unimpaired flow" represents an index of the total water available to be stored and put to any beneficial use within a watershed under current physical conditions and land uses. This index represents something different than the "natural flow" that would have occurred absent human development of land and water supply.

Previous work on unimpaired flows in the Sacramento watershed has been completed by the California Department of Water Resources' (DWR's) Bay-Delta office to provide estimates throughout the Central Valley. DWR's unimpaired flow estimates are produced by "removing the impacts of most upstream alterations as they occurred over the years" (DWR 2007, DWR 2016a). Land use, levees, flood bypasses, and weirs are all assumed to exist as they do currently. DWR produces unimpaired estimates for 24 locations in the Central Valley and the Sacramento-San Joaquin Delta (Delta) for October 1920 through September 2014 on a monthly basis. These estimates are considered to be accurate higher in the watershed but are not considered to be as accurate lower in the valley floor and Delta. DWR's methods for estimating unimpaired flow in the Valley floor and Delta did not account for any stream/groundwater interaction and took a very simplified approach to estimating surface runoff from ungaged streams (DWR 2007, DWR 2016a).

In addition to the work by DWR's Bay-Delta Office, DWR's Division of Flood Management estimates "full natural flow" (FNF) on a monthly basis for 36 locations around the state and on a daily basis for 19 locations. DWR's methods for calculating FNF have not been documented, however the estimates are used by users throughout the Bay-Delta watershed to calculate indices of water availability such as water year types and the Eight River Index. In turn, these indices are used to determine water supply allocations and water quality objectives for multiple beneficial uses of water, including objectives to protect fish and wildlife. Nearly all of the FNF locations within the Sacramento Watershed estimated by the Division of Flood Management are at the rim of the Sacramento Valley. The methods used by the Division of Flood Management are similar to those utilized by the Bay-Delta Office, where the effects of diversions and storage are removed from the time series.

The methods used by both groups at DWR do not provide unimpaired estimates at the bottom of each watershed, with the exception of the Sacramento Valley Total Outflow, which includes an estimate of valley floor runoff. DWR's estimate of valley floor runoff is based on rationale that is "subjective [and] that need to be revisited and verified in future updates" (DWR 2007). To provide estimates at the bottom of the watershed, better estimates of surface runoff and stream gains and losses to groundwater are needed. This is a challenge, however because most diversions are not gaged, most of the watersheds in the Sacramento Valley do not have gages near the mouths, and it is very difficult to estimate stream gains and losses to groundwater.

This study was undertaken to better estimate unimpaired flows at the mouths of the tributaries in the Sacramento River Watershed, at locations on the mainstem Sacramento River, and at the mouths of the Delta eastside tributaries.

The overall approach used to estimate unimpaired flows was to calculate a mass-balance in the lower reaches of each major tributary and along the mainstem Sacramento River. The inflows to the reaches are the unimpaired flows at the rim locations, surface runoff from the valley floor, and stream-groundwater gains. The only losses from the mainstem and tributaries are stream losses to groundwater and weir spills to bypasses. Groundwater levels and stream-groundwater interactions were assumed to be at the same level as is estimated for current conditions.

Unimpaired flows were estimated with the Sacramento Valley Unimpaired Flow Model (SVUFM). Inputs to the model include rim inflows that were estimated based on measured data and stream-groundwater interaction from a California Central Valley Groundwater-Surface Water Simulation Model (C2VSim) simulation of current conditions. These model inputs are described in greater detail below.

A.2 Rim Watershed Hydrology

A.2.1 Introduction

Rim inflows are flows that come from outside of the region simulated by a hydrologic model. They are flows that enter the model domain from outside of the model domain. The SVUFM model domain includes the Delta and the valley floor of the Sacramento River, its tributaries, and eastside tributaries to the Delta, generally extending upstream to the foothills. The unimpaired rim inflows used as model input include estimates of unimpaired inflow to the locations of the large reservoirs at the edges of the Sacramento Valley such as Lake Shasta, Oroville Reservoir, and Folsom Lake (although these reservoirs are simulated as being empty in the unimpaired flow model). Unimpaired rim inflows are also used as inflow to the smaller tributaries that originate outside of the SVUFM domain.

Rim watersheds typically are characterized by complex topography, steep slopes, shallow soils, and limited aquifer systems. Precipitation percolating to groundwater quickly returns to streams as base flow. Rim watersheds are generally mountainous and highly productive in terms of runoff. The hydrology of rim watersheds at higher elevations is largely determined by the snowfall and snowmelt cycle. Streamflow records (directly gaged, extended through correlation, and adjusted for upstream regulation) are considered to be the most appropriate basis for estimating water supplies from these watersheds.

The rim inflow dataset was generated for water years 1922–2009. It represents the flows that would occur under a repeat of historical weather conditions. It is assumed that a repeat of these conditions would result in identical surface runoff and stream flows as historically observed. In many cases historical streamflow records have been extended through correlation. Rim inflows have been developed assuming stationarity over the historical period and assuming that statistical relationships between unimpaired stream flows in adjacent watersheds are constant. This assumption of stationarity is not appropriate when there has been significant land use change in the rim watersheds. Assumptions of stationarity are not valid when climate change has occurred.

Unimpaired rim inflow estimates based on historical streamflow data were obtained for the Sacramento Valley Hydrologic Region from DWR, and for the Delta Eastside Tributary Region from the Bureau of Reclamation (Reclamation). The data are stored as monthly time series. The first row in the dataset denotes the name of the time series data used in SVUFM. Inflow names contain the prefix "I_" followed by a five or six letter string. The five-letter string is an acronym for inflows to reservoirs or lakes. The six-letter string denotes the river followed by the river mile (RM). For example, I_SHSTA represents the inflow to Lake Shasta, and I_NFY029 represents inflow to the North Fork Yuba River at RM 29.

A.2.2 Methods

A.2.2.1 Watersheds

Figure A-1, Rim Watersheds, displays the 71 primary rim watersheds that provide inflow to the Sacramento River watershed and Delta eastside tributaries. Watershed numbers are provided in the figure for cross-referencing to subsequent tables. Many of the rim watersheds in the Sierra Nevada have been extensively developed for both hydropower generation and water supply. Natural stream flows in these watersheds are significantly altered by storage regulation and interbasin water transfers. As part of the process to remove this upstream impairment, rim watersheds were divided into sub-watersheds to estimate local inflows to reservoirs or stream flows at diversion dams. Sub-watersheds are not shown in Figure A-1. Of the 71 rim watersheds shown in Figure A-1, 12 were further subdivided for analytical purposes (Table A-1). Three of the 71 rim watersheds shown in Figure A-1 do not contribute to the SVUFM model domain because they either only contribute under impaired conditions (watersheds 44 and 45, Trinity River) or are south of the model domain (watershed 60, Littlejohns Creek).

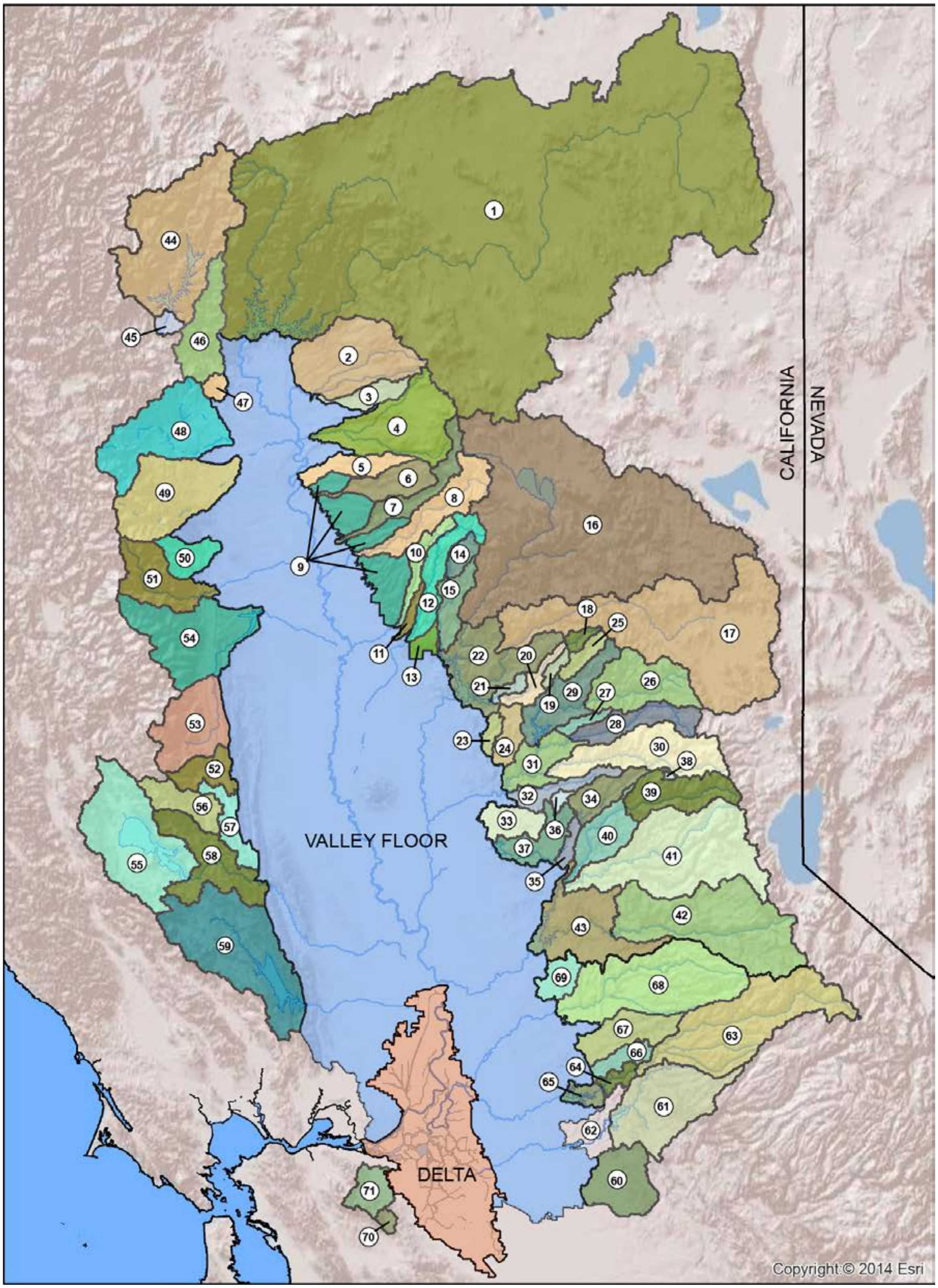

Figure A-1. Rim Watersheds that Provide Inflow to the Valley Floor of the Sacramento River Watershed and Delta Eastside Tributaries

Table A-1. Subdivision of Watersheds

Watershed	Watershed Number (as shown in Figure A-1)	Number of Sub-Watersheds
West Branch Feather River at Hendricks Diversions Dam	14	2
West Branch Feather River near Yankee Hill	15	2
North Fork Feather River at Pulga	16	7
Middle Fork Feather River near Merrimac	17	4
Middle Fork Yuba River above Our House Diversion Dam	28	2
South Fork Yuba River at Jones Bar	30	4
Deer Creek inflow at Yuba River	32	4
Camp Far West Reservoir	37	2
Middle Fork American River	41	12
South Fork American River near Placerville	42	10
Mokelumne River near Mokelumne Hill	63	6
Cosumnes River at Michigan Bar	68	4

A.2.2.2 Approaches for Estimating Rim Inflows

Only in limited cases are streamflow records available over the entire period of simulation. For the majority of streams, historical time series data have been extended using various statistical methods assuming stationarity over the historical period. Methods used to develop each inflow are summarized in Table A-2. These methods are as follows:

- Direct gage measurement: Stream gage data exist at the watershed outflow point for water years 1922 through 2009.
- Streamflow correlation: Stream gage data exist at the watershed outflow point for only a limited period between water years 1922 and 2009. Gage data are extended through linear correlation of annual flows with streamflow records from adjacent watersheds. Double mass plots of monthly flows are used to check that a constant (and linear) relationship exists between the dependent and independent variables. Annual synthetic flows are disaggregated to a monthly time step based on the cumulative fraction of annual runoff that has occurred by the end of month, while attempting to preserve the shape of the hydrograph of the dependent watershed.
- Proportionality: No gage data exist for the watershed. It is assumed that runoff is proportional to the product of drainage area and average annual precipitation depth over the watershed.[1] Outflow is determined through association of the watershed with a similar, but gaged watershed and the use of multiplicative factors representing the ratio of watershed areas and ratio of precipitation depths.

[1] Determined using PRISM data of the 30-year average annual precipitation for 1971-2000 (PRISM 2013).

- Mass balance: Typically, this method is used when watersheds have significant storage regulation. Reservoir operating records of dam releases and reservoir storage, together with estimated reservoir evaporation, are used to estimate inflows to the reservoir.

Table A-2. Data Sources and Calculation Methods for Upper Watershed Inflows

Inflow Label	Watershed Number	Observed Period	Agency	Gage ID	Flow Correlation	Propor-tionality	Mass Balance
I_ALD001	42	10/22 - 09/81	USGS	11440000	●		
I_ALMMW	16	10/21 - present	USGS	11399500			●
I_AMADR	66	–	–	–		●	
I_ANT011	6	10/40 - 09/82	USGS	11379000	●		
I_ANTLP	16	10/30 - 09/93	USGS	11401500	●		●
I_BCC014	10	10/21 - 09/86	USGS	11384000	●		●
I_BCN010	3	10/59 - 09/67	USGS	11374100	●		
I_BKILD	41	11/90 - present	USGS	11428400	●		●
I_BLKBT	54	01/53 - present	USACE	Report of Operations	●		●
I_BOWMN	30	02/27 - present	USGS	11416500	●		
I_BRC003	57	10/98 - present	USGS	11451715	●	●	
I_BRR023	37	–	–	–	●	●	●
I_BRYSA	59	01/57 - present	Reclamation	Report of Operations	●		●
I_BTC048	12	10/30 - present	USGS	11390000			●
I_BTL006	4	10/40 - 09/61, 10/61 - present	USGS, USGS	11376500, 11376550	●		
I_BTVLY	16	10/36 - present	USGS	11400500	●	●	
I_BUKSL	16	10/80 - present	USGS	11403530	●		●
I_CAPLS	42	10/22 - 09/92	USGS	11437000	●		●
I_CCH053	58	10/60 - present	USGS	11451760	●	●	●
I_CLR011	47	10/40 - present	USGS	11372000	●		●
I_CLR025	46	10/64 - present	Reclamation	Report of Operations	●	●	
I_CLRLK	55	10/44 - present	USGS	11451000			●
I_CLV026	62	–	–	–		●	
I_CMBIE	35	–	–	–	●	●	●
I_CMCHE	65	–	–	–		●	
I_CMP001	68	10/56 - 09/04	USGS	11333000	●		
I_CMP012	68	10/49 - 09/54	USGS	11331500	●	●	

Inflow Label	Watershed Number	Observed Period	Agency	Gage ID	Flow Correlation	Propor-tionality	Mass Balance
I_CMPFW	37	–	–	–	●	●	●
I_COW014	2	10/49 - present	USGS	11374000	●	●	
I_CSM035	68	10/21 - present	USGS	11335000			●
I_CWD018	48	09/71 - 09/86	USGS	11375810	●		
I_DAVIS	17	10/25 - 09/80, 12/67 - present	USGS, DWR	11391500, Report of Operations	●	●	
I_DCC007	41	09/60 - present	USGS	11427700	●		●
I_DEE023	69	10/60 - 09/77	USGS	11335700	●	●	
I_DER001	32	10/35 - present	USGS	1418500			
I_DER004	32	–	–	–		●	
I_DHC001	33	–	–	–		●	
I_DRC012	8	10/21 - present	USGS	11383500	Data for all years		
I_DSC035	67	10/61 - 09/70, 10/35 - 09/41	USGS, USGS	11326300, 11327000	●	●	
I_ELD027	50	10/48 - present	USGS	11379500	●		
I_ENF001	16	10/50 - 09/60	USGS	11403000	●		●
I_ENGLB	31	10/21 - 09/41, 10/41 - present	USGS, USGS	11418000, 11419000	●		●
I_EPARK	52	10/21 - present	Reclamation	Report of Operations			●
I_FOLSM	43	10/21 - present, 02/55 - present	USGS, Reclamation	USGS Report of Operations			●
I_FRDYC	30	07/66 - present	USGS	11414100	●		●
I_FRMAN	17	10/65 - present	DWR	Report of Operations	●		●
I_FRMDW	41	10/64 - present	USGS	11427500	●		●
I_GRZLY	16	10/85 - present	USGS	11404300	●		●
I_HHOLE	41	10/85 - present	USGS	11428800	●		●
I_HON021	23	10/50 - 09/86	USGS	11407500	●		
I_ICEHS	42	10/1923 - present	USGS	11441500	●		●
I_INDVL	56	10/74 - present	USGS	11451300	●		●

Inflow Label	Watershed Number	Observed Period	Agency	Gage ID	Flow Correlation	Propor-tionality	Mass Balance
I_JKSMD	28	10/26 - present	USGS	11407900	●		●
I_JNKSN	68	10/46 - 09/54	USGS	11332500	●		
I_LBEAR	63	–	–	–		●	
I_LCC038	11	02/59 – present, 02/59 - 09/93	DWR, DWR	A04910, A04280	●		●
I_LDC029	13	–	–	–		●	
I_LGRSV	18	10/63 - present	USGS	11395030	●		●
I_LJC022[a]	60	10/51 - 09/95	USACE	multiple data sources	●		●
I_LKVLY	38	–	–	–		●	
I_LNG000	41	10/66 - 09/92	USGS	11433100	●	●	●
I_LOONL	41	10/62 - present	USGS	11429500	●		●
I_LOSVQ	70	10/97 - present	CCWD		●		
I_LST007	19	10/73 - present	USGS	11396000	●		●
I_LWSTN[a]	45	10/21 - present	USGS	11525500	●		●
I_MERLC	24	10/63 -present	BVID	Report of Operations	●		●
I_MFA001	41	10/21 - 09/85	USGS	11433500	●		●
I_MFA036	41	10/65 - present	USGS	11427770	●		●
I_MFF019	17	10/51 - 09/86	USGS	11394500	●		
I_MFF073	17	10/68 - 09/80	USGS	11329100	●		●
I_MFM010	63	10/21 - present	USGS	11317000			
I_MFY013	28	10/68 - present	USGS	11408870			●
I_MLC006	7	10/28 - present	USGS	11381500	●		
I_MNS000	9	–	–	–		●	
I_MOK079	63	10/27 - present	USGS	11319500			●
I_MSH015	71	04/53 - 09/83	USGS	11337500			
I_NBLDB	29	10/66 - 09/40	USGS	11413520	●		●
I_NFA022	40	10/21 - 09/41, 10/41 - present	USGS, USGS	11426500, 11427000		●	●
I_NFA054	39	10/21 - 09/41, 10/41 - present	USGS, USGS	11426500, 11427000		●	●

Inflow Label	Watershed Number	Observed Period	Agency	Gage ID	Flow Correlation	Propor-tionality	Mass Balance
I_NFF027	16	10/21 - present	USGS	11404500	●		●
I_NFM006	63	09/84 - present	USGS	11316700	●		●
I_NFY029	26	10/30 - present	USGS	11413000	●	●	
I_NHGAN	61	10/63 - present	USACE	Report of Operations	●		●
I_OGN005	27	10/21 – 09/69, 09/68 - present	USGS, USGS	11409500	●	●	●
I_OROVL	22	10/21 - present, 10/67 - present	USGS, DWR	11407000, Report of Operations			●
I_PARDE	64	–	–	–	●	●	●
I_PLM001	42	10/22 - 09/39	USGS	11440500	●		
I_PYN001	5	10/49 - 09/66	USGS	11377500	●	●	
I_RBCON	41	10/91 - present	USGS	11427960	●		●
I_RLLNS	34	04/50 - present	USGS	11422500	●	●	●
I_RUB001	41	10/58 – 09/84	USGS	11433200	●		●
I_RVPHB	14	–	–	–	●	●	●
I_SCOTF	32	–	–	–		●	●
I_SCW008	49	12/76 - 09/86	USGS	11375870	●		
I_SFA021	42	10/64 - present	USGS	11444500	●		●
I_SFA035	42	10/22 - present	USGS	11443500	●		●
I_SFA056	42	10/22 - present	USGS	11439500	●		●
I_SFD003	32	–	–	–		●	
I_SFF008	21	10/21 - 09/66	USGS	11397000	●		●
I_SFF011	20	10/21 - 09/66	USGS	11397000	●		●
I_SFM006	63	10/21 - present	USGS	11317000	●		
I_SFR005	41	10/62 - present	USGS	11430000	●		●
I_SFY007	30	10/40 - present	USGS	11417500	●		
I_SGRGE	53	11/28 - present	Reclamation	Report of Operations			●
I_SHSTA	1	10/25 - 09/42 01/44 - present	USGS, Reclamation	11369500, Report of Operations		●	●

Inflow Label	Watershed Number	Observed Period	Agency	Gage ID	Flow Correlation	Propor-tionality	Mass Balance
I_SILVR	42	10/22 - present	USGS	11436000	●		●
I_SLT009	25	10/60 - present	USGS	11413300	●		●
I_SLTSP	63	10/27 - present	USGS	11314500	●		●
I_SPLDG	30	12/65 - present	USGS	11414250	●		●
I_STMPY	41	04/46 - 09/60	USGS	11432500	●		
I_THM028	51	10/21 - 09/96	USGS	11382000	●		
I_TRNTY[a]	44	10/21 - present, 10/61 - present	USGS, Reclamation	11525500, Report of Operations	●		●
I_UNVLY	42	10/61 - present	USGS	11441002			
I_WBF006	15	10/30 - 09/63	USGS	11406500	●	●	●
I_WBF015	15	10/30 - 09/63	USGS	11406500	●	●	●
I_WBF030	14	10/30 - 09/63	USGS	11406500	●	●	●
I_WLF013	36	–	–	–	●	●	●

Key:

cfs = cubic feet per second; DWR = California Department of Water Resources; PG&E = Pacific Gas and Electric; USGS = U.S. Geological Survey; WBA = Water Budget Area

[a] Littlejohns Creek, Trinity Reservoir, and Lewiston Lake are not part of the Sacramento Valley watershed, as such, their inflows do not contribute to SVUFM.

A.2.3 Results

Total average annual unimpaired rim inflow to the Sacramento and Delta Valley floor (the SVUFM model domain) is approximately 21,500 thousand acre-feet per year (TAF/yr)(Table A-3). This includes all significant rim watersheds that provide inflow to the Delta except for the San Joaquin River watershed. Year-to-year variation in unimpaired rim inflow is high, with a standard deviation of approximately 10,000 TAF/yr.

The largest rim inflow to the Sacramento and Delta Valley floor comes from the watershed upstream of Shasta Dam, which includes the Sacramento, Pit, and McCloud River watersheds. The average annual inflow from this watershed is 26% of the total. This watershed combined with the rim inflows from the Feather, Yuba, and American Rivers generally provides 70% of the total unimpaired rim inflow to the Sacramento and Delta Valley floor (Table A-3). The Sacramento River rim watershed provides much more inflow (93%) to the valley floor than the Delta tributaries (7%).

Table A-3. Average Annual Rim Inflow to the Sacramento and Delta Valley Floor

Label	Watershed Number	Description	Type	Average Annual Flow (TAF)	Standard Deviation of Annual Flow (TAF)	Average as Percent of Total Rim Inflow
Lake Shasta Inflow			**Total**	**5,667**		**26.4%**
I_SHSTA	1	Shasta Lake	Reservoir inflow	5,667	2,030	26.4%
Sacramento River Eastside Tributaries North of the Feather River Watershed			**Total**	**2,066**		**9.6%**
I_COW014	2	Cow Creek near Millville	Stream inflow	420	231	2.0%
I_BCN010	3	Bear Creek (North) near Millville	Stream inflow	60	26	0.3%
I_BTL006	4	Battle Creek near Cottonwood	Stream inflow	351	120	1.6%
I_PYN001	5	Paynes Creek and Sevenmile Creek	Stream inflow	53	31	0.2%
I_ANT011	6	Antelope Creek near Red Bluff	Stream inflow	101	52	0.5%
I_MLC006	7	Mill Creek near Los Molinos	Stream inflow	217	86	1.0%
I_DRC012	8	Deer Creek near Vina	Stream inflow	231	114	1.1%
I_MNS000	9	Minor northeast streams	Stream inflow	237	123	1.1%
I_BCC014	10	Big Chico Creek near Chico	Stream inflow	101	58	0.5%
I_LCC038	11	Little Chico Creek near Chico	Stream inflow	22	15	0.1%

Label	Watershed Number	Description	Type	Average Annual Flow (TAF)	Standard Deviation of Annual Flow (TAF)	Average as Percent of Total Rim Inflow
I_BTC048	12	Butte Creek	Stream inflow	245	126	1.1%
I_LDC029	13	Little Dry Creek	Stream inflow	26	17	0.1%
Feather River Watershed			**Total**	**4,382**		**20.4%**
I_WBF030	14	West Branch Feather River at Hendricks Diversion Dam	Stream accretion	96	45	0.4%
I_RVPHB	14	Round Valley and Philbrook lakes	Reservoir inflow	20	10	0.1%
I_WBF006	15	West Branch Feather River near Yankee Hill	Stream accretion	69	33	0.3%
I_WBF015	15	West Branch Feather River at Miocene Diversion Dam	Stream accretion	148	70	0.7%
I_ALMMW	16	Lake Almanor and Mountain Meadows Reservoir	Reservoir inflow	728	231	3.4%
I_BTVLY	16	Butt Valley Reservoir	Reservoir inflow	75	31	0.3%
I_ANTLP	16	Antelope Reservoir	Reservoir inflow	33	23	0.2%
I_BUKSL	16	Bucks Lake	Reservoir inflow	85	40	0.4%
I_GRZLY	16	Grizzly Creek	Stream inflow	52	21	0.2%
I_ENF001	16	East Branch of North Fork Feather River near Rich Bar	Stream accretion	621	398	2.9%
I_NFF027	16	North Fork Feather River at Pulga	Stream accretion	754	286	3.5%
I_DAVIS	17	Lake Davis	Reservoir inflow	26	21	0.1%
I_FRMAN	17	Lake Frenchman	Reservoir inflow	23	18	0.1%
I_MFF073	17	Middle Fork Feather River near Portola	Stream accretion	115	64	0.5%
I_MFF019	17	Middle Fork Feather River near Merrimac	Stream accretion	962	540	4.5%
I_LGRSV	18	Little Grass Valley Reservoir	Reservoir inflow	78	36	0.4%
I_LST007	19	Sly Creek Reservoir	Reservoir inflow	75	36	0.3%

Label	Watershed Number	Description	Type	Average Annual Flow (TAF)	Standard Deviation of Annual Flow (TAF)	Average as Percent of Total Rim Inflow
I_SFF011	20	South Fork Feather River at Ponderosa Dam	Stream accretion	94	56	0.4%
I_SFF008	21	South Fork Feather at Enterprise	Stream accretion	21	13	0.1%
I_OROVL	22	Lake Oroville	Local reservoir inflow	282	243	1.3%
I_HON021	23	South Fork Honcut Creek near Bangor	Stream inflow	24	16	0.1%
Yuba River Watershed			**Total**	**2,354**		**10.9%**
I_MERLC	24	Merle Collins Reservoir	Reservoir inflow	48	33	0.2%
I_SLT009	25	Slate Creek at Slate Creek Diversion Dam	Stream inflow	141	67	0.7%
I_NFY029	26	North Fork Yuba River below Goodyears Bar	Stream inflow	539	245	2.5%
I_OGN005	27	Oregon Creek at Log Cabin Diversion Dam	Stream inflow	53	30	0.2%
I_JKSMD	28	Jackson Meadows Reservoir	Reservoir inflow	76	34	0.4%
I_MFY013	28	Middle Fork Yuba River above Our House Diversion Dam	Stream accretion	152	86	0.7%
I_NBLDB	29	New Bullards Bar Reservoir	Local reservoir inflow	402	221	1.9%
I_BOWMN	30	Bowman Lake	Reservoir inflow	93	36	0.4%
I_FRDYC	30	Fordyce Lake	Reservoir inflow	87	38	0.4%
I_SPLDG	30	Lake Spaulding	Local reservoir inflow	306	112	1.4%
I_SFY007	30	South Fork Yuba River at Jones Bar	Stream accretion	207	110	1.0%
I_ENGLB	31	Englebright Reservoir	Stream inflow	147	85	0.7%
I_SCOTF	32	Scotts Flat Reservoir	Local reservoir inflow	33	18	0.2%
I_DER004	32	Deer Creek at Wildwood Dam	Stream accretion	33	18	0.2%
I_DER001	32	Deer Creek near Smartville	Stream accretion	29	16	0.1%

Label	Watershed Number	Description	Type	Average Annual Flow (TAF)	Standard Deviation of Annual Flow (TAF)	Average as Percent of Total Rim Inflow
I_SFD003	32	South Fork Deer Creek at Wildwood Dam	Stream inflow	8	5	0.0%
Bear River Watershed			**Total**	**372**		**1.7%**
I_DHC001	33	Dry Creek and Hutchinson Creek	Stream inflow	54	36	0.2%
I_RLLNS	34	Rollins Reservoir natural inflow	Local reservoir inflow	160	102	0.7%
I_CMBIE	35	Combie Reservoir	Local reservoir inflow	31	16	0.1%
I_WLF013	36	Wolf Creek at Tarr Ditch Diversion Dam	Stream inflow	19	10	0.1%
I_CMPFW	37	Camp Far West Reservoir	Local reservoir inflow	16	8	0.1%
I_BRR023	37	Camp Far West Reservoir	Local reservoir inflow	93	49	0.4%
American River Watershed			**Total**	**2,705**		**12.6%**
I_LKVLY	38	Lake Valley Reservoir	Reservoir inflow	9	5	0.0%
I_NFA054	39	North Fork American River	Stream inflow	353	187	1.6%
I_NFA022	40	North Fork American River at North Fork Dam local inflow	Stream accretion	219	116	1.0%
I_FRMDW	41	French Meadows Reservoir	Reservoir inflow	114	54	0.5%
I_RBCON	41	Rubicon Lake	Reservoir Inflow	75	29	0.4%
I_DCC007	41	Duncan Canyon Creek	Stream inflow	28	13	0.1%
I_BKILD	41	Bucks Island Lake	Stream inflow	20	6	0.1%
I_RUB001	41	Local Inflows to Rubicon River	Stream accretion	100	64	0.5%
I_HHOLE	41	Hell Hole Reservoir	Local reservoir inflow	207	94	1.0%
I_LOONL	41	Loon Lake	Reservoir inflow	22	9	0.1%
I_SFR005	41	South Fork Rubicon River Inflow	Stream inflow	80	38	0.4%

Label	Watershed Number	Description	Type	Average Annual Flow (TAF)	Standard Deviation of Annual Flow (TAF)	Average as Percent of Total Rim Inflow
I_STMPY	41	Stumpy Meadows Reservoir	Reservoir inflow	22	13	0.1%
I_LNG000	41	Long Creek Canyon at mouth	Stream inflow	74	46	0.3%
I_MFA036	41	Middle Fork American River at Interbay Diversion Dam	Stream accretion	51	26	0.2%
I_MFA001	41	Middle Fork American River near Auburn local inflow	Stream accretion	245	152	1.1%
I_UNVLY	42	Union Valley Reservoir	Reservoir inflow	168	85	0.8%
I_ICEHS	42	Ice House Reservoir	Reservoir inflow	56	25	0.3%
I_CAPLS	42	Caples Lake	Reservoir inflow	27	11	0.1%
I_SILVR	42	Silver Lake	Reservoir inflow	26	12	0.1%
I_SFA056	42	South Fork American River at Kyburz	Stream inflow	247	121	1.1%
I_ALD001	42	Alder Creek near Whitehall	Stream inflow	28	17	0.1%
I_PLM001	42	Plum Creek Inflow	Stream inflow	7	4	0.0%
I_SFA035	42	South Fork American River near Camino	Stream accretion	171	107	0.8%
I_SFA021	42	South Fork American River near Placerville	Stream accretion	107	75	0.5%
I_FOLSM	43	Folsom Lake	Local reservoir inflow	249	309	1.2%
Sacramento River Westside Tributaries			**Total**	**1,529**		**7.1%**
I_CLR025	46	Whiskeytown Lake	Reservoir inflow	285	173	1.3%
I_CLR011	47	Clear Creek near Igo	Stream accretion	46	28	0.2%
I_CWD018	48	North Fork and Middle Fork Cottonwood Creek near Olinda	Stream inflow	298	215	1.4%
I_SCW008	49	South Fork Cottonwood Creek near Olinda	Stream inflow	178	137	0.8%
I_ELD027	50	Elder Creek near Paskenta	Stream inflow	68	49	0.3%

Label	Watershed Number	Description	Type	Average Annual Flow (TAF)	Standard Deviation of Annual Flow (TAF)	Average as Percent of Total Rim Inflow
I_THM028	51	Thomes Creek at Paskenta	Stream inflow	217	128	1.0%
I_EPARK	52	East Park Reservoir inflow	Reservoir inflow	66	37	0.3%
I_SGRGE	53	Stony Gorge Reservoir	Local reservoir inflow	165	120	0.8%
I_BLKBT	54	Black Butte Lake	Local reservoir inflow	205	170	1.0%
Yolo Bypass Tributaries			**Total**	**998**		**4.6%**
I_CLRLK	55	Clear Lake	Reservoir inflow	436	248	2.0%
I_INDVL	56	Indian Valley Reservoir	Reservoir inflow	111	78	0.5%
I_BRC003	57	Bear Creek above Holsten Chimney	Stream inflow	34	28	0.2%
I_CCH053	58	Cache Creek above Rumsey	Stream accretion	55	48	0.3%
I_BRYSA	59	Lake Berryessa	Reservoir inflow	362	263	1.7%
Calaveras River Watershed			**Total**	**162**		**0.8%**
I_NHGAN	61	New Hogan Reservoir	Reservoir inflow	154	119	0.7%
I_CLV026	62	Calaveras River at Bellota	Stream inflow	8	7	0.0%
Mokelumne River Watershed			**Total**	**848**		**3.9%**
I_LBEAR	63	Lower Bear Reservoir	Reservoir inflow	73	31	0.3%
I_MFM010	63	Middle Fork Mokelumne near West Point	Stream inflow	47	32	0.2%
I_NFM006	63	North Fork Mokelumne below Tiger Creek Reservoir	Stream accretion	153	81	0.7%
I_SFM006	63	South Fork Mokelumne near West Point	Stream inflow	56	39	0.3%
I_SLTSP	63	Salt Springs Reservoir	Reservoir Inflow	332	142	1.5%
I_MOK079	63	Mokelumne River at Mokelumne Hill	Stream accretion	70	46	0.3%
I_PARDE	64	Pardee Reservoir	Local reservoir inflow	11	10	0.1%

Label	Watershed Number	Description	Type	Average Annual Flow (TAF)	Standard Deviation of Annual Flow (TAF)	Average as Percent of Total Rim Inflow
I_CMCHE	65	Camanche Reservoir	Local reservoir inflow	11	8	0.1%
I_AMADR	66	Amador Reservoir	Reservoir inflow	29	21	0.1%
I_DSC035	67	Dry and Sutter creeks	Stream inflow	65	51	0.3%
Cosumnes River Watershed			**Total**	**399**		**1.9%**
I_JNKSN	68	Jenkinson Lake	Reservoir inflow	17	12	0.1%
I_CMP001	68	Camp Creek at mouth	Stream inflow	12	7	0.1%
I_CMP012	68	Camp Creek at Camp Creek Diversion Tunnel	Stream inflow	32	19	0.1%
I_CSM035	68	Cosumnes River at Michigan Bar	Stream accretion	305	217	1.4%
I_DEE023	69	Deer Creek	Stream inflow	33	26	0.2%
Delta Tributaries			**Total**	**16**		**0.1%**
I_LOSVQ	70	Los Vaqueros Reservoir	Reservoir inflow	1	2	0.0%
I_MSH015	71	Marsh Creek	Stream inflow	14	16	0.1%
Total				**21,498**	**10,080**	

A.3 C2VSim Current Conditions Simulation for Estimating Stream-Groundwater Interaction

Estimating stream-groundwater interaction throughout the Sacramento Valley under current conditions with 82 years of historical hydrology presents a challenge. Historical simulations that assume changing land use, regulations, and hydrology using C2VSim show a trend of declining groundwater elevations over the 82-year study with the steepest declines over the last decade of simulation (DWR 2016b). Long-term trends in groundwater elevation result in trends of declining stream gains and increasing stream losses to groundwater. In contrast, the purpose of this report is to estimate unimpaired flows that would occur under current groundwater storage conditions given the range of variability in hydrology during the 82-year record. This requires a method for holding the relationship between stream flow and gain or loss to groundwater constant over the duration of the simulation. This was accomplished in the C2VSim model by repeatedly re-setting groundwater storage levels to recent (2009) conditions instead of allowing groundwater levels to trend downward through the 82-year simulation period. This approach allowed for a better estimate of stream-groundwater interaction under current conditions over the 82-year simulation period for use in estimating unimpaired flows, and is discussed in more detail below in Section A.3.1, *Methods*.

A.3.1 Methods

C2VSim is a monthly finite element model that simulates linked groundwater and surface water flow throughout California's Central Valley (DWR 2016b). C2VSim requires initial conditions, land use, urban demands, inflows, and diversion information as model inputs. Each of these inputs was developed from previous contract amounts, C2VSim studies, or CalSim II baseline studies. Monthly land use and urban demands were set equal to their respective monthly levels in water year 2005 from version R374 of the C2VSim coarse-grid (C2VSim-CG) historical simulation developed by DWR (DWR 2016b). Land use and urban demands were assumed to be constant throughout the simulation period. Major inflows and diversions used in the current condition C2VSim simulation came from the 2015 Delivery Capability Report studies and smaller inflows and diversions came from the C2VSim historical run (Table A-4 and Table A-5).

To remove long-term trends in groundwater elevation and better simulate current stream-groundwater interaction over the 82-year simulation period, an ensemble approach was taken. The ensemble runs were created by running multiple 3-year simulations, with an individual ensemble run beginning in each year of the 82-year C2VSim simulation period, and each with the initial condition equal to the October 2009 groundwater storages. The results for the first 2 years of each ensemble run were treated as a warm-up period to allow each ensemble run to stabilize, and were discarded. The results for year 3 of each ensemble run were then stitched together to create a new 82-year time series that represents the stream gains and losses to groundwater with the variability in hydrology provided in the 82-year data set, while maintaining the current range of groundwater storages.

Table A-4. C2VSim Inflow Information Sources for the Current Conditions Model Run

Inflow Number	Stream Node	C2VSim Stream Name	Source of Inflow to C2VSim
1	205	Sacramento River	CalSim II (C5)
2	211	Cow Creek	CalSim II (C10801)
3	220	Battle Creek	CalSim II (C10803)
4	218	Cottonwood Creek	CalSim II (C10802)
5	225	Paynes and Sevenmile Creek	CalSim II (C11001)
6	233	Antelope Creek Group	CalSim II (C11307)
7	243	Mill Creek	CalSim II (C11308)
8	237	Elder Creek	C2VSim Historical
9	248	Thomes Creek	CalSim II (C11304)
10	256	Deer Creek Group	CalSim II (C11309)
11	263	Stony Creek	CalSim II (C42 + D42)
12	269	Big Chico Creek	CalSim II (C11501)
13	283	Butte and Chico Creek	CalSim II (I217)
14	341	Feather River	CalSim II (C203)
15	349	Yuba River	CalSim II (I230)
16	357	Bear River	CalSim II (I285)

Inflow Number	Stream Node	C2VSim Stream Name	Source of Inflow to C2VSim
17	390	Cache Creek	C2VSim 2000–2009 Matching[a]
18	374	American River	CalSim II (C8)
19	400	Putah Creek	C2VSim 2000–2009 Matching
20	188	Cosumnes River	CalSim II (C501)
21	182	Dry Creek	C2VSim Historical
22	173	Mokelumne River	CalSim II (I504) + C2VSim Diversion 84
23	161	Calaveras River	CalSim II (C92)
24	146	Stanislaus River	CalSim II (C520)
25	135	Tuolumne River	CalSim II (C540)
26	128	Oristimba Creek	C2VSim Historical
27	116	Merced River	CalSim II (C20)
28	105	Bear Creek Group	C2VSim Historical
29	93	Deadman's Creek	C2VSim Historical
30	80	Chowchilla River	CalSim II (C53)
31	69	Fresno River	CalSim II (C52)
32	54	San Joaquin River	CalSim II (C18)
33	23	Kings River	C2VSim 2000–2009 Matching
34	420	Kaweah River	C2VSim 2000–2009 Matching
35	10	Tule River	C2VSim 2000–2009 Matching
36	1	Kern River	C2VSim 2000–2009 Matching
37	24	FKC Wasteway Deliveries to Kings River	C2VSim 2000–2009 Matching
38	11	FKC Wasteway Deliveries to Tule River	C2VSim 2000–2009 Matching
39	421	FKC Wasteway Deliveries to Kaweah River	C2VSim 2000–2009 Matching
40	4	Cross-Valley Canal deliveries to Kern River	C2VSim 2000–2009 Matching
41	4	Friant-Kern Canal deliveries to Kern River	C2VSim 2000–2009 Matching

Notes: CalSim II data are from the 2015 Delivery Capability Report CalSim II study. Model node is listed in parentheses. C2VSim historical data are from version R374 of the C2VSim-CG model.

[a] "C2VSim 2000–2009 Matching" indicates that the values for 1992–1999 were chosen from the most similar year from 2000 to 2009 based on the Sacramento Valley index.

Table A-5. C2VSim Diversion Information Sources for the Current Conditions Model Run

C2VSim ID	C2VSim Diversion	Assumed Current Conditions Diversion
1	Whiskeytown and Shasta for Ag	Contract amount, CalSim annual allocation, 2000–2009 C2VSim historical monthly pattern
2	Whiskeytown and Shasta for M&I	Contract amount, CalSim annual allocation, 2000–2009 C2VSim historical monthly pattern
3	Sacramento River to Bella Vista conduit for Ag	Contract amount, CalSim annual allocation, 2000–2009 C2VSim historical monthly pattern
4	Sacramento River to Bella Vista conduit for M&I	Contract amount, CalSim annual allocation, 2000–2009 C2VSim historical monthly pattern

C2VSim ID	C2VSim Diversion	Assumed Current Conditions Diversion
5	Sacramento River to Bella Vista conduit for export	Contract amount, CalSim annual allocation, 2000–2009 C2VSim historical monthly pattern
6	Sacramento River, Keswick Dam to Red Bluff, for Ag	Contract amount, CalSim annual allocation, 2000–2009 C2VSim historical monthly pattern
7	Sacramento River, Keswick Dam to Red Bluff, for M&I	Contract amount, CalSim annual allocation, 2000–2009 C2VSim historical monthly pattern
8	Cow Creek riparian diversions	Average 2000–2009 C2VSim historical
9	Battle Creek riparian diversions	Average 2000–2009 C2VSim historical
10	Cottonwood Creek riparian diversions	Average 2000–2009 C2VSim historical
11	Clear Creek riparian diversions	Zero
12	Sacramento River diversions to the Corning Canal	CalSim II arc D171
13	Stony Creek to North Canal	CalSim II arc D17301
14	Stony Creek to South Canal	CalSim II arc D42
15	Stony Creek to the Tehama-Colusa Canal	Zero
16	Stony Creek to the Glenn-Colusa Canal	Zero
17	Sacramento River to Subregion 2	Contract amount, CalSim annual allocation, 2000–2009 C2VSim historical monthly pattern
18	Antelope Creek riparian diversions	Average 2000–2009 C2VSim historical
19	Mill Creek riparian diversions	Average 2000–2009 C2VSim historical
20	Elder Creek riparian diversions	Average 2000–2009 C2VSim historical
21	Thomes Creek riparian diversions	Average 2000–2009 C2VSim historical
22	Deer Creek riparian diversions	Average 2000–2009 C2VSim historical
23	Sacramento River to the Tehama-Colusa Canal to Subregion 2	CalSim II arc D172
24	Sacramento River to the Tehama-Colusa Canal to Subregion 3	CalSim II arc C171 less D172
25	Sacramento River to the Glenn-Colusa Canal for Ag	CalSim II arc D114 less D143B, less 145B
26	Sacramento River to the Glenn-Colusa Canal for Refuges	Contract amount, CalSim annual allocation, 2000–2009 C2VSim historical monthly pattern
27	Sacramento River to Subregion 3	Average 2000–2009 C2VSim historical * CalSim annual allocation
28	Sacramento River to Subregion 4	Average 2000–2009 C2VSim historical * CalSim annual allocation
29	Little Chico Creek	Average 2000–2009 C2VSim historical
30	Tarr Ditch	Average 2000–2009 C2VSim historical
31	Miocine and Wilenor Canals	Average 2000–2009 C2VSim historical
32	Palermo Canal	Average 2000–2009 C2VSim historical
33	Oroville-Wyandotte ID through Forbestown Ditch	Average 2000–2009 C2VSim historical
34	Little Dry Creek	Average 2000–2009 C2VSim historical
35	Bangor Canal	Average 2000–2009 C2VSim historical

C2VSim ID	C2VSim Diversion	Assumed Current Conditions Diversion
36	Thermalito Afterbay	Average 2000–2009 C2VSim historical, except in 1924, 1931, 1934, 1977, 1988, and 1991 assume 525,000 AF/year (Jan-Dec)
37	Feather River to Subregion 5 for Ag (replaced by Thermalito Afterbay)	Zero
38	Feather River to Thermalito ID	Average 2000–2009 C2VSim historical, but not more than 8,200 AF/year
39	Feather River to Subregion 5 for Ag	Average 2000–2009 C2VSim historical, except in 1924, 1931, 1934, 1977, 1988, and 1991 assume 65,895 AF/year (Jan–Dec)
40	Feather River to Yuba City	Average 2000–2009 C2VSim historical
41	Feather River to Subregion 7 for Ag	Average 2000–2009 C2VSim historical
42	Yuba River for Ag	Average 2000–2009 C2VSim historical, except in 1977 assume cut by 50%.
43	Yuba River for M&I	Zero
44	Bear River to Camp Far West ID North Side	Average 2000–2009 C2VSim historical
45	Bear River to Camp Far West ID South Side	Average 2000–2009 C2VSim historical
46	Bear River to South Sutter WD	Average 2000–2009 C2VSim historical
47	Bear River Canal to South Sutter WD	Average 2000–2009 C2VSim historical
48	Boardman Canal	Average 2000–2009 C2VSim historical
49	Combie (Gold Hill) Canal	Average 2000–2009 C2VSim historical
50	Cross Canal	Average 2000–2009 C2VSim historical excluding Shasta critical years. In Shasta critical years, average data from 1991, 1992, 1994 C2VSim historical.
51	Butte Creek at Parrott-Phelan Dam	Average 2000–2009 C2VSim historical
52	Butte Creek at Durham Mutual Dam	Average 2000–2009 C2VSim historical
53	Butte Creek at Adams & Gorrill Dams	Average 2000–2009 C2VSim historical
54	Butte Creek to RD 1004	Average 2000–2009 C2VSim historical
55	Butte Creek to Sutter and Butte Duck Clubs	Average 2000–2009 C2VSim historical
56	Butte Slough	Average 2000–2009 C2VSim historical
57	Sutter Bypass East Borrow Pit to Sutter NWR	Average 2000–2009 C2VSim historical
58	Sutter Bypass West Borrow Pit North of Tisdale Bypass	Average 2000–2009 C2VSim historical
59	Sutter Bypass East Borrow Pit to lands within Sutter Bypass	Average 2000–2009 C2VSim historical
60	Sutter Bypass East Borrow Pit from North of Wadsworth Canal to Gilsizer Slough	Average 2000–2009 C2VSim historical
61	Sutter Bypass East Borrow Pit South of Gilsizer Slough	Average 2000–2009 C2VSim historical
62	Colusa Basin Drain to Subregion 3 for Ag	Average 2000–2009 C2VSim historical

C2VSim ID	C2VSim Diversion	Assumed Current Conditions Diversion
63	Colusa Basin Drain to Subregion 3 for Refuges	Average 2000–2009 C2VSim historical
64	Knights Landing Ridge Cut	Average 2000–2009 C2VSim historical
65	Sacramento River between Knights Landing and Sacramento to Subregion 6 for Ag	Average 2000–2009 C2VSim historical excluding Shasta critical years. In Shasta critical years, average data from 1991, 1992, 1994 C2VSim historical.
66	Sacramento River to City of West Sacramento	Average 2000–2009 C2VSim historical
67	Sacramento River between Knights Landing and Sacramento to Subregion 7 for Ag	Average 2000–2009 C2VSim historical excluding Shasta critical years. In Shasta critical years, average data from 1991, 1992, 1994 C2VSim historical.
68	Sacramento River to City of Sacramento	Average 2000–2009 C2VSim historical
69	Cache Creek	Average 2000–2009 C2VSim historical
70	Yolo Bypass	Average 2000–2009 C2VSim historical
71	Putah South Canal for Ag	Average 2000–2009 C2VSim historical
72	Putah South Canal for M&I	Average 2000–2009 C2VSim historical
73	Putah South Canal exports	Average 2000–2009 C2VSim historical
74	Putah Creek riparian diversions	Average 2000–2009 C2VSim historical
75	Folsom Lake for Ag	Average 2000–2009 C2VSim historical
76	Folsom Lake for M&I	Average 2000–2009 C2VSim historical
77	Folsom South Canal for Ag	Zero
78	Folsom South Canal for M&I	Contract amount, CalSim annual allocation, 2000–2009 C2VSim historical monthly pattern
79	Folsom South Canal exports	Zero
80	American River to Carmichael WD	Average 2000–2009 C2VSim historical
81	American River to City of Sacramento	Average 2000–2009 C2VSim historical
82	Cosumnes River	Average 2000–2009 C2VSim historical
83	Mokelumne River from Camanche Reservoir	Average 2000–2009 C2VSim historical
84	Mokelumne River	Average 2000–2009 C2VSim historical
85	Calaveras River	CalSim II arc D506A + D506B + D506C +D507
86	Sacramento-San Joaquin Delta for Ag	Average 2000–2009 C2VSim historical
87	Sacramento-San Joaquin Delta for M&I	Average 2000–2009 C2VSim historical
88	Sacramento-San Joaquin Delta to North Bay Aqueduct for Ag	Zero
89	Sacramento-San Joaquin Delta to North Bay Aqueduct for M&I	CalSim II arc (1/3)*D403C
90	Sacramento-San Joaquin Delta to North Bay Aqueduct export	CalSim II arc D403A + D403B + (2/3)*D403C +D403D
91	Sacramento-San Joaquin Delta to Contra Costa Canal	CalSim II arc D408_OR + D408_RS +D408_VC
92	Sacramento-San Joaquin Delta to CVP	CalSim II arc D418 + D419_CVP

C2VSim ID	C2VSim Diversion	Assumed Current Conditions Diversion
93	Sacramento-San Joaquin Delta to SWP	CalSim II arc D419_SWP

Notes: CalSim II data are from the 2015 Delivery Capability Report CalSim II study. C2VSim historical data are from version R374 of the C2VSim-CG model.
Ag = agriculture
M&I = municipal and industrial
WD = water district
ID = irrigation district
CVP = Central Valley Project
SWP = State Water Project
NWR = National Wildlife Refuge

A.3.2 Results

Table A-6 presents a summary of the stream-groundwater interactions for the C2VSim reaches that are represented in SVUFM. These reaches include the valley floor portion of the Sacramento Valley watershed, the lower sections of the Delta eastside tributaries, and the Delta (DWR 2016c). On average, this region lost an estimated 876 TAF/yr, with average annual gains or losses varying by subregion:

- The Delta eastside tributaries lost an average of 151 TAF/yr, with the greatest loss (91 TAF/yr) occurring along the Mokelumne River upstream of its confluence with the Cosumnes River.
- The Sacramento River valley floor watershed lost an average of 494 TAF/yr, with the northern portion of the watershed (north of Thomes Creek) experiencing an average gain of 126 TAF/yr and the southern portion of the watershed experiencing an average loss of 620 TAF/yr, with the biggest losses occurring along the Sacramento River north and south of the American River (reaches 65 and 67).
- The Yolo Bypass and its tributaries (Cache and Putah Creeks) lost an average of 152 TAF/yr.
- The Delta (including reaches 26, 28, 29, and 71–74) experienced relatively small change in flow associated with stream-groundwater interaction (average loss of 78 TAF/yr).

Additional information regarding the magnitude of the stream-groundwater interaction in relation to total flow and variation in stream-groundwater interaction through the year is presented in Section A.4.

Table A-6. Average Annual Stream-Groundwater Interaction Simulated by the C2VSim Current Conditions Run

C2VSim Reach Name[a]	Average Annual Gain (+)/ Loss (-) (TAF)
REACH 25 - CALAVERAS RIVER	-53
REACH 26 - SAN JOAQUIN RIVER (part of Delta)	-33
REACH 27 - MOKELUMNE RIVER	-91
REACH 28 - DRY CREEK	-3
REACH 29 - COSUMNES RIVER	-3
REACH 30 - MOKELUMNE (SOUTH) (part of Delta)	-23

C2VSim Reach Name[a]	Average Annual Gain (+)/ Loss (-) (TAF)
REACH 31 - SAN JOAQUIN RIVER (part of Delta)	-5
REACH 32 - SACRAMENTO RIVER	1
REACH 33 - COW CREEK	-11
REACH 34 - SACRAMENTO RIVER	18
REACH 35 - COTTONWOOD CREEK	-7
REACH 36 - BATTLE CREEK	10
REACH 37 - SACRAMENTO RIVER	25
REACH 38 - PAYNES CREEK	12
REACH 39 - SACRAMENTO RIVER	43
REACH 40 - ANTELOPE CREEK	14
REACH 41 - SACRAMENTO RIVER	9
REACH 42 - ELDER CREEK	2
REACH 43 - MILL CREEK	2
REACH 44 - SACRAMENTO RIVER	8
REACH 45 - THOMES CREEK	-18
REACH 46 - SACRAMENTO RIVER	4
REACH 47 - DEER CREEK	-1
REACH 48 - SACRAMENTO RIVER	0
REACH 49 - STONY CREEK	-69
REACH 50 - BIG CHICO CREEK	0
REACH 51 - SACRAMENTO RIVER	-22
REACH 52 - BUTTE CREEK	-122
REACH 53 - SACRAMENTO RIVER	-24
REACH 54 - GLENN COLUSA CANAL	0
REACH 55 - COLUSA BASIN DRAINAGE CANAL	80
REACH 56 - COLUSA BASIN DRAINAGE CANAL	63
REACH 57 - SACRAMENTO RIVER	-14
REACH 58 - SUTTER BYPASS	-44
REACH 59 - FEATHER RIVER	6
REACH 60 - YUBA RIVER	-22
REACH 61 - FEATHER RIVER	-67
REACH 62 - BEAR RIVER	-40
REACH 63 - FEATHER RIVER	31
REACH 64 - FEATHER RIVER	-26
REACH 65 - SACRAMENTO RIVER	-175
REACH 66 - AMERICAN RIVER	-56
REACH 67 - SACRAMENTO RIVER	-104
REACH 68 - CACHE CREEK	-87
REACH 69 - PUTAH CREEK	-54
REACH 70 - YOLO BYPASS - CACHE SLOUGH	-12
REACH 71 - SACRAMENTO RIVER	-17

C2VSim Reach Name[a]	Average Annual Gain (+)/ Loss (-) (TAF)
REACH 72 - SACRAMENTO-SAN JOAQUIN DELTA	-2
REACH 73 - SUISUN MARSH	80
REACH 74 - EXTEND SJR TO CARQUINEZ STRAIGHT	-79
Total	-876

[a] Reaches presented in hydrologic order with reaches 25–31 covering the Delta eastside tributaries and the southern and central Delta from south to north, and reaches 32–74 covering the Sacramento Valley and northern and western Delta from north to south.

A.4 Sacramento Valley Unimpaired Flow Model

A.4.1 Introduction

For many years DWR has been using the Water Resources Integrated Modeling System (WRIMS) to create, use, and improve the CalSim model for simulating water operations in the California Central Valley. CalSim II is the current working version of the model, but DWR is working on an improved version of this model, CalSim 3. In order to help the State Water Board assess unimpaired flow in the Sacramento Valley, DWR staff developed a SVUFM that was developed with WRIMS utilizing relevant parts of the CalSim framework.

A.4.2 Methods

A.4.2.1 Basic Assumptions

To simulate unimpaired flow using SVUFM, the following basic assumptions were made:

- No reservoir operations
- No diversions
- No imports or exports
- No return flows
- Existing weirs operate under current conditions
- Delta Cross Channel Gate is open all the time
- No groundwater pumping. Groundwater pumping does not connect or affect the stream network of SVUFM
- San Joaquin River unimpaired inflows are not modeled in SVUFM and are instead represented by model input as unimpaired flows estimated using methods outlined in DWR's Unimpaired Flows Report (DWR 2007).

A.4.2.2 SVUFM Modeling Approach

SVUFM is simply a data integration model with limited routing capability. It is assumed that the valley floor unimpaired flow (UF) consists of three components, as shown in Figure A-2, Unimpaired

Flow Components in SVUFM. The three components of the valley floor UF are the unimpaired rim watershed inflow (URI), the valley floor surface rainfall runoff (SR), and the stream gain from the groundwater aquifer or loss to the groundwater aquifer (SG). Three time series input datasets are used to incorporate these three flow components into the SVUFM channel network:

1. Rim watershed inflows (URIin)
2. Valley floor surface rainfall runoff (SRin)
3. Stream gain/losses (SGin)

The rim watershed inflow dataset was developed based on historical observations. Its development is described above in Section A.2, *Rim Watershed Hydrology*. The valley floor surface rainfall runoff dataset was simulated by CalSimHydro (discussed further below). The stream gain/loss dataset was simulated by a current-condition run of the C2VSim standalone model, and its development is described above in Section A.3, *C2VSim Current Conditions Simulation for Estimating Stream-Groundwater Interaction.*

In general, the unimpaired flow at the outlet of a tributary in the valley floor can be written as

$$UF_i = URI_i + SR_i + SG_i$$

Where

UFi = Unimpaired flow at the i-th tributary outlet,

URIi = Sum of unimpaired rim watershed inflows of the i-th tributary,

SRi = Sum of valley floor surface rainfall runoff along the i-th tributary, and

SGi = Sum of stream gain/losses (SG) along the i-th tributary.

In the impaired case, the full water balance would also include the sum of terms

Di = Sum of diversions (D) along the i-th tributary, and

Ri = Sum of return flows (R) along the i-th tributary,

which are taken to be zero in the unimpaired case.

The flow continuity in the SVUFM channel network is ensured by mass balance calculations at all stream nodes. In a few instances, estimated stream losses are greater than the flow in the river. Because negative flow is not physically possible, the input stream gain/loss (SGi) terms are modified internally in SVUFM to ensure that they are not greater than stream flow. This means that the SG used by SVUFM may be different from SGi. There are no other alterations to the model inputs and there is no addition of “closure terms” as is used with CalSim II modeling to compensate for differences between model results and measurements (partly because there are no direct measurements of unimpaired flow on the valley floor). The accuracy of SVUFM is mainly determined by the data quality of the three input datasets.

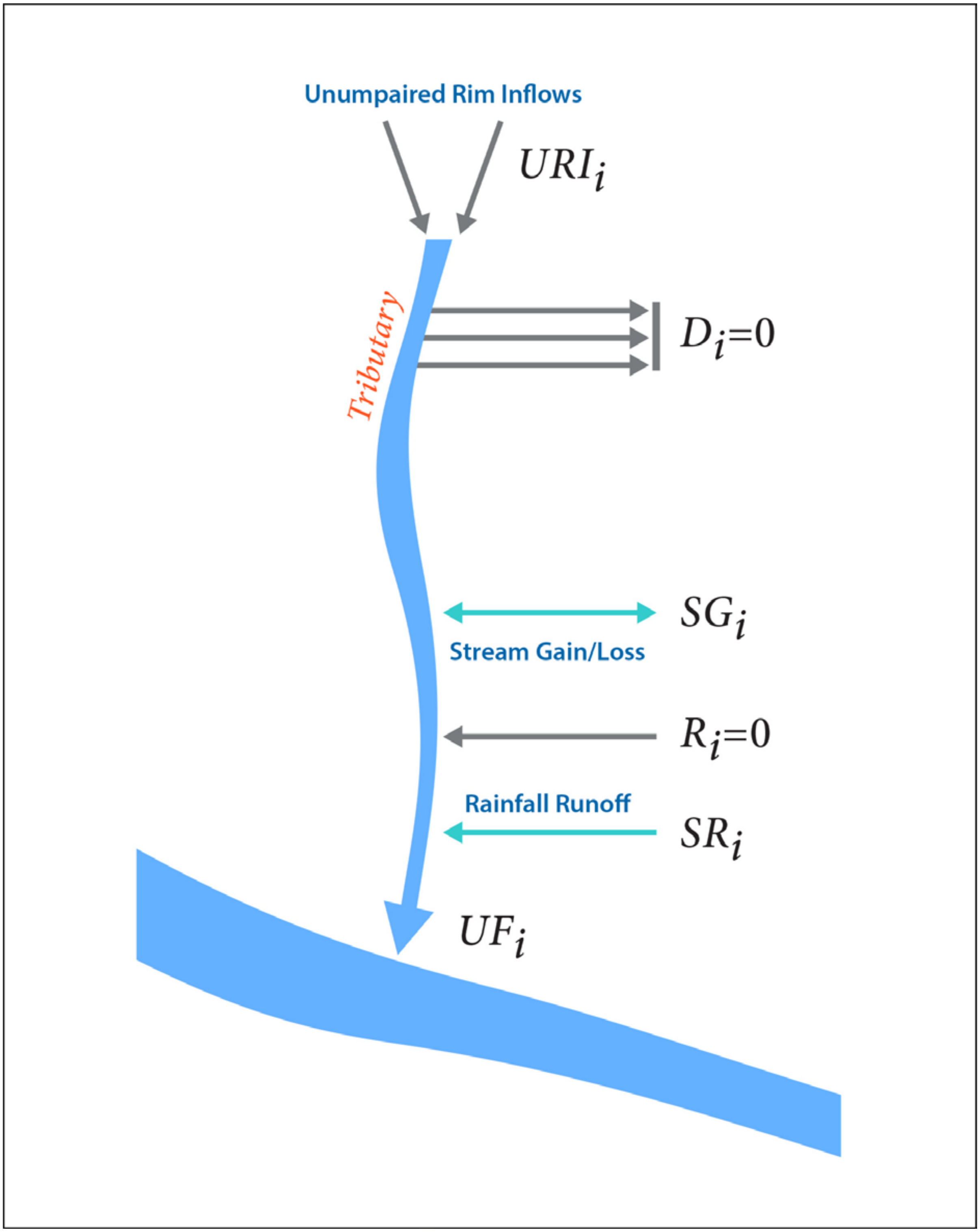

Figure A-2. Illustration of Unimpaired Flow Components in SVUFM

A.4.2.3 SVUFM Channel Network

SVUFM routes channel flows through the channel network of the Sacramento Valley, which is shown in the SVUFM schematic (Attachment A). The SVUFM network represents the water conveyance system of the Sacramento River hydrologic region and the Delta. The network is the foundation of SVUFM.

The SVUFM channel network is in the form of a node-arc network. Nodes represent specific locations, such as weirs, tributary confluences, and groundwater seepages. Flow arcs represent flows between nodes. Mass balance must be observed at each node (i.e., flows in the incoming arcs equal flows in the outgoing arcs except at nodes representing reservoirs where a change in storage may occur).

Flow arcs in SVUFM represent average monthly flows to, from, or between nodes. Arcs must connect to at least one node. Drawing conventions for arcs and nodes are shown in Figure A-3, Schematic Conventions for Flow Arcs and Nodes. Flow direction is indicated by an arrow pointing in the direction of flow. In SVUFM, arc names are generally composed of three parts: a prefix denoting the type of arc (e.g., inflow, channel, surface runoff); the arc's node of origin; and the arc's destination node. SVUFM does not include diversion or return flow arcs because diversions and returns are set to zero.

Nodes

Conveyance Nodes

The SVUFM schematic displays conveyance nodes as circles bearing a six-character "license plate" abbreviation of the conveyance name and RM or channel milepost (MP). Line types and colors are used to represent a variety of node attributes. Blue outlines represent natural conveyance channels. A gray fill color indicates a gaging station or gage location. A node with gray fill and dashed outline indicates that the gage has been discontinued.

Reservoir Nodes

Reservoir storages are not included in SVUFM. However, the reservoir nodes are shown to indicate location of the reservoirs. They have a five-character abbreviation of either the name of the dam or reservoir. For example, "SHSTA" is used to denote the location of Shasta Lake.

Flow Arcs

Channel Arcs

Channel arcs (C_*oooooo*) are used to represent flow in a stream reach or constructed channel. The destination node is omitted from the channel arc name. For example, Cottonwood Creek is abbreviated as "CWD" and the node near RM 4 of the Cottonwood Creek is shown as "CWD004". The channel arc C_CWD004 (C_*oooooo*) represents flow downstream of the stream node CWD004 near RM 4 of the Cottonwood Creek, as shown in Figure A-3.

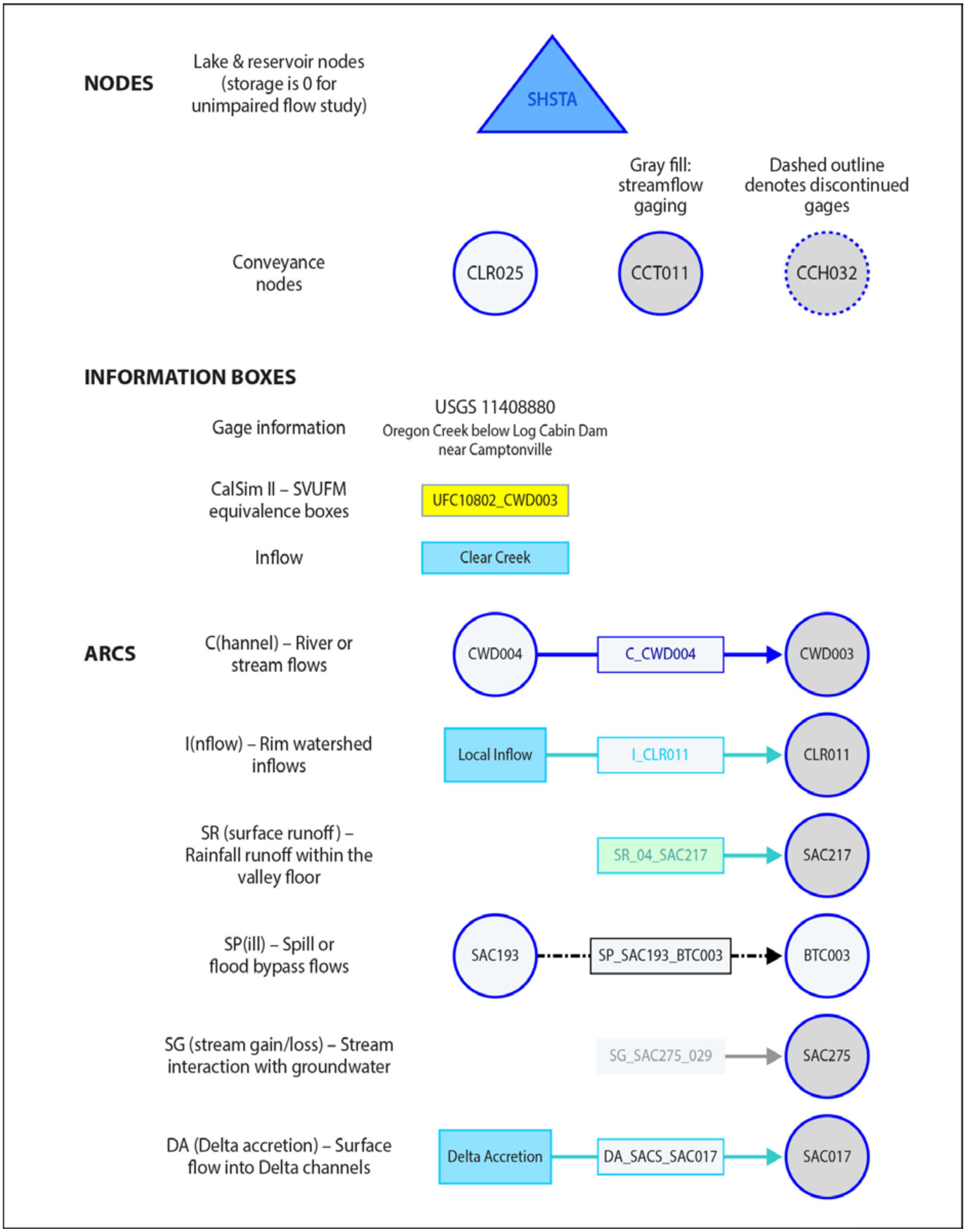

Figure A-3. Schematic Conventions for Flow Arcs and Nodes

Stream Gain/Loss Arcs

Stream gain/loss arcs are labeled with an "SG_" prefix, followed by the receiving node name and the corresponding C2VSim groundwater node. For example, the stream gain/loss arc SG_SAC259_056 represents stream gain/loss at the node SAC259 near RM 259 of the Sacramento River and "056" is used to indicate the C2VSim groundwater node. Groundwater inflow to the stream system only occurs at stream nodes with corresponding C2VSim stream nodes. On the SVUFM schematic, groundwater inflow to nodes is indicated by an incoming gray arc.

Inflow Arcs

Inflow arcs (I_*dddddd*) are used to represent rim inflow or local inflow to a node in the channel network (e.g., a reservoir node). For example, the inflow arc I_SHSTA (I_*dddddd*) represents inflow to the Shasta Lake node SHSTA. These inflows are model inputs.

Surface Runoff Arcs

Surface runoff arcs (SR_*ooo_dddddd*) are used to represent surface runoff from a water budget area (WBA) to a node in the channel network. For example, the surface runoff arc SR_04_SAC217 represents surface runoff from WBA 04 (*ooo*) to the stream node SAC217 (*dddddd*) near RM 217 of the Sacramento River. These runoff values are calculated by SVUFM based the contributing area fraction of the surface runoff from the WBA, which is from CalSimHydro as explained below.

Delta Accretion Arcs

Delta accretion arcs (DA_*oooo_dddddd*) are used to represent local surface inflow to the Delta. For example, the Delta accretion arc DA_SACS_SAC017 represents delta accretion from the south side of the Delta near the Sacramento River (*oooo*) to stream node SAC017 (*dddddd*) near RM 17 of the Sacramento River. The six Delta accretion arcs are Sacramento North, Sacramento South, Sacramento West, San Joaquin River West, San Joaquin River East, and Mokelumne.

Weir Spill Arcs

Weir spill arcs (SP_*oooooo_dddddd*) are used to represent flood spills from the Sacramento River flood control system weirs and flood relief structures (FRS). For example, the weir spill arc SP_SAC148_BTC003 represents flood spill at the node SAC148 (*oooooo*) of the DWR Colusa Weir near RM 148 of the Sacramento River to the node BTC003 (*dddddd*) near RM 3 of Butte Creek.

CalSim II – SVUFM Equivalence Labels

To facilitate comparison with CalSim II, yellow highlighted boxes appear throughout the SVUFM schematic representing equivalent CalSim II flow arcs at selected key locations. For example, the yellow box with the label "UFC10802_CWD003" appears next to the channel arc with label "C_CWD003" to indicate that it is an unimpaired flow of the tributary Cottonwood Creek, and that the flow "C_CWD003" in SVUFM is the same arc "C10802" in CalSim II.

A.4.2.4 Operations

In general, a model of unimpaired flow does not include operations because water is allowed to flow downstream unimpeded. However, based on existing structure and channel configurations, some assumptions regarding the movement of water between channels are necessary.

Delta Cross Channel and Georgiana Slough Operation

In the SVUFM model, the Delta Cross Channel gates are assumed to be open all the time. A regression equation from CalSim II is used to compute flow through the Delta Cross Channel and Georgiana Slough (C_SAC029B) as a function of flow in the Sacramento River near the Delta Cross Channel (C_SAC041):

$$C\_SAC029B = 0.1321 \times C\_SAC041 + 1087.0$$

Weir Operations

To determine flood spills from existing FRSs and weirs in the Sacramento River, a piecewise linear function is used in SVUFM for each structure as its weir rating curves, as shown in the equation below,

$$Q_{spill} = \begin{cases} \alpha_0 \times Q & Q < Q_1 \\ \alpha_0 \times Q_1 + \alpha_1 \times (Q - Q_1) & Q_1 < Q \leq Q_2 \\ \alpha_0 \times Q_1 + \alpha_1 (Q_2 - Q_1) + \alpha_2 \times (Q - Q_2) & Q_2 < Q \end{cases}$$

Where Q represents the upstream inflow and Qspill represents the spill from the structure. α0, α1, α2, Q1, and Q2 are the rating curve parameters.

The SVUFM arc name and its equivalent CalSim II arc name of the FRSs and weirs in the Sacramento River are listed in Table A-7. The weir spill equation parameters are listed in Table A-8. These calculations are intended to represent existing functionality of these structures.

Table A-7. Sacramento Flood Relief Structures and Weirs

Name	SVUFM Arc	CalSim II Name
M&T Flood Relief Structure	SP_SAC193_BTC003	N/A
3Bs Flood Relief Structure	SP_SAC188_BTC003	N/A
Goose Lake Flood Relief Structure	SP_SAC178_BTC003	D117B
Moulton Weir	SP_SAC159_BTC003	D124
Colusa Weir	SP_SAC148_BTC003	D125
Tisdale Weir	SP_SAC122_SBP021	D126
Fremont Weir	SP_SAC083_YBP037	D160
Sacramento Weir	SP_SAC066_YBP020	D166A

Table A-8. Weir Spill Equation Parameters

Weir Name	α0	α1	α2	Q1	Q2
M&T Flood Relief Structure	0	0.73071	0.73071	90000	90000
3Bs Flood Relief Structure	0	0.73071	0.73071	90000	90000
Goose Lake Flood Relief Structure	0	0.73071	0.73071	90000	90000
Moulton Weir	0	0.1239	0.1621	26160	60707
Colusa Weir	0	0.4942	0.5718	16760	47178
Tisdale Weir	0	0.75177	0.75177	18000	18000

Fremont Weir	0	0.645	0.8566	36125	93308
Sacramento Weir	0	0.563	0.563	67800	67800

A.4.2.5 Input Dataset Preparation

Preparation of the three time series input datasets for SVUFM is described in the following sections.

Rim Watershed Inflows

Estimated unimpaired inflow to the SVUFM network comes from the disaggregated unimpaired rim inflows described in Section A.2, *Rim Watershed Hydrology*. There are some locations where disaggregated rim inflows need to be summed to provide unimpaired inflow to the SVUFM model network because the SVUFM schematic is not expanded as far upstream as the disaggregated rim inflows. Table A-9 shows the disaggregated rim inflows that were aggregated to create unimpaired rim inflows at the boundary locations on the SVUFM network.

Because the San Joaquin River is not part of the SVUFM model, unimpaired San Joaquin River inflow to the Delta is input to the SVUFM schematic domain in the same manner as the other rim inflows. Total San Joaquin River unimpaired inflow to the Delta is a model input that was estimated per the methods in California Central Valley Unimpaired Flow Data (DWR 2007). This inflow is named I_SJR042_SJVUF and is assigned to the channel arc C_SJR042 in SVUFM.

CalSimHydro (Valley Floor) Surface Rainfall Runoff

The surface rainfall runoff dataset used as input for SVUFM surface runoff arcs is generated by CalSimHydro as monthly time series for each WBA in the Sacramento Valley Floor from October 1921 to September 2009 in HEC DSS data format. CalSimHydro computes surface rainfall runoff for each WBA, whereas SVUFM requires these runoff values to be provided at channel node level. This difference was resolved by calculating surface runoff fractions. Using geographic information system (GIS) tools, surface runoff fractions were developed based on the WBA areas that intersect with the watershed areas adjacent to the stream. These surface runoff fractions were then used to scale down the WBA-level surface runoff to reflect the amount of surface runoff that flows into different sections of SVUFM Channel network. Locations of the SVUFM surface runoff arcs can be found in the SVUFM schematic.

Table A-9. Aggregation of Rim Inflows to Create Rim Inflows for SVUFM Schematic

Location	Rim Inflow Label in SVUFM Schematic	Disaggregated Rim Inflows Summed to Create SVUFM Rim Inflow[a]
North Fork Feather River at Pulga	I_NFF027	I_ALMMW, I_BTVLY, I_ANTLP, I_BUKSL, I_GRZLY, I_ENF001, and I_NFF027
Middle Fork Feather River near Merrimac	I_MFF019	I_DAVIS, I_FRMAN, I_MFF073, and I_MFF019
Middle Fork Yuba River above Our House diversion Dam	I_MFY013	I_JKSMD and I_MFY013
South Fork Yuba River at Jones Bar	I_SFY007	I_BOWMN, I_FRDYC, I_SPLDG, and I_SFY007
Deer Creek inflow to Yuba River	I_DER001	I_SCOTF, I_DER004, I_DER001, and I_SFD003

Middle Fork American River near Forest Hill	I_MFA023	I_FRMDW, I_RBCON, I_DCC007, I_BKILD, I_RUB001, I_HHOLE, I_LOONL, I_SFR005, I_STMPY, I_LNG000, and I_MFA036
South Fork American River near Placerville	I_SFA030	I_UNVLY, I_ICEHS, I_CAPLS, I_SILVR, I_SFA056, I_ALD001, I_PLM001, I_SFA035, and I_SFA021
Mokelumne River near Mokelumne Hill	I_MOK079	I_LBEAR, I_MFM010, I_NFM006, I_SFM006, I_SLTSP, and I_MOK079
Cosumnes River at Michigan Bar	I_CSM035	I_JNKSN, I_CMP001, I_CMP012, and I_CSM035

[a] Some of the disaggregated rim inflows have the same name as the SVUFM rim inflows, but they do not represent the same flow (typically they represent a local inflow instead of the total unimpaired flow in the river at that location).

CalSimHydro uses a daily rainfall runoff model to simulate the daily rainfall runoff for all un-ponded lands, including crops, urban areas, and native vegetation. The U.S. Soil Conservation Service (SCS) curve number method is used in the model. The SCS method is used to divide rainfall into surface runoff and associated “losses” (infiltration and evapotranspiration).The curve number used in these calculations depends on soil type, hydrologic condition (e.g., if ground cover is present to slow runoff and promote infiltration), land use, and antecedent moisture condition (estimated using an antecedent precipitation index). CalSimHydro uses land use conditions based on the ten year average of 1998-2007 DWR Division of Planning and Local Assistance (DPLA) land use survey data for agriculture and uses the 2006 data for urban area. The daily rainfall data used in CalSimHydro are spatially distributed precipitation from October 1921 to September 2009 based on historical National Climatic Data Center (NCDC) gage records and Parameter-Elevation Regressions on Independent Slopes Model (PRISM) data. Monthly surface rainfall runoff for all un-ponded lands was obtained by summing the daily rainfall runoff results.

For runoff from ponded water, CalSimHydro includes a refuge water use model to simulate monthly rainfall runoff from refuges (managed wetlands) and it includes a rice water use model to simulate monthly rainfall runoff from rice fields under ponded conditions.

Many of the smaller tributaries and the Delta do not receive surface runoff below the rim inflows in the SVUFM model. These small streams include Clear Creek, Battle Creek, Paynes Creek, Elder Creek, Thomes Creek, Stony Creek, Antelope Creek, Mill Creek, Big Chico Creek, Cosumnes River, and Calaveras River. Any local surface runoff to these creeks is expected to be relatively small and is routed to the mainstem Sacramento River, Mokelumne River, or San Joaquin River. The aggregation of surface runoff results in an underestimate of unimpaired flow at the mouth of these tributaries. Future work should include higher resolution surface runoff to better simulate unimpaired flows on all tributaries.

C2VSim Stream – Groundwater Interaction (Stream Gains and Losses)

The C2VSim model was designed to assess the groundwater aquifer and its interaction with surface water, whereas SVUFM is simply a flow routing tool. C2VSim estimates of surface water – groundwater interaction, specifically stream gain/loss to groundwater, are used within SVUFM to represent this interaction on the Valley floor. C2VSim estimates of surface water – groundwater interaction are based on a simulation of current water use conditions (described above). Current conditions were used as opposed to unimpaired flow conditions so the C2VSim model results will represent values that may be expected in the near term when modifications to the Bay-Delta Plan may be implemented. In order to use the stream-groundwater interaction output from the current-condition run of the C2VSim model, mapping from the C2VSim stream nodes to SVUFM stream gain/loss arcs is required.

In the SVUFM schematic, the surface water-groundwater interaction is indicated by stream gain/loss arcs that reflect the direct effect of groundwater on the surface water system. A positive SG value represents a gaining stream whereas a negative value represents a losing stream that is recharging the groundwater aquifer.

Most of stream segments in C2VSim and channel arcs in SVUFM overlap each other. In general, the SVUFM streamflow network contains a node at each node location in C2VSim's streamflow network. These nodes are associated with stream-groundwater interaction, and the C2VSim estimates of stream-groundwater interaction are incorporated into SVUFM at these nodes. The SG values from C2VSim are modified by SVUFM using soft constraints to ensure the channel arc flows in SVUFM are greater or equal to zero by reducing the magnitude of the negative value of the relevant SG arcs if necessary.

The C2VSim stream network is represented by reaches. Each tributary can have one or more reaches, and the main stems of the Sacramento River and the Feather River have multiple reaches. A reach is further divided into segments. There is one node at each end of a segment. A one-segment reach has two nodes; a two-segment reach has three nodes; and so on. When two or more stream segments are from different reaches at a juncture (i.e., a confluence location or a reach connection location), C2VSim will have multiple nodes at the juncture, each of which belongs to different stream segments. In contrast, SVUFM has one node at junctures.

In general, the following mapping methods are used in order to reconcile the conceptual differences in how stream nodes in C2VSim and nodes in SVUFM are represented (Figure A-4, Assignment of C2VSim Stream-Groundwater Interaction to SVUFM Nodes).

- Stream gain or loss of a SVUFM internal node = Stream gain/loss of the C2VSim stream node at the SVUFM node, where an SVUFM internal node is defined as a node which is not at a confluence and not on a tributary immediately upstream of the confluence;
- Stream gain or loss of a SVUFM node located at a confluence = Sum of stream gains or losses at all C2VSim stream nodes that occur at the SVUFM node excluding all C2VSim tributary reach nodes at the confluence (i.e., the sum of stream gains and losses at the two C2VSim stream nodes on the main channel upstream and downstream of the confluence);
- Stream gain or loss of a SVUFM tributary node immediately upstream of a confluence = Sum of all C2VSim stream gain or loss nodes at the SVUFM node plus the C2VSim tributary reach node at the confluence. This approach allows for all stream gain or loss along a tributary to be assigned to the tributary as opposed to having some of it assigned to the SVUFM main channel node at the confluence.

The C2VSim and SVUFM schematics differ in the Lower Feather River - Sutter Bypass region (Figure A-4). C2VSim represents the Sutter Bypass as flowing into the lower Feather River above the confluence with the Sacramento River, which is what occurs when the Sutter Bypass is flooded. In contrast, the SVUFM schematic has Sutter Bypass flowing into the Sacramento River near the Fremont Weir, which is where the Sutter Bypass irrigation channel flows when the Sutter Bypass is not inundated. This may result in occasional inconsistencies in the stream-groundwater interactions in C2VSim versus SVUFM during periods when Sutter Bypass flows are high. Because stream loss is a function of streamflow, some stream loss occurring at the downstream end of the Feather River in C2VSim would more appropriately be associated with the Sacramento River in the SVUFM schematic.

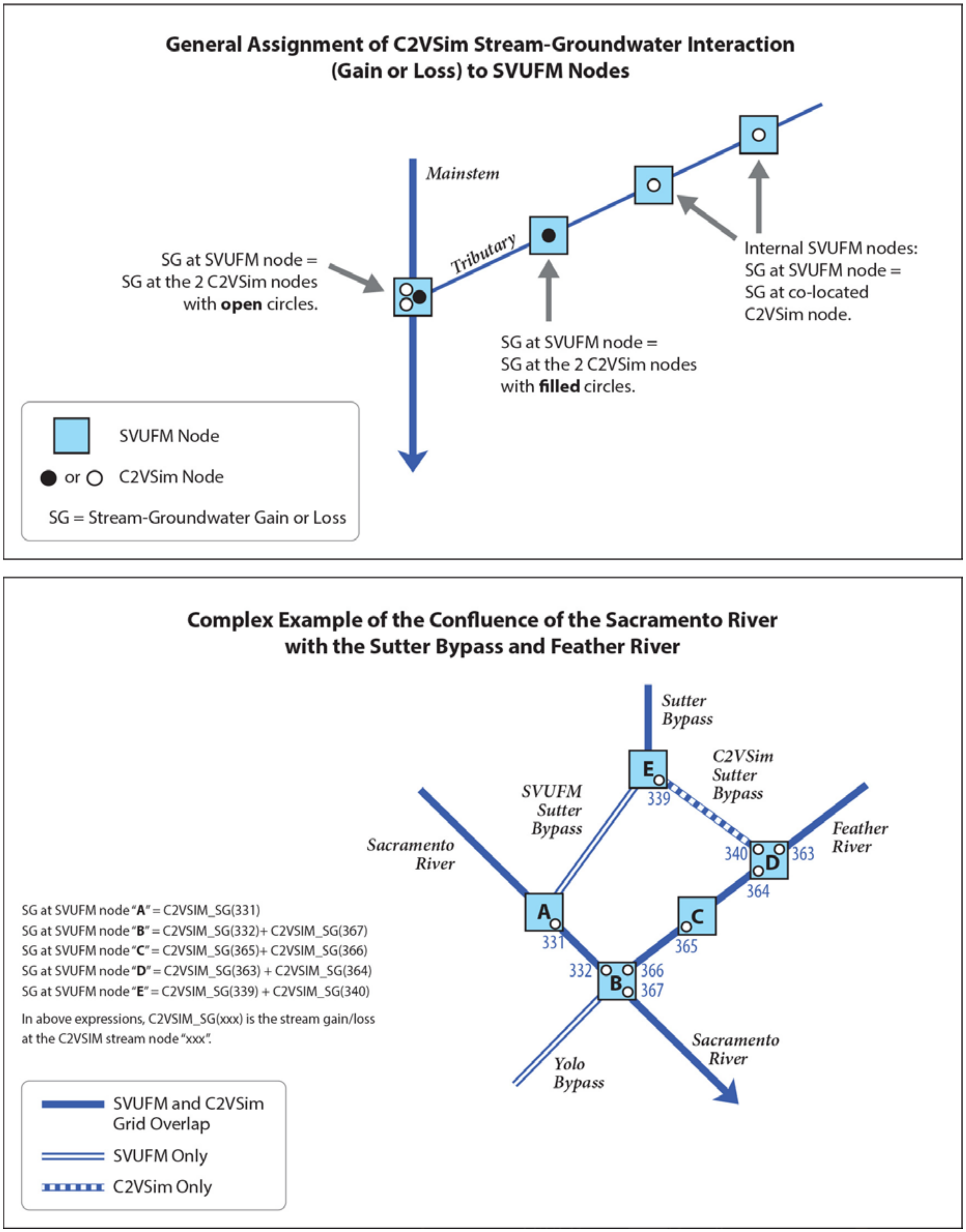

Figure A-4. Assignment of C2VSim Stream-Groundwater Interaction to SVUFM Nodes

Delta Accretions

The Delta accretion arcs represent land surface processes (as opposed to the SG arcs that represent change in flow resulting from stream-groundwater interaction). Because SVUFM represents unimpaired conditions, the SVUFM model assumes that positive net Delta depletions do not affect flow in the Delta. However, when net Delta depletions are negative, the model is indicating that precipitation (and sometimes discharge of leach water) would be contributing accretions to the Delta. Net Delta accretions are estimated on a monthly basis with a Delta consumptive use model that is similar to the evaluation used by CalSim II. When precipitation is more than sufficient to meet consumptive use, the excess is assumed to contribute to the Delta channels. Consumptive use is based on existing land use including Stone Lakes National Wildlife Refuge. If consumptive use is greater than what is provided by precipitation, SVUFM assumes the deficit would not be met with water from Delta channels (i.e., no Delta depletions).

San Joaquin Inflow

Unimpaired inflow from the San Joaquin River was assumed from DWR unimpaired flow report 4th Edition and expanded to 2009 (DWR 2007). The San Joaquin Valley unimpaired runoff estimated using these methods suffers from the similar issues discussed above in the Sacramento Valley such as not including stream gains/losses to groundwater. However, this is the best available estimate of unimpaired flows from the San Joaquin River at this time.

A.4.3 Results

The following bar charts show the monthly average SVUFM results by tributary broken up by flow component (Figures A-5 through A-30, presented in alphabetical order). The flow components include rim inflow, surface runoff, groundwater gain/loss, and outflow at tributary confluences. Table A-10 presents the annual average SVUFM results per water year type.

Two figures (Figures A-20 and A-25) provide examples of how flow components contribute to unimpaired flows on tributaries and bypasses. Tributary inflow for the Feather River shown in Figure A-20 comes from the Bear River (Figure A-8), Yuba River (Figure A-30), Honcut Creek, and Jack Slough. Tributary inflow for the Sacramento River at Freeport (Figure A-25) comes from all the upstream tributaries. “Inflows” (rim inflows) in this figure are the Lake Shasta rim inflows. The Yolo Bypass flows shown for the Sacramento River at Freeport (Figure A-25) are negative because they represent water that leaves the Sacramento River system upstream of Freeport and does not return until downstream of Freeport. The Sutter Bypass flows in Figure A-25 are small because they represent only the net change in flow that occurs within the Sutter Bypass and not water that leaves and returns to the Sacramento River via the Sutter Bypass, which would have no effect on Sacramento River flow at Freeport.

There are pattern differences between rain-fed and snow-melt fed tributaries. The monthly results show pattern differences between low altitude streams that are supplied primarily by rainfall and streams that extend higher into the mountains and receive substantial snowmelt. Snowmelt streams typically show peak flows from March to May. These include the American River (Figure A-5), the Feather River (Figure A-20), the Mokelumne River (Figure A-22), and the Yuba River (Figure 30). Most other streams show a pattern expected for streams that are fed by rainfall, with peak flows during January – March. The Sacramento River as a whole shows a pattern that is indicative of a mixture of rainfall and snowmelt runoff, with flows remaining high January – May (Figure A-25).

Almost all streams show substantially reduced unimpaired flow during July – October compared to other months. However, Battle Creek (Figure A-7) and Mill Creek (Figure A-21) show relatively high inflows during these dry months, which may indicate contribution from springs.

The valley rim inflows are by far the largest contribution to the unimpaired tributary outflows, however for some locations, surface runoff and stream gain/loss have a large influence on the unimpaired tributary outflow, such as Butte Creek (Figure A-10) and Natomas East Main Drain (Figure A-18). In the case of Natomas East Main Drain, all of its inflow comes from surface runoff.

SVUFM underestimates the unimpaired outflow from many tributaries. As described above in the SVUFM methods section, many of the small tributaries do not receive surface runoff from the valley floor in SVUFM, rather the surface runoff for these tributaries is routed directly to the mainstem Sacramento River. For the watershed as a whole, this does not affect total unimpaired runoff, and in general, rainfall runoff from the valley floor represents a relatively small percent of the total Delta inflow. Rainfall runoff to small creeks would occur during the months with highest inflow, so its inclusion would not likely cause a large percent change in total unimpaired tributary outflow, but it could be a larger percent than what is expected for rivers with large watersheds. SVUFM surface runoff results for Cottonwood Creek (Figure A-15) and Cow Creek (Figure A-16) may be indicative of what rainfall runoff could be for the small creeks that do not have surface runoff arcs.

Almost all tributaries have stream gain/loss arcs. In general, the stream gain/loss component is relatively small compared to total tributary outflow. However, for some small northern creeks, gains during the driest months (June – October) may provide most of the flow in the creek. This occurs for Elder Creek (Figure A-19), Paynes Creek (Figure A-23), and Thomes Creek (Figure A-28).

For all watersheds represented in Figures A-5 through A-30 (Sacramento Valley and Delta eastside Tributaries excluding the Delta), the total average annual rim inflow is approximately 21,500 TAF/yr, whereas the net stream-groundwater interaction (gain/loss) is an average net loss of approximately 900 TAF/yr (4% of the rim inflow), and the surface rainfall runoff from the valley floor is approximately 1,700 TAF/yr (only 8% of the rim inflow). There is very little change in unimpaired hydrology through the Delta as shown in Figure A-31. Nearly all of the unimpaired Delta outflow originates from its tributary inflows and a relatively small amount comes from Delta accretions and stream gain/loss.

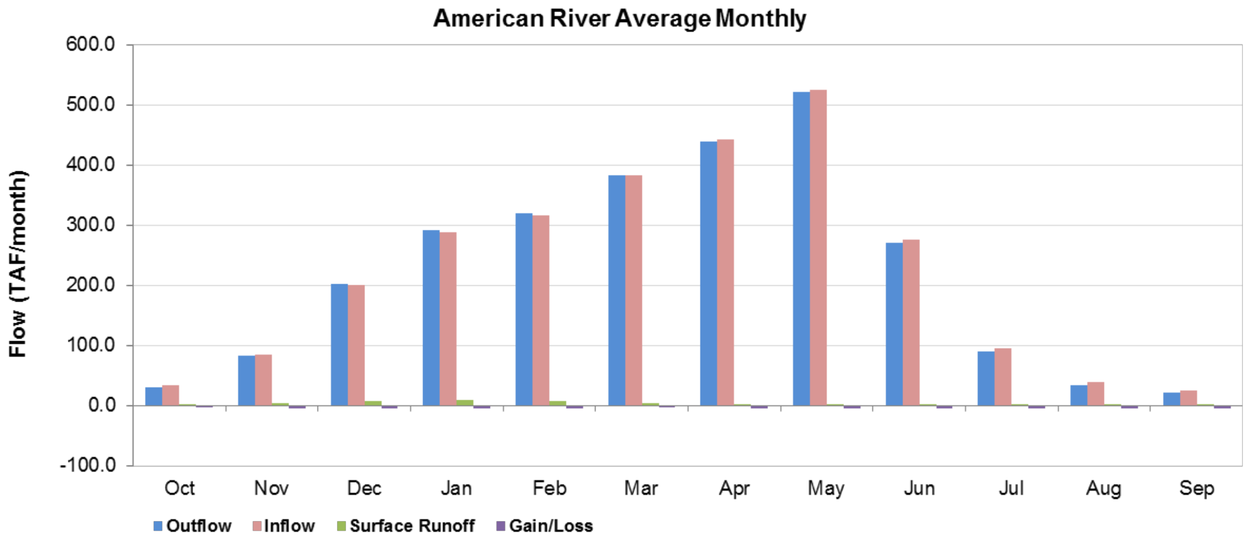

Figure A-5. Monthly Average Unimpaired Flow Components for the American River

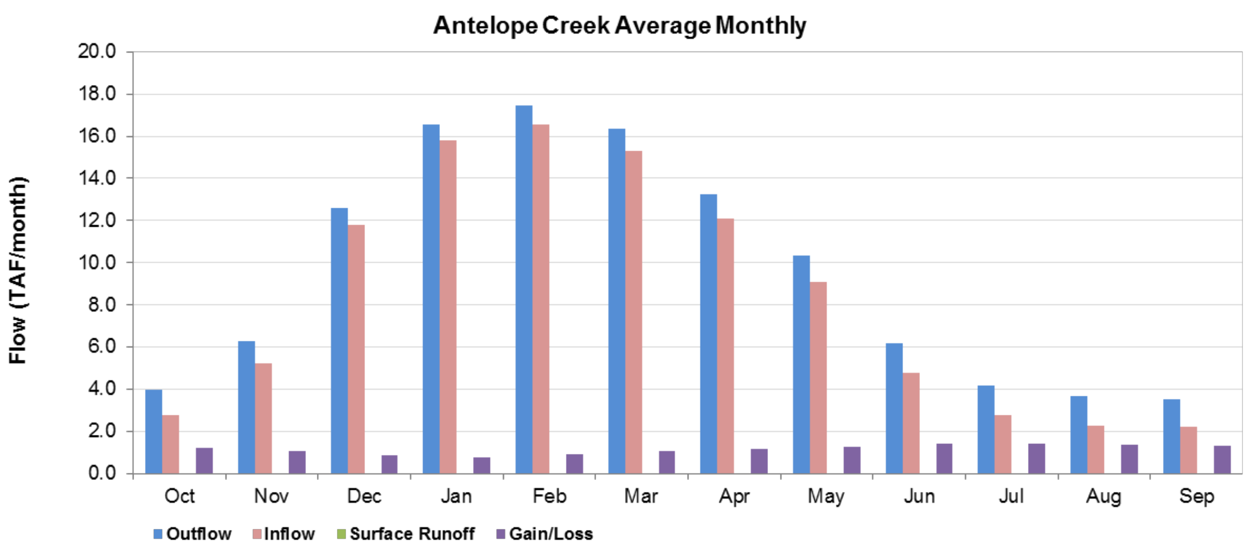

Figure A-6. Monthly Average Unimpaired Flow Components for Antelope Creek

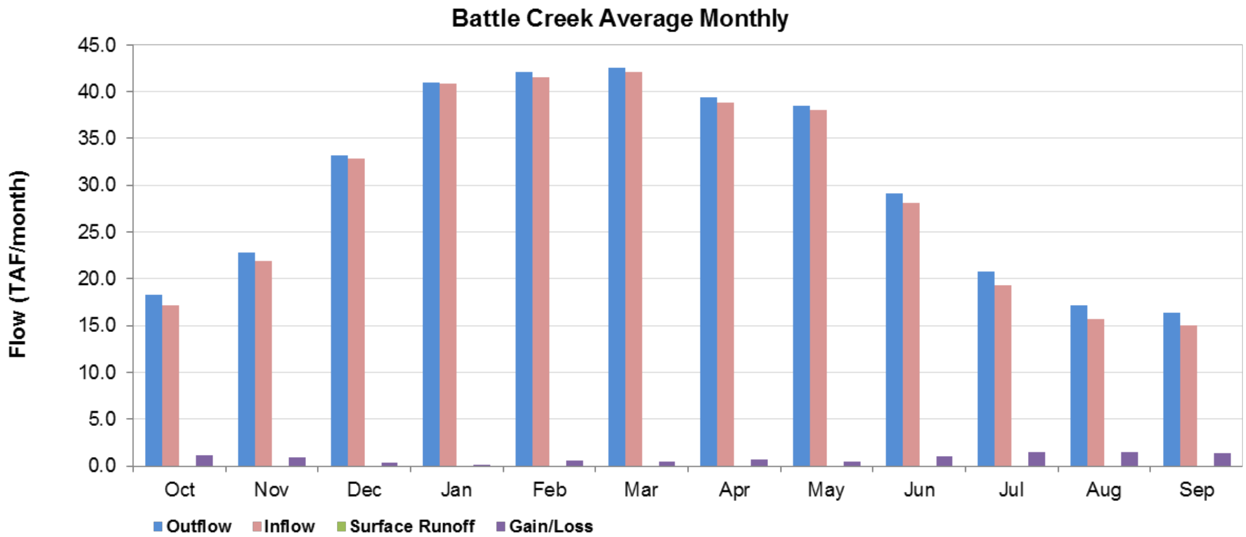

Figure A-7. Monthly Average Unimpaired Flow Components for Battle Creek

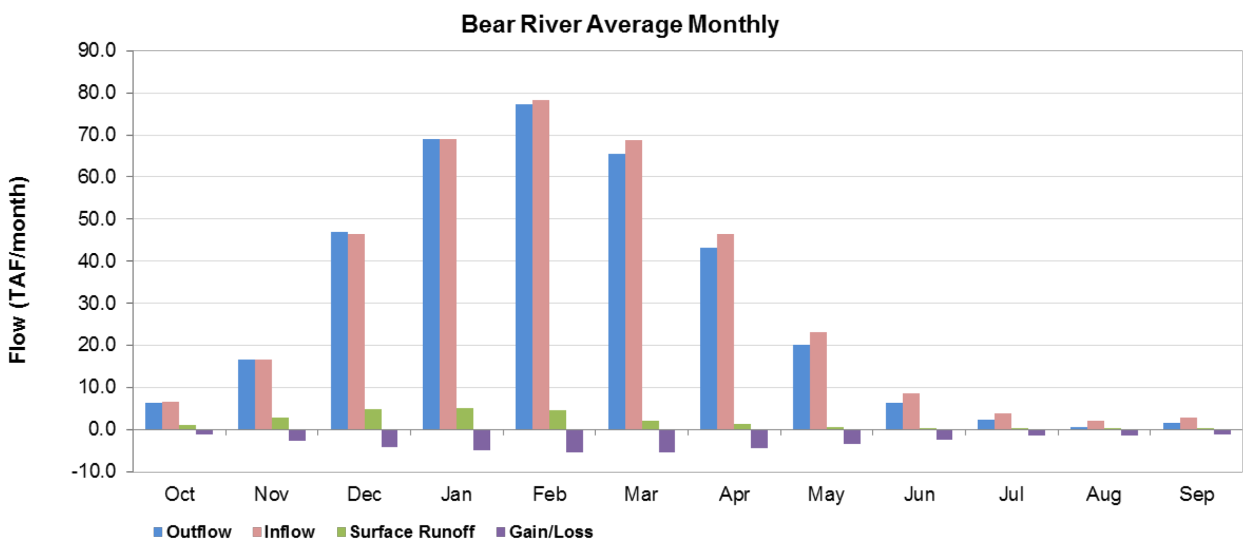

Figure A-8. Monthly Average Unimpaired Flow Components for the Bear River

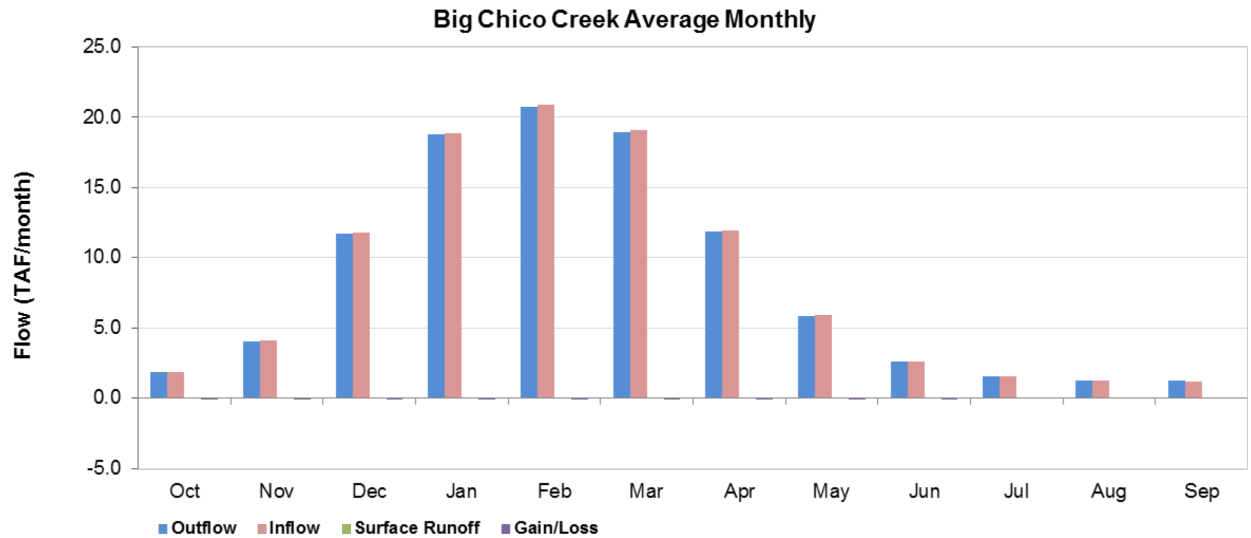

Figure A-9. Monthly Average Unimpaired Flow Components for Big Chico Creek

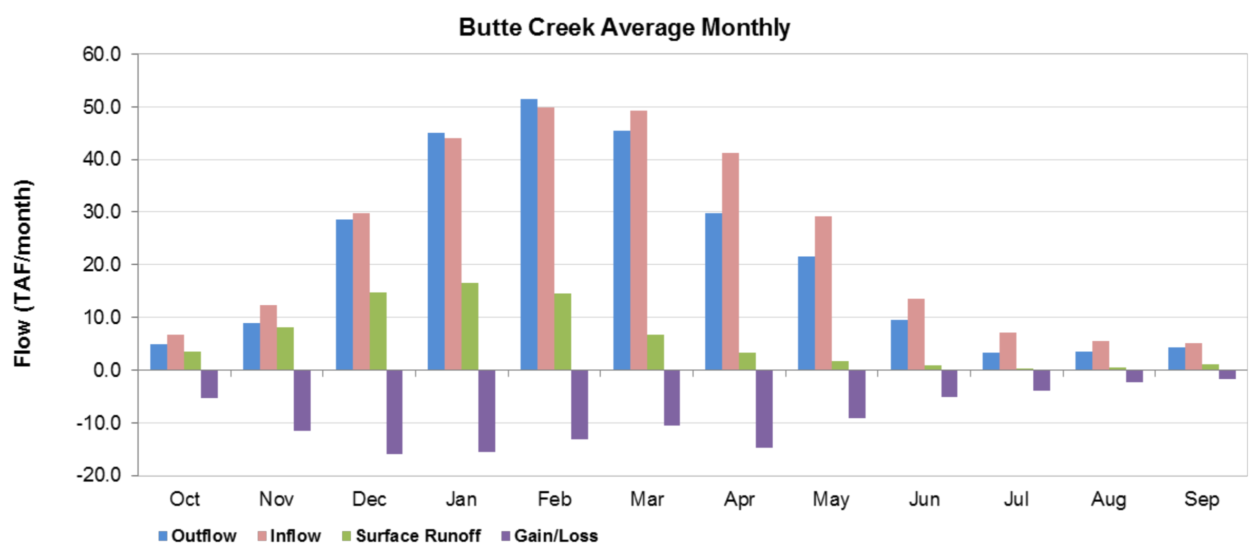

Figure A-10. Monthly Average Unimpaired Flow Components for Butte Creek

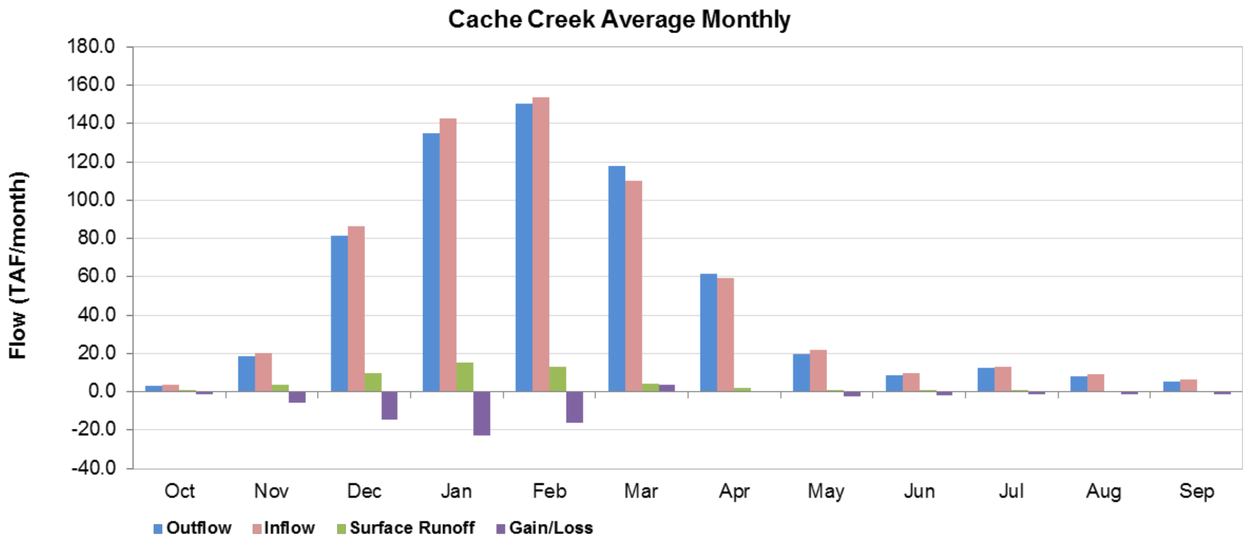

Figure A-11. Monthly Average Unimpaired Flow Components for Cache Creek

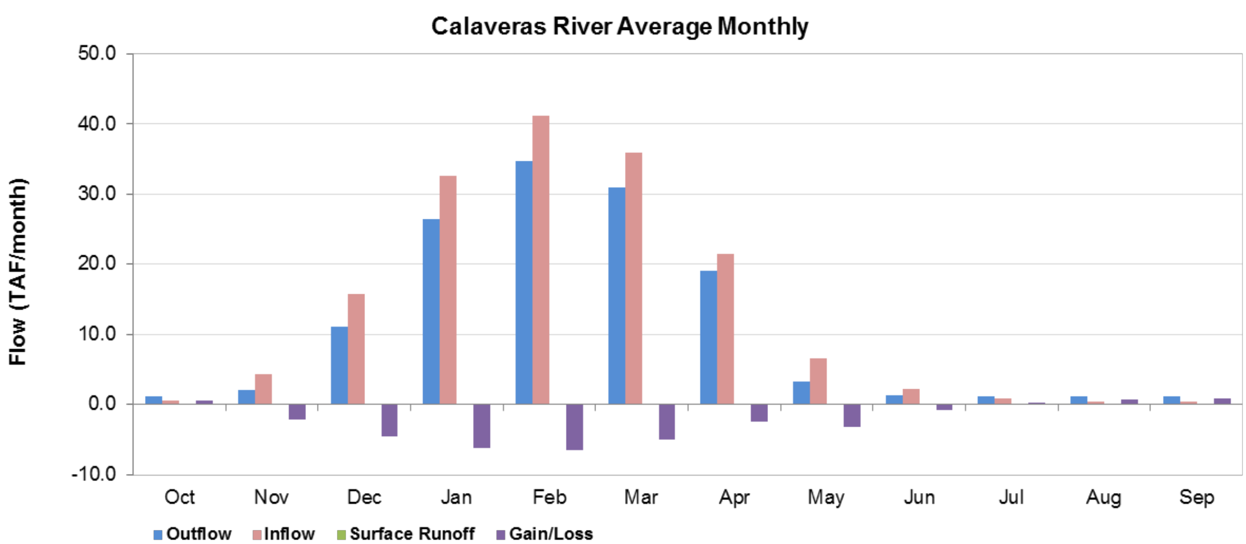

Figure A-12. Monthly Average Unimpaired Flow Components for the Calaveras River

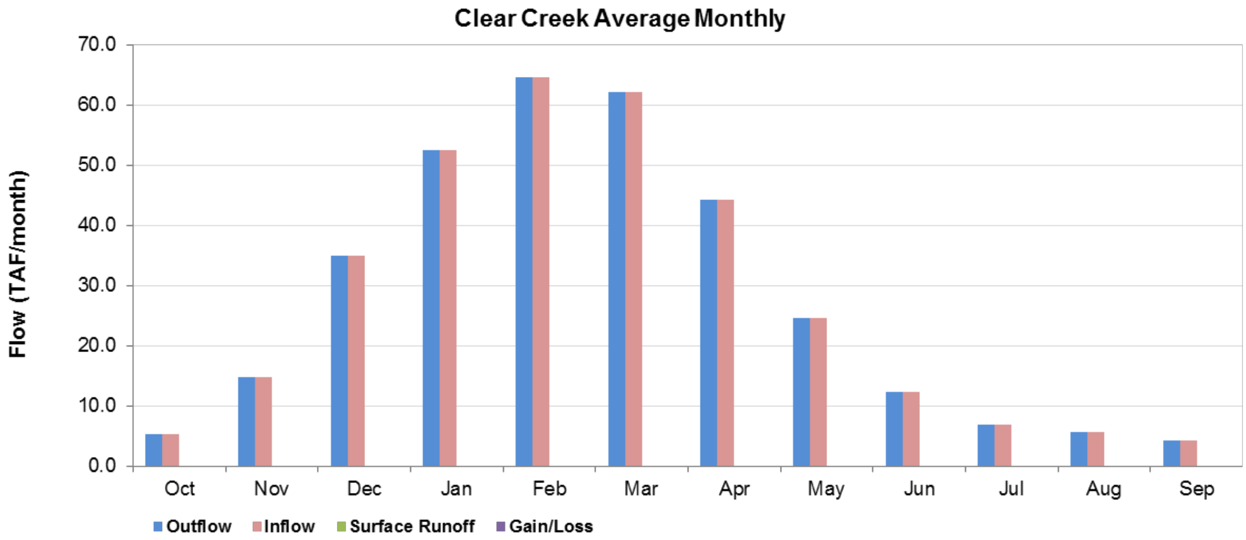

Figure A-13. Monthly Average Unimpaired Flow Components for Clear Creek

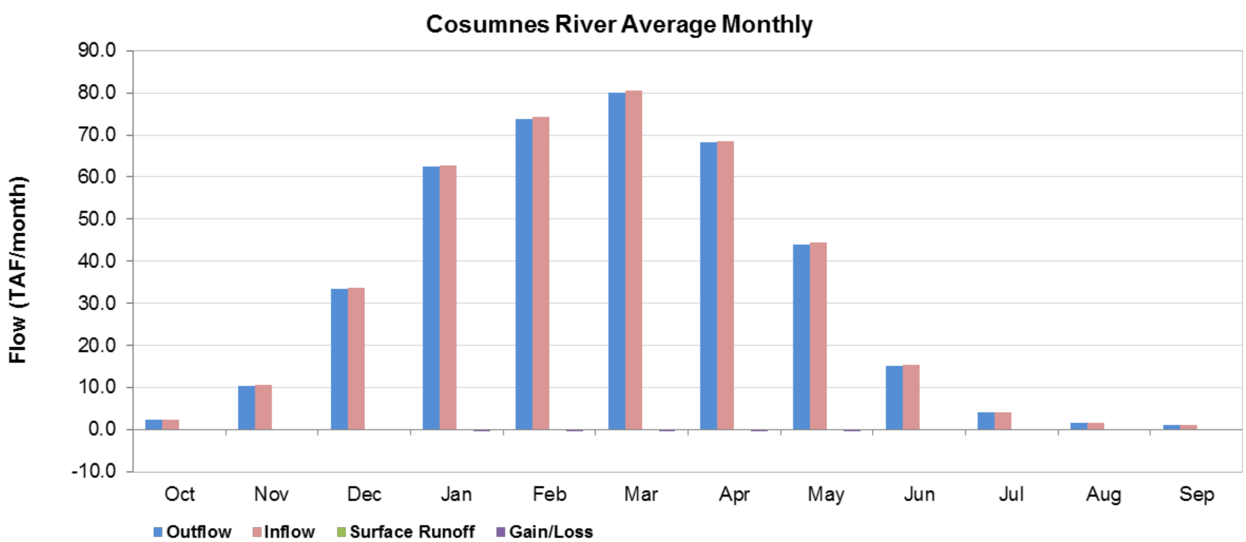

Figure A-14. Monthly Average Unimpaired Flow Components for the Cosumnes River

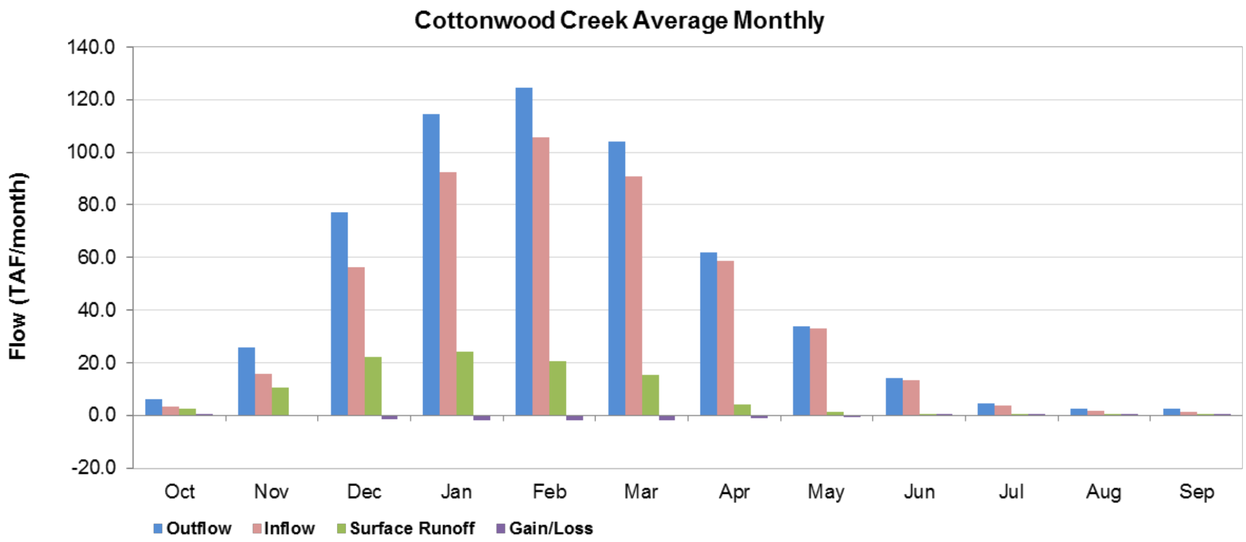

Figure A-15. Monthly Average Unimpaired Flow Components for Cottonwood Creek

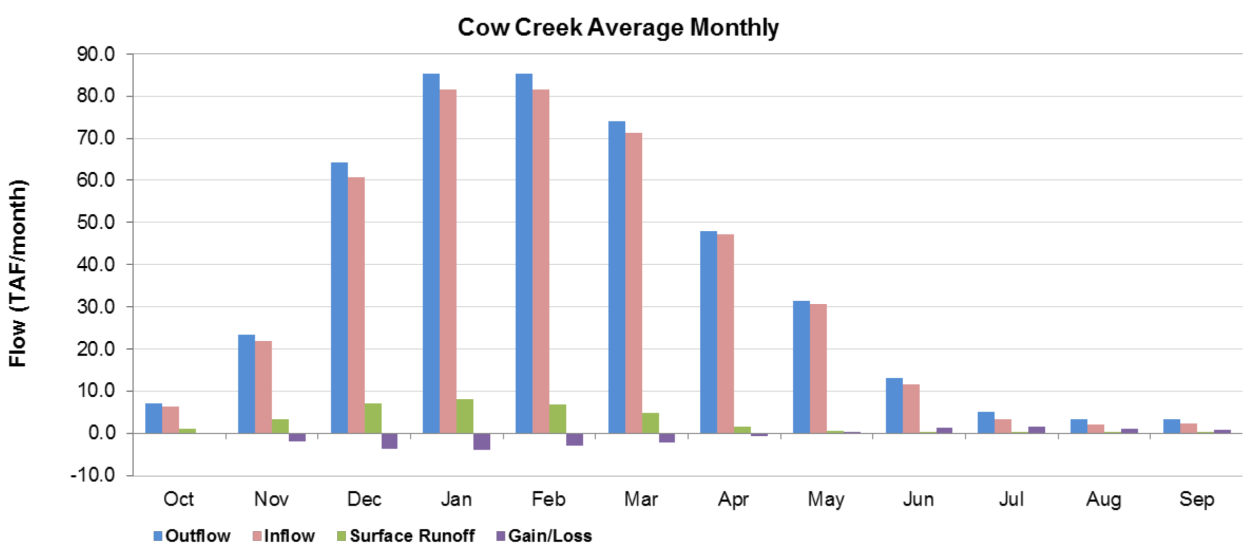

Figure A-16. Monthly Average Unimpaired Flow Components for Cow Creek

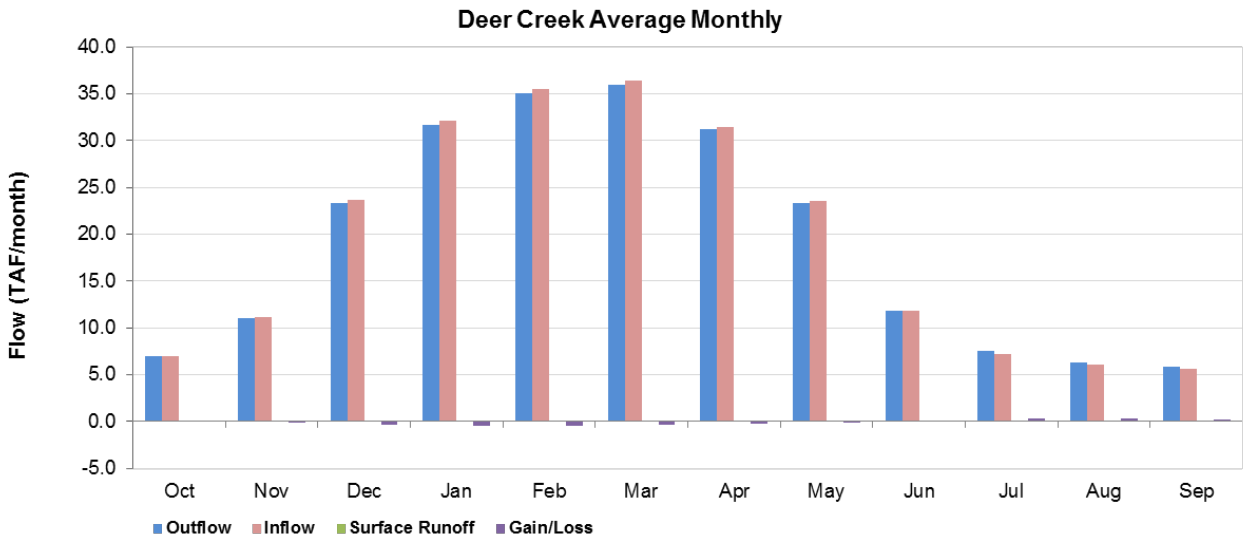

Figure A-17. Monthly Average Unimpaired Flow Components for Deer Creek (tributary of the Sacramento River)

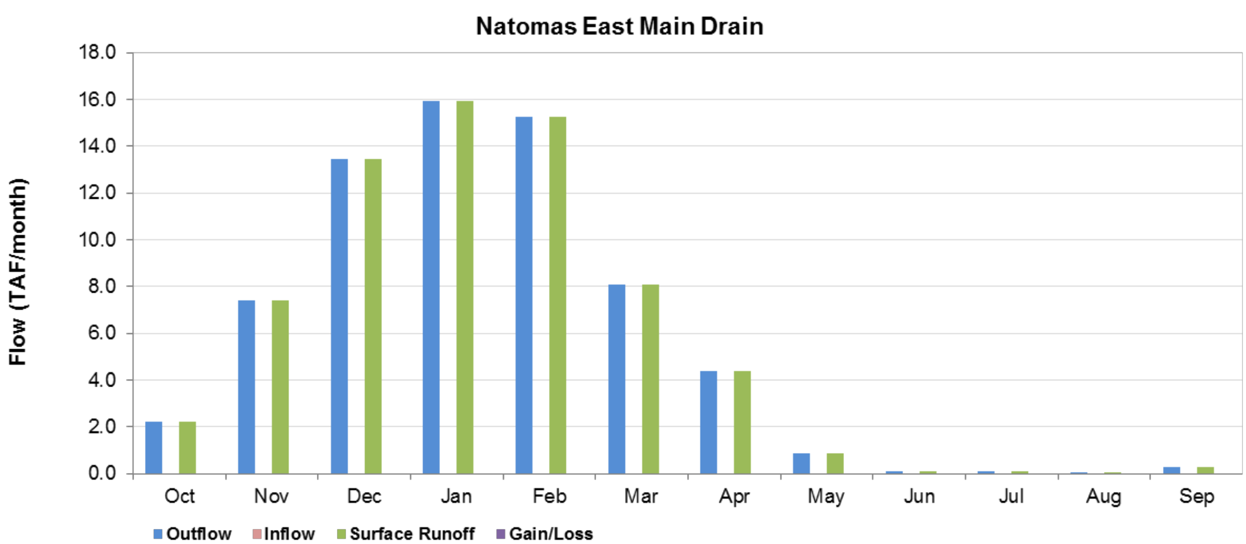

Figure A-18. Monthly Average Unimpaired Flow Components for Natomas East Main Drain

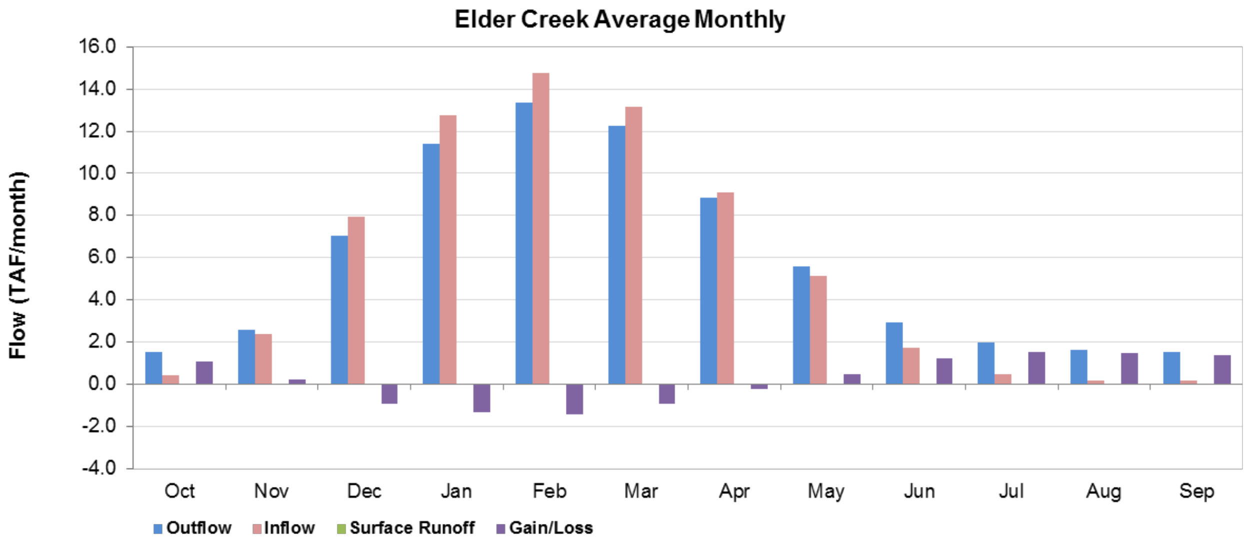

Figure A-19. Monthly Average Unimpaired Flow Components for Elder Creek

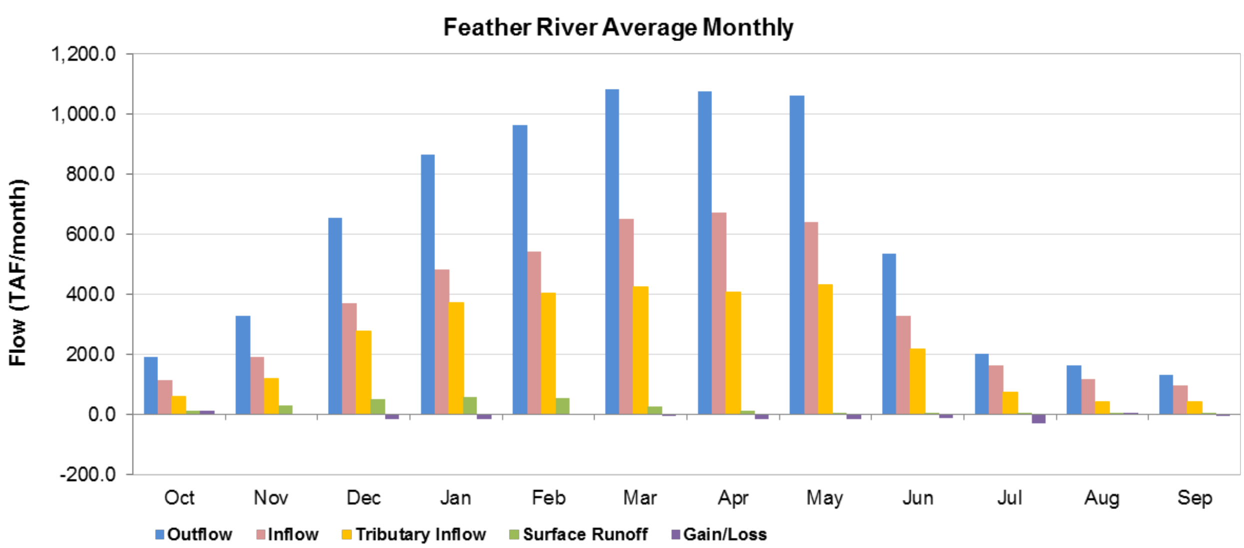

Figure A-20. Monthly Average Unimpaired Flow Components for the Feather River

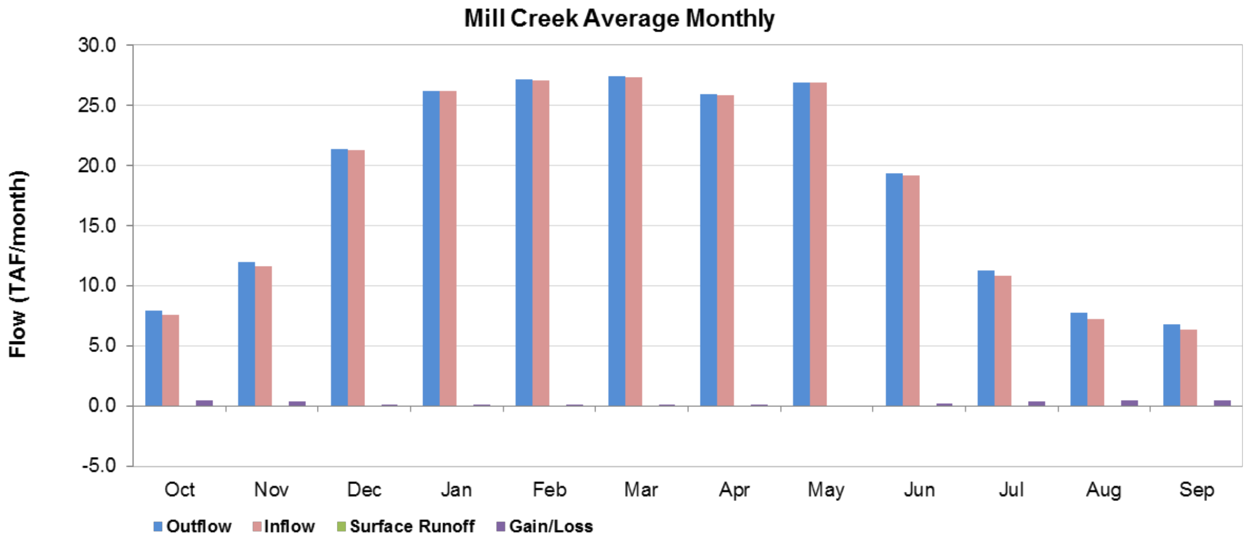

Figure A-21. Monthly Average Unimpaired Flow Components for Mill Creek

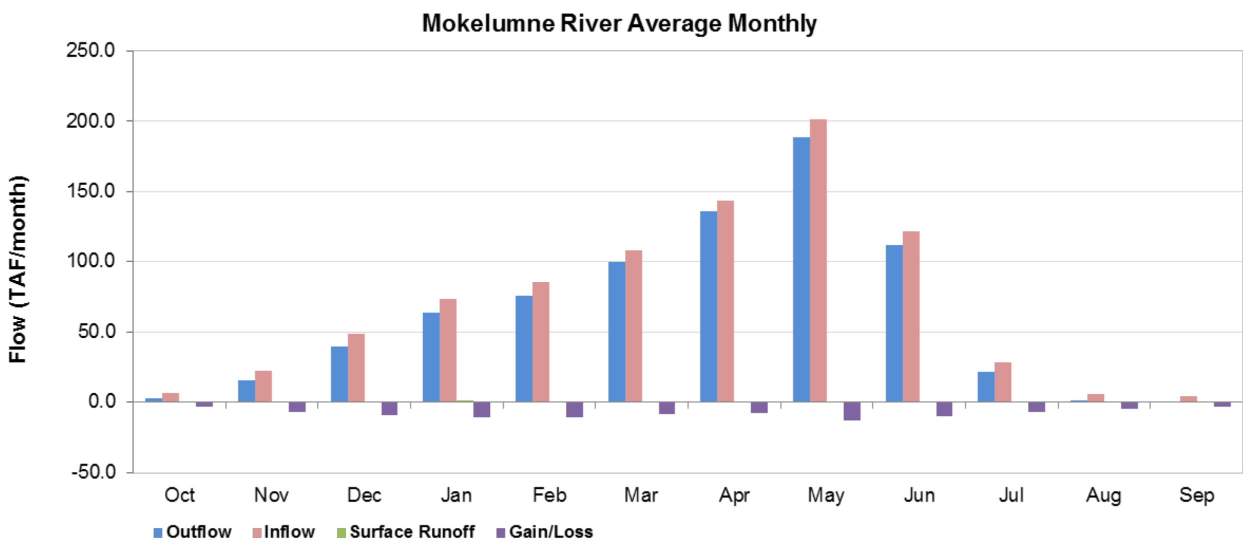

Figure A-22. Monthly Average Unimpaired Flow Components for the Mokelumne River

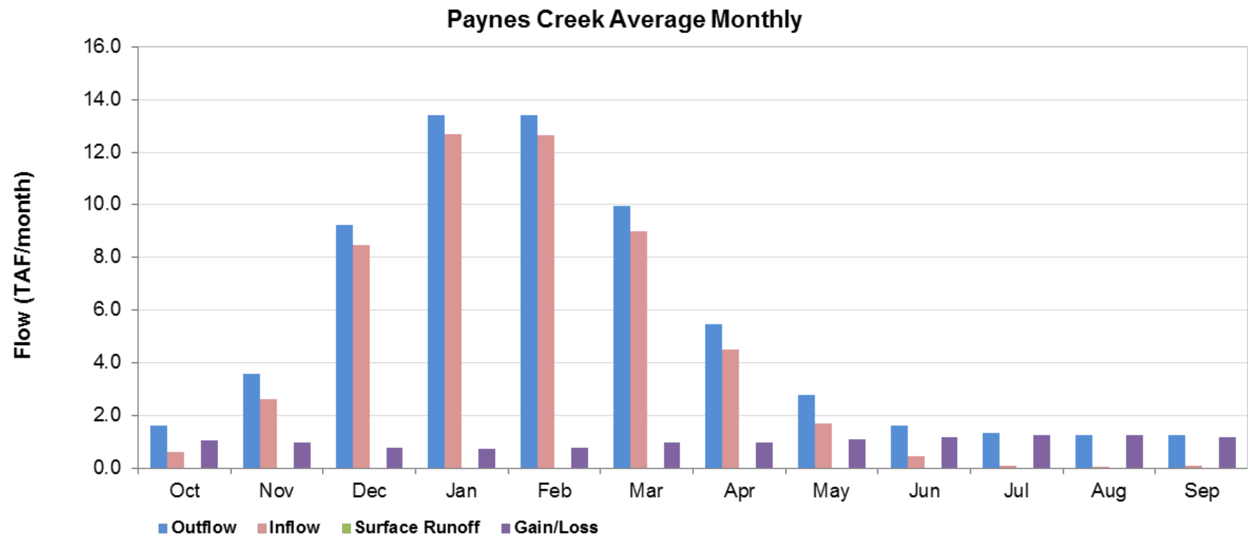

Figure A-23. Monthly Average Unimpaired Flow Components for Paynes Creek

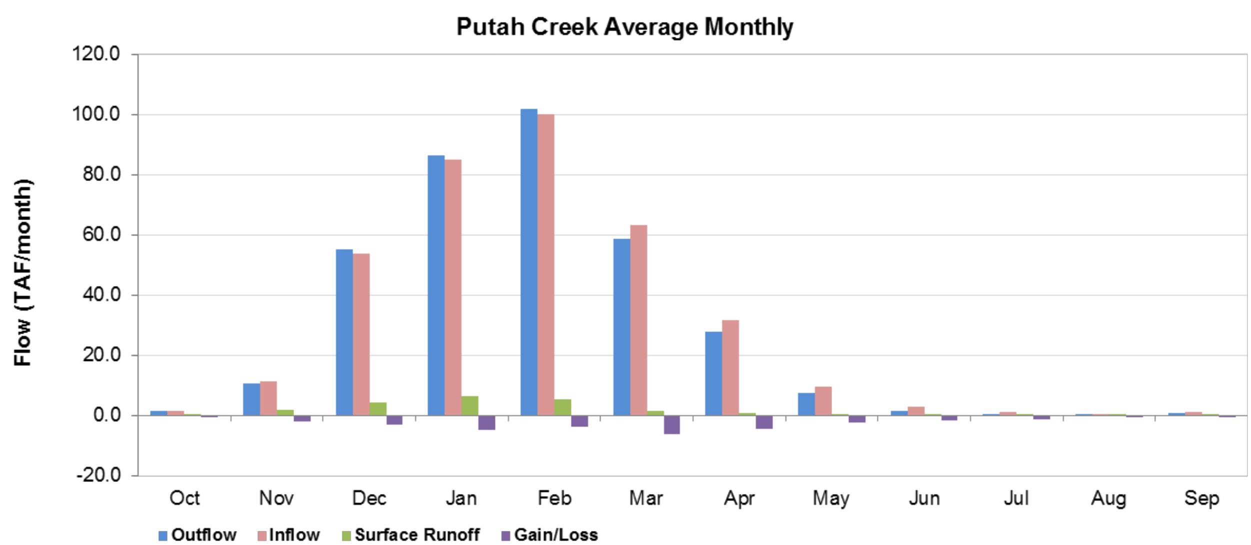

Figure A-24. Monthly Average Unimpaired Flow Components for Putah Creek

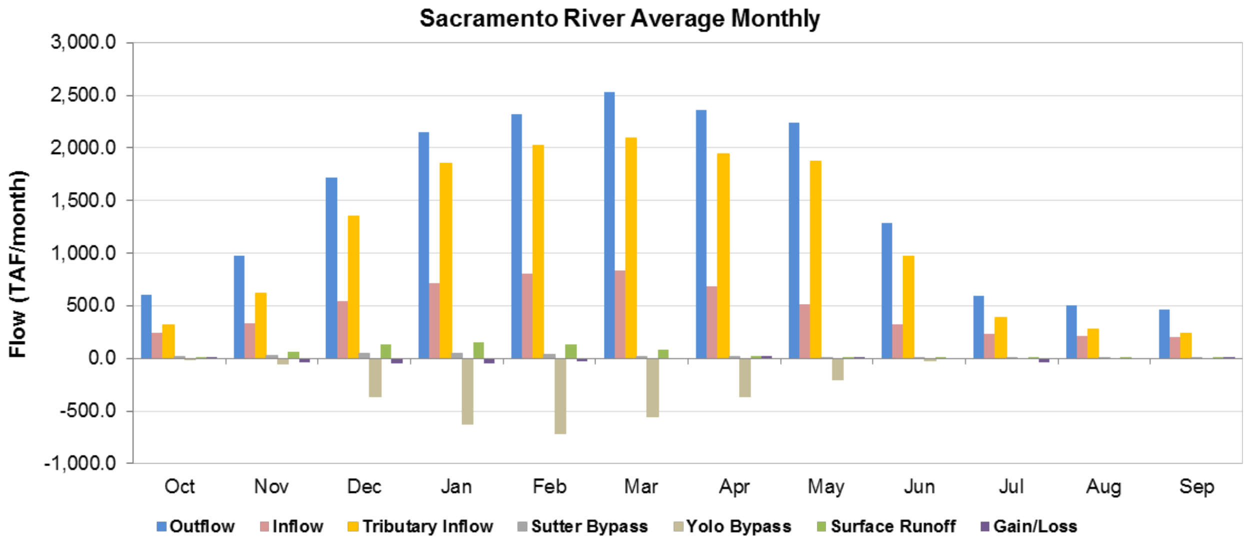

Figure A-25. Monthly Average Unimpaired Flow Components for the Sacramento River at Freeport

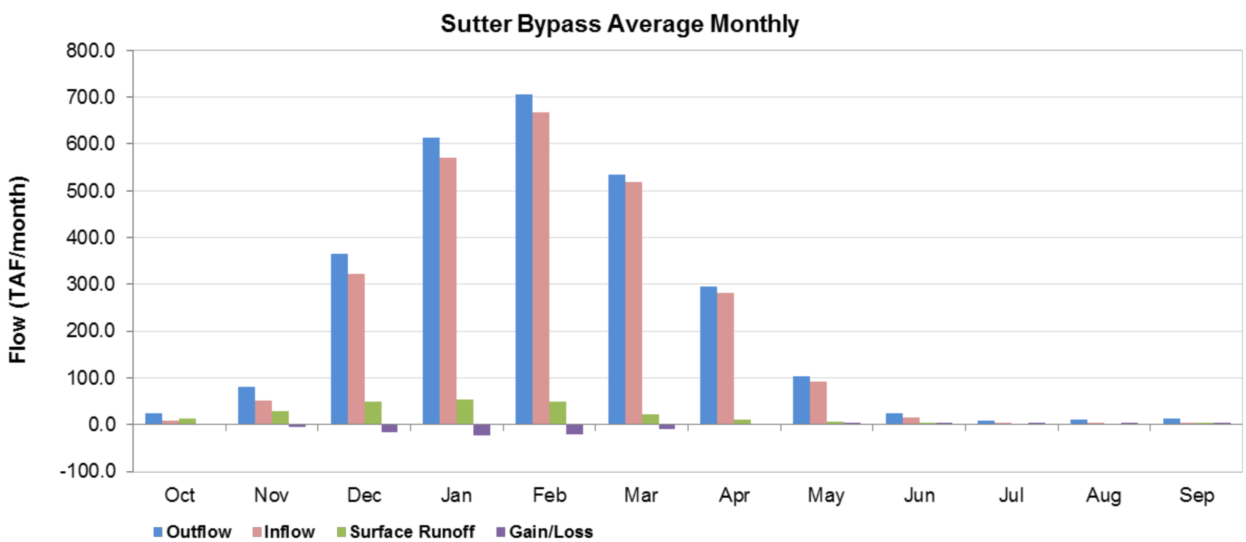

Figure A-26. Monthly Average Unimpaired Flow Components for the Sutter Bypass

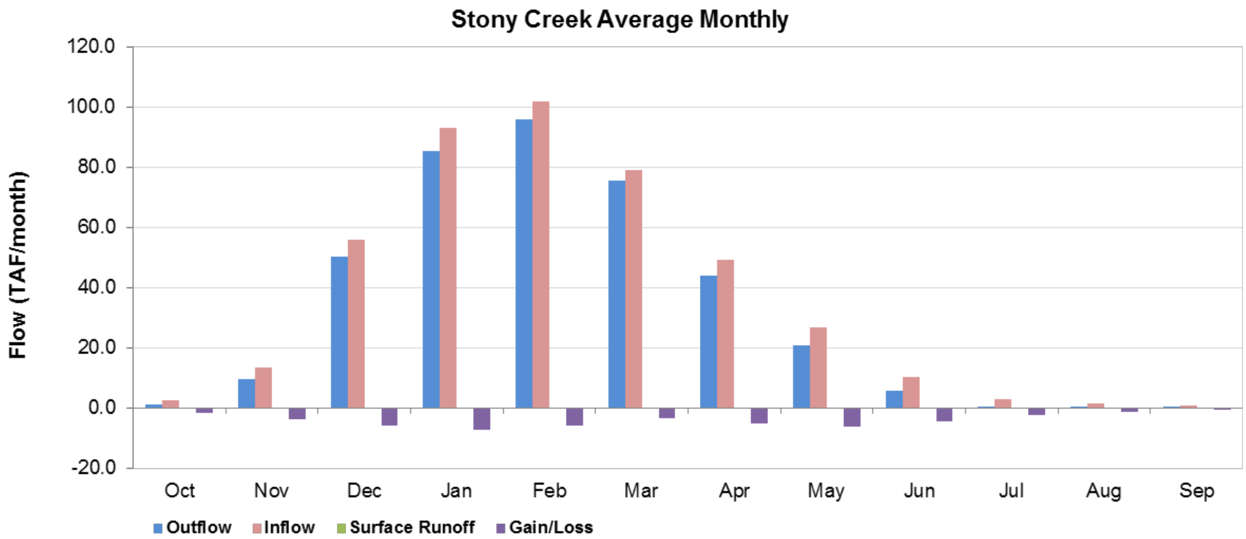

Figure A-27. Monthly Average Unimpaired Flow Components for Stony Creek

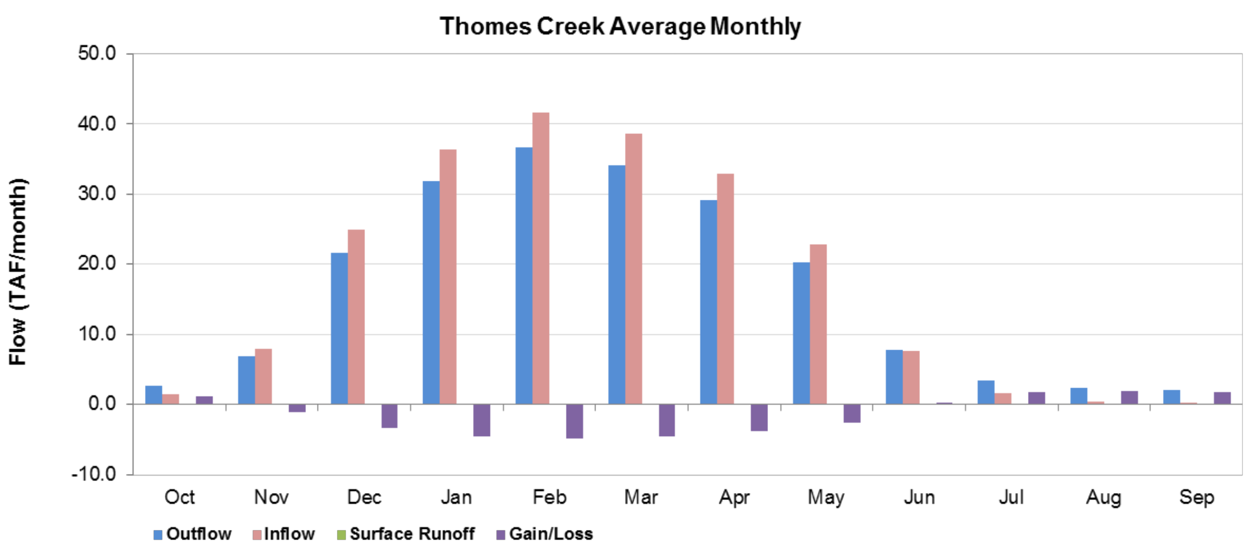

Figure A-28. Monthly Average Unimpaired Flow Components for Thomes Creek

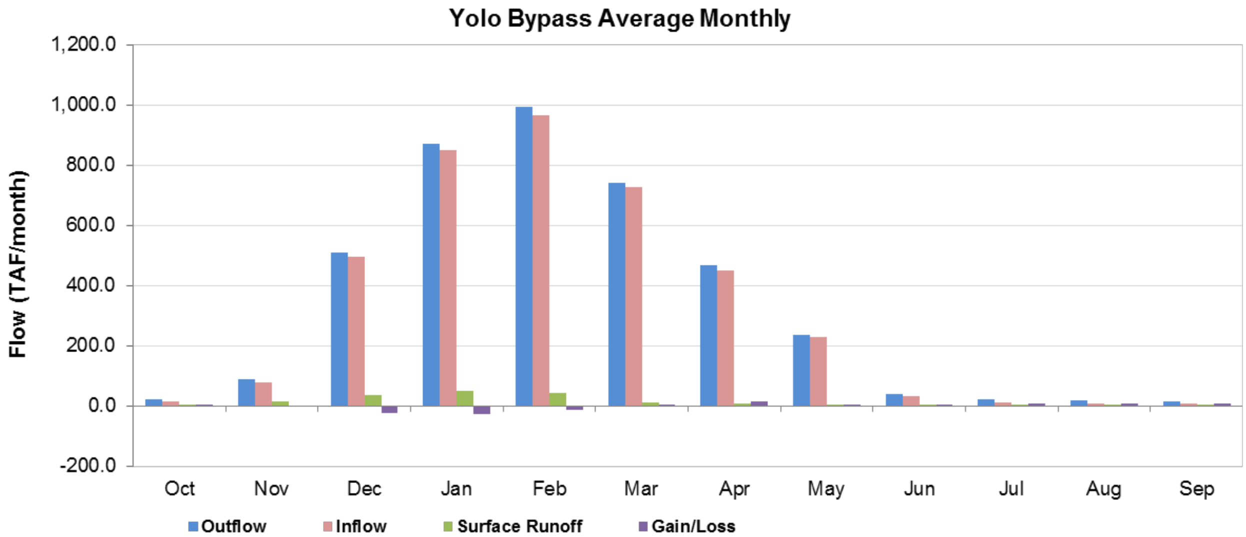

Figure A-29. Monthly Average Unimpaired Flow Components for the Yolo Bypass

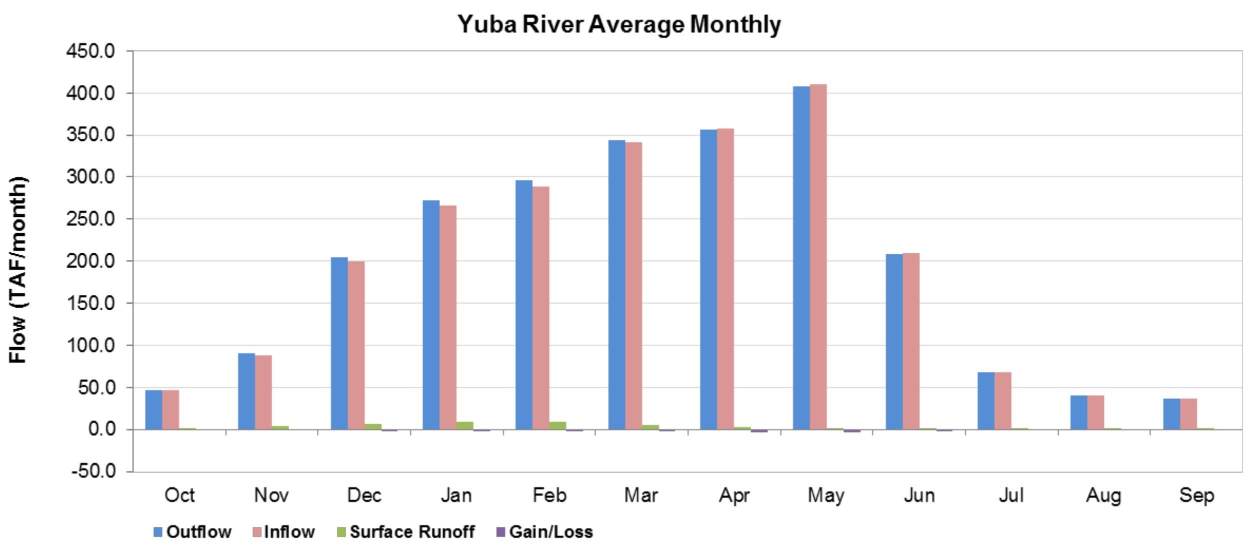

Figure A-30. Monthly Average Unimpaired Flow Components for the Yuba River

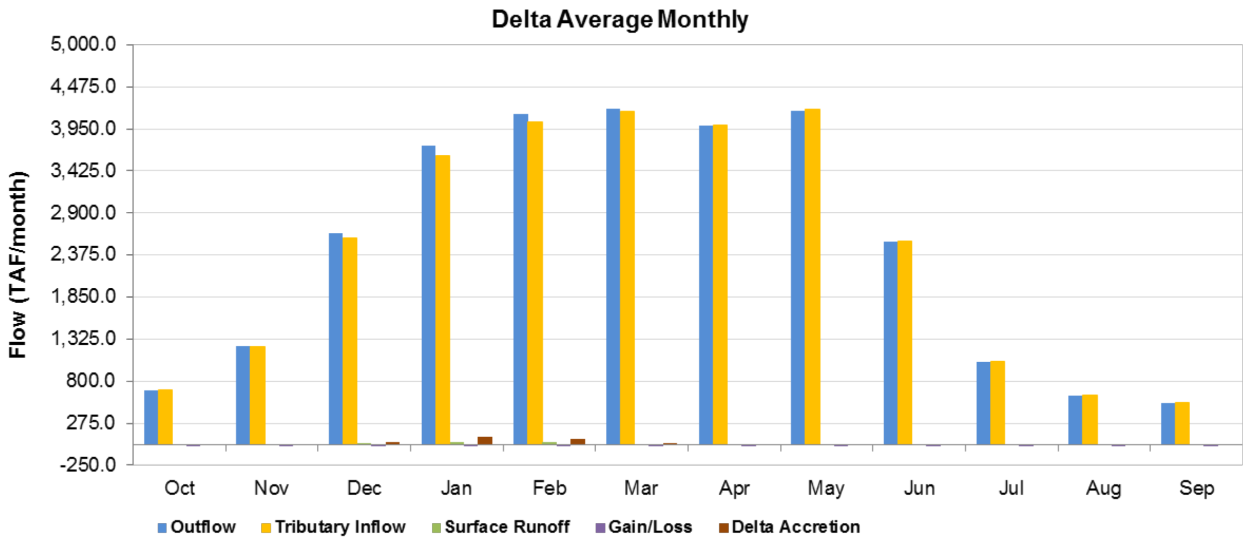

Figure A-31. Monthly Average Unimpaired Flow Components for the Delta

Table A-10. Average Annual Values per Water Year Type

	Mean Annual Values WY 1921–2009					
	All	W	AN	BN	D	C
Flow Component	**TAF**	**TAF**	**TAF**	**TAF**	**TAF**	**TAF**
American River Unimpaired Flows						
American River Outflow	2,684	4,270	3,059	2,184	1,749	1,028
American River Inflow	2,705	4,278	3,073	2,212	1,779	1,060
American River Surface Runoff	35	53	44	30	21	15
American River Stream Gain/Loss	-56	-60	-58	-58	-52	-47
Antelope Creek Unimpaired Flows						
Antelope Creek Outflow	114	177	130	95	74	52
Antelope Creek Inflow	101	162	116	82	61	40
Antelope Creek Surface Runoff	0	0	0	0	0	0
Antelope Creek Stream Gain/Loss	14	15	13	13	13	12
Battle Creek Unimpaired Flows						
Battle Creek Outflow	361	504	385	316	278	222
Battle Creek Inflow	351	497	375	305	266	210
Battle Creek Surface Runoff	0	0	0	0	0	0
Battle Creek Stream Gain/Loss	10	7	10	10	12	12
Bear River Unimpaired Flows						
Bear River Outflow	356	591	435	286	200	109
Bear River Inflow	372	610	454	302	214	120
Bear River Surface Runoff	22	33	26	20	15	11
Bear River Stream Gain/Loss	-39	-52	-45	-36	-29	-23
Big Chico Creek Unimpaired Flows						
Big Chico Creek Outflow	100	166	121	78	57	37
Big Chico Creek Inflow	101	167	122	79	57	37
Big Chico Creek Surface Runoff	0	0	0	0	0	0
Big Chico Creek Stream Gain/Loss	0	-1	-1	0	0	0
Butte Creek Unimpaired Flows						
Butte Creek Outflow	256	458	302	193	123	69
Butte Creek Inflow	293	476	347	236	172	114
Butte Creek Surface Runoff	72	106	83	63	50	36
Butte Creek Stream Gain/Loss	-109	-124	-128	-106	-98	-82
Cache Creek Unimpaired Flows						
Cache Creek Outflow	622	1,098	735	445	322	187
Cache Creek Inflow	636	1,091	740	469	349	219
Cache Creek Surface Runoff	52	84	67	40	27	22
Cache Creek Stream Gain/Loss	-66	-77	-72	-65	-54	-54
Calaveras River Unimpaired Flows						
Calaveras River Outflow	134	233	162	108	65	34
Calaveras River Inflow	162	291	195	130	74	34
Calaveras River Surface Runoff	0	0	0	0	0	0

	Mean Annual Values WY 1921–2009					
	All	**W**	**AN**	**BN**	**D**	**C**
Flow Component	**TAF**	**TAF**	**TAF**	**TAF**	**TAF**	**TAF**
Calaveras River Stream Gain/Loss	-29	-58	-33	-23	-9	0
Clear Creek Unimpaired Flows						
Clear Creek Outflow	332	531	414	234	206	141
Clear Creek Inflow	332	531	414	234	206	141
Clear Creek Surface Runoff	0	0	0	0	0	0
Clear Creek Stream Gain/Loss	0	0	0	0	0	0
Cosumnes Unimpaired River Flows						
Cosumnes River Outflow	396	697	475	326	190	90
Cosumnes River Inflow	399	701	478	329	193	92
Cosumnes River Surface Runoff	0	0	0	0	0	0
Cosumnes River Stream Gain/Loss	-3	-4	-3	-3	-3	-2
Cottonwood Creek Unimpaired Flows						
Cottonwood Creek Outflow	571	1,010	682	379	305	180
Cottonwood Creek Inflow	476	853	578	305	248	140
Cottonwood Creek Surface Runoff	102	168	114	79	63	42
Cottonwood Creek Stream Gain/Loss	-7	-11	-10	-6	-5	-2
Cow Creek Unimpaired Flows						
Cow Creek Outflow	443	719	520	359	268	162
Cow Creek Inflow	420	678	495	342	256	153
Cow Creek Surface Runoff	34	54	39	27	21	15
Cow Creek Stream Gain/Loss	-11	-13	-14	-11	-9	-6
Deer Creek Unimpaired Flows						
Deer Creek Outflow	230	369	258	184	144	100
Deer Creek Inflow	231	371	260	185	145	100
Deer Creek Surface Runoff	0	0	0	0	0	0
Deer Creek Stream Gain/Loss	-1	-2	-2	-1	-1	0
Natomas East Main Drain Unimpaired Flows						
Natomas East Main Outflow	68	103	84	61	42	29
Natomas East Main Inflow	0	0	0	0	0	0
Natomas East Main Surface Runoff	68	103	84	61	42	29
Natomas East Main Gain/Loss	0	0	0	0	0	0
Elder Creek Unimpaired Flows						
Elder Creek Outflow	71	120	89	46	39	27
Elder Creek Inflow	68	118	89	44	36	21
Elder Creek Surface Runoff	0	0	0	0	0	0
Elder Creek Stream Gain/Loss	2	2	0	2	4	5
Feather River Unimpaired Flows						
Feather River Outflow	7,246	11,513	8,276	5,947	4,612	2,902
Feather River Inflow	4,357	6,910	4,872	3,557	2,804	1,855
Feather River Surface Runoff	255	384	300	220	166	117

	Mean Annual Values WY 1921–2009					
	All	**W**	**AN**	**BN**	**D**	**C**
Flow Component	**TAF**	**TAF**	**TAF**	**TAF**	**TAF**	**TAF**
Feather River Stream Gain/Loss	-117	-102	-124	-119	-102	-161
Feather River Tributary Inflow	2,857	4,299	3,206	2,267	1,723	1,069
Mill Creek Unimpaired Flows						
Mill Creek Outflow	220	321	246	188	157	118
Mill Creek Inflow	217	319	244	185	153	114
Mill Creek Surface Runoff	0	0	0	0	0	0
Mill Creek Stream Gain/Loss	2	1	2	3	3	4
Mokelumne River Unimpaired Flows						
Mokelumne River Outflow	757	1,212	902	650	459	253
Mokelumne River Inflow	848	1,340	997	733	524	311
Mokelumne River Surface Runoff	4	6	5	3	2	1
Mokelumne River Stream Gain/Loss	-95	-134	-100	-86	-68	-60
Paynes Creek Unimpaired Flows						
Paynes Creek Outflow	65	102	73	54	42	27
Paynes Creek Inflow	53	89	60	43	31	16
Paynes Creek Surface Runoff	0	0	0	0	0	0
Paynes Creek Stream Gain/Loss	12	14	12	11	11	11
Putah Creek Unimpaired Flows						
Putah Creek Outflow	352	657	417	232	161	86
Putah Creek Inflow	362	658	424	249	175	103
Putah Creek Surface Runoff	21	34	28	17	11	9
Putah Creek Stream Gain/Loss	-31	-36	-34	-33	-26	-26
Sacramento River Unimpaired Flows						
Sacramento River Outflow	17,761	24,974	20,284	16,032	13,251	9,192
Sacramento River Inflow	5,667	8,067	6,237	4,862	4,216	3,276
Sacramento River Surface Runoff	632	1,045	706	480	383	256
Sacramento River Stream Gain/Loss	-179	-241	-237	-127	-107	-162
Sacramento River Tributary Inflow	13,942	22,231	16,029	11,220	8,842	5,625
Sutter Bypass	241	334	276	217	184	127
Yolo Bypass	-2,894	-7,069	-3,139	-891	-452	-47
Sutter Bypass Unimpaired Flows						
Sutter Bypass Outflow	2,779	6,003	3,200	1,322	841	324
Sutter Bypass Inflow	2,538	5,669	2,924	1,105	658	197
Sutter Bypass Surface Runoff	236	345	271	203	163	123
Sutter Bypass Stream Gain/Loss	-50	-91	-58	-34	-20	-25
Stony Creek Unimpaired Flows						
Stony Creek Outflow	388	730	479	239	166	99
Stony Creek Inflow	436	787	534	285	209	135
Stony Creek Surface Runoff	0	0	0	0	0	0
Stony Creek Stream Gain/Loss	-49	-57	-55	-46	-43	-36

	Mean Annual Values WY 1921–2009					
	All	**W**	**AN**	**BN**	**D**	**C**
Flow Component	**TAF**	**TAF**	**TAF**	**TAF**	**TAF**	**TAF**
Thomes Creek Unimpaired Flows						
Thomes Creek Outflow	198	336	237	139	116	71
Thomes Creek Inflow	217	361	259	155	130	78
Thomes Creek Surface Runoff	0	0	0	0	0	0
Thomes Creek Stream Gain/Loss	-18	-25	-22	-16	-14	-7
Yolo Bypass Unimpaired Flows						
Yolo Bypass Outflow	4,023	9,069	4,492	1,689	1,021	385
Yolo Bypass Inflow	3,868	8,824	4,292	1,568	935	319
Yolo Bypass Surface Runoff	173	276	224	137	93	74
Yolo Bypass Stream Gain/Loss	-19	-31	-24	-17	-7	-8
Yuba River Unimpaired Flows						
Yuba River Outflow	2,373	3,708	2,771	1,981	1,523	960
Yuba River Inflow	2,354	3,668	2,745	1,969	1,518	965
Yuba River Surface Runoff	41	63	49	34	26	17
Yuba River Stream Gain/Loss	-22	-22	-23	-22	-20	-21
Delta Unimpaired Flows						
Delta Outflow	29,529	46,421	34,121	24,334	18,770	12,401
Delta Tributary Inflow	29,258	45,859	33,720	24,158	18,708	12,432
Delta Surface Runoff	145	227	189	122	82	57
Delta Gain/Loss	-148	-138	-148	-154	-149	-162
Delta Accretion	251	403	327	193	133	106

WY = Water Year
W = Wet
AN = Above normal
BN = Below normal
D = Dry
C = Critical

A.5 Citations

Department of Water Resources (DWR) 2007. California Central Valley Unimpaired Flow Data. Fourth Edition – Draft. Available: http://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/bay_delta_plan/water_quality_control_planning/docs/sjrf_spprtinfo/dwr_2007a.pdf.

Department of Water Resources (DWR) 2016a. Estimates of Natural and Unimpaired Flows for the Central Valley of California: Water Years 1922-2014. Draft. Available: https://msb.water.ca.gov/documents/86728/a702a57f-ae7a-41a3-8bff-722e144059d6.

Department of Water Resources (DWR) 2016b. Development and Calibration of the California Central Valley Groundwater-Surface Water Simulation Model (C2VSim). Available: http://baydeltaoffice.water.ca.gov/modeling/hydrology/C2VSim/download/C2VSim_Model_Report_2016-03_vR374.pdf.

Department of Water Resources (DWR) 2016c. User's Manual for the California Central Valley Groundwater-Surface Water Simulation Model (C2VSim), Version 3.02-CG. Available http://baydeltaoffice.water.ca.gov/modeling/hydrology/C2VSim/download/C2VSim_Users_Manual_2016-03_vR374.pdf.

PRISM. 2013. PRISM Climate Group, Oregon State University, Corvallis, Oregon. Available: prism.oregonstate.edu. Accessed: July 2016.