Scientific Basis Report in Support of New and Modified Requirements for Inflows from the Sacramento River and its Tributaries and Eastside Tributaries to the Delta, Delta Outflows, Cold Water Habitat, and Interior Delta Flows

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CALIFORNIA
Water Boards
STATE WATER RESOURCES CONTROL BOARD
REGIONAL WATER QUALITY CONTROL BOARDS

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Appendix A Modeling Approaches Used to Develop Unimpaired Watershed Hydrology

Errata

Tables and Figures

Acronyms and Abbreviations

7DADM	7-day average of daily maximum
AF	acre-feet
AFRP	Anadromous Fish Restoration Program
AFSP	Anadromous Fish Screen Program
BAFF	bio-acoustic fish fence
Bay	San Francisco Bay
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 River Delta Estuary
BBM	Building Block Method
BiOp	biological opinion
CALFED ERP	CALFED Ecosystem Restoration Program
CAMT	Collaborative Adaptive Management Team
CDBW	California Division of Boating and Waterways
CCF	Clifton Court Forebay
CCV	California Central Valley
CCWD	Contra Costa Water District
CDEC	California Data Exchange Center
CDFG	California Department of Fish and Game
CDFW	California Department of Fish and Wildlife
CDFW ITP	2009 California Department of Fish and Wildlife Incidental Take Permit for longfin smelt issued to DWR for the on-going and long-term operation of the SWP
CEC	contaminants of emerging concern
CEQA	California Environmental Quality Act
Central Valley Regional Water Board	Central Valley Regional Water Quality Control Board
CESA	California Endangered Species Act
CDEC	California Data Exchange Center
CFGC	California Fish and Game Commission
cfs	cubic feet per second
cm	centimeters
CPUE	catch per unit effort
CSAMP	Collaborative Science and Adaptive Management Program
CVP	Central Valley Project
CVPIA	Central Valley Project Improvement Act
CWT	coded wire tag
D-1641	State Water Board Revised Water Right Decision 1641
D-1644	State Water Board Water Right Decision 1644
D-893	State Water Board Water Right Decision 893

DCC	Delta Cross Channel
DDT	dichlorodiphenyltrichloroethane
DEFG	Delta Environmental Flows Group
Delta	Sacramento-San Joaquin Delta
Delta Conservancy	Sacramento-San Joaquin Delta Conservancy
Delta Flow Criteria Report	*Development of Flow Criteria for the Sacramento-San Joaquin Delta Ecosystem*
Delta ISB	Delta Independent Science Board
Delta Reform Act	Sacramento-San Joaquin Delta Reform Act of 2009
Delta RMP	Delta Regional Monitoring Program
DETAW	Delta Evapotranspiration of Applied Water
DJFMP	Delta Juvenile Fish Monitoring Program
DMC	Delta-Mendota Canal
DO	dissolved oxygen
DPIIC	Delta Plan Interagency Implementation Committee
DPS	distinct population segment
DRIFT	Downstream Response to Imposed Flow Transformation
DSC	Delta Stewardship Council
DSP	Delta Science Program
DST	Decision Support Tool
DWR	California Department of Water Resources
DWSC	Deep Water Ship Channel
EBMUD	East Bay Municipal Utility District
EC	electrical conductivity; salinity
EDC	endocrine disrupting chemicals
ELOHA	Ecological Limits of Hydrologic Alteration
ERI	Eight River Index
ERP	Ecosystem Restoration Program
ESA	federal Endangered Species Act
ESU	evolutionary significant unit
FAS	Fully Appropriated Streams
FERC	Federal Energy Regulatory Commission
fisheries agencies	California Department of Wildlife, National Marine Fisheries Service, U.S. Fish and Wildlife Service
FFGS	floating fish guidance structure
FMWT	fall midwater trawl
FNF	Full Natural Flows
FSIP	Feasibility Study and Implementation Plan
GLC	Grant Line Canal
HAB	harmful cyanobacteria algal bloom
HFC	High Flow Channel
HORB	Head of Old River Barrier
HSRG	Hatchery Scientific Review Group
Hydro Project	Oroville Facilities Hydroelectric Project

I:E	inflow to export ratios
IEP	Interagency Ecological Program
IEP MAST	Interagency Ecological Program Management, Analysis, and Synthesis Team
IFIM	Instream Flow Incremental Methodology
IPM	Integrated Pest Management
IRP	Independent Review Panel
JSA	Joint Settlement Agreement
km	kilometers
LFC	Low Flow Channel
LMMWC	Los Molinos Mutual Water Company
LSNFH	Livingston Stone National Fish Hatchery
LSZ	low salinity zone
MAF	million acre-feet
mmhos/cm	millimhos per centimeter
MOA	memorandum of agreement
mi^2	square mile
MR	Middle River
MRDO	minimum required Delta outflow
NDO	net Delta outflow
NDOI	net Delta outflow index
NH3	un-ionized ammonia
NH4	ammonium
NMFS	National Marine Fisheries Service
NMFS BiOp	NMFS BiOp on the Long-Term Operational Criteria and Plan for coordination of the CVP and SWP
NPDES	National Pollutant Discharge Elimination System
NTU	Nephelometric Turbidity Units
OC	organochlorine
OCAP	Long-Term Operational Criteria and Plan
OIMA	Office of Information Management and Analysis
OMR	Old and Middle Rivers
ORT	Old River near Tracy
PAH	polycyclic aromatic hydrocarbons
PAI Fund	Preservation Agreement Implementation Fund
PCB	polychlorinated biphenyls
PCPP	personal care products and pharmaceuticals
PCWA	Placer County Water Agency
PFMC	Pacific Fisheries Management Council
PG&E	Pacific Gas and Electric Company
PHABSIM	Physical Habitat Simulation
PCWA	Placer County Water Agency
POTW	publically owned wastewater treatment works

ppb	parts per billion
ppt	parts per thousand
Projects	the Department of Water Resources' State Water Project and the U.S. Bureau of Reclamation's Central Valley Project
psu	practical salinity unit
PTM	particle tracking model
Putah Creek Accord	Putah Creek Council, City of Davis, and UC Davis settlement agreement with the Solano County Water Agency, Solano Irrigation District, and other Solano water interests
RAFT	River Assessment for Forecasting Temperature
RBDD	Red Bluff Diversion Dam
Reclamation	U.S. Bureau of Reclamation
Report	Scientific Basis Report in Support of New and Modified Requirements for Inflows from the Sacramento River and its Tributaries and Eastside Tributaries to the Delta, Delta Outflows, Coldwater Habitat, and Interior Delta Flows
RM	river mile
RMP	Regional Monitoring Program for Water Quality in San Francisco Bay
RMT	River Management Team
RPA	Reasonable and Prudent Alternative
SacWAM	Sacramento Water Allocation Model
San Francisco Bay Regional Water Board	San Francisco Bay Regional Water Quality Control Board
SAV	submerged aquatic vegetation
Science Report	Scientific Basis Report in Support of New and Modified Requirements for Inflows from the Sacramento River and its Tributaries and Eastside Tributaries to the Delta, Delta Outflows, Coldwater Habitat, and Interior Delta Flows
SEI	Stockholm Environment Institute
SEWD	Stockton East Water District
SFEI	San Francisco Estuary Institute
SFEP	San Francisco Estuary Partnership
SMP	*2014 Suisun Marsh Habitat Management, Preservation, and Restoration Plan*
SPW	supplemental project water
SRWTP	Sacramento Regional Wastewater Treatment Plant
SST	Salmonid Scoping Team
State Water Board	State Water Resource Control Board
STN	Summer Tow Net Survey
SWP	State Water Project
TAF	thousand acre-feet
TAF/yr	thousand acre-feet per year
TBI	The Bay Institute
TCD	temperature control device
TCP	temperature compliance points
TMDL	total maximum daily loads
TNC	The Nature Conservancy

µg/g	microgram per gram
UF	unimpaired flow (modeled scenarios)
USACE	U.S. Army Corps of Engineers
USDOI	U.S. Department of the Interior
USEPA	U.S. Environmental Protection Agency
USFWS	U.S. Fish and Wildlife Service
USFWS BiOp	USFWS BiOp on the Long-Term Operational Criteria and Plan for coordination of the CVP and SWP
USGS	U.S. Geological Survey
UYRSPST	Upper Yuba River Studies Program Study Team
Water Boards	State Water Board, Central Valley Regional Water Quality Control Board, and San Francisco Bay Regional Water Quality Control Board
WCF	Wastewater Control Facility
WDR	waste discharge requirement
WET	Water Engineering and Technology, Inc.
YCI	Year Class Index
YCWA	Yuba County Water Agency
YRDP	Yuba River Development Project

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 Bay-Delta Plan identifies beneficial uses of water in the Bay-Delta, water quality objectives to reasonably protect those uses and a program of implementation to achieve the objectives, including actions the State Water Board will take (e.g., implementing flow requirements) and actions the State Water Board will take with others or recommendations to others for actions they should take (e.g., habitat restoration actions).

The State Water Board is conducting a review and update of the 2006 Bay-Delta Plan to ensure that beneficial uses of water in the Bay-Delta watershed are reasonably protected. Phase I addresses potential changes to San Joaquin River flow requirements for the protection of fish and wildlife and potential changes to southern Delta salinity requirements for the protection of agriculture.[1] Phase II addresses changes to the Bay-Delta Plan to protect native fish and wildlife in the Sacramento River, Delta, and associated tributaries.

This Scientific Basis Report (Science Report or Report) is being prepared to support the Phase II update of the Bay-Delta Plan. It describes the science on which proposed changes to the Bay-Delta Plan will be based. A working draft version of the Report was released on October 19, 2016, to receive early scientific and public input on the science related to Phase II prior to submittal of the Report for external peer review. The State Water Board received input from a number of interested parties including water users; environmental groups; and local, state, and federal agencies. In recognition of the vision for "one Delta, one science" articulated in the Delta Stewardship Council's (DSC) Delta Plan, the State Water Board also requested that the Delta Independent Science Board (Delta ISB) conduct a review of the Report. The State Water Board appreciates the valuable comments and suggestions that have helped further strengthen the scientific content in this version of the Report.

In addition, comments related to regulatory and policy issues were raised that have further informed the development of proposed changes to the Bay-Delta Plan, including implementation approaches. The general components of these changes are summarized below and in more detail in Chapter 5 for context, and will continue to be refined as the planning process moves forward. This Report and the peer reviewers' responses will be posted on the State Water Board web site and

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[1] Phase I is a separate process from Phase II. 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.

become part of the record for this Bay-Delta Plan update. Content from this Report will be included in a larger Staff Report that will also contain information on environmental, economic, and other analyses of potential changes to the Bay-Delta Plan, including regulatory and policy considerations of competing uses of water (including municipal, industrial, agricultural, power production, and other environmental uses of water such as wetland and wildlife refuge supplies). These issues are not addressed in this Science Report. Further, while a description of the approach for proposed changes to the Bay-Delta Plan is provided, the exact regulatory language is still under development and will be informed by the science in this Report and other information that will be included in the Staff Report. The public and agencies will continue to have opportunities to provide input throughout this process.

The proposed Phase II changes to the Bay-Delta Plan include: new inflow requirements for the Sacramento River, its tributaries, and eastside tributaries to the Delta; new and modified Delta outflow requirements; new requirements for cold water habitat; new and modified interior Delta flow requirements; recommendations for complementary ecosystem protection actions that others should take; and adaptive management, monitoring, evaluation, special study, and reporting provisions.

While the science summarized in this Report clearly supports the need for the flow and associated water project operational requirements for the protection of the ecosystem and native fish and wildlife beneficial uses, there are significant challenges that exist to establishing flow requirements for a watershed of this size and complexity, particularly given the importance of the watershed to the State's water supply needs. At the same time, the need for action is critical given the degraded status of the ecosystem and the lack of a comprehensive regulatory structure in the face of increasing water demands and climate change. Thus, the task before the State Water Board requires crafting the flow requirements with enough flexibility to work and adapt to new information and changing circumstances, but also with enough specificity to prompt meaningful and timely improvement in flow conditions and habitat.

The proposed changes to the Bay-Delta Plan are structured to address the complexities of the watershed while responding to new information and changing conditions and providing for meaningful action in the near term to protect the Bay-Delta ecosystem. The proposed changes are structured to work together and with other planning, science, restoration, and regulatory efforts in a timely, adaptive, flexible, and comprehensive manner so that meaningful action can be taken to ensure the protection of fish and wildlife before imperiled species in the watershed are no longer able to be restored.

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. However, the State Water Board recognizes that other actions, such as habitat restoration, are important to protect the Bay-Delta ecosystem. 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 complementary non-flow measures are pursued, including those that may result in the need for less flow to achieve the protection of native fish and wildlife (e.g., temperature control may be achieved with a temperature control device more efficiently than through flow alone, habitat alterations/restoration can yield food or predator evasion or take less water to create floodplain habitat).

The State Water Board's Bay-Delta planning and implementation efforts are part of a multi-faceted approach needed to address the systemic 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 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. The proposed changes to the Bay-Delta Plan described in this Science Report are designed to encourage and facilitate such agreements.

1.2 Final Draft Scientific Basis Report

This Science Report provides a review and summary of the best available science supporting potential changes to the Bay-Delta Plan's flow and water project operational requirements, building on science contained in the Delta Flow Criteria Report and other analyses. It also provides a summary of the science on other non-flow stressors and proposed actions to address those stressors in concert with flow actions. While perfect science is not available and exact mechanisms behind flow-related functions and other stressors are not fully understood, there is a significant and compelling amount of information supporting the need for new and modified 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 management and implementation processes are proposed 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 and changing conditions.

This chapter (Chapter 1) introduces the Science 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 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. It 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, how those stressors interact in the ecosystem and actions that are being taken or should be taken to address those stressors. Chapter 5 describes how the biological and hydrologic information provided in earlier chapters 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 environmental flows, the Report includes a comparison of a range of flows with the flow needs of multiple species to identify the range of protection that could be achieved at different flow levels. These protections are expected to be enhanced through targeted adaptive management and when combined with other measures.

1.2.1 The Bay-Delta Watershed

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, irrigation to the largest agricultural economy in the U.S., and recreational opportunities for a thriving tourism industry. The Delta is the hub of California's water supply system, serving as the source of water for the State's two largest water supply projects—the Department of Water Resources' (DWR) State Water Project (SWP) and the U.S. Bureau of Reclamation's (Reclamation) Central Valley Project (CVP) (collectively, the Projects)—as well as many other large and small diverters. Water is essential to the economy of California. The economy has proven resilient to fluctuations in water supply, but faces profound management challenges (Hanak et al. 2012).

The Bay-Delta is where California's two major river systems meet to form the largest estuarine ecosystem for fish and waterfowl production on the west coast of the Americas. The Bay-Delta includes the Delta, Suisun Marsh, and the San Francisco Bay. The Delta is about 738,000 acres of which about 48,000 acres are now open freshwater and the remainder is agricultural or urban, reflecting an almost complete loss of wetland habitats since California became a state (Whipple et al. 2012). Suisun Marsh comprises approximately 85,000 acres of duck clubs, game refuges, and sloughs. Landforms in Suisun Marsh have changed little from natural conditions, but salinities have generally risen (Whipple et al. 2012). San Francisco Bay includes about 306,400 acres of open water, with almost half of its wetland habitats having been restored in the last 20 years (SFEP 2015).

The Bay-Delta supports an exceptionally diverse array of migratory and resident fish, birds, and other valued wildlife and plants. The estuary is a crucial part of the Pacific Flyway. Some birds, particularly sandhill cranes, Canada geese, and snow geese, over-winter on flooded Delta fields while many other waterfowl rely on habitats in Suisun Marsh and San Francisco Bay. Migratory fish include green and white sturgeon; spring-run, winter-run, fall-run and late-fall-run Chinook salmon; and steelhead. These native species include important commercial and sport fisheries as well as taxa listed under the California and federal Endangered Species Acts (CESA and ESA, respectively). Unlike birds, migratory fish must travel through the entire estuary to get to and from their spawning habitats in the upper watershed. To migrate successfully, fish must find suitable habitats and withstand multiple stressors throughout the estuary. Almost all resident native fish species in the Bay-Delta have declined in abundance, particularly the longfin smelt (listed under CESA) and the Delta smelt (listed under both ESA and CESA). Two resident species have been extirpated: Sacramento perch and thicktail chub, primarily due to loss of suitable habitat. The most abundant fishes of the upper estuary are now all introduced and do not rely on the habitats and conditions historically found in California. These nonnatives, include striped bass, largemouth bass, and carp that were introduced for harvest and other species that invaded by various pathways. Habitat restoration and the effects of climate change are likely to further shift the abundance and distributions of species throughout the estuary (Goals Project 2015).

1.2.2 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 due to agricultural practices, urbanization, and flood control combined with substantial and widespread water development, including the construction and operation of the Projects, have been accompanied by significant declines in nearly all species of native fish, as well as other native and nonnative species dependent on the aquatic ecosystem. Fish species have continued to experience precipitous declines since the last major update and implementation of the Bay-Delta Plan in 1995 that was intended to halt and reverse the aquatic species declines occurring at that time. 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. Simultaneously, natural production of all runs of Central Valley salmon and steelhead remains near all-time low levels.

These declines are attributed in part to flow modifications due to dams and water diversions and related operations. At certain times in some streams, flows are completely eliminated or significantly reduced by direct water diversions and impoundment in reservoirs. At other times, flows are increased from reservoirs, but then exported from the watershed before contributing to Delta outflows. At the same time, the dams that impound that water block access to upstream cold water habitat and may cause significant warming of water downstream. Further, water project operations in the southern Delta alter circulation patterns, interfering with fish migration, changing water quality, and entraining fish and other aquatic organisms. A significant and compelling amount of scientific information indicates that restoration of more natural flow functions throughout the watershed from natal streams to the nearshore ocean is needed now to reverse the species declines in an integrated fashion with physical habitat improvements and other actions. While it is not possible to replicate natural flows or the natural landscapes in which those flows occurred and interacted in the Bay-Delta, it is possible to take actions to provide more natural functional flows in coordination with other complementary actions to improve and restore habitat functions to support a resilient ecosystem. The science summarized in this report documents these needs.

As described in Chapter 2, upstream diversions and water exports in the Delta have reduced January to June outflows by an estimated 56 percent (average), and annual outflow by an estimated 52 percent (mean). In the driest condition, in certain months outflows are reduced by more than 80 percent, January to June flows are reduced by more than 70 percent and annual flows are reduced by more than 65 percent. Richter et al. (2011) concluded that flow modifications greater than 20 percent likely result in moderate to major changes in natural structure and ecosystem function. 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). Native fish and wildlife in the Bay-Delta watershed have been significantly impacted by these reductions of flow, with many species currently on the verge of extinction. As discussed in Chapter 4, there are other factors involved in the decline of these species, but water diversions and the corresponding reduction in flows 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 focus on flow-related issues while acknowledging the importance of coordination with other science, planning, regulatory, and restoration efforts (discussed below) to protect 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 (BiOps) addressing Delta smelt and salmonids and an incidental take permit addressing longfin smelt. 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, including 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.

The proposed changes to the Bay-Delta Plan discussed in this Science Report are intended to begin to address these issues in a more comprehensive way by looking at the Sacramento River watershed and related tributaries and the Delta as a whole interconnected system.

1.2.3 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 ecological and water supply importance to the state. The Bay-Delta Plan addresses water diversions and use in the water quality control 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 reasonably protect those uses. Certain objectives are expressed as flows and others as salinity (electrical conductivity [EC] or chloride) and dissolved oxygen (DO) 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 the 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 monitoring, evaluation, and reporting measures to determine compliance with the objectives and evaluate the effectiveness of implementation measures.

Currently, the Projects have primary responsibility for meeting Bay-Delta Plan objectives, including existing Delta inflow, outflow, salinity, and other 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's and Reclamation's water rights for the SWP and CVP, respectively. As evidenced in the recent drought, the Projects' ability to maintain responsibility for meeting all Bay-Delta Plan flow and water quality requirements in the watershed while preserving water for cold water purposes is not realistic in the face of climate change and increasing water demands. Currently, the Projects supplement flows during much of the summer and fall with storage releases at the expense of cold water and other reserves, particularly during drought periods when water demands are increased and flows are diminished. The current Bay-Delta Plan does not provide sufficient flexibility in the program of implementation to address these and other conditions.

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 (Central Valley Regional Water Board) and San Francisco Bay Regional Water Quality Control Board (San Francisco Bay Regional Board) (collectively referred to as Water Boards) Bay-Delta planning and regulatory activities to address environmental and water supply crises in the Bay-Delta within the Water Boards' authorities, 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 recommending further review of existing and potential new Bay-Delta Plan requirements including: Delta outflow and Suisun Marsh parameters, various interior Delta flow limits, floodplain habitat, and monitoring and special studies. Inflows were added to the water quality planning considerations consistent with the 2010 Delta Flow Criteria Report findings that proportionate inflows should generally be provided from tributaries to the Delta watershed to provide for continuity and diversification of flows and increased Delta outflows for migratory and estuarine species.

1.2.4 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 (Delta Reform Act) (Wat. Code, § 85000 et seq.). The Delta Reform Act codified two coequal goals for the Delta of providing a more reliable water supply for California and protecting, restoring, and enhancing the Delta ecosystem, both of which are to be achieved in a manner that protects and enhances the unique cultural, recreational, natural resource and agricultural values of the Delta as an evolving place. To achieve this, the Delta Reform Act established the DSC and tasked the DSC with developing, adopting, and implementing an enforceable long-term plan for the Delta. The DSC's Delta Plan (DSC 2013) includes policies that are legally binding on covered activities as well as advisory recommendations.[2] The Delta Plan identified reducing reliance on the Delta through improved regional self-reliance for water and updating the Bay-Delta Plan flow and water quality requirements as priority actions to protect the Delta ecosystem and the reliability of the Delta's water supplies (DSC 2013, p. 19 [WR P1 and ER P1]). The Delta Plan 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.[3] The Delta Plan also identifies the DSC, together with DWR and the State Water Board as the lead agencies for achieving reduced reliance on the Delta. In addition, the California Water Action Plan, issued jointly by the California Natural Resources Agency, California Department of Food and Agriculture, and the California Environmental Protection Agency, establishes actions to sustainably manage California's water resources. The Water Action Plan identifies implementation of the Delta Plan and completion of the Bay-Delta Plan update as key elements to achieve the coequal goals for the Delta.

For the purpose of informing planning decisions for the Delta Plan and other efforts, the Delta Reform Act required the State Water Board to develop new flow criteria for the Delta ecosystem to protect public trust resources. 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). The Delta Flow Criteria Report made a number of findings and identified specific criteria for inflows, outflows, and interior Delta flows if fishery protection was the sole purpose for which waters were put to beneficial use without considering the need for cold water reserves and balancing of supplies for other beneficial uses of water. The report noted that there are many other important beneficial uses that these waters support such as municipal, industrial, agricultural, hydropower, recreation, and other environmental uses such as wetlands and refuge water supplies

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[2] The DSC has authority to ensure that covered actions – projects, plans, or programs that occur in the Delta and have a significant impact on achievement of the coequal goals – are consistent with the Delta Plan. (Wat. Code, §§ 85225, 85057.5.) The State Water Board's regulatory actions, including its water quality and water right proceedings, are exempt from the definition of covered actions and the DSC's consistency determinations. (*Id.*, § 85057.5, subd. (b)(1).)

[3] 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 DSC appealed and the Superior Court's invalidation of the Delta Plan is stayed pending that appeal.

that must be considered when determining regulatory flow requirements. The report noted that the State Water Board is required by law to establish flow and other requirements that ensure the reasonable protection of beneficial uses and that in order for any flow requirements to be reasonable, the State Water Board will consider and balance competing uses of water in its decision-making.

With respect to specific flow criteria, the Delta Flow Criteria Report found that flow criteria should reflect the frequency, duration, timing, and rate of change of flows, and not just volumes or magnitudes and proposed criteria based on a percentage of the unimpaired hydrograph as a way of achieving these attributes. The Delta Flow Criteria Report specifically identified a Delta outflow criteria of 75 percent of unimpaired Delta outflow from January through June and an inflow criteria of 75 percent of unimpaired Sacramento River inflow from November through June. The report also identified criteria for increased fall Delta outflow in wet and above normal years; fall pulse flows on the Sacramento River; and interior Delta flows.

The Delta Flow Criteria 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 emphasized the importance of a strong science program and a flexible management regime in implementing flow requirements. The report also included a number of other 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.

This Science Report and the proposed changes to the Bay-Delta Plan build on and refine the flow criteria concepts identified in the Delta Flow Criteria Report as discussed below.

1.2.5 Science and Technical Workshops to Inform Phase II

To inform the update of the Bay-Delta Plan, 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 categorized issues into areas of agreement, disagreement, and uncertainty (ICF 2013). The State Water Board requested input from the DSP lead scientist on the areas of disagreement or uncertainty that should be further prioritized for evaluation to inform the Phase II update of the Bay-Delta Plan. Delta outflows, interior Delta flows, and predation were identified as issues that should receive additional review. As a result of this recommendation, 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 Science 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.

1.3 Response to Comments on Working Draft Report

The State Water Board received written comments through December 16, 2016, on the October 2016 working draft version of this Science Report and held a technical workshop on December 7, 2016, to hear recommendations from the public and other agencies regarding any additional scientific information that should be considered during development of the final Science Report. Below is a summary of the primary topics raised by commenters on the working draft and how these comments have been addressed in this version of the Science Report or will be addressed in upcoming related processes.

1.3.1 Flow Requirements

During the workshop and in the written comments, there was significant discussion regarding the proposed approach to developing flow requirements, including use of unimpaired flows. Many commenters, including CDFW, NMFS, and the U.S. Fish and Wildlife Service (USFWS) (collectively "fisheries agencies"), were supportive of the proposed approach, but others requested more clarity on the use of unimpaired flows and the conceptual framework for changes to flow requirements. In particular, some commenters argued for a functional flow approach and the consideration of tributary specific circumstances and agreements while others focused on the differences between unimpaired flows and natural flows. Other commenters expressed concerns about the proposed new Delta outflow requirements assuming that those requirements would only be implemented by the Projects. This Report provides additional clarity regarding the State Water Board's proposed approach for establishing environmental flows that is based on a holistic methodology that recognizes the importance of the flow regime and providing for natural flow functions that address the ecosystem as a whole in context with human needs for water.

For inflow, the unique needs and circumstances of individual tributaries are recognized and appropriate adaptive management provisions will be proposed to address these. While tributary inflow requirements were originally recommended to be based on a numeric range of percent unimpaired flow in each tributary, the numeric inflow requirements are now proposed as combined inflows from the tributaries within a range that provides more flexibility for tributaries to work together to meet ecological and operational needs. This inflow requirement would be implemented through tributary or regional implementation plans tailored to each tributary's or region's specific circumstances. The tributary plans would be required to meet a narrative objective that describes the ecological purpose of inflow requirements and to contain a flow element that generally provides the same quantities of flow as the numeric objective. The tributary plans would then provide for that quantity of flow to be sculpted and shaped as necessary to maximize benefits for fish and wildlife within the tributary and Delta, including management of cold water resources. The tributary plans may also include complementary non-flow measures that will help to meet the narrative objective, potentially at the lower end of the range. The plans would be required to include provisions for drought as well as monitoring, reporting, and evaluation provisions. The State Water Board recognizes the local expertise and ingenuity within watersheds and the fact that coordination and cooperation with interested parties is crucial. As such, tributary plans may be proposed through voluntary agreements with locals, provided that those agreements meet the inflow requirements and other requirements regarding rigor. Where voluntary agreements are not reached, the State Water Board would develop the plans with input from stakeholders and other agencies.

Comments on recommended numeric Delta outflow requirements were critical of various technical aspects of the recommendation. In the working draft Science Report, recommended revised Delta outflow requirements (modifications to Table 4 of the existing Bay-Delta Plan) would be determined through a complex equation similar to the existing Delta outflow requirements but updated to the current month's hydrology rather than the prior month's to better link the Delta outflow and inflow requirements. Some commenters expressed concerns over the operational feasibility of such an outflow requirement under the assumption that the requirement would largely be implemented by the Projects and the potential for overburdening certain tributaries. In response to these comments and to better integrate the inflow and outflow requirements, while also providing flexibility, the proposed outflow requirements have been replaced by an "inflow-based Delta outflow" requirement. The proposed requirement specifies that required inflows be provided as outflows with appropriate adjustments for other accretions (e.g., Yolo Bypass inflows) and depletions (e.g., evapotranspiration and seepage). Similar to the inflow requirements, a plan for addressing the various technical aspects of compliance with the Delta outflow requirements would be produced with Delta water users (including the Projects), fisheries agency staff and other technical experts. The plan for implementing Delta outflows would necessarily interact with the tributary plans discussed above. The plan would also be required to address long-standing technical issues with measurement and compliance with Delta outflows, including measuring and accounting for depletions and accretions in the Delta, which currently require improvement as discussed in Chapter 2. In response to comments that the discussion of the effect of Delta outflow should not be limited to its effects on the Delta and Suisun Bay, Section 3.2.3 was added to discuss the physical and biological effects of Delta outflow on San Francisco Bay and the nearshore coastal ocean.

1.3.2 Adaptive Management

Many commenters expressed support for adaptive management provisions but requested more specificity on how adaptive management will be implemented. Comments focused on striking the right balance between flexibility and accountability. The State Water Board agrees that striking the right balance will be critical. Provisions will need to be flexible enough to address the complexities of this watershed, climate change, and new and changing information in a collaborative fashion that provides for timely and durable solutions. At the same time, those provisions will need to be rigorous enough to ensure meaningful action and the reasonable protection of fish and wildlife. The program of implementation will include specific adaptive management provisions and requirements, monitoring, reporting, and evaluation measures, including provisions for the development of biological goals by which success at achieving the narrative objectives will be measured that will inform adaptive management of the numeric requirements. Guidelines for these measures will be included in the program of implementation with specific measures that must be included in the tributary and Delta implementation plans. Processes will be established for regular planning, review, and adjustment of implementation measures based on new information and changing conditions. The State Water Board will continue to work with the DSC, DSP, Delta ISB, fisheries agencies, and others to ensure that adaptive management and associated monitoring, reporting, and assessment efforts are sufficiently rigorous. The State Water Board will specifically work to coordinate upstream actions on tributaries with downstream Delta science activities and to support a common Delta science program as recommended by the Delta ISB in its comments on the working draft Science Report. The State Water Board agrees that a common scientific and technical program will greatly support the effectiveness of environmental flow regulations, whether implemented through voluntary agreements or other mechanisms.

1.3.3 Climate Change

In its comments on the working draft Science Report, the Delta ISB noted that to address climate change effects, "longer-term adaptability, particularly in implementing regulations, will require strategic changes in regulatory philosophy and methods." Existing and prior Bay-Delta Plan requirements were written in a rigid and largely unadaptable manner requiring a lengthy multistep process to adjust that presented challenges to implement effectively at the watershed level. The proposed changes to the Bay-Delta Plan are meant to address these issues while also retaining some of the more rigid backstops from the current Bay-Delta Plan.

The proposed approach for environmental flows is a major shift in regulatory philosophy and methods, meant to address the effects of climate change and other needs for adaptive management to respond to new and changing information and conditions. In particular, the proposed approach for inflows and the inflow-based outflow requirements scale to water availability in a watershed that may change as a result of climate change allowing the State Water Board to reasonably protect the environment while considering other uses of water. A range for environmental flows provides for adjustment that may be needed to provide more protection for the environment or more consideration of limited water availability due to droughts. Sculpting and shaping of flows is provided in recognition that rainfall and snowmelt patterns have changed and will continue to change, as has the physical environment, and that consideration of and adaptation to these changes are needed to protect native fish and wildlife. In addition, cold water habitat requirements are proposed and emphasized in response to these same issues. These requirements acknowledge that different tools may be needed to address climate change and other factors, including cold water pool management in reservoirs, passage projects, riparian reforestation, and other measures.

The State Water Board also acknowledges that actions by others will be needed to address climate change, physical changes to the environment, and other issues and that the State Water Board has a role in promoting and supporting those actions. The Delta ISB specifically recommended that the Science Report discuss the effect of climate change on hydrologic conditions in the Delta and near term management actions that might be taken now to sustain native fish and the aquatic ecosystem in the long term. Potential management actions include purchasing land to prepare tidal marshes and other habitats for higher sea level later and developing plans for changing water temperature controls at dams and other infrastructures facilities to accommodate increases in water temperature in the future.

In response to the Delta ISB's comments, Section 4.6 was revised to more fully describe the effect of climate change on the hydrology in the Delta and how these changes might have cascading effects on fish and food webs. The section ends with recommended management actions that might be taken now to ameliorate the long-term effects of climate change. Section 4.3.4 was also expanded with recommendations on additional monitoring and modeling that should be undertaken in reservoirs and downstream in river channels to the Delta. Comprehensive reservoir and stream temperature monitoring and modeling is needed to provide a better estimate of the magnitude and temperature of the cold water pool available at individual reservoirs for downstream protection of salmonid spawning and rearing. Development of thermal mass balance models to predict real time temperatures in river channels between reservoirs and the Delta would provide quantitative information on the factors responsible for temperature changes and how these might be better managed now and in the future with climate change to protect native fish species.

1.3.4 Water Temperature

In its comments, the Delta ISB recommended more emphasis on managing water temperature, including (1) further assimilation and synthesis of fish temperature relationships and how the information might be used in management; (2) ongoing temperature collection, modeling, and monitoring efforts in major rivers to inform future management; and (3) recommendations for research to aid management of water temperature in real time. In addition, several commenters noted that the thermal requirements for salmonids were scattered throughout the document and required clarification.

Section 3.4.2.1, describing Chinook salmon life histories, was revised and now incorporates all the thermal requirements of each life stage in one location. In addition, a new Section 3.4.4 was written on dam and reservoir effects on salmonids. The section describes the limiting factors for Chinook salmon below major dams and identifies maintaining cold water storage as a primary factor limiting the ability of reservoirs to meet water temperature requirements for spawning and rearing, especially during droughts and critically dry periods. The section recommends additional temperature monitoring and modeling to better understand the factors influencing thermal dynamics in reservoirs and downstream channels. Calibrated models will provide quantitative information on the factors responsible for temperature changes and may suggest real-time options for managing the system in the future with climate change to protect native fish species, including implementation of the proposed cold water habitat requirement.

1.3.5 Non-Flow Stressors

The Delta ISB commented that more information and a greater scientific understanding of non-flow stressors could provide a better basis for negotiated agreements among responsible entities. Other parties requested more quantitative information on the effect of non-flow stressors on native fish, on interactions of each stressor with flow, possible methods for reducing the effect of stressors, and identification of agencies responsible for regulating stressors. In response to these comments, Chapter 4 was updated with an emphasis on a stronger problem statement for each stressor that describes its effect on the aquatic ecosystem, interactions with flow, identification of actions that are being taken or should be taken to address those issues and identification of who is or should be doing that work. While the Delta ISB requested quantitative assessments of the effects of different stressors on native species abundance and the ecosystem, this information is not readily available for many stressors. When possible, however, this information is provided. The chapter ends with a stronger conclusion section summarizing critical non-flow issues, and potential actions to address problems. This information will inform the development of recommendations for other entities in the program of implementation.

1.3.6 New Science and Uncertainty

A number of comment letters suggested that the Science Report review and include more recent information in at least three areas. First, the Collaborative Adaptive Management Team's (CAMT) Salmonid Scoping Team released their Gap Analysis Report in early 2017. Among other things, this report summarizes the most recent information on salmon survival in the interior Delta. Second, Fong et al. (2016) published results on correlations between pyrethroid insecticide use in the Central Valley and Delta and indices of native species. The analysis suggests that pyrethroid insecticides may be a contributor to fish population declines in the Delta. Finally, recent investigations into the cause of low egg to fry survival below Shasta Reservoir for winter-run Chinook salmon indicates that existing temperature requirements may not be sufficiently protective and may need to be modified to address elevated embryo mortality.

Section 3.4.5.2 was modified to include new information on salmonid survival in the interior Delta from the Salmonid Scoping Team Gap Analysis Report. The new findings do not significantly change any of the flow proposals in Chapter 5. However, in recognition that information continues to evolve, the proposed interior Delta flow requirements discussed in Chapter 5 have been refined to provide flexibility to address changing information. Section 4.3.1.1 was expanded to include a discussion of the potential impact of pyrethroid insecticides on native species. Regular monitoring for pyrethroids in the Delta and special studies to determine their effect on fish and wildlife health are recommended. Finally, a new Section 3.4.4 was added on dam and reservoir effects on salmonids. The new information on temperature-related embryo mortality is discussed there. As noted previously, a new recommendation is made for additional temperature monitoring and modeling in reservoirs and in river channels downstream of reservoirs to the Delta. These studies may provide additional information on how to manage reservoir cold water storage and the downstream system better to avoid thermal impacts and will inform implementation of the cold water habitat requirement discussed below and in more detail in Chapter 5.

Several commenters recommended that the Science Report provide estimates of uncertainty for the flow abundance and logistic regression analyses in Chapter 3 in accordance with the DSP independent panel report on Delta outflows (Reed et al. 2014). In response, the Report now includes 95 percent confidence limits for all graphs of statistical analyses in Chapter 3.

1.4 Potential Modifications to the Bay-Delta Plan

Following is a general summary of proposed changes to the Bay-Delta Plan to reasonably protect the Bay-Delta ecosystem and associated native fish and wildlife beneficial uses as well as a brief discussion regarding how these proposed changes interact with other related processes. The proposed changes reflect agency and public comments on the working draft Science Report. The exact language of proposed changes to the Bay-Delta Plan will be determined based on the final Science Report and environmental, economic, and other analyses prepared to determine what is reasonably needed to protect fish and wildlife in consideration of all of the information before the State Water Board. The policy and implementation discussion is provided for context and does not contain new scientific findings that require scientific peer review under Health and Safety Code section 57004. 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, as well as associated adaptive management, monitoring, evaluation, and reporting requirements and recommendations to others for actions they should take to address ecosystem stressors and complement the flow actions. Together the proposed changes to the inflow, outflow, cold water habitat and interior Delta flow provisions of the Bay-Delta Plan, along with other habitat restoration actions are proposed to work together to provide comprehensive protection to native aquatic species from natal streams through the Delta and Bay. To the extent that existing Bay-Delta Plan requirements are not mentioned, no substantive changes are recommended to those requirements at this time.

1.4.1 Coordination with Other Science, Planning, and Regulatory Efforts

This Science Report includes various proposed modifications to the Bay-Delta Plan that are related to other planning, science, and regulatory efforts. Specifically the report includes recommendations that are consistent with requirements included in the 2008 USFWS and 2009 NMFS BiOps on the Long-Term Operational Criteria and Plan (OCAP) for coordination of the CVP and SWP (USFWS BiOp and NMFS BiOp, respectively) and the 2009 CDFW Incidental Take Permit (ITP) for longfin smelt issued to DWR for the ongoing and long-term operation of the SWP (CDFW ITP). Any Bay-Delta Plan requirements that are related to the USFWS and NMFS BiOps, CDFW 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.

The State Water Board will continue to coordinate with the DSP and Delta 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.

1.4.2 Environmental Flows, Adaptive Management and Biological Goals

There are several methods for determining flows needed for the protection of aquatic ecosystems. Chapter 5 generally describes these different methods and recommends an approach, referred to as a holistic flow approach (discussed in more detail in Chapter 5), in which flows are developed to address the ecosystem as a whole that generally resemble the natural flow regime to which native species are adapted while providing for deviation from the natural flow regime in watersheds that have been highly altered and support a variety of beneficial uses. This approach is proposed to be implemented in a flexible way that recognizes the realities of this complex watershed and climate change while also recognizing the need for expedient action. New inflow and cold water habitat requirements are proposed for the Sacramento River and its tributaries and eastside tributaries to the Delta, and new and modified Delta outflows and interior Delta flow requirements are proposed, as well as complementary actions to address other stressors and monitoring, evaluation, and reporting requirements.

Many of the streams under consideration have no inflow, cold water habitat or Delta outflow requirements. Where requirements do exist they may only be for parts of the year or may be inadequate, particularly with respect to contribution to Delta outflows. The proposed inflow requirements would establish a uniting regulatory approach for instream flow requirements for all salmonid bearing tributaries in the Bay-Delta watershed for the entire year that provides for contributory Delta outflows and maintenance of cold water habitat. The approach is structured to address the reality of the existing altered hydrology and landscape in which these flow requirements will be established and the reality that flows are also needed for a variety of purposes. Simply put, under the proposed approach, a portion of the inflow to a watershed would be dedicated to environmental purposes. This dedicated quantity of environmental flows would then be provided based on the unique needs and circumstances of each tributary and on a regional basis to provide for critical functions within the streams and as contributory flows to the Delta.

The environmental flows are derived from the unimpaired flow of a water body that could be implemented based on the specific needs and circumstances within each tributary. 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. 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 while recognizing other consumptive uses of water. 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. Where unimpaired flows may not entirely provide for natural flow functions, those flows may be shaped and sculpted under the proposed approach. Ranges for the unimpaired flows and flexibility in implementing flows while achieving the narrative inflow requirement are proposed to address specific needs within tributaries, climate change, drought circumstances, cold water needs and other factors.

The numeric inflow and associated outflow requirement may be implemented in a variety of ways depending on the specific needs for flow to provide maximum benefits to fish and wildlife, including targeted pulses to cue migration, summer cold water releases, base flows and other functions. Flows could be implemented in a manner that generally follows unimpaired flows in watersheds where there is little alteration to the landscape and where such flows would provide for the natural functional conditions to which native species are adapted. In more physically altered watersheds, the pattern of these flows would likely be modified from unimpaired to achieve specific functions. With increasing climate change, it is expected that further sculpting and shaping of flows would be needed. New and existing tools could be used for shaping the flows based on the availability of information for a watershed (e.g., specific instream flow studies, presence of reservoirs). Monitoring and special studies would then inform adaptive management of the environmental flows. Biological goals that incorporate "SMART" (specific, measurable, achievable, relevant, and time-bound) principles that are tied to controllable factors within specific watersheds are proposed to be developed as a bar against which flow and other management actions are measured for determining adaptive management actions and assessment of flow and other actions. The specific implementation parameters for use of unimpaired flows, adaptive management, and biological goals are being developed in the draft proposed water quality objectives and program of implementation language.

1.4.3 Tributary Inflows

This report describes the science supporting proposed 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 1.4-1.

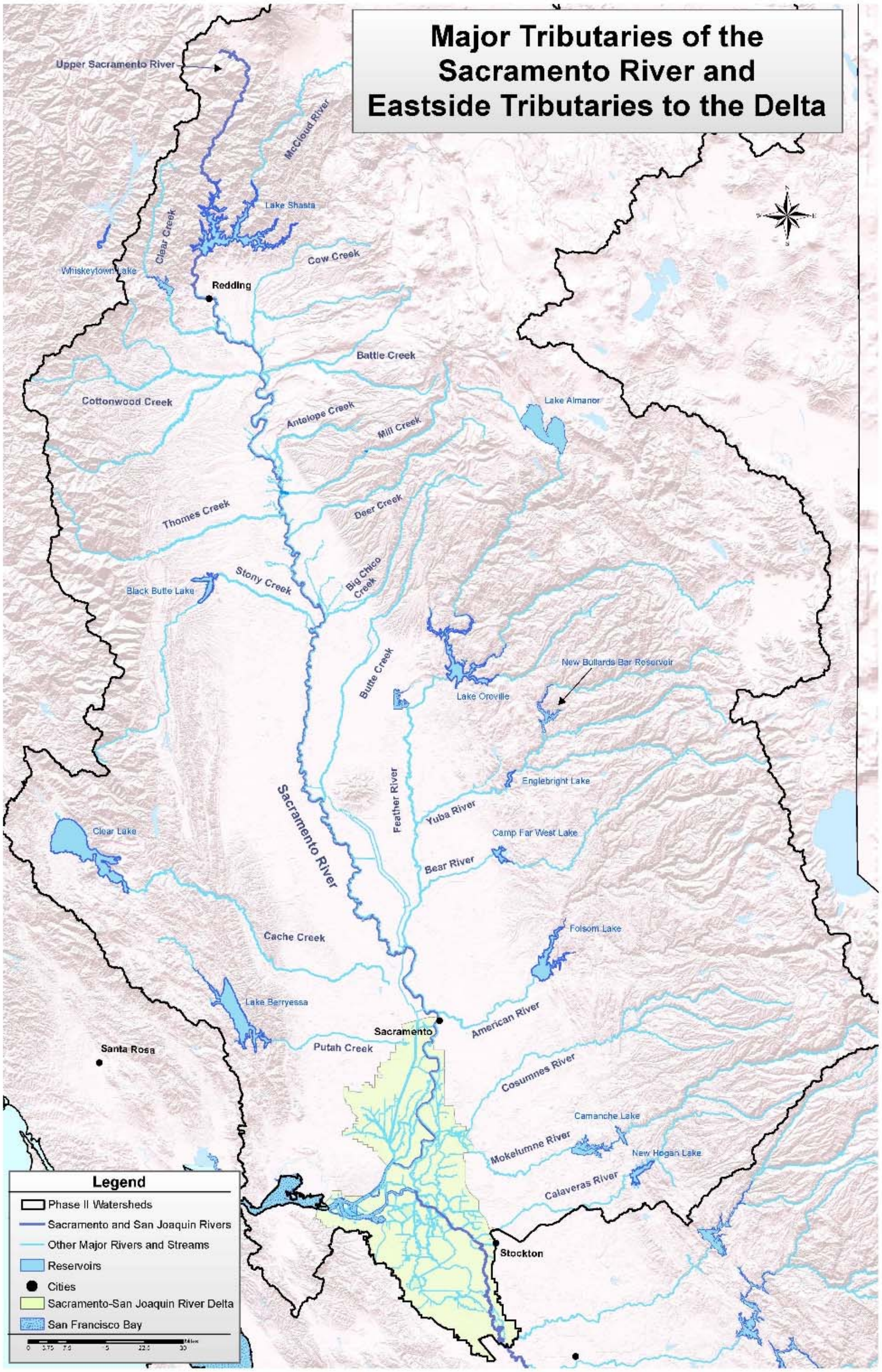

Figure 1.4-1. Major Tributaries of the Sacramento River and Eastside Tributaries to the Delta

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 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 on fish and wildlife. In addition, some of these tributaries may dry up at times of year impacting fish and wildlife 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, cold water habitat, and interior Delta flows are necessarily interconnected.

This Report describes how year-round inflow requirements are needed to provide for ecological processes including continuity of flows and specifically 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 have runs 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 humanmade stressors present to populations. Given the altered physical and hydrologic state of the watershed, the Science Report acknowledges that adaptive management should be provided to maximize the effectiveness of flow measures and to respond to additional science and changing conditions.

As discussed above, the proposed changes to inflow requirements and other requirements are structured to provide necessary flexibility and adaptive management provisions to address the complexities of inflow needs and constraints in the watershed in a reasonable and protective manner. The proposed new inflow objectives are expressed both numerically and narratively.[4] The narrative portion of the objectives describes the inflow conditions necessary to reasonably protect native fish populations, including through contribution to Delta outflows to protect estuarine species as discussed below. The new numeric inflow objective is proposed to reasonably protect native fish populations, including by implementing the narrative objective and integrating inflows

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[4] The existing Sacramento River at Rio Vista inflow requirements during September through December would be retained in order to maintain the minimal level of protection currently provided by these base flows.

and outflows in a comprehensive manner. The numeric inflow requirement would require a combined amount of the inflow from the Sacramento River, its tributaries, and the Delta eastside tributaries to remain in the stream for environmental flows. The proposed numeric requirements may be managed as a block of water for the environment to provide functional and other scientifically based flow regimes. That block would be established based on a percentage of the inflows to the watersheds assuming there were no diversions occurring (unimpaired flows), thereby allocating a portion of the water in the watershed to the environment to be managed to optimize benefits for fish and wildlife for inflow and outflow purposes (percent of unimpaired flow requirement). Through adaptive management, unimpaired flows could 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 proposed inflow requirements are also specifically intended to provide for increasing the frequency and duration of floodplain inundation to improve ecological functions in the Bay-Delta for the benefit of native species. The adaptive management provisions of the inflow and outflow requirements will provide for floodplain inundation and the accounting and other factors needed for that to occur. Preservation of flow levels in some less impaired tributaries is also proposed where existing flows are providing important functions. This will ensure that those flows are not reduced and thus will maintain existing protective conditions.

The numeric inflow requirement is proposed to include a range for the flows such that flow levels could be adjusted up or down within the range in order to address the unique needs and conditions of the tributaries (including cold water pool needs), changing information (new science) and changing conditions (implementation of non-flow measures, drought, etc.) in a way that reasonably protects fish and wildlife. The proposed range for the inflow objective has not yet been determined and will be determined after considering the information in this Science Report, along with information the State Water Board needs to consider. This includes the past, present, and future beneficial uses of water; the environmental characteristics of the hydrographic unit under consideration; economic considerations; environmental effects of alternatives; public comments; and other information. The range under consideration is from 35 to 75 percent of unimpaired flows and generally does not provide for flows lower than existing conditions. In some tributaries where flows are currently significantly impaired, these new 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, new inflow requirements are needed to ensure that those flows do not become impaired to the detriment of fish and wildlife.

The exact method by which the flows will be achieved has not been determined. The program of implementation would require the development of tributary plans (discussed in more detail in Chapter 5), containing a flow element that will achieve the narrative requirement and fall within the range of the numeric requirement. A specific tributary flow may fall outside of the range of the numeric if two or more tributaries work together such that their combined flows meet the numeric requirement and the specific tributary flow still meets the narrative requirement (e.g., maintain connectivity and contribute to outflow). In recognition of the local expertise within tributaries and the potential benefit of collaborative solutions, the program of implementation would provide a period of time for regional and tributary-based flow and other measures to be developed by stakeholders for approval by the State Water Board. If a tributary plan is not developed or is found to be unsatisfactory, the State Water Board would exercise its legislative or adjudicative powers involving water rights and water quality, or both, to require implementation of the objectives.

1.4.4 Delta Outflows

This report describes the science supporting proposed new and modified Delta outflow requirements to protect fish and wildlife beneficial uses from the Delta out to the nearshore ocean. Monitoring of fish and invertebrate abundance in the Bay-Delta estuary continues to show the importance of Delta outflows for the protection of various species and the ecosystem. The location where lighter freshwater from the rivers mixes with heavy seawater from the ocean in the estuary (referred to as the low salinity zone or "LSZ") is correlated with the survival and abundance of many species. This mixing concentrates suspended solids and aquatic organisms to comprise the estuarine habitat that supports multiple life stages for a diversity of fishes and other species. The location and extent of estuarine habitat fluctuates in response to river flows, ocean tides, weather, and geographic features (e.g., levees, the depth and breadth of stream channels, connectivity to adjacent wetlands).

The location of the LSZ is measured by the location of the two parts per thousand salinity isohaline (or X2) (as measured in kilometers (km) from the Golden Gate). Generally, the further X2 is located downstream of the confluence of the confined deep channels of the Sacramento and San Joaquin Rivers and the effects of the Project export facilities and downstream into the broad, shallow, cool channels of Suisun Marsh and Suisun Bay, the better fish and other species respond. While the exact mechanisms behind this relationship are not understood, these more westerly X2 positions generally provide significantly improved habitat conditions for native species.

The relationships between outflow and estuarine fish abundance and several other measures of the health of the 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 indicates that fall and summer outflows are also 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 2014a). 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 5 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 4 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 that improves habitat conditions for native species.

As discussed above, 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 proposed 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 declines in population size of Sacramento splittail and longfin and Delta smelt have continued since implementation of D-1641. The declines suggest that the current Bay-Delta Plan as implemented in 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, this report includes proposed new and modified narrative and numeric Delta outflow objectives. The narrative Delta outflow objective is proposed to describe the outflow conditions that reasonably protect native estuarine and anadromous fish and aquatic species populations. Specifically, it requires maintenance of Delta outflows sufficient to support and maintain the natural production of viable native fish and aquatic species populations rearing in or migrating through the Bay-Delta. Changes to the numeric Delta outflow requirements are proposed to achieve the narrative requirement and better integrate the Delta outflow requirements with the proposed inflow requirements. Together the Delta outflow, inflow, and other requirements are proposed to provide comprehensive protection for fish and wildlife from natal streams through the Delta and Bay and nearshore ocean while providing necessary flexibility and adaptive management provisions to address the complexities of providing Delta outflows from the watershed in a reasonable and protective manner.

Proposed changes to the numeric Delta outflow requirements include maintaining some existing requirements, removing some existing requirements, adding new requirements, and incorporating existing BiOp requirements for the Projects. In order to ensure that minimum quantities of Delta outflow are provided to the estuary in all months and all years, base Delta outflows from the current Bay-Delta Plan would be maintained. Specifically, the existing base Delta outflow requirements that are included in Table 3 of the Bay-Delta Plan that range from 3,000 to 8,000 cubic feet per second (cfs) would be maintained. However, as discussed below, the methods by which this requirement may be met are proposed to be reevaluated to ensure that intended protections are provided, while providing flexibility to reduce water supply impacts. The remaining existing Delta outflow requirements are proposed to be replaced with an “inflow-based Delta outflow” objective that is expected to better achieve the proposed new narrative Delta outflow objective in an integrated fashion with the proposed new inflow requirements discussed above.

The proposed new inflow-based Delta outflow objective specifies that the required inflows from the Sacramento and San Joaquin Rivers and their tributaries and the three Delta eastside tributaries are provided as outflows with appropriate adjustments for depletions and accretions, including adjustments for floodplain inundation flows and other side flows. The intent of the inflow-based Delta outflows is to provide continuity of flows from upstream tributaries through the Delta and out to the Bay to improve estuarine habitat conditions. Like the inflow objectives, the outflow objectives are not proposed to be lower than existing conditions. Also like the inflow objectives, the inflow-based Delta outflow objective would allow for adaptive management and shifting and sculpting of flows and would require the development of a plan that addresses implementation measures by

Delta users, including the Projects, as well as monitoring and evaluation measures. The plan would address accounting measures for the existing and new requirements, including integration with tributary plans to the extent possible, accretions and depletions, and evaluation of the existing and new methods of compliance with Delta outflows to ensure they are protective, including the compliance methods for the base flows discussed above.

In addition to the above, the fall Delta outflow requirements from the USFWS BiOp would be incorporated into the Bay-Delta Plan. These requirements include additional Delta outflow requirements in September through December when the preceding hydrologic period was a wet or above normal water year. The proposed changes to the Bay-Delta Plan would allow for adjustments to these requirements based on new information, including changes in the BiOp.

1.4.5 Cold Water Management

This 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 objective for cold water management with specific implementation actions to be developed on a stream-by-stream basis and included in the tributary plans discussed above.

1.4.6 Interior Delta Flows

This Report describes the science supporting new and modified narrative and numeric interior Delta flow requirements to protect fish and wildlife beneficial uses. Specifically, this report discusses the science supporting the need for interior Delta flow requirements to provide for more natural flow patterns from natal streams out to the ocean and to provide more natural ecosystem functions. Diversions in the south Delta and associated operations cause unnatural flow patterns with inflows traveling toward the Project export facilities, rather than toward the ocean. Here poor habitat conditions exist for native species and mortality is high due to predation, impingement, and other factors. More natural flow patterns are specifically needed to protect fish and other species migrating out of the Delta and rearing in the Delta and to provide for homing fidelity for fish migrating upstream through the Delta. The narrative requirement would establish the overall flow conditions in the Delta to reasonably protect native fish populations migrating through and rearing in the Delta.

Changes to the numeric interior Delta flow requirements would reasonably protect beneficial uses and help to implement the narrative requirement. Numeric objectives would be consistent with requirements that are already included in the USFWS BiOp, NMFS BiOp, and CDFW ITP including: new Old and Middle River (OMR) reverse flow limitations and changes to export and Delta Cross Channel (DCC) gate restrictions to expand the level of protection for those existing requirements in the Bay-Delta Plan. Similar to the existing process, the interior Delta flow requirements for OMR reverse flows, export limits, and DCC gate closures would be determined and based on monitoring of fish presence and a consultation process involving staff from the fisheries agencies, DWR, and Reclamation, with the addition of the State Water Board. 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, IEP, and other efforts.

1.4.6.1 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. When open, salmonids and other fish from the Sacramento River and its tributaries may be diverted through the gates into the interior Delta, where chances of survival and outmigration are greatly reduced. The DCC gates are required to be closed at certain times pursuant to D-1641 and the NMFS BiOp to protect fish and wildlife (specifically migrating salmonids). The Science Report proposes to extend the time period when the DCC gates may be required to be closed in the fall to include a greater portion of the salmonid migration period. The gates would be closed at times in October when monitoring information indicates that migrating salmonid are in the vicinity of the DCC gates consistent with the NMFS BiOp and in coordination with the implementation of the BiOp and any modified BiOp that may be issued in the future.

1.4.6.2 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 BiOp, the NMFS BiOp, and the CDFW ITP. The Science Report proposes inclusion of the BiOp and ITP OMR reverse flow limits in the Bay-Delta Plan in a coordinated fashion with the BiOps and ITP (and consideration of any new federal ESA or CESA requirements) to protect natural ecosystem functions and specifically for the protection of salmonids, Delta smelt, and longfin smelt.

1.4.6.3 Project Export Limits

Project exports have a significant effect on continuity of San Joaquin River flows out to the ocean because of the location of facilities in the south Delta immediately adjacent to the San Joaquin River and the relatively lower flows of the San Joaquin River compared to the Sacramento River. The 2006 Bay-Delta Plan includes limitations that constrain exports during a 30-day period in the spring to a ratio of 1 to 1 between San Joaquin River flows and exports, or minimal specified pumping levels (1,500 cfs), to minimize entrainment and salvage losses of outmigrating juvenile salmonids from the San Joaquin River. The NMFS BiOp 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 Science Report proposes more restrictive export constraints as a function of San Joaquin River flows up to the NMFS BiOp levels of between 4 to 1 and 1 to 1 of San Joaquin River flows to exports during the spring to protect outmigrating juvenile Chinook salmon. Adaptive management provisions are proposed such that the constraints could be adaptively managed for up to 60 days between February and June time period in coordination with NMFS. The requirement would also be coordinated with the NMFS BiOp, Phase I, and installation of the Head of Old River Barrier discussed in more detail in Chapter 3.

1.5 Next Steps

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). The State Water Board has made revisions to the working draft Science Report and has refined the description of proposed changes to the Bay-Delta Plan in this version of the report. This report will be updated as needed based on the peer review and the substance of this report will provide a portion of the Staff Report supporting the proposed changes to the Bay-Delta Plan. There will be additional opportunities for public participation and comment on the Staff Report as the planning process moves forward.

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 environmental documentation. 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, 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 Staff Report for the 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 analyses and documents the State Water Board may decide to include. The Staff Report will include the identification of any potentially significant environmental impacts of any new or changed requirements 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 changes to the requirements. The public will have the opportunity to review and comment on the Staff Report and associated analyses.

Chapter 2
Hydrology

2.1 Introduction

This chapter provides a description of the hydrology of the Delta, main stem Sacramento River, its tributaries, and the three eastside tributaries to the Delta. Throughout the watershed, current hydrologic conditions are compared with unimpaired conditions to assess the types of changes in the flow regime that have occurred. This information is provided as background and supporting information for subsequent chapters.

The hydrologic analysis of Delta outflows indicates that diversions and exports have reduced average annual outflow, reduced winter and spring outflow, and reduced seasonal variability. The hydrologic analysis also indicates that water development in regulated tributaries, such as the Sacramento River at Freeport, has generally resulted in reduced annual Delta inflow, a reduction in spring inflow, an increase in summer inflow, and a decrease in hydrologic variability. The analysis indicates that tributaries without large reservoirs generally have lower flows in late spring and summer. Finally the hydrodynamic analysis indicates that Project pumping in the south Delta and associated operations have increased the magnitude and frequency of reverse (upstream) flows on Old and Middle Rivers and other alterations in the hydrodynamics of the Delta.

2.1.1 Natural and Unimpaired Flow

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. Unimpaired flow is different than the “natural flow” that would have occurred absent human development of land and water supply. The use of unimpaired flows in the Bay-Delta watershed is often misunderstood and to some degree controversial, owing in part to genuine uncertainty regarding the relationship between unimpaired and natural flows and their intended use from a regulatory perspective. Differences between natural flows and unimpaired flows are thought to be relatively small in the upper watersheds where fewer physical modifications to the landscape have occurred and more natural runoff patterns exist (Figure 2.1-1) (DWR 2016a). While unimpaired flows and natural flows may be very similar in these areas, flow management must still consider the effects of dams and other physical modifications that block access to historical habitats and alter temperatures and other conditions important to aquatic species. On the valley floor and in the Delta, where the greatest land use changes have occurred, the differences between unimpaired flow and natural flows may be substantial at times (DWR 2016a), but are not known with certainty. Estimating natural flow requires making assumptions about many physical attributes of the pre-development landscape, including the distribution of wetland and riparian vegetation, channel configurations, detention of overbank flows, and groundwater accretions. All of these conditions differ from the current physical condition and land use of the watershed to unknown degrees (DWR 2016a). Estimates of evapotranspiration by natural vegetation (Howes et al. 2015) and its combined effects with other elements of a hypothetical pre-development condition on net Delta outflow (Fox et al. 2015) and throughout the Bay-Delta watershed (DWR 2016a) have been published recently. These estimates are produced by routing historical unimpaired flows from the upper watersheds over a hypothetical, reconstructed valley floor and Delta (Fox et al. 2015; DWR 2016a), producing estimates of the flow that “would have” occurred over the historical record in the absence of human development. DWR (2016a) concludes that “relative seasonal (i.e., monthly) distributions of unimpaired and natural Delta outflow estimates are not widely different,” but that, due to an imperfect scaling and difference in annual magnitude, “unimpaired flow estimates are poor surrogates for natural flow conditions.”

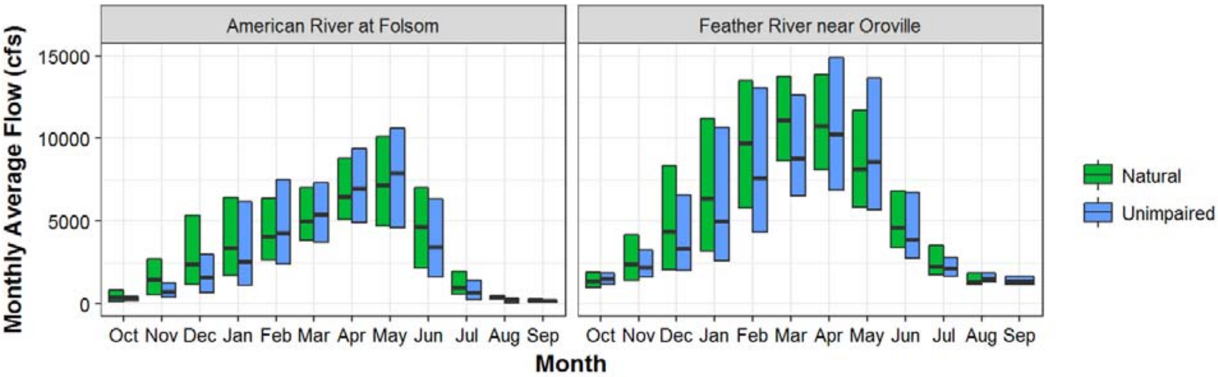


Figure 2.1-1. Quartile Distributions of Natural and Unimpaired Flows at Two Sample Rim Dam Locations, as Estimated by DWR (2016a). Monthly patterns and magnitudes are similar, but not identical.

To evaluate the potential differences between unimpaired flow and natural flow, the monthly distributions of DWR’s (2016a) estimates of the two, along with estimates of historical flow (also provided by DWR (DWR 2017) are compared over time. Figures 2.1-2 and 2.1-3 show these comparisons for Delta inflow and net Delta outflow as quartile distributions on a monthly time scale. As with a box and whisker plot, the black horizontal line shows the median, and the box spans the range between the 25th and 75th percentile; whiskers and outliers are omitted for clarity. The figures show the most significant differences between unimpaired and natural Delta flows during the peak snowmelt season of April through June, and generally throughout the drier months, due largely to the assumed presence of significant additional vegetation in the natural flow estimates. At the same time, the figures also show other significant differences between historical flows and estimates of unimpaired and natural flows over time, particularly during the wet months of winter and spring, due to water development. This increasing alteration of flows identifies a pattern of decreasing Delta outflow over time that can be expected to continue without additional regulation.

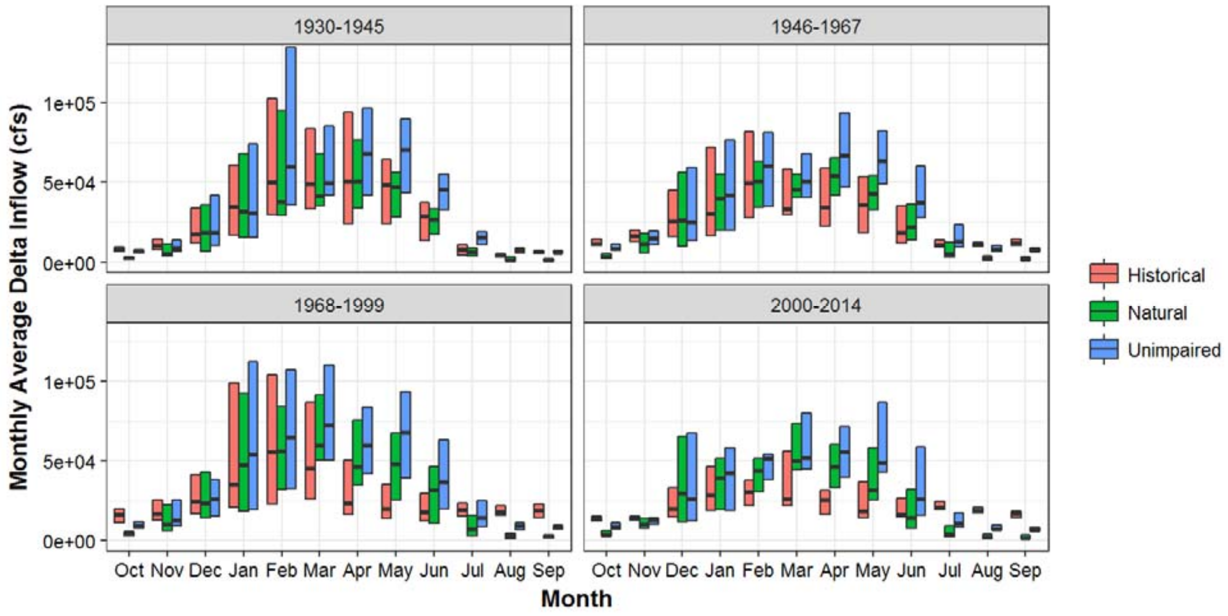


Figure 2.1-2. Quartile Distributions of DWR Estimates of Historical, Natural, and Unimpaired Delta Inflow. Water supply development has reduced wet season Delta inflow and increased dry season Delta inflow relative to both estimated unimpaired and natural flows over time. Natural and unimpaired flow estimates are from DWR (2016a), and historical estimates are from Dayflow (DWR 2017).

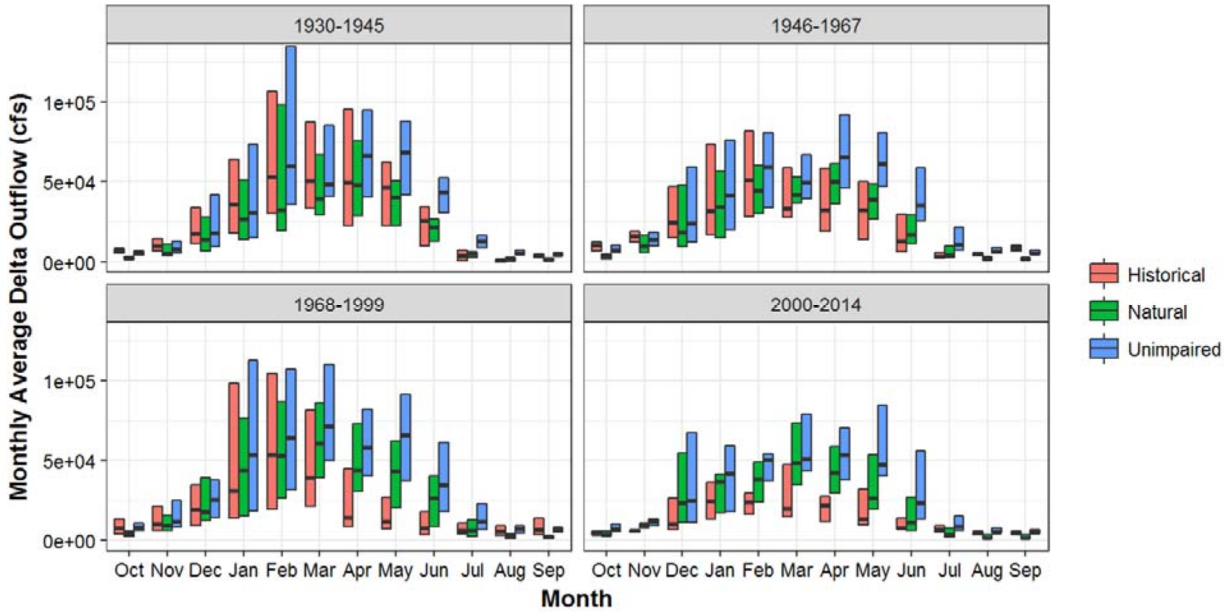


Figure 2.1-3. Quartile Distributions of DWR Estimates of Historical, Natural, and Unimpaired Delta Outflow. Water supply development has reduced wet season Delta outflow relative to both estimated unimpaired and natural flows over time. Natural and unimpaired flow estimates are from DWR (2016a), and historical estimates are from Dayflow (DWR 2017).

Unimpaired flows are used throughout this report in several ways that acknowledge and respect the differences between natural and unimpaired flows discussed above. Unimpaired flows are used to help characterize how human uses of water have altered the magnitude, timing, and duration of flows in the watershed under the current physical configuration of the watershed over time. This information can then be evaluated against species declines to help understand how changes in hydrology have contributed to those declines. At the same time, impacts from the changes in the physical configuration of the watershed are also discussed. In addition, unimpaired flows are used as an index of water availability to understand and help balance between environmental and other uses since water supplies for all purposes are limited. Unimpaired flows are also used as an approximation of more natural flow conditions protective of native aquatic species. However, as discussed further in Chapters 1 and 5, regulatory requirements based on unimpaired flows, acknowledge that the physical environment has been modified and that adaptive management is needed to allow for sculpting and shaping of those flows to address the realities of that altered landscape that native species now inhabit and the fact that this landscape will change over time with climate change, habitat restoration, and other factors.

2.1.2 Watershed Overview

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, with Sacramento Valley runoff ranging from an estimated 5.1 million acre-feet (MAF) in water year 1977 to 37.7 MAF in water year 1983 (DWR 2016b). For over 150 years, humans have altered the Sacramento River and its tributaries to reclaim wetlands, tame floods and provide irrigation during the dry months. Two of the largest water projects in the world, the SWP and the CVP, move water from the Sacramento watershed through the Delta and deliver it to farmers and cities in southern California.

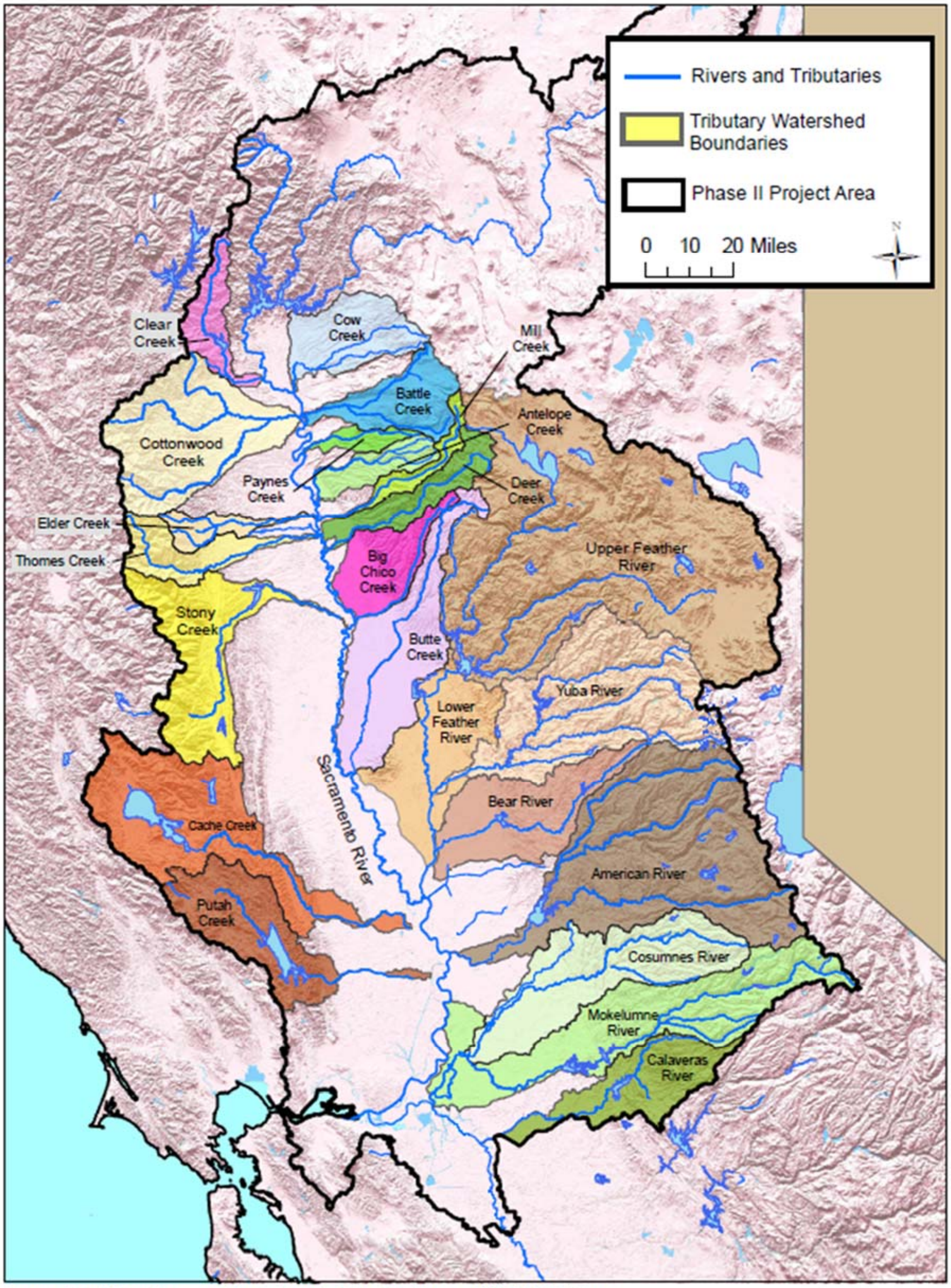
The Sacramento River extends from the Modoc Plateau and the southern Cascades near the Oregon border to the Pacific Ocean, draining an area of 27,000 square miles. The Sacramento River has an average annual unimpaired flow of 21 MAF (based on values for water years 1922–2014), which is approximately one-third of the total runoff in California (DWR 2016a). 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, and 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 are 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.

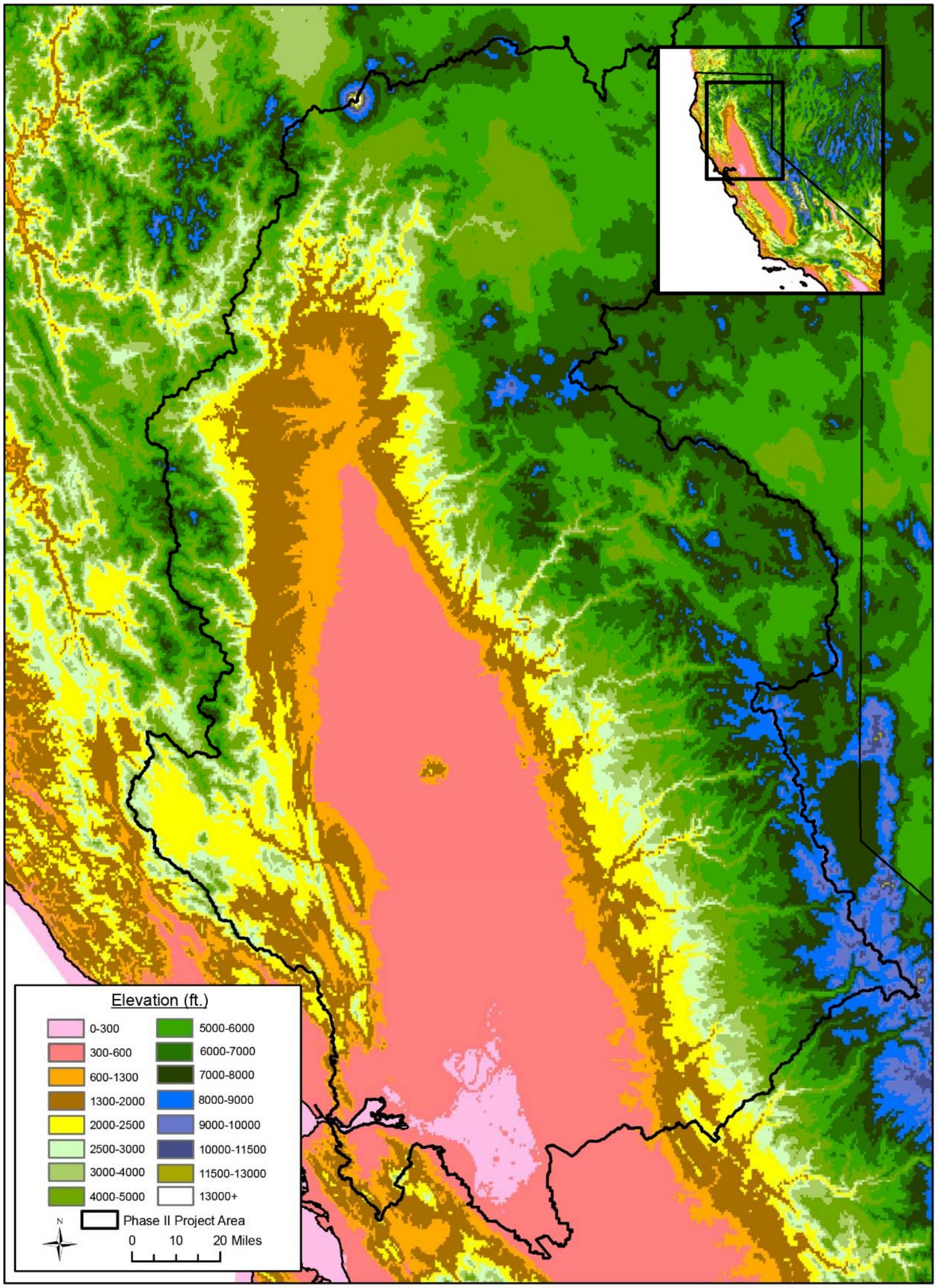
- Main Stem Sacramento
- Tributaries of Mt. Lassen
  - Cow Creek, Battle Creek
- Tributaries of the Chico Monocline
  - Antelope Creek, Deer Creek, Mill Creek, Paynes Creek
- Tributaries of the Klamath Mountains
  - Clear Creek
- Tributaries of the Paleochannels and Tuscan Formation
  - Butte Creek, 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 2.1-4. 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 II project area varies enormously from east to west and from north to south (Figure 2.1-5). 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 2.1-6 does not necessarily correspond to the highest areas of the mountain ranges and why the watersheds of the American and Feather Rivers 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.



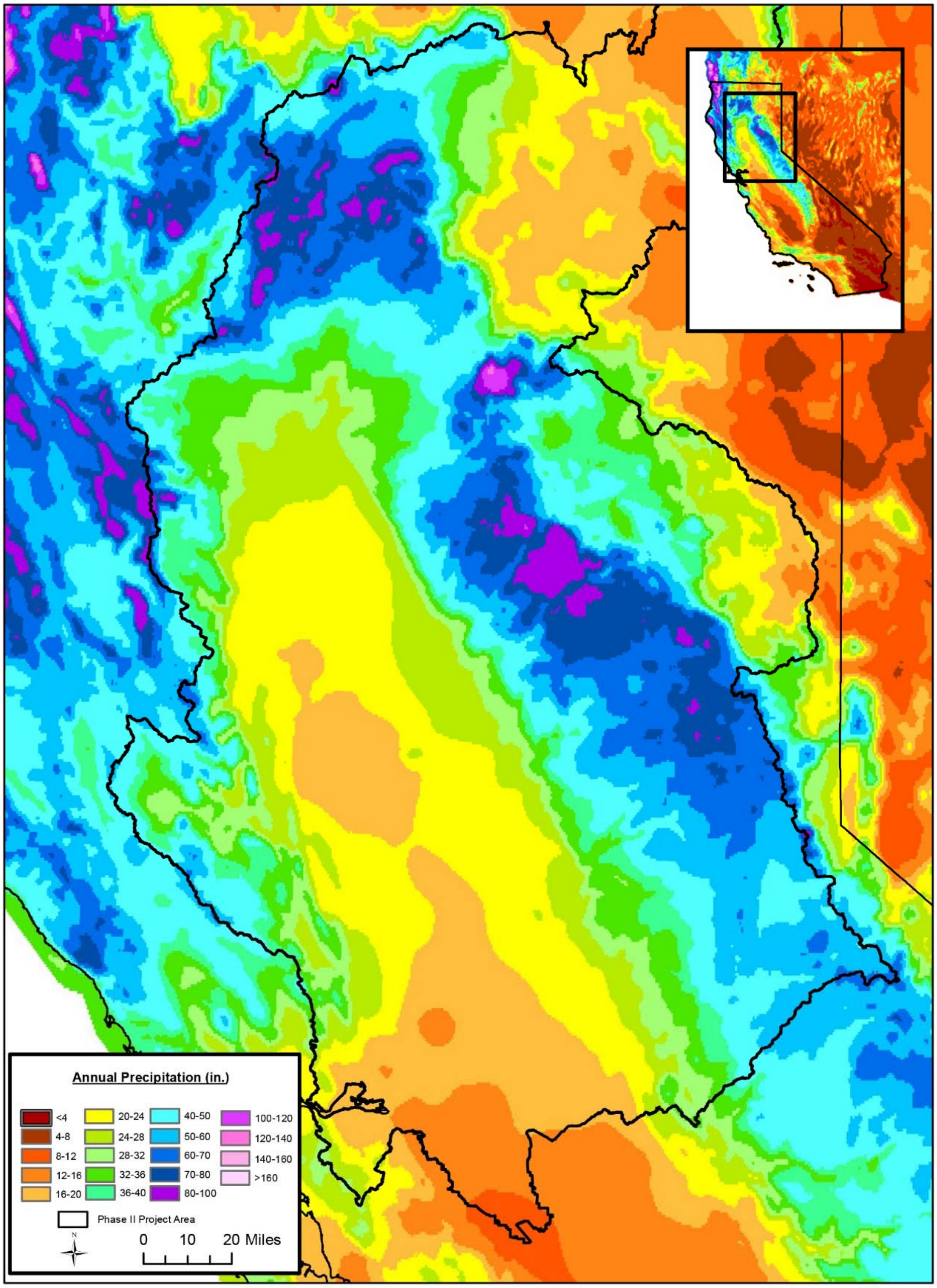
Source: State Water Resources Control Board, 2016 Data Source: SWRCB GIS Library

Figure 2.1-4. 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

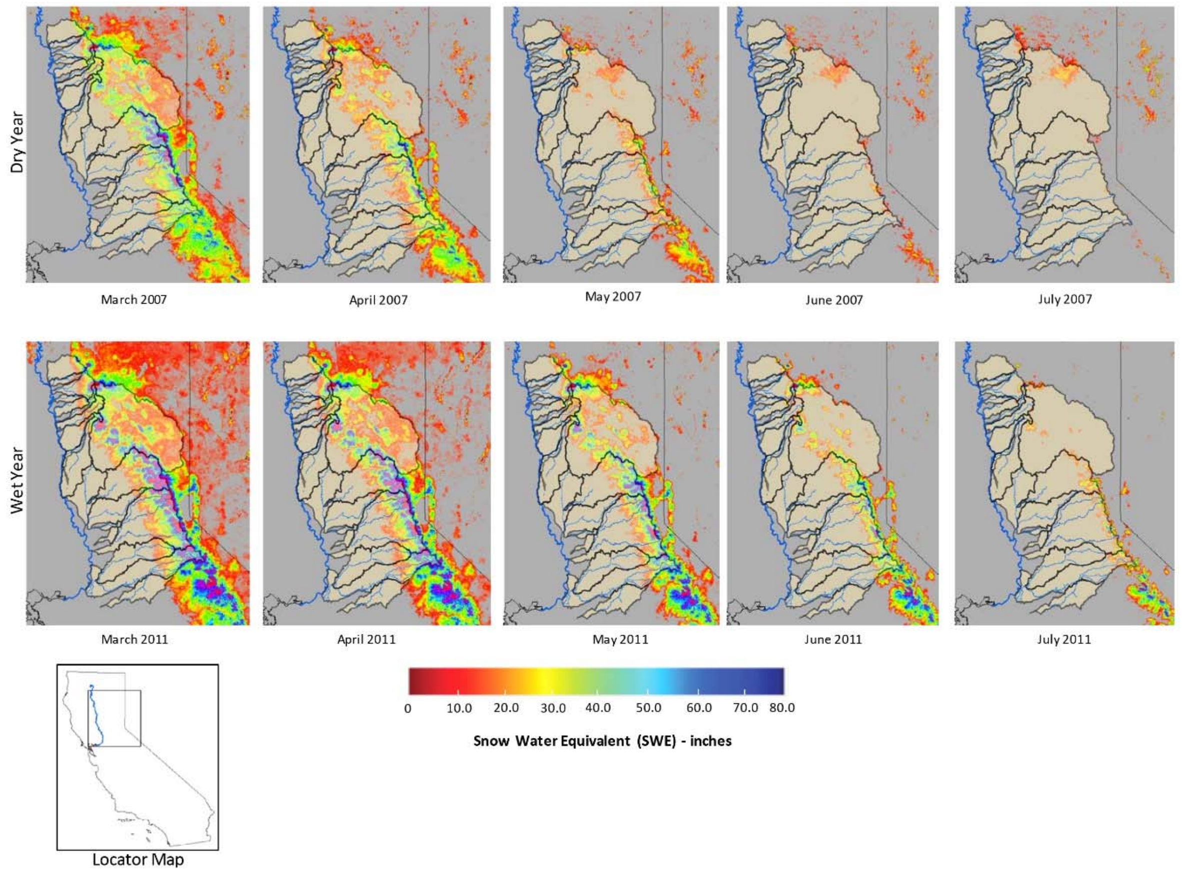
Figure 2.1-5. Elevation Map of Northern California



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

Figure 2.1-6. 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 2.1-7 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.

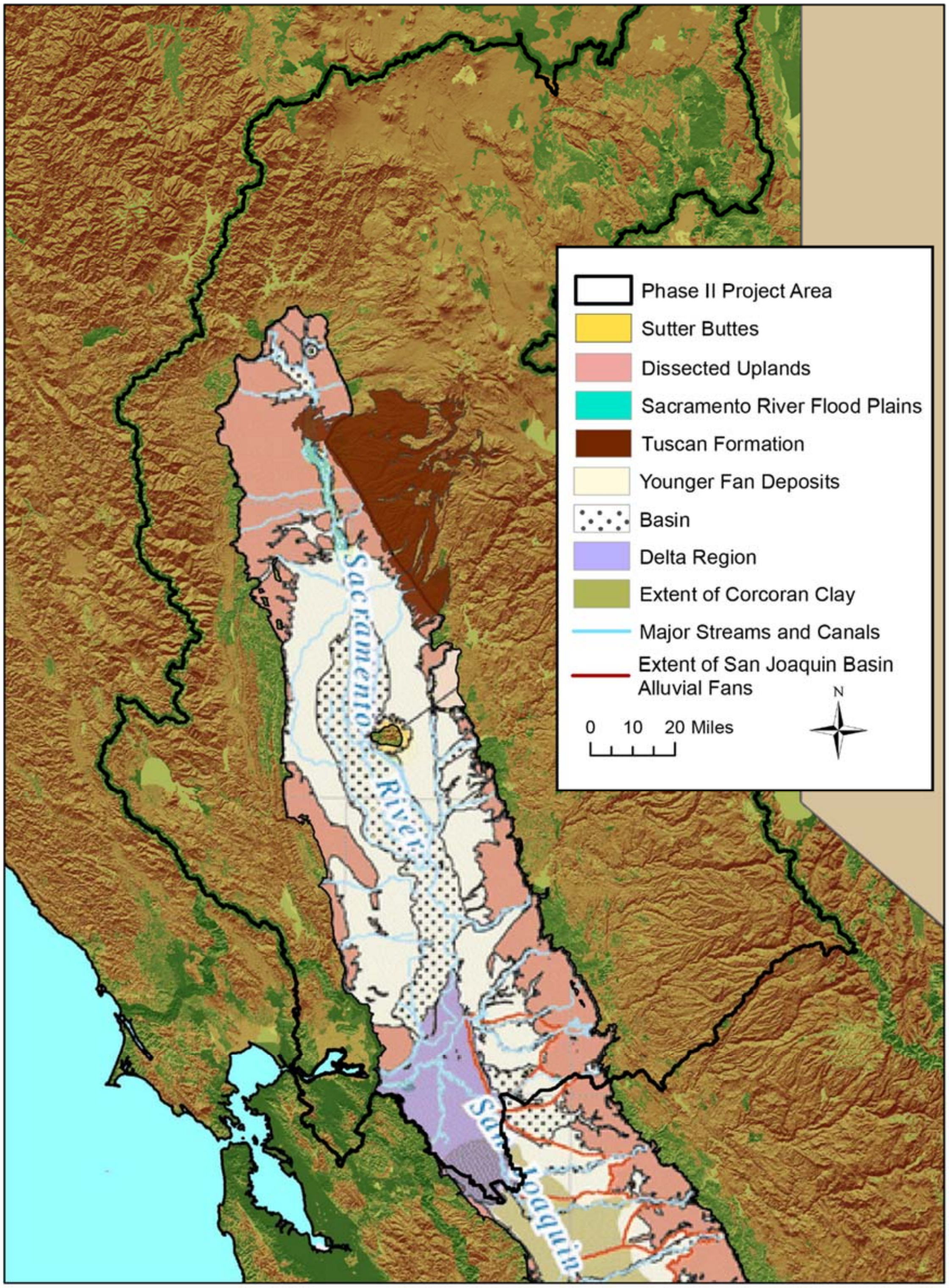


Source: State Water Resources Control Board, 2016 Data Source: Karl Rittger, http://alexandria.ucsb.edu/lib/ark:/48907/f3gm8581

Figure 2.1-7. Water Year Type Snow Water Equivalents

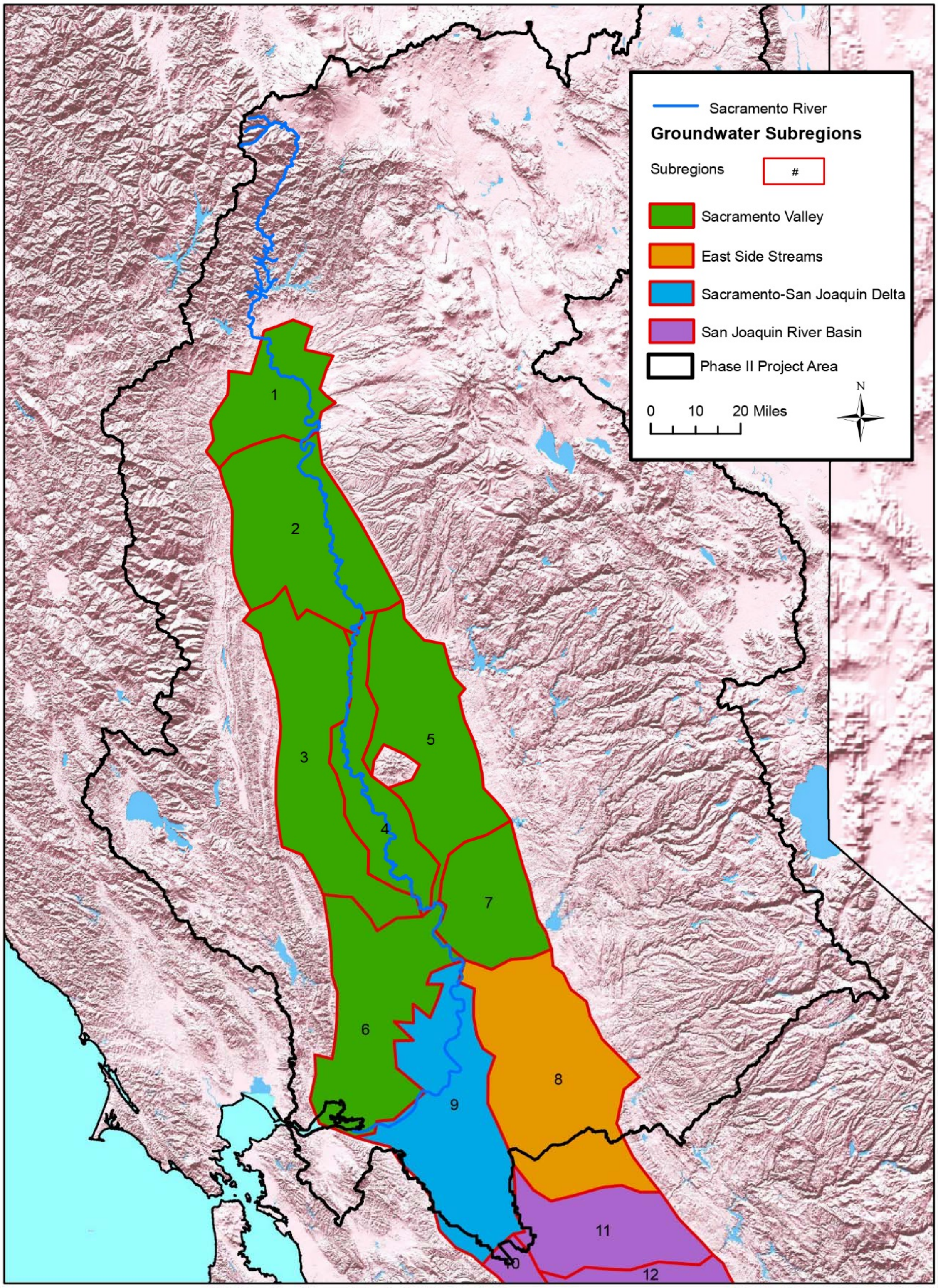
As the streams leave the foothills their lowest reaches interact with the many different sedimentary rock formations of the valley (Figure 2.1-8) and the stream channels running over those formations have complex groundwater/aquifer and surface water interactions that vary by each stream. The natural boundaries of aquifers are difficult to map but groundwater models require subdivisions to reduce the computational requirements. Figure 2.1-9 shows the subregions used for the C2VSim model that has been widely adopted for use in the Central Valley (Brush et al. 2013).

The amount of water flowing into and out of the Sacramento River Valley groundwater storage has fluctuated significantly from year to year with groundwater levels declining in dry years and recovering in wet years. Average annual stream depletion throughout the Central Valley has been approximately 700 thousand acre-feet per year (TAF/yr) from 1989–2009 and shows an increasing trend. Assuming 2009 land use conditions, studies estimate stream losses to groundwater will reduce instream flows by an average of 1.3 MAF per year across the Central Valley over the next several decades (TNC 2014).



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

Figure 2.1-8. 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 2.1-9. 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. The consumptive uses are primarily in the valley floor. However, large quantities of water from Shasta, Oroville, and Folsom Reservoirs flow all the way to the Delta and are then exported for use in other watersheds. Some non-project tributaries such as the Yuba River also move water through the Delta under water transfer agreements. The altered hydrology of each tributary has a unique story summarized in Table 2.1-1; however, two general patterns dominate. In watersheds with reservoirs, winter and spring runoff peaks are now lower and summer flows are now higher and warmer. In watersheds without reservoirs but with substantial land use development, winter and early spring flows typically resemble unimpaired flows, and late spring through fall flows are reduced by direct diversion, mainly for irrigation. 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 and unimpaired conditions, results from the Sacramento Water Allocation Model (SacWAM) were used (State Water Board 2017). 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 River tributaries. Therefore, to better describe the impairment of each entire tributary, SacWAM results were used. Unimpaired flows used in this analysis have been estimated using SacWAM as well with different sets of assumptions described in detail 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.

SacWAM is a peer-reviewed hydrology/system operations model developed by the Stockholm Environment Institute (SEI) and State Water Board to assess potential revisions to instream flow and other requirements in the 2006 Bay-Delta Plan. SacWAM is currently the most advanced representation of the Sacramento watershed which includes 69 reservoirs, 131 demands, complex operations of the SWP and CVP, and an artificial neural network to estimate Delta salinity. More information about the SacWAM model can be found in the SacWAM Model Documentation (State Water Board 2017).

The following analysis provides information on the level of impairment in the main stem Sacramento River and various tributaries on a monthly, seasonal, and annual basis given different hydrologic conditions (cumulative distributions of the percent of unimpaired flow). 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 2.1-10 shows simulated impaired flows as a percentage of unimpaired flows for the Sacramento River and its major tributaries ranked by Sacramento water year index. The water year index is an index of total runoff, 3.11 being the driest year and 15.29 being the wettest (DWR 2016b). Darker red colors indicate a greater reduction in the flow at this location relative to unimpaired, and the darker blue colors indicate a greater increase in current conditions flow relative to 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.

WY	WYI	Water Year Type	Delta Outflow	American River	Bear River	Yuba River	Feather River at Sac. River	Feather abv. conf. of Yuba River	Sacramento River below Keswick	Sacramento River at Freeport	Mokelumne River	Calaveras River	Cache Creek	Putah Creek	Clear Creek	Stony Creek	Antelope Creek	Mill Creek	Deer Creek	Battle Creek	Big Chico Creek	Cosumnes River	Cottonwood Creek	Cow Creek	Thomes Creek	Paynes Creek	Butte Creek
1977	3.11	C	63%	86%	112%	57%	68%	70%	136%	83%	32%	23%	118%	71%	161%	77%	91%	61%	87%	98%	100%	99%	105%	85%	57%	100%	305%
1931	3.66	C	44%	48%	68%	32%	51%	57%	138%	73%	21%	13%	68%	36%	89%	47%	87%	71%	95%	99%	100%	90%	101%	90%	89%	100%	240%
1924	3.87	C	53%	62%	74%	37%	67%	78%	163%	84%	27%	17%	81%	31%	142%	70%	86%	67%	91%	100%	100%	91%	104%	89%	92%	100%	221%
2015	4.01	C	47%	44%	72%	31%	57%	66%	133%	74%	22%	13%	51%	17%	64%	25%	89%	70%	92%	96%	100%	90%	101%	94%	90%	100%	200%
1992	4.06	C	42%	32%	53%	36%	34%	29%	84%	60%	10%	13%	40%	13%	30%	13%	96%	79%	97%	97%	100%	95%	100%	98%	94%	100%	196%
1934	4.07	C	38%	56%	44%	22%	34%	37%	88%	55%	21%	12%	25%	14%	73%	23%	90%	76%	100%	100%	100%	91%	100%	95%	85%	100%	190%
2014	4.07	C	43%	53%	46%	25%	41%	47%	119%	66%	18%	23%	69%	20%	167%	22%	91%	76%	98%	98%	100%	92%	102%	97%	87%	100%	199%
1991	4.21	C	39%	36%	41%	30%	37%	38%	89%	57%	17%	21%	49%	8%	89%	11%	96%	79%	98%	99%	100%	92%	101%	96%	92%	100%	180%
1933	4.63	C	29%	52%	40%	19%	28%	30%	65%	47%	16%	6%	30%	14%	46%	14%	100%	75%	96%	100%	100%	89%	102%	94%	82%	100%	222%
1988	4.65	C	38%	35%	40%	37%	41%	42%	86%	59%	17%	17%	22%	13%	60%	67%	99%	74%	100%	100%	100%	90%	100%	97%	88%	100%	191%
1990	4.81	C	37%	48%	64%	28%	34%	32%	85%	58%	19%	16%	56%	22%	65%	35%	100%	82%	91%	100%	100%	91%	102%	98%	81%	100%	255%
1994	5.02	C	39%	59%	77%	37%	46%	47%	109%	69%	18%	11%	37%	22%	77%	26%	95%	79%	94%	100%	100%	93%	101%	96%	89%	100%	236%
2008	5.16	C	37%	55%	46%	27%	31%	31%	73%	58%	16%	13%	32%	9%	46%	47%	100%	78%	100%	99%	100%	91%	100%	96%	92%	100%	224%
1929	5.22	C	30%	41%	37%	22%	35%	41%	93%	54%	19%	6%	65%	26%	99%	29%	100%	68%	100%	100%	100%	89%	101%	94%	75%	100%	233%
1976	5.29	C	39%	63%	80%	47%	54%	55%	109%	68%	26%	5%	62%	41%	82%	28%	99%	68%	100%	100%	100%	90%	101%	95%	76%	100%	258%
1932	5.48	D	28%	48%	58%	42%	29%	16%	61%	45%	8%	11%	27%	14%	49%	24%	100%	81%	97%	100%	100%	94%	101%	97%	88%	100%	177%
1939	5.58	D	38%	54%	77%	24%	41%	46%	103%	62%	20%	17%	37%	36%	90%	38%	93%	74%	95%	100%	100%	92%	102%	95%	78%	100%	236%
1947	5.61	D	35%	55%	62%	25%	36%	37%	77%	55%	17%	12%	34%	14%	83%	13%	100%	79%	97%	100%	100%	93%	101%	96%	88%	100%	201%
1961	5.68	D	38%	35%	47%	18%	31%	34%	77%	55%	16%	24%	17%	13%	43%	33%	100%	83%	99%	100%	100%	92%	100%	98%	91%	100%	207%
1926	5.75	D	42%	53%	70%	30%	32%	27%	79%	58%	17%	13%	57%	6%	39%	54%	97%	85%	98%	100%	100%	95%	101%	97%	94%	100%	192%
2001	5.76	D	42%	54%	51%	34%	39%	39%	86%	64%	17%	55%	34%	10%	31%	35%	100%	78%	98%	99%	100%	94%	101%	96%	93%	100%	227%
2009	5.78	D	32%	39%	63%	43%	30%	19%	57%	47%	12%	14%	48%	13%	34%	14%	100%	82%	100%	100%	100%	93%	101%	97%	90%	100%	176%
2013	5.83	D	37%	73%	68%	36%	45%	45%	105%	66%	19%	12%	29%	13%	124%	56%	100%	76%	98%	100%	100%	91%	101%	94%	83%	100%	217%
1987	5.86	D	42%	35%	79%	37%	41%	37%	84%	61%	20%	29%	39%	18%	65%	16%	97%	80%	100%	100%	100%	94%	101%	97%	91%	100%	206%
1930	5.9	D	35%	38%	68%	45%	32%	21%	71%	52%	13%	13%	27%	8%	46%	16%	100%	84%	98%	100%	100%	92%	101%	98%	94%	100%	178%
1949	6.09	D	40%	55%	71%	35%	36%	32%	79%	59%	16%	10%	48%	8%	39%	49%	95%	84%	96%	100%	100%	95%	101%	96%	93%	100%	215%
1989	6.13	D	38%	56%	88%	45%	34%	21%	76%	61%	14%	15%	23%	14%	43%	11%	100%	85%	99%	100%	100%	92%	100%	98%	93%	100%	175%
1955	6.14	D	32%	42%	45%	24%	31%	32%	75%	49%	15%	10%	18%	26%	76%	37%	100%	79%	97%	100%	100%	93%	101%	96%	81%	100%	207%
2007	6.19	D	37%	44%	78%	39%	43%	41%	89%	58%	16%	12%	20%	19%	102%	22%	100%	75%	100%	100%	100%	94%	100%	96%	82%	100%	209%
1960	6.2	D	34%	43%	53%	39%	29%	20%	62%	49%	15%	9%	23%	7%	44%	49%	100%	81%	100%	100%	100%	92%	101%	98%	93%	100%	203%
1981	6.21	D	44%	54%	75%	28%	40%	42%	85%	63%	18%	18%	29%	10%	33%	45%	96%	84%	97%	100%	100%	95%	100%	98%	94%	100%	213%
1944	6.35	D	34%	36%	61%	27%	32%	30%	73%	51%	15%	14%	36%	9%	93%	16%	100%	80%	98%	100%	100%	96%	101%	97%	84%	100%	209%
2002	6.35	D	38%	42%	71%	40%	32%	21%	82%	55%	15%	12%	31%	10%	35%	67%	100%	82%	97%	100%	100%	95%	100%	98%	93%	100%	179%
1925	6.39	D	38%	57%	65%	38%	28%	17%	47%	55%	26%	23%	34%	5%	24%	45%	100%	85%	99%	100%	100%	95%	100%	98%	95%	100%	179%
1964	6.41	D	36%	42%	72%	31%	37%	36%	87%	55%	17%	23%	29%	18%	71%	58%	100%	74%	100%	100%	100%	94%	101%	93%	82%	100%	222%
1985	6.47	D	35%	50%	70%	29%	37%	37%	97%	57%	15%	13%	30%	14%	103%	25%	100%	74%	96%	100%	100%	96%	101%	95%	85%	100%	222%
1950	6.62	BN	37%	63%	74%	50%	32%	16%	64%	53%	28%	8%	29%	8%	71%	28%	100%	85%	99%	100%	100%	96%	101%	98%	92%	100%	177%
1962	6.65	BN	38%	39%	68%	47%	33%	20%	80%	56%	12%	10%	39%	6%	38%	52%	100%	85%	98%	100%	100%	93%	100%	97%	89%	100%	178%
1979	6.67	BN	41%	54%	87%	40%	36%	26%	65%	56%	28%	57%	32%	7%	47%	36%	100%	83%	99%	100%	100%	97%	101%	98%	94%	100%	197%
1959	6.75	BN	42%	44%	71%	23%	31%	31%	83%	58%	17%	15%	32%	10%	36%	52%	98%	84%	98%	100%	100%	94%	101%	98%	92%	100%	193%
1945	6.8	BN	40%	63%	82%	51%	34%	19%	70%	56%	35%	30%	28%	9%	50%	36%	100%	91%	94%	100%	100%	98%	101%	99%	91%	100%	174%
1937	6.87	BN	43%	61%	80%	42%	36%	26%	53%	56%	28%	54%	41%	7%	45%	40%	100%	84%	99%	100%	100%	98%	101%	98%	91%	100%	175%
2012	6.89	BN	39%	51%	85%	39%	37%	30%	75%	57%	15%	12%	30%	9%	45%	21%	99%	82%	99%	100%	100%	96%	101%	97%	90%	100%	181%
1935	6.98	BN	37%	52%	83%	54%	33%	16%	42%	54%	21%	7%	44%	4%	37%	37%	100%	88%	100%	100%	100%	96%	100%	98%	94%	100%	155%
1923	7.06	BN	40%	64%	89%	50%	39%	24%	82%	57%	30%	36%	22%	13%	47%	40%	99%	80%	97%	100%	100%	99%	101%	96%	88%	100%	186%
2010	7.08	BN	42%	57%	70%	42%	29%	18%	74%	58%	24%	10%	37%	5%	20%	59%	100%	93%	95%	100%	100%	95%	100%	99%	95%	100%	178%
1948	7.12	BN	39%	45%	76%	46%	28%	14%	67%	53%	14%	4%	14%	11%	43%	10%	100%	100%	93%	100%	100%	94%	101%	100%	95%	100%	168%
1966	7.16	BN	40%	43%	77%	34%	35%	31%	88%	59%	15%	15%	34%	7%	33%	51%	100%	82%	97%	100%	100%	95%	101%	97%	92%	100%	189%

WY	WYI	Water Year Type	Delta Outflow	American River	Bear River	Yuba River	Feather River at Sac. River	Feather abv. conf. of Yuba River	Sacramento River below Keswick	Sacramento River at Freeport	Mokelumne River	Calaveras River	Cache Creek	Putah Creek	Clear Creek	Stony Creek	Antelope Creek	Mill Creek	Deer Creek	Battle Creek	Big Chico Creek	Cosumnes River	Cottonwood Creek	Cow Creek	Thomes Creek	Paynes Creek	Butte Creek
1968	7.24	BN	50%	58%	96%	36%	44%	43%	87%	66%	16%	17%	58%	7%	41%	60%	100%	86%	98%	100%	100%	96%	101%	98%	94%	100%	191%
1972	7.29	BN	35%	40%	71%	42%	33%	24%	82%	52%	16%	5%	13%	23%	49%	27%	100%	83%	98%	100%	100%	95%	100%	97%	91%	100%	202%
2004	7.51	BN	48%	44%	91%	47%	40%	31%	94%	67%	17%	12%	77%	33%	27%	68%	100%	87%	98%	100%	100%	95%	100%	99%	95%	100%	157%
1946	7.7	BN	44%	63%	86%	52%	51%	48%	69%	61%	33%	17%	70%	18%	56%	60%	100%	84%	97%	100%	100%	99%	101%	98%	89%	100%	180%
1936	7.75	BN	49%	73%	94%	59%	44%	28%	71%	66%	42%	60%	40%	6%	28%	63%	100%	87%	99%	100%	100%	98%	100%	98%	94%	100%	163%
1957	7.83	AN	39%	48%	84%	43%	31%	19%	76%	53%	17%	9%	18%	10%	33%	43%	100%	91%	94%	100%	100%	96%	101%	98%	92%	100%	197%
2003	8.21	AN	45%	57%	92%	59%	38%	21%	83%	63%	22%	10%	61%	7%	23%	60%	100%	94%	96%	100%	100%	96%	100%	99%	94%	100%	142%
1928	8.27	AN	50%	63%	107%	59%	54%	45%	85%	70%	31%	35%	34%	6%	25%	63%	100%	86%	99%	100%	100%	98%	100%	98%	93%	100%	156%
2005	8.49	AN	46%	71%	88%	57%	42%	28%	75%	64%	49%	43%	35%	9%	26%	72%	100%	94%	94%	100%	100%	98%	100%	99%	95%	100%	165%
1954	8.51	AN	50%	48%	90%	47%	47%	43%	86%	67%	15%	8%	44%	6%	24%	65%	100%	95%	95%	100%	100%	97%	100%	99%	95%	100%	164%
1993	8.54	AN	48%	64%	94%	60%	45%	32%	57%	64%	34%	53%	60%	5%	20%	78%	100%	100%	93%	100%	100%	97%	101%	100%	97%	100%	155%
1973	8.58	AN	55%	71%	100%	66%	56%	44%	85%	75%	37%	56%	62%	9%	21%	78%	100%	95%	93%	100%	100%	98%	101%	99%	95%	100%	165%
1978	8.65	AN	50%	58%	84%	54%	42%	31%	75%	73%	23%	11%	55%	4%	18%	74%	100%	95%	97%	100%	100%	95%	100%	100%	97%	100%	152%
1940	8.88	AN	56%	65%	93%	60%	52%	44%	83%	74%	33%	25%	53%	4%	22%	64%	100%	91%	99%	100%	100%	98%	100%	99%	97%	100%	148%
2000	8.94	AN	53%	58%	89%	54%	46%	35%	87%	69%	32%	58%	53%	7%	19%	59%	100%	93%	94%	100%	100%	99%	100%	99%	96%	100%	176%
1922	8.97	AN	46%	66%	101%	66%	55%	43%	63%	64%	46%	64%	32%	11%	30%	32%	100%	95%	93%	100%	100%	97%	101%	99%	93%	100%	153%
1980	9.04	AN	61%	77%	109%	68%	59%	47%	90%	77%	54%	63%	62%	5%	26%	77%	100%	90%	99%	100%	100%	99%	100%	99%	96%	100%	150%
1951	9.18	AN	55%	70%	120%	61%	65%	62%	78%	70%	42%	61%	55%	8%	37%	57%	100%	91%	95%	100%	100%	99%	101%	98%	93%	100%	164%
1975	9.35	W	52%	56%	95%	55%	51%	44%	81%	67%	33%	41%	60%	20%	23%	71%	100%	100%	90%	100%	100%	98%	101%	100%	95%	100%	173%
1927	9.52	W	56%	76%	102%	69%	55%	42%	85%	72%	35%	24%	70%	4%	22%	73%	100%	95%	93%	100%	100%	98%	100%	99%	95%	100%	162%
1953	9.55	W	54%	60%	97%	56%	58%	57%	81%	70%	24%	18%	59%	6%	29%	68%	100%	100%	93%	100%	100%	97%	101%	100%	95%	100%	150%
1963	9.63	W	56%	74%	116%	70%	65%	57%	82%	78%	42%	16%	53%	4%	31%	71%	100%	93%	97%	100%	100%	98%	100%	99%	95%	100%	158%
1943	9.77	W	60%	77%	109%	68%	65%	59%	76%	76%	54%	73%	70%	15%	50%	64%	100%	94%	96%	100%	100%	99%	101%	99%	95%	100%	167%
1999	9.8	W	59%	74%	101%	65%	70%	70%	82%	74%	53%	63%	71%	22%	24%	60%	100%	95%	93%	100%	100%	99%	101%	99%	93%	100%	162%
1986	9.96	W	65%	80%	107%	71%	63%	54%	96%	76%	59%	70%	67%	42%	26%	80%	100%	91%	99%	100%	100%	99%	100%	99%	97%	100%	149%
1984	10	W	49%	63%	106%	59%	57%	52%	76%	64%	44%	30%	79%	73%	46%	40%	100%	85%	98%	100%	100%	99%	100%	96%	88%	100%	165%
1965	10.15	W	56%	73%	120%	69%	69%	66%	78%	73%	56%	50%	77%	5%	33%	67%	100%	93%	96%	100%	100%	99%	100%	99%	94%	100%	153%
1967	10.2	W	56%	76%	106%	70%	58%	48%	80%	71%	52%	42%	60%	15%	23%	68%	100%	100%	93%	100%	100%	98%	101%	100%	95%	100%	158%
1996	10.26	W	62%	77%	112%	68%	71%	70%	84%	76%	51%	66%	71%	5%	28%	76%	100%	93%	97%	100%	100%	98%	100%	99%	96%	100%	164%
1971	10.37	W	50%	66%	97%	63%	57%	52%	78%	66%	36%	27%	63%	39%	25%	56%	100%	100%	89%	100%	100%	98%	101%	100%	94%	100%	162%
1970	10.4	W	67%	76%	105%	67%	73%	73%	94%	75%	48%	69%	76%	70%	26%	79%	100%	90%	100%	100%	100%	99%	100%	99%	96%	100%	150%
2011	10.54	W	61%	78%	109%	73%	67%	59%	81%	80%	64%	71%	67%	4%	26%	65%	100%	100%	94%	100%	100%	100%	101%	100%	95%	100%	152%
1997	10.82	W	70%	79%	108%	72%	75%	73%	88%	72%	63%	82%	89%	69%	35%	75%	100%	90%	99%	100%	100%	100%	100%	98%	94%	100%	147%
1969	11.05	W	64%	81%	104%	73%	66%	58%	87%	80%	61%	70%	72%	55%	20%	79%	100%	95%	97%	100%	100%	99%	100%	100%	97%	100%	151%
1942	11.27	W	64%	77%	109%	71%	72%	69%	84%	79%	51%	48%	85%	64%	23%	78%	100%	100%	94%	100%	100%	98%	101%	100%	96%	100%	150%
1956	11.38	W	64%	76%	118%	71%	74%	72%	85%	77%	60%	67%	85%	3%	25%	78%	100%	94%	97%	100%	100%	99%	100%	99%	96%	100%	146%
1941	11.47	W	65%	68%	104%	67%	62%	55%	91%	86%	38%	46%	83%	22%	17%	88%	100%	100%	94%	100%	100%	97%	100%	100%	97%	100%	144%
1958	12.16	W	69%	78%	102%	72%	68%	63%	92%	84%	51%	52%	80%	22%	23%	86%	100%	100%	94%	100%	100%	99%	100%	100%	98%	100%	149%
1952	12.38	W	63%	82%	108%	74%	71%	67%	80%	84%	60%	75%	69%	4%	25%	76%	100%	100%	93%	100%	100%	99%	101%	100%	95%	100%	155%
1938	12.62	W	69%	80%	107%	76%	76%	74%	87%	84%	63%	73%	82%	3%	19%	81%	100%	100%	93%	100%	100%	99%	100%	100%	96%	100%	147%
1982	12.76	W	67%	83%	110%	78%	78%	74%	85%	84%	71%	68%	83%	56%	20%	72%	100%	90%	99%	100%	100%	100%	100%	99%	94%	100%	140%
1995	12.89	W	65%	79%	105%	73%	67%	61%	83%	84%	55%	61%	66%	3%	17%	83%	100%	100%	96%	100%	100%	98%	100%	100%	98%	100%	140%
1974	12.99	W	66%	76%	114%	74%	76%	74%	89%	79%	50%	50%	89%	64%	18%	77%	100%	95%	98%	100%	100%	99%	100%	99%	96%	100%	135%
2006	13.2	W	72%	82%	114%	76%	78%	76%	108%	91%	72%	67%	92%	81%	19%	79%	100%	100%	94%	100%	100%	100%	100%	100%	97%	100%	135%
1998	13.31	W	70%	73%	105%	70%	65%	58%	89%	81%	56%	64%	79%	56%	20%	89%	100%	100%	96%	100%	100%	99%	100%	100%	99%	100%	147%
1983	15.29	W	80%	84%	109%	78%	81%	81%	98%	87%	73%	78%	94%	82%	18%	88%	100%	100%	96%	100%	100%	100%	100%	100%	98%	100%	146%

Figure 2.1-10. 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

Table 2.1-1. Summary Information used in SacWAM for the Major Tributaries to the Sacramento River and the Eastside Tributaries to the Delta

River	Drainage Area (mi^2)	Mean Annual Runoff (TAF/yr)[1]	Total Storage as modeled in SacWAM (TAF)	Runoff to Storage Ratio	Average Annual Stream Gain/Loss to GW (TAF/yr)[2]	Hydrologic Regime	Major Reservoirs	Instream Flow Requirements[3]
Cow Creek	430	431	No Major Storage	No Major Storage	-7	Mixed rain and snow- rain dominant- unimpaired	None	None
Battle Creek	357	347	No Major Storage	No Major Storage	8	Mixed rain and snow, significant discharge from springs- rain dominant- hydropower and diversion impacts	None	None
Butte Creek	797	926	No Major Storage	No Major Storage	-32	Mixed rain and snow-interbasin import and diversion impacted during irrigation season	None	None
Antelope Creek	202	100	No Major Storage	No Major Storage	13	Mixed rain and snow- rain dominant- diversion impacts in Valley	None	None
Deer Creek	298	228	No Major Storage	No Major Storage	-1	Mixed rain and snow- rain dominant- diversion impacts in Valley	None	None
Mill Creek	130	215	No Major Storage	No Major Storage	2	Mixed rain and snow- rain dominant- diversion impacts in Valley	None	None
Paynes Creek	93	52	No Major Storage	No Major Storage	8	Rain driven- flashy- diversion impacts in valley	None	None
Clear Creek	249	140	241	0.58	0	Interbasin import dominated- regulated	Whiskeytown Reservoir	Combination of 1960 MOA between DWR and CDFG, (b)2 actions, and 2009 NMFS BiOp
Big Chico Creek	72	101	No Major Storage	No Major Storage	0	Rain driven- flashy- flood control impacts in valley	None	None
Feather River	4,400	4,998	5,131	1.17	-7	Mixed rain and snow- heavily regulated- diversion and flood control impacts in valley	Lake Oroville; Lake Davis; Bucks Lake; Butt Valley; Antelope Reservoir; Frenchman Lake; Lake Almanor; Poe Reservoir; Cresta Reservoir; Rock Creek Reservoir; Belden Reservoir; Little Grass Valley Reservoir; Philbrook-Round Valley Reservoirs; Mountain Meadows Reservoir	1986 MOU between CDFG and DWR (High Flow Channel, Low Flow Channel and Verona)
Yuba River	1,339	1,654	1,408	1.17	-16	Mixed rain and snow- heavily regulated- diversion and flood control impacts in valley	Englebright Reservoir; New Bullard's Bar Reservoir; Bowman Lake; Scotts Flat Reservoir; Lake Fordyce; Merle Collins Reservoir; Jackson Meadows Reservoir; Lake Spaulding	Lower Yuba River Accord/State Water Board Revised D-1644 (Yuba River near Marysville, Yuba River near Smartville)
Bear River	292	472	176	2.67	-20	Rain dominated- heavily regulated- import/export impacted	Camp Far West Reservoir; Rollins Reservoir; Lake Combie	1994 Settlement Agreement between DWR, South Sutter Water District, and Camp Far West Irrigation District
American River	1,900	2,711	1,759	1.54	-44	Mixed rain and snow- heavily regulated- import/export impacted	Folsom Lake; Lake Natoma; Caples Lake; Loon Lake; Gerle Creek Reservoir; Buck Island; Sly Creek Reservoir; French Meadows; Lake Valley; Stumpy Meadows; Hell Hole; Union Valley Reservoir; Camino Reservoir; Junction Reservoir; Silver Lake; Jenkinson Lake; Chili Bar; Slab Creek; Ice House	Lower American River Flow Management Standard; 1958 WDR-893 (H St.)

River	Drainage Area (mi^2)	Mean Annual Runoff (TAF/yr)[1]	Total Storage as modeled in SacWAM (TAF)	Runoff to Storage Ratio	Average Annual Stream Gain/Loss to GW (TAF/yr)[2]	Hydrologic Regime	Major Reservoirs	Instream Flow Requirements[3]
Mokelumne River	660	744	998	0.74	-75	Mixed rain and snow- snow dominant- heavily regulated- diversion impacted	Pardee Reservoir; Camanche Reservoir; Lower Bear; Salt Springs; Lake Amador	1998 Joint Settlement Agreement and FERC license for the Lower Mokelumne Hydroelectric Project (FERC No. 2916) (below Comanche, below Woodbridge Diversion Dam); 2001 FERC License for the North Fork Mokelumne Project (FERC No. 137) (Below PG&E Dams, below Electra Powerhouse, Below Electra Dam)
Cosumnes River	940	387	No Major Storage	9.43	-2	Mixed rain and snow- rain dominant- mostly unimpaired- diversion impacts in valley	Jenkinson Reservoir	None
Calaveras River	470	160	317	0.50	-46	Rain driven- regulated- diversion impacts in valley	New Hogan Dam	None
Stony Creek	741	418	245	1.71	-23	Rain driven- regulated- diversion and export impacted	East Park reservoir; Stony Gorge Reservoir; Black Butte Reservoir	Below Black Butte Reservoir and Below Northside Dam
Cottonwood Creek	927	551	No Major Storage	No Major Storage	-9	Rain driven- flashy- mostly unimpaired- import impacts in valley during irrigation season	None	None
Thomes Creek	301	263	No Major Storage	No Major Storage	-19	Rain driven- flashy- unimpaired	None	None
Elder Creek	151	67	No Major Storage	No Major Storage	0	Rain driven- flashy- unimpaired	none	None
Cache Creek	1,139	508	1,456	0.35	-90	Rain driven- natural lake buffers extreme events- some regulation on tribs-flood control and diversion impacts in valley	Clear Lake; Indian Valley Reservoir	None
Putah Creek	710	358	1,602	0.22	-10	Rain driven- regulated- impacted by exports in valley	Lake Berryessa	2000 Putah Creek Accord/Settlement Agreement flow requirements: below Putah Diversion Dam; at I-80 road bridge

mi^2 = square miles.
TAF/yr = thousand acre-feet per year.
MOA = memorandum of agreement.
CDFG = California Department of Fish and Game.
DWR = California Department of Water Resources.
WDR = waste discharge requirement.
FERC = Federal Energy Regulatory Commission.
PG& E = Pacific Gas and Electric Company.

[1] Estimated using SacWAM Current Conditions results by adding all upstream inflows and rainfall-runoff.

[2] As estimated in SacWAM (State Water Board 2017).

[3] As estimated in SacWAM (State Water Board 2017).

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 Delta.

The Sacramento River watershed above Shasta and Keswick dams is 6,500 square miles (DWR 2013a). 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 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. Water is transferred to the Sacramento River basin from the Trinity River basin through a system of dams, reservoirs, tunnels, and power plants. Releases from Trinity Dam through the Trinity Power Plant are stored downstream at Lewiston Reservoir where the water can be diverted to the Sacramento River watershed through the Clear Creek Tunnel to Whiskeytown Lake, where it can then either be released to Keswick Reservoir through the Spring Creek Tunnel or be released to Clear Creek, which enters the Sacramento River downstream of Keswick Reservoir (DWR 2013a). Annual imports from the Trinity River into Keswick Reservoir averaged 734 TAF per year from water years 1985–2009 (Figure 2.2-1).

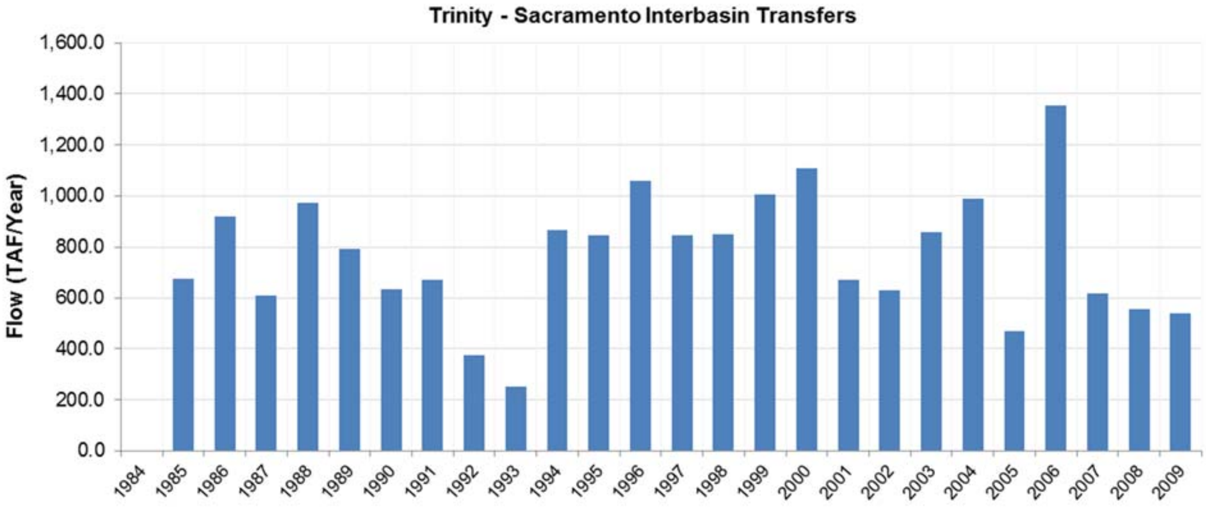


Figure 2.2-1. Annual Total Observed Imports from the Trinity River to the Sacramento Watershed via the Clear Creek Tunnel for Water Years 1985–2009 (Source: CDEC)

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 2013a). 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 2013a).

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 below Keswick Reservoir boxplot below (Figure 2.2-2). Boxplots within this chapter summarize monthly current simulated hydrologic conditions (gray box) and simulated 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 as well as major urban centers in southern California and the San Francisco Bay area (Reclamation 2017). Mean annual current flow conditions are higher than mean annual unimpaired flow conditions below Keswick because of imports from the Trinity River. In all but the most extreme years, the Sacramento River below Keswick Reservoir under current conditions is greater than 65 percent of unimpaired flow on average during the winter-spring period, although monthly flows are often more impaired, with monthly median flows in March and April less than 50 percent of unimpaired flows (Table 2.2-1). In late spring through fall, flows below Keswick Reservoir are generally higher than unimpaired, due to storage releases for use within the basin, export, and salinity control.

For 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 base flows (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 below Keswick Reservoir. Though the overall flow magnitudes may be different, the other characteristics of the flow regimes of the other regulated tributaries are similar. Water diversion and storage has significantly changed the shape of the instream hydrograph. In both water year types shown, fall and winter peak flows are reduced. The recession limb of the spring snowmelt is truncated or absent, and summer base flows are augmented.

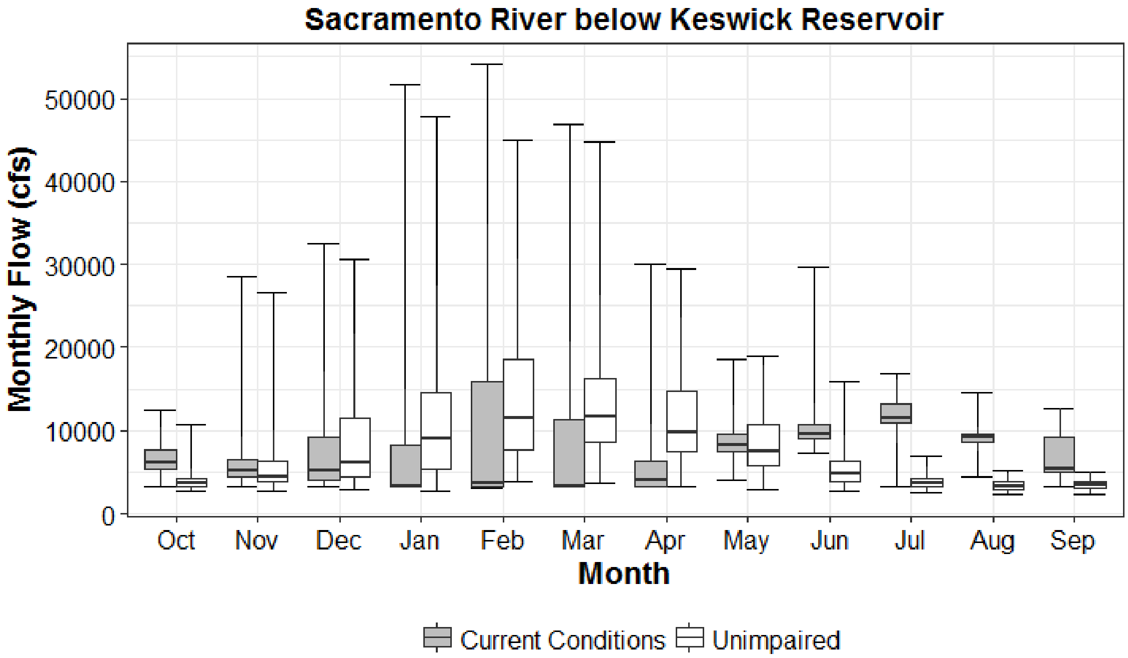


Figure 2.2-2. Sacramento River below Keswick Reservoir Simulated Current Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-1. Cumulative Distribution of Current Conditions as Percent of Unimpaired Flow in Sacramento River below Keswick Reservoir

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan–Jun	Jul–Dec	Annual Total
0%	70	36	21	20	14	19	16	43	106	137	173	82	42	90	73
10%	121	74	58	41	30	27	30	70	109	235	223	138	65	145	100
20%	147	100	72	47	36	32	36	85	127	252	247	155	75	151	103
30%	158	104	77	52	43	35	41	96	162	265	260	161	78	160	105
40%	164	108	85	59	51	42	43	100	179	297	274	170	81	165	108
50%	171	114	92	64	59	49	46	103	200	316	280	182	83	175	110
60%	177	123	96	70	65	56	54	116	216	334	289	202	85	181	112
70%	180	129	102	83	84	68	60	138	245	349	300	241	87	189	116
80%	192	147	106	89	98	80	68	150	281	386	310	258	90	193	120
90%	202	166	145	105	115	94	89	202	354	422	327	278	102	205	129
100%	228	217	192	147	132	122	168	391	488	601	355	304	163	244	184

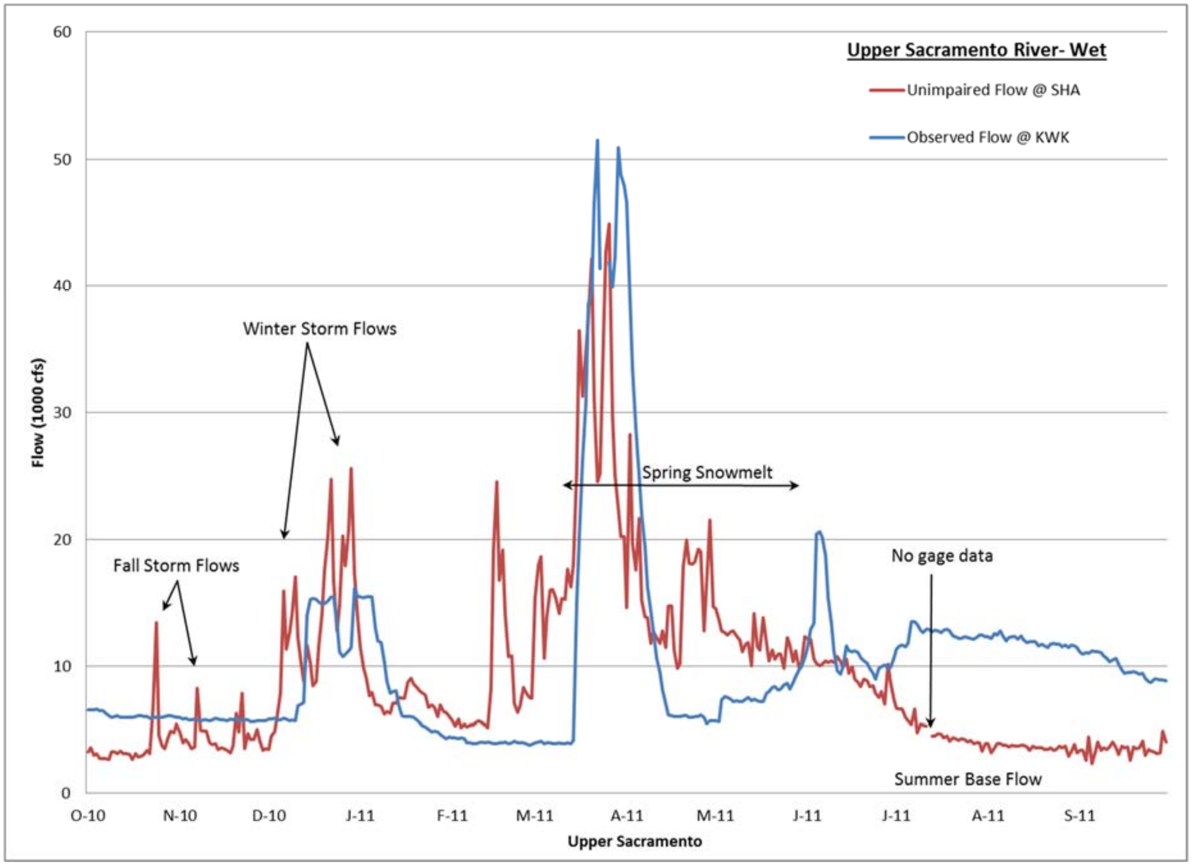


Figure 2.2-3. Daily Hydrograph of the Sacramento River below Keswick Reservoir for Water Year 2011 with Unimpaired Flow (SHA) and Observed Flow (KWK)[1]

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

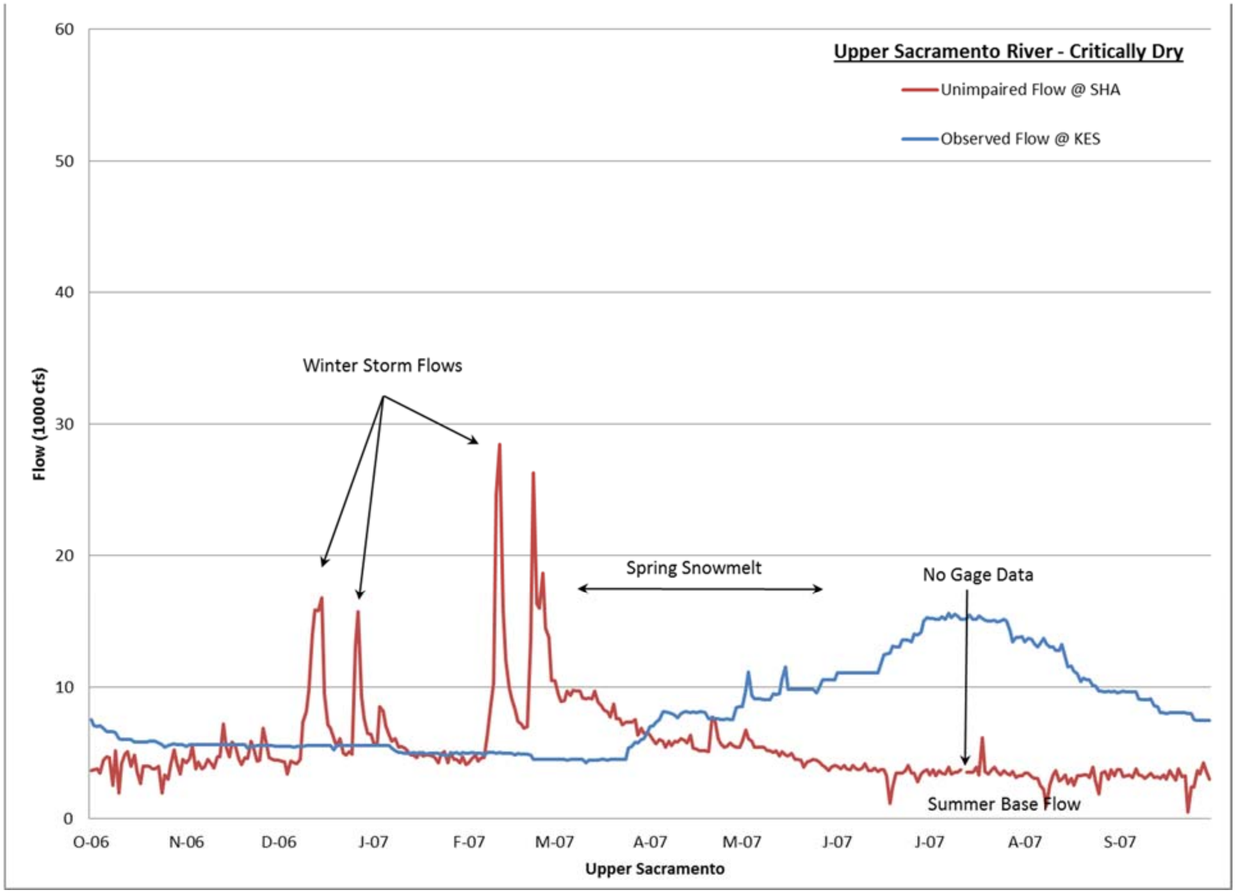

Figure 2.2-4. Daily Hydrograph of the Sacramento River below Keswick Reservoir for Water Year 2007 with Unimpaired Flow and Observed Flow[2]

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 2013a). Between Red Bluff to just above Stony Creek the Sacramento River has established a wide floodplain 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. The flow at Freeport includes all water that has entered the Sacramento River, except Sacramento River water that passes through the Yolo Bypass. At Freeport, the Sacramento River has a greater level of impairment than it does upstream below Keswick Reservoir (Figure 2.2-5). The largest difference between current conditions and unimpaired flows at Freeport are in the months of April and May where in half of the years the flows are below 39 percent and 48 percent of unimpaired flows, respectively (Table 2.2-2).

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

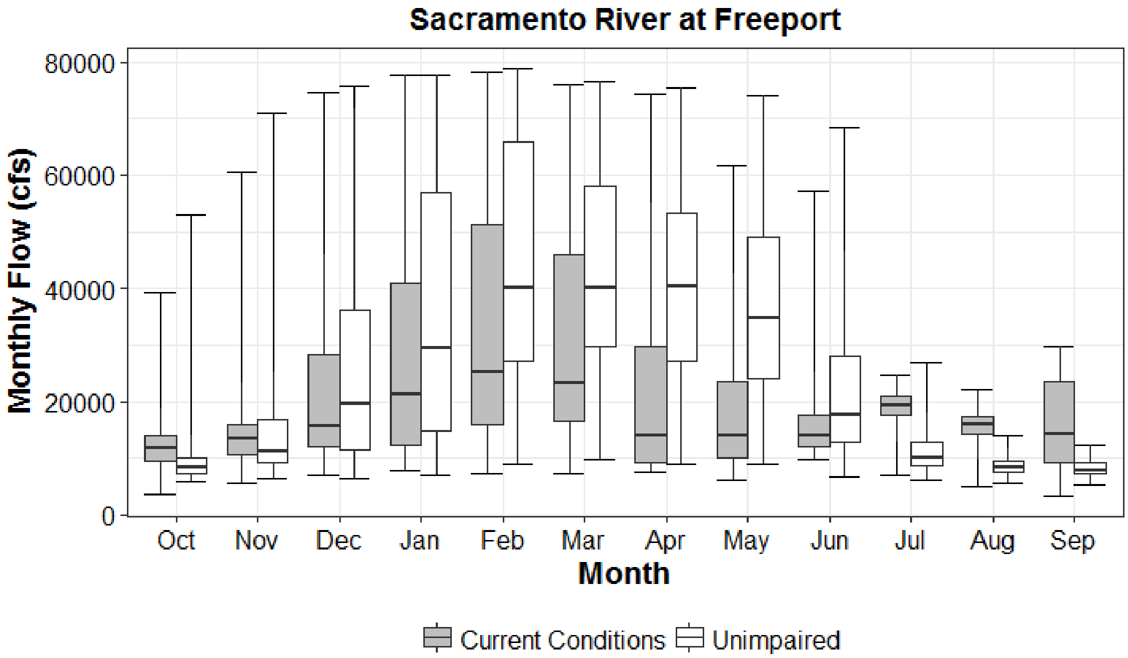


Figure 2.2-5. Sacramento River at Freeport Simulated Current Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-2. Cumulative Distribution of Current Conditions as Percent of Unimpaired Flow in Sacramento River at Freeport

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan–Jun	Jul–Dec	Annual Total
0%	55	57	47	46	43	41	29	26	47	79	83	47	45	70	61
10%	94	79	74	60	54	49	32	34	65	111	133	108	53	107	73
20%	105	87	76	67	59	52	34	40	67	133	155	126	56	112	76
30%	114	94	79	73	65	56	37	42	69	149	168	143	58	118	79
40%	122	99	84	76	69	58	38	45	72	164	180	182	60	123	80
50%	128	108	91	79	71	61	39	48	79	182	188	194	64	128	84
60%	137	118	96	85	76	66	45	51	83	195	192	218	68	134	86
70%	142	123	100	90	85	72	52	56	91	207	197	239	73	140	88
80%	148	130	111	98	94	81	59	65	109	221	205	253	76	146	89
90%	156	137	130	100	100	96	73	70	128	231	214	299	83	158	91
100%	180	166	178	125	100	100	99	119	185	284	236	339	91	189	105

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 others 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 second (cfs) (Reclamation 2001). The numerous springs in the watershed contribute to a relatively high late-summer and fall base flow 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). An ongoing restoration program 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 2017).

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 in the summer months (see also Table 2.2-3).

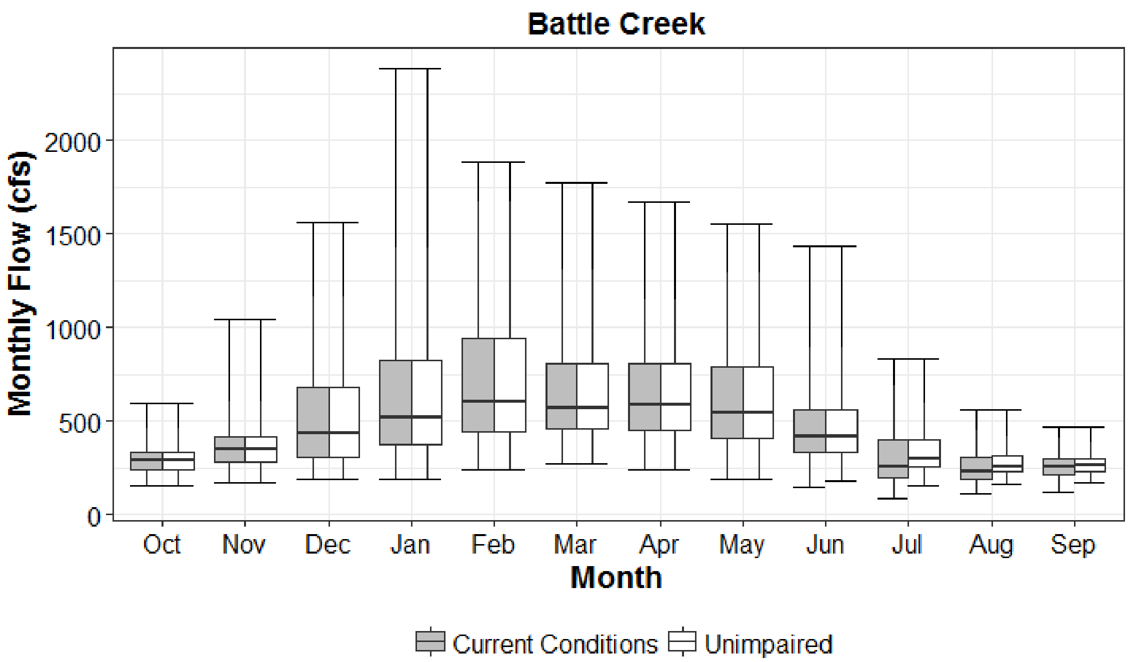


Figure 2.2-6. Battle Creek Simulated Current Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-3. Cumulative Distribution of Current Conditions as Percent of Unimpaired Flow in Battle Creek

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan–Jun	Jul–Dec	Annual Total
0%	92	100	100	100	100	100	100	93	67	55	59	72	96	88	93
10%	100	100	100	100	100	100	100	100	96	75	71	86	100	91	96
20%	100	100	100	100	100	100	100	100	100	79	80	89	100	93	97
30%	100	100	100	100	100	100	100	100	100	82	82	93	100	94	98
40%	100	100	100	100	100	100	100	100	100	85	86	95	100	95	98
50%	100	100	100	100	100	100	100	100	100	90	89	98	100	96	99
60%	100	100	100	100	100	100	100	100	100	94	92	100	100	98	99
70%	100	100	100	100	100	100	100	100	100	99	100	100	100	99	100
80%	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
90%	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
100%	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

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 6,500–7,300 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; 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 2007).

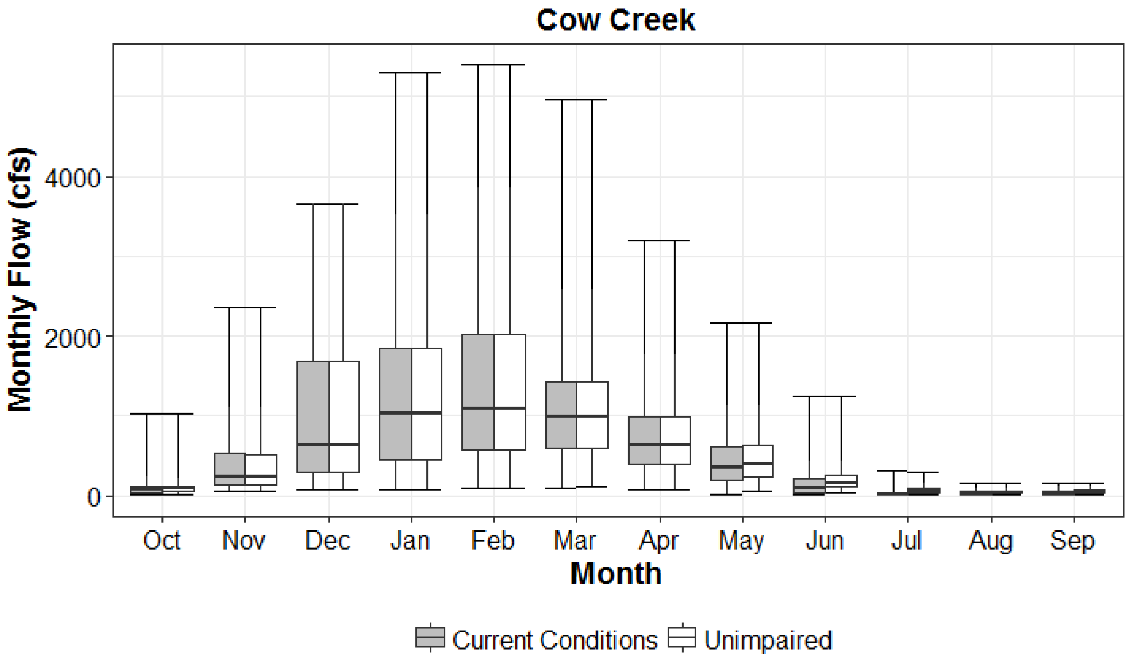


Figure 2.2-7. Cow Creek Simulated Current Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-4. Cumulative Distribution of Current Conditions as Percent of Unimpaired Flow in Cow Creek

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan–Jun	Jul–Dec	Annual Total
0%	3	87	98	100	100	76	69	21	19	17	23	22	85	75	87
10%	58	99	100	100	100	100	91	62	30	23	34	33	95	87	95
20%	71	99	100	100	100	100	100	79	42	26	39	38	96	90	96
30%	77	100	100	100	100	100	100	84	51	29	43	40	97	91	96
40%	84	100	100	100	100	100	100	86	59	34	46	46	98	93	97
50%	88	100	100	100	100	100	100	90	67	39	55	51	98	95	97
60%	93	100	100	100	100	100	100	96	70	43	68	58	99	95	98
70%	99	100	100	100	100	100	100	100	77	50	92	84	99	96	98
80%	100	100	100	100	100	100	100	100	83	57	101	101	99	97	99
90%	100	100	100	100	100	100	100	100	100	101	102	101	100	99	100
100%	101	100	100	100	100	100	100	100	100	113	105	102	100	100	100

2.2.3 Tributaries of the Chico Monocline

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 have not been well studied, but results from C2VSIM and SacWAM show that it is a gaining reach (State Water Board 2017).

Fish migration is blocked approximately 2–3 miles above the confluences of each of the three forks on 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). Diversions in the summer months reduce the instream flow by 50 percent or more in more than half of the years (Figure 2.2-8; Table 2.2-5).

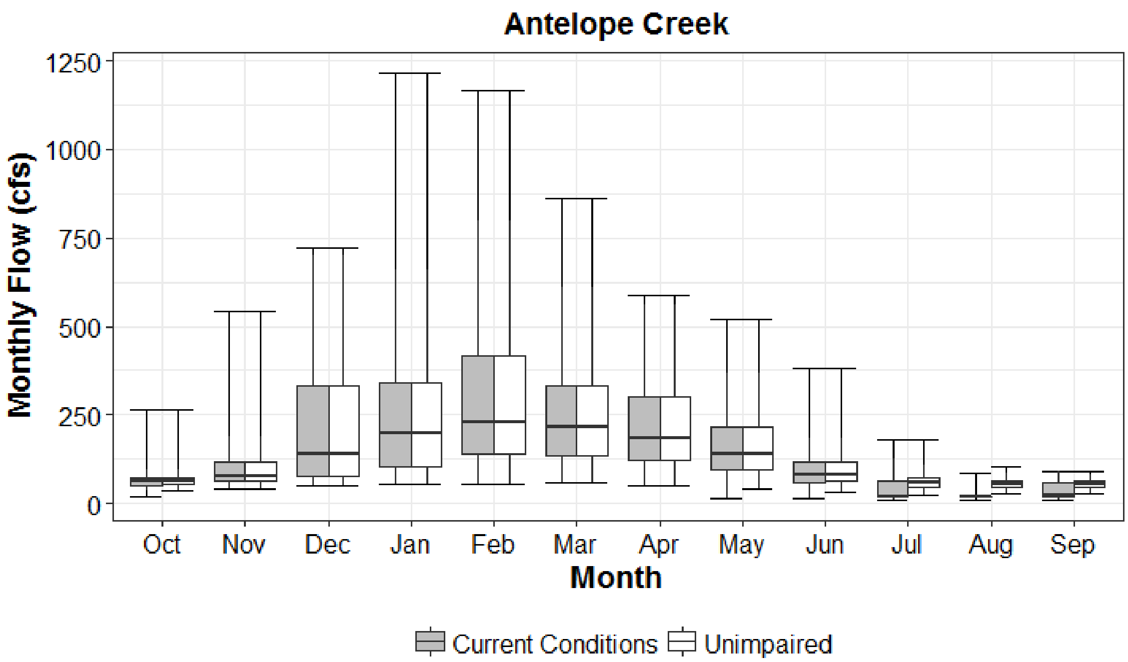


Figure 2.2-8. Antelope Creek Simulated Current Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-5. Cumulative Distribution of Current Conditions as Percent of Unimpaired Flow in Antelope Creek

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan–Jun	Jul–Dec	Annual Total
0%	52	100	100	100	100	100	100	34	29	26	18	22	86	65	81
10%	100	100	100	100	100	100	100	100	41	31	29	33	96	74	90
20%	100	100	100	100	100	100	100	100	95	33	32	36	100	76	92
30%	100	100	100	100	100	100	100	100	100	36	33	38	100	79	93
40%	100	100	100	100	100	100	100	100	100	37	35	40	100	81	94
50%	100	100	100	100	100	100	100	100	100	39	38	43	100	83	95
60%	100	100	100	100	100	100	100	100	100	44	39	69	100	84	96
70%	100	100	100	100	100	100	100	100	100	58	41	87	100	87	96
80%	100	100	100	100	100	100	100	100	100	100	44	100	100	91	98
90%	100	100	100	100	100	100	100	100	100	100	53	100	100	95	98
100%	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

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 2007a) 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 2007a). 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 2007a). 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 2007a). 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 2007a).

Studies have shown that minimal streamflow is lost to shallow aquifers on the lower portion of Deer Creek (Brown and Caldwell 2013; DWR 2004, 2009a). Only 1 TAF/yr is estimated to be lost on Deer Creek to groundwater on average in the current conditions simulation in SacWAM.

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). Diversions primarily affect the instream flows on Deer Creek in the summer months when the unimpaired flows are already very low. Deer Creek has essentially no water in the summer months in many years (Figure 2.2-9; Table 2.2-6).

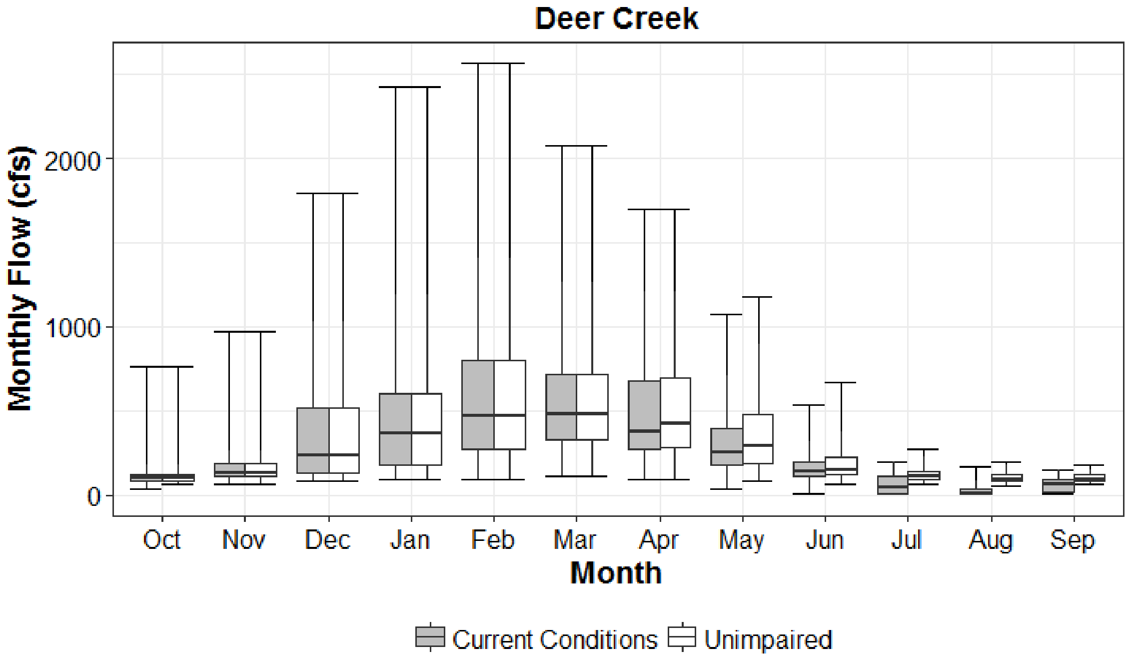


Figure 2.2-9. Deer Creek Simulated Current Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-6. Cumulative Distribution of Current Conditions as Percent of Unimpaired Flow in Deer Creek

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan–Jun	Jul–Dec	Annual Total
0%	32	100	100	100	100	100	77	25	1	2	2	3	87	52	81
10%	100	100	100	100	100	100	88	75	42	3	3	4	93	63	87
20%	100	100	100	100	100	100	89	81	74	4	4	7	94	71	89
30%	100	100	100	100	100	100	92	86	98	6	4	28	95	74	90
40%	100	100	100	100	100	100	94	95	100	20	5	51	96	78	91
50%	100	100	100	100	100	100	96	100	100	29	6	81	97	79	92
60%	100	100	100	100	100	100	97	100	100	61	13	94	98	83	93
70%	100	100	100	100	100	100	100	100	100	86	28	100	98	85	94
80%	100	100	100	100	100	100	100	100	100	100	58	100	99	89	95
90%	100	100	100	100	100	100	100	100	100	100	84	100	100	95	97
100%	100	100	100	100	100	100	100	100	100	100	100	100	100	100	99

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 afterward bends to the southwest toward the Sacramento Valley (Armentrout et al. 1998; Kondolf et al. 2001; CDFW 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 2014; 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 base flow 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 floodplain section of Mill Creek has been affected by two diversion dams: Upper Diversion Dam and Ward Dam Diversion (Armentrout et al. 1998; CDFW 2014; Tehama Environmental Solutions 2015). Diversions from those dams significantly affect late-spring, summer, and fall flows but those impacts are partially mitigated through surface water transfer and groundwater conjunctive use agreements (USDOI 2002; LMMWC 2007) (Figure 2.2-10). A stream and groundwater interaction study for a Mill Creek found that interactions were very small (Brown and Caldwell 2013). SacWAM estimates that 2 TAF/yr is gained on Mill Creek from groundwater on average in the current conditions simulation.

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 (Table 2.2-7) and related temperature issues (Armentrout et al. 1998; USDOI 2002; LMMWC 2007).

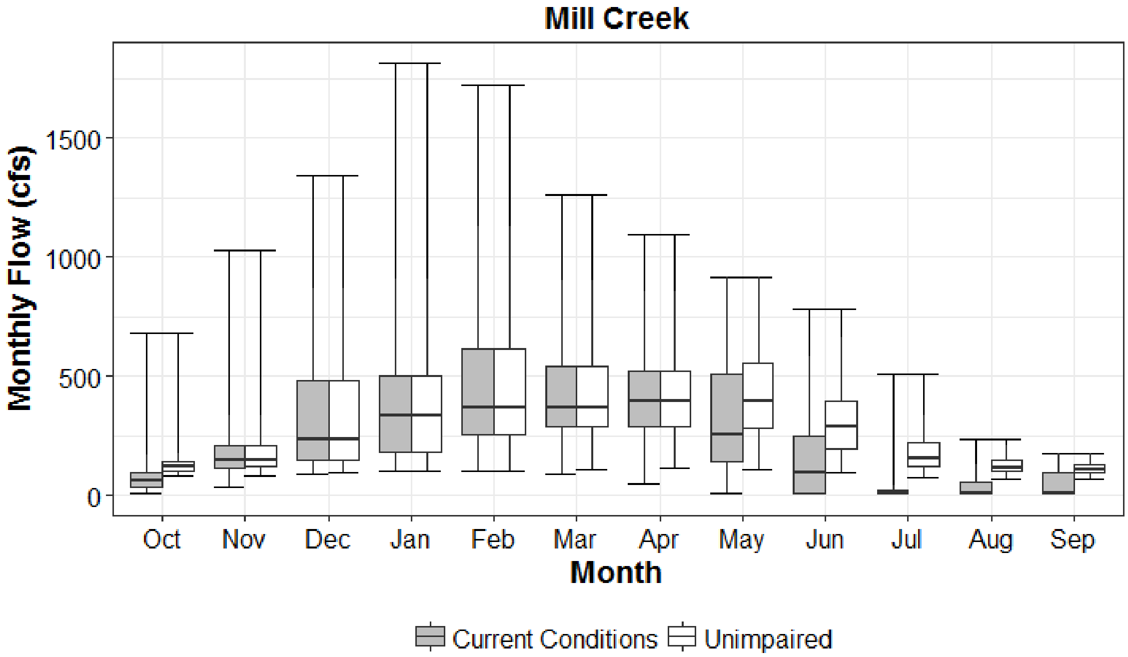


Figure 2.2-10. Mill Creek Simulated Current Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-7. Cumulative Distribution of Current Conditions as Percent of Unimpaired Flow in Mill Creek

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan–Jun	Jul–Dec	Annual Total
0%	6	39	99	100	100	80	31	2	2	4	3	5	61	36	51
10%	19	99	100	100	100	100	82	23	4	4	6	6	74	45	68
20%	32	99	100	100	100	100	100	40	4	5	7	7	79	50	71
30%	40	100	100	100	100	100	100	53	15	5	7	8	82	55	74
40%	44	100	100	100	100	100	100	60	21	6	8	8	84	58	76
50%	49	100	100	100	100	100	100	65	35	6	8	9	85	61	79
60%	56	100	100	100	100	100	100	76	45	7	9	10	90	64	84
70%	66	100	100	100	100	100	100	100	55	8	10	27	93	71	86
80%	82	100	100	100	100	100	100	100	62	16	72	99	95	77	90
90%	100	100	100	100	100	100	100	100	100	100	98	100	100	92	97
100%	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

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 flows (Tehama County Resource Conservation District 2010). SacWAM does not include any diversions from Paynes Creek; therefore, the current simulated conditions are equal to the unimpaired results, so the box plot and table are not presented.

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 1998). Occasionally there are large winter peak flow events and snow can remain on the peaks through June. Approximately 21 percent of the volume of water in the Whiskeytown Reservoir is from Upper Clear Creek and the other 79 percent is imported from the Trinity River. About 13 percent of the stored water is released into Lower Clear Creek and the remaining 87 percent is diverted to the Spring Creek Powerhouse and discharged into the Keswick Reservoir, which reduces the instream flow in Clear Creek in the spring (Figure 2.2-11; Table 2.2-8). Flows on Clear Creek are often higher than unimpaired flows in the summer and fall due to an instream flow requirement at Igo designed to protect native fisheries during the hot summer months.

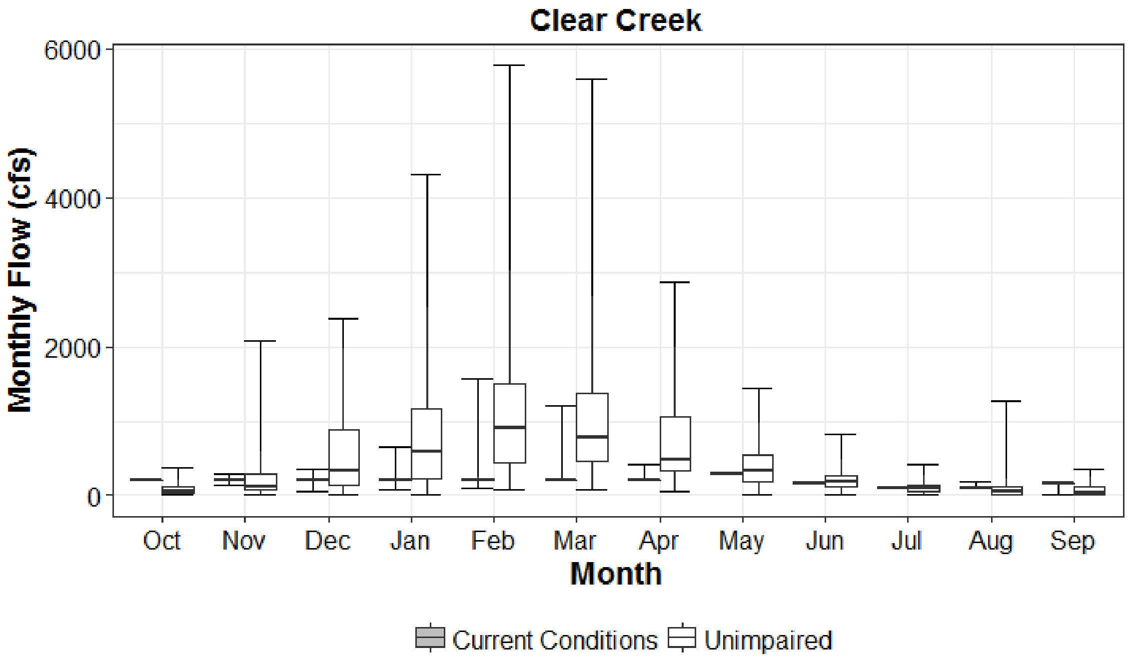


Figure 2.2-11. Clear Creek Simulated Current Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-8. Cumulative Distribution of Current Conditions as Percent of Unimpaired Flow in Clear Creek

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan–Jun	Jul–Dec	Annual Total
0%	54	14	14	14	14	14	14	19	19	24	14	15	17	24	20
10%	117	32	15	14	15	14	14	39	37	49	60	79	20	46	28
20%	135	59	20	15	15	15	18	47	53	61	75	115	23	54	30
30%	190	86	31	21	16	18	23	55	63	80	116	145	25	69	35
40%	272	132	41	26	19	21	31	74	75	93	172	257	29	78	39
50%	328	172	64	36	23	26	41	86	89	104	213	337	35	89	48
60%	417	189	86	55	32	34	48	118	102	155	324	600	43	112	59
70%	523	253	101	75	44	40	56	143	131	220	458	909	47	171	67
80%	729	345	199	101	58	53	71	176	158	287	814	AZ	65	255	80
90%	AZ	590	369	159	98	79	101	253	228	984	AZ	AZ	89	372	116
100%	AZ	AZ	AZ	AZ	258	279	339	AZ	AZ	AZ	AZ	AZ	167	1,057	251

"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 affect water temperature (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). Normally, the Colusa Weir does not overtop until after the Tisdale Weir is also spilling, when Sacramento River flow is greater than about 23,000 cfs, except for flood events that are characterized by rapid rise in Sacramento River stage (CDFW 2017; USGS 2017). 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 (DWR 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 by site-specific studies (Moran et al. 2005). SacWAM estimates the stream loss to groundwater to be -32 TAF/yr on average from Butte Creek (State Water Board 2017).

The Quartz Bowl Falls, about a mile below the DeSabla Powerhouse, is a natural barrier that can block fish passage (Butte Creek Watershed Project 1998). Salmon and steelhead cannot get upstream of the Quartz Bowl Falls on a regular basis but have been observed in several instances when spring flows were greater than 2,000 cfs (Ward and Moberg 2004; DWR 2005). 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 2.2-12; Table 2.2-9).

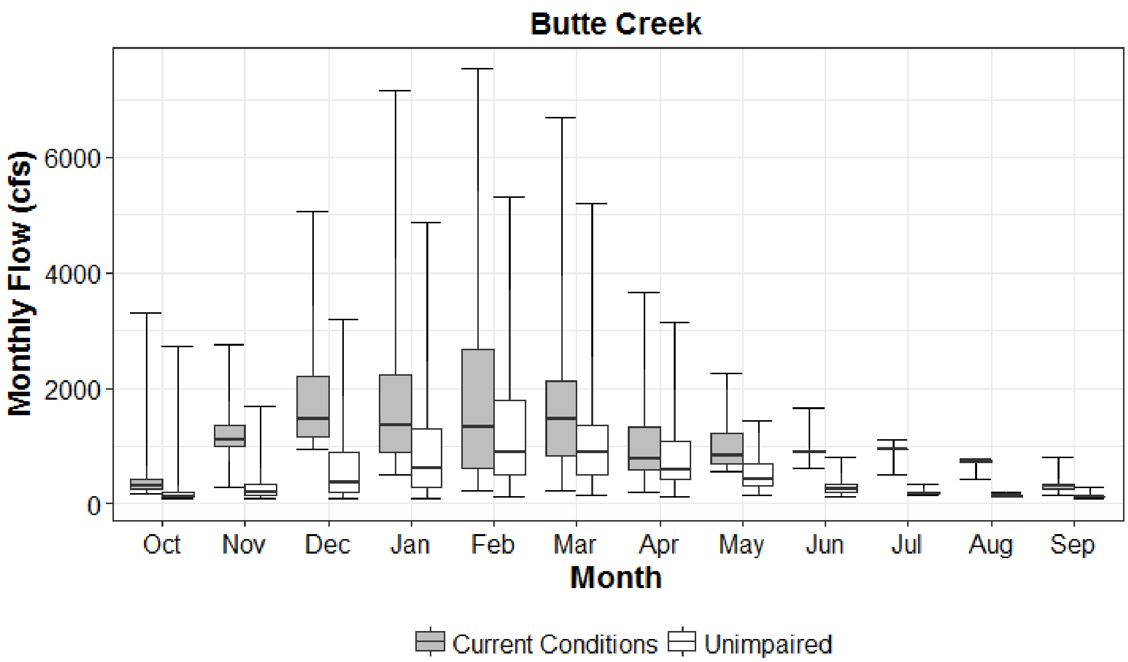


Figure 2.2-12. Butte Creek Simulated Current Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-9. Cumulative Distribution of Current Conditions as Percent of Unimpaired Flow in Butte Creek

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan–Jun	Jul–Dec	Annual Total
0%	121	127	150	132	108	122	112	145	197	283	290	149	135	200	157
10%	187	272	180	145	118	134	120	161	249	381	411	209	147	237	172
20%	198	356	215	170	125	140	123	181	264	409	439	222	151	269	180
30%	212	430	260	187	131	148	126	187	294	446	470	233	158	317	196
40%	225	500	329	202	134	156	128	193	327	465	481	241	165	352	208
50%	230	585	378	227	137	159	130	204	348	480	498	252	176	395	222
60%	239	664	465	264	142	164	132	214	376	509	524	267	180	431	234
70%	252	724	573	295	147	173	135	232	409	528	544	275	196	455	258
80%	259	783	630	352	152	182	138	247	443	567	556	293	207	494	275
90%	275	861	825	422	162	200	145	278	483	585	589	311	222	525	299
100%	331	994	1,064	648	196	278	156	385	670	675	649	404	305	607	383

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 2014) 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 therefore, 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 2014). 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 base flow 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 by site-specific studies (Moran et al. 2005).

The waterfall above the Higgins Hole at river mile (RM) 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 2014). 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. SacWAM does not include any diversions from Big Chico Creek in the model; therefore, the simulated current conditions and the unimpaired flows are the same, so the chart and table are not presented.

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. Pacific Gas and Electric Company (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/yr from Slate Creek (tributary of the North Yuba River) into the Feather River 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 percent 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 2013a). 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 on fisheries although spawning habitat restoration actions are being implemented in the Lower Feather River (DWR 2007a). 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 is 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 14 and 81 percent, and more than half of the years modeled, the impaired flow is less than 42 percent of the estimated unimpaired flow during January–June (Table 2.2-10).

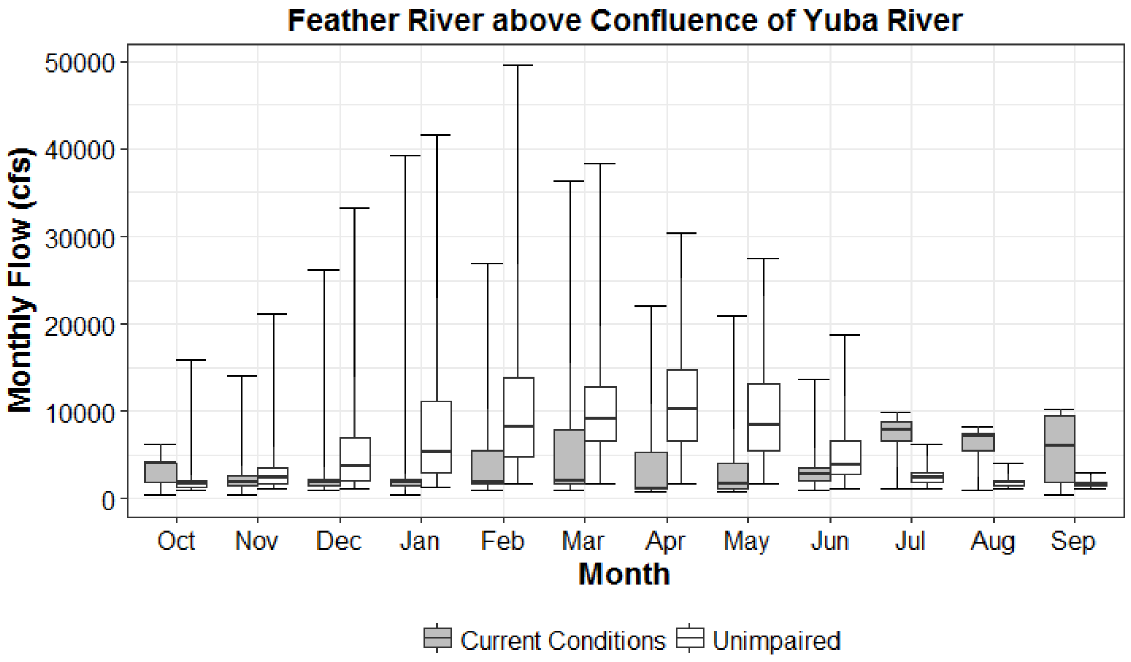


Figure 2.2-13. Feather River above Confluence with the Yuba River Simulated Current Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-10. Cumulative Distribution of Current Conditions as Percent of Unimpaired Flow in Feather River above Confluence of Yuba River

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan–Jun	Jul–Dec	Annual Total
0%	19	8	11	11	11	9	5	7	13	49	32	33	14	43	38
10%	76	35	18	19	16	16	9	12	32	107	96	83	20	98	55
20%	96	50	23	25	22	20	11	16	43	182	204	98	26	114	62
30%	139	63	34	29	25	25	12	21	52	240	266	193	31	131	68
40%	179	70	43	35	29	27	14	27	63	288	315	330	36	152	70
50%	201	80	53	43	37	37	17	31	66	330	359	371	42	167	74
60%	216	93	66	48	46	53	21	38	75	353	376	407	45	181	76
70%	231	109	75	64	56	62	34	44	93	387	406	448	54	209	80
80%	250	124	94	78	75	79	47	52	120	409	432	483	60	225	83
90%	283	135	132	94	92	91	63	63	132	439	464	531	70	252	90
100%	323	164	300	145	106	110	87	161	262	544	544	615	81	329	119

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). In SacWAM under current conditions, stream losses to groundwater are estimated to be -138 TAF/yr in a wet year but gains 61 TAF/yr on average in a critical year (State Water Board 2017).

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 current conditions as a percentage of unimpaired flow ranges from 28 to 81 percent and is less than 43 percent in half of the years. Monthly average unimpaired flows during the fall, winter, and spring are significantly lower in some years, with flows as low as 11 percent of unimpaired in April and May (Table 2.2-11).

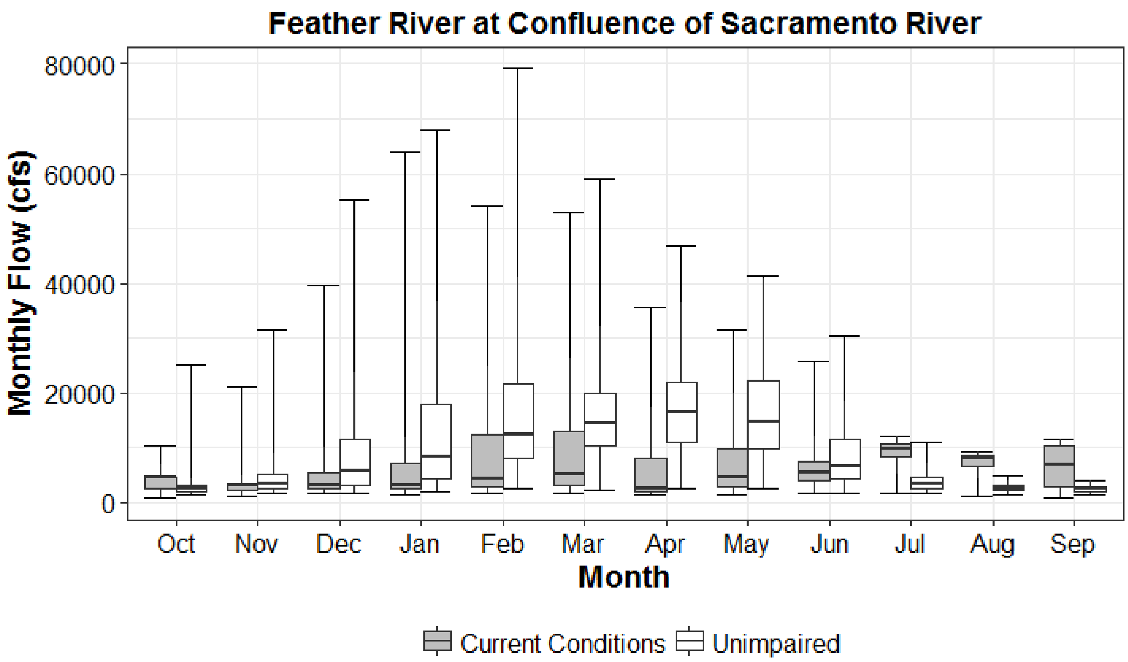


Figure 2.2-14. Feather River at Confluence with the Sacramento River Simulated Current Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-11. Cumulative Distribution of Current Conditions as Percent of Unimpaired Flow in Feather River at Confluence of Sacramento River

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan–Jun	Jul–Dec	Annual Total
0%	41	26	19	22	19	19	11	11	37	69	42	49	28	47	45
10%	77	44	30	29	28	27	15	24	61	109	110	102	31	92	56
20%	97	52	36	36	31	29	16	28	67	170	175	118	33	105	60
30%	118	59	41	41	36	32	17	31	71	206	221	187	36	117	64
40%	143	69	49	46	39	35	18	33	74	243	257	255	39	126	68
50%	152	79	52	49	45	41	21	38	83	275	278	299	43	138	71
60%	164	89	66	56	49	55	24	46	87	298	298	329	51	151	73
70%	173	97	75	67	60	64	37	51	94	322	311	347	58	169	76
80%	180	111	89	77	77	72	48	59	109	340	336	377	66	182	79
90%	197	118	114	91	87	84	62	67	135	368	364	409	71	213	81
100%	244	146	230	114	97	98	77	118	196	414	443	452	81	264	95

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, which then flows into the relatively small Englebright Lake (70 TAF). 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 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 and Englebright Reservoirs. 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/yr from the North Fork Yuba River into the Feather River watershed, and the Drum Canal diverts on average about 350 TAF/yr from the South Fork Yuba River at Lake Spaulding to the Bear River.

New Bullards Bar Reservoir on the North Fork is by far the largest reservoir in the Yuba River watershed, with storage capacity of about 960 TAF. While reservoirs on the Middle Fork are smaller, North Fork water can be transferred to either the North Fork or the South Fork upstream at Our House Diversion Dam, Log Cabin Diversion Dam, and Milton Reservoir. Similarly, reservoirs on the South Fork are relatively small, but, as stated above, South Fork water can be transferred to the Bear River at Lake Spaulding. As a result, winter and spring flows on the Lower Yuba River may be dominated by unregulated South Fork flow downstream of Lake Spaulding, Middle Fork flow that could not be transferred to the other forks, or flow from Deer and Dry Creeks. However, when flood releases are made from New Bullards Bar Reservoir on the North Fork, these flows may dominate flows in the Lower Yuba River.

Englebright Dam blocks fish passage on the Yuba River and the major impacts on fisheries are primarily due to the loss of spawning habitat above Englebright and the other dams. There have been a number of operations agreements to maintain flow and water temperature below Englebright 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 BiOp 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 2016c).

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 Dam. Reservoir storage and diversions on the Yuba River have greatly reduced flows on the Lower Yuba River 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 18 to 78 percent and is less than 47 percent half of the years. Flows in all months except September are also significantly reduced in some years, but are generally reduced in the wet season and increased in the dry season (Table 2.2-12).

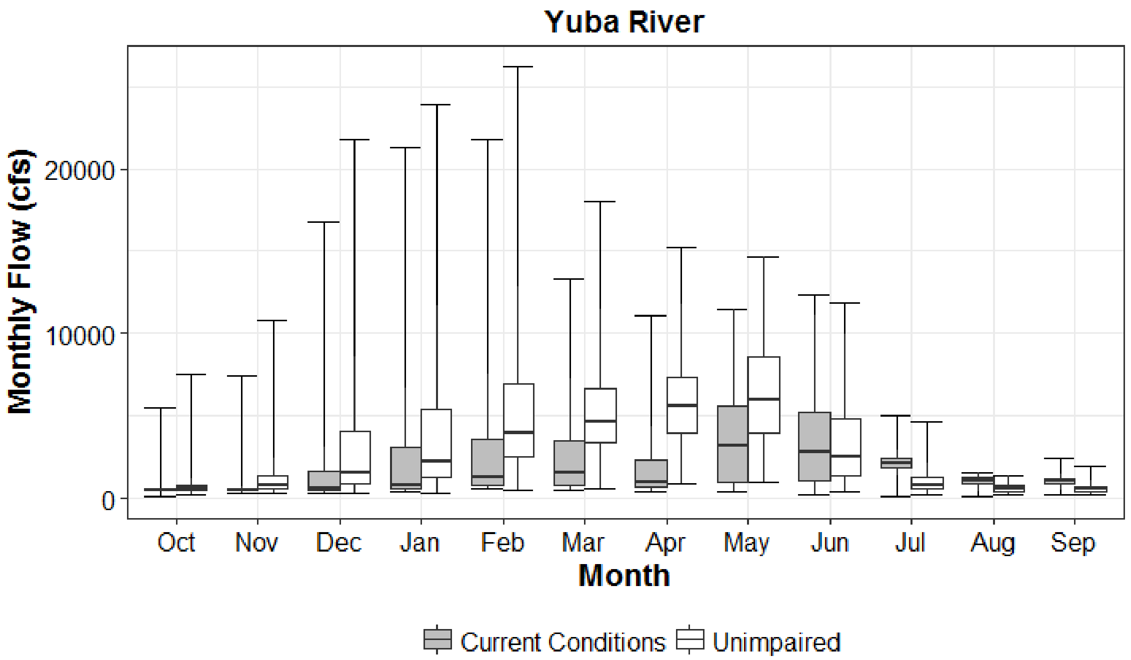


Figure 2.2-15. Yuba River Simulated Current Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-12. Cumulative Distribution of Current Conditions as Percent of Unimpaired Flow in Yuba River

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan–Jun	Jul–Dec	Annual Total
0%	35	28	17	21	18	18	10	8	10	26	37	82	18	43	34
10%	52	39	31	29	26	24	14	20	37	98	128	135	27	79	42
20%	58	44	36	34	31	25	17	30	67	116	140	150	33	82	47
30%	63	49	40	39	34	29	18	37	101	149	148	155	37	85	50
40%	70	56	46	42	39	33	19	45	104	168	157	163	42	87	55
50%	76	63	51	53	47	38	23	53	107	200	163	170	47	94	58
60%	82	69	58	59	56	42	25	60	112	218	171	177	55	105	64
70%	88	78	65	69	64	52	32	65	115	244	179	190	60	113	69
80%	93	90	71	73	70	57	40	72	124	267	186	200	68	125	72
90%	106	106	83	80	77	65	49	78	138	298	205	229	72	139	76
100%	196	131	140	185	129	79	73	84	226	387	269	269	78	173	79

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 (State Water Board 1955; James 1989; NID 2008, 2010, 2011; NMFS 2014b). 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 2014b), with flows frequently below 50 percent of unimpaired in winter-spring months (Table 2.2-13; Figure 2.2-16).

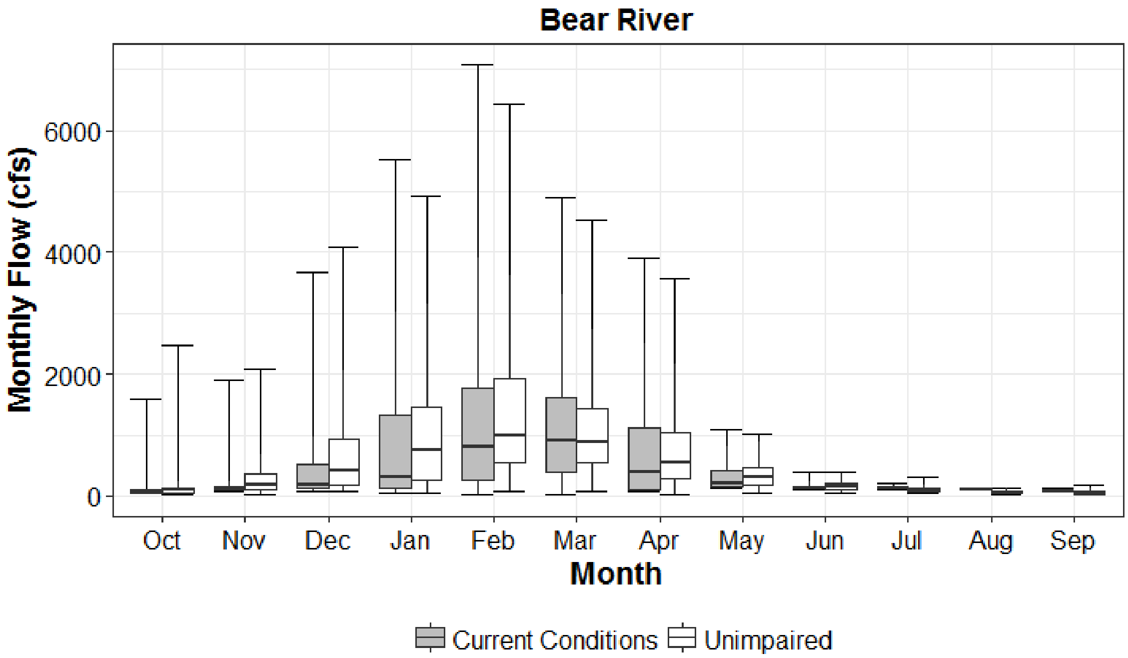


Figure 2.2-16. Bear River Simulated Current Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-13. Cumulative Distribution of Current Conditions as Percent of Unimpaired Flow in Bear River

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan–Jun	Jul–Dec	Annual Total
0%	31	28	24	16	15	24	24	33	48	55	94	65	37	40	53
10%	51	36	34	29	27	36	36	50	75	85	121	88	51	61	63
20%	55	48	42	36	38	61	42	67	82	93	140	105	68	70	71
30%	63	59	48	44	55	84	52	82	86	111	161	118	71	75	77
40%	71	66	58	55	74	95	62	89	92	124	179	133	77	84	83
50%	78	79	69	61	87	104	82	93	98	145	200	153	85	92	87
60%	87	84	78	85	97	108	92	97	104	162	225	183	92	99	91
70%	102	94	86	95	105	111	102	99	115	182	260	221	101	105	97
80%	112	112	97	103	108	113	113	110	147	207	295	242	107	117	101
90%	132	139	113	112	112	122	125	124	199	260	335	340	109	133	104
100%	305	378	144	135	138	142	210	232	299	300	406	592	120	175	128

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, and imports of water, as well as transfers between the three forks (USFWS 1995; PCWA 2007; FERC 2008; NID 2008, 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 River watershed; one via the South Canal from the Bear River which transfers about 100 TAF/yr on average and one from Sly Park Creek, a tributary of the Cosumnes River, of approximately 20 TAF/yr. There are two main diversions above Folsom Reservoir to Placer County Water Agency (PCWA) 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 percent of unimpaired flow at the mouth of the American River nearly 70 percent of the time in April and 70 percent of the time in May. January–June flows range from 32 to 86 percent of unimpaired flows.

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). In SacWAM under current conditions the reach is assumed to lose about -44 TAF/yr on average.

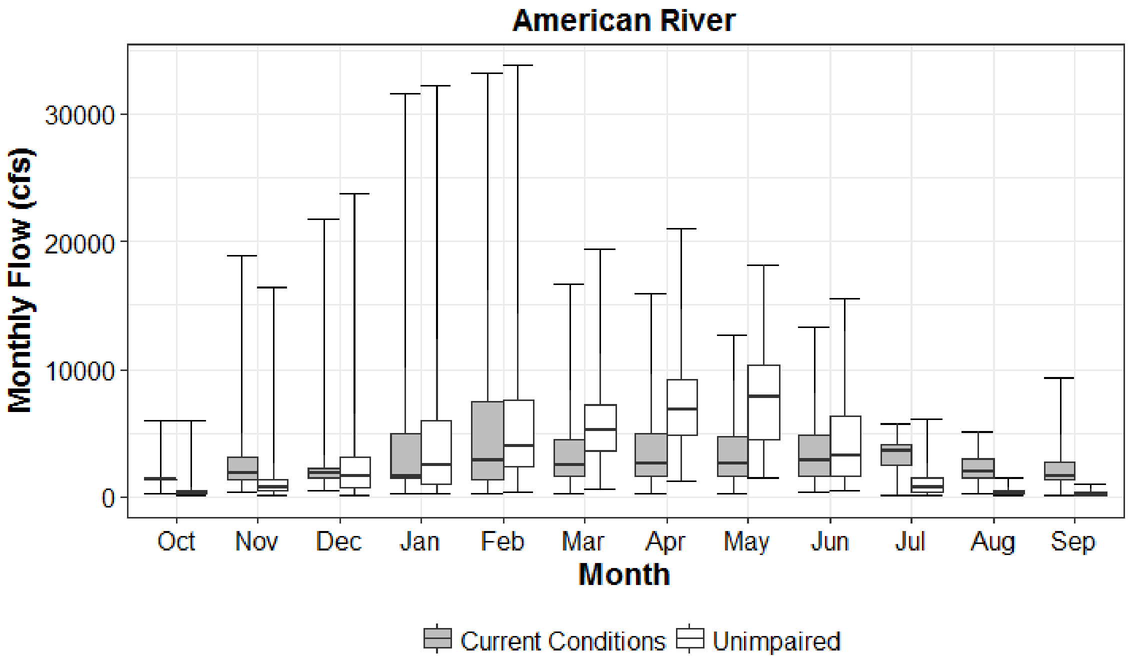


Figure 2.2-17. American River Simulated Current Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-14. Cumulative Distribution of Current Conditions as Percent of Unimpaired Flow in American River

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan–Jun	Jul–Dec	Annual Total
0%	102	43	17	18	7	10	6	8	33	66	268	73	32	115	64
10%	174	73	43	38	28	29	19	24	60	118	407	335	40	142	73
20%	227	101	81	58	37	37	27	29	70	158	452	441	44	163	81
30%	306	146	92	72	62	41	31	34	75	268	507	527	52	193	87
40%	350	207	100	85	79	45	33	36	78	332	585	602	55	259	90
50%	411	273	102	97	99	52	40	39	81	428	628	682	58	300	92
60%	475	339	119	101	101	55	45	43	86	520	741	795	63	337	94
70%	562	423	208	106	104	62	51	47	101	624	804	902	71	384	98
80%	672	535	258	113	110	70	58	54	129	783	1,060	1,262	76	492	103
90%	815	774	386	188	119	76	65	65	189	947	1,487	AZ	79	593	107
100%	1,407	1,075	564	293	185	87	76	94	366	AZ	AZ	AZ	86	904	164

“AZ” indicates that the unimpaired flow is approaching zero and is very low.

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 receives inflow from the Cosumnes River and Dry Creek. The hydrology of the Mokelumne River is dominated by the flows of its North Fork and, lower in the watershed, by releases from Pardee and Camanche Reservoirs.

The North Fork, is its largest tributary at 370 square miles and produces 85 percent 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/yr 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 approaches or reaches zero frequently in late summer through early fall (Figure 2.2-18; Table 2.2-15). Reservoir operations and diversions on the Mokelumne River have reduced the simulated current flows to below 24 percent of the unimpaired January–June flows in 50 percent of the years.

During the FERC 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 Agreement was concluded and EBMUD assumed responsibility for a range of stream flow, reservoir cold-water pool, habitat restoration, and predator control responsibilities (EBMUD et al. 1996).

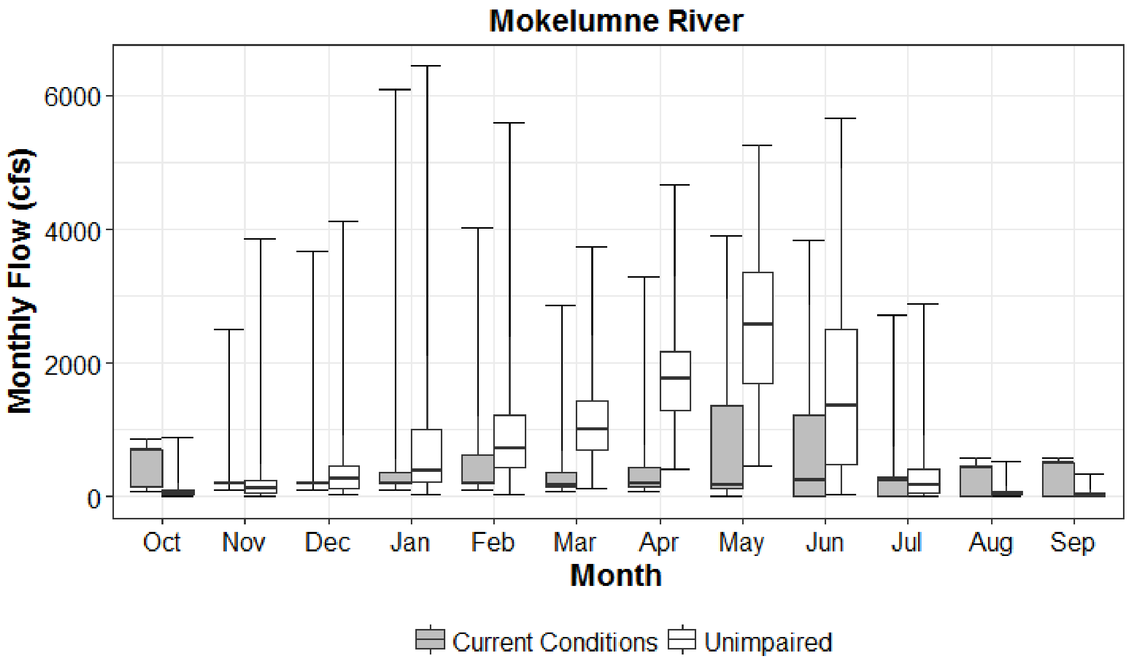


Figure 2.2-18. Mokelumne River Simulated Current Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-15. Cumulative Distribution of Current Conditions as Percent of Unimpaired Flow in Mokelumne River

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan–Jun	Jul–Dec	Annual Total
0%	89	19	20	9	10	4	5	0	0	0	0	2	8	46	18
10%	236	47	27	31	18	13	7	1	0	0	1	13	15	100	27
20%	384	83	47	37	28	17	8	7	0	0	2	29	16	112	31
30%	546	101	54	51	37	20	10	8	0	1	4	84	17	132	35
40%	651	121	69	60	41	23	12	8	15	1	8	365	20	153	39
50%	814	161	81	68	50	25	14	11	30	65	222	685	24	170	45
60%	968	222	111	77	58	27	16	24	44	75	427	881	32	209	50
70%	1,255	286	142	92	70	33	19	37	54	82	549	1,167	38	247	58
80%	1,482	336	168	110	77	43	29	45	63	93	747	1,350	51	287	63
90%	AZ	421	266	175	89	55	38	57	68	119	1,023	AZ	59	364	68
100%	AZ	AZ	808	465	456	109	70	86	76	221	AZ	AZ	73	500	80

A zero (0) indicates that the simulated current conditions are 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 main stem and only one significant dam (Sly Park [41 TAF]; 5 percent 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 et al. 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). Other than some minor diversions on the lower Cosumnes and operations of Jenkinson Lake by El Dorado Irrigation District, the current conditions are very similar to the unimpaired conditions shown in Figure 2.2-19 and Table 2.2-16

Historically, groundwater discharge maintained several large perennial ponds in the lowest reach on the valley floor (USGS 1908, 1910; Shlemon et al. 2000). More recently, 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). Previous groundwater modeling studies have shown uncertainty in stream-aquifer interactions on the Lower Cosumnes River, which range from losing up to 85 TAF/yr (Mount et al. 2001) to 2 TAF/yr (Brush et al. 2013). Stream–aquifer interactions in SacWAM are based on results from the model of Brush et al. (2013), and thus show very little stream-aquifer interaction on the lower Cosumnes River under current conditions.

Latrobe Falls, in the foothills just above the valley floor, blocks fish migration (Moyle et al. 2003). Impacts on 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).

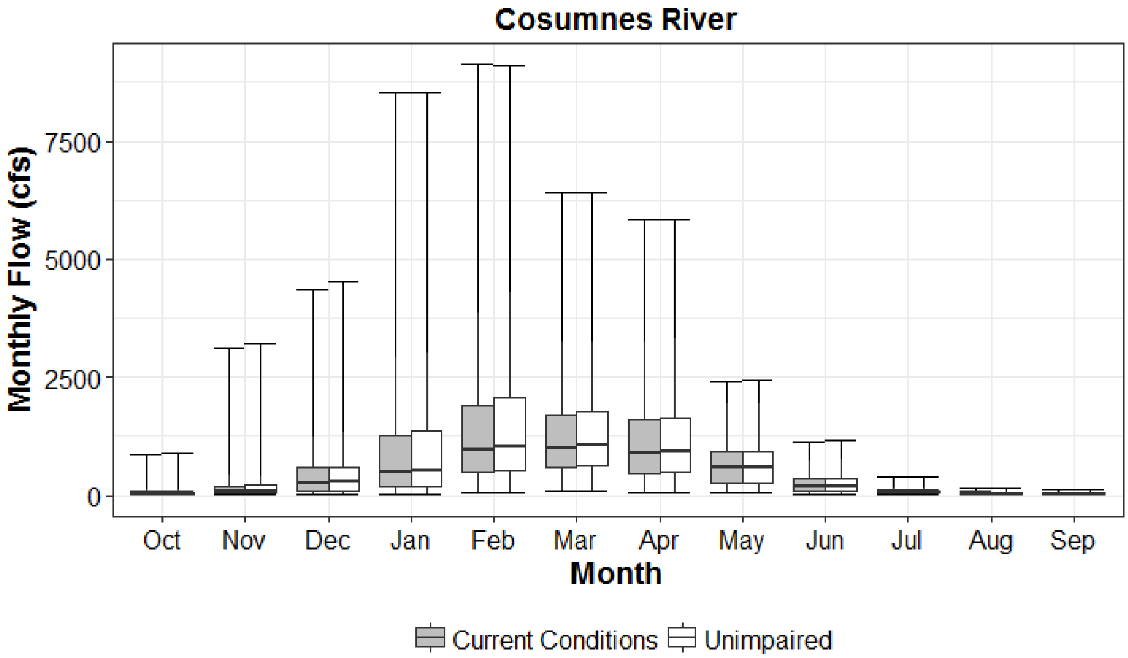


Figure 2.2-19. Cosumnes River Simulated Current Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-16. Cumulative Distribution of Current Conditions as Percent of Unimpaired Flow in Cosumnes River

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan–Jun	Jul–Dec	Annual Total
0%	86	83	86	81	85	86	80	85	85	95	90	82	89	91	92
10%	93	91	92	91	90	88	87	89	90	96	95	94	91	94	94
20%	97	93	93	92	91	91	92	92	91	96	97	105	93	95	94
30%	98	94	94	93	93	92	98	95	93	97	105	111	94	96	95
40%	101	95	95	94	94	94	99	96	93	98	109	115	95	97	96
50%	105	96	96	95	95	97	99	97	94	101	119	127	96	98	97
60%	108	97	97	97	97	100	99	98	95	106	126	133	98	100	97
70%	114	99	98	98	99	100	100	98	97	110	133	147	98	104	98
80%	126	101	99	100	100	100	100	99	98	116	143	172	99	108	98
90%	143	110	102	100	100	100	100	99	106	133	173	199	99	117	99
100%	363	150	118	107	101	101	100	99	138	176	219	1,210	100	140	109

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. 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 2007b) (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. Water from the New Hogan Project is used for irrigation and municipal purposes with the water right permit held by Reclamation. In 1970, Stockton East Water District (SEWD) and the Calaveras County Water District contracted with Reclamation for the project's entire water supply. In 1978, SEWD began to divert water at Bellota Weir, downstream of New Hogan, further altering water flow patterns in the river system. (DWR 2007b.)

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. Outside of the April to October irrigation season, Mormon Slough and the Old Calaveras River downstream of the Headworks may have little to no flow due to reduced releases from the reservoir and diversion into the SEWD municipal diversion at Bellota. (DWR 2007b.)

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 of most years (Table 2.2-17). In January–June the current conditions for the Calaveras River are less than 21 percent of the unimpaired conditions in half of the years.

Impacts on 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 2007b).

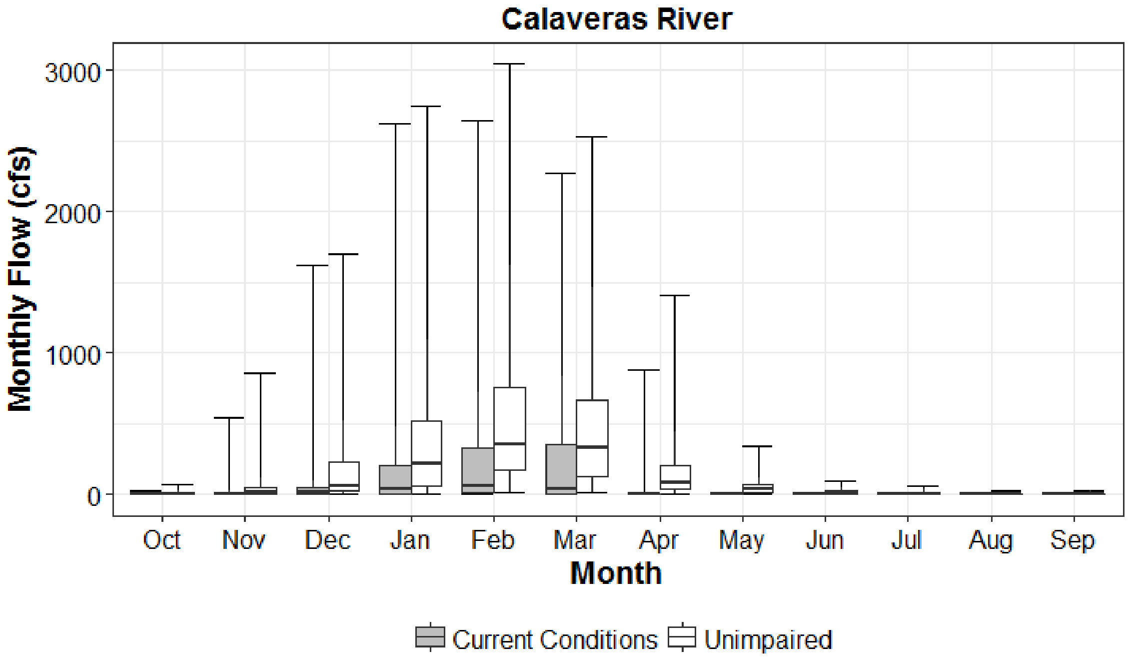


Figure 2.2-20. Calaveras River Simulated Current Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-17. Cumulative Distribution of Current Conditions as Percent of Unimpaired Flow in Calaveras River

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan–Jun	Jul–Dec	Annual Total
0%	0	0	0	5	0	0	0	0	0	0	0	0	4	0	5
10%	1	5	10	9	8	0	0	0	0	0	0	0	10	9	10
20%	2	12	12	10	11	4	0	0	0	0	0	0	12	14	13
30%	3	16	16	12	13	7	0	0	0	0	0	2	13	15	14
40%	5	19	18	14	15	9	0	0	0	1	0	3	16	18	17
50%	9	26	21	20	18	13	0	0	0	3	0	5	21	20	22
60%	21	32	26	29	29	17	0	0	0	4	0	9	29	25	35
70%	33	40	32	44	35	49	1	0	2	5	3	15	49	32	51
80%	72	50	51	63	58	61	2	0	4	15	7	44	59	37	60
90%	137	90	93	83	80	79	6	1	8	25	18	64	68	60	66
100%	AZ	AZ	830	122	91	90	62	5	56	42	90	146	82	403	89

A zero (0) indicates that the simulated current conditions are 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/yr. 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 November–March for flood control and April–October for irrigation. Prior to Black Butte Dam, daily flood flows exceeded 30,000 cfs about every 5 years, with maximum flows over 80,000 cfs (HT Harvey and Associates 2007). Orland Project operations have greatly reduced flows and variability on Stony Creek (Figure 2.2-21). For example, during March, current conditions flows are less than 18 percent of unimpaired flows in half of the modeled years (Table 2.2-18).

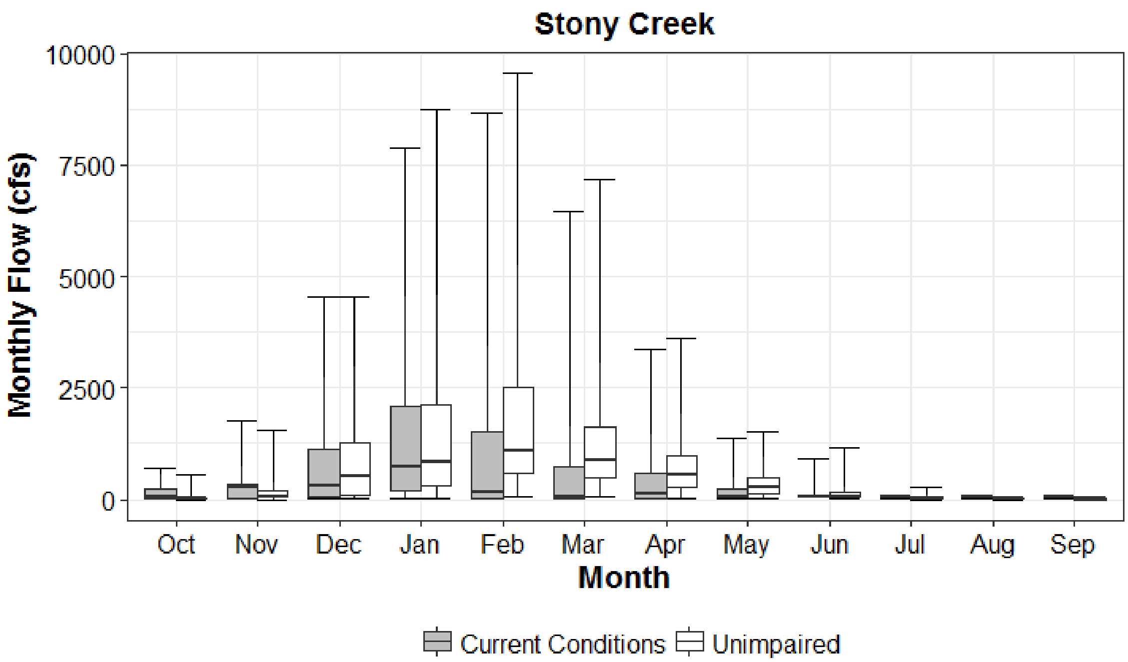


Figure 2.2-21. Stony Creek Simulated Current Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-18. Cumulative Distribution of Current Conditions as Percent of Unimpaired Flow in Stony Creek

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan–Jun	Jul–Dec	Annual Total
0%	38	9	13	9	4	3	3	6	16	18	77	71	10	42	16
10%	82	37	30	47	5	5	9	16	20	80	124	144	17	58	34
20%	139	72	55	69	7	6	13	18	27	104	158	238	27	91	50
30%	189	100	71	78	10	8	15	25	41	135	223	300	37	101	59
40%	323	125	78	82	15	13	23	31	52	156	283	423	47	114	66
50%	461	182	86	93	23	18	37	38	71	189	357	504	57	125	73
60%	541	249	91	97	43	29	46	50	79	217	442	773	63	140	77
70%	961	347	94	99	56	46	63	59	92	266	687	958	68	184	79
80%	AZ	456	97	99	68	61	74	69	136	361	1,022	AZ	76	261	84
90%	AZ	578	100	99	77	72	85	77	192	644	AZ	AZ	79	341	87
100%	AZ	1,318	101	100	91	90	168	182	457	AZ	AZ	AZ	89	567	115

“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 Northern Coast Range (8,000 feet) and the southernmost peaks of the Klamath Range (CH2M Hill 2002; Graham Matthews and Associates 2003). 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 2003). Cottonwood Creek, like all of the larger creeks with headwaters in the Northern 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).

Results from SacWAM show that Cottonwood Creek loses 9 TAF/yr on average to groundwater under current conditions; however, previous studies showed that historically it was a gaining reach under dry conditions (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 base flows (Blodgett et al. 1992) (Table 2.2-19).

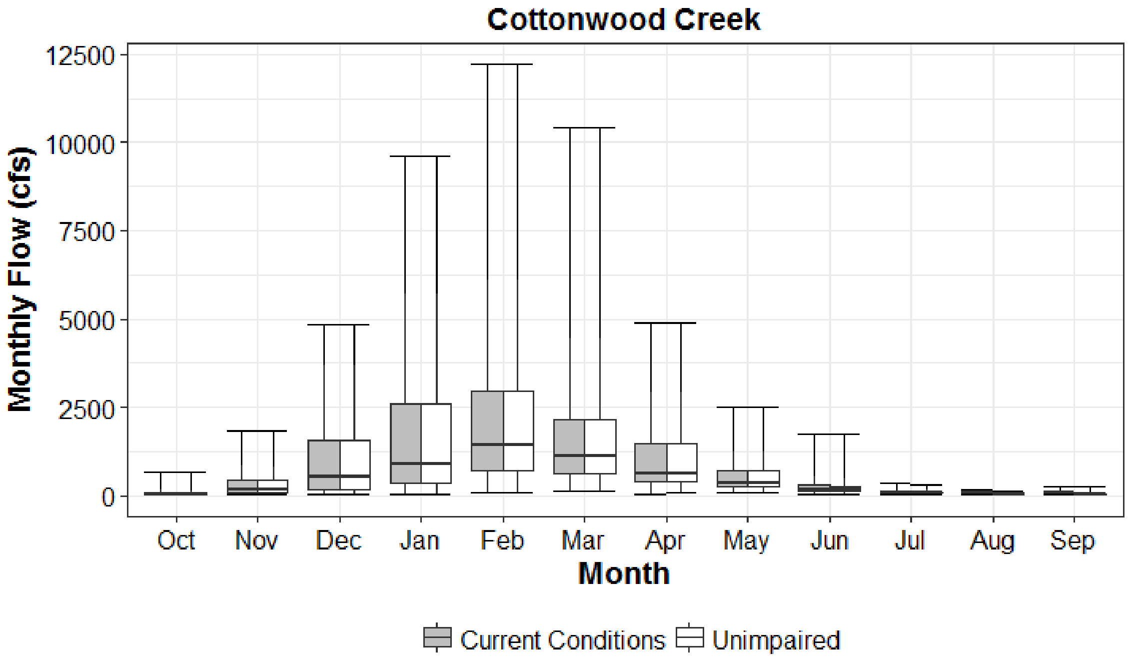


Figure 2.2-22. Cottonwood Creek Simulated Current Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-19. Cumulative Distribution of Current Conditions as Percent of Unimpaired Flow in Cottonwood Creek

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan–Jun	Jul–Dec	Annual Total
0%	77	98	100	100	100	100	83	94	91	104	102	98	100	101	100
10%	100	100	100	100	100	100	98	101	103	107	119	106	100	102	101
20%	100	100	100	100	100	100	100	101	104	111	132	117	100	103	101
30%	101	100	100	100	100	100	100	102	104	114	139	126	100	104	101
40%	102	101	100	100	100	100	100	102	105	121	145	132	100	105	101
50%	103	101	100	100	100	100	100	103	106	126	153	136	101	107	102
60%	105	101	101	100	100	100	100	103	107	135	160	145	101	109	102
70%	109	101	101	100	100	100	100	104	109	146	173	151	101	111	102
80%	114	102	101	101	100	100	100	105	110	151	188	157	101	115	103
90%	119	102	102	101	101	100	102	106	113	163	201	166	101	121	104
100%	181	104	105	103	101	121	105	111	206	224	261	240	105	135	109

2.2.8.3 Thomes Creek

Thomes Creek has a watershed area of 301 square miles which heads in the Inner Northern Coast Range at an elevation of 6,600 feet (VESTRA Resources 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 Northern 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. The current conditions simulation shows very similar hydrology when compared with the unimpaired flows in the winter months (Figure 2.2-23; Table 2.2-20). Diversions during the summer months reduce flows compared with unimpaired conditions. About 88 percent of the water used in the region is obtained from groundwater for irrigated agriculture (VESTRA Resources 2006).

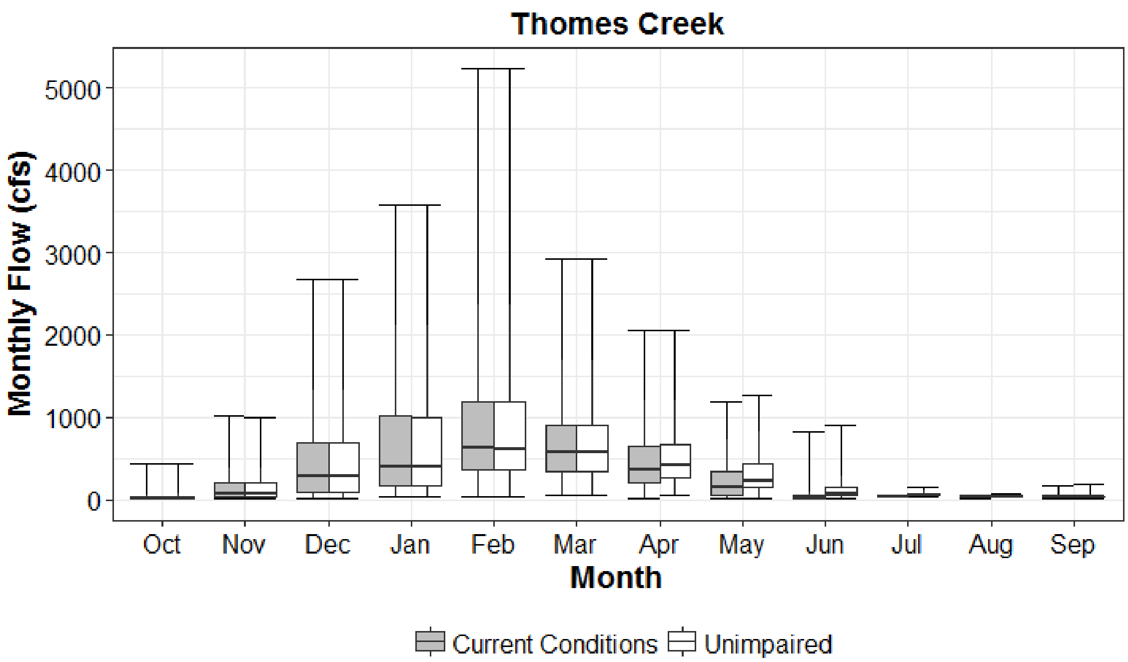


Figure 2.2-23. Thomes Creek Simulated Current Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-20. Cumulative Distribution of Current Conditions as Percent of Unimpaired Flow in Thomes Creek

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan–Jun	Jul–Dec	Annual Total
0%	21	43	73	100	100	58	7	8	6	24	52	61	57	73	64
10%	31	88	95	100	100	95	65	15	9	43	72	82	83	84	87
20%	44	94	99	100	100	100	77	28	11	50	75	84	88	86	90
30%	50	97	100	100	100	100	84	42	12	57	81	86	91	90	92
40%	52	98	101	100	100	100	87	53	14	63	85	87	92	92	93
50%	57	100	101	101	100	100	93	64	17	71	88	90	94	95	94
60%	70	101	101	101	100	100	94	75	25	76	92	93	94	96	95
70%	74	101	101	101	101	100	96	79	30	79	95	97	95	97	95
80%	82	102	102	102	101	100	97	86	40	82	96	99	96	98	96
90%	95	103	103	103	101	101	100	90	61	88	100	101	97	99	96
100%	109	105	106	108	102	101	101	97	92	101	102	102	99	101	98

2.2.8.4 Elder Creek

Elder Creek has a watershed area of 151 square miles which heads in the Inner Northern Coast Range at an elevation of 5,500 feet (VESTRA Resources 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 base flow 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. SacWAM does not include any diversions from Elder Creek; therefore, the current simulated conditions are equal to the unimpaired results, so the box plot and table are not presented.

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 Northern 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 basin 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. Clear Lake loses an estimated 171 TAF/yr on average to net evaporation under current conditions as estimated in SacWAM (State Water Board 2017). 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 301 TAF 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; Table 2.2-21).

In about 10 percent of the years, Cache Creek January–June current conditions are more than 80 percent unimpaired flows, but in half of the years, the current conditions are less than 53 percent of unimpaired flows during the January–June period.

Surface water in the channel of Cache Creek loses water to groundwater 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). Current condition simulations estimate an average -90 TAF/yr of streamflow is lost to groundwater from Cache Creek (State Water Board 2017).

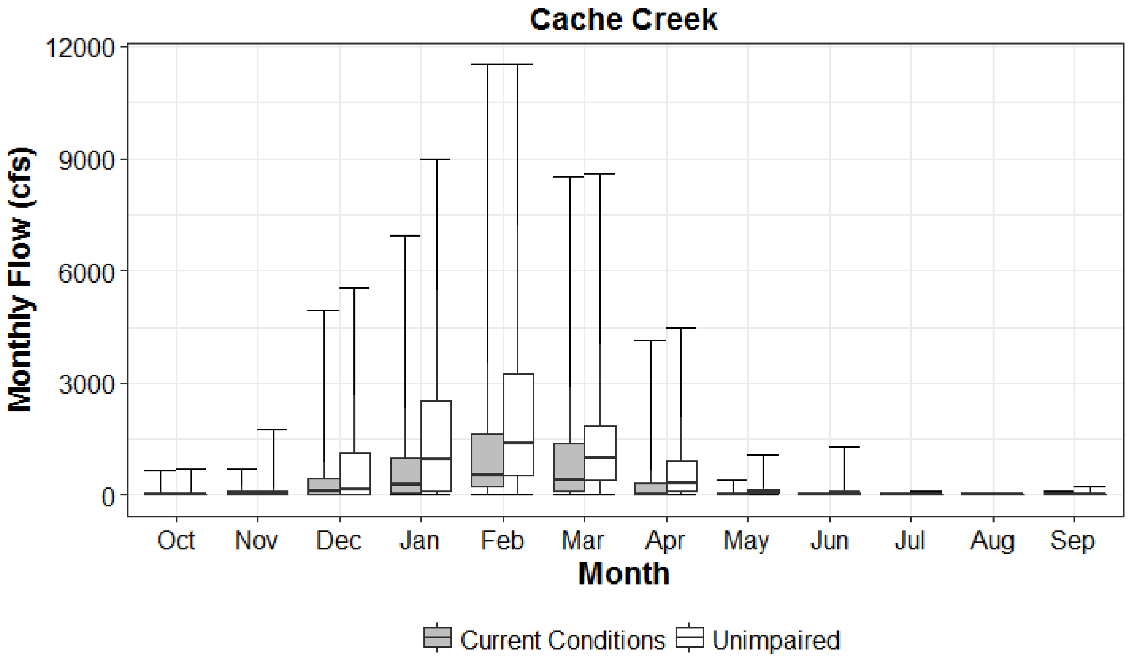


Figure 2.2-24. Cache Creek Simulated Current Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-21. Cumulative Distribution of Current Conditions as Percent of Unimpaired Flow in Cache Creek

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan–Jun	Jul–Dec	Annual Total
0%	10	21	9	8	8	1	6	6	3	14	18	9	13	20	16
10%	69	69	21	20	21	13	9	14	35	36	50	42	24	30	30
20%	81	75	33	27	28	22	13	24	48	50	70	64	30	40	35
30%	92	91	41	34	35	28	17	28	57	61	86	83	34	52	38
40%	100	103	52	41	45	47	25	35	68	77	92	98	40	67	43
50%	108	108	70	48	59	58	35	43	83	94	106	116	53	77	53
60%	118	115	81	63	74	79	44	49	89	109	124	128	60	86	58
70%	126	130	90	74	84	83	53	58	95	120	143	146	66	98	62
80%	135	152	103	82	94	89	68	65	101	131	147	156	71	104	70
90%	146	182	121	100	99	96	85	91	110	138	159	166	82	116	75
100%	540	411	191	188	130	107	103	125	138	189	223	424	118	137	121

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 Northern 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 city 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, 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).

Simulated current conditions 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 July–October in about 30 percent of the years (Table 2.2-22). In more than half of the years, current conditions are less than 13 percent 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). Current stream losses to groundwater average -10 TAF/yr (State Water Board 2017). Self-sustaining populations of anadromous fish have returned to Putah Creek in response to the flow releases of the Putah Creek 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).

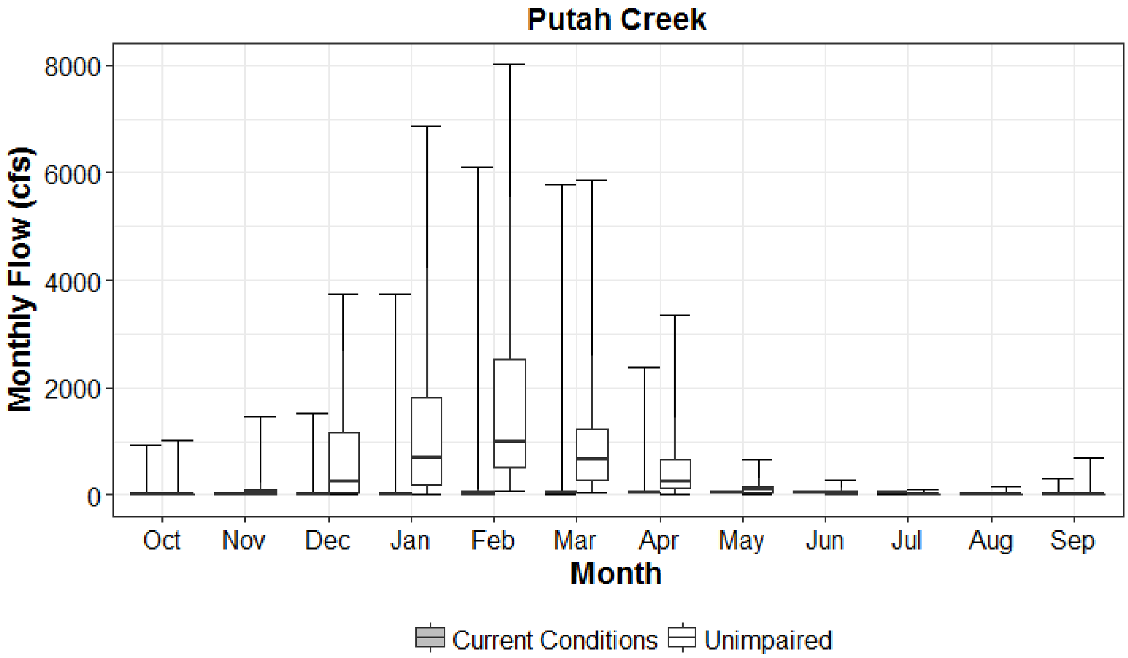


Figure 2.2-25. Putah Creek Simulated Current Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-22. Cumulative Distribution of Current Conditions as Percent of Unimpaired Flow in Putah Creek

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan–Jun	Jul–Dec	Annual Total
0%	20	1	1	1	1	2	2	6	15	32	12	31	3	5	4
10%	46	6	2	2	2	4	6	11	35	74	144	93	4	7	6
20%	94	11	2	2	3	6	8	18	43	104	337	173	6	9	8
30%	209	24	4	3	3	7	12	26	66	164	602	262	7	13	10
40%	324	40	5	4	4	9	18	31	78	320	1,034	498	9	22	12
50%	504	62	8	6	5	17	21	38	98	571	AZ	830	13	35	14
60%	1,167	131	12	10	6	25	26	47	149	1,010	AZ	AZ	14	52	17
70%	AZ	348	38	16	9	32	32	60	235	AZ	AZ	AZ	19	76	22
80%	AZ	1,225	95	25	24	45	51	76	322	AZ	AZ	AZ	26	183	29
90%	AZ	AZ	299	68	61	88	68	120	888	AZ	AZ	AZ	56	299	52
100%	AZ	AZ	AZ	AZ	99	113	324	AZ	AZ	AZ	AZ	AZ	82	AZ	96

“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, 3–5 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 groundwater 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 waterfowl 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 floodplain; 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 2 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 2 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 et al. 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 (California Department 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 (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, which has a designed capacity of 25,000 cfs (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 (DWR 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 Northern 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).

Historically, flood waters 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 Northern Coast Range, and through levee breaks immediately above and below the town of Colusa (California 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 flood waters westward into the Colusa basin (California Department of Engineering 1914).

The start of rice growing in the Colusa basin was 2 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 (California Department 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 Northern 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, 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 Northern 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 caused 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; Singer and Alto 2009; DWR 2012). Today and historically, the majority of its flood waters originate from Butte Slough (Bryan 1923; Singer et al. 2008; Singer and Alto 2009; DWR 2012; Kelley 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; Singer and Alto 2009). The Sutter Bypass was established to convey flood flows down the central portion of the basin (Figure 2.3-1; Table 2.3-1). The bypass receives flows from Butte Slough (150,000 cfs), the Tisdale Weir (38,000 cfs), 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).

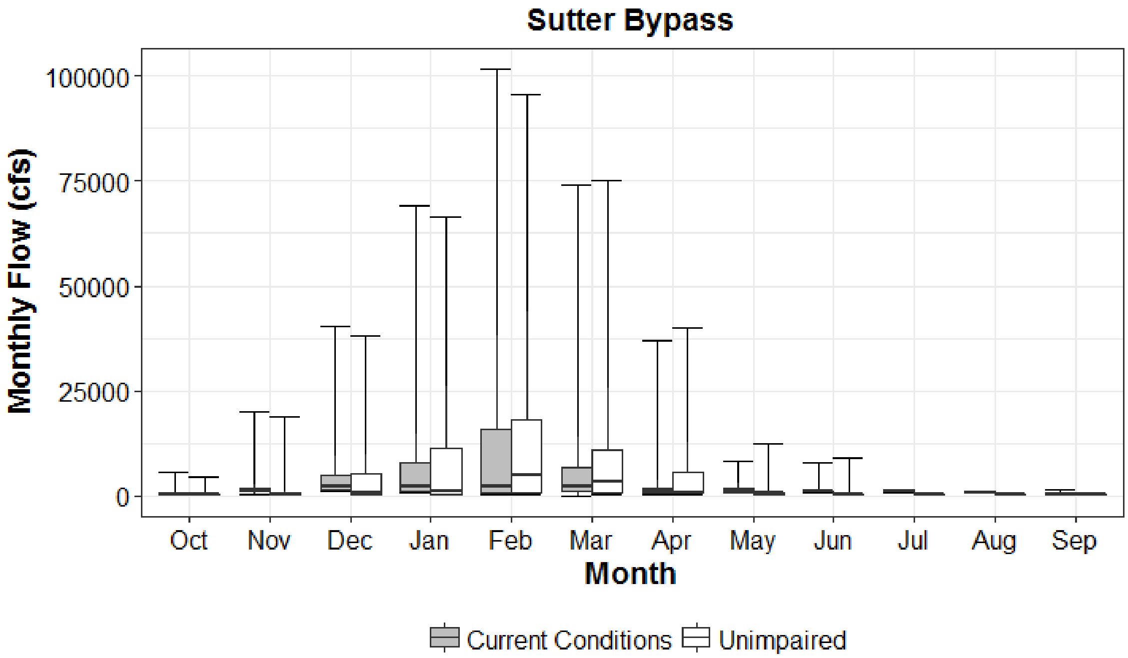


Figure 2.3-1. Sutter Bypass Simulated Current Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.3-1. Cumulative Distribution of Current Conditions as Percent of Unimpaired Flow in Sutter Bypass

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan–Jun	Jul–Dec	Annual Total
0%	74	72	36	33	14	22	13	27	74	185	243	124	46	57	59
10%	101	267	101	66	42	43	29	58	215	293	297	148	67	112	84
20%	106	337	106	84	53	53	43	136	237	309	313	156	78	139	91
30%	111	390	189	94	68	63	58	157	248	327	319	161	84	224	95
40%	115	454	336	104	78	78	73	168	266	351	335	166	88	300	100
50%	120	546	417	225	91	99	88	177	277	366	344	175	91	327	105
60%	128	609	487	260	99	111	104	190	282	396	349	187	94	359	111
70%	133	671	547	328	111	134	135	207	291	454	356	219	103	378	128
80%	141	710	650	358	119	156	139	216	319	481	362	239	147	394	188
90%	166	781	788	430	137	179	145	226	342	508	383	307	194	416	250
100%	275	943	1,016	563	177	320	161	345	1,465	615	552	407	229	462	309

2.3.4 American Flood Basin

The American flood 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 creeks and 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). The tributaries of the American River basin include, from north to south, Coon Creek, Auburn Ravine, and the Dry Creek system, including Secret and Miners Ravines. While Coon Creek and Auburn Ravine enter the Sacramento River via the Natomas Cross Canal, the Dry Creek system does so via the Natomas East Main Drainage Canal, which enters the Sacramento River via Bannon Slough.

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 Northern Coast Range streams, principally Cache and Putah Creeks, flooded (Bryan 1923; Water Resources Association of Yolo County 2005). The main upstream entry point for flood water 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 2 weeks of downstream floodplain inundation only occur in about 40 percent 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 & 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 (California 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 waterfowl in the late fall and during the wet season (CDFG 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; CDFG 2008; Sommer et al. 2014).

Within the bypass there is a network of drainage canals that convey flows from the Northern 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; Table 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.

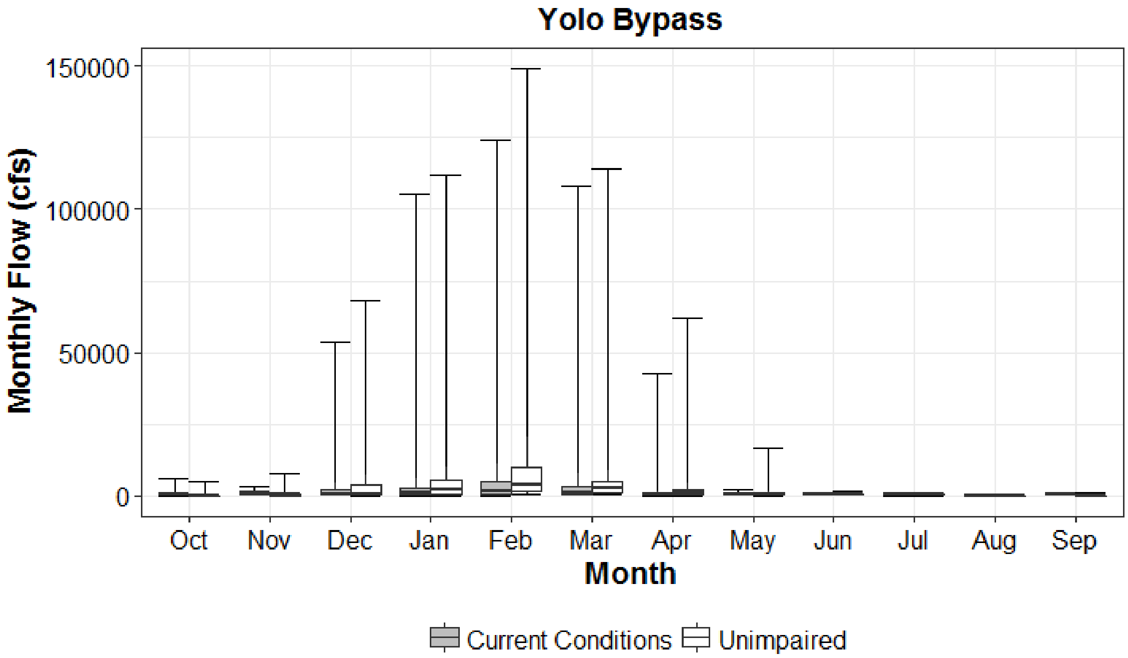


Figure 2.3-2. Yolo Bypass Simulated Current Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.3-2. Cumulative Distribution of Current Conditions as Percent of Unimpaired Flow in Yolo Bypass

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan–Jun	Jul–Dec	Annual Total
0%	70	20	18	10	10	8	4	2	15	31	22	46	15	27	22
10%	121	67	30	22	21	19	12	19	75	56	58	152	33	47	44
20%	211	101	40	26	28	24	17	28	99	76	69	169	38	88	54
30%	588	149	53	35	35	35	19	57	128	396	78	187	46	110	63
40%	812	294	64	43	42	41	23	66	141	439	84	195	50	140	67
50%	880	527	74	56	49	52	28	82	172	479	92	202	55	216	71
60%	954	884	93	61	59	61	38	91	202	531	120	218	61	282	77
70%	1,023	1,113	137	68	66	78	51	111	390	556	584	719	69	385	82
80%	1,086	1,427	184	93	83	91	65	132	548	586	641	888	78	469	92
90%	1,192	AZ	523	110	98	104	135	453	619	626	695	997	87	648	124
100%	1,426	AZ	AZ	894	373	318	421	710	788	710	813	AZ	397	813	476

"AZ" indicates that the unimpaired flow is approaching zero and is very low.

2.3.6 Sacramento Flood Basin

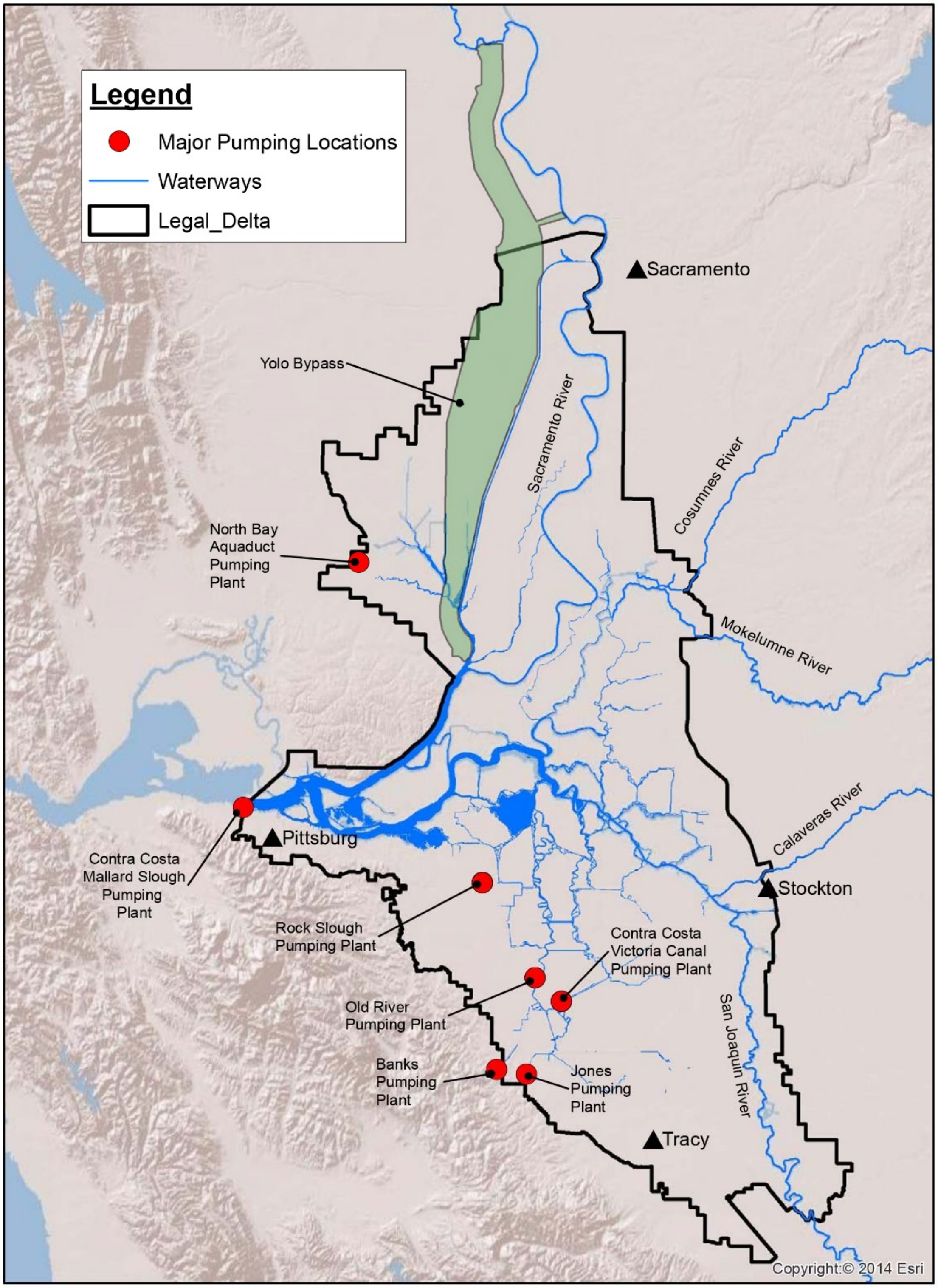
The Sacramento basin is approximately 20 miles long and extends from near the current southern border of the city of Sacramento to just beyond the southern end of Snodgrass Slough near the north and south Delta forks of the Mokelumne River (Whipple et al. 2012).

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 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). While not part of the "legal Delta," Suisun Marsh is an important ecological area closely associated with the Delta. It is the marshland located north of Suisun and Honker Bays, west of Pittsburg.

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 freshwater 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. 2009), 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). While these diversions are managed to satisfy multiple objectives they influence flow through the Delta and can have consequences such as entrainment loss and increased predation to imperiled native species of fish. Agricultural diversions and pumped exports remove phytoplankton biomass and reduce the Delta's carrying capacity for consumers in this low productivity ecosystem where food limitation is pervasive across trophic levels (Monsen et al. 2007).

In the north, the Freeport Regional Water Authority 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 CVP, SWP, Contra Costa Water District (CCWD), East Contra Costa Irrigation District, and Byron-Bethany Irrigation District divert from the Old River channel of the San Joaquin River and other southern Delta channels. The Sacramento River is a major source of the freshwater in the Old River channel which is pulled upstream through Georgiana Slough and the DCC gates (DWR 2010a).

2.4.1 Delta Inflows

Despite its name, the 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 eastside 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 July–November compared to December–June (TBI 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, groundwater discharge from this volcanic system historically maintained a summer base flow at Red Bluff of approximately 4,000 cfs and about 800 cfs in the Feather River, without which the Sacramento River would have nearly dried up during the fall (TBI 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 (California Department of Public Works 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 (California Department of Public Works 1931; Jackson and Patterson 1977; TBI 1998). The economic impacts of these diversion-caused saltwater intrusions ultimately led to the creation of the CVP 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 (Figure 2.4-2; Table 2.4-1). 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 2002a, 2004).

Table 2.4-1 and Figure 2.4-2 show the large effects of water development upstream of the Delta. Current conditions in the spring are less variable and inflows are less than 57 percent of unimpaired flows in half of the years. The months of April and May are the most extreme where current Delta inflow is less than 50 percent of unimpaired flows more than 70 percent of the period. Table 2.4-2 shows that Delta inflows from the San Joaquin River are the most impaired followed by Delta eastside tributaries and the Sacramento River is the least impaired contribution to Delta inflow.

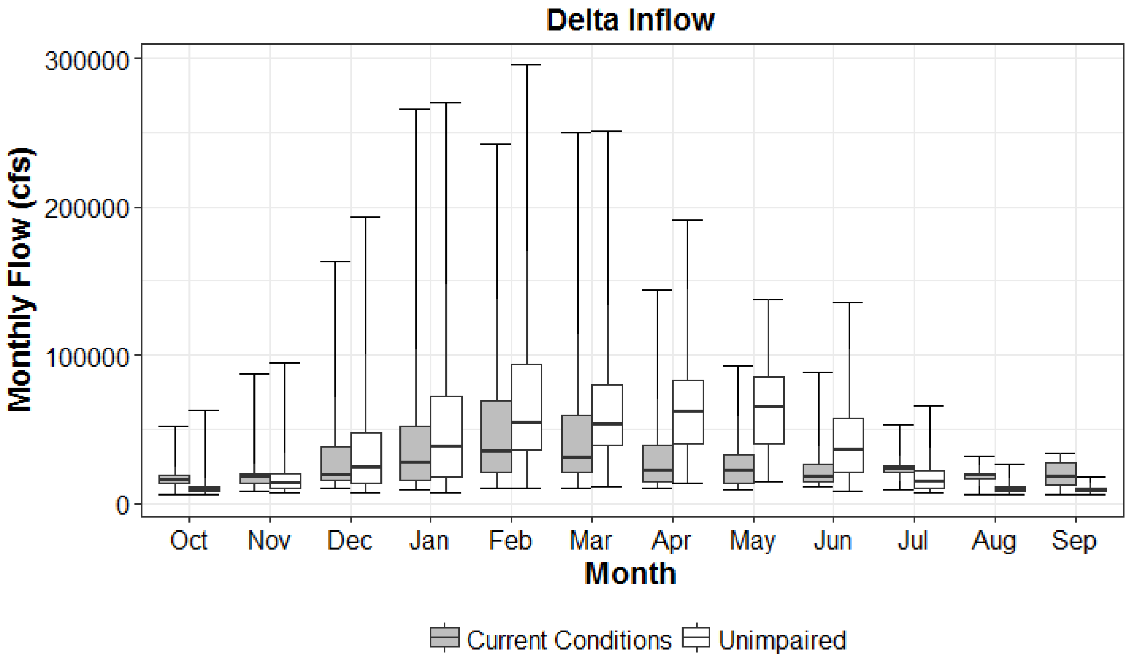


Figure 2.4-2. Delta Inflow Simulated Current Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.4-1. Cumulative Distribution of Current Conditions as Percent of Unimpaired Flow for Delta Inflow

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan–Jun	Jul–Dec	Annual Total
0%	83	59	47	49	42	38	28	24	30	72	93	71	38	78	53
10%	104	81	68	60	53	48	32	29	42	83	140	133	48	99	65
20%	129	90	74	65	59	52	35	33	47	98	152	148	50	107	69
30%	140	97	76	69	65	55	36	34	50	113	166	167	53	114	72
40%	150	109	81	73	68	58	39	37	52	127	172	190	54	118	73
50%	158	120	87	78	71	63	41	39	56	142	178	207	57	129	75
60%	164	135	96	82	76	65	43	40	60	164	187	230	61	134	77
70%	171	145	106	90	83	72	49	46	66	180	194	243	65	146	79
80%	179	151	122	95	89	78	54	51	81	196	204	262	71	155	82
90%	191	161	145	101	95	87	66	57	103	210	210	297	75	165	86
100%	216	197	185	141	106	100	82	83	163	256	239	351	87	193	105

Table 2.4-2. Median Current Conditions as Percent of Unimpaired Flow for Delta Inflow by Major Tributary

	January–June	July–December	Annual
Yolo Bypass	55	216	71
Sacramento at Freeport	64	128	84
San Joaquin at Vernalis	35	114	48
Eastside Tributaries	46	129	62

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 CCWD facility, for subsequent delivery to farms and cities in the San Joaquin Valley, southern California, and/or other areas outside the watershed (Kimmerer 2002a).

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). Along with these facilities, Reclamation directs the operation of the DCC to improve the transfer of water from the Sacramento River to the pumping plant (Reclamation 2009). 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), the California Aqueduct and also the Barker Slough Pumping Plant for export through the North Bay Aqueduct (Reclamation 2009). 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 (USDOI 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.

Habitat conditions in the Delta are driven by the rise and fall of the tides, which results in upstream and downstream movement of large volumes of water and produces flows and velocities that are generally much greater than what is associated with net flows. However, net flows also play a role in the ecosystem. Export operations combined with changes in channel geometry, gates, and barriers and have greatly altered the natural direction of net 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 River, San Joaquin River, and eastside tributaries westward toward San Francisco Bay. Currently, net flow is generally from the Sacramento River southward toward the export pumps, except during high flow events (Figure 2.4-3). 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.

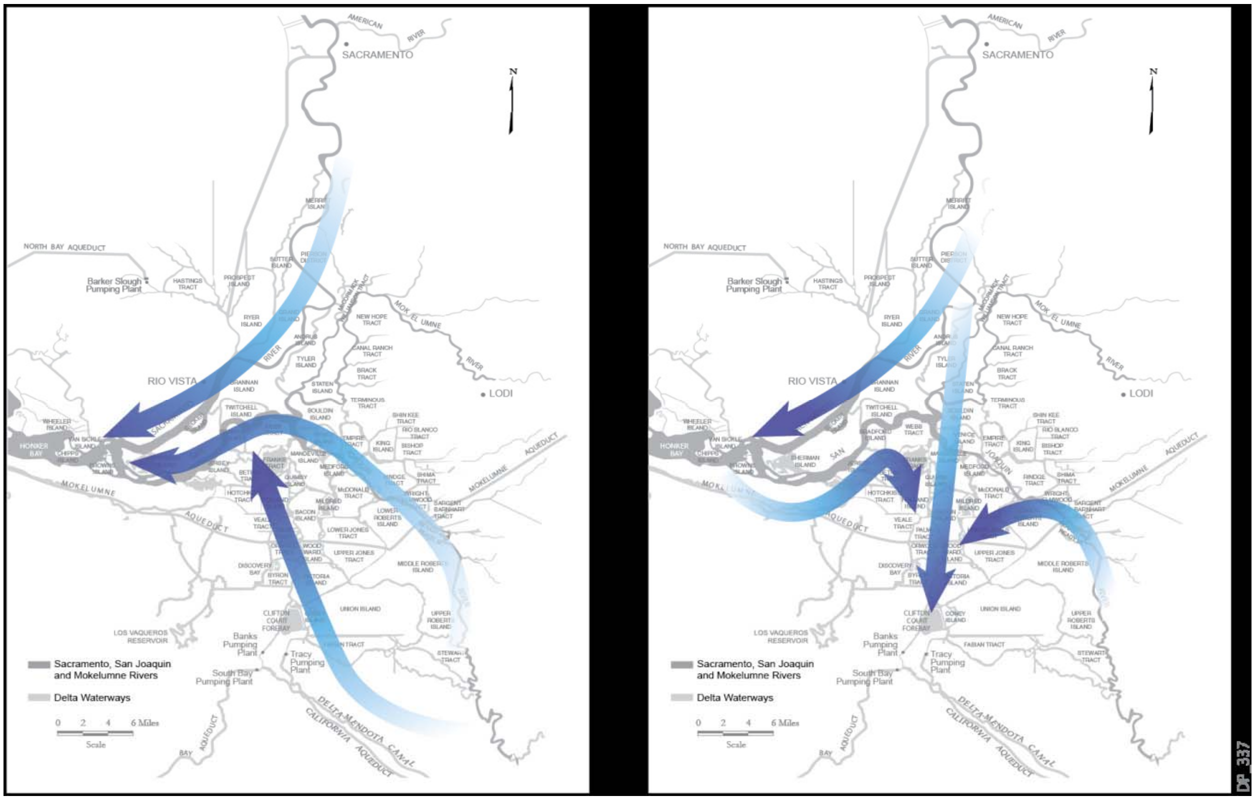


Figure 2.4-3. Flow Direction in the South Delta. The left panel depicts the tidally averaged flow direction in the absence of export pumping. The right panel depicts reversal of tidally averaged flows that occurs during times of high exports (pumping) and low inflows to the Delta (DSC 2012).

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 levels 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) near its confluence with Victoria and North Canals, 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 ORT, MR, and GLC. 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 2009a).

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 DO conditions in the Stockton Deep Water Ship Channel (DWSC) by increasing flow (NMFS 2012). The barrier is fitted with culverts to allow a minimum of approximately 500 cfs to flow into Old River. HORB is installed in mid-September, at the discretion of CDFW, and is completely removed by November 30. Throughout this period, the barrier is notched to allow 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 agricultural barriers reduces tidal exchange 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 HORB reduces net flows into Old River (NMFS 2012). There is evidence that the presence of the HORB magnifies negative OMR flows, thus increasing entrainment of Delta smelt (NMFS 2009b). This can occur when water that is blocked by the HORB from entering Old River proceeds down the San Joaquin River and then is drawn into Old and Middle Rivers toward the CVP and SWP diversion points.

Areas of null flows (flows with no net upstream or downstream motion) can occur in the interior sections of the south Delta channels. Null flows become more common when south Delta irrigation demands are high and inflow from the San Joaquin River is low (e.g., when HORB is in place). 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).

2.4.4 Delta Cross Channel Gate Operations

The DCC is a 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 (State Water Board 2010). Flows are controlled by gates that are normally kept open to maintain cross-Delta flows. The DCC gates are closed in the late summer and autumn, to facilitate salmon emigration (Monsen et al. 2007). The DCC significantly affects Delta hydrodynamics by sending Sacramento River water into Snodgrass Slough and the North Fork Mokelumne River and then to the interior Delta (Reclamation 2006). This diversion significantly improves water quality in the southern Delta and at the export pumps, but also increases the probability of entrainment of juvenile salmon migrating past its gates into the interior Delta, resulting in lower survival. When the gates are open, 40–50 percent of the Sacramento River flow enters the interior Delta via the DCC and Georgiana Slough. When the gates are closed, only 15–20 percent of the Sacramento River flow enters the interior Delta (Low et al. 2006). The gates are closed during migration periods to protect Chinook salmon and also at high flows to prevent flooding (Reclamation 2006). The effect of the DCC on fish is discussed in more detail in Section 3.4.5, *Flow Effects on Salmonids*.

Closure of the DCC gates alters the circulation in the north Delta by directing more Sacramento River water down its main stem and away from the central Delta. This closure results in less freshwater available to prevent salinity intrusion on the San Joaquin River stem of the Delta. While salinity will decrease at Emmaton on the Sacramento River, salinity will increase on the San Joaquin at Jersey Point (Monsen et al. 2007).

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 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 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 2.4-4). During 2010–2015, south Delta exports have been reduced by the implementation of the BiOps to protect endangered species (NMFS 2009a; USDOI 2008) and reduced available water for export due to drought conditions.

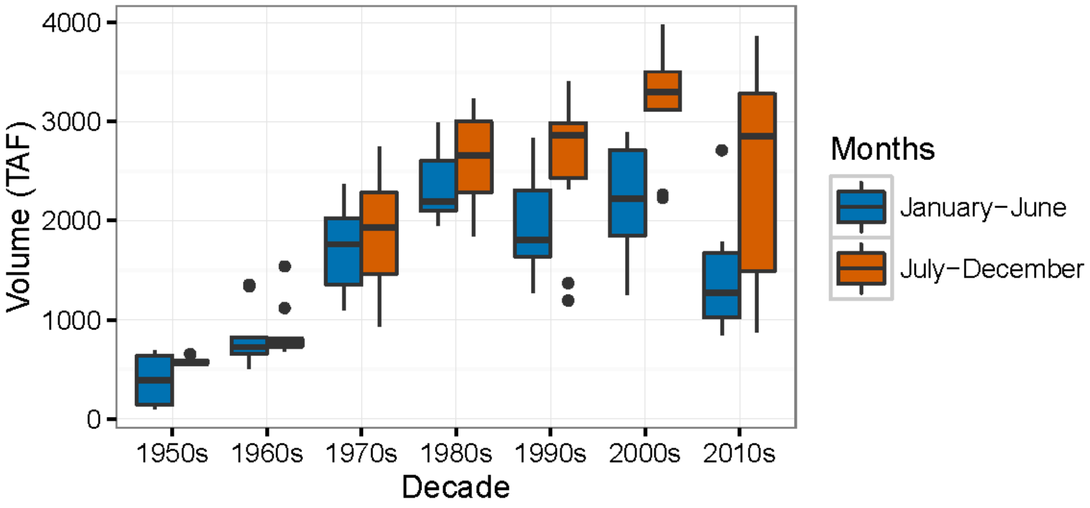


Figure 2.4-4. Total Seasonal SWP and CVP South Delta Exports by Decade (Source: Dayflow). The year shown on the x-axis represents the start year of the decade, for example "2000s" represents 2000–2009 and "2010s" represents 2010–2015.

The most prominent example of changes in net 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 2.4-5). 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 net reverse flows can at times be as great as 12,000 cfs flowing from the central Delta toward 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 2.4-5 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 percent of the time before modern water development (Figure 2.4-5, 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 2.4-5, Point B).

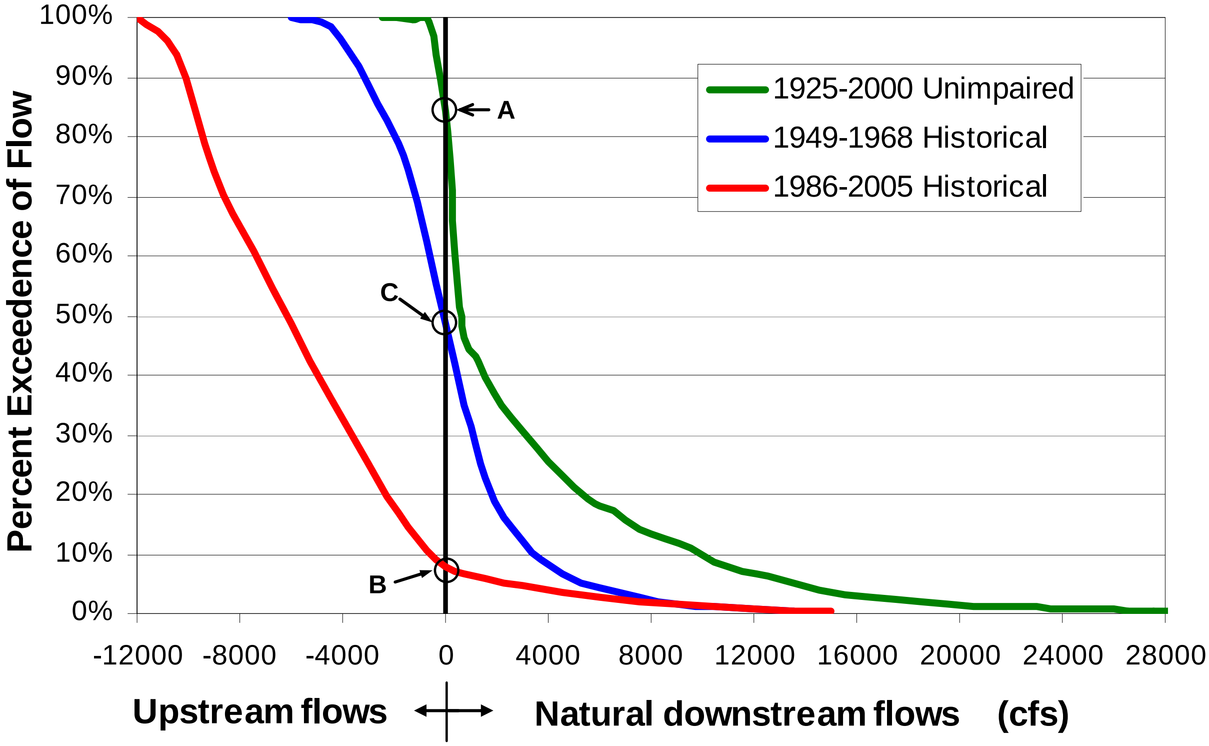


Figure 2.4-5. Cumulative Probability of OMR Flows from Fleenor et al. 2010

OMR 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 the public. The USGS measured net OMR flow has been criticized as being a poor compliance index and difficult to operate to because of 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 1-year demonstration project, which was later extended, to test the ability to manage OMR through a numerical index developed by Metropolitan Water District of Southern California. During the project duration, the SWP and CVP 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 (Reclamation 2014; NMFS 2014c).

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), with the lag being inversely dependent on the magnitude of Delta outflow.

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 closer to the ocean. Summer tidal flows can reach up to 340,000 cfs at the mouth of the estuary near Pittsburg and are weaker upstream on the Sacramento and San Joaquin Rivers (Figure 2.4-6). 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 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. During these times, measured salinity values can be used to estimate Delta outflow using historical relationships between salinity and outflow (Brown and Huber 2015; DWR 2016d). Discrepancies between salinity values and NDOI may be indicative of errors in the NDOI terms, particularly Delta consumptive use.

DWR, UC Davis, and others 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 LSZ (Medellín-Azuara et al. 2016). One of these new tools is 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 LSZ estimates when compared to newer estimates using DETAW (DWR 2016d). The future release of DETAW and other models will hopefully more accurately estimate Delta uses and improve estimates of Delta salinity, outflow, and hydrodynamics.

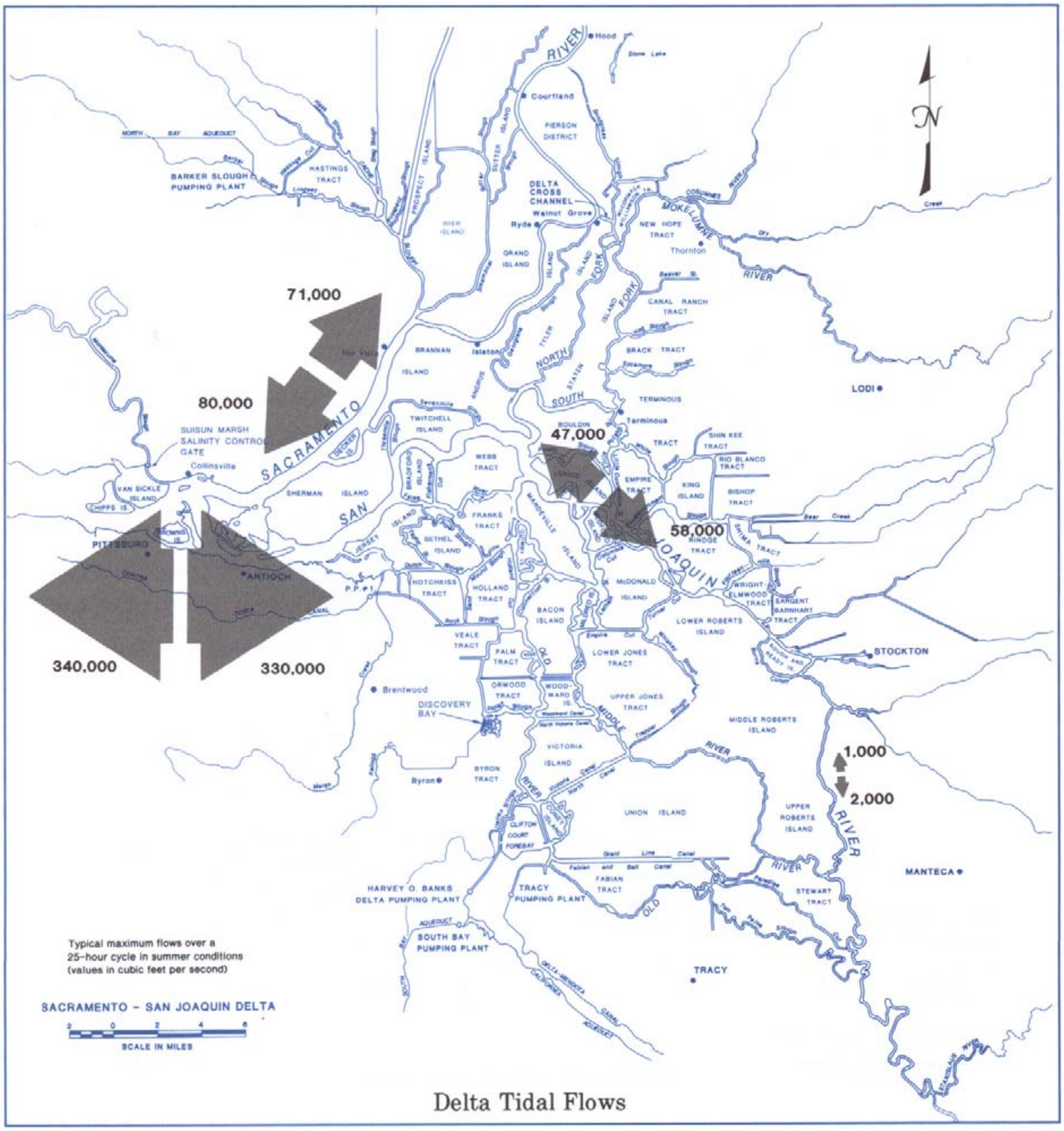


Figure 2.4-6. Delta Tidal Flows over a 25-Hour Cycle in Summer Conditions (values in cfs) (DWR 1995)

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 2016d). In the absence of measurement error or error in the estimates of the NDOI components, NDO and NDOI would be similar except for differences caused by the spring–neap tidal cycle, which causes the Delta to fill and drain over a 2-week period. At times of very low Delta outflow, the filling and draining of the Delta associated with the spring–neap tidal cycle can cause negative NDO. When NDO is very low, errors in the components of the Dayflow estimate of NDOI and the spring–neap filling and draining of the Delta can cause a relatively large discrepancy between NDOI and actual NDO (DWR 2012). The State Water Board recently conducted a peer review through the DSC's DSP of the above issues as summarized by DWR (2016d) to provide recommendations on improvements to Delta outflow estimates. The peer review report (Fleenor et al. 2016) was received in the fall of 2016, and will be used to inform the future implementation of regulatory requirements for Delta outflow.

The combined effects of water exports and upstream diversions have contributed to reduce the average annual net outflow from the Delta by 33 percent and 48 percent during the 1948–1968 and 1986–2005 periods, respectively, as compared to unimpaired conditions (Fleenor et al. 2010). Dayflow data also show a trend for decreasing Delta outflow through time. Since the 1990s, there has been a reduction in spring outflow and a reduction in the variability of Delta outflow throughout the year (Figure 2.4-8) due largely to the combined effects of exports, diversions, and variable hydrology.

SacWAM results for unimpaired and current conditions indicate the degree and variability of impairment of total Delta outflow by month (Table 2.4-3; Figure 2.4-7). The San Joaquin River watershed is not part of the SacWAM model. Instead, San Joaquin River inflow to the Delta is a model input. For the SacWAM simulation of unimpaired conditions, the Vernalis inflow values came from DWR as outlined in the fourth edition unimpaired flows report (DWR 2007c). For the SacWAM simulation of current, impaired conditions, the Vernalis inflow values were those simulated by CalSim II for the 2015 Delivery Capability Report (DWR 2015).

May and June show the largest impairment, where in 80 percent of those months Delta outflow is less than 44 percent and 46 percent of the unimpaired flow, respectively (Table 2.4-3). For simulated current conditions, Delta outflow is much lower in the spring and frequently higher in September compared with unimpaired Delta outflow, and variability is reduced in all months except September (Figure 2.4-7). Table 2.4-4 shows the contributing sources of unimpaired Delta outflow by season. The Sacramento River at Freeport contributes 61 percent of the outflow in the winter-spring, and 77 percent in the summer and fall. The other major annual average contributions to Delta outflow originate from the Feather, American, and San Joaquin River watersheds (25 percent, 9 percent, and 21 percent, respectively).

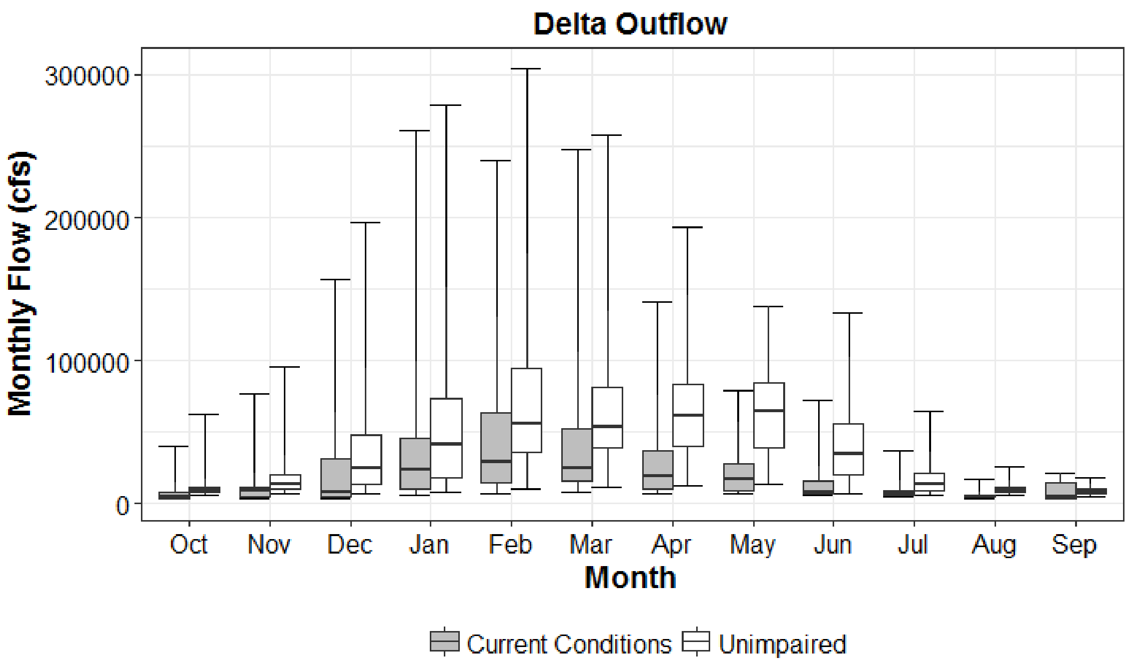


Figure 2.4-7. Delta Outflow Simulated Current Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.4-3. Cumulative Distribution of Current Conditions as Percent of Unimpaired Flow in Delta Outflow

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan–Jun	Jul–Dec	Annual Total
0%	27	27	26	34	34	28	20	16	17	28	36	31	28	38	32
10%	40	33	30	45	40	35	23	21	23	35	44	44	35	44	39
20%	45	40	34	50	43	38	26	24	25	39	47	45	38	49	40
30%	49	45	37	52	48	42	28	27	27	43	50	48	39	53	43
40%	52	52	45	56	52	43	33	29	29	47	52	55	42	55	45
50%	55	55	50	58	56	46	34	30	32	49	54	59	44	57	48
60%	61	62	52	63	60	52	37	34	36	55	57	103	50	60	53
70%	74	71	57	66	67	60	42	36	40	59	63	131	55	63	56
80%	86	85	62	71	77	66	50	44	46	65	67	144	61	67	62
90%	104	91	68	82	84	75	60	51	60	72	78	179	65	73	66
100%	122	107	98	122	95	96	77	62	102	108	98	237	80	92	78

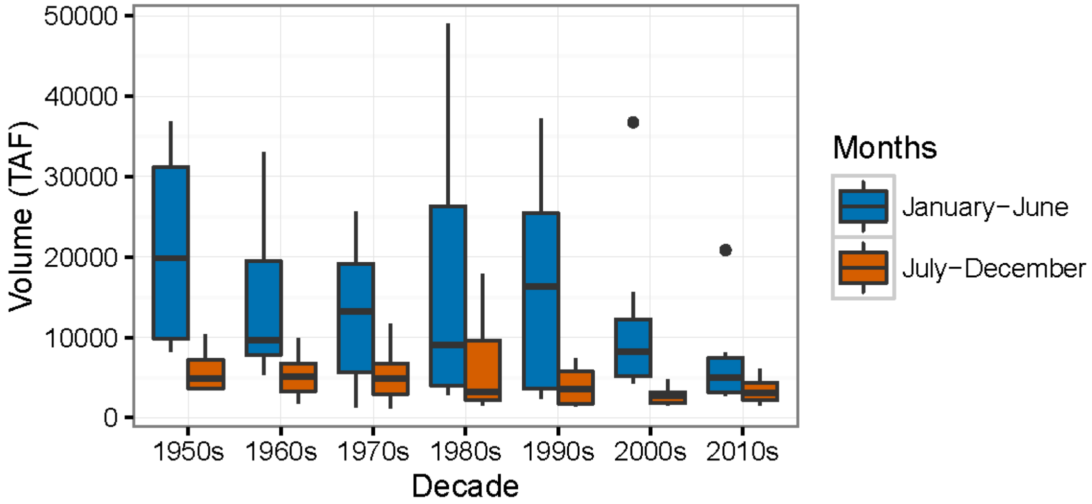


Figure 2.4-8. Seasonal Net Delta Outflow Index by Decade (Source: Dayflow). The year shown on the x-axis represents the start year of the decade, for example "2000s" represents 2000–2009 and "2010s" represents 2010–2015.

Table 2.4-4. Simulated Unimpaired Contributions to Total Delta Outflow from Various Locations in the Project Area (percent of Delta outflow)

Location	Jan–Jun	Jul–Dec	Annual Total
Sacramento River below Keswick	17.4	27.7	19.7
Sacramento River at Freeport	61.2	77.1	64.8
Cow Creek at Confluence with Sacramento River	1.5	1.6	1.5
Battle Creek at Confluence with Sacramento River	1	2	1.2
Butte Creek near Durham	1.4	1.5	1.4
Antelope Creek at Confluence with Sacramento River	0.4	0.5	0.4
Deer Creek	0.8	0.9	0.8
Mill Creek	0.7	1	0.8
Paynes Creek	0.2	0.2	0.2
Clear Creek	1.2	1.1	1.1
Big Chico Creek	0.4	0.4	0.4
Feather River at Confluence with Sacramento River	24.2	25.9	24.6
Feather River above Confluence with Yuba River	15.1	17	15.5
Yuba River	8.3	7.6	8.1
Bear River at Confluence with Feather River	1.3	1.4	1.3
American River at Confluence with Sacramento River	9.7	6.7	9.1
Mokelumne River above the confluence with Cosumnes	2.4	1.3	2.2
Cosumnes River at confluence with Mokelumne	1.7	1	1.5
Calaveras River	0.5	0.3	0.4
Stony Creek	1.5	1.1	1.4
Cottonwood Creek	2	1.6	1.9
Thomes Creek	0.9	0.8	0.9

Location	Jan–Jun	Jul–Dec	Annual Total
Elder Creek	0.2	0.2	0.2
Cache Creek	1.7	1	1.5
Putah Creek	1.2	0.8	1.1
Sutter Bypass Outflow	10.1	6.1	9.2
Yolo Bypass	9.6	5.1	8.6
San Joaquin River at Vernalis	22.7	15.9	21.2
Delta Outflow	100	100	100

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, especially at times when there is a large variability in daily outflow, the relationship between current 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 2.4-9.

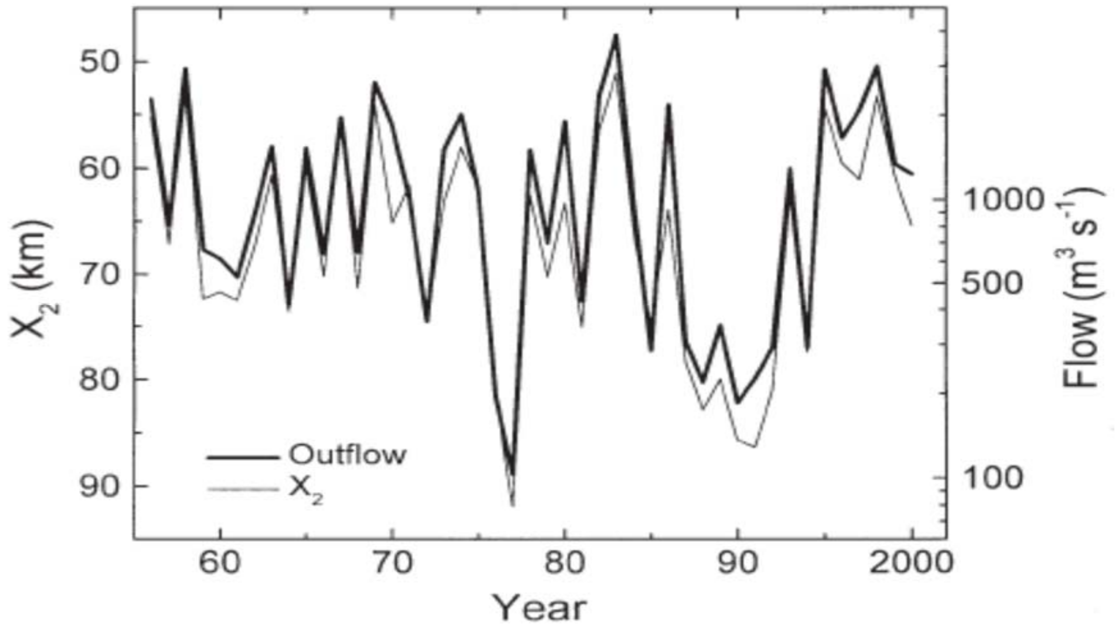


Figure 2.4-9. Time Series of X2 (thin line, left axis, scale reversed) and Outflow (heavy line, right axis, log scale), Annual Averages for January to June. Flow data from DWR; X2 calculated as in Jassby et al. (1995) (Source: Kimmerer 2002b, Figure 3).

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 2.4-10).

Figure 2.4-10 shows the cumulative probability distributions of simulated 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 LSZ 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 percent of the time, as opposed to unimpaired flows which were equally likely to place X2 upstream or downstream of the 71 km location (50 percent probability). (Fleenor et al. 2010.)

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

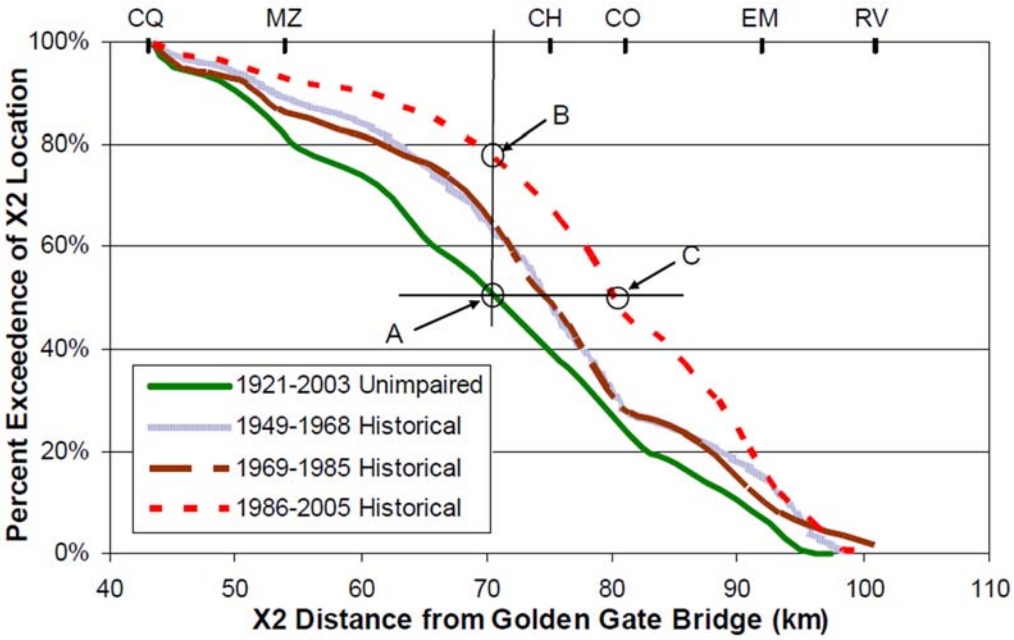


Figure 2.4-10. Cumulative Probability of Daily X2 Locations, from Fleenor et al. 2010

Hutton et al. (2015) estimated X2 position based on salinity measurements for 1922–2012. This analysis evaluated trends through time by month, as opposed to the analysis presented above that combined results for all months (Fleenor et al. 2010). As might be expected based on increases through time in the storage and release of water, analysis for the entire 91 years showed increases in X2 through time (i.e., more saltwater intrusion) during the period when water is most typically stored (November–June) and decreases in X2 (i.e., less saltwater intrusion) during dry months when water is typically released from storage (August and September). Comparison of X2 position during

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[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 2007c).

pre-Project water years (1922–1967) and post-Project water years (1968–2012) showed the largest monthly differences occurring during critical water years, when reservoir storage and release has a greater effect on hydrology. Figure 2.4-11 was produced from the Hutton et al. (2015) daily X2 position data and resembles Figure 2.4-10 in most salient features. The inclusion of the 1922–1945 highlights one of the problems that occurred in the watershed after the diking and draining of the Delta and the development but before the completion of upstream storage projects, including Shasta Reservoir. During dry months, and in particular during severe droughts, salinity intruded deep into the Delta, as shown in the red line in Figure 2.4-11. Such severe salinity intrusions were likely much rarer prior to the widening and deepening of Delta channels (Whipple et al. 2012). In the period since 1945, X2 positions have reduced in variability due in part to a greater ability to repel salinity during dry conditions, but have generally skewed upstream under all but the driest conditions, as shown in both Figures 2.4-10 and 2.4-11.

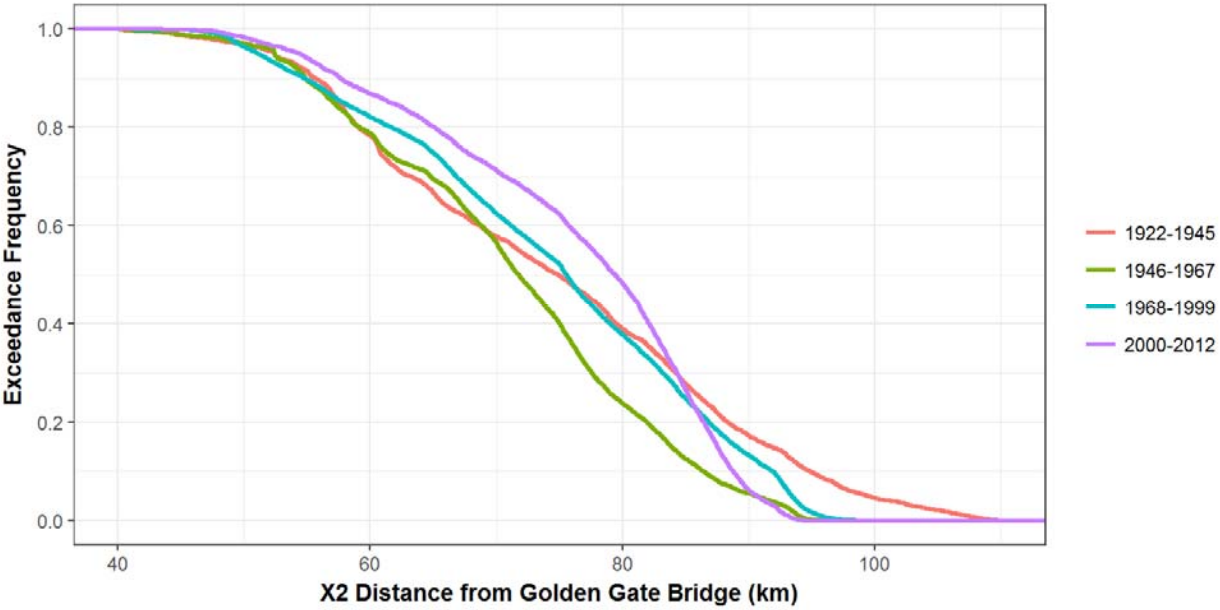

Figure 2.4-11. Exceedance Frequency Distribution of Daily X2 Positions. Data are divided into four historical periods: prior to the completion of Shasta Reservoir (1922–1945), prior to the completion of Oroville Reservoir (1946–1967), prior to the adoption of D-1641 (1968–1999), and following the adoption of D-1641 (2000–2012). Data shown are the Sacramento River daily X2 positions from Hutton et al. 2015.

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*). Work by USFWS (2011) has shown that, since 1967, fall X2 has increased and variability has decreased through time (Figure 2.4-12). This increase in fall X2 during project water years (1968–2012) was corroborated in work by Hutton et al. (2015) that showed increases in X2 during September–December. However, the Hutton et al. (2015) work showed that during pre-Project water years (1922–1967), there was a trend of decreasing X2 during August–December.

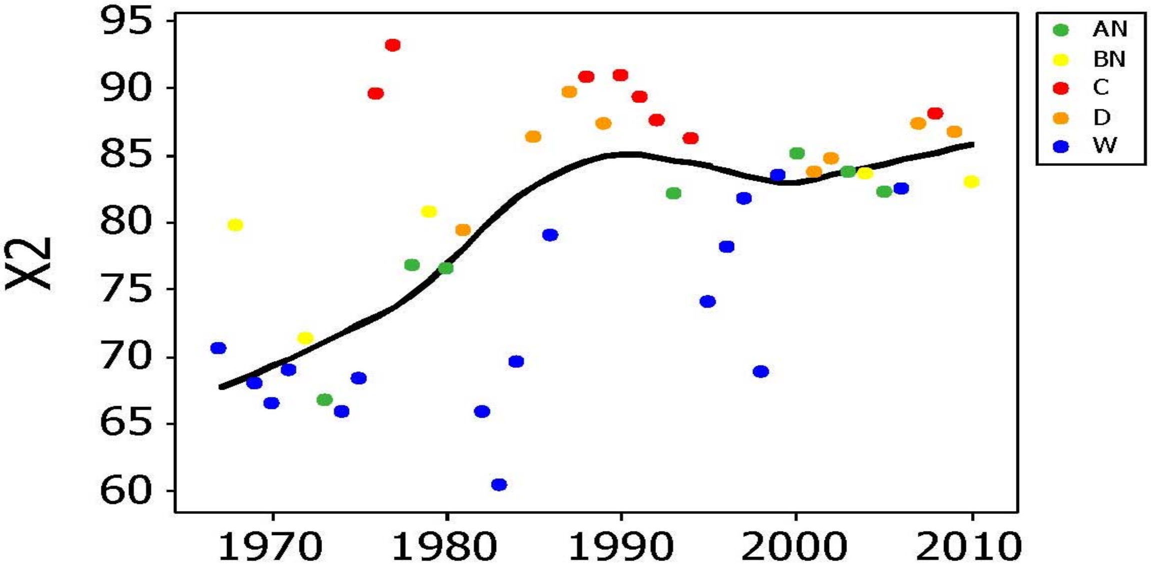

Figure 2.4-12. Time Series of Fall X2 since 1967. Water year types represent the preceding spring. A LOESS smooth is fitted to the data (USFWS 2011).

The Dayflow methodology is often used to estimate X2 based on outflow for operational and management decisions. Dayflow'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 2.4-13) (Mueller-Solger 2012). Various alternative approaches have been described for improving the method for calculating daily X2 (Monismith et al. 2002; Huber and Brown 2014; MacWilliams et al. 2015; Hutton et al. 2015; Rath et al. 2016).

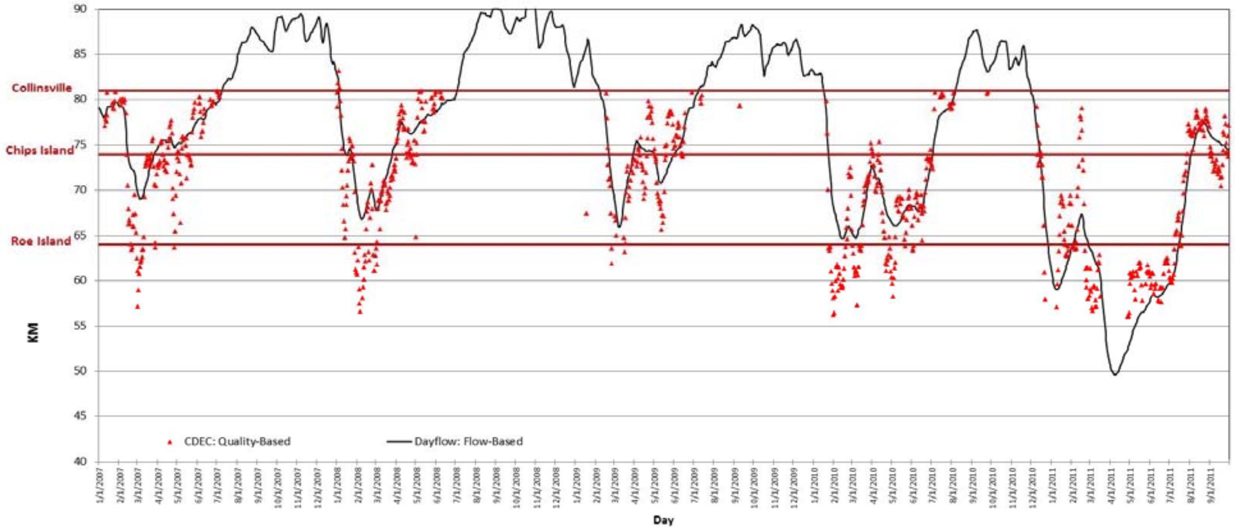

Figure 2.4-13. Dayflow, Flow-Based Estimation of X2, and CDEC Water-Quality Based X2 Values (Bourez 2012)

2.5 Suisun Region

Functionally, Suisun Marsh is similar to the larger Delta in having a delta (Green Valley Creek/Suisun Creek/Cordelia Slough) embedded within a tidal marsh. It differs because it lies between the 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 and EDAW 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 Water 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 San Francisco Bay Estuary and 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 cycling of the tides affects the tidal marsh ecosystem by flooding some areas only during the highest of the two daily high tides and some areas only during the period of the highest tides each month, affecting 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 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 3 very dry years in a row (2013–2015). Modeling data for the current drought period is included in the analysis throughout this chapter.

The recent drought period was severe; however, it is similar to previous droughts throughout the 94-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 1987–1992 and 1929–1934 droughts (Table 2.6-1). The 1976–1977 drought was short and severe even when compared with 2014–2015, which were the driest 2 years of the recent drought.

Table 2.6-1. Sacramento Valley Unimpaired Runoff

Period (Water Years)	Average Annual Runoff (MAF)
2012–2015	10.2
2014–2015	8.4
1987–1992	10.0
1976–1977	6.7
1929–1934	9.8

Source: DWR 2016b.

2.7 Climate Change

Many studies indicate that the next 94 years will likely be very different than the 94 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. Air and water temperatures will likely be higher and evapotranspiration will be greater. The amount of precipitation that falls as snow in the mountains will decrease, and sea level rise will likely affect salinity intrusion in the Delta. The potential effects of climate change are discussed in more detail in Chapter 4, *Other Aquatic Ecosystem Stressors*, in Section 4.6, *Climate Change*.

2.8 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 January–June. These differences are largest for non-Project tributaries such as the Mokelumne River, Putah Creek, and Cache Creek, where flows are less than 23 percent, 13 percent, and 53 percent 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, and the Feather and American Rivers are below 20 percent, 31 percent, and 40 percent of unimpaired flow in 10 percent 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 Delta outflow under current conditions is less than 44 percent of unimpaired Delta outflow during January–June in half of the years, with the greatest impairment generally occurring during April–June. In contrast to the reduced saline intrusion during the summer, these reductions in outflow during January–June are associated with an increase in X2 and salinity intrusion.

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 Chapter 1, 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 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 associated with 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.
- 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 2002a; 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). Richter et al. (2011) concluded that "alterations greater than 20 percent will likely result in moderate to major changes in natural structure and ecosystem functions, with greater risk associated with greater levels of alteration in daily flow." Studies of river-delta-estuary ecosystems in Europe and Asia concluded 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). Upstream diversions and water exports in the Delta have reduced median January to June and average annual outflow by 56 and 48 percent, respectively (Chapter 2; Fleenor et al. 2010).

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 nonnative species (Feyrer and Healey 2003; Brown and May 2006; Brown and Michniuk 2007; Brown and Bauer 2009; Mahardja et al. 2017). Within the watershed, the regions of greatest flow alteration are the most dominated by nonnative species (Brown and May 2006; Brown and Michniuk 2007), where the altered hydrology likely creates conditions more favorable for spawning and rearing of nonnatives than natives (Brown and Bauer 2009). Implementation of a more natural flow regime with high spring flows has been shown to favor native over nonnative species in Putah Creek, although nonnatives 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 2014a). 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 2014a).

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; Lindley et al. 2007). 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-2000s, poor ocean conditions caused a collapse in nearshore 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).

A more natural flow regime is anticipated to maintain, and perhaps even enhance the remaining genetic and life-history diversity of natural stocks (Zeug et al. 2014; Sturrock et al. 2015). Preserving the genetic and life-history diversity in wild stocks helps protect salmon populations from significant loss of genetic diversity associated with hatchery production. Historically, hatchery production of fall-run Chinook salmon has resulted in artificial selection of traits that has likely led to reduced genetic diversity and fitness of wild populations due to interbreeding of hatchery salmon with wild fish (California Hatchery Scientific Review Group 2012). The increasing dominance of hatchery fish within the Central Valley coupled with substantial straying rates has likely magnified the genetic and ecological risks of hatchery production on genetic diversity and viability of wild populations (Nehlsen et al. 1991; Lindley et al. 2007; California Hatchery Scientific Review Group 2012). As discussed in Chapter 4, complementary actions that improve hatchery management and restore habitat could also help reduce these risks.

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 1997). 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 2009a). Juvenile salmonids emigrate during periods of increased turbidity that originally arose 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). Reservoir construction has reduced turbidity by capturing the majority of flow and associated sediment (Schoellhamer et al. 2016).

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 nearshore ocean during periods that are beneficial for aquatic organisms who have adapted to this system (Kondolf et al. 2006; Poff et al. 2007; TBI 2016). 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). On the Sacramento River, 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 2014a). 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 et al. 2001).

Temperature control devices (TCD) 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 2009a). See Sections 3.4.4 and 3.5.4 for more discussion on managing cold water habitat below reservoirs.

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 (62° to 68°F) during salmonid rearing periods may also promote optimal growth provided food availability is not a limiting factor (Myrick and Cech 2004). 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 2002a; 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. 2009a), 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 reduced habitat availability and 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" (State Water Board 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 a dynamic gradient between freshwater and saline waters in the estuary; however, these accounts generally indicate that freshwater predominated in the Delta during the early 1800s with a transition from saline to freshwater in upstream portions of Suisun Bay (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 LSZ (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 LSZ 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 LSZ 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 LSZ may continue to shift dramatically in coming years (Knowles and Cayan 2002, 2004).

In the Bay-Delta estuary, the LSZ is an important nursery habitat for several estuarine-dependent fish species (Kimmerer 2002a; Moyle 2002), and is maximized in area and volume in Suisun or San Pablo Bays (Kimmerer et al. 2013) (Figure 3.2-1). The intersection of freshwater and saltwater 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; Kimmerer 2002b; MacNally et al. 2010). 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 shown downward step changes in response following the 1987 spread of the invasive clam *Potamocorbula*;[1] however, other relationships have not changed through the period (bay shrimp, Sacramento splittail) (Kimmerer 2002b; Kimmerer et al. 2009). Most of the flow-abundance relationships 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.

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[1] *Potamocorbula amurensis* (e.g., Crauder et al. 2016) was previously identified as *Corbula amurensis*, and is often referred to as such in the literature. *Potamocorbula* is used throughout in this document.

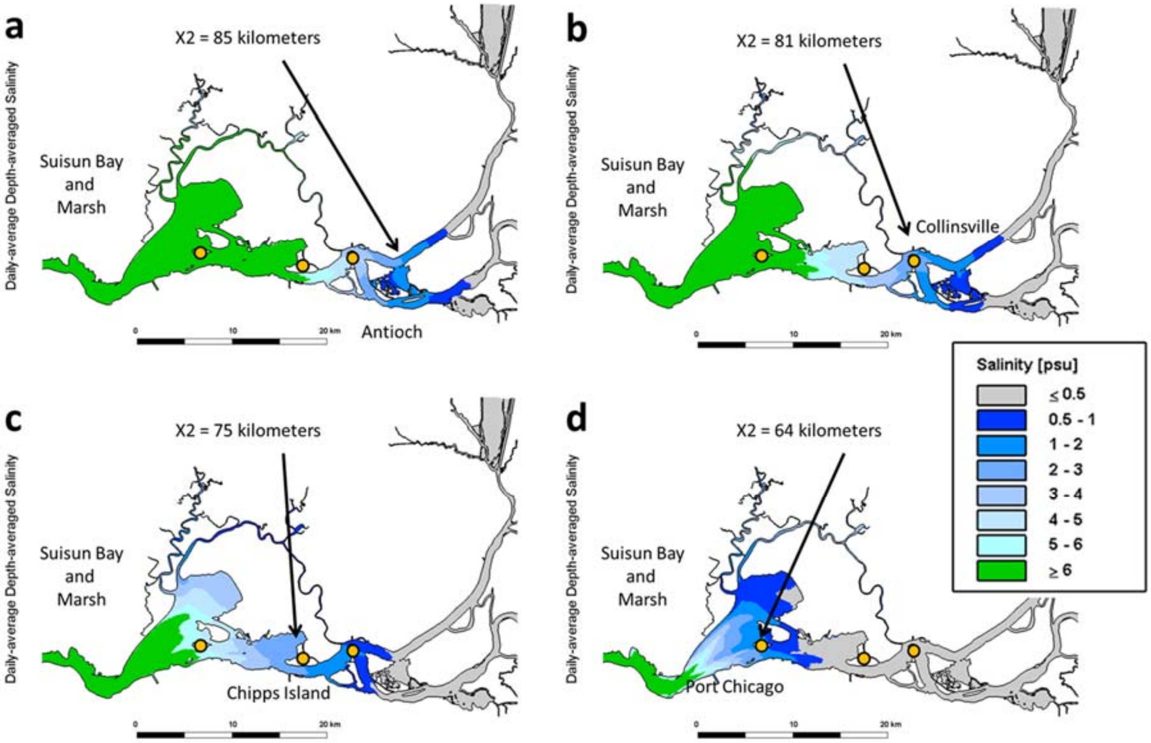

Figure 3.2-1. Variation in the Position and Extent of Low Salinity Habitat as a Function of X2. When X2 is near Antioch (a), low salinity habitat is confined to the deep channels of the western Delta. As X2 moves downstream of Collinsville (b), low salinity habitat enters Suisun Bay. With X2 near Chipps Island (c) or Port Chicago (d), low salinity and freshwater habitat occupy the broad shallows of Suisun Bay. Very high outflows can freshen Suisun Bay and push the low salinity zone into San Pablo Bay (not pictured). Figure modified from illustrations by Delta Modeling Associates 2014.

As discussed in more detail below, the specific mechanisms underlying the flow-abundance relationships are generally not resolved (Kimmerer 2002b). 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 2004; 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; Feyrer et al. 2006), improved growth for salmon smolts (Sommer et al. 2001, 2005), including endangered winter-run Chinook salmon (Del Rosario et al. 2013), increased turbidity downstream, and mobilization of sediment and food to downstream habitats (Schemel et al. 2004).

Increased turbidity associated with high flows trigger movement of Delta smelt into the Delta (Bennett and Burau 2016) and emigration 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. Under appropriate salinity and turbidity conditions, Delta smelt are found most frequently in samples from the shoals of these bays, rather than nearby channels (Bever et al. 2016). More broadly, turbidity (or its inverse, water clarity) has been identified as a significant covariate in statistical analyses of abundance and declines of several pelagic species, including Delta smelt and longfin smelt (Feyrer et al. 2007; Nobriga et al. 2008; MacNally et al. 2010; Thomson et al. 2010; Latour 2016). Multiple mechanisms may be responsible for these relationships, including effects on habitat suitability, catchability by trawl gear, and correlations with other environmental factors.

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 2002b). 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). 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 riprapped levees lining the Delta, and so longfin smelt have much greater spawning habitat when those bays are fresh.

Because the LSZ 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 LSZ. Changes in the area of the LSZ at different X2 values are inadequate to explain the fish-X2 relationships (Kimmerer et al. 2009, 2013). The position of the LSZ combines with the bathymetry at each location to provide different depths and areas of the LSZ (MacWilliams et al. 2015). If the LSZ 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 LSZ varies between 50 and 100 square kilometers with a significant decline since 1980 in the area of the LSZ 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; Baxter et al. 2015). When the LSZ 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 LSZ 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 BiOp (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 saltwater 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 San Francisco Bay and Nearshore Coastal Ocean

Delta outflow also affects biological resources in San Francisco Bay and the nearshore coastal ocean. Young salmon migrate on currents driven by Delta outflows to the ocean. These fish are prey for birds and Orca whales in the Gulf of the Farallones (NMFS 2009a). The abundance, reproductive success, and mortality rate of Orca whales that migrate and specialize in feeding on salmon outside the Golden Gate have been impacted by the major salmon declines in recent years (Ford and Ellis 2006; Ford et al. 2010; Ward et al. 2009). Their populations are food limited by the availability of salmon prey, highlighting the importance of Delta outflow all the way to the top of the aquatic food chain. Similarly, declines in forage fish such as longfin smelt, bay shrimp, and mysid shrimp due to low Delta outflow pose food limitation threats to pelagic seabirds (Cury et al. 2011) and marine mammals (Ford and Ellis 2006; Ward et al. 2009; Ford et al. 2010). The abundances of staghorn sculpin, leopard sharks, and bay shrimp that reside and rear in the nearshore coast are also correlated with Delta outflow (TBI 2016), again highlighting the far-reaching effects of freshwater outflows on the coastal ecosystem. Finally, native oysters are better able to withstand the establishment of nonnative sessile invertebrates that compete for space and resources when higher freshwater flows lower salinity in the South Bay (Chang 2014). Increased Delta outflows provide higher water quality and habitat complexity, leading to positive effects on native fish species and food webs.

Delta outflow is also important for maintaining physical and chemical processes in San Francisco Bay and the nearshore coast. Freshwater flow through the Bay transforms into a plume of surface brackish water that travels out the Golden Gate in winter and spring. This plume transports nutrients into the Gulf of the Farallones National Marine Sanctuary (NMFS 2009a), promoting phytoplankton growth and contributing to food web productivity for invertebrates, fish, birds, and marine mammals (Hurst and Bruland 2008). Cold, nutrient rich water from the ocean enters the Bay on reverse bottom currents driven by freshwater outflow moving out the Bay into the ocean. Delta outflow influences 86 percent of the variability in salinity at the Golden Gate (Peterson et al. 1994). Freshwater flow also transports sediments to help beach formation along the coastline outside the Golden Gate (Barnard et al. 2013a, 2013b). Lack of sediments causes beach erosion which removes nesting habitat for birds such as snowy plovers (Tobias 2014). Sediment transport is higher in the Bay with greater freshwater flows. This helps improve the stability of wetlands. Higher sediment loads also increase turbidity which lowers the predation risk for native fish (Gregory 1993; Gregory and Levings 1998; Baxter et al. 2015). These examples indicate that the amount of freshwater flow impacts multiple trophic levels in San Francisco Bay and the nearshore environment, cascading up the food web to top predators like herons, seals, and whales.

3.2.4 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 toward 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 DCC 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 environmental cues to guide their migrations. In the ocean they may use magnetic, chemical, and celestial cues to return to their natal stream to spawn. Within estuaries and meandering Delta channels, adults returning to spawn primarily use chemical scents to identify water from their natal streams. Evidence exists that migrating juvenile salmonids may use hydraulic, celestial (e.g., sun position), magnetic, and chemical (e.g., salinity) cues to direct their downstream migrations and navigate through tidally dominated estuaries and bays (Williams 2006). Consequently, the greatly altered hydrology, migratory pathways, hydrodynamics, and salinity gradients of the Delta and estuary are considered stressors for successful spawning migration of adults and downstream migration of juveniles 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 Bay-Delta 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 DCC 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. 2009a). 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 2009a).

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 DMC) 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 (Castillo et al. 2012). 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 in response 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 DCC or Georgiana Slough and have a lower chance of survival than fish staying in the Sacramento River's main stem (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 ESA and CESA, species of commercial, recreational and ecological importance, and recommendations from CDFG (2010b) as part of the Delta Flow Criteria Report Proceeding. The species include all four runs 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 2016a) and San Francisco Bay Study (Bay Study) otter trawl (Hieb 2017) 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 2017). 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 (State Water Board 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 2002b; CDFG 2010b; State Water Board 2010). Staff performed analyses as follows:

1. Flow-abundance relationships: following the general methodology of Jassby et al. (1995) and Kimmerer (2002b), 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 (2002b), staff incremented abundance indices containing zero values for the purposes of this analysis and included one or more step changes for species that experienced a substantial decline immediately following the introduction of *Potamocorbula* or the pelagic organism decline. 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. Although distinct differences exist in certain aspects of their life histories and habitat needs (see Section 3.4.2.2), factors that benefit salmon are also expected to benefit steelhead based on their general ecological requirements. 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 run 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 2006 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 emigration. In addition, juvenile salmon emigrating from both the Sacramento and San Joaquin River basins through the Delta have better survival if they 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 emigration. 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, 5–6 million salmon may have returned annually to California waterways (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, 2001). The commercial and recreational catch from 1975–2014 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.

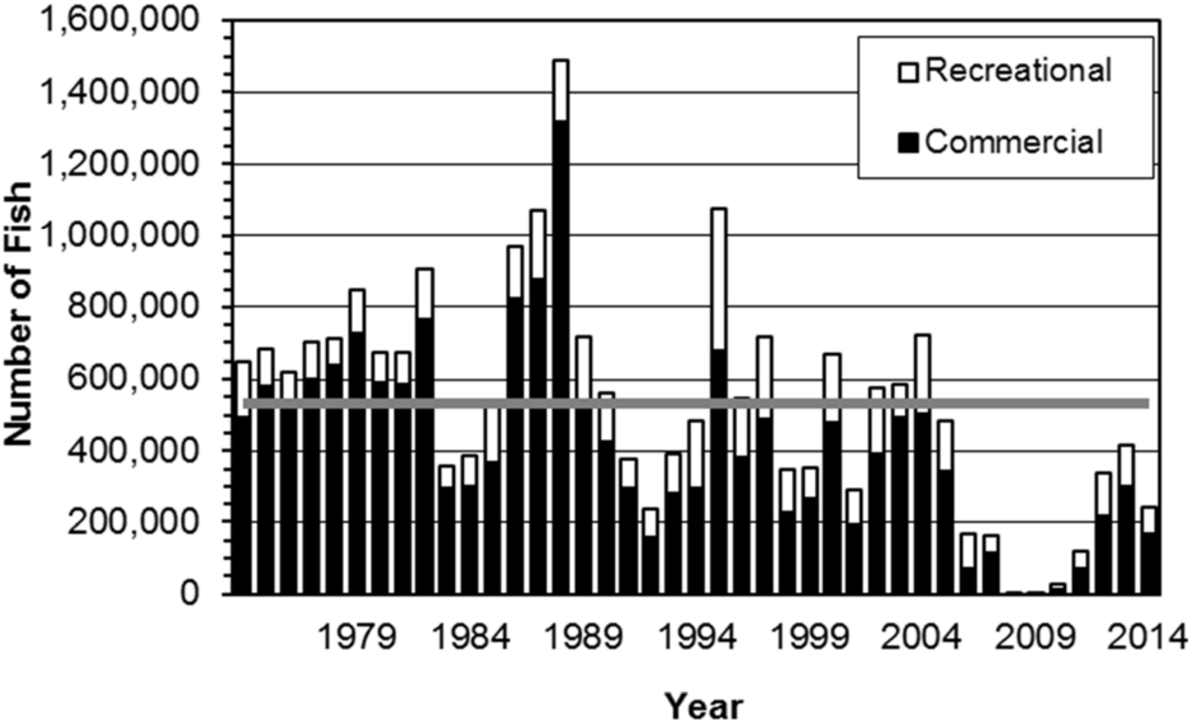

Figure 3.4-1. California Commercial and Recreational Chinook Salmon Ocean Catch, 1975 to 2014. The gray line shows the 40-year mean (from Azat 2015).

Four Chinook salmon runs are present in the Sacramento River main stem 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–mid Aug	May–Jun	July–Oct	5–10
Spring-run	Feb–Sept	May–Jun	Late Aug–Nov	Oct–Nov	Dec–Mar	12–16
Late-fall-run	Oct–Apr	Dec–Jan	Early Jan–Apr	Feb–Mar	Apr–Jun	7–13
Fall-run	Jun–Dec	Oct	Late Sep–Jan	Oct	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 (2014a).

Chinook salmon adults exhibit two general freshwater life history patterns characterized as “stream-type” and “ocean type” (Healey 1991). “Stream-type” adults enter freshwater several months before spawning and complete their maturation in their natal streams where they hold for several weeks to months before spawning. “Ocean type” Chinook salmon enter freshwater at maturity and migrate rapidly to their natal streams where they spawn shortly after arriving on the spawning grounds. Winter- and spring-run Chinook salmon exhibit a stream-type pattern as adults, migrating to upstream spawning areas where they hold for several months until sexually mature (Williams 2006). Late-fall-run Chinook exhibit a predominantly stream-type life history while fall-run Chinook exhibit a predominantly ocean-type life history.

Chinook salmon juveniles are also generally characterized as having ocean-type and stream-type life histories depending on the length of freshwater residence (Healey 1991). Central Valley Chinook salmon juveniles have a largely ocean-type life history but exhibit a broad range of juvenile life histories that differ with respect to duration of freshwater residence, habitat use, and size at which they migrate to the Delta and estuary (Williams 2012; Sturrock et al. 2015). This diversity ranges from fry that migrate rapidly to the Delta or estuary where they continue to rear before entering the ocean, to juveniles that remain and rear in their natal streams for up to a year before migrating rapidly to the ocean. Seasonal and inter annual differences in the timing of migration also reflect changing flow conditions (Sturrock et al. 2015; Del Rosario et al. 2013; Brandes and McLain 2001) with variability in flow contributing to higher survival indices and a larger proportion of juveniles migrating as pre-smolts (Zeug et al. 2014).

Generally, fall-run juveniles emigrate from their natal streams during the first few months following emergence with most migrating as fry to lower main stem rivers, Delta, or estuary in winter or early spring followed by emigration of larger juveniles later in the spring (Williams 2006). Late-fall-run juveniles typically rear in upstream spawning areas through the summer before emigrating as yearlings in the fall and winter (Williams 2006). Winter-run juveniles emigrate as fry from upstream spawning reaches in summer and early fall and apparently rear for up to several months in the Sacramento River, Delta, or estuary before migrating to the ocean in spring (Del Rosario et al. 2013). Most spring-run juveniles follow an ocean-type life history, beginning their downstream migration in winter as fry, although some rear for several months in their natal stream before emigrating later in the spring or in the following fall, winter, or spring (Williams 2006).

Adult salmon require suitable flows, water temperatures, and water quality to access their natal streams and reach the spawning grounds at the proper time and with sufficient energy reserves to complete their life cycles (Bjornn and Reiser 1991). Adult Chinook 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.

Suitable water temperatures for upstream migration of adult Chinook salmon generally range from 38° Fahrenheit (F) to 65°F (Bell 1991; Boles 1988; CDFG 1998). Boles (1988) recommended water temperatures below 65°F for adult salmon upstream migration in the Sacramento River. Suitable water temperatures for adult winter-run Chinook salmon migrating upstream to spawning grounds range from 57°F to 67°F (NMFS 1997). However, cooler water temperatures are required while holding and preparing to spawn; the maximum suitable water temperature reported for holding is 59°F to 60°F (NMFS 1997). High water temperatures and low DO levels can form barriers to adult salmon migration. In general, water temperatures above 70°F and DO levels below 5 milligrams per liter have been reported to block or cause delays in migration of Chinook salmon (Hallock et al. 1970; Richter and Kolmes 2005).

Female Chinook salmon select spawning sites with suitable water depths, velocities, and substrate sizes for redd (nest) construction and successful egg incubation (Bjornn and Reiser 1991; Quinn 2005). Preferred habitat is determined by the need for sufficient flow of oxygenated water through the interstitial spaces in the streambed to support the developing embryos. Body size also influences site selection; larger females can use sites with larger gravel and faster water (Quinn 2005). Chinook salmon have been reported to utilize a broad range of water depths and velocities for spawning. Water velocity in Chinook salmon spawning areas typically range from 1 to 5 feet deep with water velocities of 1–3.5 feet per second (USFWS 2003). The USFWS (2003) reported that winter-run prefer depths of 1.4–10 feet and velocities from 1.5–4.1 feet per second.

Optimal water temperatures for Chinook salmon egg incubation range from 41°F to 56°F (NMFS 2009a). A significant reduction in egg viability occurs above 57.5°F and total mortality can occur at temperatures above 62°F (NMFS 2014a); the lower and upper thermal range causing 50 percent pre-hatch mortality is 37°F and 61°F, respectively. The U.S. Environmental Protection Agency (USEPA) recommends that water temperatures (measured as maximum 7-day average of the daily maximums [7DADM]) for salmon and trout spawning, egg incubation, and fry emergence not exceed 55.4°F (USEPA 2003). This is generally consistent with laboratory-based studies of thermal tolerance of Chinook salmon embryos; however, oxygen limitation has also shown to be a strong determinant of thermal tolerance in the field. In a recent study, application of a thermal tolerance model based on laboratory data failed to predict the effects of temperature on survival of winter-run Chinook salmon in the Sacramento River (field-derived estimates of egg-to-fry survival). The results suggested an approximately 3°C (5.4°F) reduction in thermal tolerance in the field compared to the lab that was attributed to egg size and differences in water flow velocities that affected the ability of embryos to obtain sufficient oxygen to meet demands (Martin et al. 2016).

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 40–60 days. Alevins remain in the gravel for an additional 4–6 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 terrestrial invertebrates, zooplankton, and aquatic invertebrates (Sommer et al. 2001). 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 (Williams 2006, 2012; Sturrock et al. 2015).

When juvenile Chinook salmon reach a length of 5–6 centimeters (cm) 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 CDFG 2010a). 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 emigration 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 miles 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.

Smolting is the physiological process that increases salinity tolerance and enables salmonids to transition from freshwater to saltwater. Smolting usually starts when juveniles are 7–10 cm in length (CDFG 2010a); consequently, juveniles may begin this process in their natal streams, in the Delta or estuary, or during transit from their natal streams. Environmental factors such as increased stream flow and changes in water temperature and photoperiod can also affect the onset of smolting (Rich and Loudermilk 1991; Quinn 2005). After smolting begins, salmon often rear further downstream where ambient salinities are higher like Suisun Bay or the coastal ocean (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 and substantial variation in emigration timing from year to year depending on hydrologic conditions (e.g., drought conditions) and the timing of major storm events (Kjelson et al. 1982; Williams 2006; del Rosario et al. 2013). For example, early peak movements of winter-run Chinook salmon juveniles past Knights Landing are triggered by the first major flow events of the season (15,000 cfs at Wilkins Slough) which typically occur from late November through February (del Rosario et al. 2013).

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

Source: NMFS 2009 RPA with 2011 amendments.

RPA = Reasonable and Prudent Alternative.

[1] Midwater trawl data.

[2] All runs combined.

[3] Rotary screw trap data from Knights Landing.

Rearing by juvenile Chinook salmon in the Bay-Delta appears to be an important life history component based on otolith microchemistry analysis and broad evidence from other estuaries (Reimers 1973; Healey 1980; Kjelson et al. 1982; Lott 2004; Miller et al. 2010; Sturrock et al. 2015). Peak migrations and estuarine abundance of fry in the Bay-Delta correlated with flow magnitude, with peak abundance and downstream extent of fry being highest following major runoff events

(Kjelson et al. 1982; Brandes and McLain 2001). Rearing juveniles are known to occupy shallow water around the margins of estuaries, utilizing tidal currents to move in and out of wetland and marsh habitats where they benefit from access to shallow water, protective cover, and abundant food resources (McDonald 1960; Dunford 1975; Healey 1980; Levy and Northcote 1981; Healey 1991, Hering et al. 2010). In the Bay-Delta, Kjelson et al. (1982) reported evidence of diel movements of fry from shallow water areas near the shoreline during daylight to offshore areas at night, and a general increase in the size of juvenile salmon with increasing distance from the shore. Cladocerans, copepods, amphipods, and dipterans are common prey items in the Delta and estuary (Kjelson et al. 1982; Sommer et al. 2001; MacFarland and Norton 2002).

Migration timing, residence times, and habitat use by juvenile Central Valley Chinook salmon are highly variable as reflected by the diversity of life history patterns summarized above (Williams 2006, 2012). Mark-recapture data suggest that juvenile fall-run can enter the Delta as fry and rear for up to 2 months (Kjelson et al. 1982), while comparison of catch data for winter-run entering (Knight Landing) and leaving the Delta (Chipps Island) indicate residence times ranging from 40 to over 110 days and averaging 87 days (del Rosario et al. 2013). Following their initial downstream movements, young Chinook salmon may also rear for some time in non-natal tributaries, flood bypasses (Sutter and Yolo Bypasses), and remnant floodplains depending on the timing and duration of their connection with the river (Maslin et al. 1997, 1998, 1999; Sommer et. 2005; del Rosario et al. 2013). Later in the migration season (or subsequent migration season for yearlings in natal streams), larger sub-yearling or yearling juveniles (smolts) appear to migrate rapidly to the ocean (Williams 2012). MacFarlane and Norton (2002) presented evidence of rapid migration and minimal growth of fall-run juveniles traversing the estuary (downstream of Chipps Island), suggesting little estuarine dependency and rapid ocean entry. These results appear to be applicable primarily to large, actively migrating juveniles (including hatchery juveniles) and not to earlier fry migrants that have been shown to exhibit extended Delta and estuarine rearing and make significant contributions to adult production, especially in wet years (Brandes and McLain 2001; Williams 2012; Sturrock et al. 2015).

Studies of the thermal requirements of Central Valley Chinook salmon indicate that optimal temperatures for growth are achieved at 62.6–68.0°F, provided that food is not limiting, and other factors, such as disease, predation, and competition, have minimal effect (Myrick and Cech 2004). American River fall-run Chinook salmon achieved maximum growth at a constant temperature of 66.2°F under maximum ration and oxygen saturation levels (Myrick and Cech 2001). In another study, Myrick and Cech (2001) demonstrated that Sacramento River fall-run Chinook salmon, fed at levels reported for juvenile salmonids in the field, survived and grew at temperatures up to 75.2°F. However, juveniles reared at 69.8–75.2°F experienced significantly decreased growth rates, impaired smoltification indices, and increased predation vulnerability compared with juveniles reared at 55.4–60.8°F.

3.4.2.2 Central Valley Steelhead

Central Valley steelhead (*O. mykiss*)[2] were once widely distributed in the Sacramento and San Joaquin River systems, migrating to spawning and rearing areas primarily in intermediate to upper-elevation Sierra Nevada and Cascade streams (Quinn 2005; Yoshiyama et al. 2001). However, most of their historical spawning and rearing habitat is now blocked by dams, restricting anadromous populations to downstream reaches where habitat conditions have been highly modified by regulated flows and

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[2] Central Valley steelhead are recognized as a member of the subspecies *O. mykiss irideus* (Moyle 2002).

other abiotic and biotic stressors (McEwan 2001; NMFS 2014a). Genetic studies have revealed that Central Valley steelhead populations generally lack the strong geographic patterns of genetic differentiation that have been found in other California *O. mykiss* populations (e.g., northern California steelhead DPS) (Nielsen et al. 2005; Pearse and Garza 2015). Pearse and Garza (2015) found that Central Valley populations above and below barrier dams are not closely related and that the relationships between below-barrier populations do not fit a pattern of isolation-by-distance. These results likely reflect more than a century of habitat modification and hatchery and stocking practices, including the use of out-of-basin sources to supplement hatchery production (Pearse and Garza 2015).

O. mykiss display highly complex and diverse life histories, including both resident and anadromous forms (steelhead). Central Valley steelhead may exhibit either an anadromous or resident life history, including the capacity for resident adults to produce anadromous offspring and anadromous adults to produce resident offspring (Zimmerman et al. 2008). In addition, steelhead exhibit great variability in age at emigration and age at return and, unlike salmon, are capable of spawning more than once during their lifetime. These highly variable life history patterns reflect adaptation to local environments that can be explained by a complex interaction of genetic and environmental factors that determine the developmental pathway of individual fish (smolt transformation, maturation) based on condition, growth, and size (Satterthwaite et al. 2009, 2010). Because of blocked access to historic spawning habitat and highly altered conditions below dams, the life histories of Central Valley steelhead may have already diverged substantially from their historic patterns and now include a greater proportion of fish with a freshwater resident life history (Lindley et al. 2007; McClure et al. 2008).

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).

Peak spawning generally occurs between January and March in both the Sacramento and San Joaquin River watersheds (Hallock et al. 1961; McEwan 2001). Like Chinook salmon, redd site selection is a function of body size; steelhead are generally reported to use water depths ranging from 6 to 36 inches, water velocities ranging from 1 to 3.6 feet per second, and substrates ranging from 0.2 to 4 inches (Bjornn and Reiser 1991; McEwan 2001). The time required for egg development is approximately 4 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 4–6 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 Sommer 2008; Weber 2009; Kammerer and Heppell 2012).

Juvenile steelhead migrate to the ocean after spending 1–2 years in freshwater (McEwan and Jackson 1996). Steelhead migrants from the Sacramento River watershed are caught in the Knights Landing rotary screw traps from November–March with peak catches in February and March (Table 3.4-2). San Joaquin River steelhead migrate downstream between late December and July with a peak in March and April (USDOI 2008). Juvenile steelhead salvaged at the state and federal pumping facilities indicate that most steelhead are moving through the Delta from November–June, with a peak emigration period between February and May (NMFS 2009b).

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 CVP, particularly for the protection, restoration and enhancement of fish and wildlife. The CVPIA established the Anadromous Fish Restoration Program (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 indicates significant declines in the natural production of Sacramento River winter-run, spring-run, and late-fall-run, and San Joaquin fall-run notwithstanding the population abundance goals, although uncertainties associated with estimation methods can make estimating natural production challenging (Cummins et al. 2008). Comparable estimates are not available for steelhead because of limited baseline and post-baseline monitoring data (see Section 3.4.3.6). The best long-term data set are counts of adults passing through the fish ladder at Red Bluff Diversion Dam; however, changes in dam operations in 1994 precluded the collection of comparable post-baseline monitoring data (NMFS 2016a).

Table 3.4-3. Summary of the Natural Production of All Four Runs of Chinook Salmon in the Sacramento and San Joaquin River Basins during the Central Valley Project Improvement Act (CVPIA) Baseline Period of 1967–1991 and 1992–2015

	Natural Production Annual Average Baseline (1967–1991) Period	Natural Production Annual Average for 1992–2015 Period	Change in Average Natural Production between 1967–1991 and 1992–2015
Sacramento winter-run	54,439	6,090	-89%
Sacramento spring-run	34,374	13,385	-61%
Sacramento late-fall-run	33,941	16,175	-52%
Sacramento fall-run (main stem)	115,371	65,791	-43%
San Joaquin fall-run[1]	38,388	17,453	-55%

Data Source: Table 4 in USDOI (2016).

[1] Stanislaus, Tuolumne, and Merced Rivers.

3.4.3.2 Winter-Run Chinook Salmon

Application of genetic stock identification techniques to Chinook salmon sampled in the California recreational ocean salmon fishery during 1998–2002 indicate that winter-run Chinook salmon occur largely in central California coastal waters between Point Reyes and Monterey before migrating inland to spawn (Satterthwaite et al. 2015). 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 freshwater (Moyle 2002). Immature adults must hold in freshwater for several months before they are capable of reproducing. Winter-run are unique because they complete sexual development and spawn during summer when air temperature in the Central Valley approaches an annual maximum. Since the construction of Shasta and Keswick Dams, winter-run have been blocked from reaching their native spawning grounds in the upper Sacramento River, including the Pit, McCloud, Fall, and Little Sacramento Rivers (Yoshiyama et al. 1998). Consequently, spawning is now restricted to between Keswick Dam and the Red Bluff Diversion Dam (RBDD) where releases of cold water from Shasta Dam are used to maintain suitable water temperatures for spawning and incubation (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 2009a). Maintaining cold water in the Sacramento River below Keswick Reservoir can also benefit 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 2014a). Emigration begins as early as mid-July with most emigrants passing the RBDD in September and October (Vogel and Marine 1991; NMFS 2009a). Rearing occurs in the Delta and in the Sacramento River below the RBDD November–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 5–10 months before smolting and emigration to the ocean. Marine emigration usually begins in the fall and continues through the spring with outbound smolts passing inbound spawners (Moyle 2002).

The Sacramento River winter-run Chinook salmon population includes hatchery production from Livingston Stone National Fish Hatchery (LSNFH) located downstream of Shasta Dam (NMFS 2014a). Hatchery fish are marked with a coded wire tag (CWT) and a clipped adipose fin to allow fishery managers to differentiate between native and hatchery produced fish. The LSNFH releases between about 30,000 and 250,000 pre-smolts[3] annually each winter (NMFS 2014a). In 2014 and 2015, juvenile winter-run production at LSNFH was increased to mitigate for the effects of prolonged drought conditions (elevated water temperatures) on naturally spawning winter-run Chinook salmon in the Sacramento River. Increased hatchery production resulted in the release of 612,000 juveniles in 2014 and 420,000 juveniles in 2015 (NMFS 2016b, 2016c). Since the beginning of hatchery production at LSNFH in 1997, the proportion of hatchery origin winter-run Chinook salmon spawning in the river has increased. Prior to 2005, the proportion of in-river hatchery-origin spawners was between 5 percent and 10 percent. However, the average over the last 12 years was approximately 13 percent (with peaks of approximately 20 percent in 2005, 30 percent in 2012, and 23 percent in 2014), raising concerns about potential negative effects on the genetic integrity of the run (NMFS 2016b).

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

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). 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 89 percent less in 1992–2015 than in 1967–1991 (Table 3.4-3).

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 CESA in 1989.

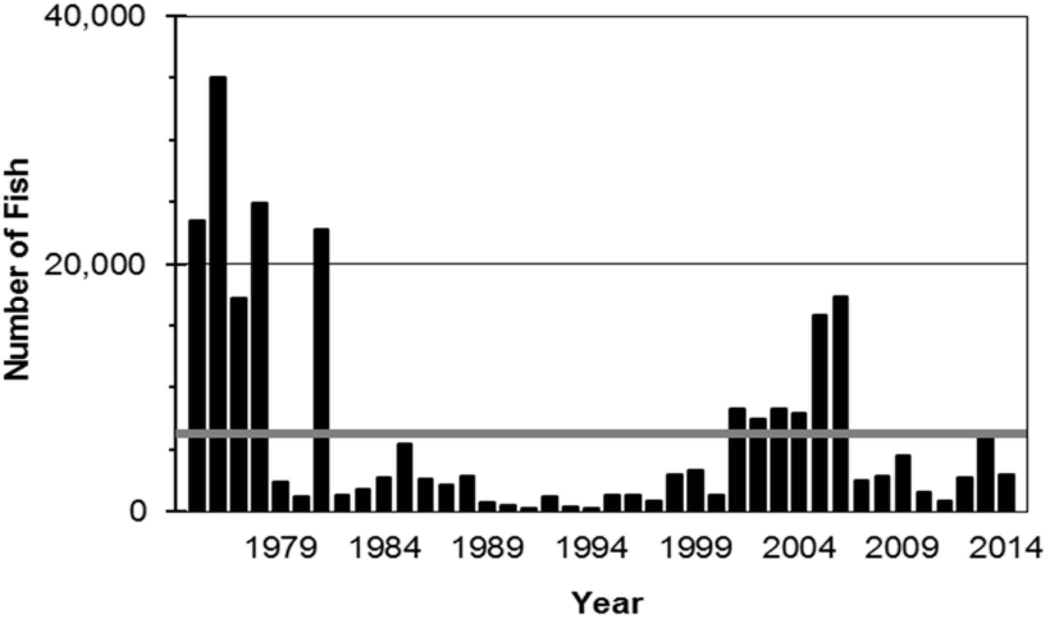

Figure 3.4-2. Annual Winter-Run Chinook Salmon Escapement from the Sacramento River Basin from 1975 to 2014 and the 40-Year Mean Population Size (gray line) (Source Azat 2015)

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[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.

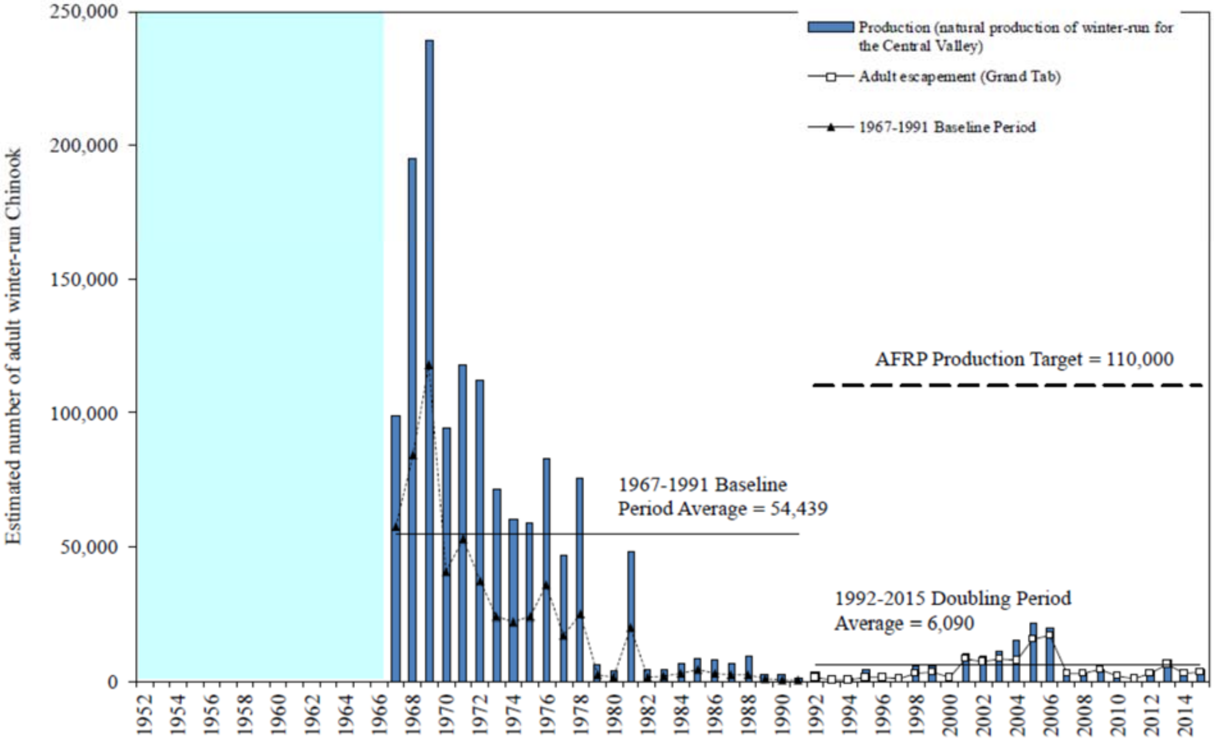

Figure 3.4-3. Estimated Yearly Adult Natural Production and in-River Adult Escapement of Winter-Run Chinook Salmon in Central Valley Rivers and Streams. Data were not available for 1952–1966. 1992–2015 numbers are from CDFG Grand Tab (Apr 11, 2016). 1967–1991 Baseline Period Numbers are from Mills and Fisher (CDFG 1994).[5]

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 2014a). Spring-run enter freshwater as immature adults and ascend to summer holding areas that provide appropriate temperatures and sufficient flow, cover, and pool depths to allow successful maturation (Yoshiyama et al. 1998). 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 2005a as cited in NMFS 2014a). 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 differ from those of winter-run in that suitable habitat is required year-round for successful completion of spring-run freshwater life stages (holding, spawning, and rearing) (Table 3.4-1). Spring-run Chinook migrate to natal streams between February and September, with peak migration in May and June (Yoshiyama et al. 1998). Following the summer holding period, spawning occurs between late August and November with a peak in October–November (Moyle 2002).

The development of embryos and emergence from the gravel is dependent on ambient water temperatures and DO levels. Optimal water temperatures for Chinook salmon egg incubation range

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[5] Figure from https://www.fws.gov/lodi/anadromous_fish_restoration/afrp_index.htm.

from 41 to 56°F (NMFS 2009a) Embryos hatch in 40–60 days under these conditions and the alevin remain in the gravel for an additional 4–6 weeks before emerging as fry (Moyle 2002). Fry leave the gravel between December and March (Table 3.4-1). Juveniles typically may remain in freshwater for 12–16 months, but some individuals migrate downstream to the ocean as young of the year in winter or early spring (NMFS 2014a).

The Feather River Fish Hatchery 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 2 million smolt 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 2014a).

Spawning habitat for Central Valley spring-run Chinook salmon also includes the main stem Sacramento (between Keswick Dam and RBDD), Feather, and Yuba Rivers and Cottonwood, Antelope, Thomes, Big Chico, Clear, 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 2014a).

The Central Valley is estimated to have produced spring-run Chinook salmon runs as large as 600,000 fish between 1880 and 1940 (CDFG 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 CVPIA baseline period of 1967–1991 was estimated at 34,374 fish. Average production in 1992–2015 decreased to 13,385 fish. This represents a 61 percent decline over the baseline period (Table 3.4-3) and is only 20 percent of the CVPIA doubling goal.

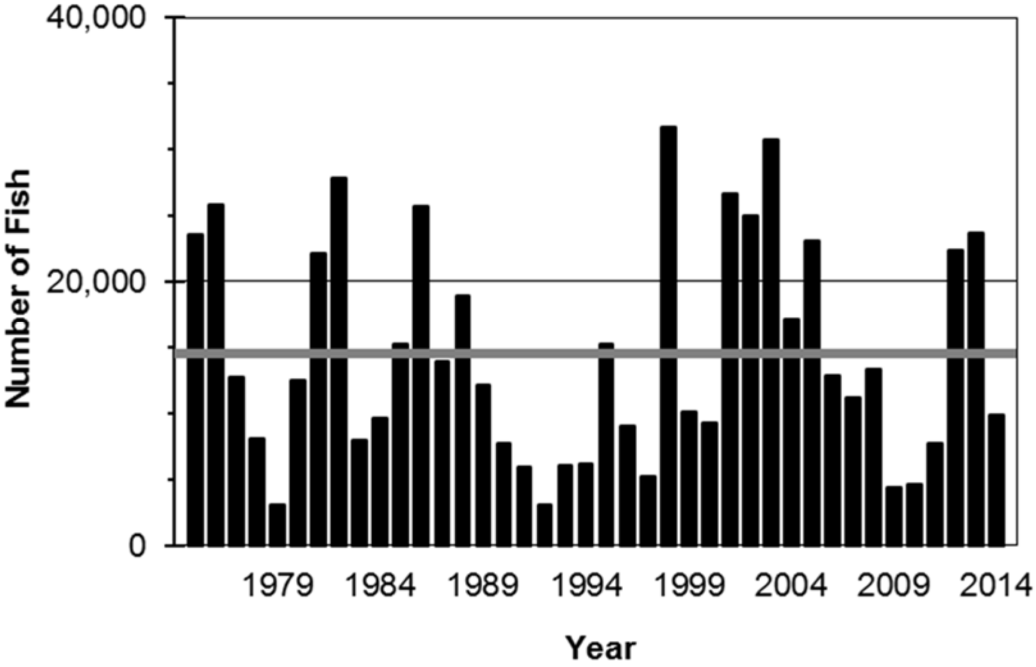

Figure 3.4-4. Annual Spring-Run Chinook Salmon Escapement to Sacramento River Tributaries from 1975 to 2014 and the 40-Year Mean (gray line) (Source Azat 2015)

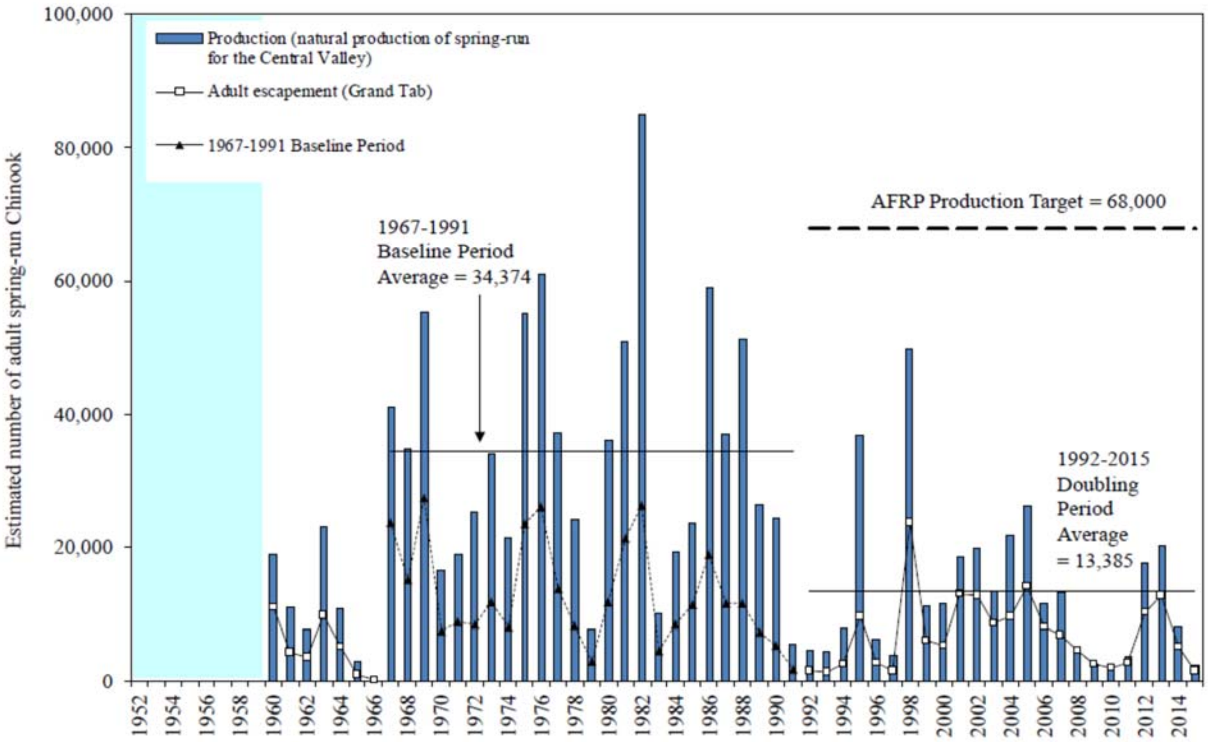

Figure 3.4-5. Estimated Yearly Adult Natural Production and in-River Adult Escapement of Spring-Run Chinook Salmon in the Central Valley Rivers and Streams. No Data Available for 1952–1966. 1992–2015 numbers are from CDFG Grand Tab (Apr 11, 2016). 1967–1991 Baseline Period Numbers are from Mills and Fisher (CDFG 1994).[6]

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 CESA. Hatcheries that propagate Central Valley spring-run Chinook salmon are the Trinity River and Feather River Fish Hatcheries (CDFW 2016b).

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 also has 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.

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[6] Figure from https://www.fws.gov/lodi/anadromous_fish_restoration/afrp_index.htm.

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 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 run 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; natural production between 1992 and 2015 was only 48 percent of the production during the base period of 1967–1991 (Figure 3.4-6). The average number of returning adults during the past 40 years (1976–2014) is about 12,000 fish (Figure 3.4-7). Coleman National Fish Hatchery on Battle Creek produces late-fall-run Chinook salmon with a target of 1 million fish per year. Juvenile fish are released in December at or near the hatchery (California Hatchery Scientific Review Group 2012).

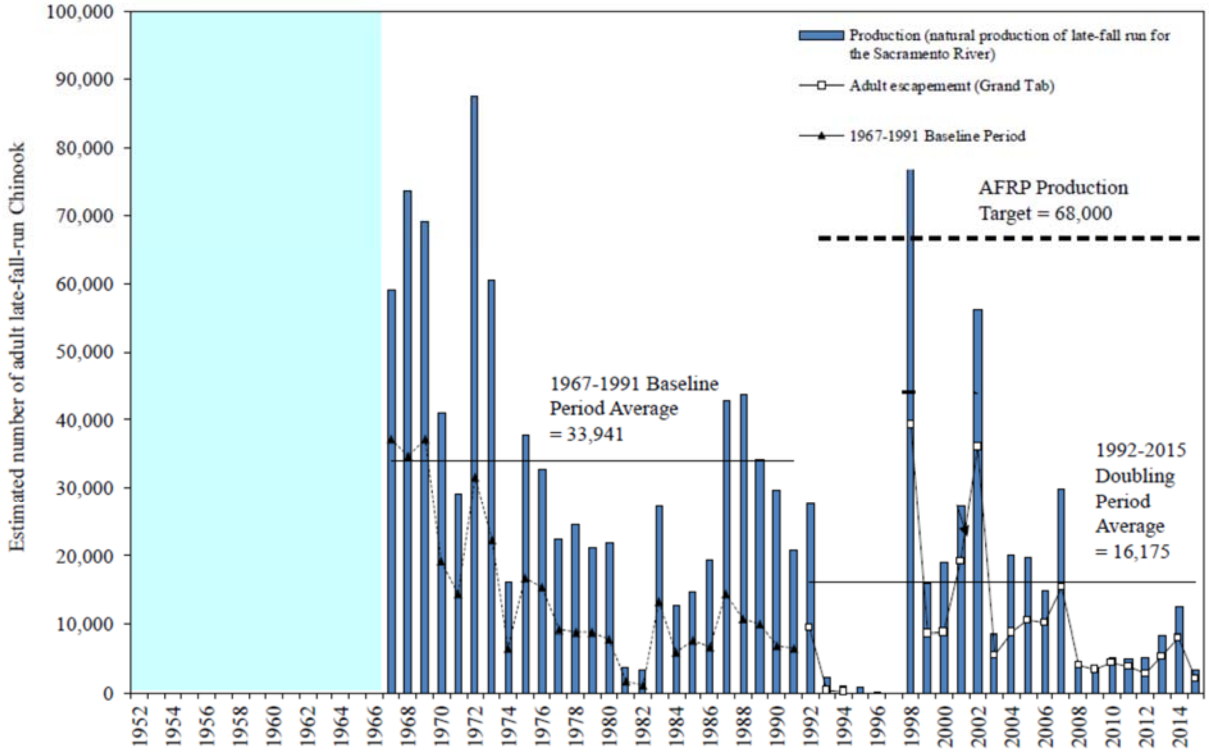

Figure 3.4-6. Estimated Yearly Adult Natural Production and in-River Adult Escapement of Late-Fall-Run Chinook Salmon in Central Valley Rivers and Streams. No Data Available for 1952–1966. 1992–2015 numbers are from CDFG Grand Tab (Apr 11, 2016). 1967–1991 Baseline Period Numbers are from Mills and Fisher (CDFG 1994).[7]

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[7] Figure from https://www.fws.gov/lodi/anadromous_fish_restoration/afrp_index.htm.

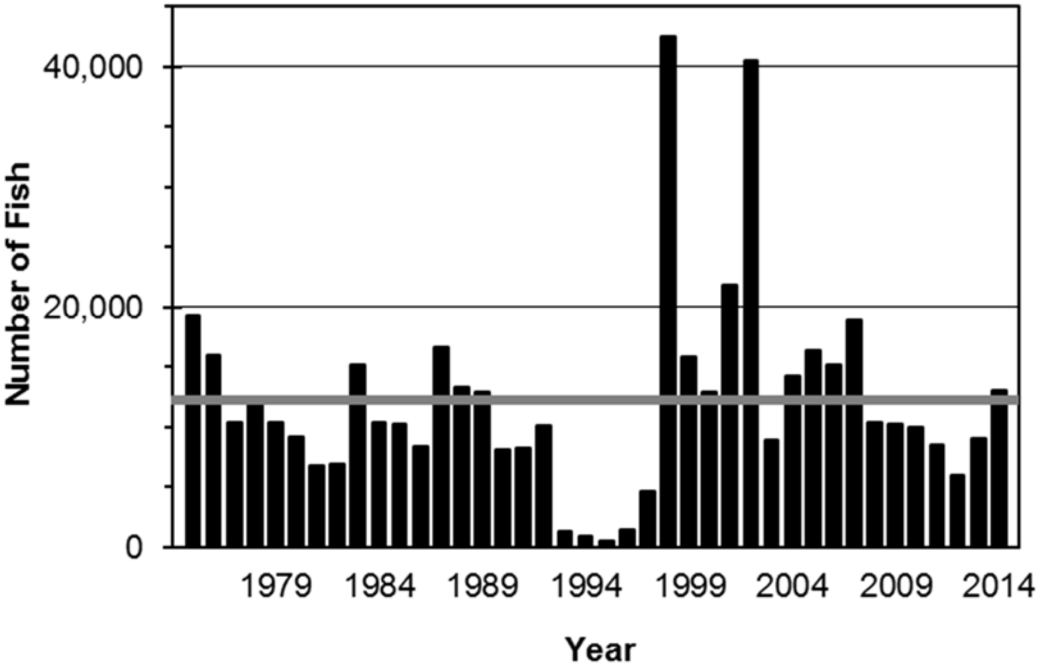

Figure 3.4-7. Annual Late-Fall-Run Chinook Salmon Escapement to the Sacramento River Watershed from 1975 to 2014 and 40-Year Mean (gray line) (Source Azat 2015)

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 select spawning sites and construct redds.

Sacramento fall-run spawn from late September through January and larval hatching occurs about 2 months later (Table 3.4-1). Egg incubation is temperature dependent and lasts 40–60 days. Upon hatching, the alevins remain in the gravel for 4–6 weeks until their yolk sac has been absorbed (Moyle 2002). Generally, fall-run juveniles emigrate from their natal streams during the first few months following emergence with most migrating as fry to the lower main stem rivers, Delta, or estuary in winter or early spring followed by emigration of larger juveniles (parr and smolts) later in the spring (Williams 2006). Peak migrations and abundance of fry in the Bay-Delta are generally correlated with flow magnitude, with peak abundance, and downstream extent of fry being highest following major runoff events (Kjelson et al. 1982; Brandes and McLain 2001). Evidence from otolith microchemistry analysis suggests that all three migratory phenotypes (fry, parr, and smolt) contribute to adult populations, with increasing contributions of fry migrants in wet years (Miller et al. 2010; Sturrock et al. 2015).

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 River 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 January in the Merced, Tuolumne, and Stanislaus Rivers, but typically happens in November (McBain and Trush 2002; CDFG 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 emigration 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 1–3 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 four Central Valley hatcheries[8] which together release more than 32 million smolt each year (CDFW 2016b). Hatchery production contributes to a large commercial and recreational ocean fishery and a popular freshwater sport fishery. However, historic levels of genetic and phenotypic diversity of Central Valley stocks have likely been substantially reduced by the cumulative effects of habitat loss and degradation, and increasing dominance of hatchery fish in spawning populations (Williamson and May 2005; Barnett-Johnson et al. 2007). These factors are believed to have contributed to the reduced resilience of Sacramento fall-run Chinook salmon and the collapse of the run in response to poor ocean conditions in 2005 and 2006 (Lindley et al. 2009) and a large decline in escapement in 2007 and 2008 (Figure 3.4-8). The number of returning adults has since recovered and is now about at the 40-year average (Figure 3.4-8).

Natural production of fall-run Chinook salmon in the main stem Sacramento River has declined since the CVPIA baseline years of 1967–1991; average natural production in the main stem Sacramento River between 1992 and 2015 was about 57 percent of the baseline period (Figure 3.4-9). Average natural production of fall-run Chinook salmon in the San Joaquin River basin (Stanislaus, Tuolumne, and Merced Rivers) during 1992–2015 has declined approximately 55 percent since the CVPIA baseline years (Figure 3.4-11).

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[8] American, Feather, Merced, and Mokelumne River fish hatcheries.

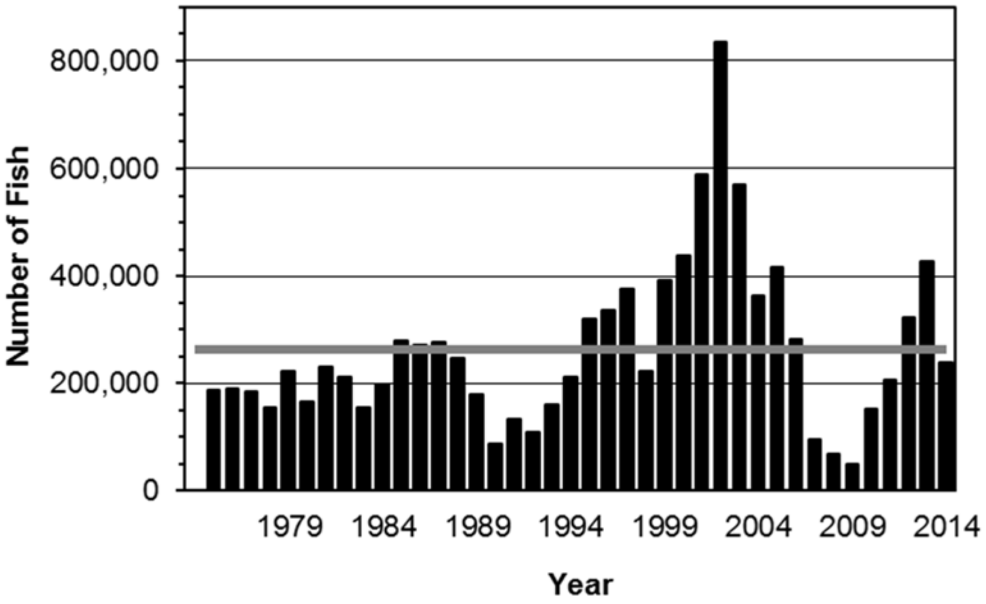

Figure 3.4-8. Annual Fall-Run Chinook Salmon Escapement to the Sacramento River Watershed from 1975 to 2014 and 40-Year Mean (gray line) (Source Azat 2015)

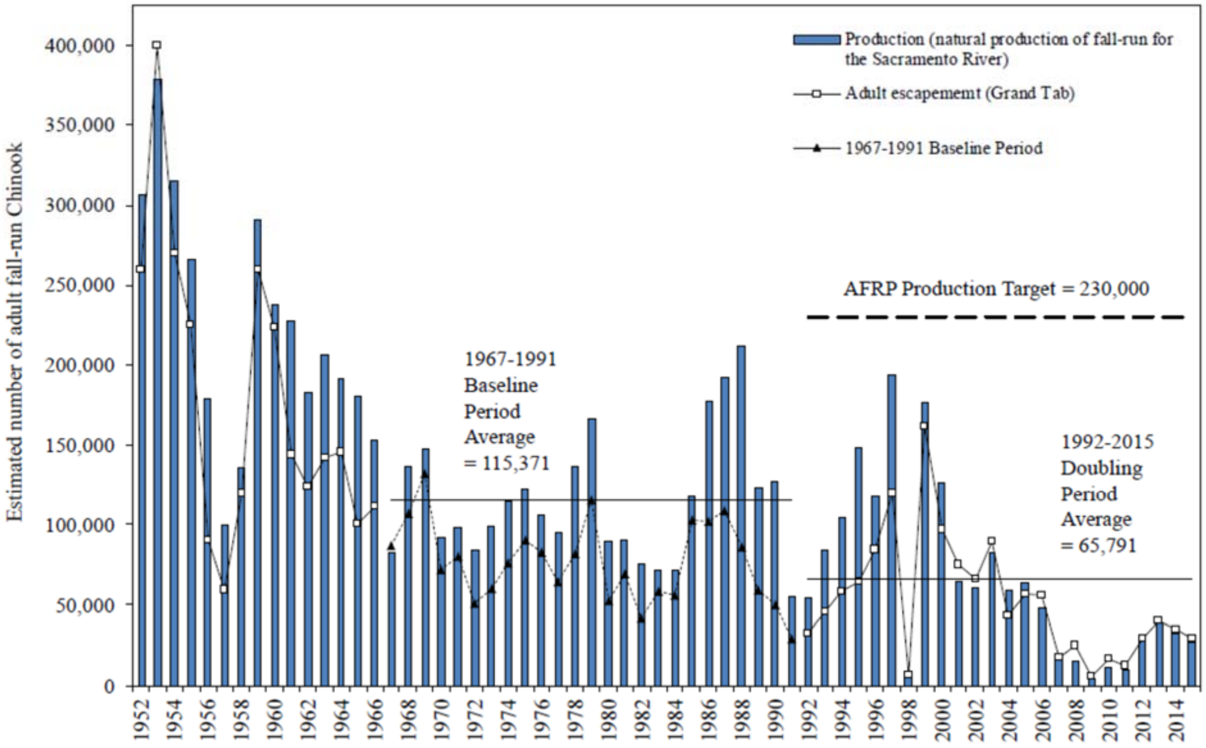

Figure 3.4-9. Estimated Yearly Adult Natural Production and in-River Adult Escapement of Fall-Run Chinook Salmon in the Main Stem Sacramento River. 1952–1966 and 1992–2015 numbers are from CDFG Grand Tab (Apr 11, 2016). 1967–1991 Baseline Period Numbers are from Mills and Fisher (CDFG 1994).[9]

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[9] Figure from https://www.fws.gov/lodi/anadromous_fish_restoration/afrp_index.htm.

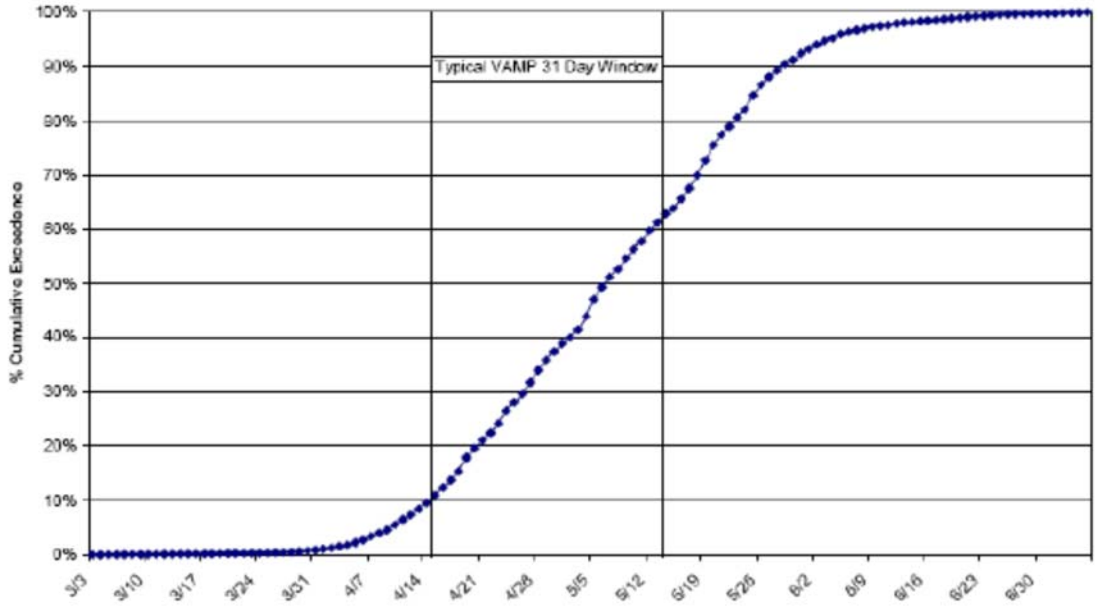

Figure 3.4-10. San Joaquin River Basin Smolt Emigration Pattern 1988–2004 (from CDFG 2005)

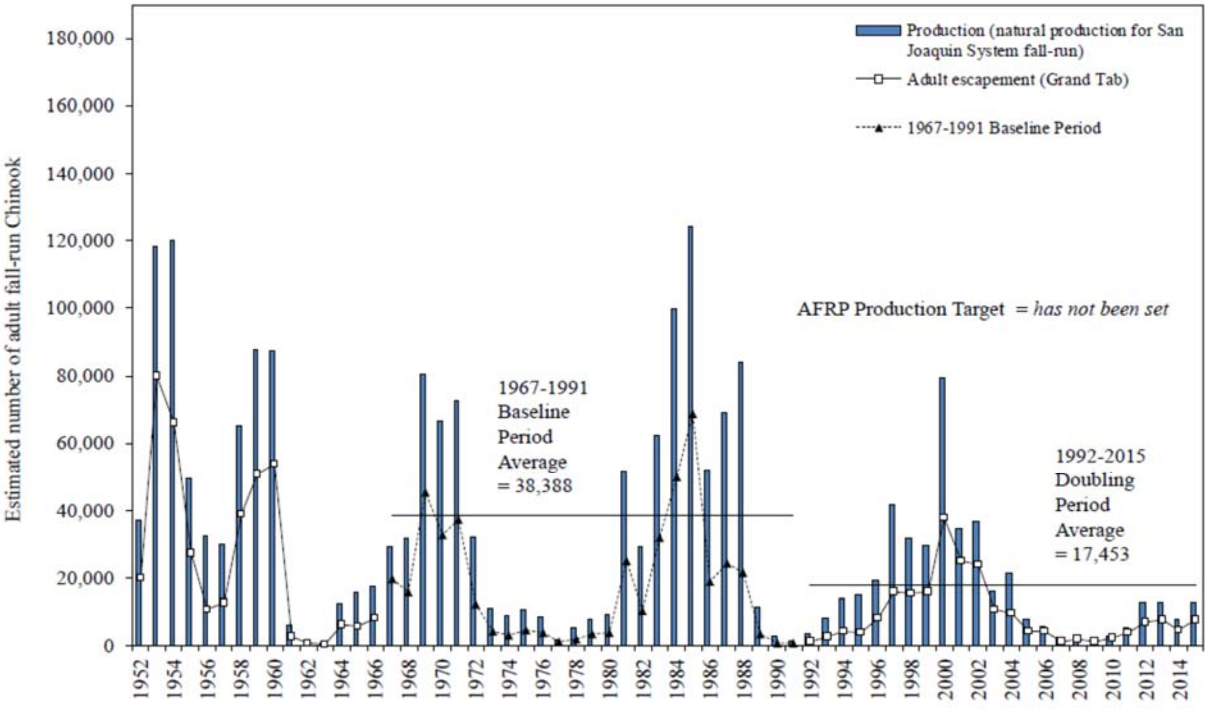

Figure 3.4.-11. Estimated Yearly Natural Production and Instream Escapement of San Joaquin Adult Fall-Run Chinook Salmon. The San Joaquin system is the sum of the Stanislaus, Tuolumne, and Merced Rivers. 1952–1966 and 1992–2015 numbers are from CDFG grand tab (April 11, 2016). 1967–1991 baseline period numbers are from Mills and Fischer (CDFG 1994).[10]

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[10] Figure from https://www.fws.gov/lodi/anadromous_fish_restoration/afrp_index.htm.

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 CESA 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.

Existing native steelhead populations now occur in the Sacramento, Yuba, Feather, Bear, and American Rivers and in Cottonwood, Butte, Big Chico, Cow, Stony, Thomes, Deer, Mill, Antelope, Clear, and Battle Creeks in the Sacramento River basin (NMFS 2014a). On the eastside of the Delta, returning adult steelhead have been observed in the Mokelumne, Cosumnes, and Calaveras Rivers. In the San Joaquin River basin, adult steelhead have been reported on the Stanislaus, Tuolumne, and Merced Rivers (NMFS 2014a). Four hatcheries in the Central Valley produce steelhead: Coleman National Fish Hatchery (Battle Creek), Feather River Fish Hatchery, Nimbus Hatchery (American River), and Mokelumne River Fish Hatchery. Together the hatcheries produce about 1.6 million fish each year (NMFS 2014a).

Available data indicate a long-term decline in escapement of steelhead from the Sacramento and San Joaquin River basins (McEwan 2001). McEwan surmised that between 1 million and 2 million adults may have spawned in the Central Valley in the mid-1880s, and that abundance declined to about 40,000 in the 1960s. The only long-term time series of adult steelhead (counts of adults passing RBDD from 1966 to 1993) indicates a persistent decline over this period from a peak of approximately 20,000 adults in 1967 to an average of approximately 2,000 adults during the late 1980s and early 1990s (Good et al. 2005). The Chipps Island midwater trawl data provide the most recent indicator of trends in natural production of juvenile steelhead in the Central Valley as a whole. Since 1998, the first year that all hatchery steelhead were marked with an adipose fin-clip, the proportion of hatchery steelhead has increased, exceeding 90 percent in some years and reaching a high of 95 percent in 2010 (NMFS 2016a). Because hatchery releases have been fairly constant, this indicates that natural production of juvenile steelhead has continued to decline (see Figure 7 in NMFS 2016a).

The California Central Valley (CCV) steelhead DPS was originally listed as threatened in March 1998 (63 FR 13347). This DPS includes naturally spawned anadromous *O. mykiss* originating below natural and constructed impassable barriers from the Sacramento and San Joaquin Rivers and their tributaries, and two artificial propagation programs: Coleman National Fish Hatchery and Feather River Fish Hatchery (78 FR 38270). In its 2016 status review, NMFS recommended that the Mokelumne River Hatchery be added to the CCV steelhead DPS based on new genetic evidence of the similarity of Mokelumne River Hatchery fish to Feather River Hatchery fish (NMFS 2016a). NMFS concluded that CCV steelhead remain listed as threatened, as the DPS is likely to become endangered within the foreseeable future throughout all or a significant portion of its range (NMFS 2016a).

Critical habitat was designated in September 2005. It includes the Sacramento and San Joaquin Rivers and Delta, and numerous tributaries (up to the first known natural or constructed barrier), including the Feather, Yuba, and American Rivers, and Deer, Mill, Battle, Antelope, and Clear Creeks in the Sacramento River basin; and the Mokelumne, Calaveras, Stanislaus, Tuolumne, and Merced Rivers in the San Joaquin River basin (70 FR 52488).

3.4.4 Dam and Reservoir Effects on Salmonids

Yoshiyama et al. (1998) describes the long-term decline of Chinook salmon in the Central Valley and its causes, citing dam construction as one of the major factors contributing to historical declines in distribution and abundance. The loss of access to historical spawning and rearing habitat above the dams and subsequent impacts of dams and reservoir operations on habitat below the dams are cited as key reasons for the listing of winter-run Chinook salmon, spring-run Chinook salmon, and steelhead (NMFS 2014a). While cold water storage and releases below these dams have allowed some populations to persist, other factors related to dam construction and reservoir operations have caused significant habitat degradation in downstream reaches, including alteration of seasonal flow and temperature patterns, disruption of spawning gravel recruitment, and alteration of other natural hydrologic and geomorphic processes.

Dam construction in the Central Valley began as early as the 1850s with the construction of permanent dams peaking in the early 1900s and continuing through the 1970s. Starting in the 1940s, the rates of decline of anadromous species (mostly referring to Chinook salmon but also including steelhead and green sturgeon) increased following the completion of major water project dams on the main stems and most major tributaries of the Sacramento and San Joaquin Rivers (USFWS 2001). Based on available information on the known or inferred distribution of historical migration, holding and spawning habitat, Yoshiyama et al. (2001) estimated that 1,126 miles remain of the more than 2,183 miles of Central Valley streams that were historically accessible to Chinook salmon, indicating an overall loss of at least 1,057 miles (48 percent). Excluding the lower migration and rearing corridors, they estimated that at least 72 percent of the original holding and spawning habitat for Chinook salmon in the Central Valley is no longer available. Steelhead also experienced major habitat losses based on their generally higher migration limits and need for suitable rearing temperatures through the summer (Yoshiyama et al. 1998). Using a modeling approach to describe the historical distribution of Central Valley steelhead, Lindley et al. (2006) estimated that about 80 percent of the historically accessible habitat defined as suitable for steelhead is now above impassable dams.

The impacts of habitat blockage by dams were particularly severe for winter-run and spring-run (and probably late-fall-run) Chinook salmon because of their requirements for cool summer water temperatures, all or most of which historically occurred in upper elevation reaches above large main stem and tributary dams (Yoshiyama et al. 1998). The result was the extirpation of spring-run Chinook salmon from the San Joaquin River basin and most of the major Sacramento River tributaries with historical spring-run populations (NMFS 2014a). Steelhead were likely similarly affected based on their general overlap in spawning distribution with spring-run Chinook salmon (McEwan 2001; Lindley et al. 2006). For winter-run Chinook salmon, the current spawning habitat, formerly used only for migration and rearing, is maintained artificially with cool water releases from Shasta Dam, requiring management of available cold water storage to maintain suitable water temperatures through the summer incubation period (Yoshiyama et al. 1998). Compared to winter- and spring-run, fall-run Chinook salmon were less affected by dams because of their use of lower elevation reaches for spawning and rearing; however, fall-run also experienced major habitat losses because of upstream diversions and lower-elevation diversion dams that impeded upstream migration and degraded habitat conditions below the dams (Yoshiyama et al. 1998).

The blockage of upstream migration of spring-run Chinook salmon by main stem dams also eliminated the spatial separation between spring- and fall-run adults, leading to interbreeding and genetic introgression of these two runs in the Sacramento River below Keswick Dam, Feather River below Oroville Dam, and Yuba River below Englebright Dam (Yoshiyama 1998; NMFS 2014a). Lack of reproductive isolation of spring- and fall-run Chinook salmon in combination with ongoing hatchery management practices that promote high straying rates (e.g., off-site releases of fall-run juveniles) of hatchery adults to natural spawning areas represent a continued threat to the genetic integrity and diversity of spring-run and fall-run stocks (Williamson and May 2005; NMFS 2014a; Lindley et al. 2009; California Hatchery Scientific Review Group 2012). Similarly, it appears that much of the historical population structure and genetic diversity of Central Valley steelhead populations has been lost or altered by dams, habitat modification, and historical hatchery practices (Lindley et al. 2006; Pearse and Garza 2015).

Habitat blockage is also recognized as an important factor contributing to the historical declines in the distribution of green sturgeon in the Sacramento River basin (Adams et al. 2007); habitat modeling predicts that suitable spawning habitat for green sturgeon historically existed in portions of the San Joaquin and lower Feather, American, and Yuba Rivers, much of which is currently inaccessible to green sturgeon because of impassable dams and altered hydrographs (Mora et al. 2009). While these predictions indicate that dams blocked access to about 9 percent of historically available habitat, it is likely that these areas contained relatively high amounts of spawning habitat based on the general distribution patterns of green sturgeon in other river systems (Mora et al. 2009).

Dam and reservoir operations also contributed to historical impacts and continue to act as stressors on native Central Valley fish populations through flow regulation and the alteration of natural hydrologic and geomorphic processes below dams. The storage and diversion of natural flows by dams have depleted stream flows and altered the natural flow and temperature patterns under which Chinook salmon, steelhead, and other fishes evolved. These flow alterations include shifts in the seasonal distribution of flows, reductions in the magnitude of peak flows, and overall reductions in flow variation compared to the natural hydrograph (see Chapter 2 for information on changes in the hydrology of the basin). Dams also disrupt the natural transport of sediment (e.g., spawning gravel) and other materials (e.g., large woody material) that maintain spawning and rearing habitat in these lower reaches. Although a number of water management actions and habitat restoration projects have been successful in improving habitat conditions for anadromous salmonids, the physical and operational effects of dams and reservoirs, coupled with other historical impacts on the river landscape below dams (e.g., levee construction), continue to be major threats to Central Valley salmon and steelhead conservation and the recovery efforts (NMFS 2016a, 2016c, 2016d).

High summer and fall water temperatures is recognized as a major limiting factor for Chinook salmon and steelhead populations below main stem and tributary dams, and limitations in cold water storage and other physical and operational constraints (e.g., carry-over storage) limit the ability of these reservoirs to meet downstream water temperature requirements, especially during drought and critically dry years (NMFS 2009a, 2014a). Currently, both physical and operational measures, including temperature control structures and seasonal storage targets, are employed at a number of Central Valley reservoirs to improve the reliability of cold water discharge during critical summer and fall spawning and rearing periods. However, increasing water demands and climate change is expected to further limit the effectiveness of reservoir flow and water temperature management in protecting anadromous fish populations below these reservoirs (Lindley et al. 2007; Cloern et al. 2011). This challenge was demonstrated during the recent drought when a lack of sufficient inflow and cold water storage in Shasta Reservoir resulted in sub-lethal to lethal water temperatures in the Sacramento River, contributing to very low egg-to-fry survival of winter-run Chinook salmon in 2014 and 2015 (NMFS 2016c). In response, measures have been taken to improve cold water pool management, including efforts to develop a two-dimensional reservoir model coupled with a watershed and river model to better understand the factors influencing thermal dynamics in Shasta Reservoir (Danner et al. 2012).

Reservoirs act as sediment traps and disrupt the natural transport of bedload material, including spawning-size gravel necessary for maintenance of Chinook salmon and steelhead spawning habitat. Over time, this results in the depletion of spawning gravel, a coarsening and armoring of the channel bed, and reductions in the overall quantity and quality of spawning habitat in the reaches below the dams. In most systems, flow regulation, levee and bank stabilization, and gravel mining have contributed to the problem by impairing other natural gravel recruitment processes below dams (e.g., channel migration). Consequently, the restoration or rehabilitation of spawning habitat below dams is identified as a high-priority restoration action in a number of Central Valley salmon and steelhead rivers, including the Sacramento River, Clear Creek, and the Feather, Yuba, American, Mokelumne, Stanislaus, Tuolumne, and Merced Rivers (NMFS 2014a). Few evaluations of the effectiveness of completed or ongoing gravel augmentation projects are available. In the American River, however, quantitative evaluation of pre- and post-project spawning utilization of gravel augmentation sites designed using a systematic modeling approach (Wheaton 2004a, 2004b) demonstrated significantly increased spawning utilization by Chinook salmon and steelhead (Zeug et al. 2013).

Flow fluctuations from reservoir and hydropower operations is a common concern below Central Valley reservoirs because of the potential for adverse effects on Chinook salmon and steelhead from redd dewatering and juvenile stranding. While current flow management and hydropower licensing agreements commonly include limits on flow fluctuations and ramping rates to minimize such impacts, alterations of the timing, magnitude, and rate of reservoir releases to meet multiple water management objectives continue to be a concern. In the upper Sacramento River, for example, efforts to maintain stable flows to protect winter-run Chinook salmon through the summer incubation period increases the potential for dewatering of fall-, spring-, and potentially late-fall-run redds when flows are subsequently reduced in the fall for water conservation purposes. Consequently, annual monitoring of Chinook salmon redds in the Sacramento River between Tehama Bridge (RM 229) and Keswick Dam (RM 302) is currently being conducted to inform within-season water management strategies to address this risk (Stompe et al. 2016).

3.4.5 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 freshwater 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). Finally, emigrating 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 emigration.

3.4.5.1 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 waiting to spawn.

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 (CDFG 2010a). Absence of a consistent pattern of chemical signals increases the likelihood of straying and a loss of genetic integrity and life history diversity (NMFS 2014a). 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 2014a) 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 (2014b, 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 that the different impairments were documented to have occurred in Sacramento River tributaries evaluated by NMFS (2014b, Appendix A) 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 studied (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 2014a). 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 2014a; NMFS 2014a).

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 Chinook Salmon and Central Valley Steelhead in Twenty-Two Salmon Bearing Tributaries of the Sacramento River. Information is from Appendix A in NMFS (2014b).

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 emigration
40	Warm water temperatures negatively affecting juvenile rearing and emigration.
32	Low flow negatively affecting juvenile rearing and emigration

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 toward the ocean. These alterations in 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 percent of the flow of the San Joaquin River at Vernalis, while straying rates decrease when export rates were less than 300 percent of Vernalis flow (Mesick 2001).[11] 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 percent vs. less than 1 percent, 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 Mokelumne River Chinook salmon and reduces straying rates to the American River (Table 3.4-6) (EBMUD 2013; CDFG 2012). CDFG (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 straying.

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[11] High straying rates of hatchery-origin adults (mostly fall-run Chinook) is also caused by the current practice of releasing most hatchery juveniles at off-site locations downstream of the hatchery of origin or in the estuary (California Hatchery Review Report 2012).

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

3.4.5.2 Juvenile Rearing and Emigration

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). 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. For example, the dominance of an ocean-type life history, in which large numbers of juveniles migrate from natal streams to lower main stem rivers, Delta, and estuary shortly after emergence, may 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 of juvenile rearing habitat and a lack of connectivity between tributaries and the river due to lack of flow and elevated ambient water temperatures (NMFS 2014b, Appendix A). Below is a discussion of the need for flow for juvenile salmonids through their migratory corridor from natal tributaries and floodplains, through the main stem rivers, and then through the Delta to the ocean.

Tributary Habitat

Natal streams are important initial rearing habitat for newly hatched larvae. The NMFS (2014b, 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 emigration*" and "*warm water temperature negatively affecting juvenile salmon rearing and emigration".* An analysis by State Water Board staff determined that these two impairments occurred in 32 and 40 percent of the tributaries evaluated by the NMFS (2014b, Appendix A) (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 2014b, 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). Terrestrial and aquatic invertebrates are a common food source for juvenile salmon (Moyle 2002). Juveniles are also 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 2014a). 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 2014a).

Analysis of information in the NMFS (2014b, 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 emigration. 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.

CDFG (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. CDFG (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 DO. 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 emigration 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 BiOp 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 2009a, 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 17,000–20,000 acres with an appropriate frequency and duration of flooding.[12]

Juvenile Emigration

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). As will be discussed below, studies indicate that higher flows during these periods are protective of emigrating 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 as early as October with most passing Knights Landing between November and April (del Rosario 2013) (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 native and hatchery steelhead is spread over an approximate 5-month period between November and March but with peak emigration in February and March. Thus, the emigration 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 emigration of juvenile salmon from the upper Sacramento River basin tributaries to the Delta. The first autumn pulse flow exceeding 15,000–20,000 cfs on the Sacramento River at Wilkins Slough[13] has been shown to trigger emigration of about half the annual catch of juvenile winter-run Chinook salmon at Knights Landing about 4 days later (Del Rosario et al. 2013). 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 delay emigration of winter-run and other salmonids to the Delta and increase the risk of predation while juvenile fish are in the upper basin.

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[12] The NMFS BiOp 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.

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

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 and inversely related to water temperature 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 above 25,000 cfs.

Brandes and McLain (2001) reported a positive relationship between abundance of unmarked emigrating 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. State Water Board staff extended this analysis using Dayflow (DWR 2017) and Delta Juvenile Fish Monitoring Program (DJFMP) data (DJFMP 2016). The results of the updated analysis (Figure 3.4-12 plot b) are substantially similar to the earlier published results.[14]

Modeling studies confirm the importance of Sacramento River flow on Chinook salmon survival in the lower River. Newman (2003) modeled survival of coded wire tagged fall run Chinook salmon and found a positive relationship between flow at Freeport and survival through the Delta. Perry (2010) modelled acoustically tagged late-fall-run Chinook salmon survival downstream of Georgiana Slough and found a positive correlation with Sacramento River and Sutter and Steamboat slough flows. In both cases the marginal increase in survival per unit increase in flow decreased with increases in flow above about 20,000 cfs (SST 2017a, Appendix E, p. E9-102). Perry (2010) also found that survival increased in the Sacramento River and in Steamboat and Sutter Sloughs as fish size increased.

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 emigration of winter-run occurs between February and April with about half the run passing Chipps Island in March (NMFS 2014a; 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 specifically for spring-run Chinook salmon, which has not been widely studied. However, these fish have similar life history characteristics as fall-run and it is likely that a similar magnitude of flow would also be beneficial for them. Peak emigration of juvenile spring-run Chinook salmon past Chipps Island is between February and May (NMFS 2014a). For emigrating steelhead, which peak in abundance at Chipps Island between March and April, higher flows during these spring months are likely to benefit this species as well (NMFS 2014a). 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.

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[14] Figures 3.4-12 a and b differ somewhat in the precise positions of individual data points. Y-axis values in Figure 3.4-12b are based on a calculation of catch per unit effort using the catch and sampled water volume data available from DJFMP (2016).

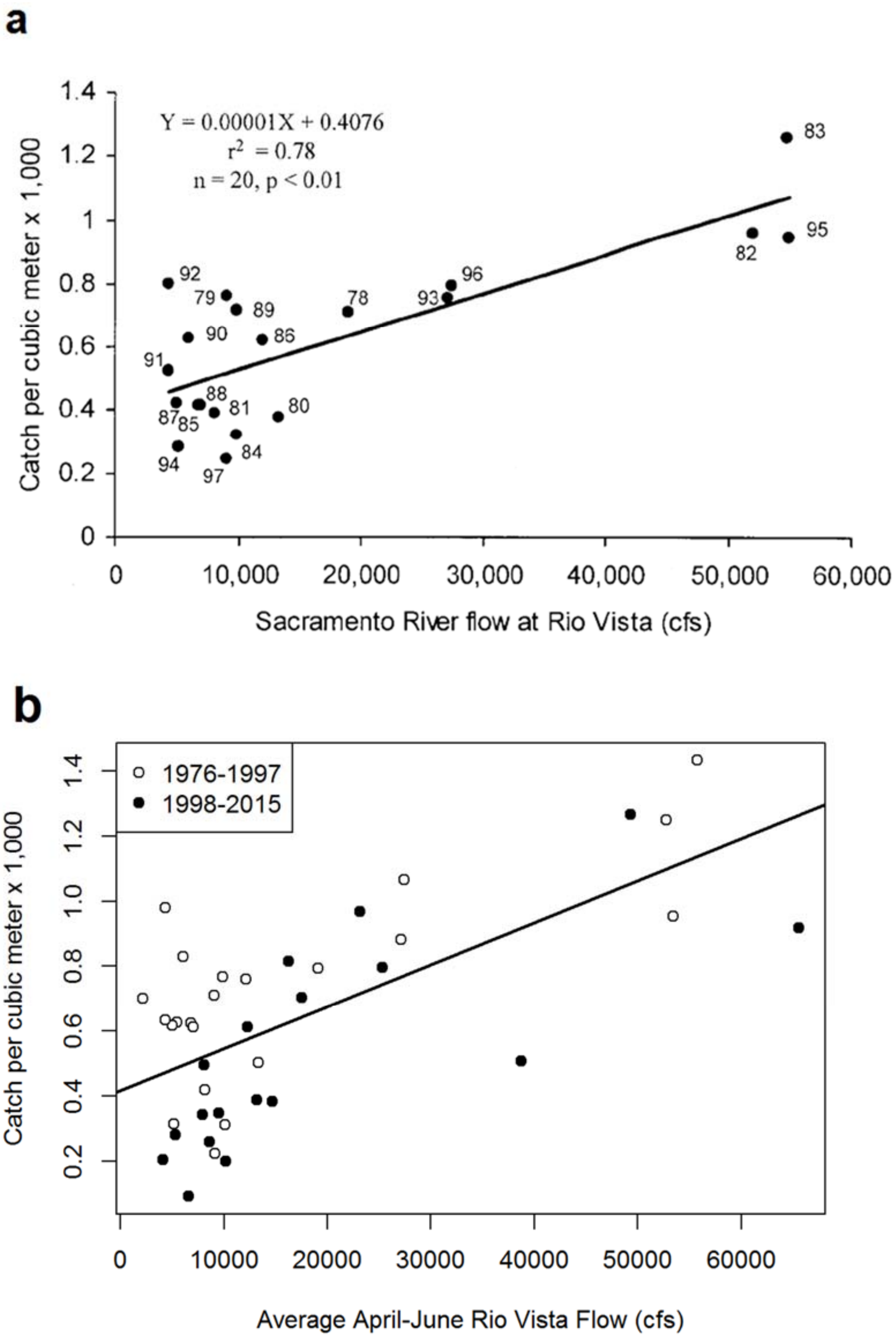

Figure 3.4-12. Mean Catch of Unmarked Chinook Salmon Smolt per Cubic Meter (x 1,000) in the Midwater Trawl at Chipps Island between April and June from (a) 1978 through 1997 versus Mean Daily Sacramento River Flow (cfs) at Rio Vista between April and June (from Brandes and McLain 2001), and (b) 1976–2015 (updated analysis by State Water Board staff). The updated analysis shows the same pattern, with somewhat weaker correlation associated with flow ($y = 0.0000129 x + 0.417$; $R^2 = 0.438$; $p < 0.01$).

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 main stem 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 2009a; 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 emigration 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).

These results are consistent with modeling of the movements of acoustically tagged fish in response to hydrodynamic conditions at Delta junctions. The modeling indicates that the proportion of flow entering various channels is an important predictor of route selection in the Delta (Cavallo et al. 2015). At channel junctions dominated by tidal influence (interior Delta channels), river inflow and diversions had relatively small effects on predicted fish routing because of the large influence of tidal action on the direction and volume of flow. The largest effect of river inflow and export pumping on predicted fish routing was at junctions dominated by riverine flow (Sacramento River at Georgiana Slough) and channel junctions with direct connections to the CVP and SWP pumping facilities (San Joaquin River at Old River) (Cavallo et al. 2015). This study is supported by other recent evidence showing that the interaction of tidal flows with river inflows and diversions can have a strong influence on the migration route of individual fish through the Delta (Perry 2010).

Modeling results have also 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).

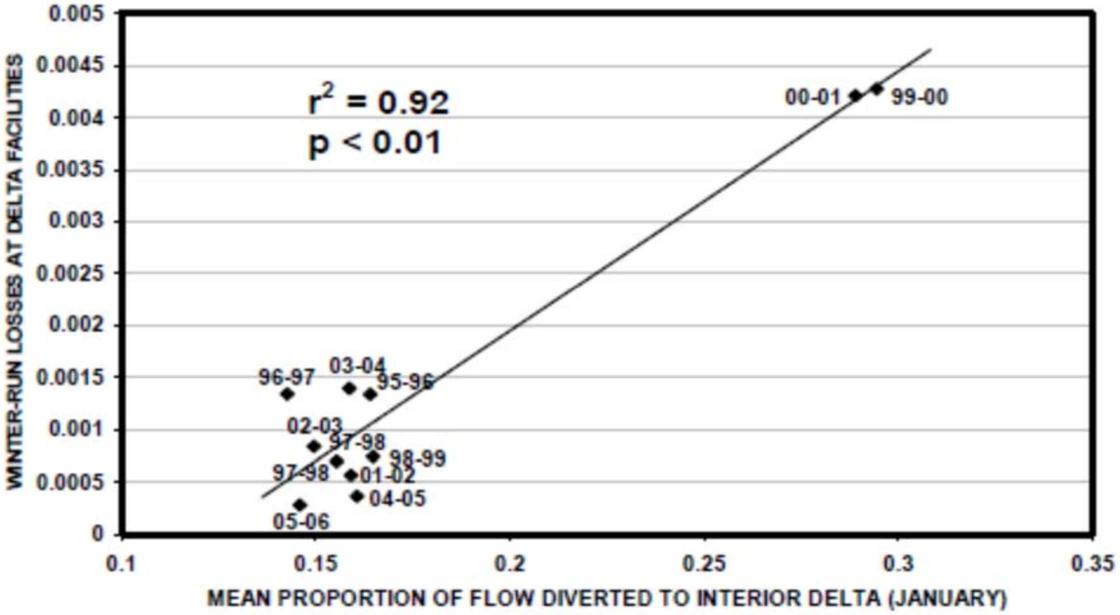

Figure 3.4-13. Relationship between the Mean Proportion of Flow Diverted into the Interior Delta in January and the Proportion of Juvenile Winter-Run Lost at the CVP and SWP Pumping Facilities (losses divided by the juvenile production index) October 1 through May 31, 1996–2006 (from Low and White 2006)

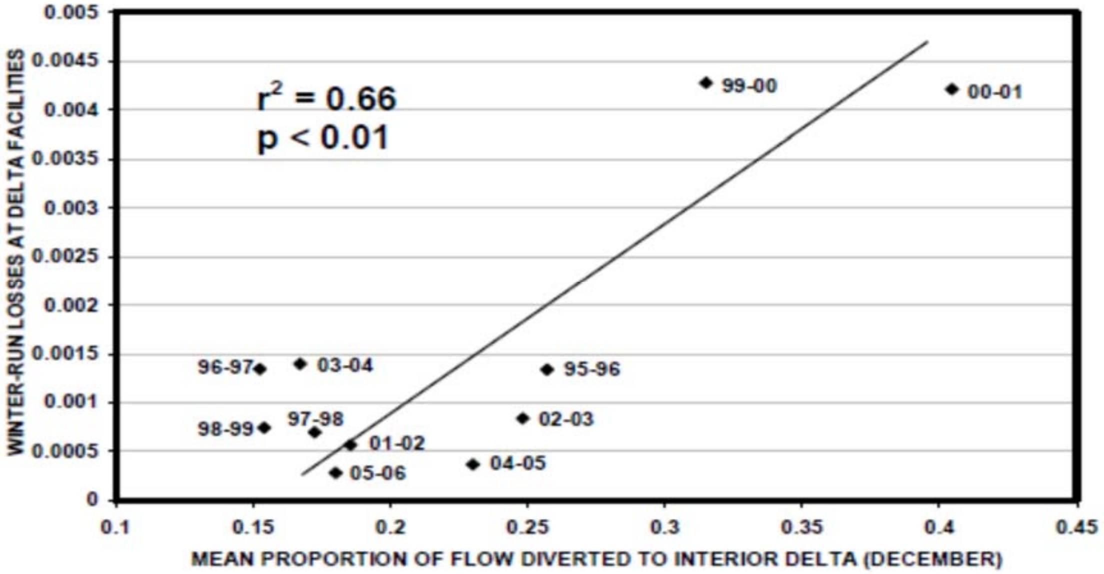

Figure 3.4-14. Relationship between the Mean Proportion of Flow Diverted into the Interior Delta in December and the Proportion of Juvenile Winter-Run Chinook Salmon Lost at the CVP and SWP Pumping Facilities (losses divided by the juvenile production index) October 1 through May 31, 1995–2006 (from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

Other 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 and the cross sectional location of juvenile salmon in the Sacramento River (Burau 2004, 2014; Steel et al. 2013; Perry et al. 2015). 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 are 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 in the Delta (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 San Joaquin River flow down the main stem of the San Joaquin River, reducing the amount of flow that enters Old River and preventing San Joaquin River salmonids from migrating down Old River, a direct route to the Project export facilities. Tagging studies and modeling have generally demonstrated that installation of the HORB improves the survival of emigrating juvenile Chinook salmon from the San Joaquin basin in spring (SJRGA 2008; Brandes and McLain 2001; Newman 2008). Survival of emigrating salmonids from the San Joaquin River has been declining since the 1990s (Perry et al. 2016). In the recent low-survival condition, one recent study found that salmon had higher survival when they were salvaged at the CVP, and were trucked back to release points near Chipps Island than fish that stayed in the San Joaquin River channel and migrated naturally through the Delta to Chipps Island (Buchanan et al. 2013). However, this result was observed with a nonphysical barrier at the Head of Old River, and it is possible that the additional flow present in the San Joaquin River when the HORB is in place is needed to increase survival of juveniles emigrating through the San Joaquin River (Perry et al. 2016).

Table 3.4-7. Sacramento River and Interior Delta Flows 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.

	Months											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Emigration flows for juvenile fall-run[1, 6]				>20,000								
Emigration flows for juvenile winter-run[1, 2]		>20,000										
Georgiana Slough[2]	17,000–20,000										▨	▨
San Joaquin at Jersey Point[3]	Positive Flow									Positive Flow		
OMR reverse flow[4]	-2,500 to -5,000											
San Joaquin River export constraint[5]		1:1–4:1								>0.3		

[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] 5-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.

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 2009a, 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 2009a, 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).

Statistical analyses have also shown that salvage of juvenile salmonids at CVP/SWP facilities increases with water exports (Kimmerer 2008; NMFS 2009a, 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 2009a, 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 2009a, 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 2009a, pp. 651–652).

Regression and PTM analyses have been used to determine the risk of salvage to juvenile salmon and steelhead and to establish 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 2009a, pp. 361–362). Both facilities show a substantial increase in loss around -5,000 cfs in most months (NMFS 2009a, 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 percent to 20 percent and then again to 40 percent when flows are -5,000 cfs (NMFS 2009a, pp. 651–652). Based on these findings, the NMFS's BiOp 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 2009a, 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.

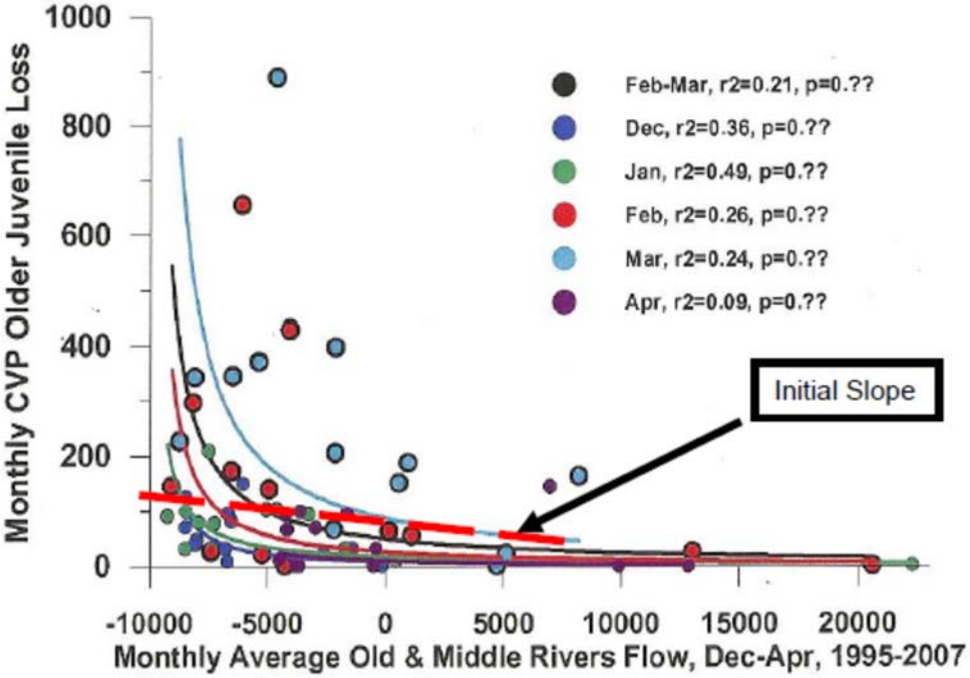

Figure 3.4-15. Relationship between OMR Reverse Flows and Entrainment at the Federal Pumping Facility, 1995–2007 (from NMFS 2009a)

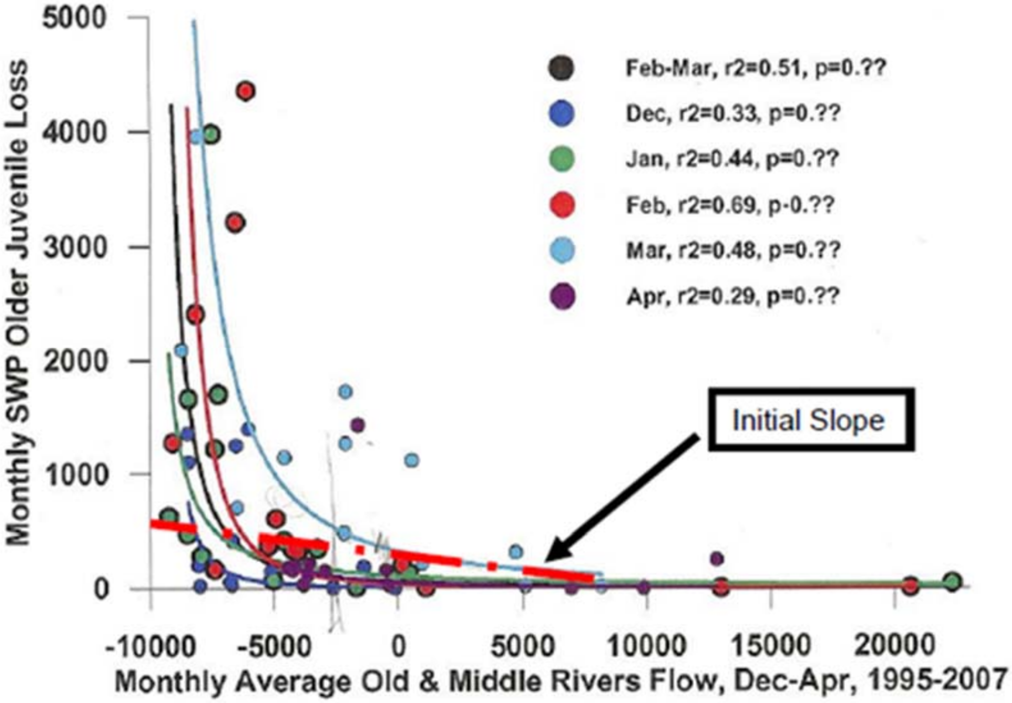

Figure 3.4-16. Relationship between OMR Reverse Flows and Entrainment at the State Pumping Facility 1995–2007 (from NMFS 2009a)

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).

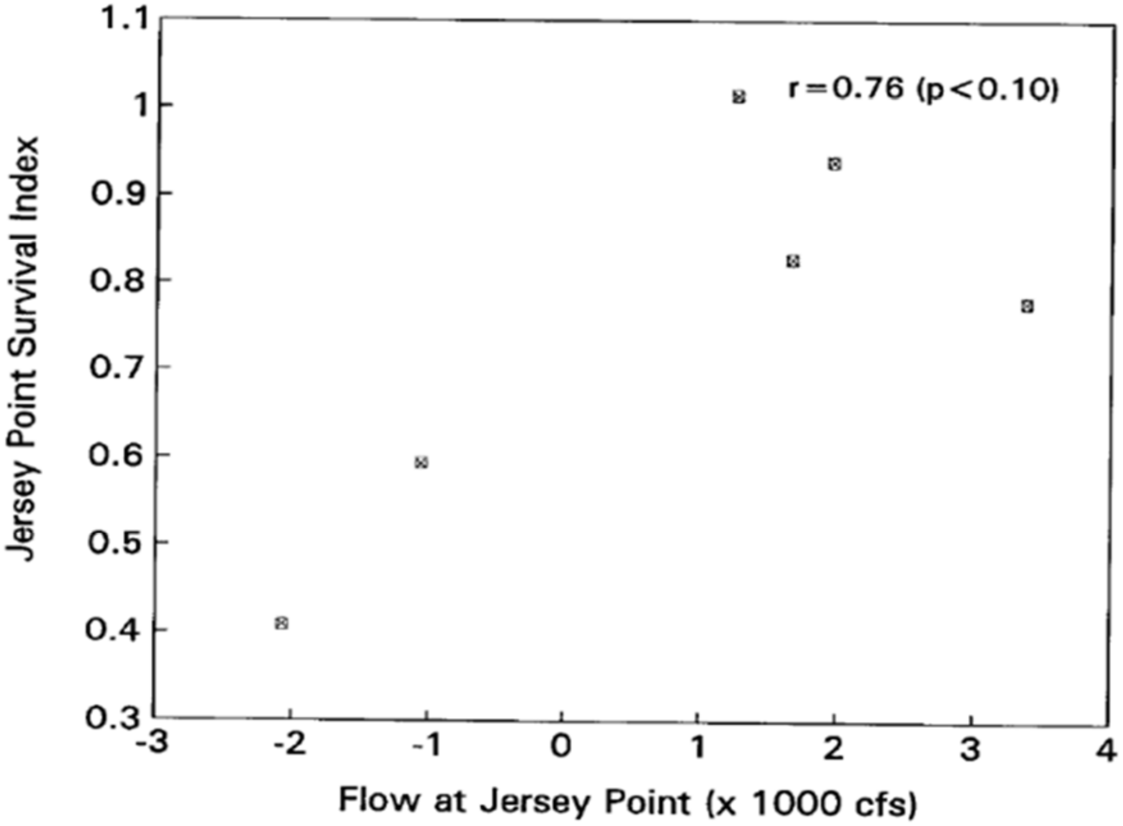

Figure 3.4-17. Temperature Corrected (to 610F) Survival Indices for CWT Salmon Smolt Released at Jersey Point and Recovered at Chipps Island between 1989 and 1991. Flow estimates were the 5-day mean value starting on the release date (from USFWS 1992).

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 (CDFG 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 BiOp 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 BiOp also requires a 6-year acoustic tagging study of steelhead survival in the south Delta to inform future management (NMFS 2009a, pp. 645–648).

In 2013, the federal district court with continuing jurisdiction in the litigation over the USFWS Delta smelt biological opinion (USFWS BiOp) and the NMFS salmonid BiOp (NMFS BiOp) for CVP and SWP Delta operations granted defendants and plaintiff intervenors a delay in the deadline to develop revised BiOps so that those parties could participate in CSAMP (*The Consolidated Delta Smelt Cases, The Consolidated Salmonid Cases,* Order Re Motion to Extend Remand Schedule, United States District Court for the Eastern District of California (March 5, 2014) Case 1:09-cv-00407-LJO-BAM). The stated goal of CSAMP is for the state and federal fisheries agencies to develop a robust science and adaptive management program with collaboration of the scientists and experts from both the state and federal contractors for SWP/CVP supplies and non-governmental environmental organizations. As part of CSAMP, a CAMT, and Salmonid Scoping Team (SST) were formed to evaluate Chinook salmon and steelhead survival in the south Delta (SST 2017a, 2017b). Among other factors, the SST investigated the effect of exports on juvenile salmonid survival through the Delta. The SST did not find a statistically significant relationship between combined CVP and SWP export rates and survival based upon modeling results by Newman (2008), Zeug and Cavallo (2013) and additional analysis by the SST. However, the SST found that the lack of a statistical relationship may be due to the strong correlation between inflows and exports and the lack of survival data for high export rates (SST 2017c, pp. E-83-84). These issues should be further evaluated in the future in the adaptive management context recommended in Chapter 5.

The SST also evaluated the relationship between San Joaquin River inflow to export ratios (I:E) and juvenile salmonid survival through the south Delta. The SST determined that a positive correlation existed between I:E ratios less than 3 in April and May and survival of coded wire tagged juvenile fall run Chinook salmon with the HORB in place (SJRGA 2007). No relationship existed without the barrier. The SJRGA (2007) also compared adult escapement against I:E ratios 2.5 years earlier for data from 1951 through 2003 and found a positive association. The SST (2017c) updated the escapement analysis through 2012 and found similar results. These conclusions are consistent with the hypothesis that higher I:E ratios result in higher juvenile survival through the Delta (SST 2017c). Juvenile salmonids migrate out of the San Joaquin basin during February through June (State Water Board 2012), and may need protection from export-related mortality at any time during this period in order to preserve life history diversity. Although peak emigration occurs in April and May (Figure 3.4-10), 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 one-tenth of 1 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 42,800 cfs in January to June are associated with a fifty percent probability of positive population growth. 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. However, entrainment is no longer considered a serious population level effect if the USFWS (2008) Delta smelt BiOp and the CDFW longfin smelt ITP for SWP Delta operations are enforced, which require OMR reverse flows between -1,250 and -5,000 cfs when fish are present in the central Delta.

3.5.2 Life History

Longfin smelt are a native semi-anadromous, open water fish moving between freshwater and saltwater (CDFG 2009; Wang 2007). Longfin smelt generally live 2 years with females reproducing in their second year (Moyle 2002; CDFG 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 as water temperatures drop below 18°C. (CDFG 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 LSZ, so the location of X2 influences how far spawning migrations extend into the Delta (Baxter et al. 2009). Larvae spawned in the 2 parts per thousand (ppt) LSZ were most abundant in sub-adult and adult surveys later in the year (Hobbs et al. 2010). 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^{0}C (Emmett et al. 1991; CDFG 2009; Wang 1986, 2007). Eggs are deposited on the bottom (Martin and Swiderski 2001; CDFG 2010b) and hatch between December and May into buoyant larvae with a peak hatch in February (CDFG 2010b; Bennett et al. 2002). Net Delta outflow transports the larvae and juvenile fish back downstream to higher salinity habitats. Larvae, 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 2016 and found a statistically significant decreasing trend (R^2=0.51, P<0.001, two-sided t-test) (Figure 3.5-1). Current indices of population abundance are less than two tenths of one percent of the earliest levels observed in the FMWT.[15]

The most recent FMWT indices are about five percent of the indices observed in the early 2000s[16] indicating that the population has continued to decline since revised Delta outflow requirements were implemented in D-1641. The last 3 years of the trend occurred during a drought, which undoubtedly contributed to the decline; however, the time since 2000 also included dry periods. As discussed in Chapter 4, multiple stressors in addition to flow may be responsible for the decline (Sommer et al. 2007).

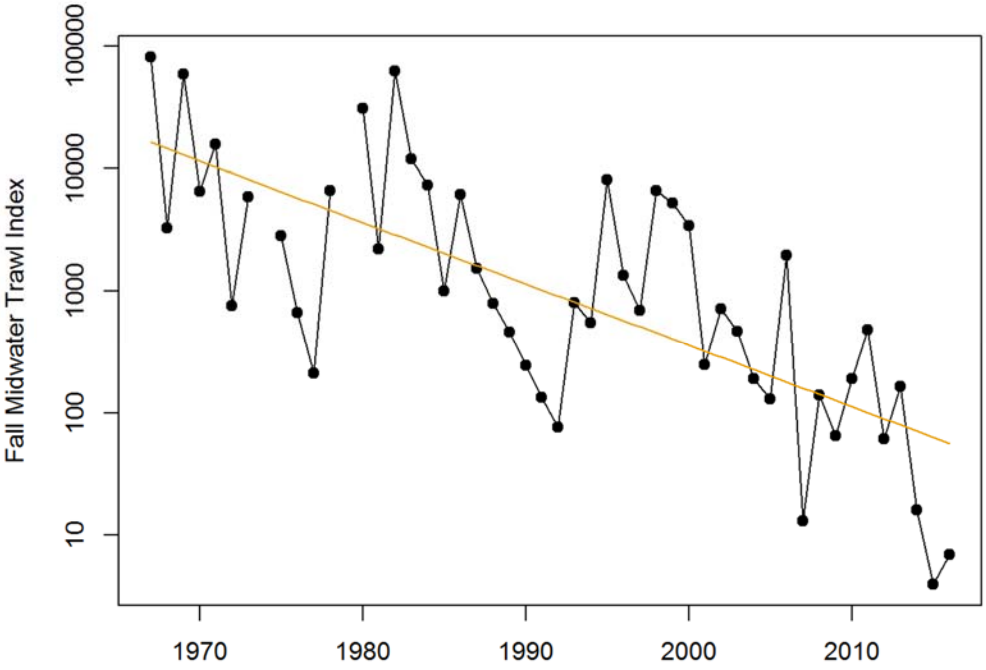

Figure 3.5-1. Inter-Annual Trend in the FMWT Index for Longfin Smelt (1967 to 2016). The solid orange line is the least squares linear regression of the logarithm of the FMWT index against years. The slope of the regression differs significantly from zero ($R^2=0.51$; $P<0.001$, two-sided t-test).

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).

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[15] The decrease was estimated from the average of the first five (1967–1971) and the last five (2012–2016) annual FMWT index values to account for inter-annual variability.

[16] The decrease was also calculated from the average of the first five FMWT index values after implementation of D1641 (2000–2004) and the most recent 5 years (2012–2016).

3.5.4 Flow Effects on Longfin Smelt

3.5.4.1 Delta Outflow

The population abundance of longfin smelt in fall is positively correlated to Delta outflow or X2 as its proxy during the previous winter and spring (Jassby et al. 1995; Rosenfield and Baxter 2007; Kimmerer 2002b; Thomson et al. 2010; Maunder et al. 2015; Stevens and Miller 1983; Nobriga and Rosenfield 2016). Statistically, the strongest relationship is with outflow between January and June. These months correspond to when adults are reproductively active and their larvae hatch, rear and are carried back downstream to more saline water.

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. The flow-abundance relationship was estimated following the methods of Kimmerer (2002b) using data collected between 1967 and 2016 (Figure 3.5-2). Two step changes were included, the first following the invasion of the clam *Potamocorbula* (year>1987), and the second following the pelagic organism decline (year>2002). No statistical support was found for interactions between slope and time period. These results are consistent with those of Kimmerer (2002b), who reported a step decline in longfin smelt recruitment per unit Delta outflow after the clam invasion, and Thomson et al. (2010), who reported a second step decline in catch per trawl after the pelagic organism decline. Higher outflow in winter and spring is associated with more smelt in fall. The regression analysis does not consider the potential importance of spawning stock size on subsequent recruitment (Nobriga and Rosenfield 2016). More adult stock could result in greater recruitment than predicted based on flow alone.

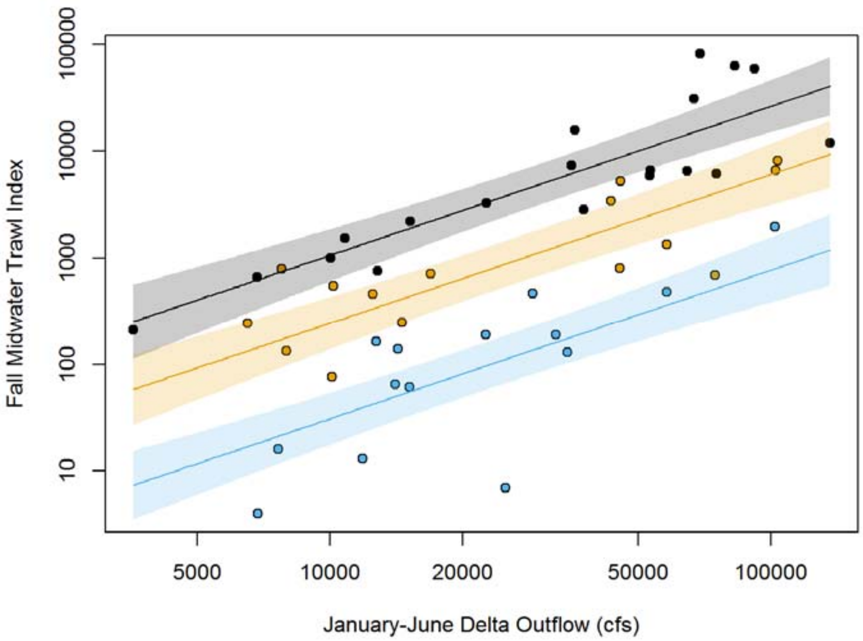

Figure 3.5-2. FMWT Index Values for Longfin Smelt Regressed against January through June Average Daily Delta Outflow for 1967–2016 with Step Changes following 1987 and 2002. Black and orange points and lines are for years before and after the invasion of *Potamocorbula* in 1987, respectively. Blue points and lines represent the post-pelagic organism decline period, beginning 2003. The estimates of flow responses and step changes differ significantly from zero (P<0.001, two sided t-tests; R^2=0.83). Colored bands around the lines represent 95 percent confidence limits.

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. The following 5 years were classified as below normal to critically dry. Longfin smelt abundance increased in 2011 and declined in the following 5 years (Figure 3.5-1). The response indicates that the longfin smelt population is still able to respond positively to favorable environmental flow conditions.

State Water Board staff conducted a logistic regression analysis[17] to estimate the magnitude of flow associated with positive longfin smelt population using data from 1967 to 2016 (Figure 3.5-3). A similar approach was used by The Bay Institute (TBI) (2010a) in analyses submitted for the 2010 Flow Criteria Report (State Water Board 2010) using data from 1988–2007. The flows in the State Water Board analyses associated with a 50 percent probability of positive population growth was 42,800 cfs between January and June, respectively (Figure 3.5-3). In comparison, TBI (2010a) found that positive population growth was predicted for 51,000 cfs between January and March or 35,000 cfs between March and May. The specific flow estimated to correspond to a 50 percent probability of population growth is sensitive to the choice of months and years included in the analysis. However, both sets of results are indicative of the positive response of longfin smelt population growth to an increase in Delta outflows. Delta outflows predicted to increase the longfin smelt population are summarized in Table 3.5-1.

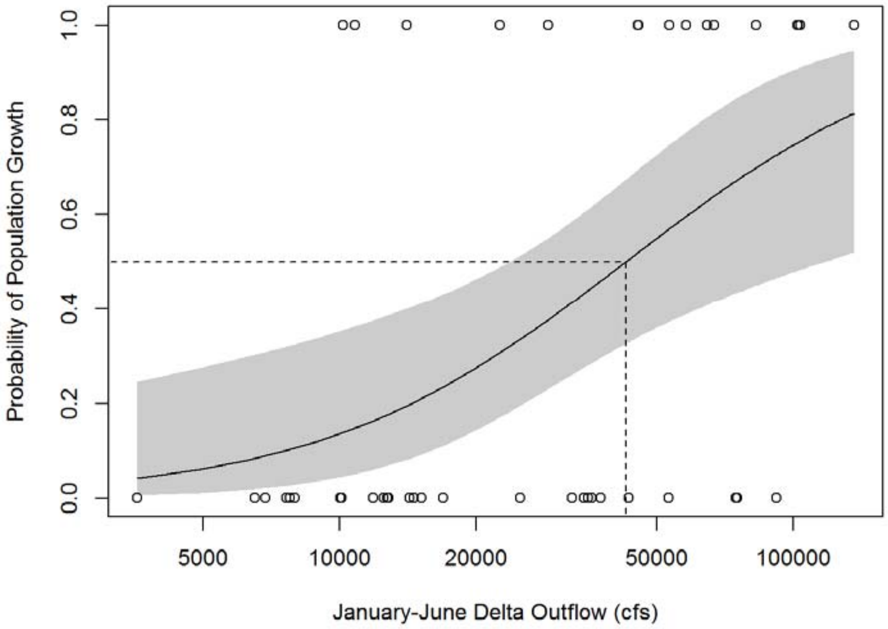

Figure 3.5-3. Probability of Positive Longfin Smelt Population Growth and 95 Percent Confidence Limits as a Function of January through June Average Daily Delta Outflow (1967 through 2016). Dashed lines indicate the flow that is associated with positive population growth in 50 percent of years. The flow effect differs significantly from zero (P<0.01, two-sided Wald test).

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[17] Logistic regression analysis is described in *Updated Quantitative Analysis* (section 3.3.1).

3.5.4.2 Interior Delta Flows

Export pumping at the State and Federal facilities that causes OMR reverse flow may result in the movement of large numbers of fish, including longfin smelt, into the interior Delta and result in their entrainment (USFWS 2008; NMFS 2009a). Grimaldo et al. (2009a) reported that 122,747 longfin smelt were salvaged at the CVP and SWP facilities between 1992 and 2005. However, entrainment loss of fish, including longfin smelt, as a result of OMR reverse flow, is difficult to quantify (Baxter et al. 2009). Estimates of salvage 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 that pass through the screen louvers, and mortalities from handling, transport, and release back into the Delta after salvage (Baxter et al. 2009). Counts of fish 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 currently exists (Thomson et al. 2010; Maunder et al. 2015; Mac Nally et al. 2010).

Baxter et al. (2009) conducted an analysis of CVP and SWP export pumping for the CDFW longfin smelt ITP 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.

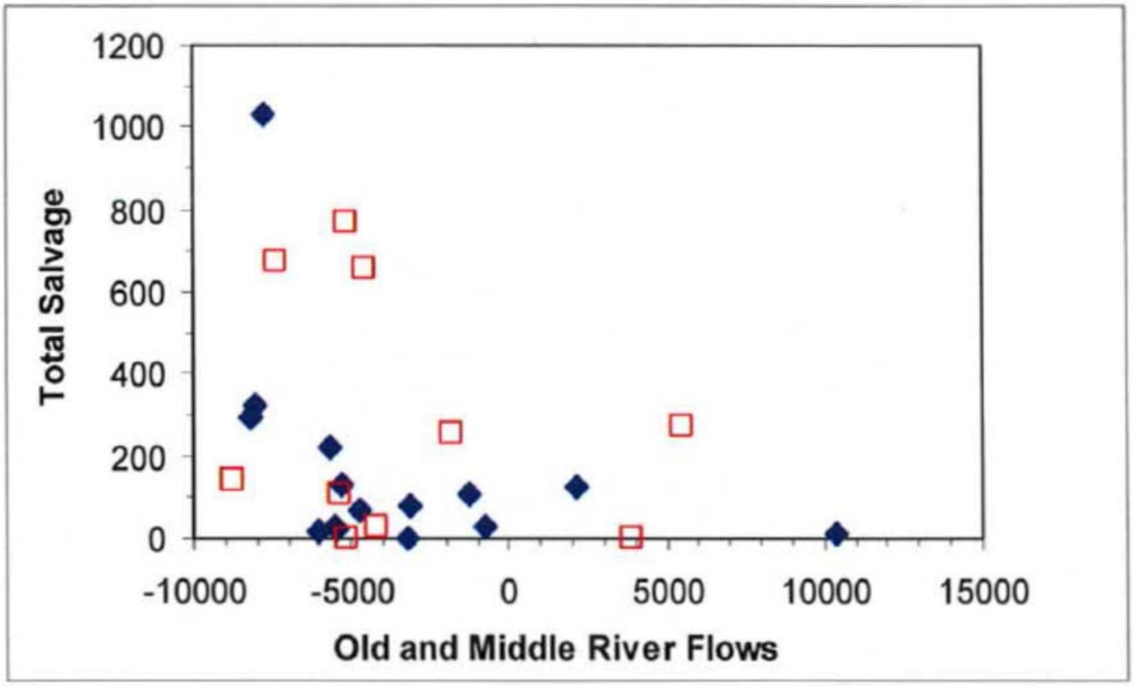

Figure 3.5-4. Total Salvage of Longfin Smelt between December and March as a Function of Average Old and Middle River (OMR) Flows during the Same Period for Water Years 1982–1992 (squares) and 1993–2007 (diamonds). OMR estimates for 1982–1992 were based upon calculations conducted by Lenny Grimaldo; 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).

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 flows. Grimaldo et al. (2009a) found a similar negative relationship between juvenile longfin smelt salvage and the magnitude of OMR flow. The lowest salvage rates occurred in the Baxter et al. (2009) analysis at positive OMR flows (Figure 3.5-5).

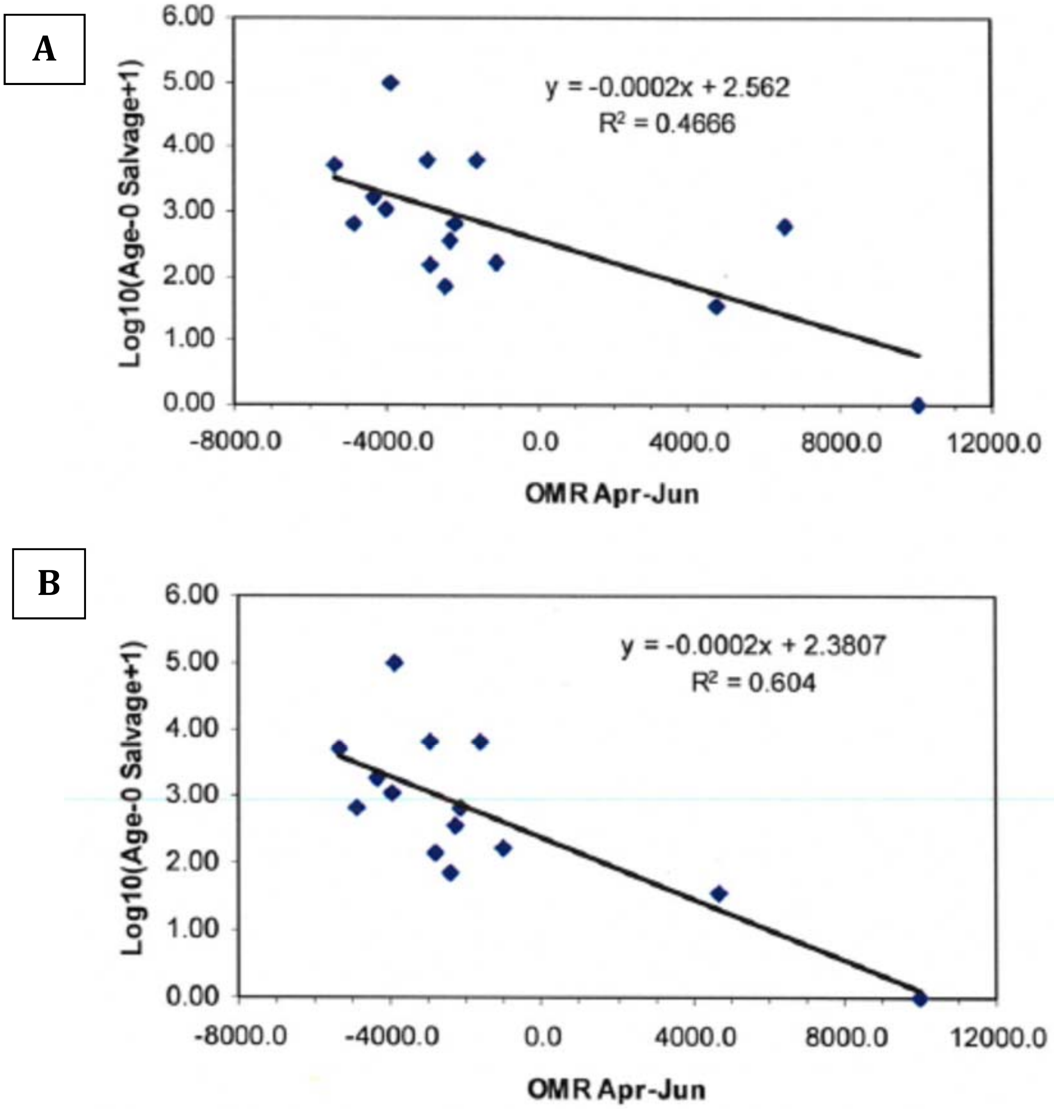

Figure 3.5-5. (A) Relationship between Average OMR Reverse Flows in April to June and the Sum of SWP and CVP Juvenile (age-0) Longfin Smelt Salvage during the Same Time Period, 1993–2007. (B) Presents the same regression as in (A) excluding 1998 when a protracted SWP export shutdown allowed longfin smelt 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 X2 and negatively associated with Delta outflow between January and June (Figure 3.5-6) (Baxter et al. 2009). 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). The Delta outflow salvage relationship is used to justify suspending the OMR reverse flow requirements when outflow exceeds 55,000 cfs.

Entrainment of longfin smelt at CVP and SWP facilities is no longer considered a major threat to the population if the USFWS Delta smelt BiOp and CDFW longfin smelt ITP are enforced (77 FR 19755; USFWS 2016).

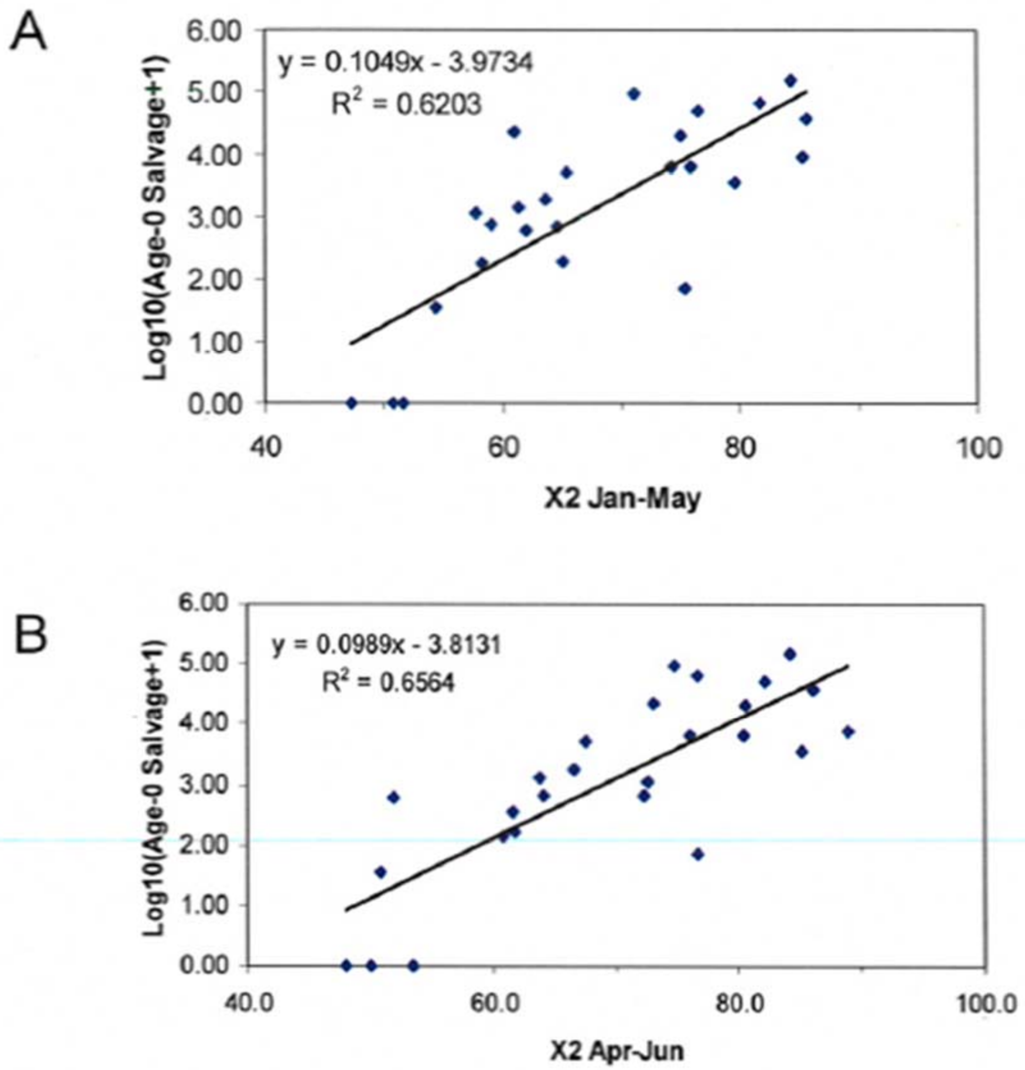

Figure 3.5-6. (A) Relationship between the Average Location of X2 between January and May and the Sum of Juvenile (age-0) Longfin Smelt Salvage between March and July at the SWP and CVP. (B) Relationship between the Average Location of X2 in April and June and the Sum of Juvenile (age-0) Longfin Smelt 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 (Rosenfield and Baxter 2007; Baxter et al. 2009). Adults may travel farther into the Delta in some low flow years to reproduce and this increases the vulnerability of their offspring to entrainment from OMR reverse flow (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 with negative OMR flows (Figure 3.5-5). The lowest salvage rate was measured at positive OMR flow (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 and are consistent with the USFWS Delta smelt BiOp and the CDFW ITP for longfin smelt.

Table 3.5-1. Delta Outflow and OMR Reverse Flows Indicated to Be Protective of Longfin Smelt Recruitment. 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	42,800											
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 white sturgeon recruitment (Klimley et al. 2015; Fish 2010), and similar relationships are likely for green sturgeon. 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 2005b, 2010) selecting river reaches with small to large sized gravel and turbulent high velocity currents for reproduction (Poytress et al. 2015; CDFG 2002; Heublein 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; CDFG 2002). Green sturgeon spawning has been documented in the Feather River and possibly in the Yuba River (Seesholtz 2014; Bergman et al. 2011). 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; CDFG 2002; Poytress et al. 2015). Spawning on the Sacramento River extends from about 36 miles below the RBDD to about 22 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 low 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[18] 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 (CDFG 2002). Larval green sturgeons are often found in the rotary screw trap at the RBDD and at the Glen Colusa Canal in May through July (Beamesderfer et al. 2004; CDFG 2002). Juveniles spend their first several years in the Delta before emigrating to saltwater (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 2 to 4 years for females and every 1 to 2 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 6 days before larvae seek cover for about 10 days to complete absorption of their egg sac (Deng et al. 2002). After the egg sac

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

is absorbed, 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).

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, *Potamocorbula*, 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 in the Sacramento basin comes from genetic studies. 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 2009a) 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 2009a). More recent monitoring data indicate that the mean number of adult green sturgeon in the Sacramento River between 2010 and 2015 ranged from an annual low of 164 to a high of 526 individuals (personal communication Ethan Mora in NMFS 2015). The USFWS (1996) Native Fish Recovery Plan recommends a restoration goal of at least 1,000 adult fish in the Sacramento River and Delta during spawning season.

A decline in green sturgeon population abundance has been inferred by the NMFS from reductions in the average number of juveniles salvaged annually at the SWP and CVP pumping facilities (NMFS 2009a). 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 2009a).

3.6.3.2 White Sturgeon

Abundance information for adult white sturgeon in the estuary comes from a mark-recapture population study and other population estimates from the CDFW (DuBois et al. 2011). The mark-recapture study estimated that in 2009 there were 70,000–75,000 individuals ≥102 cm (TL) and 3,252–6,539 age-15 fish, which is below the CVPIA recovery goal of 11,000 age-15 fish. Population estimates between 1979 and 2009 are marked with high temporal variation, having been as high as >300,000 individuals ≥102 cm (TL) in 1994 and as low as ~25,000 individuals in 1990.

Population trends of legal-sized individuals are based on Commercial Passenger Fishing Vessel catch per unit effort (CPUE) and from the mark-recapture study CPUE (Dubois and Gingras 2013). These two measurements generally track one another and indicate that CPUE is highly variable through time. DuBois and Gingras (2013) suggest that the trends can be explained by strong year classes during 1969-1975 and wet years in the early 1980s and mid- to late 1990s.

3.6.4 Flow Effects on Green and White Sturgeon

3.6.4.1 Delta Outflow

Less information exists on the flow needs of green sturgeon because of the small size of the population. 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 (for 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, though the population does not appear stable and exhibits progressively diminishing recruitment in recent wet years (Figure 3.6-1).

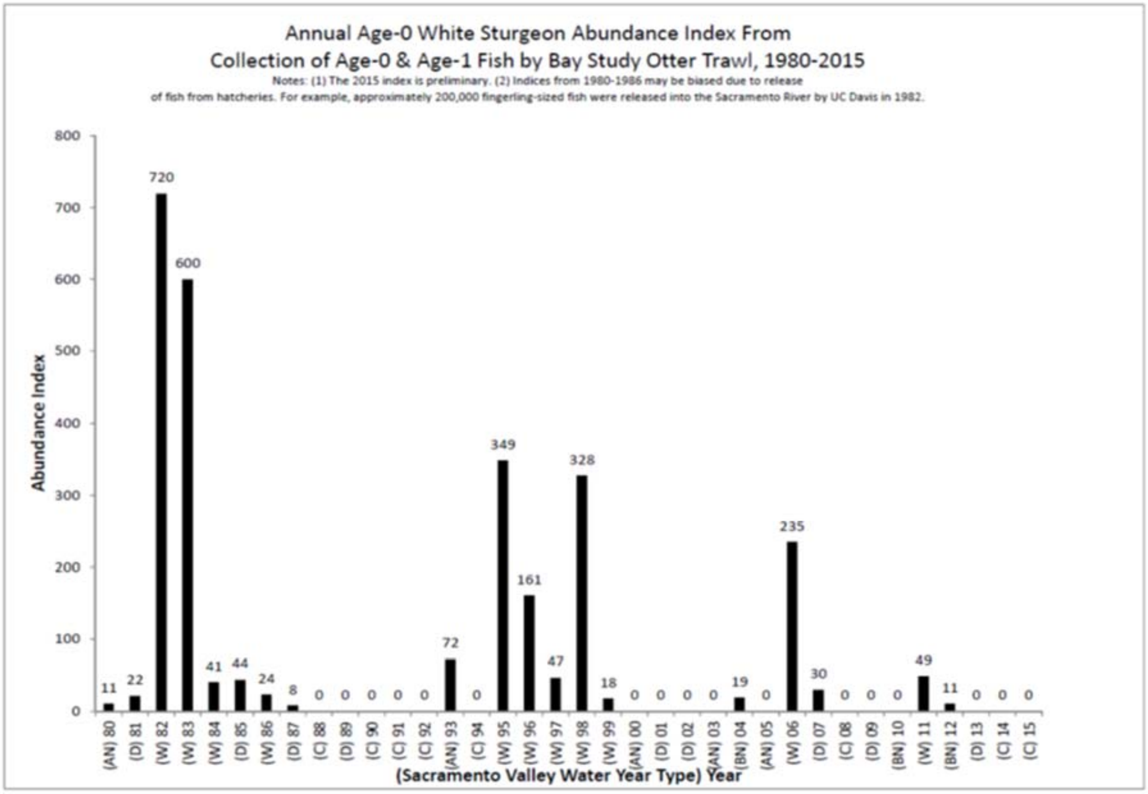

Figure 3.6-1. White Sturgeon Year Class Indices for San Francisco Bay from 1980 through 2015

CDFG (1992a) 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. CDFG (1992a) 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 et al. (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 and 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 were associated with 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. Gingras et al. (2014) also implicated recreational fishing as a factor negatively 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). This conclusion is consistent with a recent reassessment of the flow requirements for successful white sturgeon recruitment. The new analysis concluded that strong recruitment only occurred in the Sacramento basin in wet water years when the Sacramento water year index exceeded 10 (DuBois 2017). Robust monitoring and special studies will be needed to determine the causal mechanisms (temperature, habitat, food web) to establish priorities for habitat restoration and the best flow regimes to support successful reproduction and survivorship.

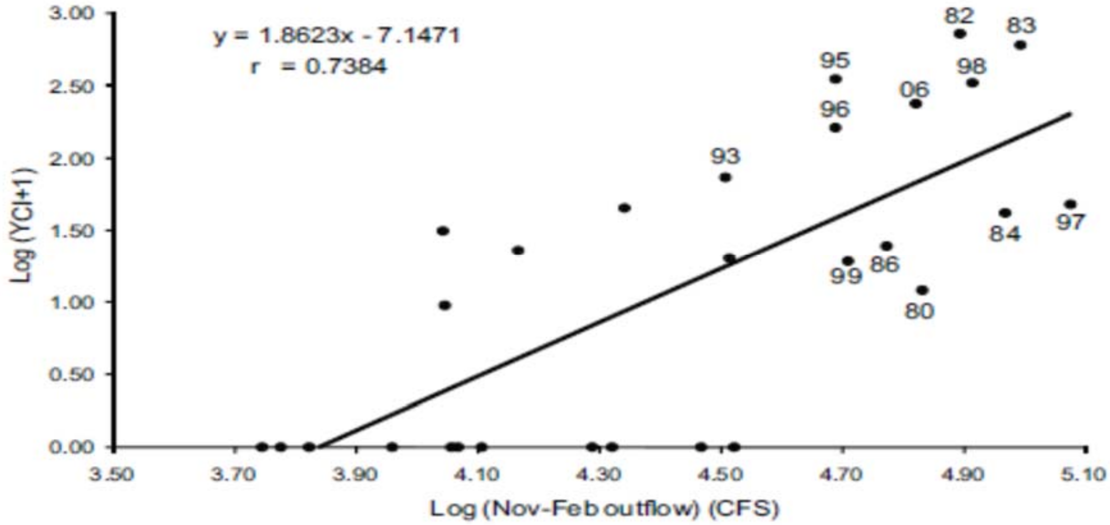

Figure 3.6-2. White Sturgeon Year Class Index (YCI) from San Francisco Bay Study Otter Trawl Catch versus Mean Daily Delta Outflow from November through February (numbers adjacent to points designate year classes [from Fish 2010])

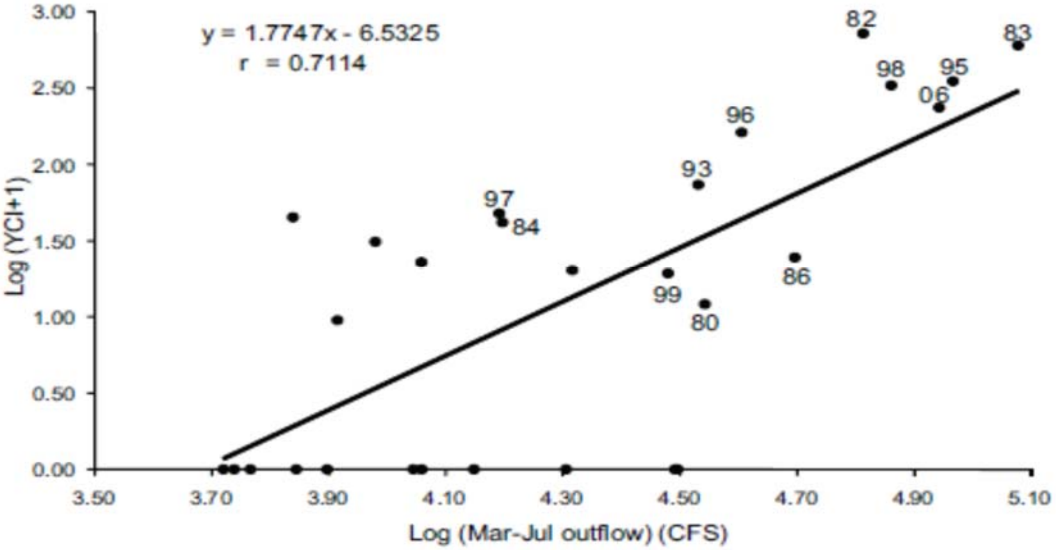

Figure 3.6-3. White Sturgeon YCI from San Francisco Bay Study Otter Trawl Catches versus Mean Daily Delta Outflow for March through July (Numbers adjacent to points designate select year classes. Log (4.7) is equivalent to a flow rate of 50,000 cfs [from Fish 2010]).

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 2009a). 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 exists that exports affect white sturgeon population abundance (CDFG 1992a, 2002) and there are currently no other OMR restrictions for green sturgeon included in the BiOps or ITPs.

3.7 Sacramento Splittail (*Pogonichthys macrolepidotus*)

3.7.1 Overview

Sacramento splittail is a native species that has decreased in abundance, and the age 0 year class 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. Analyses presented below indicate that Delta outflows of 30,000 to 47,000 cfs are needed between February and May to provide strong splittail recruitment. These are among the largest flows needed by any Bay-Delta estuarine fish species for recruitment. The magnitude of these flows might be reduced by installing an operable gate on the Fremont Weir, thereby reducing the river stage required to flood the Yolo Bypass.

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; Feyrer et al. 2015). Fish collected in the Napa and Petaluma Rivers have been identified as a genetically distinct population that has limited overlap with the Central Valley population (Baerwald et al. 2008, 2007). Analysis in this report is for the Central Valley portion of the population. 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 typically live 5 to 7 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, vegetated channel margins, and perennial marshes may be used for spawning and rearing (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 3 to 7 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*.* 2006; Sommer et al. 1997). Two factors appear important for successful floodplain recruitment (Feyrer et al. 2006). 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 under water 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 when the Yolo Bypass has been flooded for 30 or more days (Meng and Moyle 1995; Feyrer et al*.* 2006). 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

State Water Board staff reexamined the interannual trend in the FWMT index for juvenile splittail recruitment using data collected through 2016 and found a statistically significant decreasing trend (R^2=0.22, P<0.001, two-sided t-test) (Figure 3.7-1). Current estimates of population abundance are now about two percent of early values. The USFWS Beach Seine juvenile splittail abundance index also shows a decline in juvenile population abundance (La Luz and Baxter 2015). Recruitment in the FMWT index has decreased by 91 percent since implementation of D-1641 in 2000.

The 2010 Flow Criteria Report (State Water Board 2010) recommended a goal of stabilizing juvenile Sacramento splittail recruitment and beginning to grow the population. The long term population index value and recovery goal evaluated for this report was equal to the median FMWT index from 1967 to 2014 as recommended by the State Water Board (2010). The median FMWT value between 1967 and 2014 was 10. The average FMWT index from 2012 to 2014 was 1 and has not been above 10 since 2001 (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 2002b; CDFG 1992b). No change in the flow recruitment relationship was observed after the invasion of *Potamocorbula* (Kimmerer 2002b).

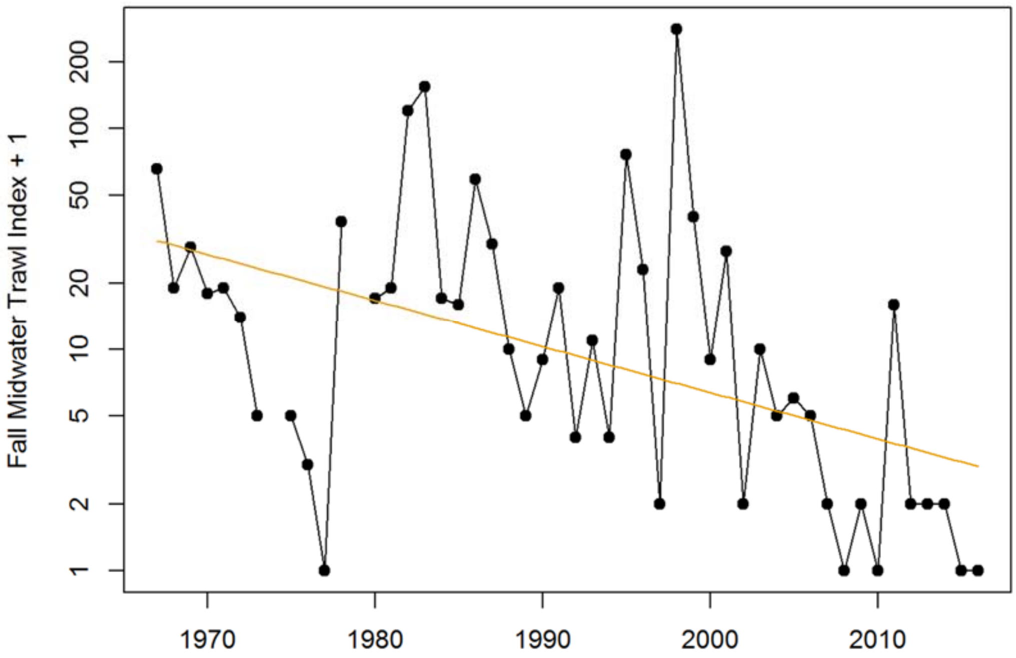

Figure 3.7-1. Sacramento Splittail Population Recruitment as Measured in the FMWT Survey (1967–2016). The solid line is the least squares linear regression of the logarithm of FMWT index (incremented by 1) against years. The slope of the regression differs significantly from zero (R^2=0.22; P<0.001, two-sided t-test).

State Water Board staff reassessed the flow recruitment relationship with new data collected through 2016 using the same method employed by Kimmerer (2002b) (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 recruitment relationship that has existed since sampling began in 1967 (Kimmerer 2002b). Increased outflow between February and May coincides with the timing of adult spawning and larval rearing in riverine floodplains and terraces and 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 recruitment goal. First, a regression analysis was conducted with Delta outflow during the February through May time frame and splittail recruitment to determine that 30,000 cfs was correlated with the recruitment 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 30,000 to 47,000 cfs is needed between February and May to meet the recruitment goal (Table 3.7-1). An alternate non-flow related recruitment goal might be to recommend the magnitude, duration, and frequency of periodic flooding of the Yolo Bypass and other floodplains.

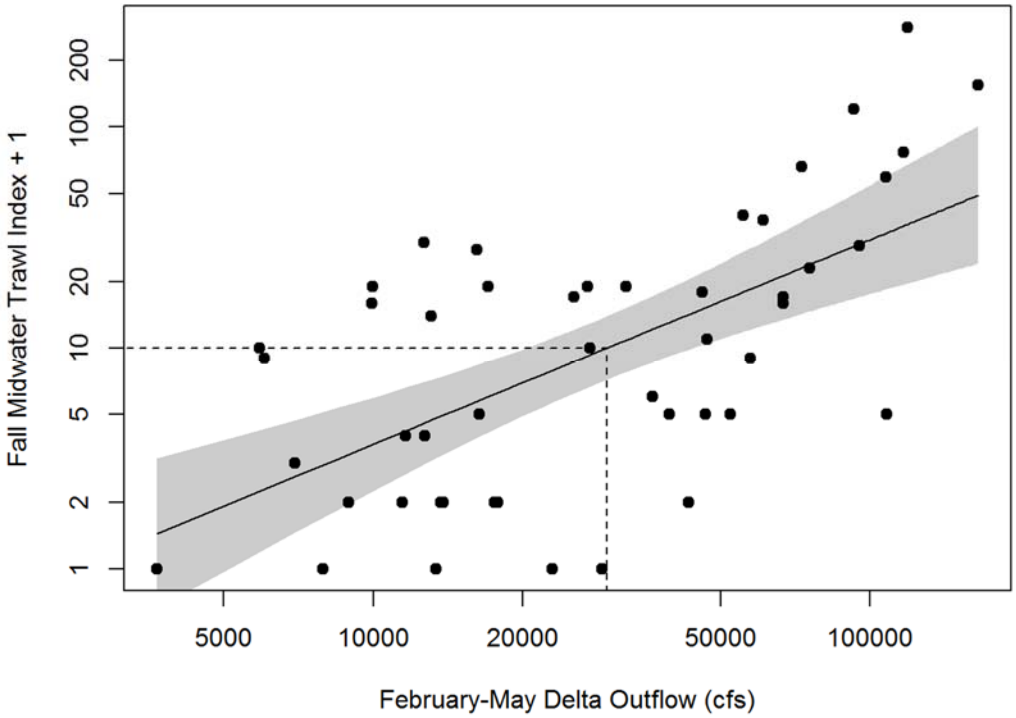

Figure 3.7-2. Correlation between the Sacramento Splittail FMWT Index (1967–2016) and Average Daily Outflow (cfs) between February and May. The slope of the flow recruitment relationship differs significantly from zero (R^2=0.31, P<0.001, two-sided t-test). The dotted line indicates that a flow rate of 30,000 cfs is correlated with the recommended abundance index of 10. The shaded band represents the 95 percent confidence limits around the regression line.

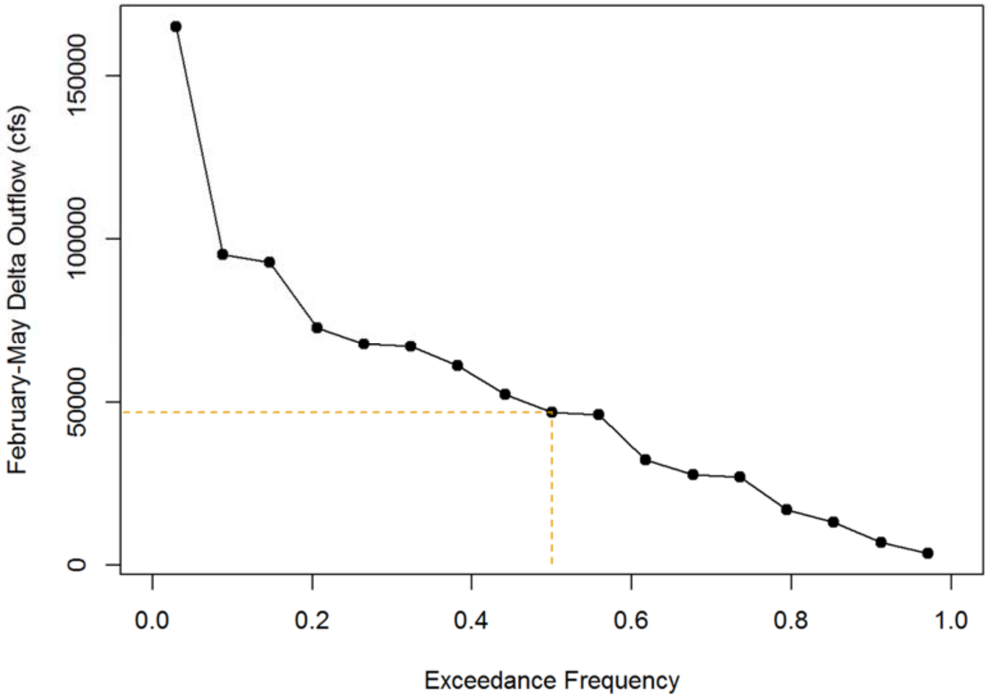

Figure 3.7-3. Cumulative Frequency Distribution of Average Daily Outflow between February and May for 1967 to 1983. The dotted line is the daily average outflow (47,000 cfs) that occurred in half of all years.

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		30,000–47,000										

3.7.4.2 Interior Delta Flow

Sacramento splittail have been salvaged at the CVP and SWP pumping facilities in many years when San Joaquin flows are high and recruitment is good throughout the Bay-Delta system. 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 3 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). In 2011, another wet year, almost 9 million splittail were salvaged at the CVP and SWP pumping facilities (Aasen 2012).

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 1 year with adults moving into areas such as the northern Delta and Suisun Marsh from Suisun Bay and the confluence of the Sacramento-San Joaquin Rivers to spawn and die and their offspring migrating back to these areas to rear. There is also a resident year-round freshwater population in the Cache Slough complex. 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. Since 2003 the population abundance of larval Delta smelt in spring has been 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 migrate back downstream in late spring and early summer. The species is listed as threatened by the USFWS and as endangered by the CDFW. In 2010, USFWS determined that uplisting Delta smelt to endangered status was warranted but was precluded by the need to address higher priority species first.

3.8.2 Life History

Delta smelt are endemic to the Delta and upper estuary. The species has an annual, 1-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 an upstream spawning migration from the LSZ to freshwater (Grimaldo et al. 2009a), though there is also evidence of freshwater resident smelt in the Cache Lindsey Slough complex, Sacramento River Deepwater Ship Channel, and lower Sacramento River in the vicinity of Sherman Island (Hobbs et al. 2007; Baxter et al. 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 upstream precipitation (Grimaldo et al. 2009a; 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 are a factor associated with population-level migrations (Grimaldo et al. 2009a; Sommer et al. 2011). Pre-spawning adults move furthest upstream during low outflow years. If the population 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 includes Grizzly Island, the lower Sacramento, San Joaquin, and Mokelumne Rivers and the northern, 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 and presumably reflects larvae emerging at the locations where the eggs were laid. Upon hatching the larvae are buoyant for the first several days before becoming semi-buoyant, staying near the bottom (Mager et al. 2004). 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 several kilometers upstream of X2. As larvae grow and water temperature increases, most larval and juvenile distributions shift downstream towards the LSZ (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 et al. 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 center of the distribution of juvenile and sub-adult Delta smelt is tightly coupled with X2 (Sommer et al. 2011) although this does not mean that all Delta smelt are confined to a narrow salinity range because fish occur from freshwater to relatively high salinity (Sommer and Mejia 2013).

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; Merz et al. 2016). The transition between the high abundance of the two copepods has been hypothesized to create a "food gap" during spring and early summer (Bennett 2005; Miller et al. 2012). The analyses of Kimmerer (2008) and Baxter et al. (2015) support the hypothesis that Delta smelt abundance and survival from summer to fall is affected by food availability in the LSZ. The diets of sub-adult Delta smelt are broader and include a higher frequency of amphipods and mysids along with *P. forbesi* (Baxter et al. 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 Tow Net Survey (STN) (June–August), Spring Kodiak Trawl Index (January–May), and the FMWT Survey (September–December), respectively (Kimmerer et al. 2009). All four surveys indicate that the Delta smelt population has declined significantly and is at a record low level (La Luz and Baxter 2015).

State Water Board staff reexamined the inter-annual trend in the FMWT index with data collected through 2016 and found a statistically significant decreasing trend ($R^2=0.53$, $P<0.001$, two-tailed t-test) (Figure 3.8-1). The most recent FMWT index values are about 2 percent of values measured around 1967.[19] Present indices are about 5 percent of values measured around 2000 when D 1641 was implemented. Eleven out of the last 12 years had the lowest FMWT index values ever recorded (Figure 3.8-1).

The Delta smelt FMWT index rebounded in 2011, a the wet year (Figure 3.8-1), when high outflows occurred throughout the year (including winter, early spring and fall) demonstrating that despite significant declines, Delta smelt are still able to respond positively to improved environmental conditions.

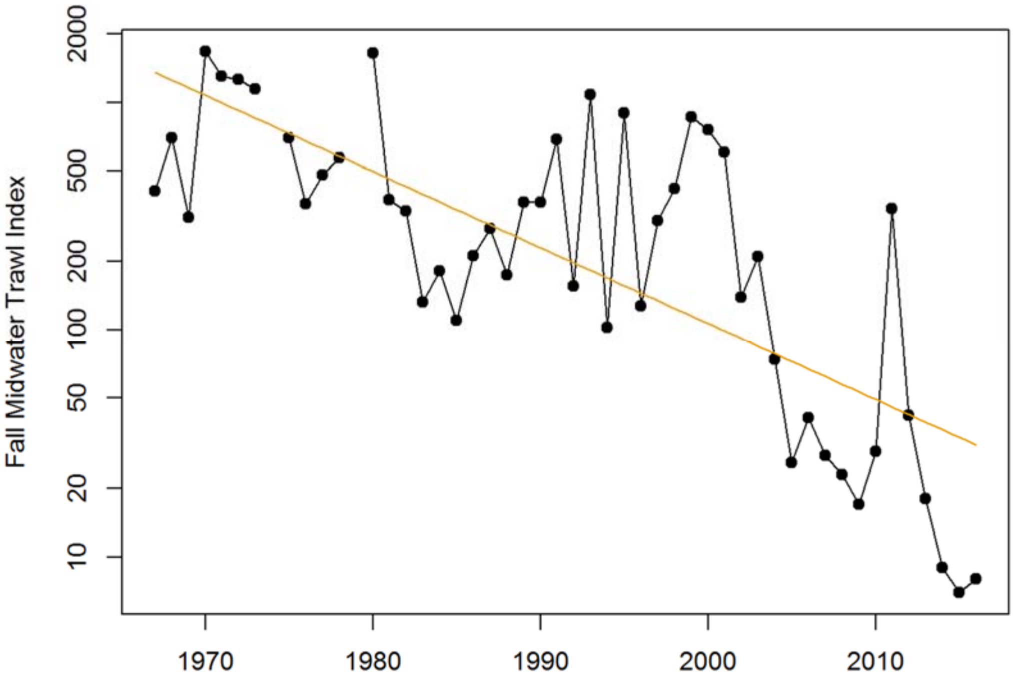

Figure 3.8-1. Inter-Annual Trend in the FMWT Index for Delta Smelt (1967–2016). The solid orange line is the least squares linear regression of the logarithm of the FMWT index against years. The slope of the regression differs significantly from zero ($R^2=0.53$; $P<0.001$, two-sided t-test).

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[19] The decrease was estimated from the average of the first five (1967–1971) and the last five (2012–2016) annual FMWT index values to account for inter annual variation in population abundance. Similarly, percent change after adoption of 1641 was calculated from the average of index values for 2000–2004 and 2012–2016.

Delta smelt was listed as threatened under the federal ESA in 1993 (58 FR 12863). As noted above, 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 also listed as threatened under CESA in 1993 (CDFW 2016c) and as endangered in 2009 (CDFW 2016c). 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).

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; Miller et al. 2012), summer water temperature (Mac Nally et al. 2010; Maunder and Deriso 2011; Miller et al. 2012; Rose et al. 2013) and predators (Maunder and Deriso 2011; Mac Nally et al. 2010). 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 (Baxter et al. 2015). Delta outflow may also be important in summer and fall to provide critical habitat for Delta smelt (Feyrer et al. 2007; Baxter et al. 2015; CDFW 2016d).

3.8.4.1 Winter and Spring Delta Outflow

Historically, Delta smelt had highest abundance indices at intermediate outflows between February and June and generally performed more poorly at both extremely high and low outflow (Baxter et al. 2015). This relationship disappeared after 2001 (Baxter et al. 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.[20] This approach is similar to the method used by Jassby et al. (1995) to describe the initial relationship between Delta outflow and the abundance of estuarine-dependent species (Baxter et al. 2015). The analyses identified a unimodal relationship between X2 or outflow (February–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[21] or by the number of spawning adults in the SKT survey[22] 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 greater during the spawning season. The spring outflow and the stock-recruitment relationships together explained 59 to 65 percent of the variation in the 20 mm index for the 11 years between 2003 and 2013 ($P<0.006$) (Baxter et al. 2015). The Baxter et al. (2015) report recommended that conclusions based upon the relationship between spring outflow and Delta smelt population abundance be considered

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[20] The 20 mm survey is conducted between March and July and indexes the abundance of large larvae and small juvenile smelt with annual indices based on data from 2 surveys prior and 2 surveys after mean Delta smelt length reaches 20 mm.

[21] The FMWT survey is conducted between September and December and allows calculation of an index of abundance of sub-adult smelt.

[22] The SKT survey is conducted between January and May to determine the distribution of adult Delta smelt, and allows calculation of an index of adults available to spawn.

preliminary until additional data, analyses and review were conducted to confirm the robustness of the results.

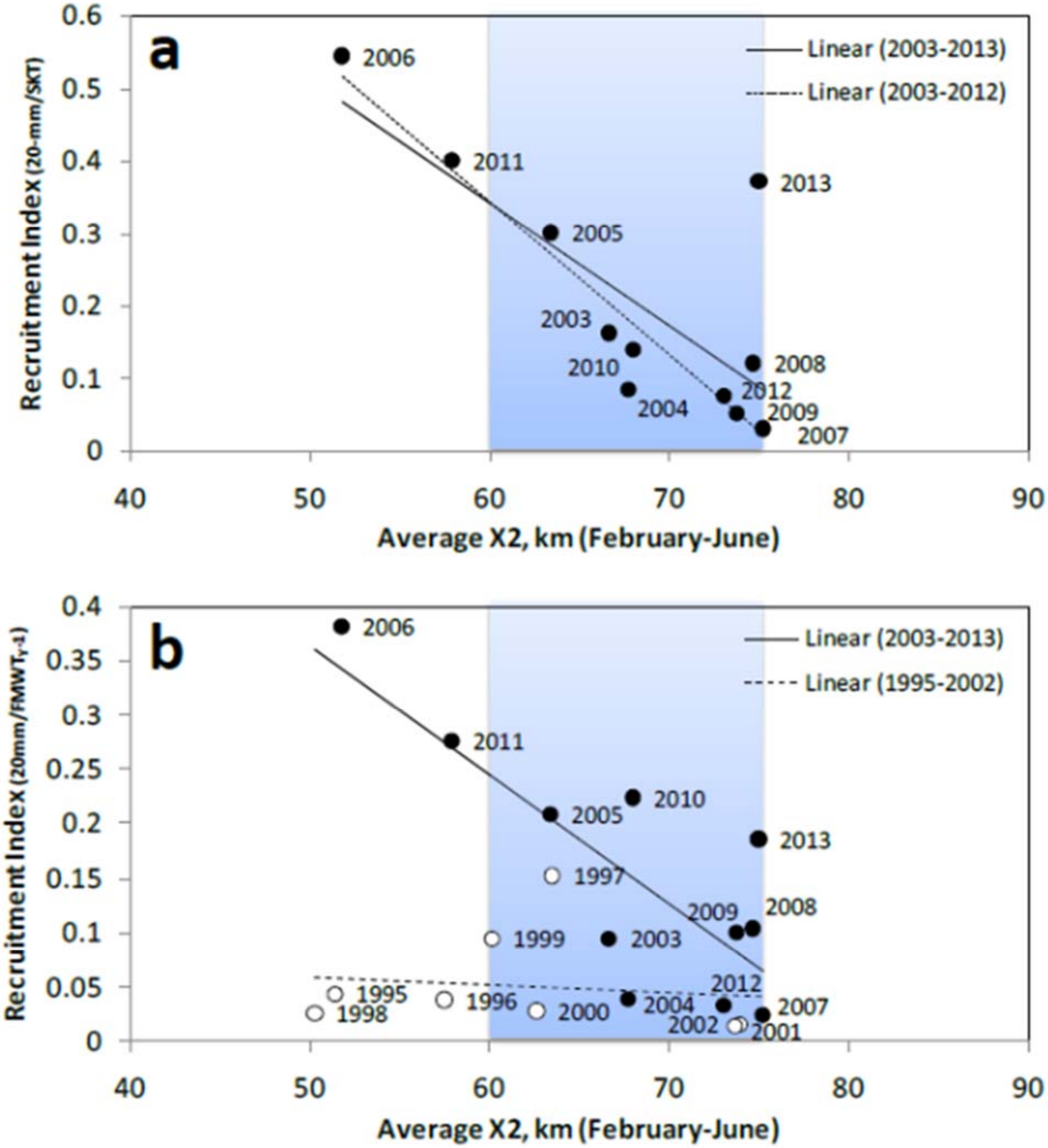

Figure 3.8-2. Adult (panel a, SKT) and Sub-Adult (panel b, FMWT from previous year) to Larval (20 mm survey) Recruitment Indices as a Function of Spring X2 (February–June) (for the 20 mm/SKT panel, a linear regression was calculated with and without 2013, which appears to be an outlier. For the 20 mm/FMWT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

3.8.4.2 Summer Outflow

Recent unpublished scientific evidence suggests that Delta smelt abundance in fall is positively related to Delta outflow during 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 2016d). In addition, survival of Delta smelt in summer, as measured by FMWT and STN,[23] was a positive function of Delta outflow (CDFW 2016d). 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. Gartrell (2016) in an unpublished report noted that outflow in July, August and September was positively correlated with flow in earlier months, including spring, when other research has noted a positive relationship between flow and recruitment (Baxter et al. 2015). The CDFW (2016d) hypothesizes that increased survival in summer 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.

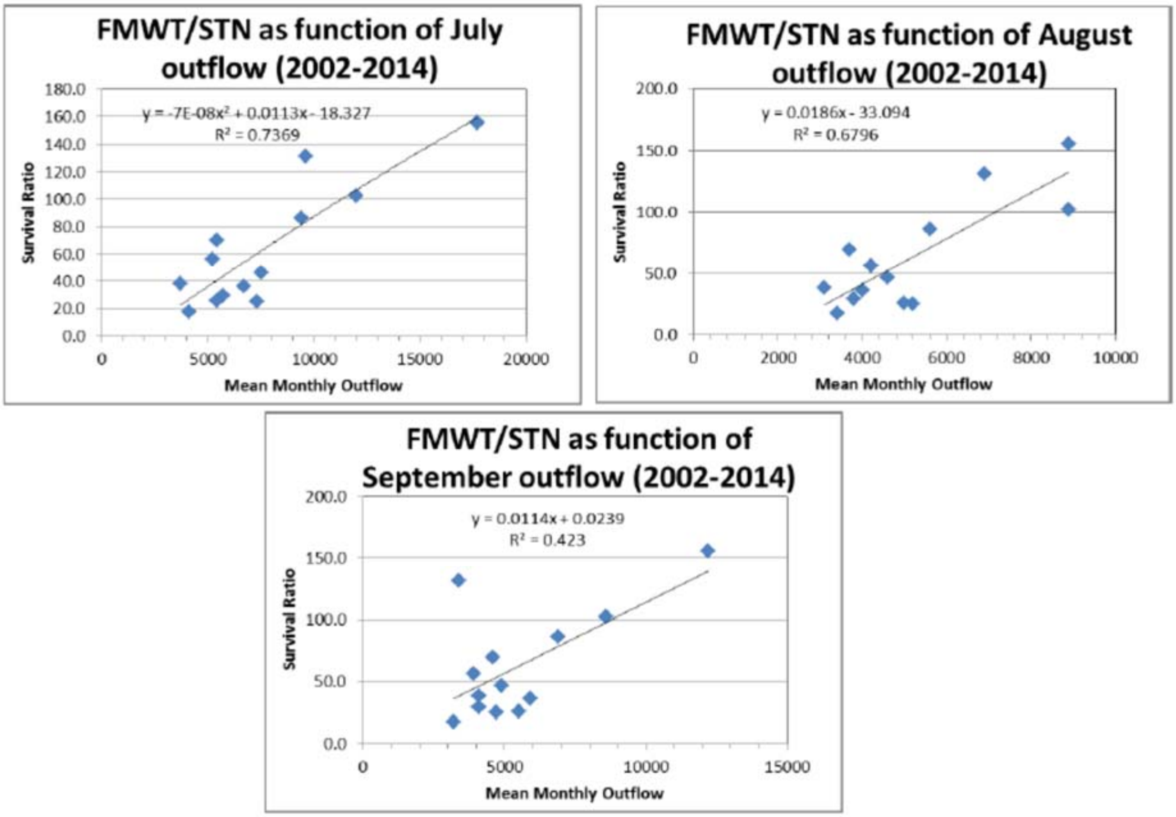

Figure 3.8-3. Delta Smelt Survival in Fall as a Function of Monthly Mean Delta Outflow (cfs), for July (top left), August (top right) and September (bottom). Survival is estimated as the quotient of the FMWT index divided by the STN index. All three relationships are statistically significant. (From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

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[23] The STN and FMWT monitoring occurs between June–August and September–December, respectively.

3.8.4.3 Fall Outflow

Feyrer et al. (2007, 2011) used the presence 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 further seaward then there was about 12,000 acres of high quality habitat located in Suisun Bay (Feyrer et al. 2011). If X2 was 85 km or more landward, then the amount of favorable habitat was about half as large and was located above the confluence of the Sacramento and San Joaquin Rivers (Feyrer et al. 2011). 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 (Baxter et al. 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 these observations, the USFWS BiOp requires that Delta outflow in September and October be managed so that X2 is no greater than 74 km[24] and 81 km[25] in wet and above normal water year types, respectively (Table 3.8-1) (USFWS 2008). In addition, the USFWS BiOp requires that all flow into CVP and SWP reservoirs in November during wet and above normal water years be released to increase Delta outflow and move X2 further downstream.

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.

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[24] This X2 value is roughly equivalent to a sustained Delta outflow of 11,400 cfs.

[25] This X2 value is roughly equivalent to a sustained Delta outflow of 7,100 cfs.

Baxter et al. 2015 report evaluated the effect of fall X2 on larval Delta smelt abundance as measured by the 20 mm index. The analysis found an inverse relationship between X2 during the previous fall and the abundance of larval smelt in the following 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 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 outflow in fall was correlated with 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 led to more offspring.

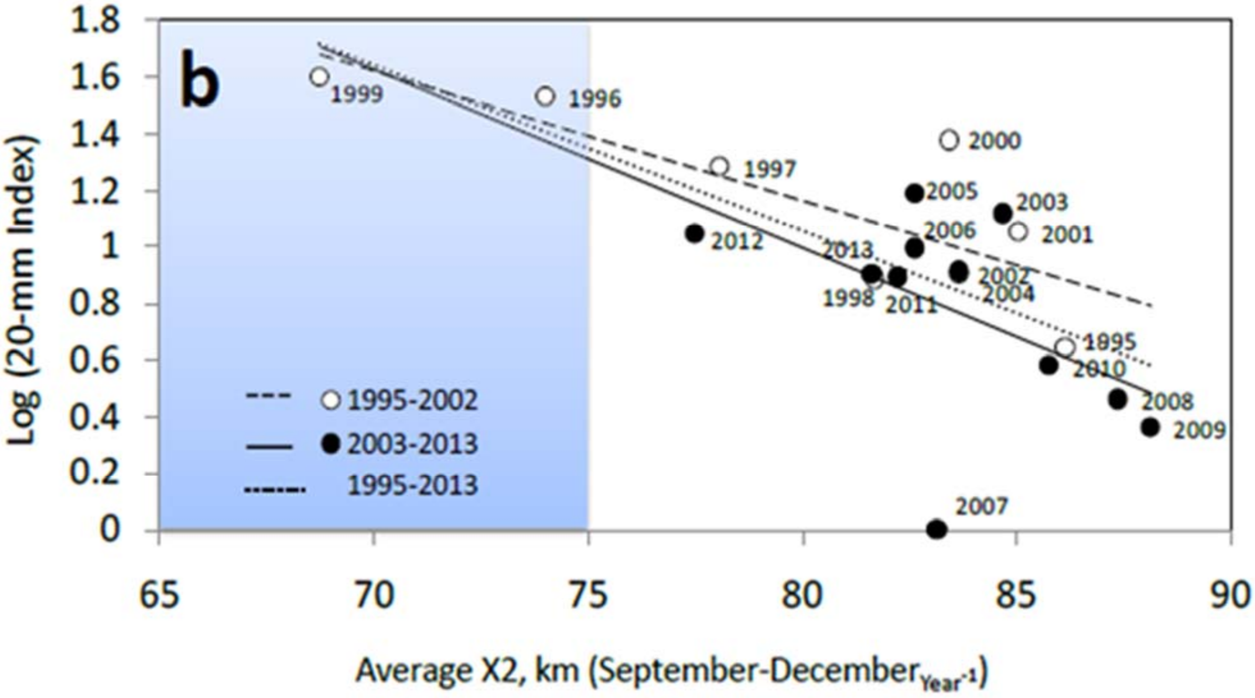


Figure 3.8-4. Plot of the Delta Smelt 20 mm Survey Abundance Index as a Function of the Location of the Previous Year's Fall X2 (figure from Baxter et al. 2015)

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 (Baxter et al. 2015; Grimaldo et al. 2009a). Larval and juvenile fish are also at risk of entrainment when hatching and rearing in the Central Delta or when moving downstream to Suisun Bay (USFWS 2008). 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 is 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. 2009a). Flows and turbidity of at least 20,000 to 25,000 cfs and 10 to 12 Nephelometric Turbidity Units (NTU) coincide with upstream migration, as indicated by peaks in salvage (Figure 3.8-6).

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). In addition, a high percentage of smelt are now found year-round in freshwater areas, such as the Cache Slough complex, Sacramento Deepwater Ship Channel, and toe drain of the Yolo Bypass (Merz et al. 2011; Sommer et al. 2011; Sommer and Mejia 2013).

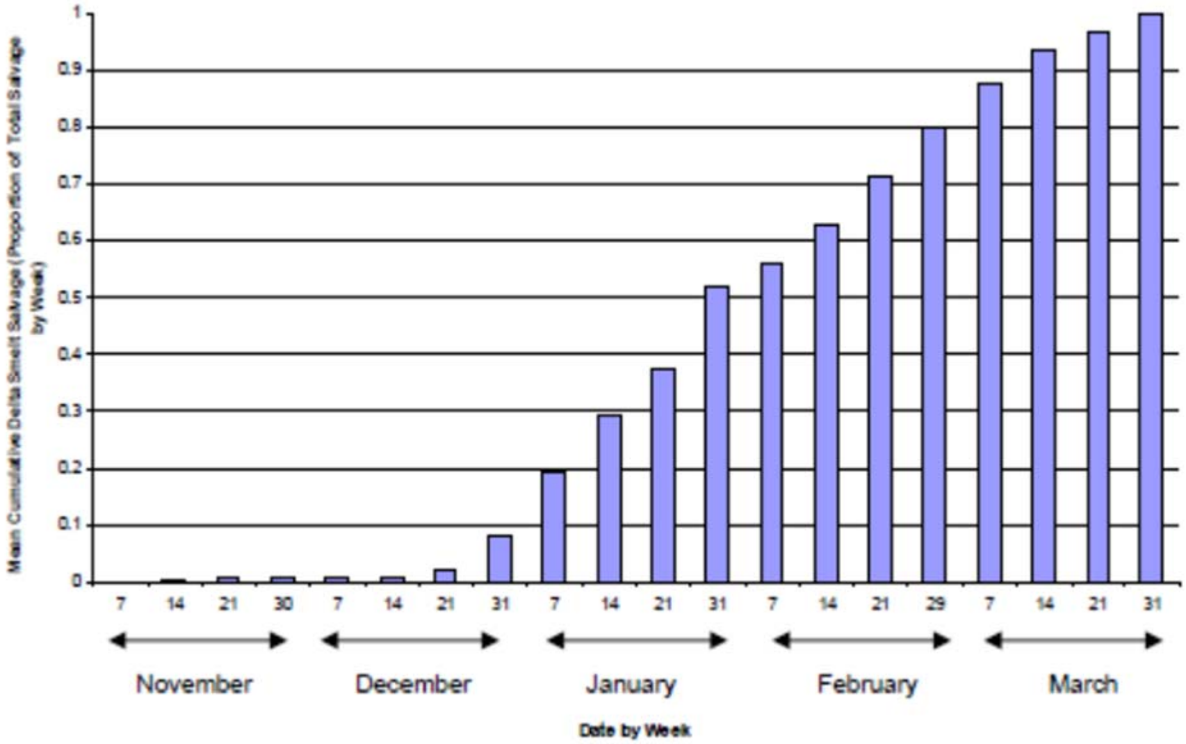


Figure 3.8-5. Cumulative Proportional Adult Delta Smelt Salvage by Week for 1993 to 2006 (from USFWS 2008)

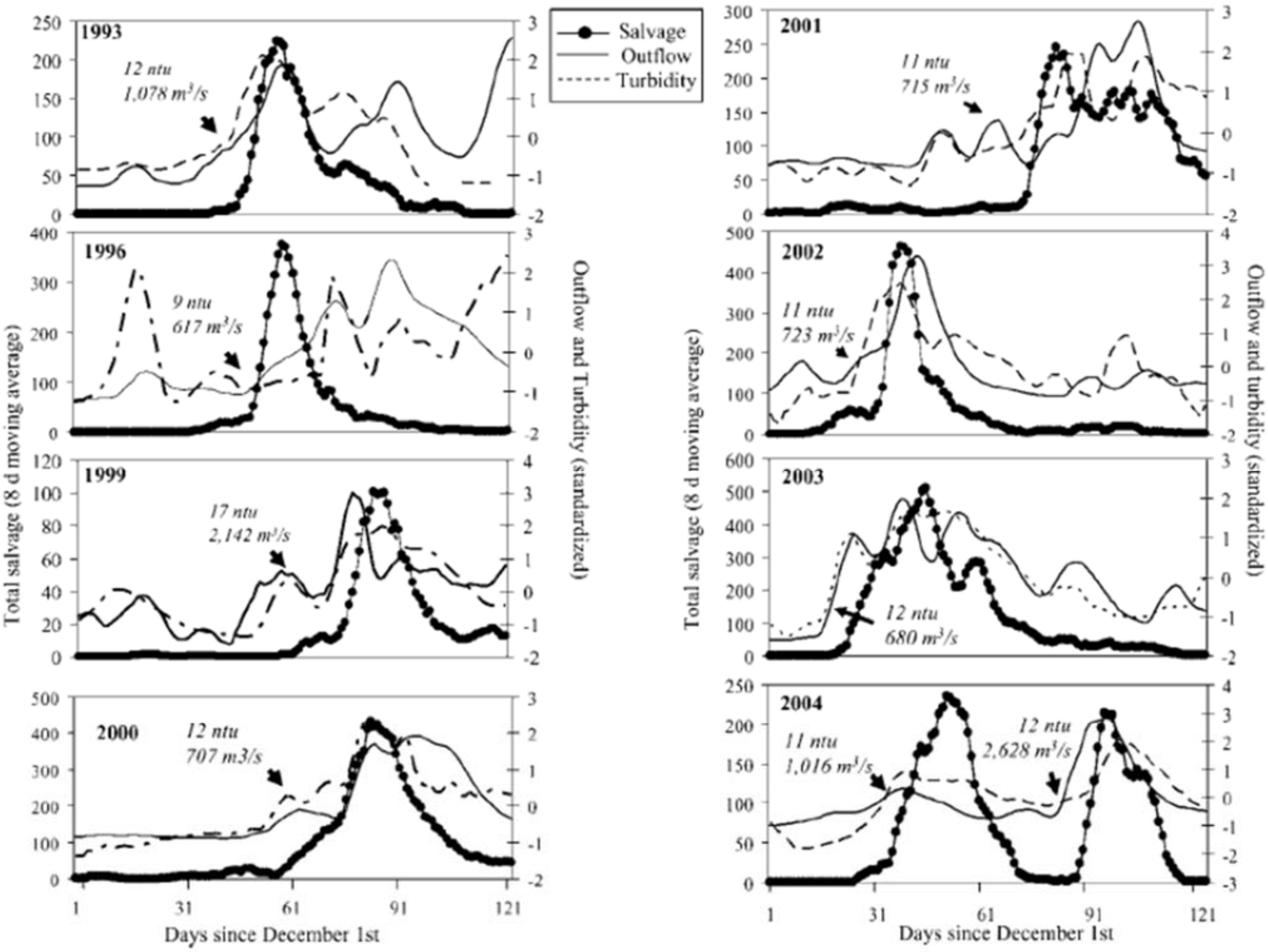
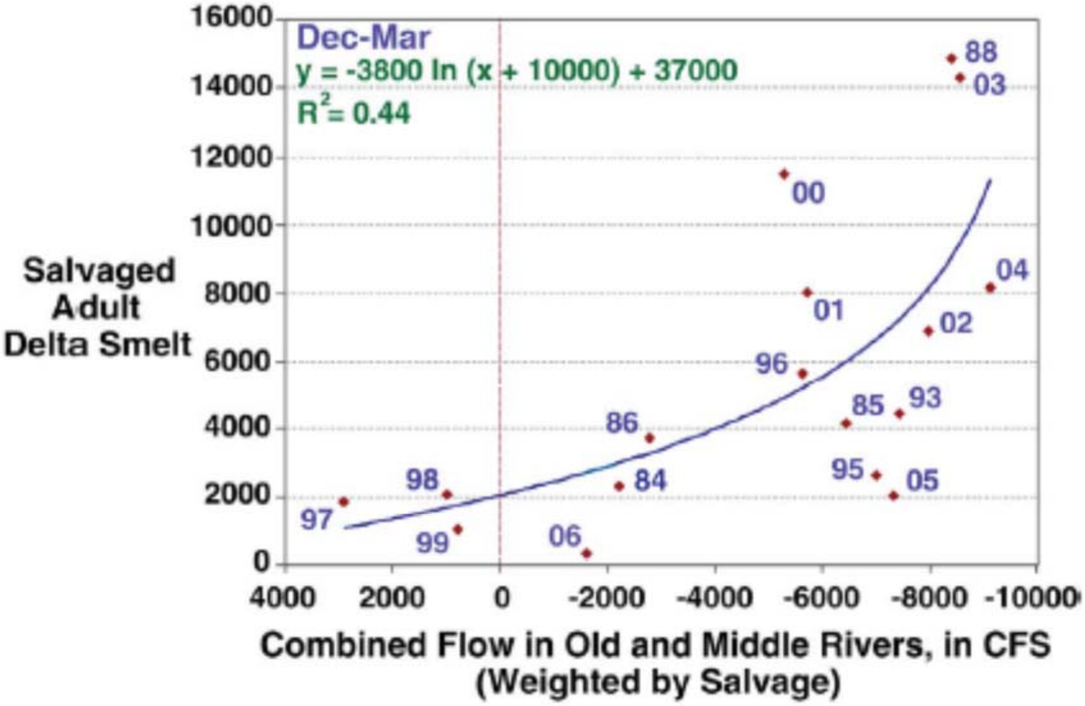


Figure 3.8-6. Eight-Day Running Averages of Adult Delta Smelt Salvage, Total Outflow (m³/s), Turbidity (NTU) for the Eight Most Abundant Delta Smelt Salvage Years between December 1992 and April 2005 at the SWP and CVP (total Delta outflow and turbidity were standardized to a mean of zero [from Grimaldo et al. 2009a])

The risk of 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. An inflection point at -5,000 cfs is consistent with similar increases in salvage for longfin smelt and salmon (Figures 3.5-4 and 3.4-16). The USFWS (2008) used a piecewise polynomial regression analysis to establish a break point in the data set and determined the 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 USFWS (2016) determined in their species assessment and listing priority assignment that entrainment at SWP and CVP Delta facilities remains a significant ongoing threat for the Delta smelt population.



Note: Data shown are for the period 1984-2007, excluding years 1987, 1989-92, 1994, and 2007 that had low (<12ntu) average water turbidity during Jan-Feb at Clifton Court Forebay.

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

The CDFW found that QWEST, the net lower San Joaquin River flow past Jersey Point in the Delta, is also a factor in controlling entrainment. A positive QWEST flow can provide net downstream transport for organisms in the San Joaquin River channel even when OMR is moderately negative (Baxter et al. 2009).

The conclusions from analyses of the salvage data are consistent with Grimaldo et al. (2009a) 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 indicate that OMR flows should be maintained between -1,250 and -5,000 cfs depending upon the presence of Delta smelt and other physical and biological factors, including turbidity, that are known to influence entrainment (Table 3.8-1). These recommendations are consistent with the requirements of Actions 2-3 from the 2008 USFWS Delta smelt BiOp reasonable and prudent alternative.

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 upper estuary 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 taken in the California commercial and recreational fishery (Wang 1986; Haugen 1992; Moyle 2002). The San Francisco estuary serves as rearing habitat for this benthic 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 freshwater and brackish water, like San Francisco Bay, between March and June (Baxter 1999). The juveniles spend the next several years in freshwater 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 (Baxter 1999b). The distribution of starry flounder is affected by temperature 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 1-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. Although there has been considerable interannual variability, a statistical trend in abundance of 1-year-old starry flounder has occurred since sampling began in 1980 ($R^2=0.22$; $P<0.05$) (Figure 3.9-1). There has been little or no additional decline since implementation of D-1641 in 2000. The large drop in population abundance in 2014 coincides with the recent drought. Similar decreases in abundance occurred in earlier droughts and were followed by a rebound in the population in succeeding years.

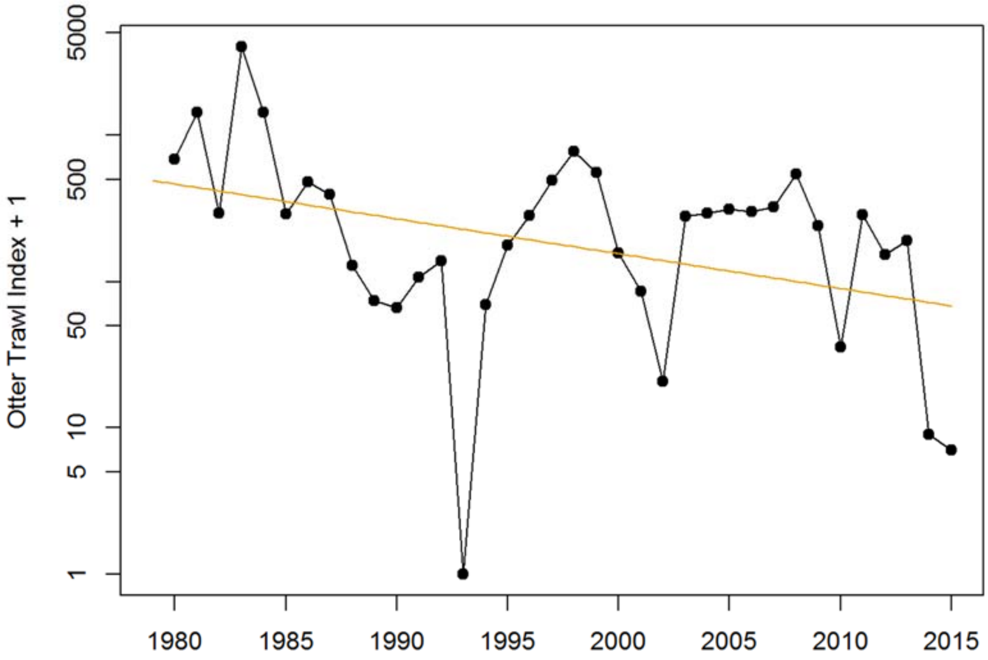


Figure 3.9-1. Population Abundance of 1-Year-Old Starry Flounder as Measured in the San Francisco Bay Study (1980–2014). The solid orange line is the least squares linear regression of the logarithm of the Bay Study Otter Trawl index (incremented by 1) against years. The slope of the regression differs significantly from zero (R^2=0.51; P<0.05, two-sided t-test).

3.9.4 Flow Effects on Starry Flounder

Age-one starry flounder abundance is positively correlated with Delta outflow between March and June of the previous year (CDFG 1992c; Jassby et al. 1995; Kimmerer 2002b). A statistically significant reduction in the abundance of starry flounder per unit outflow occurred after the invasion of *Potamocorbula* in 1987 (Kimmerer 2002b). State Water Board staff reassessed the relationship with new data to determine whether starry flounder abundance was still a positive function of Delta outflow (Figure 3.9-2). The flow-abundance relationship was estimated following the methods of Kimmerer (2002b) using data collected between 1967 and 2015 (Figure 3.9-2). A single step change was included, following the invasion of the clam *Potamocorbula* (year>1987). More outflow in the previous spring was associated with a higher Bay Study index for age-one starry flounder the following year (Figure 3.9-2), and no statistical support was found for an interaction between the slope and step change.

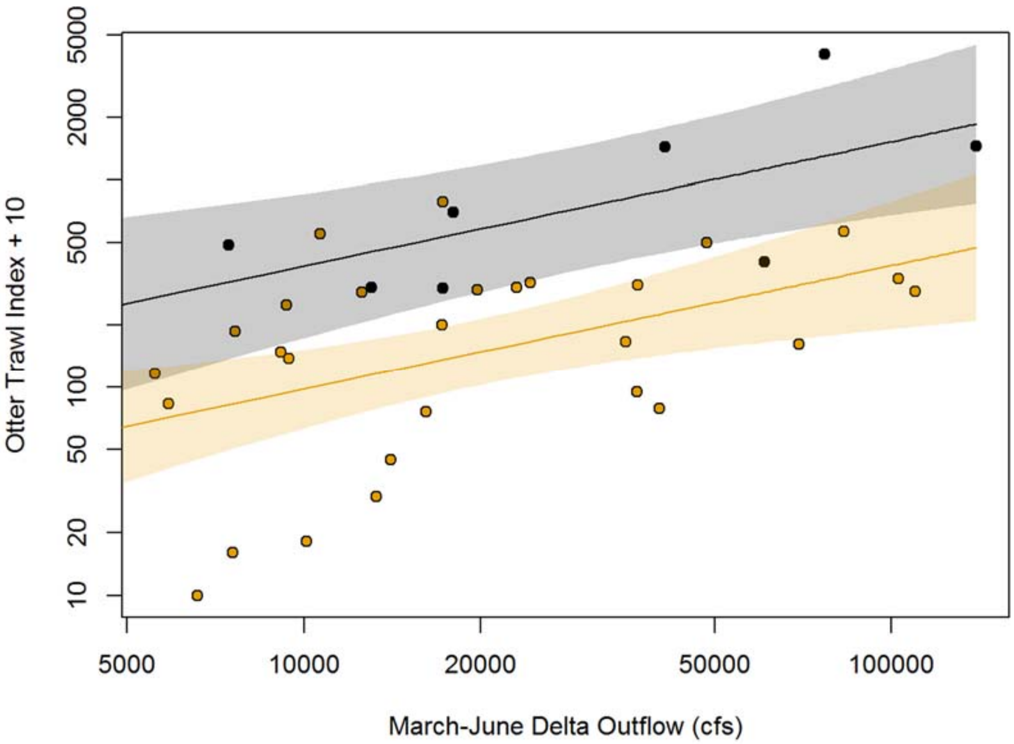


Figure 3.9-2. Correlation between the Starry Flounder Bay Study Otter Trawl Age-1 Index (1980–2015) and Average Daily Outflow (cfs) between March and June. The flow recruitment relationship is statistically significant (two sided t-test, $P<0.01$; $R^2=0.44$). The black line and points are for 1980–1987 while the orange line and points are for 1988–2015. Colored bands around the regression lines represent 95 percent confidence limits.

CDFG (2010b) suggests that there may be at least four possible mechanisms to explain the positive starry flounder flow abundance relationship. First, increasing Delta outflow may provide stronger chemical cues to aid larvae and juvenile flounder locate 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 (see *Bay shrimp* section).

A cumulative frequency distribution was calculated for average daily Delta outflow between March and June of 1994 to 2013 to determine Delta outflow needs of starry flounder (Figure 3.9-3). 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 (Table 3.9-1).

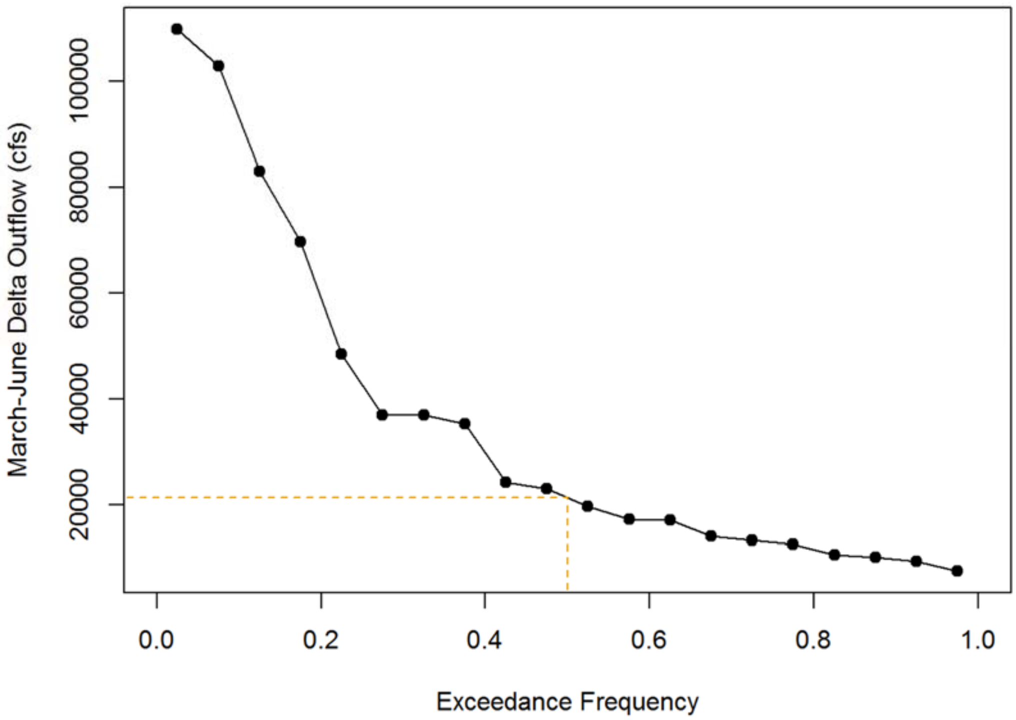


Figure 3.9-3. Cumulative Frequency Distribution of Monthly Average Daily Delta Outflow for March through June (1994–2013). The dotted line is the average daily outflow of 21,000 cfs that occurred in half of all years.

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

	Months											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Starry Flounder			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 of less than 1-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 common 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*. The California bay shrimp is widely distributed along the Pacific Coast of North America from San Diego to Southeastern Alaska (Rathbun 1904; Hieb 1999). The shrimp is primarily an estuarine species, common in bays on mud and sand bottoms and also found in nearshore coastal waters (Schmitt 1921).

California bay shrimp have been fished commercially in San Francisco Bay since the 1860s. Historically, fresh shrimp were eaten locally and dried shrimp were exported to Asia (Siegfried 1989). The annual San Francisco Bay catch exceeded 720 tons 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 (CDFG 1987; Siegfried 1989; Reilly et al. 2001). Six and one half tons were taken in San Francisco Bay in 2015 (California Commercial Landings).

Crangon spp. are 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; Ganssle 1966; McKechnie and Fenner 1971; Reilly et al. 2001). A change in shrimp abundance could have a significant “bottom up” effect on population size of important commercial and recreational fish in the estuary.

Female California bay shrimp are reproductively active throughout much of the year (Krygier and Horton 1975). Bay shrimp mature in 1 year and may live for up to 2 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 (CDFG 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 LSZ in bottom gravitational currents (Hatfield 1985). Upstream migration primarily occurs between April and June (CDFG 2010b). 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 (CDFG 1992c; 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.

Larval shrimp 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 *Potamocorbula* and the decline in *Neomysis* abundance (Kimmerer 2002b; 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.

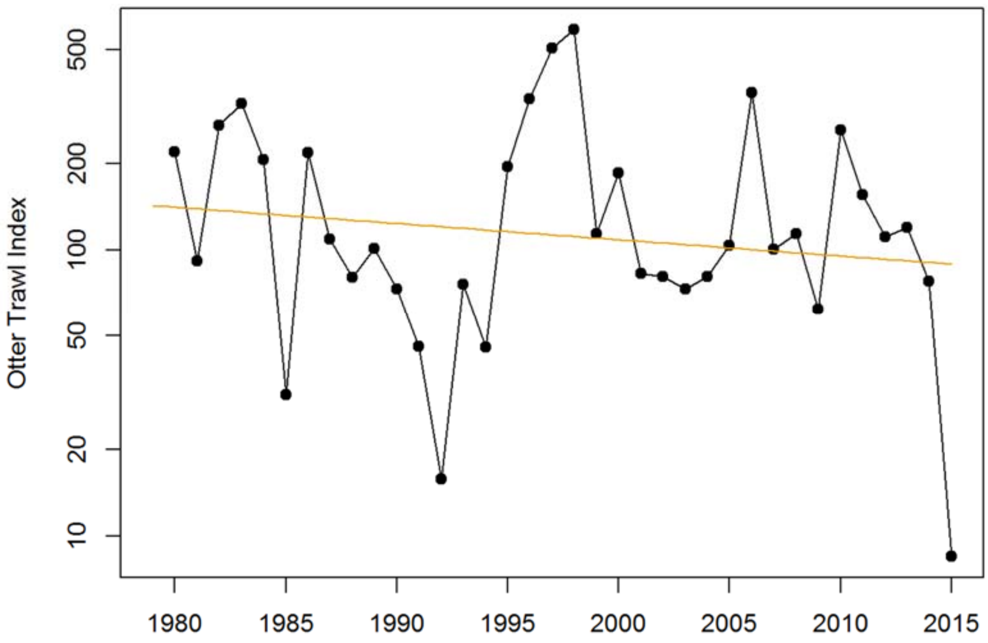


Figure 3.10-1. Index of Juvenile *Crangon franciscorum* Abundance as Measured in the San Francisco Bay Otter Trawl Survey (1980–2015). The orange line is an estimate of the trend in population abundance over time; the slope of the regression does not differ significantly from zero (two sided t-test, 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 (Hatfield 1985; CDFG 1992c; Jassby et al. 1995; Kimmerer 2002b; Hieb 2008; Kimmerer et al. 2009). The flow abundance relationship did not change with the invasion of *Potamocorbula* (Kimmerer 2002b).

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 ($P<0.001$, $R^2=0.49$). More Delta outflow is correlated with higher Bay Study index values for juvenile bay shrimp.

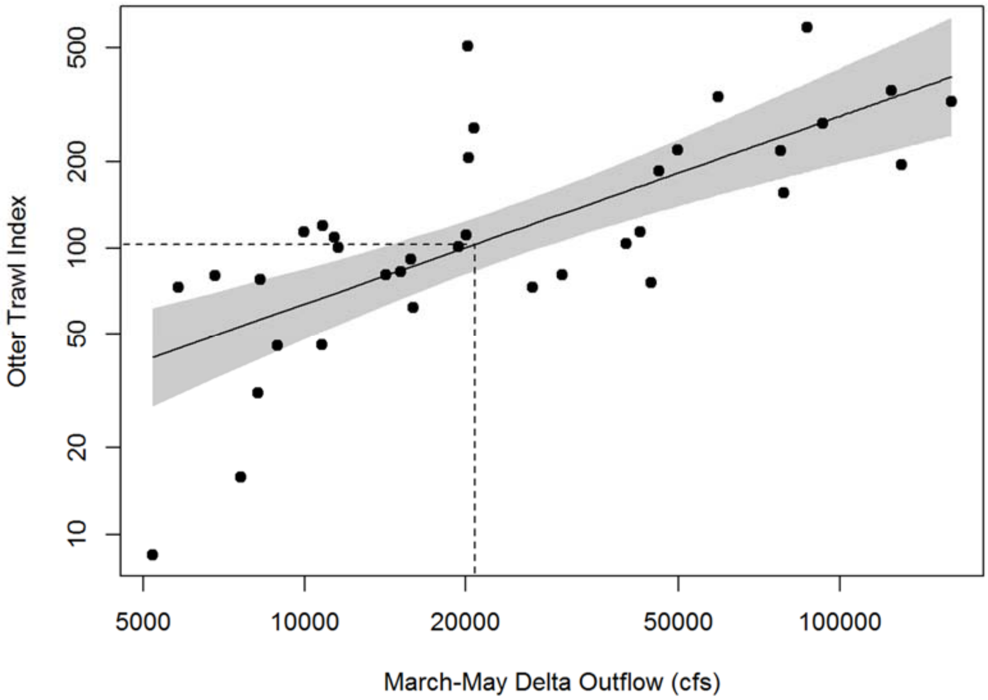


Figure 3.10-2. Relationship between Juvenile Bay Shrimp Abundance, as Measured by the San Francisco Bay Otter Trawl Survey (1980–2013), and Average Daily Outflow (cfs) between March and May of the Same Year. The flow-abundance relationship is significant ($P<0.001$, $R^2=0.49$). The dotted line indicates that a flow of 21,000 cfs is predicted to produce the recommended population abundance goal. The colored band around the regression line is the 95 percent confidence limits.

Mechanisms explaining 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 (CDFG 2010b; 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 21,000-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[26]. The median flow was 20,000 cfs (Figure 3.10-3).

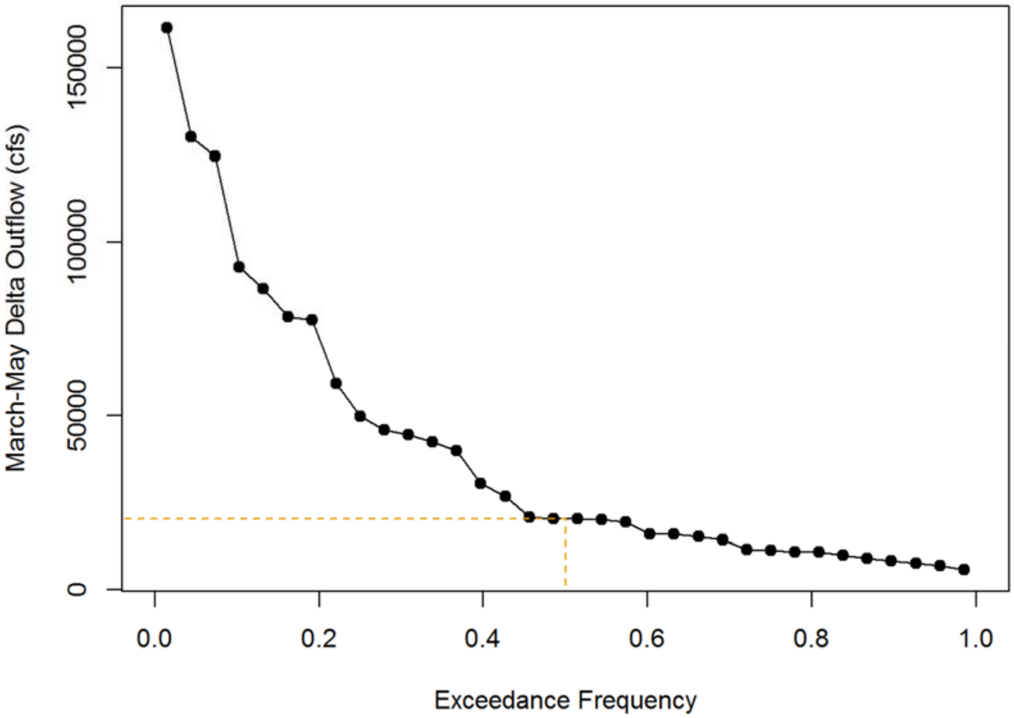


Figure 3.10-3. Cumulative Frequency Distribution of Average Daily Outflow for March to May (1980–2013). The dotted line is the average daily outflow of 20,000 cfs that occurred in half of the years.

Third, logistic regression analysis predicted that 25,000 cfs is associated with 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 (2010a), who employed the same approach for data from 1980–2007and estimated positive growth would occur in 50 percent of years at 27,600 cfs (State Water Board 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 20,000 to 25,000 cfs between March and May should be sufficient to maintain the present population size (Table 3.10-1).

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[26] 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.

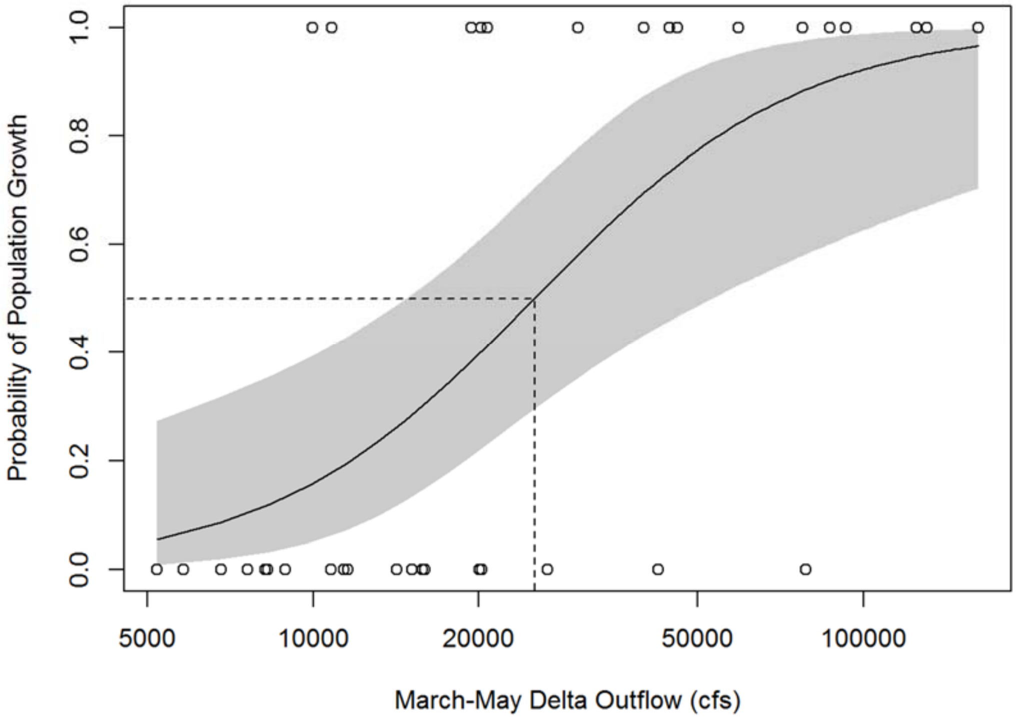

Figure 3.10-4. Probability of Juvenile Bay Shrimp Population Growth as a Function of Delta Outflow from a Logistic Regression Analysis ($P<0.01$). The dotted line indicates that an average daily outflow of 25,000 cfs between March and May is associated with a 50 percent probability of population growth. The band around the line is the 95 percent confidence limit.

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			20,000 to 25,000									

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 relationships are the mysid *Neomysis mercedis* and the calanoid copepod *Eurytemora affinis*. The population size of both species has declined since the invasion of the overbite clam, *Potamocorbula.* Both species have been replaced by a group of alien copepod taxa from East Asia that may not be as available to 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 (CDFG 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 *N. mercedis* and *E. affinis* (Jassby et al. 1995; Kimmerer 2002). *Pseudodiaptomus forbesi* is an introduced copepod that has recently become an important food resource for planktivorous fish species.

3.11.2.1 Neomysis mercedis

The mysid shrimp, *N. mercedis,* is euryhaline and in California has been found in salinities from 0.5 to 32.0 ppt (Orsi and Knutson 1979) but is most abundant in the LSZ (Orsi and Mecum 1996). The mysid shrimp has an upper thermal limit of 22^{0}C in San Francisco Bay (Orsi and Knutson 1979) with reproduction occurring year-round (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 LSZ in Suisun Bay (Orsi and Knutson 1979; Hennessy 2009; Hennessy and Enderlein 2013; Durand 2015). *E. affinis* is a major prey item of *N. mercedis* (Orsi and Mecum 1996).

3.11.2.2 Eurytemora affinis

In the San Francisco Bay estuary the calanoid copepod, *E. affinis,* has been observed from the LSZ 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; Kimmerer 2002).

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; Nobriga 2002; Moyle et al. 1992; Slater and Baxter 2014).

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 in all seasons, with a 50-fold decline in summer (Kimmerer 2002b; Orsi and Mecum 1996; Hennessy 2009; CDFG 2010b). Annual abundance now peaks between May and July (Orsi and Mecum 1996). The decline may be due to competition between juvenile mysids and the invasive clam, *Potamocorbula,* for diatom food (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-round but currently is moderately abundant in winter and spring and rare in summer and fall (Durand 2010, 2015; Merz et al. 2016). 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 *Potamocorbula* and another invasive calanoid copepod *P. 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 with and predation by *Potamocorbula* (Kimmerer 2006). Zooplankton compete with benthic filterfeeders for phytoplankton (Winder and Jassby 2011) and the naupliar larval stage of *E. affinis* is ingested by *Potamocorbula* (Kimmerer et al. 1994). Grazing rates by *Potamocorbula* 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 2002b; Jassby et al. 1995; Orsi and Mecum 1996). 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 2002b).

The abundance of adult and juvenile *N. mercedis* as a function of Delta outflow was reassessed using abundance data for the entrapment zone (Hennessy, A. and Z. Burris 2017). The entrapment zone was defined as a water mass moving up and down estuary with a bottom salinity between 1 and 3 ppt. Preliminary conclusions are that abundance increases as a function of mean daily outflow between March and May (R^2=0.32; P<0.001). These months were selected as the mysid is most abundant then.

3.11.4.2 Eurytemora affinis

Historically, *E. affinis* abundance in summer was not correlated with X2 (Kimmerer 2002b). After 1987, *E. affinis* abundance in spring became positively related to Delta outflow; higher abundances were associated with more outflow (Kimmerer 2002b).

The flow abundance relationship was reassessed for *E. affinis* with data collected between 1994 and 2015 (Hennessy, A. and Z. Burris 2017). Like for *N. mercedis*, the analysis used data for the entrapment zone. The preliminary analysis demonstrated that mean CPUE increased with Delta outflows greater than about 30,000 cfs between March and June (R^2=0.58; P<0.001) (Figure 3.11-1).

The CDFW provided a combined Delta outflow recommendation for *E. affinis* and *N. mercedis* at the 2010 Informational Proceeding (State Water Board 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).

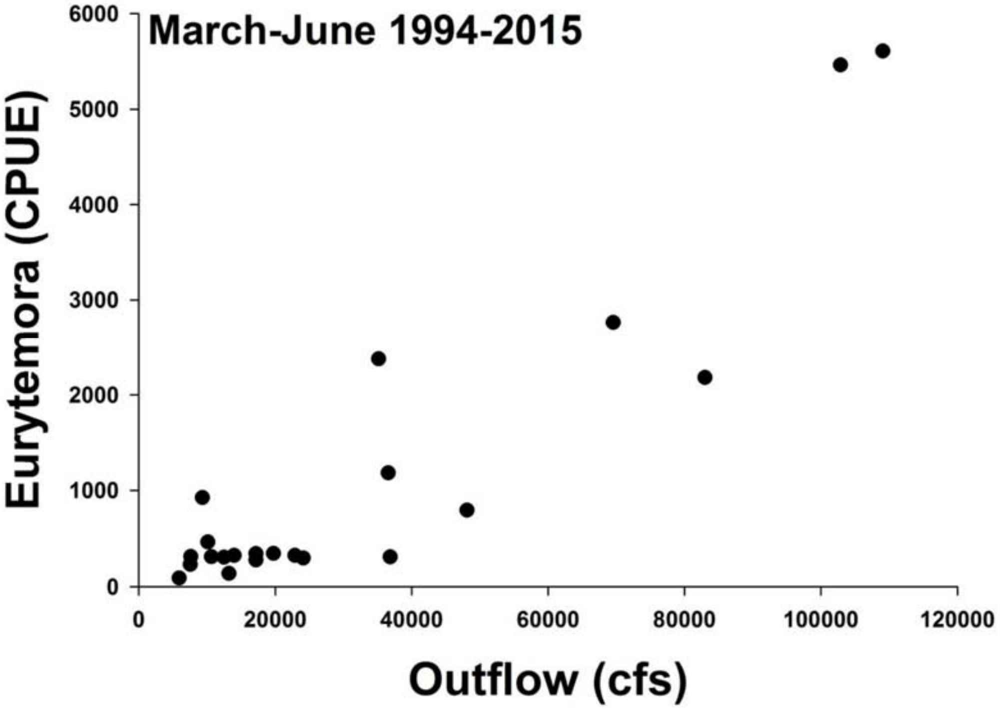

Figure 3.11-1. Mean Abundance (CPUE) in the Entrapment Zone as a Function of Delta Outflow (cfs) for *E. affinis* Adults and *Eurytemora* spp. Juveniles from March through June (1994 to 2015) (from Hennessy and Burris 2017)

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										

3.11.4.3 Nonnative 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 nonnative 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 may be more difficult to catch and therefore less available than native copepods to planktivorous fish such as Delta and longfin smelt (Winder and Jassby 2011). An exception is *Pseudodiaptomus forbesi* which is an important component in the diet of longfin smelt, Delta smelt, and other planktivorus fish.

Pseudodiaptomus forbesi

P. forbesi is an introduced calanoid copepod that was first observed in the Bay-Delta estuary in 1987 (Orsi and Walter 1991). The copepod is stenohaline and distributed from freshwater to about 7 ppt (Orsi and Walter 1991; Durand 2010). This corresponds to a range between about Rio Vista on the Sacramento River and Stockton on the San Joaquin River to as far west as Suisun Bay. *P. forbesi* is a selective filter feeder consuming primarily diatoms (Durand 2010; Winder and Jassby 2011).

P. forbesi has become an important component of the zooplankton community in the Bay-Delta estuary. Population levels increased rapidly after the copepod's introduction and it now represents about a third of the total zooplankton biomass in the Delta (Winder and Jassby 2011). The abundance of the most common copepods change seasonally in the Delta (Winder and Jassby 2011). *P. forbesi* is most common in summer and fall (Durand 2010) when it comprises over half the diet of Delta smelt, longfin smelt and other zooplankton consuming fish (Hobbs et al. 2006; Bryant and Arnold 2007; Slater and Baxter 2014).

Hennessy and Burris also assessed the relationship between mean abundance of P. *forbesi* and delta outflow (Figure 3.11-2). In the preliminary analysis, the authors found a positive relationship between abundance in Suisun Bay and Delta outflow between June and September (R2=0.39, P<0.001). Monthly outflows greater than about 5,000 cfs resulted in increasing abundance of P. *forbesi*.

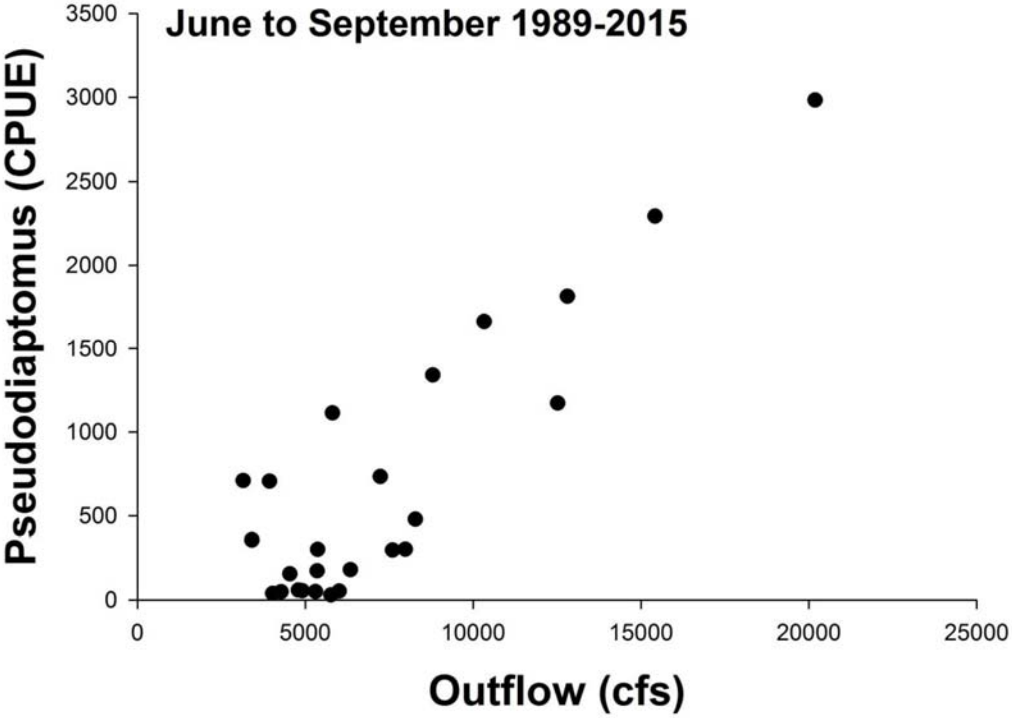

Figure 3.11-2. Mean Suisun Bay Abundance (CPUE) as a Function of Delta Outflow (cfs) for Adult *P. forbesi* and Juvenile *Pseudodiaptomus* spp. from June to September (1989 to 2015) (from Hennessy and Burris 2017)

3.12 Nonnative Fish Species

American shad and striped bass are popular nonnative 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 in favor of a rapidly developing recreational fishery (Moyle 2002; Dill and Cordone 1997). Shad are now a popular sport fish in the Central Valley, especially on the Sacramento, Feather and American Rivers (Titus et al. 2012).

Three- to 5-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 2002b; 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 *Potamocorbula* invasion (Kimmerer 2002b; Kimmerer et al. 2009).

Striped bass (*Morone saxatilis*) was first introduced to the Bay-Delta estuary in 1879 and within 10 years had increased in abundance sufficiently to support 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 (Titus et al. 2012; 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).

There is a positive correlation between the survival of striped bass eggs through their first summer and Delta outflow between April and June (Kimmerer 2002b; Kimmerer et al. 2009). Population abundance indices from the TNS, FMWT, Bay midwater trawl and otter trawl indices are also positively correlated with Delta outflow in spring (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 pelagic 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 98, 98, and 99 percent since sampling began in 1967. The three native species have continued to decline since implementation of D-1641 in 2000 (Table 3.13-1). Several of these species are protected under the federal ESA and CESA (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 (ESA) Acts and Changes in Indices of Their Population Abundance in the San Francisco Estuary

	Listing		Statistically Significant Long Term Decline Since Sampling Began?	Continued Decline Since Adoption of D-1641 in 2000?	
Species	CESA	Federal ESA			Present Abundance[3]
Starry flounder			Yes[1]	No	Lowest on record
Sacramento splittail	Species of concern		Yes[2] (-97%)[4]	No (-91%)	Lowest on record
Longfin smelt	Threatened	Candidate	Yes[2] (-99%)	Yes (-95%)	Lowest on record
Delta smelt	Endangered	Threatened	Yes[2] (-98%)	Yes (-95%)	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 3 and last 3 years of index values to account for inter-annual variability.

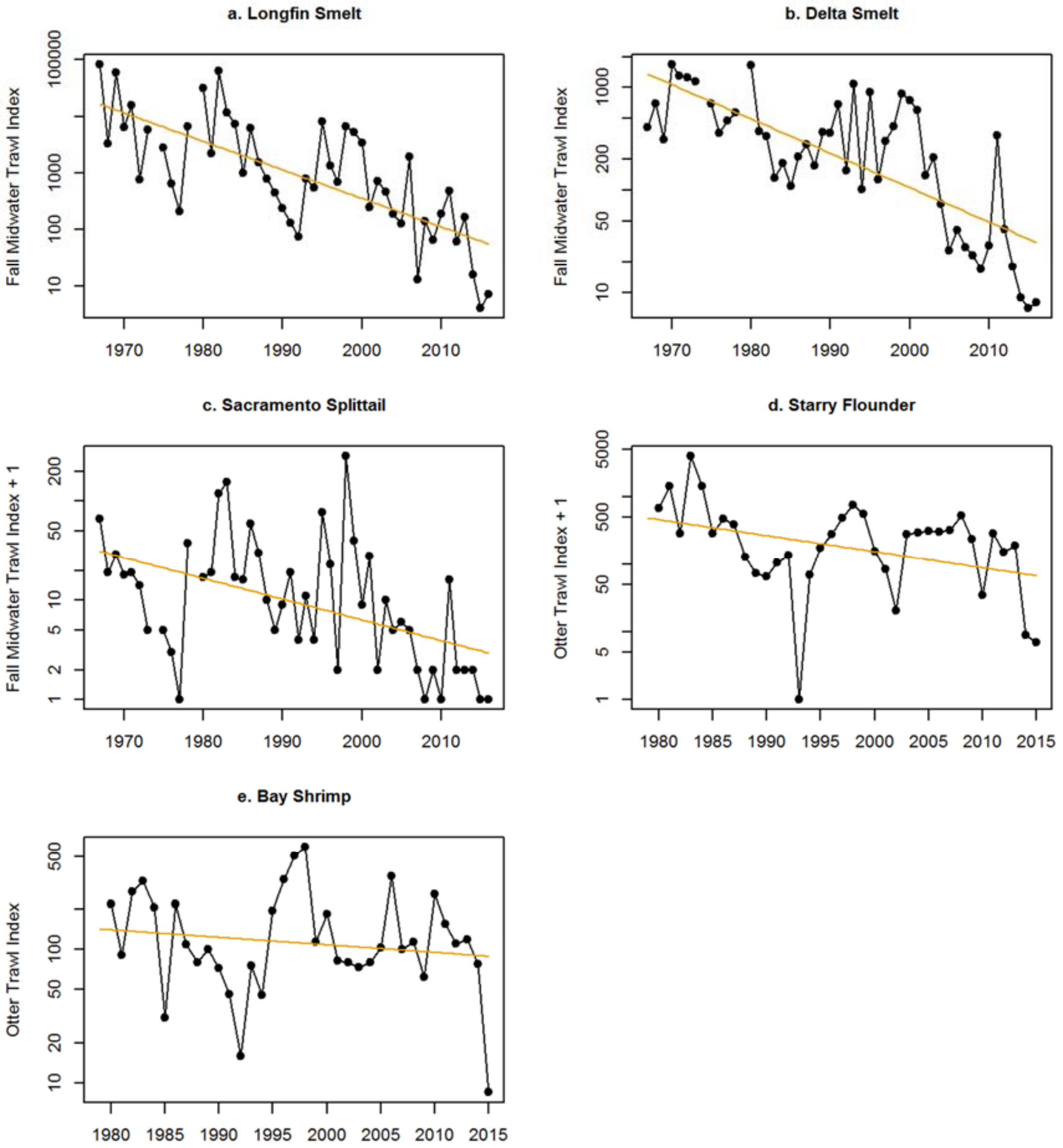

Figure 3.13-1. Trends Over Time in Indices of Abundance for Native Fish and Invertebrate Species from the San Francisco Estuary

Population abundance increases for all the native estuarine species and nonnative 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 January through June for longfin smelt will also meet the flows predicted to support the populations of starry flounder, California bay shrimp, Sacramento splittail and zooplankton during the same months. Sturgeon need higher flows after June 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, although the population does not appear stable and exhibits progressively diminished recruitment in recent wet years. Spring recruitment of Delta smelt in the 20 mm index increases if X2 was located in the previous fall in the LSZ (Figure 3.8-2). The USFWS (2008) BiOp 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[27], 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).

The timing of the 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 42,800 cfs in January through June for longfin smelt, 30,000–47,000 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 February and May is greater than 50,000 cfs, but flows of this magnitude rarely occur now under current conditions in the watershed (Figure 2.4-7). Median unimpaired flows in June are less than 50,000 cfs but near 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.

Another indication of the importance of flow comes from a comparison of the response of the estuarine community to wet and dry water years. 2011 was wet with high Delta outflow in winter and spring. The following 3 years were classified as dry or critically dry. FMWT indices of population abundance of longfin smelt, Delta smelt, and Sacramento splittail all increased in 2011 and declined in the following 3 years (Figure 3.13-2). The increased population size of these estuarine-dependent

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

species indicates that their populations are still able to respond positively to favorable environmental flow conditions.

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 89, 61, 52, and 43 percent, respectively (Table 3.2-3). Natural production of steelhead 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 (2014b, 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 emigration 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 (2009a) BiOp 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 cfs (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 (Figure 2.2-5). The median flow is now 64 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 (Figures 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 at 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 on the San Joaquin River at Vernalis to combined CVP and SWP exports increase. The NMFS (2009a) BiOp requires export restrictions from April 1 through May 31[28]. However, 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).

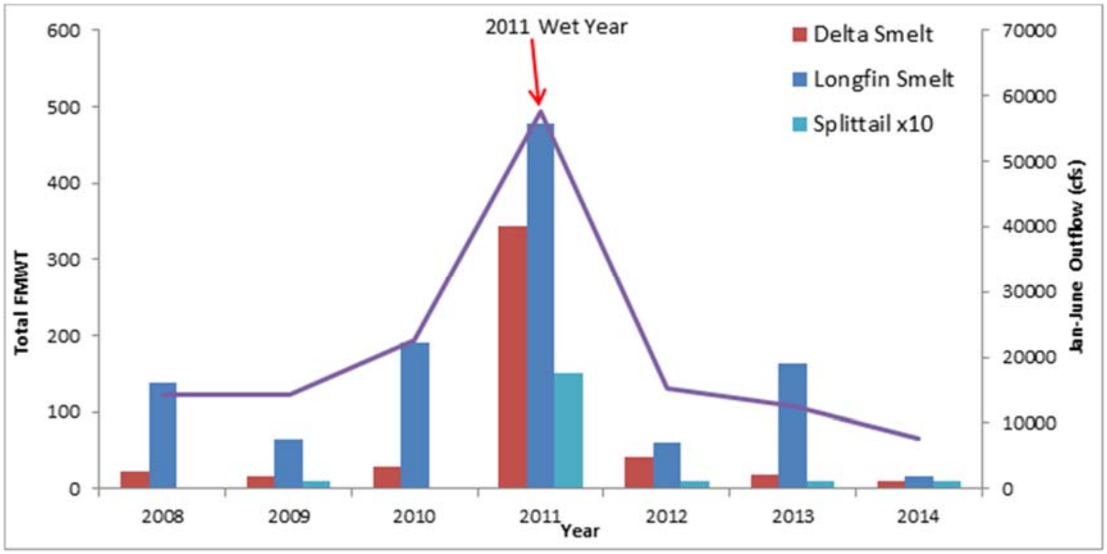

Figure 3.13-2. Comparison of the Change in Magnitude of FMWT Indices for Delta Smelt, Longfin Smelt, and Sacramento Splittail in Wet and Dry Water Years

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[28] 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 rowspan="2">Species or Purpose</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>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="6">42,800</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">20,000–25,000</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">30,000–47,000</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>
<tr><td colspan="13">[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.</td></tr>
</table>

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, brackish 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	Floodplain inundation, spawning (can be short)	•	•	•	•								
Sacramento splittail	Eggs, larvae	Floodplain 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 State Water Board (2010) and CDFG (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

<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>NMFS Biological Opinion for OMR flow[1, 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>USFWS Biological Opinion for OMR flow[2, 4]</td><td colspan="6">-1,250 to -5,000</td><td></td><td></td><td></td><td></td><td></td><td>▨</td></tr>
<tr><td>CDFW Incidental Take Permit for OMR flow[3, 4]</td><td colspan="6">-1,250 to -5,000</td><td></td><td></td><td></td><td></td><td></td><td>▨</td></tr>
<tr><td>Georgiana Slough[5]</td><td colspan="6">17,000-20,000</td><td></td><td></td><td></td><td></td><td colspan="2">▨</td></tr>
<tr><td>San Joaquin River @ Jersey Point[6]</td><td colspan="6">Positive flow</td><td></td><td></td><td></td><td colspan="3">▨</td></tr>
<tr><td>San Joaquin River Export Constraint[7]</td><td></td><td colspan="5">1:1 - 4:1</td><td></td><td></td><td></td><td>>0.3[8]</td><td></td><td></td></tr>
</table>

[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).

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). The recognition that many factors stress the Delta's ecosystem is also reflected in the Delta Plan (DSC 2013), a long-term enforceable plan for the Delta which calls for the consideration of multiple stressors to improve ecosystem restoration success. 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 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 five 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 of each on the aquatic ecosystem. The following sections 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. While a comprehensive assessment of each stressor is beyond the scope of this report, each section generally identifies non-flow actions that are being, or should be, taken to address stressors that will be expanded on in the program of implementation. Many of those actions are within the purview of other agencies and entities and should appropriately be further developed and implemented by those agencies and entities. The State Water Board will help to facilitate those efforts in a coordinated fashion with the flow actions discussed in Chapter 5.

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 also has been a dramatic loss in other aspects of physical habitat suitable for native fish species. For example, the channels of the Delta have been significantly modified by the raising of levees and armoring of the levee banks with stone and concrete riprap. This reduces the complexity and functionality of habitat for native species, including 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 2009a). Habitat loss exacerbates the effects of other stressors, especially in ecosystems with low freshwater flows (Mount et al. 2012). Increased habitat complexity and hydrologic connectivity is needed to maximize the effectiveness of increased flows in supporting native fish (Mount et al. 2012).

A reconciliation strategy has been proposed for the Delta, "that blends the needs of humans and the ecosystem in a landscape and hydrology that has irreversibly changed" (Hanak et al. 2011). Reconciliation includes actions to create better conditions to support native species, recognizing that a return to pristine or historical conditions is not possible, particularly in areas that have been transformed by farming and urbanization. A multi-agency collaboration among government, academia, and non-government entities, guided by best available science and adaptive management, is needed to implement actions to restore and preserve marsh, riparian, and upland habitat in the Delta and its tributaries (Mount et al. 2012) in a coordinated fashion between upstream and downstream actions accounting for the effects of existing and future climate change. Actions may include land acquisition to prepare tidal marshes and other habitats for higher sea level, acquisition and preservation of riparian and floodplain habitat, breaching or removing levees to increase connectivity between floodplains and open water, and periodic flooding to encourage establishment and preservation of native riparian habitat.

Federal, state, and local agencies as well as non-governmental organizations have made and are making significant investments in habitat restoration to benefit native species. Some of the major efforts are discussed below and in the specific habitat sections that follow, though many smaller projects are also being undertaken.

The Ecosystem Restoration Program (ERP), a multi-agency effort, between CDFW, USFWS and NMFS primarily, was formed to improve and increase aquatic and terrestrial habitats and ecological function in the Delta and its tributaries. The ERP has implemented restoration projects through grants administered by the ERP Grants Program, with over 700 million dollars dedicated to restoration and other between as of 2014 for over 500 restoration projects. ERP projects include enhancement or restoration of over 9,000 acres of habitat as well as protection of over 48,000 acres of existing habitat including, but not limited to, non-tidal perennial aquatic, riparian and riverine aquatic, freshwater emergent wetland, and seasonal wetland habitats on the Sacramento River, Feather River, and Big Chico, Butte, Clear, and Mill Creeks (ERP 2014b).

In 2014, the Water Quality, Supply, and Infrastructure Improvement Act was enacted allocating significant additional funding for restoration and related projects in the Bay-Delta watershed, including nearly 1.5 billion dollars for ecosystem and watershed protection and restoration projects (California Natural Resources Agency 2015). California EcoRestore, a California Natural Resources Agency initiative implemented in coordination with state and federal agencies to advance the restoration of at least 30,000 acres of Delta habitat by 2020 is proposed to be funded in part by Proposition 1. EcoRestore restoration targets include 3,500 acres of managed wetlands, 9,000 acres of tidal and subtidal habitat, and 17,500 acres of floodplain restoration, as well as fish passage improvements (California Natural Resources Agency 2016b).

In addition to the above efforts, in 1992, Congress passed the CVPIA (Title 34 of Public Law 102-575) in order to address impacts of the CVP on fish, wildlife, and associated habitats. Included among the purposes of the CVPIA is to "contribute to the State of California's interim and long-term efforts to protect the San Francisco Bay/Sacramento-San Joaquin Delta Estuary." To date, significant funding has been provided for restoration efforts in the Bay-Delta watershed. The 2016 federal budget included $49.5 million for the CVPIA Restoration Fund for projects such as American River spawning and rearing habitat, Clear Creek spawning gravels and channel restoration, and a and are associated with water temperature above 20°C, long wat). These CVPIA Restoration Fund Fund projects were consistent with the conservation priorities identified by ERP.

To help guide restoration efforts in the Delta, the San Francisco Estuary Institute and the Aquatic Science Center through the Delta Landscapes Project has produced an instructive report titled: *A Delta Renewed: A Guide to Science-Based Ecological Restoration in the Sacramento-San Joaquin Delta.* The report emphasizes process-based recovery of landscape functions that integrate natural and cultural processes, and maximize resilience to climate change, invasive species, and other challenges. (SFEI-ASC 2016.) The report includes regional recommendations and on-the-ground strategies, and discusses the potential for establishing smaller, modified landscapes that are resilient, productive, sustainable, and supportive of people and native wildlife.

The habitat within the Bay-Delta can be divided into distinct segments that include tidal marsh in the north and south Delta and Suisun Marsh, riparian habitat and open channels throughout the Delta and its tributaries, and floodplain and wetland habitat in the north and south Delta and its tributaries (Mount et al. 2012; Whipple et al. 2012). Each habitat is discussed in more detail below.

4.2.1 Riparian Habitat and Open Channels

Riparian vegetation is a critical resource for native aquatic species, providing numerous important habitat features including: shade, refugia, habitat structure, food resources and other functions. Historically, the Sacramento River system and surrounding tributaries included significant vegetated riparian areas including stands of oak, cottonwood and other deciduous and coniferous trees (Rood et al. 2003) as well as vines, shrubs, and grasses that sprung up when fluvial and alluvial sediments and their associated flows were more prevalent (Roberts et al. 1980; Whipple et al. 2012).

The Sacramento River had 800,000 acres of riparian vegetation in 1848 but only 12,000 acres or about 1 percent remained by 1972 (Sands and Howe 1977). The conversion of forests to orchard and field crops, logging, streambank stabilization, channelization, and freshwater flow reduction due to dams and irrigation all contributed to this loss of riparian habitat (Whipple et al. 2012). Channelization, leveeing, and riprapping of river reaches and sloughs is now common in the Sacramento River system and typically creates channels with minimal habitat complexity, which results in low food availability and little protection from either fish or avian predators (USACE and CDFG 2010). In addition, the proliferation of nonnative submerged and floating aquatic vegetation significantly decreases open water habitat quantity and quality for native fish.

A combination of land use restoration actions coordinated with flow actions are needed to address the ecological degradation caused by the loss of riparian forests and construction of levees and channelized waterways. Those actions include riparian reforestation, channel modifications and level design and management actions (setback levees and other actions) that produce more natural hydrologic and geomorphic processes that promote natural ecological processes. Flow actions are needed that support and promote riparian processes, including the establishment and maintenance of native riparian vegetation and other natural hydrologic and geomorphic processes through perennial and periodic storm flows that overtop channel banks, saturate soils, and encourage seed regeneration and other functions.

Federal, state, and local agencies as well as non-governmental organizations have made and are making significant investments in riparian restoration projects to benefit native species, including through the ERP, CVPIA and other programs and projects. For example, a significant effort has been made to restore habitat on Battle Creek, one of the more ecologically valuable tributaries to the Delta. Over $110 million has been invested in the Battle Creek Salmon and Steelhead Restoration Project, which is a collaborative effort between Reclamation, USFWS, NMFS, CDFW, and PG&E. The Battle Creek Project seeks to reestablish approximately 42 miles of prime salmon and steelhead habitat on Battle Creek, a tributary to the Sacramento River, by improving fish passage and restoring ecological processes (Reclamation 2016).

4.2.2 Tidal Marsh Habitat

Extensive freshwater tidal marshes in the Bay-Delta watershed historically provided critical habitat for many native species. Tidal marsh habitat supports many native plant species and sustains diverse food webs and ecosystem processes (Atwater et al. 1979). Networks of sloughs also provide habitat structure and cool water refugia during summer heat spells (Mount et al. 2012). Tidal marshes also influence the recycling and retention of nutrients.

Tidal marshes have changed dramatically over the past 150 years, largely due to filling and diking (Figure 4.2-1) (Atwater et al. 1979; Nichols et al. 1986; Moyle 2002; Whipple et al. 2012). The Delta currently supports less than 10,000 acres of tidal wetland, all of which is small and fragmented (USFWS 2008). This represents about 3 percent of the acreage of tidal wetland before the gold rush (Whipple et al. 2012) and less than 30 percent of tidal mudflats and wetland originally present in San Francisco Bay (Callaway et al. 2011). Landscape changes of this magnitude suggest comparable changes in the magnitude, transport, and fate of estuarine derived organic matter and primary production (Brown et al. 2016). The conversion of tidal wetlands to diked seasonal wetlands resulted in habitat loss for many native species including Delta smelt and longfin smelt.

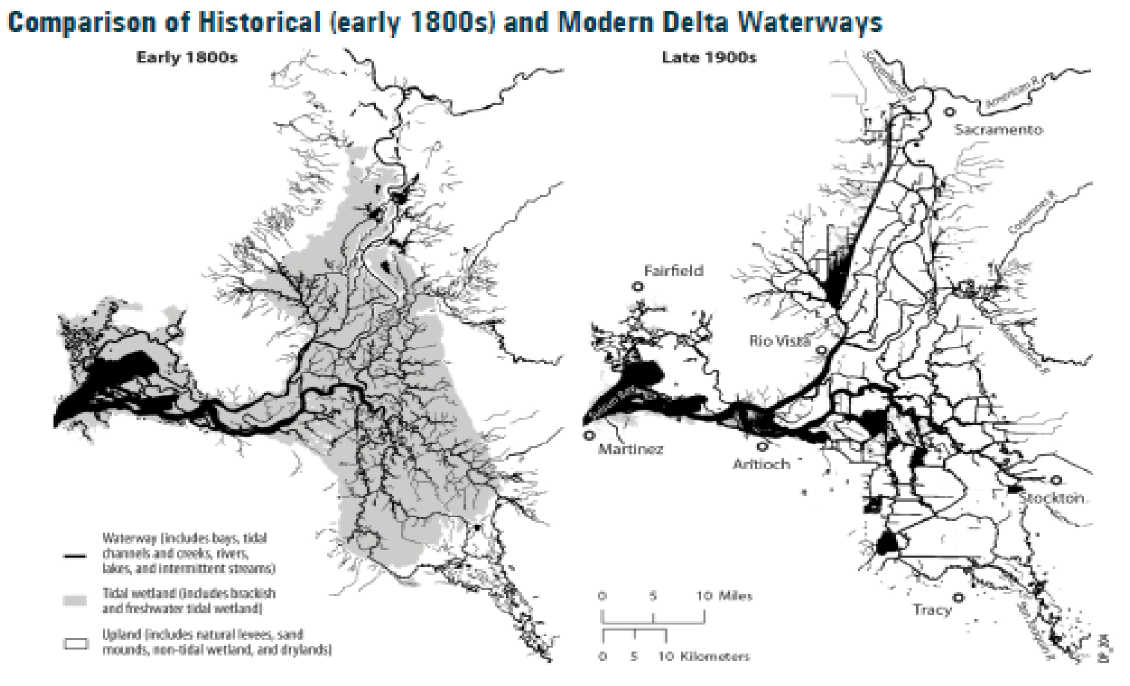

Figure 4.2-1. Comparison of Historical and Modern Delta Waterways, Tidal Wetland, and Upland Areas (Whipple et al. 2012)

Altered tidal marsh habitat may be restored by growing tules, cordgrass, and cattails to reverse subsidence (Wilson and Peter 1988; Miller et al. 2008). Alternatively, breaching or removal of levees along with better flow management may restore hydrologic connectivity and improve tidal marsh habitats in anticipation of sea level rise (Mount et al. 2012). Brown et al. (2016) recommend that tidal wetland restoration in the Delta be conducted as an experimental program because there are still many unanswered questions about the outcome of planned restoration actions. Adoption of an experimental adaptive management approach may achieve the most for native species in the long run with the limited resources available.

Effectiveness monitoring of restoration activities is important to determine the capacity, opportunity, and realized functioning of tidal wetlands to meet the needs of native fish and other aquatic species. The IEP, a multiagency collaborative monitoring, research, modeling, and synthesis effort to inform planning and regulatory decisions, has formed a Tidal Wetland Monitoring Project Work Team (Team). The purpose of the Team is to collaborate on the design of monitoring programs for fish and foodweb resources in restored tidal wetlands in the Bay Delta system. In this effort, the Team has developed a monitoring framework that includes effectiveness monitoring tools and project-specific monitoring plans to inform adaptive management and planning for future projects. The Delta Restoration Network has also been developed by the Sacramento-San Joaquin Delta Conservancy (Delta Conservancy) as a forum for information sharing and coordination to ensure an integrated and accountable restoration program in the Delta. The purpose of the network is to coordinate and integrate restoration actions to ensure integrated performance tracking among governmental and non-governmental entities engaged in restoration and habitat management in the Delta and Suisun Marsh (Delta Conservancy 2015).

Suisun Marsh is the largest expanse of tidal marsh in the 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 birds, mammals, reptiles, and more than 40 fish species (O'Rear and Moyle 2009; Reclamation and USFWS 2014). It also provides important tidal rearing areas for juvenile salmonids. Suisun Marsh currently consists of a variety of habitats, including managed diked wetlands, unmanaged seasonal wetlands, tidal wetlands, sloughs, and upland grasslands. It encompasses more than 10 percent of California's remaining natural wetlands (Whipple et al. 2012) with 6,300 acres of its total 116,000 acres in tidal wetlands. As a result of diminished freshwater inflow in Suisan Marsh (Feyrer et al. 2011), increased salinity intrusion has reduced primary productivity and biodiversity (Reclamation and USFWS 2015).

The 2014 Suisun Marsh Habitat Management, Preservation, and Restoration Plan (SMP) is intended to be a flexible, science-based, management plan designed to address the varied beneficial uses of Suisun Marsh, with a focus on achieving an acceptable multi-stakeholder approach to the restoration of tidal wetlands and the management of managed wetlands and their functions. 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 Suisun Marsh. The SMP proposes that Reclamation and DWR implement a Preservation Agreement Implementation Fund (PAI Fund). The PAI Fund is a single cost-share funding mechanism that would contribute to the funding of some activities needed to improve managed wetland facility operations and to implement restoration actions. (Reclamation and USFWS 2015). The SMP and other activities should continue to be implemented to protect native species in Suisun Marsh and other tidal areas, including appropriate monitoring, evaluation and coordination. Periodic updates should be provided to the State Water Board and public on progress with, and effectiveness of, restoration and management actions.

4.2.3 Floodplain and Wetland Habitat

Functioning floodplains are important components of the aquatic ecosystem providing abundant food and refugia, spawning grounds and other critical habit functions(Jeffres et al. 2008; Sommer et al. 2001) (Li et al. 1994). Healthy floodplains are morphologically complex and 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 2014a).

A significant amount of floodplain habitat in the Delta has been lost through the channelization of rivers, including construction of levees and channel straightening, deepening, and lining (Mount 1995). Since the early 1800s, freshwater emergent wetlands have been reduced by more than 70 percent in the Delta due to land conversion for agricultural and urban uses (Whipple et al. 2012). At the same time, water storage and conveyance, flood control and navigation activities have impaired the amount and timing of flows onto the floodplain. Further, hydraulic mining, especially in the Yuba and Feather Rivers, and other activities have caused changes in sediment deposition within channels and floodplains, loss of channel capacity, and aggradation of river courses (Mount 1995).

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 2009a). Native salmonids that rear on floodplain habitat in the Delta watershed grow larger and faster than fish that do not due to higher food production. In one study, zooplankton biomass was found to be 10–100 times higher on the floodplain than in open river habitat (Jeffres et al. 2008). Efforts are underway through EcoRestore and other efforts to restore floodplain habitat in the Delta watershed in a collaborative fashion with agricultural practices. Included amongst these projects is The Knaggs Ranch Agricultural Floodplain Study in the Yolo Bypass which seeks to emulate highly productive salmon rearing habitat through a collaborative effort between farmers and researchers to help restore salmon populations by reintroducing them during winter to inundated floodplains that are farmed with rice during the summer (California Trout 2017).

4.3 Water Quality

Water quality conditions, including contaminants and associated toxicity, nutrients, low DO, increased temperature, and reduced turbidity can adversely affect native fish and other aquatic organisms in the Bay-Delta watershed. In addition to affecting aquatic organisms, various contaminants may affect terrestrial wildlife, including birds, and may bioaccumulate in edible fish tissue to become a human health concern. DO concentrations, turbidity, and temperatures are all 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 publically owned wastewater treatment works (POTW), 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).

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 may not be lethal, but sub-lethal 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 sub-lethal pollutant effects on keystone species that play a disproportionate role in controlling ecosystem function may manifest 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.

The Bay-Delta Plan operates in conjunction with the Water Quality Control Plan for the Sacramento River and San Joaquin River basins adopted and implemented by the Central Valley Regional Water Board and the San Francisco Bay Regional Control Board, addressing point source and nonpoint source discharges and other controllable water quality factors. (See also Water Boards' 2008 Strategic Workplan for Activities in the Bay-Delta [and 2014 update by the Central Valley Regional Water Board].) The Water Boards have regulatory programs that control discharges of wastes from wastewater treatment facilities, industrial facilities, urban areas, irrigated agricultural lands, dredging operations, and other sources of wastewater to the Bay-Delta and tributaries. Water Code section 13260, subdivision (a) requires that any person discharging waste or proposing to discharge waste that could affect the quality of the waters of the state, other than into a community sewer system, shall file with the appropriate regional water board a report of waste discharge containing such information and data as may be required by the regional water board, unless the regional water board waives such requirement. Waste discharge requirements (WDR) prescribe requirements, such as limitations on temperature, toxicity, or pollutant levels, as to the nature of any discharge. (Wat. Code, § 13260, subd. [a].) WDRs may also include monitoring and reporting requirements. (See *id.* § 13267, Cal. Code Regs., tit. 23, § 2230.)

The Water Boards address water quality impairments that are caused by multiple dischargers by developing total maximum daily loads (TMDL), which set water quality objectives or targets and allocate allowable loads to sources of contaminants. TMDLs have been adopted and are in the process of being implemented for various constituents in the Delta and the Bay as discussed below. Over the years the contaminants and discharge sources have changed and there have been significant improvements in controlling most types of contaminants. Nevertheless, additional efforts are still needed. There are a suite of contaminants that pose a concern for some Delta beneficial uses and there is also concern for an emerging list of new contaminant categories (pharmaceuticals and endocrine disrupters), discussed in more detail below and the need for comprehensive monitoring and assessment activities to ensure that the occurrence and effects of contaminants are understood and addressed.

4.3.1.1 Pesticides and Other Pollutants

Water samples have detected the widespread occurrence of a number of pesticides currently used throughout the Central Valley and Bay-Delta estuary (Orlando et al. 2013). USGS measured 26–27 pesticides or their primary degradation product in samples collected from the Sacramento and San Joaquin Rivers in 2011 and 2012 (Orlando et al. 2013). The average number of detections was 6 and 9 pesticides per sample, respectively. The toxicity of most of these pesticides singly or in combination to aquatic life is largely unknown (Orlando et al. 2013; Fong et al. 2016). However, pyrethroid insecticides have been detected in the Delta at toxic concentrations as discussed below

(Holmes et al. 2008; Weston et al. 2008), and pyrethroids and other insecticides have been implicated as one of the factors in the decline in the population of Delta smelt and other pelagic fishes (Sommer et al. 2007; Orlando 2013; Fong et al. 2016).

Negative relationships were found between total pyrethroid insecticide use in the six Delta counties and annual FMWT indices (1978–2014) of longfin smelt, Delta smelt, Sacramento splittail, American shad, threadfin shad, and striped bass (Figure 4.3-1) (Fong et al. 2016). Pesticide use explained more variation in recruitment than flow in all species except longfin smelt, suggesting pyrethroid insecticides may contribute to the decline in fish recruitment (Fong et al. 2016), though there is a strong relationship between pesticide concentrations and flow. The toxicological mechanisms responsible for reduced fish recruitment are not known, although pyrethroid insecticides have been documented to induce nervous, immune, muscular, and osmoregulatory impacts at the genetic level in Delta smelt (Jeffries et al. 2015). Pyrethroid insecticides have also elicited histopathological lesions, stress responses, and abnormalities in splittail larvae (Teh et al. 2005). Salmonids may also be negatively affected by insecticides at the neurophysiological level as suggested by a recent study that showed that the effects of pyrethroids led to decreased feeding behavior in juveniles (Baldwin et al. 2009). Pyrethroid insecticides also may negatively affect food resources for native fish. Weston et al. (2010a) measured toxic effects leading to death or reduced swimming ability in the amphipod *Hyalella Azteca* in samples containing urban runoff collected from the cities of Sacramento and Vacaville. Toxic concentrations of pyrethroid insecticides have also been detected in sediment samples collected from water bodies draining agricultural and urban areas in the Central Valley (Weston et al. 2014), including those with wastewater effluent (Weston and Lydy 2010). At some locations, peak pesticide concentrations during runoff events coincided with high population densities of Delta smelt (Bennett 2005; Kuivila and Moon 2004).

A pyrethroid pesticide control program for the Central Valley and the Delta is being developed by the Central Valley Regional Water Board that includes: a conditional prohibition of discharges of pyrethroid pesticides above certain concentrations into surface waters with aquatic life beneficial uses; TMDLs in selected surface waters; recommendations for agencies that regulate the use of pesticides; monitoring requirements and other provisions to ensure data and information is produced to assess progress and inform future Water Board actions; and policies and monitoring requirements that address alternative pesticides to pyrethroids.

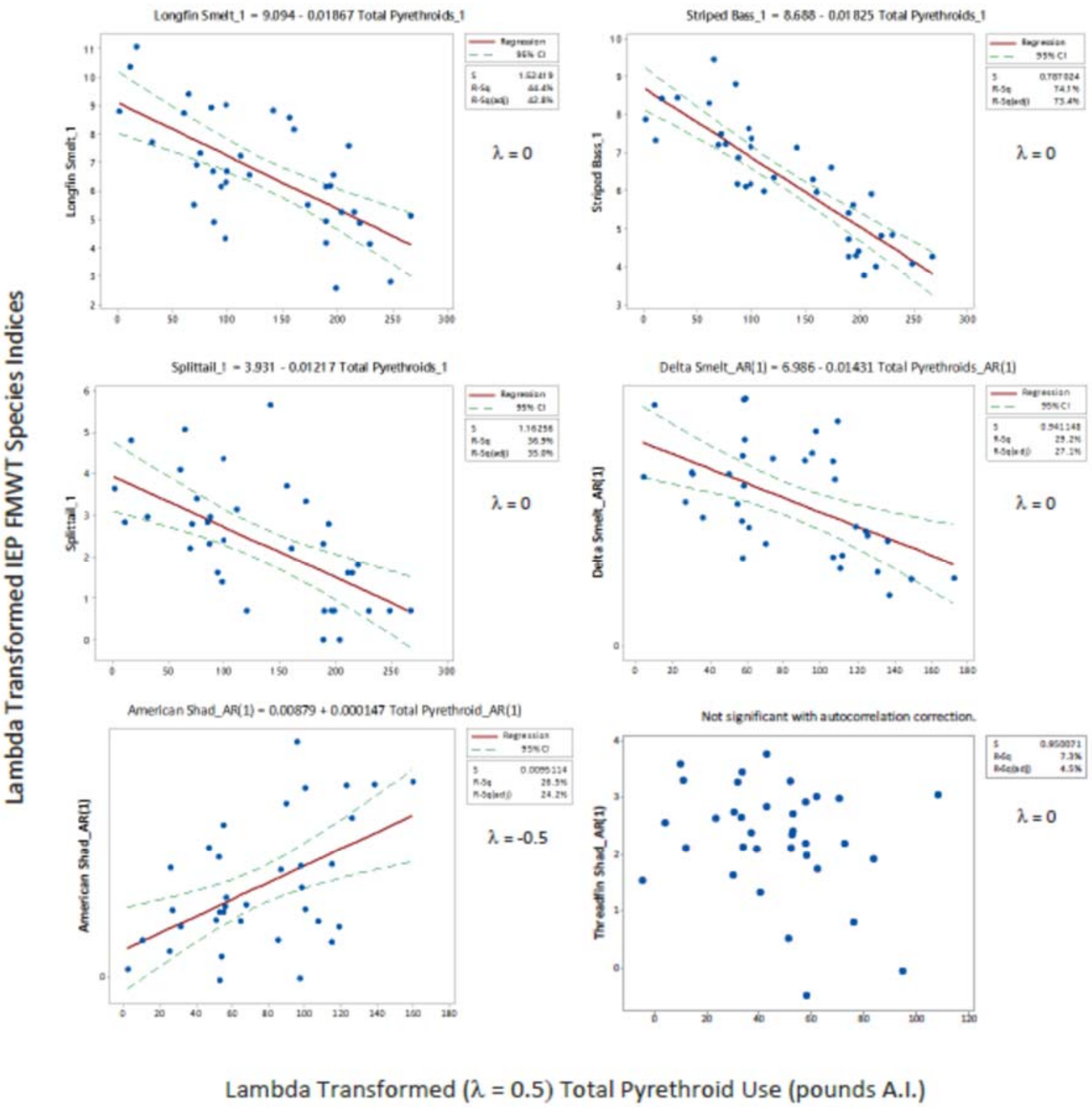

Figure 4.3-1. Least Squares Regressions with 95 Percent Confidence Intervals for FMWT Species Abundance as a Function of Annual Pyrethroid Pesticide Use in Six Delta Counties (1978–2014) (From Fong et al. 2016)

Herbicide applications for control of invasive aquatic plants may also have negative effects on native fish and invertebrates. The California Division of Boating and Waterways (CDBW) applies glyphosate, 2,4-D and Imazamox herbicides directly to water bodies to control invasive aquatic weeds (CDBW 2017). Close to 4,300 acres of waterways were treated in 2016 for control of water hyacinth, Brazilian waterweed, and curly leaf pondweed (CDBW 2017). Like insecticides, little is known about the toxic effect of these herbicides singly and in combination on aquatic life. The herbicides may decrease the health of Delta fish species and their prey (Fong et al. 2016; Hasenbein et al. 2017). Sub-lethal effects such as decreased condition factors and energy reserves were measured in Delta smelt in response to mixtures containing Imazamox (Hoffman et al. 2017).

Similarly, Imazamox glyphosate, 2,4-D, and fluridone herbicides were found to induce sub-lethal effects in Delta smelt embryos and larvae and cause mortality to *E. affinis* at concentrations measured in the estuary (Stillway et al. 2016).

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. These chemicals are applied at toxic concentrations to kill mosquito larvae and likely also injure other small invertebrates.

The State Water Board administers state-wide general National Pollutant Discharge Elimination System (NPDES) permits for pesticides, including aquatic animal invasive species control, spray applications, vector control, and weed control. These permits require compliance with applicable water quality standards, best management practices, and compliance with relevant federal and state law (including Department of Pesticide regulations). The permits do not authorize discharges of chemicals in water bodies listed as impaired for that specific chemical. The permits include monitoring and reporting provisions, and contain requirements for corrective action in the event of any adverse effect on a federally listed threatened or endangered species or its federally designated critical habitat, that may have resulted from the chemical application.

Fong et al. (2016) and Healey et al. (2016) recommended that a dedicated contaminant monitoring and assessment program be established in the Delta to better understand the biological effects of pesticide applications on native fish and wildlife. A description of current monitoring efforts and potential improvements is discussed below.

4.3.1.2 Legacy Contaminants

There are several legacy contaminants that are no longer in use but are still present in the Bay-Delta watershed. Organochlorine (OC) pesticides like dichlorodiphenyltrichloroethane (DDT), chlordane, and dieldrin are now banned, but were used extensively in agriculture in the Central Valley half a century ago (Lee and Jones-Lee 2002). Like OCs, polychlorinated biphenyls (PCB), and polycyclic aromatic hydrocarbons (PAH) are legacy contaminants that were used for industrial purposes and were banned in the late 1970s. OCs and PCBs are linked to thyroid and endocrine disorders, genital malformities, and cancer in humans, and have also led to reproductive declines in birds and wildlife (Bergman et al. 2012). Fish and aquatic organisms can absorb these chemicals through sediment resulting in in fish kills and harm to lower food chain aquatic invertebrates (USGS 2012; Vivekanandhan and Duraisamy 2012).

Presence of legacy pesticides in fish tissue collected from Central Valley rivers and the Delta has resulted in the issuance of advisories recommending limited human consumption of some fish species (De Vlaming 2008). OC and PCB pesticide concentrations have declined and were significantly lower in fish caught in 2005 than during the 1970s; however, some individual fish still had concentrations above levels of concern for human health (De Vlaming 2008). PCB concentrations in San Francisco Bay sport fish have also declined but are still more than 10 times higher than the threshold of concern for human health and may adversely affect wildlife (Lee and Jones-Lee 2002; Davis et al. 2007).

There are no control programs for reducing OC, PCB, or PAH concentrations in the Central Valley or Delta largely because there are no feasible means for doing so. The San Francisco Bay Regional Water Board, however, adopted a PCB control program in 2007 (San Francisco Bay Regional Water Board 2007). Periodic fish tissue monitoring should continue to be conducted for OCs, PCBs, and PAHs in the Central Valley and San Francisco Bay to establish when concentrations of these legacy chemicals are no longer of concern for human and wildlife health.

4.3.1.3 Endocrine Disruptors

Endocrine disrupting chemicals (EDC) are substances found in pesticides, personal care products and pharmaceuticals (PCPPs), household cleaning products, and industrial chemicals that disrupt the endocrine (hormone) system of fish and wildlife (Brander et al. 2016; Fong et al. 2016). At the organismal level, EDCs impair reproductive health and development and can cause tumors and malformities. At the population level EDCs can lead to skewed sex ratios (Fong et al. 2016; Bergman et al. 2012) resulting in declines in population abundance of aquatic organisms (Bergman et al. 2012).

Special studies in the Bay-Delta estuary have shown that EDC substances are present and may be causing organismal and population level effects (Brander et al. 2013; Tadesse 2016; Riar et al. 2013). Skewed sex ratios were documented in Mississippi silverside (*Menidia audens*) at sites with high urban runoff in Suisun Marsh (Brander et al. 2013). Sacramento splittail and other fish have shown evidence of feminization through high levels of female egg yolk protein expression in males. Water samples with EDC mixtures were collected in the same areas that feminization occurred (Tadesse 2016). Impacts of EDCs were also observed in invertebrate salmon prey in the American River. However, the chemicals did not appear to be at concentrations that affected the reproductive health of local salmonids (Weston et al. 2014; Riar et al. 2013; de Vlaming et al. 2006).

Common EDC substances in the Bay-Delta estuary include pesticides such as pyrethroids and fipronil, and PCPPs such as latent birth control hormones and microplastics. Urban and agricultural runoff are sources of EDC substances, as are discharges from POTWs (Weston and Lydy 2010; Fong et al. 2016). PCPPs may be hard to detect (Fong et al. 2016). Because of detection difficulties, EDCs are also defined as a subset of a group of chemicals called contaminants of emerging concern (CEC) (Anderson et al. 2010). Generally, CECs are not commonly monitored in the environment but have the potential to cause adverse ecological or human health impacts (Klosterhaus et al. 2013). The Water Boards have various monitoring programs and special studies for drinking water and recycled water for CECs, including endocrine disruptors.

The State Water Board convened a Science Advisory Panel in 2010 to identify strategies and methods for regulating CECs, including EDC substances, in recycled water. The panel's primary recommendations were to develop analytical methods to measure chemical concentrations and to identify trigger levels for biological assessment (Anderson et al. 2010). The State Water Board's Office of Information Management and Analysis (OIMA) is coordinating efforts to gather information and develop a monitoring program for CEC substances in the Bay-Delta estuary with Regional Water Board assistance. Overall goals of OIMA's program include verifying the occurrence of CECs in water, sediment, and tissue samples to better identify status and trends and the biological impacts of CECs on aquatic organisms (Tadesse 2016). This information would be reviewed by the Central Valley and San Francisco Bay Regional Boards to determine whether control efforts are warranted. An existing stakeholder-driven Regional Monitoring Program (RMP) for CECs in San Francisco Bay may provide information to inform future control programs (Tadesse 2016; RMP 2014). Similar monitoring programs are under development for the Central Valley and Bay-Delta estuary.

4.3.1.4 Ammonia/Ammonium

Ammonia is a toxic chemical with the potential at elevated concentrations to reduce growth, reproduction and survival of aquatic organisms (USEPA 2013). 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). NH3 is the more toxic of the two forms. Both NH3 and NH4 are present in effluent from POTWs 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).

Toxicity has been observed in bioassays at ammonia concentrations comparable to those measured in the Sacramento River and Delta. The USEPA criteria summary of ammonia toxicity found that unionid mussels were the most sensitive warm, freshwater aquatic organisms evaluated, while juvenile salmonids were the most sensitive cold water fish species tested (USEPA 2013). Surface water monitoring in the Delta determined that ammonia concentrations were lower than values reported to be toxic to freshwater unionid mussels and juvenile salmonids (Foe et al. 2010). Acute 7-day larval Delta smelt bioassay testing was conducted with ambient surface water from the Delta amended with ammonia, though no toxicity was detected (Werner et al. 2010b). However, Delta smelt exposed to ammonia at concentrations measured in the Delta exhibited immune and muscular system, developmental, and behavioral abnormalities (Connon et al. 2011; Hasenbein et al. 2014). Ammonia concentrations comparable to values measured in the Sacramento River were toxic to *Pseudodiaptomus forbesi* and *Hyallela azteca*, important food resources for native larval fishes including Delta smelt (Teh et al. 2011; Werner et al. 2010a, 2010b).

Ammonia concentrations may also have negative effects on algal primary production, standing biomass, and species composition in the Delta. The effect of ammonia concentrations on algal primary production and species composition in the Delta is controversial (Dahm et al. 2016; Cloern al 2014). Some recent work has indicated that elevated NH4 levels reduce algal primary production 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. 2012). High filtration rates by the overbite clam, *Potamocorbula*, and high turbidity levels are additional factors responsible for reducing primary production and standing algal biomass in Suisun Bay. Elevated NH4 levels have also been hypothesized to contribute to the observed shift in algal species composition from diatoms to blue-greens and greens (Brown 2010) by selecting for species less sensitive to NH4 (Glibert 2010; Glibert et al. 2011). The shift in phytoplankton community composition is being questioned because of data quality issues with the initial algal cell count data that the Glibert papers were based upon (SFEI-ASC 2016). A non-peer reviewed reanalysis of the cell count data does not support the observation that a shift in algal species composition has occurred (SFEI-ASC 2016).

The Sacramento Regional Wastewater Treatment Plant (SRWTP), located at Freeport on the Sacramento River, is the largest POTW discharging into the Delta and contributes about 90 percent of the Delta's annual ammonia load (Jassby 2008). The SRWTP is being upgraded, which should reduce the ammonia loading by 95 percent or more by 2021 (Dahm et al. 2016). Healey et al. (2016) and Brown et al. (2016) observed that the upgrade to the SRWTP provides a unique opportunity to evaluate the effect of nutrient reductions, including ammonia, on algal primary production rates and community composition and the overall health of the Delta ecosystem

Low flows in the estuary and Delta accentuate the effects of degraded water quality, such as high NH3 and NH4 levels. Thus, increased flows would dilute this contaminant and enhance water quality by flushing the estuary more often. Similarly, enhanced flows may decrease indirect effects of NH3 and NH4, such as blue green algal blooms when excess nutrients are in the water (Brown 2010).

The primary control and monitoring programs for ammonia are through the Central Valley Regional Board and San Francisco Bay Regional Water Board. The regional boards regulate ammonia in discharge permits through application of effluent limits that implement narrative and numeric water quality objectives. In addition, the Irrigated Lands Regulatory Program regulates waste discharge, including nitrogen-based fertilizers, from irrigated lands to prevent discharges from causing or contributing to exceedances of water quality objectives. Monitoring of ammonia is conducted by the IEP, NPDES permit holders, and USGS. The two regional boards recently held a joint workshop to evaluate the role that NH4, other nutrients, and nutrient ratios play on algal growth and species composition in the Bay-Delta estuary. The goal of the workshop was to inform further development of nutrient research plans and control efforts.

4.3.1.5 Cyanobacteria

Harmful cyanobacteria algal blooms (HAB) have become a regular occurrence in the Delta since 1999 (Lehman 2005; Kurobe et al. 2013; Lehman et al. 2013). *Microcystis aeruginosa* is the most common cyanobacteria species although *Anabaena* spp. and *Aphanizomenon* spp. have also been detected (Berg and Sutula 2015). Blue-green algal species secrete hepato and central nervous system toxins, which can be toxic to humans and aquatic wildlife (Lehman et al. 2008; Berg and Sutula 2015).

The toxicological effect of HAB species on aquatic life in the Delta is not known. Recent research has measured microcystin in zooplankton, amphipods, and fish in the Delta (Lehman et al. 2010, 2017; UC Santa Cruz 2015). Striped bass and Mississippi silversides collected from the Delta had liver lesions consistent with sub-lethal exposure to microcystin (Lehman et al. 2010). Laboratory studies with threadfin shad and Sacramento splittail fed *Microcystis* contaminated food developed similar liver and gonadal lesions (Acuña et al. 2012a, 2012b). The survival of *E. affinis* and *P. forbesi* was reduced in laboratory bioassays with increasing concentrations of dissolved microcystin although the levels inducing toxicity were higher than commonly measured in the Delta (Ger et al. 2009). Survival of both copepod species was reduced when *Microcystis* exceeded 10 percent of their diet (Ger et al. 2010). Dissolved microcystin concentrations in the Delta have occasionally exceeded both the Office of Environmental Health and Hazard Assessment's action level for human health and the World Health Organization's recreational use guideline (Berg and Sutula 2015).

The magnitude and frequency of HABs are influenced by a number of environmental factors that are becoming more common in the Delta. These include higher water temperature, longer water residence time, increased water clarity, salinity, and high nutrient concentrations, particularly ammonia. *Microcystis* blooms occur now during the summer and fall in the central Delta and are associated with water temperature above 20°C, long water residence time, high irradiance, and elevated ammonium concentrations (Jacoby et al. 2000; Berg and Sutula 2015). Ammonium has been the preferred nitrogen source for cyanobacteria blooms in the Delta (Lehman et al. 2017). Many of these environmental factors are more common during drought years which may, at least partially, explain the recent increase in cyanobacteria blooms in the Delta. Climate change is also associated with these factors and may result in increasing the frequency and magnitude of HABs in the future (Lehman et al. 2017). However, climate change is also associated with sea level rise and increasing salinities in the Delta. Salinities greater than 10 ppt suppress *Microcystis* growth (Berg and Sutula 2015).

Cyanobacteria and their toxin levels are not routinely measured in the Delta in spite of their regular occurrence at potentially toxic concentrations. Brown et al. (2016) recommend that "quantitative monitoring should be developed and implemented so blooms and their effect on food webs can be better understood." The Central Valley Regional Water Board is developing a research plan to determine whether nutrient control, including ammonia, would reduce the magnitude and frequency of cyanobacteria blooms and toxin formation in the Delta.

4.3.1.6 Selenium and Mercury

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). Both 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). It has been shown to biomagnify in the invasive clam, *Potamocorbula,* which is a food source for bottom feeding fish such as sturgeon (Linville et al. 2002). High selenium concentrations were shown to cause reproductive harm to sturgeon (Linares-Casenave et al. 2015; Stewart et al. 2004). Historically, the primary controllable sources of selenium to the San Francisco estuary were subsurface agricultural drainage from the west side of the San Joaquin Valley and discharge of oil processing waste from refineries in the North Bay (81 FR 46030). TMDLs were adopted to control loads from both sources. Over the last decade, the loads from agricultural and refinery sources have been significantly reduced. In recent years, the average selenium water concentrations in the Bay have been ~0.1 parts per billion (ppb) in 2011, much lower than the existing water quality objective of 5 ppb. Ambient water column concentrations and selenium levels in fish are generally below the targets established by the North San Francisco Bay TMDL adopted in 2015. Only bottom feeding species with a high proportion of *Potamocorbula* in their diet, such as white sturgeon, show selenium concentrations that are occasionally higher than the TMDL target of 11.3 microgram per gram (μg/g) (Baginska 2015). Selenium concentrations in all other sport fish are well below levels of concern for human health.

Mercury was mined in the California Coast Range and used in gold mining in the Sierra Nevada (Churchill 2000). The mining resulted in widespread inorganic mercury contamination in water courses in the Coast Range, valley floor and Sierra Nevada. Methylmercury 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). As described in Section 4.2, restoration and reconnection of floodplains benefit ecosystems and native species in a variety of ways; however, elevated flow could increase environmental methylmercury by flooding riparian habitat and seasonal wetlands, which are the primary sources of methylmercury production in northern California (Wood et al. 2009). Control measures exist for sources of inorganic mercury. For example, improving the sediment trapping efficiency of the Cache Creek Settling Basin would reduce the loads of mercury that enter the Yolo Bypass from the Cache Creek watershed.

Like selenium, methylmercury bioaccumulates in the aquatic food chain with the primary route of exposure being through consumption of mercury contaminated fish (USEPA 1997). At greatest risk are human and wildlife fetuses and young (NRC 2000). Mercury has also been implicated in tissue accumulation causing gill, liver, kidney, and gastrointestinal tract damage to higher trophic-level species like sturgeon and splittail (Huang et al. 2012; Deng et al. 2008). Fish advisories were issued recommending limited human consumption of several fish species caught in the Central Valley and Bay-Delta estuary (OEHHA 2009). The San Francisco Bay and Central Valley Regional Water Boards adopted mercury TMDL control programs for San Francisco Bay and the Delta. Fong et al. (2016) recommended that monitoring be conducted to characterize long-term trends in bioaccumulative substances in fish. The trend analysis would serve as a performance measure to evaluate the effectiveness of ongoing mercury and selenium control programs.

4.3.2 Dissolved Oxygen

DO is critical to the health and survival of aquatic organisms. Low DO concentrations or hypoxia reduces the growth, swimming ability, and survival of aquatic organisms (USEPA 1986). DO concentrations in waterways are affected by many environmental factors including flow, temperature, salinity, and discharge of oxygen requiring substances. DO levels fluctuate diurnally with oxygen levels typically being highest during daylight hours when photosynthesis produces oxygen as a byproduct. DO levels also fluctuate seasonally with oxygen concentrations typically being lowest in summer during night time when freshwater flows are low and water temperature high (Spence et al. 1996; Newcomb et al. 2010). Warm water holds less DO than cold water and higher water temperatures also increase the metabolic and associated oxygen consumption rates of aquatic organisms making warm water conditions potentially stressful for aquatic life (Myrick and Cech 2000). Cold water species, such as developing salmonid embryos and larvae, are among the most sensitive organisms to low DO concentrations (USEPA 1986). Temperature and oxygen requirements of salmonids are discussed in Chapter 3.

Several locations in the Bay-Delta periodically experience low DO concentrations which may have negative impacts on native fish. Seven creeks and sloughs in the southern and eastern Delta and the lower Calaveras, Middle, Mokelumne, and Old Rivers in the central Delta are listed as impaired because of low DO. The Central Valley Regional Water Board has begun to evaluate the cause of these low DO situations. Low DO also occurs in low flow channels and dead-end sloughs in Suisun Marsh (O'Rear and Moyle 2009). Fish mortality has been observed when managed wetlands in Suisun Marsh are flooded and subsequently drained, releasing large loads of organic rich matter and water with low DO concentrations into adjacent channels (O'Rear and Moyle 2009; Tetratech 2013). The San Francisco Bay Regional Water Board is in the process of refining the DO objectives and developing a TMDL to correct the low DO impairment in Suisun Marsh. In the meantime, the Suisun Resource Conservation District together with the duck clubs owners have started interim actions to reduce conditions that may produce DO sags in marsh sloughs. As a result, no fish kills have been observed in the marsh since 2009.

Since the 1930s, the San Joaquin River and DWSC near the city of Stockton has experienced regular periods of low DO. These low DO conditions occurred year-round and have resulted in fish kills and delayed the upstream migration of fall-run adult Chinook salmon (McConnell et al. 2015). In 2005, the State Water Board approved the TMDL which included, as part of its implementation requirements, reductions in point and nonpoint sources of oxygen requiring substances and a requirement to assess the feasibility of operating an experimental aeration facility in the Stockton DWSC. In 2011 the assessment of the experimental aeration demonstration project was successfully completed and showed that aeration improved water quality with no redirected detrimental effects. A 5-year voluntary agreement was finalized in 2012 that provided funding for operation and maintenance with possible extensions after 2016. An upgrade of the City of Stockton's Regional

Wastewater Control Facility (WCF) and the operation of the aeration facility have contributed to significant improvements in DO conditions in the DWSC. The DO water quality objective has been violated less than 1 percent of the time since 2013, when both the upgrade to the City of Stockton WCF and the aeration facility were operational (McConnell et al. 2015).

4.3.3 Sediment and Turbidity

Turbidity is a measure of water clarity related to suspended sediment that is important for estuarine species in the Bay-Delta estuary (Bennett 2005; USFWS 2001). The Sacramento River is the largest source of suspended sediment to the Delta and is estimated to have provided about 85 percent of the load between 1999 and 2005 (Wright and Schoellhamer 2004). Most of the sediment enters the Delta between December and April and is carried in first flush events and in high winter storm flows. Sediment loads from the Sacramento basin have declined by about 50 percent since stream gaging began in 1957 (Wright and Schoellhamer 2004). Construction of dams is thought to be the primary reason for the decreased sediment load (Schoellhamer et al. 2016). Dams reduce sediment supply because large reservoirs trap the incoming sediment load behind the dam and discharge clear water downstream below the dam. The primary source of suspended sediment in the Sacramento basin is now from unregulated tributaries that discharge below rim reservoirs on the valley floor (Schoellhamer et al. 2016).

Turbidity in the estuary has declined by about 40 percent over the last half century (Cloern et al. 2011). The decline is attributed to reduced sediment input from reservoirs and from the spread of submerged aquatic vegetation (SAV) in the Delta (Schoellhamer et al. 2016). Areas in the Delta with the largest expanse of SAV have the greatest decrease in suspended sediment (Hester et al. 2016). SAV slows water movement, promoting increased sedimentation and reductions in turbidity. Between 20 and 70 percent of the increase in clarity in the Delta may have resulted from the expansion in SAV coverage (Hester et al. 2016).

Turbidity affects multiple important biological processes in the Bay-Delta estuary. For example, turbidity influences the amount of food available for the entire food web. Phytoplankton production in the estuary is light limited (Cloern 1999). Decreasing turbidity levels increase algal production and phytoplankton biomass, assuming that primary consumers are unable to keep up with the increasing algal supply (Dahm et al. 2016). Several native fish species and their invertebrate prey are food limited (see Chapter 3; Brown et al. 2016; Moyle et al. 2016). Phytoplankton are an important food resource for these organisms and increasing food levels are likely to increase population abundance. However, higher water clarity may lead to phytoplankton blooms, eutrophication, and harmful cyanobacteria blooms (Dahm et al. 2016). Reductions in turbidity are also 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 high turbidity (Hasenbein et al. 2012).

The reason for the fish distributions are not altogether clear, but laboratory studies have shown that Delta smelt require turbidity for successful feeding (Baskerville et al. 2004) and for refuge from predators (Nobriga et al. 2008). The Delta Smelt Resiliency Strategy is assessing the feasibility of adding suspended sediment to the LSZ for the benefit of Delta smelt (California Natural Resources Agency 2016a). Another example of the importance of turbidity is the positive feedback loop between reductions in turbidity and expansion of SAV coverage. Nonnative SAV, like *Egeria densa*, are light limited. An expansion in their range promotes additional sedimentation, further reductions in turbidity, and further range expansion (Hester et al. 2015). Monitoring of sediment via a sentinel monitoring system throughout the estuary should be a high priority to track trends in suspended sediment in the water column, and to better understand sediment budgets, as well as sediment fate and transport. Increasing sediment loads with sea level rise could help maintain tidal wetlands at an optimal elevation for plant establishment and growth (Schoellhamer et al. 2016).

Improved reservoir management and SAV control may increase sediment loading and turbidity in the Delta. Currently, reservoirs capture peak flood flows and their associated suspended sediment loads for flood control, irrigation, and water supply. Studies should be undertaken to determine the increase in suspended sediment load that would result if first flush events were bypassed through reservoirs and allowed to be discharged down river channels to the Delta. Similarly, a study should be undertaken to determine the increase in turbidity in the Delta that would result from a vigorous aquatic weed control program.

4.3.4 Temperature

Water temperature is a key factor in defining habitat suitability for aquatic organisms. High water temperature can be stressful for many aquatic organisms (Kammerer and Heppell 2012), particularly fish that are near the southern edge of their distribution (Matthews and Berg 1997). High water temperature also increases the growth and distribution of many nonnative species, increasing their ability to successfully compete for limited food and habitat with native organisms (Moyle 2002; Kiernan et al. 2012). Major factors that increase water temperature and negatively impact the health of the Bay-Delta ecosystem include disruptions of historical streamflow patterns, loss of riparian forest vegetation, reduced flows, discharges from agricultural drains, and climate change (USFWS 2001). Many of these factors occur in unregulated Sacramento River tributaries and negatively affect salmonid spawning and rearing. The effect of elevated temperature on juvenile and adult salmonids in tributaries is discussed in Chapter 3.

Exposure of Chinook salmon and steelhead populations to elevated water temperature is a major factor contributing to their decline (see Section 3.4; Myrick and Cech 2001). Reductions in cold water storage impede reservoirs from meeting their downstream water temperature requirements, especially during critically dry years (NMFS 2009a, 2014a). Physical and operational measures, including TCDs and seasonal storage targets, are employed at Central Valley reservoirs to improve the reliability of cold water discharge during critical summer and fall spawning and rearing periods. Increasing water demand and climate change is expected to further limit the effectiveness of reservoir flow and water temperature management in protecting anadromous fish populations below reservoirs (Lindley et al. 2007; Cloern et al. 2011). These conditions occurred in 2014 and 2015 when a lack of sufficient inflow and cold water storage in Shasta Reservoir resulted in sub-lethal to lethal water temperatures in the downstream Sacramento River, contributing to very low egg-to-fry survival for winter-run Chinook salmon (NMFS 2016c).

There is recognition of the need to improve data collection and modeling at Shasta Reservoir and other rim reservoirs to better understand the physical processes affecting thermal dynamics and determine the most effective strategies for meeting the downstream temperature requirements of salmonids (Anderson et al. 2015). Current efforts to improve water temperature management at Shasta Reservoir include developing a river temperature model (River Assessment for Forecasting Temperature [RAFT]) and incorporating it into a publically available Decision Support Tool (DST) (Danner et al. 2012; Danner 2015). RAFT uses a reservoir model and 7- day meteorological data to predict downstream river temperatures. RAFT does not model the 17 km reach between Shasta and Keswick Dams (Danner 2015). The goal for Shasta Reservoir is to use the suite of DST models to more effectively manage the reservoir's limited cold water resources for protection of winter-run

Chinook salmon**.** The DST would link reservoir models, including operation of the TCD, and RAFT, with biological models that evaluate temperature exposure and sub-lethal effects on downstream salmon redds. The DST would have the capability to operate in both a fore and hindcast mode to examine a range of operating alternatives for managing downstream temperatures while minimizing impacts on cold water resources in the reservoir. If the DST is successfully developed and used at Shasta Reservoir, then similar modelling tools should be considered at other rim reservoirs.

Flow and temperature data continue to be collected in Shasta Reservoir and downstream in the river to calibrate, validate, and refine the suite of linked models in the DST to determine potential biological effects. A refined suite of linked DST models would have the added value of providing the means to evaluate potential thermal impacts of restoration projects (riparian forest habitat restoration, gravel replenishment, channel and floodplain rehabilitation) and alternatives for minimizing climate change. If the DST is found to be valuable, then it should be expanded and used to manage temperature at other rim reservoirs.

4.3.5 Monitoring and Assessment

A thorough contaminant monitoring and assessment program is needed to ensure that the nature and extent of the effects of existing and new contaminants that may be introduced in the Delta are understood and addressed as needed through regulatory and other actions (Healey et al. 2016). The CALFED Ecosystem Restoration Program (CALFED ERP) and the DSP recognized the potential negative effects of contaminants on Delta organisms and identified pollutants that enter the Delta as a topic requiring further research (DSC 2013; Healey et al. 2008; CALFED 2000). Fong et al. (2016) and Healey et al. (2016) in their assessments of 2016 Bay-Delta Science also concluded that a dedicated contaminant monitoring and assessment program was needed for the Delta. The monitoring and assessment should be developed to answer management questions about the biological effect of natural and anthropogenic toxicants being detected in the Bay. To answer management questions, the program will need to include temporal and spatial chemical monitoring to establish sources, transport, fate, and trends over time. Chemical monitoring should be coupled with biological studies to determine the effect on fish and wildlife. In the past, water quality monitoring has emphasized acute bioassays coupled with toxicity identification evaluations and chemical analysis. Future monitoring should also include an evaluation of biochemical and molecular end points that are linked to sub-lethal effects (Fong et al. 2016). TMDL control programs have been developed for a number of contaminants, including bioaccumulative substances, like legacy pesticides, PCBs, PAHs, mercury, and selenium. However, there is no long-term fish tissue monitoring program to ascertain whether fish tissue concentrations are declining as expected. Periodic special studies may be needed to answer short-term management questions. For example, before and after studies are needed to determine the effect of the SRWTP upgrade on nitrogen cycling in the estuary and potential changes of nitrogen concentrations on algal species composition, primary production rates, and reductions in the magnitude of cyanobacteria blooms (Dahm et al. 2016; Brown et al. 2016).

The Delta Regional Monitoring Program (Delta RMP) began in 2015 and is now monitoring mercury, pathogens, and pesticides and synthesizing nutrient information to identify knowledge gaps and inform future nutrient monitoring efforts. Participation in the Delta RMP is required for any discharger impacting Delta water quality. Fong et al. (2016) recommended that the Delta RMP be supported to enable it to evolve into a long-term comprehensive monitoring and assessment effort capable of informing regulatory and management decisions. The Delta RMP should be closely coordinated with other ongoing monitoring efforts in the estuary including the San Francisco Bay Regional Monitoring Program, the Environmental Monitoring Program, the State Water Board Surface Water Ambient Monitoring Program, and the USGS National Water Quality Assessment Program. Closer integration of these different efforts would facilitate better interdisciplinary evaluations of data and lead to a more informed understanding of potential negative water quality effects of contaminants. Finally, the Delta RMP should insure regular synthesis and analysis of the monitoring and biological effects data to both inform adaptive management and be responsive to management questions.

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 nonnative species (Brown and May 2006; Brown and Michniuk 2007). All parts of the ecosystem are highly invaded with the majority of individuals or biomass at any location being introduced organisms (Brown et al. 2016). The presence of so many nonnative species is considered a major impediment to recovery of native taxa (Healey et al. 2016).

Nonnative species include fish, invertebrates, and aquatic plants, each discussed in more detail below. Invasive species are very difficult to eradicate once a successful introduction has occurred; however, various efforts have been and continue to be made to address the problem. The California Natural Resources Agency recognizes the importance of controlling aquatic invasive species and has developed the California Aquatic Invasive Species Management Plan (CDFG 2008). The plan provides a comprehensive coordinated effort to prevent new invasions, minimize impacts from established nonnative aquatic species, and establish a suite of priority actions. The management plan also lays out a process for annual evaluations of the program so that it can continue to be managed in an efficient manner. The plan should continue to be implemented with periodic reports to the State Water Board and the public on progress in achieving management goals.

4.4.1 Fishes

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). The altered hydrology creates more competitively favorable conditions for spawning and rearing of nonnative species than for native organisms (Brown and Bauer 2009) suggesting that a return to a more natural hydrology may be one of the few ways of favoring native species at the expense of introduced ones (Bunn and Arthington 2002).

NMFS considers predation by nonnative species an important factor affecting Sacramento River winter-run Chinook salmon, Central Valley spring-run Chinook salmon, Central Valley fall- and late-fall-run Chinook salmon, and Central Valley steelhead (CDFG 2011a). Native predators of salmon and steelhead include pikeminnow (*Ptychocheilus grandis*), several avian species (BPA 2010) in the Delta, along with the occasional marine mammal (CDFG 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).

Silversides (*Menidia beryllina*) are an example of a nonnative species that both preys upon and competes with native species for limited food resources. Silversides school in large numbers over sand and gravel bottoms and are the most abundant fish in many shallow areas of the estuary (Chernoff et al. 1981; Kramer et al. 1987; Moyle 2002). Their distribution overlaps that of native species like Delta smelt, juvenile salmonids, and Sacramento splittail (Moyle 2002). Silversides may outcompete other small planktivorous fish for limited food resources (Moyle 2002). They are also voracious predators on larval fish and are abundant in shallow areas where Delta smelt spawn, especially during low flow years (Swanson et al. 2000; Moyle 2002). Silversides also prey heavily on Delta smelt eggs and larvae (Baerwald et al. 2012). The introduction of silversides coincided with and may have contributed to the decline of Delta smelt populations. The continued abundance of silversides may inhibit the recovery of Delta smelt (Swanson et al. 2000; Moyle 2002). Other important nonnative predators include striped bass, white and channel catfish, and largemouth bass. These species also better tolerate highly altered environments characterized by low flow and low DO conditions than native species (Moyle 2002; Feyrer et al. 2004).

Predation by nonnative fish on Chinook salmon larvae remains a controversial issue in the Bay-Delta estuary (Grossman et al. 2013). Removal of striped bass or other predacious fish species has been suggested as a method to improve juvenile Chinook salmon survival. Predator removal experiments improved juvenile Chinook salmon survival in small areas of the Delta for a short time (Cavallo et al. 2012) but did not increase salmon survival in the long-run (Grossman et al. 2016). The majority of fish predators in the Bay-Delta are nonnative species (more than 20 taxa) and many consume juvenile Chinook (Grossman et al. 2016). Removing a single species increases the number of other nonnative competitors (Grossman 2016). For example, a field study found that predation by other nonnative fish tripled after striped bass removal (Cavallo et al. 2012). Bridges, water infrastructure facilities, unnatural bends, and gravel removal pits in river channels have been identified as predator hotspots (Sabal et al. 2016). Identification and modification of these structures to eliminate hiding and ambush sites for nonnative predators may be a limited but more effective predator control method than predator removal.

The extent of predation by nonnative fish on native populations remains largely unknown since multiple stressors negatively impact native fish. Predation is only one of these factors. Other factors include warm water, lower turbidity, contaminants, and low flow. Stressors interact and may act in conjunction with each other so it is difficult to determine how much each stressor affects fish in isolation. Increasing winter and spring flows to maintain low temperatures and elevated turbidity may be better solutions for recovery of native species than predator removal. This is consistent with the observation that more permanent or more constant flows created by damming and diverting river flows favor introduced species (Moyle and Mount 2007; Poff et al. 2007). The reestablishment of more natural flow regimes in Putah Creek provided higher spring flows, cooler water temperatures, and more shaded habitat, which improved native fish spawning and rearing at the expense of nonnative species (Marchetti and Moyle 2001; Kiernan et al. 2012). Studies may be warranted that examine the consequences if nonnative fish are not salvaged at the SWP and CVP. The CVP and SWP salvaged over 32 million striped bass, 3 million silversides, half a million largemouth bass, and 5 million white catfish between 1992 and 2005 (Grimaldo et al. 2009a). More than 95 percent of the fish salvaged at the CVP and SWP facilities were nonnative species (Aasen 2016). Not salvaging these fish may be a cost-effective way to reduce the population size of nonnatives without having a negative impact on native organisms.

Four recommendations are made to reduce the abundance and distribution of nonnative fish species. First, the California Fish and Game Commission (CFGC) should deny all requests for the introduction of new aquatic species unless it finds that the introduction will not have deleterious effects on native organisms. Second, Reclamation and DWR should evaluate the cost effectiveness and efficacy of not salvaging nonnative fish species at the CVP and SWP. Third, large numbers of salmonids are lost at predation hot spots (Sabal et al. 2016). Studies should be conducted to determine the location of these sites, the characteristics that make them valuable ambush sites for predators, and how the locations might be modified to reduce their availability to predators. Finally, studies should be undertaken to determine the efficacy of a more natural flow pattern for discouraging the growth and reproduction of nonnative fish species while increasing the abundance and distribution of native taxa in both upstream tributaries of the Sacramento River and the downstream Bay-Delta estuary.

4.4.2 Invertebrates

The value of the Bay-Delta estuary as a nursery area for native species has been compromised by the successful invasion of nonnative invertebrates including several species of bivalves, crustaceans, and jelly fish. These organisms now dominate both the benthic and planktonic environments of the estuary and disrupt the base of the estuarine food web (Jassby et al. 2002; Sommer et al. 2007; Mount et al. 2012). Complex trophic interactions make it difficult to predict the biological effect of these invasions on the native invertebrate community, including its composition and abundance (York et al. 2013). However, observed changes in the Bay-Delta suggest a shift has occurred in energy flow from a phytoplankton-based pelagic food web to a detritus-derived benthic food web (Winder and Jassby 2011).

Potamocorbula and *Corbicula fluminea* are two common introduced bivalves in the Bay-Delta estuary. A long-term decline in phytoplankton biomass (chlorophyll-a) occurred in Suisun Bay after the introduction of *Potamocorbula* in 1986 (Figure 4.4-1) (Jassby et al. 2002; Lucas et al. 2002; Kimmerer 2006; Jassby 2008). *Corbicula fluminea* is native to Asia and was first reported in the Bay-Delta in 1945 (Cohen and Carlton 1995). As filter feeders, the two clam species consume large quantities of phytoplankton, bacterioplankton, and small zooplankton such as rotifers and copepod nauplii (Greene et al. 2011; Durand 2010) which decreases food availability for larger zooplankton and mysids that serve as prey for fish species in the Bay-Delta (Mount et al. 2012).

Invasive bivalves have affected native fish species in the Bay-Delta. Soon after the *Potamocorbula* invasion there was a large decline in the carrying capacity of the estuary for Delta smelt, longfin smelt, and starry flounder (Bennett 2005; Moyle et al. 2016; see discussion in Chapter 3). Recruitment per unit Delta outflow for longfin smelt and starry flounder decreased by 4.3±1.4 and 3.9±1.5[1] fold, respectively and has not recovered (Figure 3.5-2 and Figure 3.9-2). Today *Potamocorbula* dominates the entire brackish transition zone of the estuary. *C. fluminea* is widely dispersed as the most abundant bivalve species in the freshwater portion of the Delta (Lucas et al. 2002). Because of the widespread distribution of these two invasive clams, there are very few locations in the estuary where phytoplankton assemblages can develop as occurred prior to the two invasions. Reduced standing chlorophyll levels are considered a major factor in controlling secondary production and fish abundance in the estuary (Kimmerer 2002; Brown et al. 2016). As a result, the capacity of the system to produce food for fish is now more limited. Studies are needed to determine whether physical or biological control of *Potamocorbula* is practical and feasible. Biological controls might include encouraging more predation by diving ducks and white sturgeon.

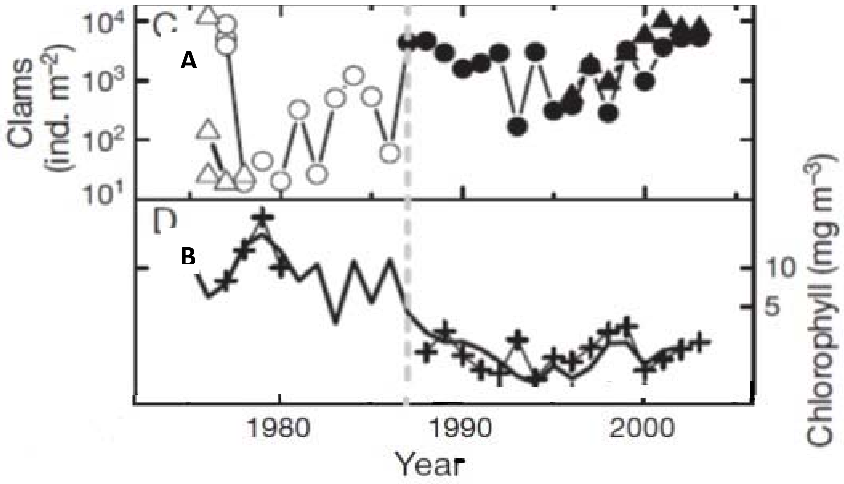

Figure 4.4-1. Clam Abundance and Chlorophyll Concentrations in the Low Salinity Zone before and after the Invasion of the Clam *Potamocorbula* in 1987 (vertical dashed line). Figure from Kimmerer 2006.

Between the early 1960s and mid-1990s, eight East Asian pelagic copepods invaded the Bay-Delta estuary where they replaced native species and disrupted the aquatic food chain. Those species included *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 *Potamocorbula* became abundant in the low-salinity reaches of the estuary (Winder and Jassby 2011). *E. affinis* still achieves high population levels during spring, but it is replaced by *P. forbesi* in summer and fall. While small native fish such

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[1] Mean ± standard error.

as smelts can switch between the two prey types, they may not benefit consuming the nonnative copepod, *P. forbesi,* which is a faster swimmer than *E. affinis* and may be more difficult to catch and not as cost-efficient a prey item to consume (Meng and Orsi 1991; 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. *P. forbesi*, *Acartiella* spp., and *Limnoithona* are smaller than native copepods such as *Eurytemora* spp. and *Acartia* spp., take more energy to capture, and are less available to predators (Meng and Orsi 1991; Winder and Jassby 2011; Mount et al. 2012).

The Native mysid, *N. mercedis,* and the *Crangonid* shrimp, *Crangon franciscorum*, were common species in the estuary. 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) and have been replaced by nonnatives including *Gammarus daiberi* (Kimmerer 2004). A recent unpublished analysis of the outflow requirements of important introduced and native zooplankton was summarized in Chapter 3. The analysis suggested that increasing net Delta outflow between March and September will increase the abundance of *E affinis, P. forbesi*, and *N. mercedis* (Hennessy and Burris 2017).

Two species of jelly fish (*Maeotias marginata*, *Moerisia* sp.) are now established in Suisun and San Pablo Bays (Rees and Gershwin 2000; Wintzer et al. 2011). Not much is known about these species but there is concern that these predatory jelly fish will further alter the aquatic community by capturing and consuming zooplankton, larvae, and juvenile fish (Rees and Gershwin 2000).

4.4.3 Aquatic Plants

A suite of nonnative plants have colonized the Delta (Boyer and Sutula 2015). These include Brazilian waterweed (*Egeria densa*), water hyacinth (*Eichhornia crassipes*), water primrose (*Ludwigia* sp.), curly leaf pondweed (*Potamogeton* sp.), and Eurasian watermilfoils (*Myriophyllum spicatum*) (Ferrari et al. 2013; CDBW 2014; DSC 2013; Boyer and Sutula 2015). Native submerged and floating aquatic vegetation also occur in the Delta. Common native species are pondweed (*Stuckenia* sp.) and coontail (*Ceratophyllum demersum*). The most problematic nonnative aquatic plants are Brazilian waterweed and water hyacinth because of their ability to spread rapidly under the right environmental conditions, displacing native species, clogging waterways, altering turbidity, and negatively affecting other aquatic species. These invasive species are called “ecosystem engineers” because of their ability to affect food chains and other aquatic species by modifying the surrounding physical environment (Mount et al. 2012).

Brazilian waterweed has detrimental effects on the Bay-Delta ecosystem (Boyer and Sutula 2015). Brazilian waterweed is native to South America, was introduced to the United States in 1893, and became established in shallow littoral areas of the freshwater Delta during the 1980s. From 2004 to 2006, the distribution of Brazilian waterweed increased by more than 10 percent per year and has continued to increase during the recent drought (Conrad et al. 2016). Brazilian waterweed now covers 60 percent of central Delta channels (Santos et al. 2011) and 5–10 percent of all Delta waterways (Santos et al. 2016). These estimates are only approximate because no regular monitoring program exists to determine biomass and coverage of aquatic vegetation (Boyer and Sutula 2015). *E. densa* occurs in dense canopies that shade the understory and reduce phytoplankton growth and exclude other submerged native aquatic plants, decrease oxygen levels at night, and increase water temperature and water clarity by reducing water circulation and promoting sedimentation. Brazilian waterweeds also provide cover for large nonnative fish predators that prey on smaller native fish. USFWS (2016) considers predation in SAV a limiting factor for Delta smelt survival. Brazilian waterweed does not occur in Suisun Bay because of its intolerance of salinities greater than 5 ppt (Borgnis and Boyer 2015). Colonization of the Delta by SAV established a new food web. Brazilian waterweed provides structural complexity and surface area for attached epiphytic algae and invertebrates and a refuge for fish (Brown and Michnick 2007; Schultz and Dibble 2012; Brown et al. 2016). A stable isotope diet study found that centrarchids ate amphipods that were consuming epiphytic algae attached to SAV (Grimaldo et al. 2009b). Some open water fish—juvenile Chinook salmon and silversides—may also have also entered the SAV canopy at high tide and consumed attached food organisms.

Water hyacinth also has detrimental effects on the Bay-Delta ecosystem (Boyer and Sutula 2015). Water hyacinth is native to South America and was introduced to the United States in 1884 (DSC 2013). Since its introduction into the Delta, water hyacinth has proliferated and eradication is no longer an option (CDBW 2012). Water hyacinth increased four-fold from 2004–2007 to 2014 and now covers about 800 hectares in the Delta (Boyer and Sutula 2015). Negative issues associated with water hyacinths are similar to those caused by Brazilian waterweed. Water hyacinths now cover the entire water surface of many back sloughs, blocking sunlight for phytoplankton and other submersed autotrophs, decreasing DO, creating barriers to navigation, changing turbidities in the water column, and affecting fish feeding and passage (Villamagna and Murphy 2010). Water hyacinths are sensitive to salinity and exhibit stress at 2.5 ppt (Haller et al. 1974) and mortality above 6–8 ppt (as summarized in Boyer and Sutula 2015). Little is known about the food web effect of water hyacinths on native fish and the aquatic ecosystem (Brown et al. 2016).

Climate change may increase the abundance and distribution of invasive aquatic plants in the Delta (Boyer and Sutula 2015). Climate change is predicted to result in warmer water temperatures and an increased frequency of droughts. These factors will favor the increased dominance of Brazilian waterweed and water hyacinth. However, sea level rise and increased saltwater intrusion into the western Delta could slow the spread of these salt intolerant plants.

Control measures to reduce the biomass and spread of nonnative aquatic vegetation have not been effective. This has resulted in the search for novel, more effective ways to control nonnative aquatic plants. The CDBW routinely applies chemical herbicides to control the spread of both *E. densa* and *E. crassipes* and has experimented with mechanical shredding (Boyer and Sutula 2015; CDBW 2006). Sub-lethal effects on aquatic organism have been documented from these herbicide applications (see Section 4.3). Mechanical shredding of water hyacinth resulted in low DO levels and localized fish kills because of decomposition of the shredded organic material (Greenfield et al. 2007). 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 (reviewed in Boyer and Sutula 2015). The Central Valley Regional Water Board has assembled a Science Work Group and is developing a research plan to determine whether nutrient control could reduce the abundance and distribution of nonnative macrophytes (Central Valley Water Board 2014). A more variable flow pattern that allowed periodic low Delta outflow and some saltwater intrusion into the western Delta could naturally restrict the distribution of these nonnative aquatic plants.

Nonnative aquatic plants are now a permanent part of the Bay-Delta ecosystem. Three recommendations are made to better understand their effect on the aquatic ecosystem and to develop control strategies. First, routine monitoring of floating and submerged aquatic vegetation is needed to assess trends over time and estimate biomass, net primary production, and species composition (Boyer and Sutula 2015). Second, potential control strategies need to be evaluated to determine their effectiveness at reducing live biomass and limiting colonization of new habitat. The review of control strategies should include an evaluation of mechanical, chemical, biological, salinity and nutrient management (Boyer and Sutula 2015). Finally, more research needs to be undertaken to understand the effect of invasive aquatic plants and their control on native fish and the Bay-Delta aquatic ecosystem.

Two groups, the Delta Region Areawide Aquatic Weed Project and the IEP Aquatic Vegetation Project Work Team are beginning to carry out these recommendations. The Delta Region Areawide Aquatic Weed Project—a collaboration among National Aeronautics and Space Administration, U.S. Department of Agriculture-Agricultural Research Service, University of California-Davis, and local agencies—was formed in 2011 and is evaluating the use of remote sensing-based geospatial information to determine aquatic weed distributions and is also conducting research on more effective herbicides and biocontrol methods. The IEP Aquatic Vegetation Project Work Team—composed of federal and state scientists—was formed in 2016 and is investigating the impacts of nonnative aquatic vegetation and treatment efforts on Bay-Delta habitats and wildlife.

4.5 Fishery Management

This section focuses on the effects of fisheries management activities on the aquatic ecosystem in the Delta and its tributaries such as harvest, hatchery operations, and unscreened diversions.

4.5.1 Harvest

The Delta and its tributaries currently support recreational and commercial fisheries. Recreational fisheries include a marine and freshwater fishery for striped bass, largemouth bass, black bass, white sturgeon, Chinook salmon, steelhead, catfish, and American shad (CDFG 2011b). The only commercial fisheries in the Delta are for threadfin shad and crayfish, though the Delta and its tributaries also support a commercial ocean salmon fishery (Water Science and Technology Board et al. 2012; Mesick 2001; Moyle 2002). As discussed in Chapter 3, there has been a substantial decline in population abundance of salmonids, sturgeon, splittail, starry flounder, and bay shrimp over the last 50 years. There are a number of factors contributing to these declines, including loss of flow and physical habitat, along with the effects of other stressors (Sommer et al. 2007; Fong et al. 2016). An additional factor may be a potentially unsustainable take of adult breeding stock in commercial and recreational fisheries. Loss of adult breeding stock can reduce recruitment, future population abundance, and the viability of the fishery.

In its recommendations to other agencies, the 2006 Bay-Delta Plan's program of implementation suggested that the CDFW, CFGC, Pacific Fisheries Management Council (PFMC), and NMFS review and modify, if necessary, existing commercial and sport fish take regulations; and, that CDFW should expand efforts to reduce illegal harvest.

The CFGC, PFMC, and NMFS has evaluated the effect of take and recommended more stringent fishing regulations to the CFGC for native and special status Bay-Delta species (CDFW 2017). Some of these regulations are summarized in Table 4.5-1. In addition, PFMC conducts a dynamic annual regulatory setting process to adjust salmonid harvest rates based on stock size and distribution. For example, PFMC implemented a near full closure of the ocean salmon fishery in 2008–2009 because of reduced stock size. Reductions in the recreational take of sturgeon and Sacramento splittail have also occurred. Finally, poaching represents an illegal form of harvest and has been a continuing problem in the Delta especially for sturgeon (Mount et al. 2012). CDFW uses wardens and other surveillance methods to discourage and prosecute illegal poaching.

Table 4.5-1. Summary of Recent Take Regulations to Reduce the Impact of Commercial and Recreational Harvest on Native Fish Species

Effective Year	Regulation Change	Intended Impact
Salmonids		
2008-2009	Near-full closure of ocean salmon fisheries	Protection of collapsed fall-run Chinook salmon population
>1989	Winter-run Chinook salmon: Since winter-run Chinook salmon were listed as ESA threatened in 1989, various ocean area and river reach fishing closures and reduced size limits, and truncated seasons have been used to reduce the catch of winter-run Chinook salmon in commercial and recreational fisheries	Reduced winter-run Chinook salmon harvest rates (which has been successful)
Sturgeon		
2006	Green sturgeon: zero bag limit	No legal harvest
2007	White sturgeon: 1-fish daily, 3-fish annual bag limits	Reduced adult harvest rate
2007	White sturgeon: Reduced maximum legal size	Improved survival of older/larger spawners
>2006	Sturgeon general: Various fishing restrictions, including substantial river-reach closures, weir basin closures, and gear restrictions	Reduced catch of non-legal sizes, reduced legal and illegal harvest in vulnerable areas
Other Species		
2010	Splittail: 2-fish daily bag limit	Reduction in total annual harvest

CDFW, CFGC, PFMC, and NMFS are responsible for maintaining sustainable populations of native Bay-Delta fish species. These agencies should continue to review the status of native species of concern at least every 2 years. The status review should include an evaluation of the effect of commercial and recreational harvest on population dynamics and the sustainability of the population. The status review should make recommendations on whether additional harvest regulations are needed. Management actions may also include development and implementation of a fisheries management program to provide short-term protection for aquatic species of concern through area closures and gear restrictions to reduce capture and mortality of species of concern. An enhanced program to further restrict illegal harvest may also be beneficial.

4.5.2 Hatcheries

Hatchery production is recognized as an important component of salmon and steelhead conservation and recovery efforts but historically has posed a threat to wild Chinook salmon and steelhead stocks through genetic, ecological, and management impacts (Waples 1991; California Hatchery Scientific Review Group 2012; NMFS 2014a). Most hatcheries in California are operated as production hatcheries to mitigate for the loss of habitat (lost access to spawning and rearing habitat above dams) with the primary goal of supporting ocean commercial and recreational salmon fisheries and in-river recreational salmon and steelhead fisheries (California Hatchery Scientific Review Group 2012). Annual production from salmon and steelhead hatcheries in California approaches 50 million juveniles, with over 32 million fall-run Chinook salmon produced at five Central Valley hatcheries in most years (California Hatchery Scientific Review Group 2012). Currently, hatchery-origin Chinook salmon make up a substantial proportion of Central Valley salmon runs, and spawning escapement of fall-run Chinook salmon in some of the major tributaries are now dominated by hatchery-origin fish (Yoshiyama et al. 2000; Barnett-Johnson et al. 2007).

Hatcheries can have positive effects on salmonid populations. Artificial propagation has been shown to be effective in bolstering the numbers of naturally spawning fish, conserving genetic resources, and guarding against catastrophic loss of naturally spawned populations at critically low abundance levels, as was the case for the winter-run population during the 1990s (NMFS 2014a). The Livingston Stone National Fish Hatchery was established as a conservation hatchery program to augment the naturally spawning winter-run Chinook salmon population in the Sacramento River and is currently managed to maintain genetic diversity and minimize potential adverse effects associated with artificial propagation. However, an increasing proportion of hatchery fish among returning adults in recent years has raised concerns about potential effects on the genetic integrity and fitness of the population (NMFS 2016a).

Fish produced in hatcheries can also have detrimental genetic, ecological, and management effects on natural salmonid populations (Kostow 2009; Araki et al. 2008; California Hatchery Scientific Review Group 2012). Hatcheries can cause unintentional evolutionary change in populations that can lead to loss of local adaptations and reductions in genetic diversity and fitness of wild populations (Reisenbichler and Rubin 1999; Bisson et al. 2002). For example, evidence exists that large off-site releases of fall-run Chinook salmon from Central Valley hatcheries and resulting high levels of straying of hatchery adults to natural spawning areas has genetically homogenized the ESU, contributing to losses in biodiversity and reduced resilience and viability of the ESU (Williamson and May 2005; Lindley et al. 2009). In addition, high levels of straying of hatchery fish can adversely affect natural stocks through ecological interactions, including disease transmission, predation, and competition for spawning habitat or other resources (California Hatchery Scientific Review Group 2012). Large-scale hatchery production and historically high harvest rates in mixed-stock fisheries has also contributed to reductions in natural diversity through overharvest of naturally produced stocks (Lindley et al. 2009). The California Hatchery Scientific Review Group (HSRG) identified current harvest rates on naturally produced Sacramento River fall-run Chinook salmon as a continued concern because of degraded conditions for downstream migration throughout the basin (California Hatchery Scientific Review Group California Hatchery Review Report 2012).

Along with habitat loss and degradation, hatchery management was identified as an important factor contributing to the listings of Central Valley spring-run Chinook salmon and steelhead (NMFS 2014a). Most of the spring-run Chinook salmon production in the Central Valley is of hatchery-origin, and introgression of spring- and fall-run and significant straying of adults from Feather River Hatchery have posed a significant threat to the genetic integrity of natural spawning fall- and spring-run Chinook salmon in other watersheds (NMFS 2014a). Over the past several decades, the genetic integrity of Central Valley steelhead has been diminished by increases in the proportion of hatchery fish relative to naturally produced fish, use of out-of-basin stocks for hatchery production, and straying of hatchery produced fish (NMFS 2014a). Recent reviews and evaluations of these hatchery programs (California Hatchery Scientific Review Group 2012 and Hatchery Genetic Management Plans) have led to a number of proposed strategies or recommended changes in hatchery policies and management to address these impacts and assist in the conservation and recovery of listed evolutionary significant units and distinct population segments and other naturally spawning Chinook salmon populations. In addition, NMFS is currently in the process of reviewing Hatchery Genetic Management Plans to evaluate hatchery impacts and assist in the development of hatchery management strategies to support the conservation and recovery of listed salmon and steelhead.

4.5.3 Unscreened Diversions

Loss of juvenile salmonids at unscreened water diversions in the Sacramento River and Delta has been identified as a reason for the listing of winter- and spring-run Chinook salmon, and steelhead (NMFS 2014a). The potential for entrainment of young fish at unscreened or poorly screened diversions used for agricultural, municipal, and industrial use, and managed wetlands continues to be recognized as a major stressor to these species and other special-status fish (USFWS 1996; NMFS 2014a). While entrainment losses have likely increased with increases in water withdrawals, the role of this stressor in the historical declines and current status of these populations remains largely unquantified (Moyle and Israel 2005). As part of the CVPIA's fish restoration efforts, the Anadromous Fish Screen Program (AFSP) was established in 1994 to address this issue and provide technical guidance and cost-share funding for fish screen projects. The AFSP[2] also supports activities and studies to assess the potential benefits of fish screening, determine the highest priority diversions for screening, improve the effectiveness and efficiency of fish screens, encourage the dissemination of information related to fish screening, and reduce the overall costs of fish screens.

Many of the large water diversions (greater than 150 cfs) on the Sacramento River are screened or are currently proposed for screening (NMFS 2014a). However, there are over 3,700 water diversions on the Sacramento and San Joaquin Rivers, their tributaries, and in the Delta; most of these are unscreened (Mussen et al. 2013). In 2009–2012, the AFSP and CALFED ERP conducted fish entrainment monitoring at 12 agricultural diversion sites on the Sacramento River and Steamboat Slough to evaluate site-specific physical, hydraulic, and habitat characteristics to assist with future fish screening prioritization efforts. This monitoring program, like past studies, indicated that entrainment of salmon was low relative to other fish species (Vogel 2013). In general, the factors affecting fish entrainment at unscreened diversions are complex and poorly understood because of the many site-specific variables that influence the exposure and vulnerability of fish to entrainment (Vogel 2013). Laboratory experiments using a large river-simulation flume indicate that entrainment losses of juvenile salmon are likely related to several factors, including the numbers of unscreened diversions to which the fish are exposed; the proximity of individual fish to the diversion intake structure as they pass the site; water velocity (sweeping velocities); water diversion rates; turbidity; and, light levels (Mussen et al. 2013). The 2009–2012 study monitoring results indicate that some of the most important determinants of salmon entrainment likely include the initial timing of irrigation diversions in the spring, hydrologic conditions preceding the onset of irrigation diversions, and the natural emigration timing of salmon in relation to the timing of diversions. For example, a major factor contributing to the low incidence of salmon entrainment in these years appears to be the timing of emigration (as influenced by the timing of peak flow events) relative to the timing of diversions (Vogel 2013).

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[2] https://www.fws.gov/cno/fisheries/cvpia/AnadromFishScreen.cfm.

CDFW, NMFS, USFWS, and local water district and landowners should continue to evaluate unscreened diversions in the Sacramento River basin and in the Bay-Delta for their potential to cause mortality to migrating salmonids and other threatened and endangered fish species and implement fish screening solutions, including modifications to the timing of water diversions, as appropriate.

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). In the Bay-Delta climate change impacts are predicted to include higher ambient temperatures, increased salinity intrusion, and reduced water supply reliability. 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 2013b). 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). Climate change may alter the magnitude and timing of future unimpaired flow. 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 and maintenance of cold water habitat below reservoirs for salmonids (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. 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). Climate-induced increases in ambient water temperature in Sierra Nevada streams could be from 1 to 5°C (Ficklin et al. 2013). Water temperature increases of 2–2.5°C will result in a 10 percent reduction of DO (Ficklin et al. 2013). Higher temperature and lower DO levels will favor nonnative species that are better adapted to those conditions than native fish (Kiernan et al. 2012; Moyle et al. 2013). Moreover, warmer water and more extreme events will decrease cold water habitats for important fisheries. The projected effects of climate change are particularly problematic for species like Delta smelt because of their low temperature tolerances (Wagner et al. 2011). By the end of the 21st century, warming temperatures is projected to compress Delta smelt maturation windows by 15–25 percent, leading to declines in growth and egg production (Brown et al. 2016). Similar reductions in habitat quality may occur for other native species. Elevated ambient water temperatures can stimulate growth of nuisance aquatic plants and blooms of harmful algae, which can also 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).

Sea level rise, predicted to increase by as much as 55 inches by 2100 (OPC 2011; DSC 2013), is already occurring in the San Francisco Bay (Grenier 2016). 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 2016). Increased salinity intrusion may also change the distribution, range, and abundances of organisms because X2 may move upstream of Suisan Bay and into habitat which is less ideal for growth and reproduction of native fish (see Section 3.2). 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). Increased salinity intrusion into the Delta may require higher freshwater releases from upstream reservoirs to repel saltwater (DWR 2009b). This may result in a 10 percent reduction in available freshwater by mid-century and a 25 percent reduction by end of the century (DWR 2009b). 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 2014; Grenier 2016).

Actions to prepare and mitigate effects of climate change may include acquisition of additional higher elevation wetland habitat for wildlife to escape flooding in the estuary (ERP 2104; Grenier et al. 2016; Goals Project 2015). In the upper basin, fish passages may need to be built around dams to facilitate upstream migration of salmonids above reservoirs to cooler habitats. Additionally, operators may need to change water temperature controls from dams and other infrastructure to adjust for climate change effects. Acquisition of additional wetland habitat is the responsibility of local entities and the Resource Agency while alterations in dam construction and operations are the responsibility of reservoir operators. However, the extent and magnitude of climate change is uncertain, making planning and management difficult.

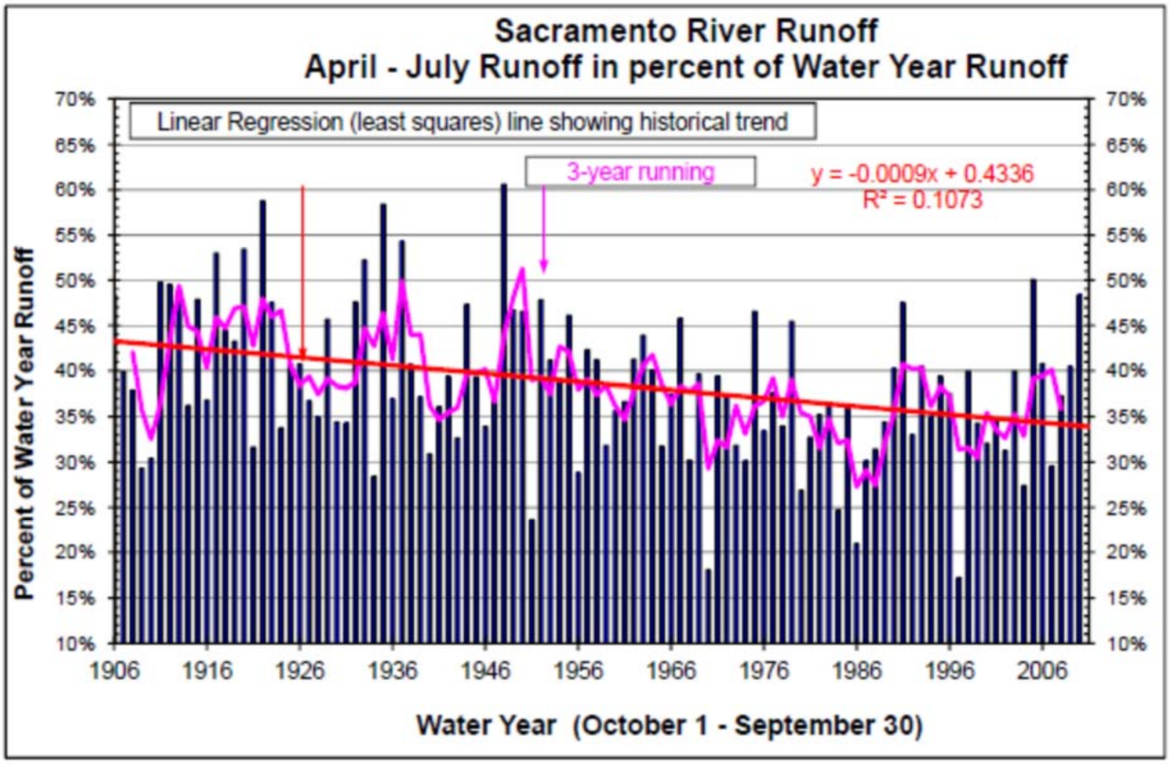

Figure 4.6-1. Declining Trend in April–July Contribution to Total Water Year Runoff in the Sacramento River System, 1907–2010 (from Roos 2012)

4.7 Summary

The State Water Board's Bay-Delta planning and implementation efforts are part of a multi-facetted approach needed to address the systemic ecological and water supply concerns in the Bay-Delta and reconcile an altered ecosystem. Other actions are important to protect the Bay-Delta ecosystem, such as habitat restoration. The proposed changes to the Bay-Delta Plan are structured to address the complexities of the watershed while responding to new information and changing conditions and providing for meaningful action in the near term to protect the Bay-Delta ecosystem. The proposed changes are structured to work together and with other planning, science, restoration, and regulatory efforts in a timely, adaptive, flexible and comprehensive manner so that meaningful action can be taken to ensure the protection of fish and wildlife before imperiled species in the watershed are no longer able to be restored. Like the flow measures, non-flow measures should be accompanied by research and coordinated adaptive management to adjust to further scientific understanding of the Delta ecosystem and changing circumstances.

The precise effect of non-flow stressors on the abundance and distribution of native species is not known. It is difficult to determine how much each stressor affects fish in isolation because stressors interact and may act in conjunction with each other. A few stressors have been shown to have measurable effects on native fish and the aquatic ecosystem. The invasion of *Potamocorbula* reduced both chlorophyll biomass in Suisun Bay (Figure 4.4-1) and the carrying capacity per unit Delta outflow for starry flounder and longfin smelt (Figures 3.5-2 and 3.9-2) (Kimmerer 2002b).

Construction of dams blocked upstream migration of salmonids and lack of cold water habitat below dams have reduced the abundance of Chinook salmon and Central Valley steelhead (Section 3.4.4). A negative relationship exists between application of pyrethroid insecticides and the FMWT index for five fish species in the Delta (Figure 4.3-1) (Fong et al. 2016) suggesting that insecticides may contribute to the decline in fish recruitment. Other stressors have been documented to cause toxicity in laboratory bioassays, to reduce the size and quality of critical habitat, and to increase competition and predation on native species. The presumption is that these stressors have negatively impacted native taxa (Moyle 2002; Mount et al. 2012) but further studies would be needed to quantify the magnitude of these impacts.

A dedicated contaminant monitoring and research program is needed for the Delta (Fong et al. 2016; Healey et al. 2016). The monitoring program should include traditional temporal and spatial chemical monitoring and be coupled with acute and sub-lethal toxicity endpoints of organismal health. Special studies to evaluate the effect of other non-flow stressors on fish and wildlife are also needed. Regular synthesis of data will be required to answer management questions and adaptively manage the program. The RMP has a history of conducting high-quality monitoring and assessment studies in the San Francisco Bay. The Delta RMP has recently been established and begun to monitor contaminants in the Delta. The two programs should consider developing and implementing a coordinated, comprehensive non-flow stressor program for the Bay-Delta estuary under the direction of the San Francisco Bay and Central Valley Regional Water Boards. The goal of the program should be to inform water quality management and evaluate success in meeting water quality goals.

In addition, there are many other 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. The program of implementation will include specific adaptive management provisions and requirements, monitoring, reporting and evaluation measures, including provisions for the development of biological goals by which success at achieving the narrative objectives will be measured that will inform adaptive management of the numeric requirements. Information on other stressors, and non-flow actions will be included in the assessments as appropriate. The State Water Board will continue to work with the DSC's DSP, Delta ISB, fisheries agencies, and others to ensure that adaptive management and associated monitoring, reporting, and assessment efforts are sufficiently rigorous. This includes efforts to coordinate upstream actions on tributaries with downstream Delta science activities and to support a common Delta science program.

The population abundance of native fish in the Bay-Delta is in decline. Recovery of the native fish community will require investment in increased instream flows and Delta outflows, habitat restoration and reductions in other non-flow stressors. 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 complementary non-flow measures are pursued. In addition, management actions, including habitat restoration may, at least in part, be implemented through tributary plans discussed in Chapter 5.

Chapter 5
Recommended New and Revised Flow Requirements

5.1 Introduction

This chapter describes proposed 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 requirements consist of new and revised water quality objectives that describe flow and other water quality conditions necessary to protect beneficial uses, and the program of implementation that describes how objectives will be achieved, including specific adaptive management, monitoring, evaluation, and reporting requirements. This chapter includes a description of the proposed changes to water quality objectives and articulates a general approach to the program of implementation. However, the exact regulatory language is still under development and will be informed by the science in this Report, environmental and economic analyses, and public comment as the planning process moves forward.

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 flow requirements are intended to be implemented in coordination with complementary actions described in Chapter 4. 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, cold water and interior Delta flow requirements throughout the year in a coordinated manner.

While the science summarized in this Report clearly supports the need for the flow and associated operational requirements for the protection of fish and wildlife beneficial uses, there are significant challenges that exist to establishing flow requirements for a watershed of this size and complexity, particularly given the importance of the watershed to the State's water supply needs. At the same time, the need for action is critical given the degraded status of the ecosystem and the lack of a comprehensive regulatory structure in the face of increasing water demands and climate change. Thus, the task before the State Water Board requires crafting the flow requirements with enough flexibility to work and adapt to new information and changing circumstances, but also with enough specificity to prompt meaningful and timely improvement in flow conditions and habitat.

Currently, the Bay-Delta Plan does not include adequate environmental flow and related 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 (including cold water flows) to protect fish and wildlife, 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

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[1] Mokelumne, Calaveras, and Cosumnes Rivers.

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.

The Projects have primary responsibility for meeting existing Bay-Delta Plan objectives, including existing Delta outflow, salinity, and other 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's and Reclamation's water rights for the SWP and CVP, respectively. As evidenced in the recent drought, the Projects' ability to maintain responsibility for meeting all Bay-Delta Plan flow and water quality requirements in the watershed while preserving water for cold water purposes is not realistic in the face of climate change and increasing water demands. Currently, the Projects supplement flows during much of the summer and fall with storage releases at the expense of cold water and other reserves, particularly during drought periods when water demands greatly exceed supplies and flows are diminished. The Bay-Delta Plan does not provide sufficient flexibility in the program of implementation to address these and other conditions.

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. Additional analyses are presented in this chapter to synthesize the information in prior chapters and to develop the proposed changes to the Bay-Delta Plan that will be further refined in the Staff Report. The bases for all of the requirements are supported by the best available scientific information, including functional flow needs of individual species and the ecosystem as well as statistical and other correlation relationships between flows and species needs. Because the Bay-Delta ecosystem is exceedingly complex it is not possible to identify every function that drives a correlation relationship with certainty, particularly since it may change 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 in part through monitoring and adaptive 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. 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 more 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 is also 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 Methods for Developing Environmental Flow Requirements

The recognition of the adverse effects of flow alteration on aquatic ecosystems has led to the development of a large number of methods for determining flows needed to preserve the physical and biological integrity of these systems, often referred to as environmental flows (Tharme 2003; Annear et al. 2004; Linnansaari et al. 2013). Although an exhaustive review of environmental flow methods is beyond the scope of this Report, a brief summary of different methods is provided below, including a description of the method the proposed approach aligns with. Environmental flow methods can be classified into four mostly distinct categories: (1) hydrological methods, (2) hydraulic rating methods, (3) habitat simulation methods, and (4) holistic methods (Tharme 2003; Linnansaari et al. 2013). Most of the research to date has focused on formulating methods for rivers, while estuaries have received much less attention (Adams 2014).

Hydrological methods range in sophistication from rules of thumb based on mean annual flows (e.g., the Tennant or “Montana” method; Tennant 1976), and do not include flow variability, to more contemporary methods that attempt to capture physically and biologically important variability in the flow regime (e.g., the “Range of Variability Approach”; Richter et al. 1997) (Linnansaari et al. 2013). These methods are the least resource-intensive, because they require only hydrological information and can be carried out in office settings, provided that gaged or modeled hydrological data are available for the region of interest. Hydrological methods have been subject to criticism for lack of a strong scientific basis, particularly in the absence of information on flow-ecology relationships (Linnansaari et al. 2013). Additionally, many hydrological methods result in fixed minimum flows, omitting biologically important variability (often referred to as “flatlining” rivers; Linnansaari et al. 2013).

Hydraulic rating methods are based on the premise that habitat for stream and riparian plants and animals is related to habitat quantity that varies with flow. Most often this is expressed as the wetted area of a channel cross-section at a critical riffle or some other limiting location (Tharme 2003). The general methodology involves collecting the necessary data to plot wetted area as a function of flow, and choosing a breakpoint that is interpreted as a significant degradation of habitat (Tharme 2003; Linnansaari et al. 2013). Hydraulic rating methods have also been criticized for lacking a strong scientific basis and for resulting in flow recommendations that do not protect the full range of conditions needed to support river ecosystems (Tharme 2003; Moyle et al. 2011; Linnansaari et al. 2013).

Habitat simulation methods were developed as an attempt to more explicitly capture the relationship between flow and the physical habitat requirements of fish. Similar to hydraulic rating methods, the premise is that flow is related to the quantity and quality of habitat for one or more life stages of the species of concern (Linnansaari et al. 2013). The most frequently used habitat simulation method is the Physical Habitat Simulation (PHABSIM), the central tool of the Instream Flow Incremental Methodology (IFIM; Bovee et al. 1998; Tharme 2003; Moyle et al. 2011; Linnnansaari et al. 2013). Habitat simulation methods require considerable data, including the physical data needed to support hydraulic rating methods, as well as observational data on habitat use by the focal species (Linnansaari et al. 2013). Habitat simulation methods have frequently been criticized for their typical focus on a single species of management concern, although it is possible to deploy these methods more broadly. The most serious criticism of habitat simulation methods is that the habitat indices derived from them have not been demonstrated to predict performance at the population level, and thus may offer a false sense of a strong quantitative basis for flow recommendations (Anderson et al. 2006; Moyle et al. 2011 and references therein; Linnansaari et al. 2013). Nonetheless, habitat simulation methods can provide valuable information for establishing environmental flows when the appropriate data are available and the significance of the habitat index is well-understood (Railsback 2016).

Holistic methodologies began emerging in the 1990s, and currently comprise the most actively developed approaches for determining environmental flows (Arthington et al. 1992; King and Louw 1998; Tharme 2003; Linnansaari et al. 2013). Holistic methods first emerged in Australia and South Africa, where highly variable hydrology and the lack of detailed ecological information presented challenges to using existing environmental flow methods effectively (Arthington et al. 1992; King and Louw 1998; Tharme 2003). These methods also emerged in response to a realization that riverine and estuarine processes operate at the scale of the whole ecosystem, and thus the status of the whole ecosystem and all of the abiotic and biotic processes influencing it must be considered in setting environmental flows (Arthington et al. 1992; King and Louw 1998; Tharme 2003; Annear et al. 2004; Petts 2009; Poff et al. 2010). Thus, holistic methods rely on a wide range of information, including hydrological data reflecting developed and undeveloped conditions, regional or location-specific understanding of flow-ecosystem relationships, and more general ecological understanding of aquatic systems. Specific holistic frameworks that have been developed include the Building Block Method (BBM; King and Louw 1998; King et al. 2008), Downstream Response to Imposed Flow Transformation (DRIFT; King et al. 2003), and Ecological Limits of Hydrologic Alteration (ELOHA; Poff et al. 2010). Each of these methods is based on the premise that managed flow regimes need to generally resemble the natural flow regime to which native species are adapted, but that some deviation from the natural flow regime is needed in watersheds that must support other consumptive uses of water (Linnansaari et al. 2013).

Recent literature and input from stakeholders has begun to emphasize a philosophy that environmental flows should be designed to serve specific, well-understood functions of flow, particularly in heavily-modified systems such as the Bay-Delta (Acreman et al. 2014; Yarnell et al. 2015), and that a greater understanding of the mechanisms behind flow-ecosystem relationships is needed to improve management of flow to protect aquatic ecosystems (Delta ISB 2015). Similar to the BBM (King and Louw 1998; King et al. 2008), a “functional-flow” (Yarnell et al. 2015) or “designer flow” (Acreman et al. 2014) approach relies on an understanding of the functions provided by particular hydrograph components, such as large floods that maintain channels, flows that create and maintain floodplain connectivity that supports spawning, food production, and rearing, and predictable rates of decline in flow resulting from snowmelt recession. The risk inherent in a wholesale adoption of this approach is similar to the risks associated with approaches solely based on habitat needs of single species or life stages—flow components may be omitted simply because their significance is not appreciated or understood, resulting in less protection than intended (Acreman et al. 2014).

The scientific information summarized in this Report is consistent with the information that is used to support holistic methodologies for development of environmental flows. Chapter 2 reviews the hydrology and hydrodynamics of the Sacramento River, its tributaries, the Delta eastside tributaries, and the Delta itself. Comparisons of a 94-year record of modeled flows under current conditions and unimpaired conditions provide an indication of the level of flow alteration that has resulted from water development, although it is acknowledged that unimpaired flows do not exactly represent natural flows that would have occurred in a pre-development landscape. Chapter 3 reviews the available information on the relationship between flow and ecosystem structure and function. Chapter 3 also includes information on species-specific responses to flow, including statistical analyses of the relationships between flow and abundance or population growth. Although mechanistic understanding of these flow-ecosystem and flow-species relationships is not complete, the information available in the Bay-Delta watershed and summarized in this Report is on par with that used in other environmental flow assessments, and provides a reliable basis for assessing the likely relative outcomes of new flow requirements (see, e.g., the discussion of flow alteration-ecological response relationships in Poff et al. 2010).

The scientific information summarized in this Report establishes the need for inflow requirements in the Sacramento River, its tributaries and the Delta eastside tributaries and the needs for Delta outflow, cold water habitat and interior Delta flow requirements that work together in a comprehensive framework with other complementary actions to protect the Bay-Delta ecosystem. Inflow requirements are needed to provide for instream flow needs within tributaries for salmonids and other native species and to contribute to Delta outflows and the critical functions those flows provide for estuarine species. Inflow requirements are needed on some tributaries to preserve existing protective flows and are needed on others to improve existing flow conditions. While the needs for inflows and associated outflows are clear, there are significant challenges to establishing flow requirements for a watershed of this size and complexity that is so critical to the State’s water supply needs. At the same time, the need for action is critical given the degraded status of the ecosystem and lack of a comprehensive regulatory structure in the face of increasing water demands and climate change. A holistic instream flow approach applied at the programmatic and regional level is proposed to address these issues. In particular, the approach recognizes that (1) the flow regime is the primary determinant of structure and function in riverine ecosystems, (2) environmental flows should be based generally on the natural flow regime, (3) all features of the ecosystem should be considered and (4) that the reality of multiple needs for water must play a significant role.

Together the proposed changes to the inflow, outflow, and interior Delta flow requirements of the Bay-Delta Plan, along with other habitat restoration actions of others are proposed to work together to provide comprehensive protection to the ecosystem and native aquatic species from natal streams through the Delta and Bay in a manner consistent with the holistic approach. Similar to the draft Phase I San Joaquin River flow requirements, the use of unimpaired flows is recommended to create a water supply budget for the protection of the ecosystem and native fish and wildlife in the Sacramento River, its tributaries and eastside tributaries to the Delta. Those inflows, and inflows from the San Joaquin River would provide outflow to protect fish and wildlife throughout their migratory range as discussed further below. 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 previously, 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, particularly in tributaries. Where unimpaired flows may not provide for all of the attributes of natural flow functions that would be protective of the ecosystem, adaptive management provisions are proposed. A flow requirement based on a percent of unimpaired flow is intended to ensure that a minimum amount of available supply from a watershed is allocated for the reasonable protection of native fish and wildlife beneficial uses. Adaptive management provisions, including any necessary sculpting of that flow, would provide specific functional flows to improve fish and wildlife protection. Biological goals would be used to help inform adaptive management decisions.

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). For these reasons 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, 2004; NRC 2005; Florida Administrative Code 2010). The World Bank also 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 (State Water Board 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 use of the unimpaired flow approach for inflows and outflows. Adaptive management would allow for the percent of unimpaired flow budget to be sculpted 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 River 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 of 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 current 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, unimpaired flow data from SacWAM (Appendix A) are combined with results from the SacWAM model of current conditions (State Water Board 2017) to compare the flow that would occur under a range of unimpaired flows to the modeled SacWAM current conditions flows. For the analysis of Delta outflow, modeled values of existing minimum required Delta outflow (MRDO) pursuant to the requirements of the 2006 Bay-Delta Plan, D-1641, and the USFWS BiOp are provided for comparison as well.

The percent of unimpaired flow lines in the figures contained in this chapter represent the minimum flows that would be required if the specified percent of unimpaired flow was imposed as a flow requirement in the specified reach (see Appendix A for more information on the development of unimpaired flows). Thus, these lines illustrate the flows that would be expected to occur if meeting the percent of unimpaired flow level was the only factor controlling flows in the reach. The percent of unimpaired flow lines in the figures do not include other flows that would occur as a result of flood control releases, other regulatory flow requirements, or other reasons that are not associated with the percent of unimpaired flow requirement. In reality, these additional flows would occur, particularly in wetter conditions, and would increase the actual expected flows under each scenario. As such, while the unimpaired flow lines do not represent the expected flows that would occur under an unimpaired flow regulatory requirement, they generally represent the expected minimum flows that would result under such a requirement. Modeling analyses that include the additional expected flows from flood control, other regulatory requirements etc., will be provided in the Staff Report.

Likewise, for the Delta outflow figures, similar to the percent of unimpaired flow lines, the MRDO lines in the figures do not include any other flows beyond the Bay-Delta Plan or USFWS BiOp flow requirements that would occur as a result of flood control releases, other regulatory flow requirements or other reasons. Additional flows expected to occur in reality as a result of flood control releases, other regulatory flow requirements, or other reasons are reflected in the existing flows shown in the figures. The difference between the MRDO lines in the figures and the existing flow level in the figures represents flows that are not required under the Bay-Delta Plan and the USFWS BiOp that could potentially be diminished in the future as the result of additional diversions in the absence of additional regulatory flow requirements. The significant difference between these flow levels indicates that existing Bay-Delta Plan and BiOp flow requirements are not adequate to ensure Delta outflow conditions necessary for the reasonable protection of fish and wildlife beneficial uses.

Because there are very limited existing flow requirements for inflows in the Bay-Delta Plan and BiOps, a similar comparison for inflows would be with zero flow instead of the MRDO lines, meaning that on many streams there are limited or no requirements that prevent flows from being completely removed from streams. Again, this circumstance indicates that existing inflow requirements included in the Bay-Delta Plan and BiOps are inadequate to reasonably protect fish and wildlife beneficial uses. The inflow and outflow levels that are needed to reasonably protect fish and wildlife beneficial uses in a way that balances those needs with other needs for water is, in part, a policy decision that will be informed by the science in this Report, evaluation of the potential environmental and economic effects of different alternatives, public and agency comments and other relevant information.

5.2 Tributary Inflows

5.2.1 Introduction

New inflow requirements are proposed for anadromous fish-bearing tributaries in the Sacramento River basin and Delta eastside tributaries (see map in Figure 1.4-1).[2] Year-round inflows are needed to protect anadromous and other native 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, and to

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[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 (CDFG 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 3.4.5.2).

contribute to Delta outflows needed to support migrating, spawning, and rearing estuarine species. Preservation of high flow levels that are already being provided in some less impaired tributaries is also proposed where existing flows are providing important functions to ensure that those flows are not reduced (e.g., maintain existing protective conditions). The proposed changes to inflow requirements are structured to provide necessary flexibility and adaptive management provisions (for specific functional flows, scientifically based experiments, and coordination with other complementary restoration efforts) to address the complexities of inflow needs and constraints in the watershed in a reasonable and protective manner. In recognition of the local expertise within tributaries and the potential benefit of collaborative solutions, the program of implementation would provide a period of time for regional and/or tributary based flow and other measures to be developed by stakeholders, approved, and implemented that achieve the inflow and cold water habitat requirements while also contributing to Delta outflows.

5.2.2 Current Bay-Delta Plan and D-1641 Requirements

The only inflow requirements for the Sacramento River, its tributaries and Delta eastside tributaries in the Bay-Delta Plan are minimal monthly average flows on the Sacramento River at Rio Vista for September through December that range from 3,000 to 4,500 cfs based on water year types.[3] 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.

D-1641 currently assigns responsibility to DWR and Reclamation for meeting these flow requirements through conditions of their water rights for the SWP and CVP. 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.

D-1641 specifically includes flow requirements on the Mokelumne River system from the Mokelumne River Joint Settlement Agreement as that tributary's contribution to meeting existing Bay-Delta Plan requirements.[4] D-1641 requires releases from Camanche Reservoir based on time period and water year type. From July through September, releases are required to be at least 100 cfs and for all other months of the year, releases are required to be at least 100 to 325 cfs.

5.2.3 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 upstream habitat for salmonids and other species on many tributaries is blocked by dams and other structures. 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

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[3] Flows in September of all year types are required to be 3,000 cfs. Flows in October of critical year types are required to be 3,000 cfs and in all other year types flows are required to be 4,000 cfs. Flows in November and December of critical year types are required to be 3,500 cfs and in all other year types are required to be 4,500 cfs.

[4] See D-1641 pages 170 through 178.

river system with less seasonal and annual variability and a smaller total outflow, with outflows reduced by more than 60 percent in some years and by more than 80 percent in certain months. Regulated (reservoir controlled) tributaries to the Sacramento River and Delta show similar altered seasonal and annual flow patterns with flow significantly reduced in some of the tributaries by more than 80 percent on an annual basis and 100 percent in certain months.

Water development has also altered the hydrology of unregulated tributaries to the Sacramento River and Delta (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 and Delta. 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.

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. 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 are needed to prevent future impacts on fish and wildlife. In addition, some of these tributaries may dry up at times of year impacting native fish and wildlife due to the lack of flow requirements, and others may have inadequate flow and water quality conditions to protect fisheries resources. Year-round inflow requirements are needed in the Sacramento River, its tributaries, and the Delta eastside tributaries to address these issues.

Inflows are needed to provide for ecological processes including continuity of flows from tributaries to the Delta and specifically to protect anadromous and other fish and wildlife species that inhabit the Bay-Delta and its tributaries throughout the year as juveniles or adults. Inflows are needed to provide appropriate habitat conditions for migration and rearing of anadromous fish species like salmonids that have runs that inhabit the Delta and its tributaries all year. Those flows are also needed to contribute to Delta outflows to protect native estuarine species. Specifically, flows are needed that more closely mimic the conditions to which native fish species have adapted, including the frequency, quality, 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.

As discussed in Chapter 3, at least one salmonid run is migrating through, rearing in, or holding in the Sacramento River, its tributaries or the Delta and its tributaries 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 salmonids also require continuous tributary flows with adequate temperature and dissolved oxygen levels for rearing and successful emigration. A lack of tributary flow affects hydrologic connectivity between tributaries and the main stem Sacramento River and Delta and reduces juvenile rearing habitat quantity and quality.

As discussed in Chapter 3, flows greater than about 20,000 cfs from February through June on the lower Sacramento River have been found to increase survival and abundance of juvenile fall- and winter-run Chinook salmon. Flows of this magnitude are also expected to aid in emigration of juvenile spring-run Chinook salmon and steelhead. In half of all years, flow in April and May are currently less than 50 percent of unimpaired in the lower Sacramento River. 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 at Rio Vista under modeled current conditions (SacWAM; State Water Board 2017) and 35 to 75 percent of unimpaired flow (SacWAM; Appendix A) during April–June and February–April, respectively. The existing flows do not represent required flows, particularly since many tributaries do not have flow requirements. Also, the 35 to 75 percent of unimpaired flow scenarios do not include any other regulatory flows that may exist on tributaries and do not include uncontrolled flows that would occur that may exceed the percent of unimpaired flow scenario. As discussed previously, 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 Staff Report 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 provides 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 55 percent of unimpaired increase the frequency of average April through June and February through June flows exceeding 20,000 cfs relative to current conditions (Figures 5.2-1 and 5.2-2).

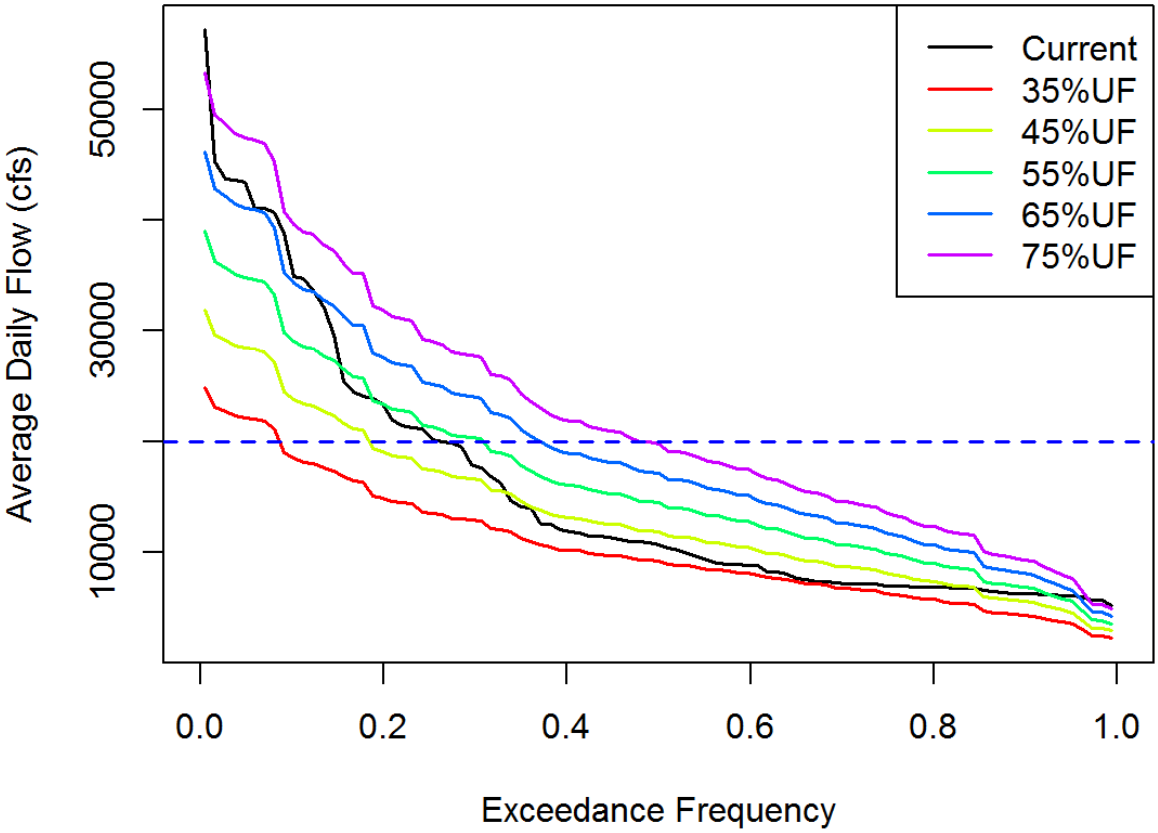

Figure 5.2-1. Frequency of Meeting April–June Sacramento River at Rio Vista Flows of 20,000 cfs for Current Conditions as Modeled by SacWAM, and 35 to 75 Percent of Unimpaired Flow at Rio Vista

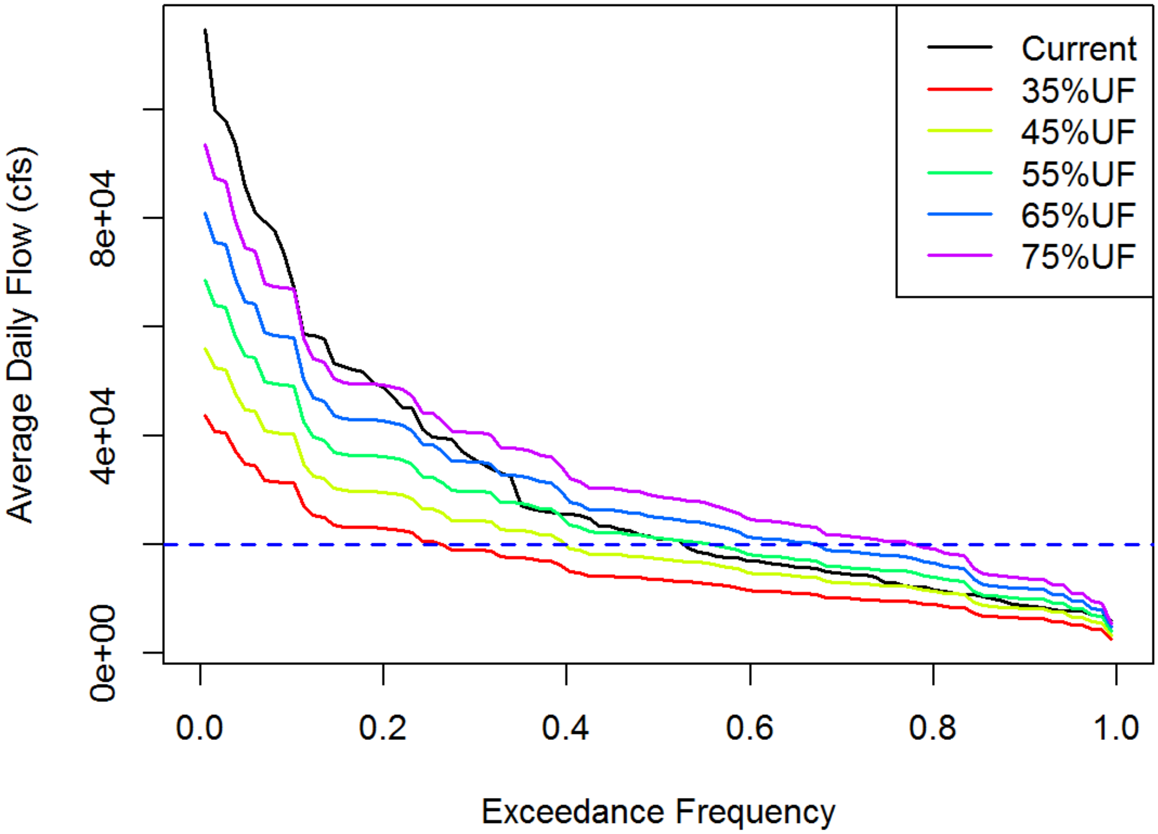

Figure 5.2-2. Frequency of Meeting February–April Sacramento River at Rio Vista Flows of 20,000 cfs for Current Conditions as Modeled by SacWAM, and 35 to 75 Percent of Unimpaired Flow at Rio Vista

In addition to the Rio Vista flow levels discussed above, Chapter 3 also explains how flows exceeding 17,000–20,000 cfs at Freeport on the Sacramento River prevent reverse flows 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 current conditions and the range of 35 to 75 percent 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 of unimpaired flow levels 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 percent and higher. Because there are only limited flow requirements for this time period, additional flow requirements will ensure that minimal levels of flow are provided as well.

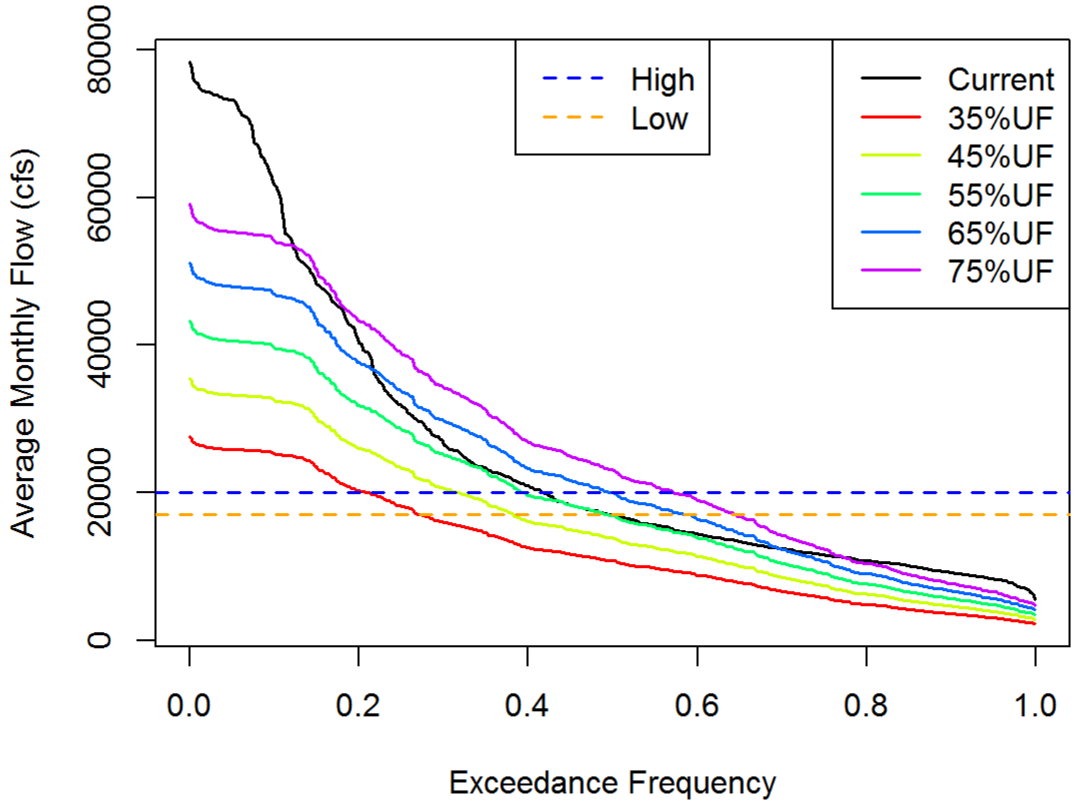

Figure 5.2-3. Exceedance Frequency of Monthly Flow at Freeport on the Sacramento River for November–May under Current Conditions as Modeled by SacWAM, and 35 to 75 Percent of Unimpaired Flow. Flows greater than 17,000 (orange dashed line) to 20,000 cfs (blue dashed line) prevent tidal reversal at Georgiana Slough.

In addition to the Sacramento River inflow relationships discussed above, year-round flow is needed on other tributaries to the Sacramento River and Delta to support migration, rearing, and holding of salmonids and to contribute to Delta outflow. As discussed in Chapter 3, the most common stressor for both adult and juvenile salmonids is a lack of hydrologic connection between tributaries and the Sacramento River, particularly during the summer when water temperatures are often too high and flows are too low to fully sustain salmonids. As discussed above, some tributaries have no flow 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 also contribute to Delta outflows that are critical for both salmonids and estuarine-dependent species. Table 3.13-2 summarizes the flow relationships of several estuarine species that serve as indicators of ecosystem health.

Based on the above, new inflow requirements are proposed for the Sacramento River and its tributaries and eastside tributaries to the Delta. The proposed changes to inflow requirements are structured to provide necessary flexibility and adaptive management provisions to address the complexities of inflow needs and constraints in the watershed in a reasonable and protective manner. Biological goals are proposed to inform 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.

In accordance with the holistic instream flow method, the proposed inflow requirements would establish a uniting regulatory approach for instream flow requirements for all salmonid-bearing tributaries in the Bay-Delta watershed for the entire year that provides for contributory Delta outflows emphasizing the need to protect the ecosystem as a whole. Further, the approach is structured to address the realities of the existing altered landscape in which these flow requirements will be established in terms of the physical alterations from channelization, construction of dams and other issues and the realities that flows are also needed for human purposes.

The proposed new inflow requirements include a numeric and narrative component. The narrative portion describes the inflow conditions necessary to reasonably protect native fish populations, including through contribution to Delta outflows to protect estuarine species. The new numeric inflow requirement is proposed to reasonably protect native fish populations, including by implementing the narrative component and integrating inflows and outflows in a comprehensive manner. The proposed inflow requirements would dedicate a portion of the inflow of a watershed to environmental purposes based on the unimpaired flow of that stream. This dedicated quantity of environmental flows would then be provided based on the unique needs and circumstances of each tributary and on a regional basis to provide for critical functions within the streams and as contributory flows to the Delta. Given the altered physical and hydrologic state of the watershed and its size and complexity, inflow requirements need to be developed in an adaptive and flexible framework in a coordinated fashion with outflows, cold water habitat, and interior Delta flows to maximize the effectiveness of flow measures while providing for meaningful and prompt action that responds to new science and changing conditions.

5.2.4 Conclusion and Proposed Requirements

Available scientific information supports the proposed year-round inflow requirements 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. In tributaries where flows are currently significantly impaired, these new inflow requirements are needed to improve conditions for fish and wildlife and to provide for connectivity and contribution of flow to the Delta. In tributaries where flows are less impaired, new inflow requirements are needed to ensure that those flows do not become impaired to the detriment of fish and wildlife. The purpose of the proposed changes to inflow requirements is to improve ecosystem functions by providing appropriate habitat conditions for adult salmonid immigration and holding and juvenile rearing and outmigration, and contributing to Delta outflow to support native anadromous and estuarine species. The proposed inflow requirements are also specifically intended to provide for increasing the frequency and duration of floodplain inundation for the benefit of native species, including for Sacramento splittail spawning and Sacramento splittail and salmonid rearing, as well as the production of estuarine food supplies for other species. The existing Sacramento River at Rio Vista inflow requirements during September through December would be retained in order to maintain the minimal level of protection currently provided by these base flows.

The proposed new inflow objective is expressed both numerically and narratively. The narrative portion of the objective describes the inflow conditions necessary to reasonably protect native fish populations, including through contribution to Delta outflows. The numeric inflow objective is proposed to include a range for the flows such that flow levels could be adjusted up or down within the range in order to address the unique needs and conditions of the tributaries (including cold water pool needs), changing information (new science) and changing conditions (implementation of non-flow measures, drought, etc.) in a way that reasonably protects fish and wildlife. The proposed numeric requirements may be managed as a budget of water for the environment. That budget would be established based on a percentage of the inflows to the watersheds assuming there were no diversions occurring (percent of unimpaired flow), thereby allocating a portion of the water in the watershed to the environment to be managed to improve benefits for fish and wildlife for inflow and outflow purposes. Through adaptive management, unimpaired flows could 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 tributary inflows are intended to be protected from the tributaries out through the Delta and to provide for floodplain inundation.

The proposed range for the numeric inflow objective has not yet been determined and will be determined after considering the information in this Report, along with information the State Water Board needs to consider when establishing water quality objectives, including past, present, and future beneficial uses of water, the environmental characteristics of the hydrographic unit under consideration, economic considerations, the environmental effects of alternatives, public comments and other information. The range under consideration is from 35 to 75 percent of unimpaired flows and generally does not provide for flows lower than current conditions.

The proposed narrative inflow component of the objective is as follows:

> *Maintain inflow conditions from the Sacramento River and its tributaries and the Delta Eastside Delta tributaries sufficient to support and maintain the natural production of viable native fish populations and to contribute to Delta outflows. Inflow conditions that reasonably contribute toward maintaining viable native fish populations include, but may not be limited to, flows that more closely mimic the natural hydrographic conditions to which native fish species are adapted, including the relative magnitude, duration, timing, quality and spatial extent of flows as they would naturally occur.*
>
> *Indicators of native fish species viability include population abundance, spatial extent, distribution, productivity and genetic and life history diversity. Viability is dependent on maintaining migratory pathways, sufficient quantities of high quality spawning and rearing habitat and a productive food web.*

The proposed numeric inflow component of the objective is as follows:

> *Combined inflows from the Sacramento River and its tributaries and Delta tributaries (excluding the lower San Joaquin River inflows specified below) shall be maintained between X (e.g., 45) percent–X (e.g., 65) percent of unimpaired flow.*

Together the proposed changes to the inflow, outflow, and interior Delta flow provisions of the Bay-Delta Plan, along with other habitat restoration actions of others are proposed to work together to provide comprehensive protection to fish and wildlife from natal streams through the Delta and Bay. The proposed changes to inflow requirements are structured to provide necessary flexibility and adaptive management provisions to address the complexities of inflow needs and constraints in the watershed in a reasonable and protective manner.

The exact method by which the inflows will be achieved has not been determined. The program of implementation would require the development of tributary plans, containing a flow element that will achieve the narrative requirement and fall within the range of the numeric requirement. A specific tributary flow may fall outside of the range of the numeric objective if two or more tributaries work together such that their combined flows meet the numeric requirement and the specific tributary flow still meets the narrative requirement (e.g., maintain connectivity and contribute to outflow). Flow from tributary streams to connect migration corridors and contribute to Delta outflow will necessarily involve contributions from other water users, as the requirements cannot reasonably be achieved by the Projects alone. In recognition of the local expertise within tributaries and the potential benefit of collaborative solutions, the program of implementation would provide a period of time for regional and/or tributary-based flow and other measures to be developed by stakeholders for approval by the State Water Board. If a tributary plan is not developed or is found to be unsatisfactory, the State Water Board would exercise its legislative or adjudicative powers involving water rights and water quality to require implementation of the objectives.

The program of implementation would clarify that the tributary inflows are to be protected from the confluences of the tributaries out through the Delta. These flows would not be considered abandoned, and could not be diverted by downstream users. The program of implementation would direct State Water Board staff to continue developing proper enforcement mechanisms, and as necessary, draft regulations for the State Water Board’s consideration to assist with this effort, and consider updates to the Fully Appropriated Streams (FAS) list to ensure that tributaries already protective are not degraded.

5.3 Delta Outflow

5.3.1 Introduction

New and modified Delta outflow requirements are proposed throughout the year to support and maintain the natural production of viable native fish populations residing in, rearing in, or migrating through the estuary. Delta outflows have been reduced over time as the result of water withdrawals resulting in reduced suitable habitat for estuarine species. Existing Delta outflow requirements are far below existing Delta outflows and are likely to be reduced over time without additional requirements as water use intensifies. To ensure that minimum quantities of Delta outflow are provided to the estuary, base Delta outflows that range from 3,000 cfs to 8,000 cfs based on water year type from July through January and February through June flows of 7,100 cfs from the current Bay-Delta Plan would be maintained. In addition, a new inflow-based Delta outflow is proposed that would be consistent with the range for inflows discussed above. The requirement specifies that the required inflows from the Sacramento and San Joaquin Rivers and their tributaries and the three Delta eastside tributaries are provided as outflows with appropriate adjustments for depletions and accretions, including adjustments for floodplain inundation flows and other side flows. A fall outflow requirement consistent with the USFWS BiOp is also proposed. Like the inflow requirements, the outflow requirements would allow for adaptive management and shifting and sculpting of flows. The program of implementation would require the development of a plan that addresses implementation measures by Delta users, including the Projects, as well as monitoring, reporting, and evaluation. The plan would address accounting for the existing and new requirements, including integration with tributary plans to the extent possible, accretions and depletions, and evaluation of the existing and new methods of compliance with Delta outflows to ensure they are protective.

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 (including associated footnotes and figures) of the Bay-Delta Plan and D-1641, and vary depending on water year type and season. Outflow objectives include requirements for calculated minimum net flows from the Delta to Suisun and San Francisco Bays (the Net Delta Outflow Index or NDOI) and maximum salinity requirements (measured as electrical conductivity or EC). Since salinity in the Bay-Delta system is closely related to freshwater outflows, both types of objectives are indicators of the extent and location of low salinity estuarine habitat. The NDOI is a calculated flow expressed as Delta inflow, minus net Delta consumptive use, minus Delta exports (Bay-Delta Plan Figure 4). Chapter 2 discusses various issues associated with the accuracy of this calculated value.

For February through June, Delta outflow objectives are identified in footnote 10 of Table 3 and Table 4. Pursuant to footnote 10, the minimum daily NDOI during February through June is 7,100 cfs calculated as a 3-day running average.[5] This requirement may also be met by achieving either a daily average or 14-day running average EC at the confluence of the Sacramento and San Joaquin Rivers of less than or equal to 2.64 millimhos per centimeter (mmhos/cm) (Collinsville station C2). Additional Delta outflow objectives are also contained in Table 4, which require a certain number of days of compliance with flows of 11,400 cfs or salinity compliance at Chipps Island or flows of 29,200 cfs or salinity compliance at Port Chicago based on the previous month’s Eight River Index (ERI), which is an index of unimpaired flows from the eight major tributaries to the Delta.[6]

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[5] An additional requirement applies in February following wetter January conditions that requires X2 to be downstream of Collinsville for at least 1 day between February 1 and February 14. There are also exceptions to the February through June flow requirements in extremely dry conditions.

[6] Pursuant to footnote 9 of Table 3 of D-1641, 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.

For July through January, the minimum Delta outflow varies within the range of 3,000 cfs to 8,000 cfs based on month and water year type as specified below.

Table 5.3-1. Existing Delta Outflow Objectives from July to January*

Water Year Type	Month	Minimum Monthly Average Net Delta Outflow Index (cfs)
Wet (W) and Above Normal (AN)	July	8,000
Below Normal BN)		6,500
Dry (D)		5,000
Critical (C)		4,000
W, AN, BN	August	4,000
Dry		3,500
C		3,000
All	September	3,000
W, AN, BN, D	October	4,000
C		3,000
W, AN, BN, D	November and December	4,500
C		3,500
All (if Dec ERI < 800 TAF)	January	4,500
All (if Dec ERI > 800 TAF)		6,000

* For January, the objective is increased to 6,000 cfs if the December ERI is greater than 800 TAF. For all months, if the value is less than or equal to 5,000 cfs, the 7-day running average shall not be less than 1,000 cfs below the value and if the value is greater than 5,000 cfs, the 7-day running average shall not be less than 80 percent of the value.

The Projects are solely responsible for meeting Delta outflow and other salinity requirements in the Delta included in the Bay-Delta Plan. Much of the time these requirements are met incidentally, but in most years the Projects must release some water from storage to comply. Table 5.3-2 summarizes the estimated amount of additional water that the Projects had to import from the Trinity River or release from storage to meet Bay-Delta Plan/D-1641 requirements (referred to as supplemental project water) since 2000. With climate change, sea level rise, and increasing water demand in the watershed, the Projects will likely have to release additional supplemental project water to meet existing requirements to the detriment of cold-water reserve and carryover storage to meet the next years' requirements. This issue surfaced in the recent drought when, despite minimal exports from the Delta, the Projects were unable to meet Bay-Delta Plan flow requirements while maintaining cold water for fish.

Table 5.3-2. SWP and CVP Supplemental Project Water Releases from 2000 to 2016

Water Year	Sacramento 40-30-30 Water Year Type	San Joaquin 60-20-20 Water Year Type	Term 91 Supplemental Project Water (AF, Total)*
2000	AN	AN	731,800
2001	D	D	1,368,500
2002	D	D	1,218,800
2003	AN	BN	741,700
2004	BN	D	1,332,900
2005	AN	W	229,100
2006	W	W	269,600
2007	D	C	1,812,500
2008	C	C	1,611,800
2009	D	BN	1,423,000
2010	BN	AN	416,800
2011	W	W	94,400
2012	BN	D	1,924,000
2013	D	C	2,393,700
2014	C	C	2,408,000
2015	C	C	2,465,400
2016	BN	D	2,123,300

* Supplemental project water can be calculated in different ways. The supplemental project water used here is a number calculated daily by Reclamation according to an equation in State Water Board Order WR 81-15. The published data was aggregated and adjusted downward for excess conditions, when more water is released from storage than is needed for exports + inbasin demands + Delta water quality and outflow requirements.

DWR and Reclamation have additional outflow obligations under the USFWS BiOp to improve fall habitat for Delta smelt during the months of September through December following wet and above normal years. The USFWS BiOp 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. In December, any storage accrued in CVP and SWP reservoirs in the Sacramento River basin during November is required to be released to augment D-1641 Delta outflow objectives. 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

As discussed in the preceding chapters, the hydrology and other characteristics of the Delta ecosystem have been significantly altered due to development of agriculture and urbanization in the watershed and other areas of the state that rely on water supplies from the Delta. Every major stream in the watershed includes significant diversions of water for consumptive uses, power production, and flood control and nearly every major tributary includes several dams for these purposes. These diversions of water and the other alterations have significantly impacted the ecosystem and future such modifications due to increasing water demands and climate change have the potential to further impact the ecosystem. The combined effects of water exports and upstream diversions have contributed to reduce the average annual net outflow from the Delta by 33 percent and 48 percent during the 1948–1968 and 1986–2005 periods, respectively, as compared to unimpaired conditions (Fleenor et al. 2010). There has also been a trend of decreasing Delta outflow through time. Since the 1990s, there has been a reduction in spring outflow and a reduction in the variability of Delta outflow throughout the year (Figure 2.4-8) due largely to the combined effects of exports, diversions, and variable hydrology.

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 to support estuarine processes, habitat, and the species that depend upon them. Native species specifically benefit from increasing the area, duration and frequency of flows that place the LSZ downstream of the confluence of the Sacramento and San Joaquin Rivers.

Outflow requirements are needed to provide for ecological processes including continuity of flows from tributaries and the Delta and to the Bay to protect native estuarine and anadromous aquatic species that inhabit the Bay-Delta and its tributaries throughout the year as juveniles or adults. Those outflows are needed to provide appropriate habitat conditions for migration and rearing of estuarine and anadromous fish species. Flows are needed that more closely mimic the conditions to which native fish species have adapted, including the frequency, quality, 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 maintaining appropriate LSZ habitat, 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. As with inflows, given the altered physical and hydrologic state of the watershed and its size and complexity, outflow requirements need to be developed in an adaptive and flexible framework in a coordinated fashion with inflows, cold water habitat and interior Delta flows to maximize the effectiveness of flow measures while providing for meaningful and prompt action that responds to new science and changing conditions.

5.3.3.1 Current Conditions Compared to Minimum Required Delta Outflow

MRDO represents existing regulatory minimum flows, and is often substantially lower than flows observed under current conditions.[7] Over time with increasing water development and climate change, it is expected that flows under future conditions will be reduced below current conditions without additional regulatory requirements, perhaps to a substantial degree to a level approaching MRDO flows, which Chapter 3 indicates are not protective of fish and wildlife.

Figure 5.3-1 shows seasonal comparisons of MRDO pursuant to Bay-Delta Plan and D-1641 requirements and the USFWS BiOp requirements with SacWAM modeled flows under current regulatory conditions (State Water Board 2017) and observed Delta outflows (DWR 2017) divided into four historical periods based on significant events in the development of Bay-Delta water resources and regulations. Modeled flows are most similar to regulatory minimums during the dry season of July–October, but deviate substantially during wetter months (Figure 5.3-1). 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 2000–2016 reflects increased water development relative to earlier periods, dry hydrology relative to both earlier periods and the 1922–2015 SacWAM record, and the absence of a fall X2 requirement in the first half of the period. Higher winter-spring outflows and lower summer-fall outflows during 1930–1945 reflect the lack of major storage regulation in the watershed, and the inability to maintain outflows during dry months of dry years. Although a portion of the wet season difference between MRDO and modeled outflows 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 above MRDO and observed under current 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 would be needed to ensure the existing level of protection of estuarine-dependent fish and wildlife these higher flows provide.

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[7] 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 SacWAM (State Water Board 2017), and are obtained by taking the maximum of the flow requirements REG_X2, REG_MRDO, and Delta outflow needed for salinity control. This procedure is equivalent to summing the arcs D407 and C407_ANN in CalSim II (DWR 2015).

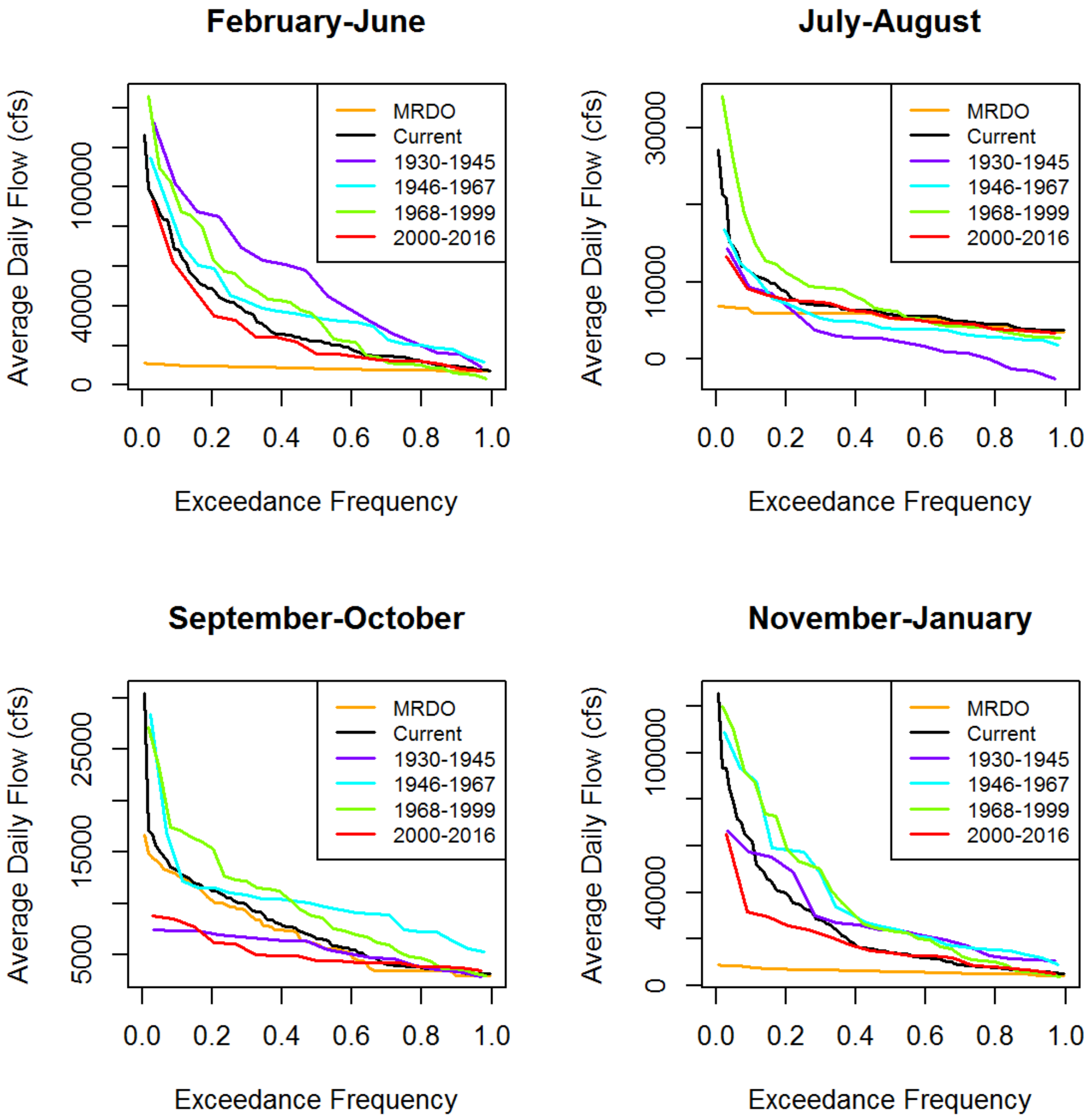

Figure 5.3-1. Seasonal Comparisons of Minimum Required Delta Outflow ("MRDO", orange line), SacWAM Modeled Delta Outflow ("Current", black line), and Observed Delta Outflow. Observed Delta outflow is divided into four historical periods: prior to the completion of Shasta Reservoir (1930–1945, purple line), prior to the completion of Oroville Reservoir (1946–1967, cyan line), prior to the adoption of D-1641 (1968–1999, green line), and following the adoption of D-1641 (2000–2016, red line) (Dayflow data, DWR 2017).

5.3.3.2 Benefits of Increased Delta Outflow

A new Delta outflow objective is proposed to better protect the ecosystem as a whole and to provide for continuity of inflows and outflows, referred to as an inflow-based Delta outflow objective, in which required inflows in the Bay-Delta Plan would be required as Delta outflow (with appropriate adjustment for accretions and depletions). The range for outflow requirements would be consistent with the range for new inflow requirements. An analysis is provided below of the modeled Delta outflows that would result from this range of inflows and existing expected flows from the San Joaquin River. The analysis compares these flow levels to modeled current conditions, modeled existing Delta outflow and salinity requirements included in the Bay-Delta Plan and USFWS BiOp (referred to as minimum required Delta outflow or MRDO) and the flow levels identified in Chapter 3 that are correlated with improved abundance and survival of certain native species that are believed to be indicative of the relative hydrologic conditions that would benefit native species.

The inflow-based Delta outflow scenarios reflect inflows 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, as well as other expected accretions and depletions. 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 are being addressed through the separate Phase I process. Because revised San Joaquin River flow objectives have not yet been adopted by the State Water Board, for purposes of this Report, it is assumed that San Joaquin River contributions would continue to reflect existing current regulatory conditions. With the Phase I changes to the Bay-Delta Plan, these contributions would potentially increase.[8]

As previously discussed, the percent of unimpaired flow scenarios do not yet account for other regulated and unregulated flows that would also contribute to Delta outflows above the inflow-based Delta outflow requirement, and predicted flows would be higher at times. The relative magnitude of this difference can be discerned by comparing current conditions with MRDO. The Staff Report will include modeling analyses that include these additional expected flows. 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 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 current conditions that help to illustrate the increased outflows that would be provided if the scenarios were implemented.

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

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[8] The inflow-based Delta outflow scenarios are derived by: (1) estimating unimpaired Delta outflow using SacWAM, as described in Chapter 2 and Appendix A; (2) subtracting the modeled unimpaired San Joaquin River inflow at Vernalis to provide an estimate of the Delta outflow contributed by the Sacramento River basin and eastside tributaries to the Delta; (3) scaling the values obtained in (2) by the percent of unimpaired inflow being provided from the Sacramento River basin tributaries and eastside tributaries; and (4) adding the required inflow at Vernalis pursuant to the current regulatory requirements of D-1641 and the Bay-Delta Plan.

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 may need higher flows after March than most other species, 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 all of the species discussed below.

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 Staff 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 5.3-2 through 5.3-6 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 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 5.3-3. As discussed above, caution should be used in interpreting the results for 35 percent and 45 percent unimpaired flow (UF) scenarios and under wetter conditions for all scenarios. The frequencies shown for some species flows are lower than current conditions, particularly for higher flows. This reflects the fact that the 35 to 75 percent 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 percent and 45 percent scenarios are expected to resemble current 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 5.3-3). For example, flows that correspond to an average X2 position downstream of Port Chicago occur 40 percent of the time under current conditions but are estimated to occur 58 percent of the time at 75 percent UF (Figure 5.3-2). 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 53 percent of the time under current conditions and increased to 86 percent of the time at 75 percent UF (Figure 5.3-3). In contrast, the high flow target of 47,000 cfs for Sacramento splittail is met 27 percent of the time under current conditions and only increases to 37 percent of the time at 75 percent UF (Table 5.3-2, Figure 5.3-5). None of the species-specific flows is met 100 percent of the time, even at 75 percent UF.

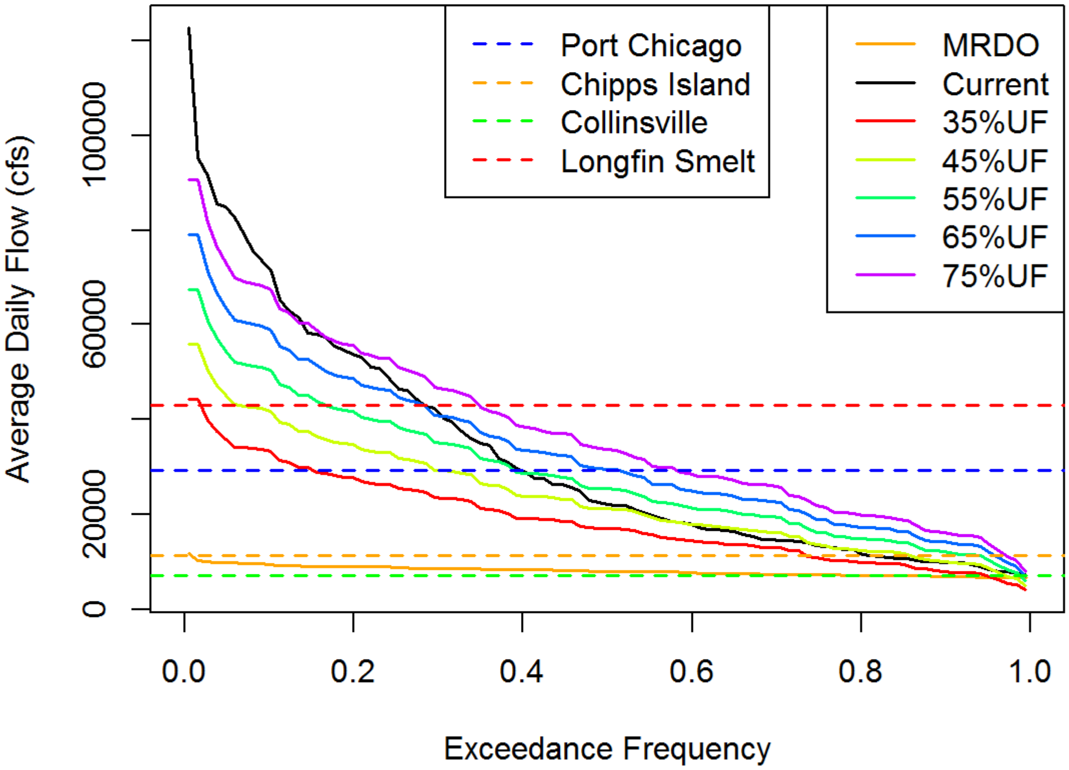

Figure 5.3-2. Frequency of Meeting January–June Delta Outflows to Benefit Estuarine LSZ Habitat and Longfin Smelt for MRDO, Current Conditions as Modeled by SacWAM, and Inflow-Based Delta Outflow Scenarios Corresponding to Sacramento River and Eastside Delta Tributary Inflows from 35 to 75 Percent of Unimpaired Flow

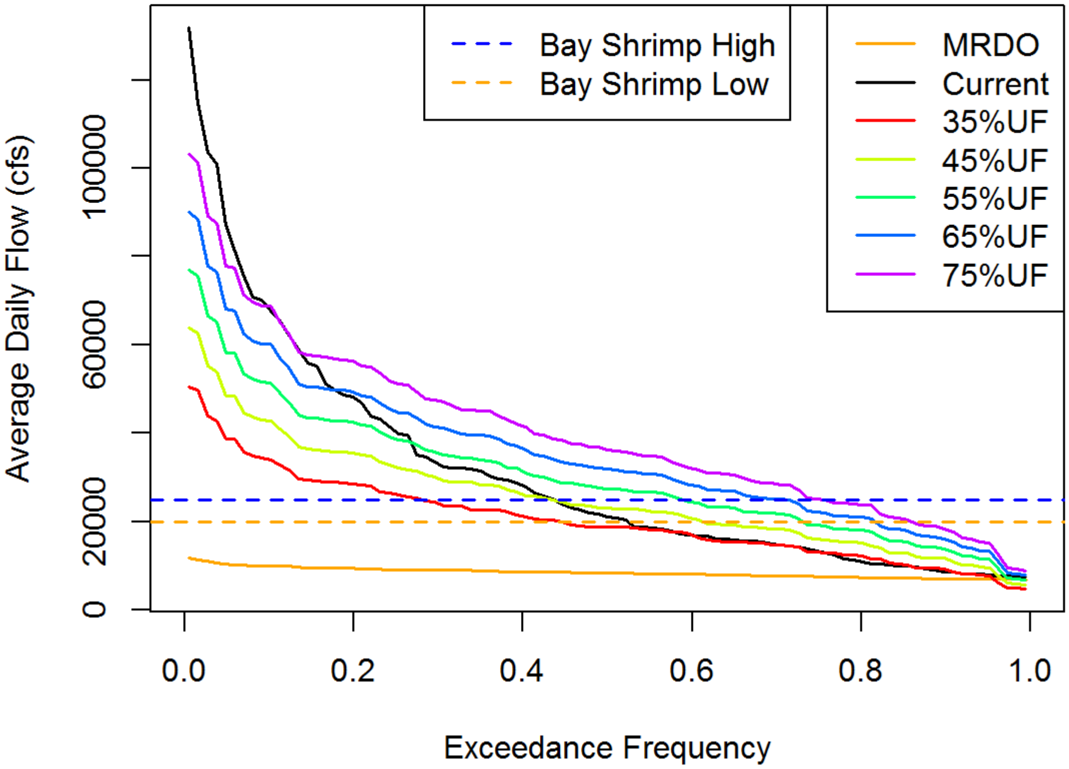

Figure 5.3-3. Frequency of Meeting March–May Delta Outflows to Benefit California Bay Shrimp for MRDO, Current Conditions as Modeled by SacWAM, and Inflow-Based Delta Outflow Scenarios Corresponding to Sacramento River and Eastside Delta Tributary Inflows from 35 to 75 Percent of Unimpaired Flow

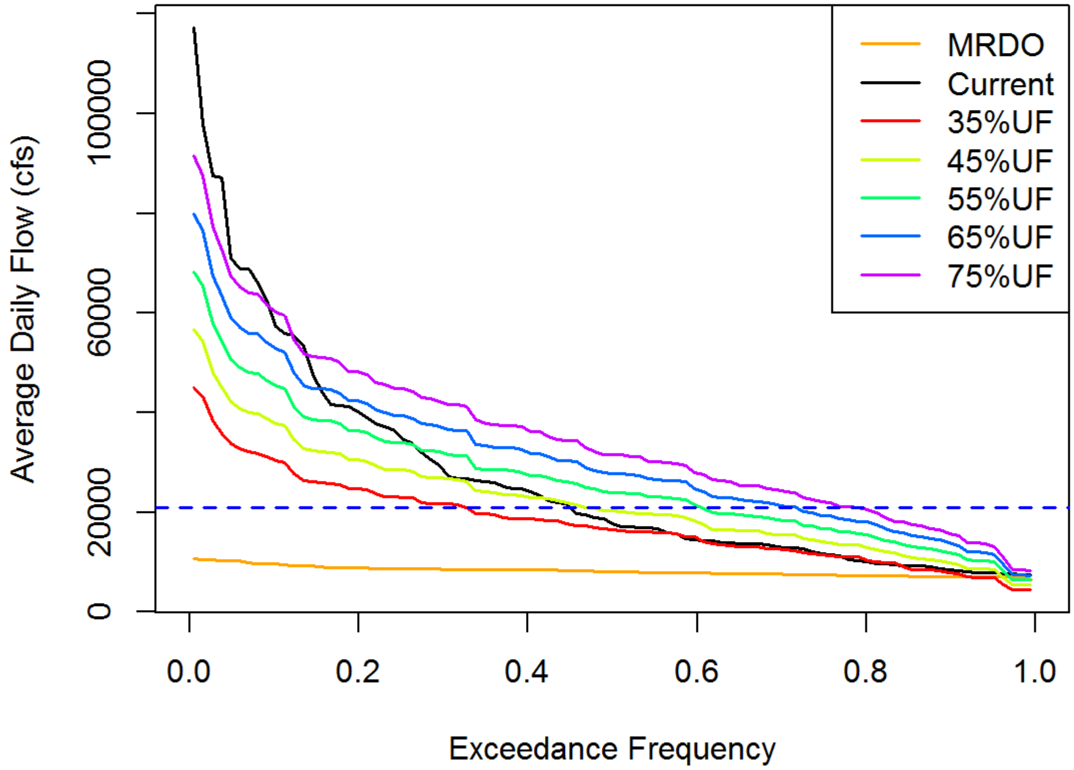

Figure 5.3-4. Frequency of Meeting March–June Delta Outflows to Benefit Starry Flounder for MRDO, Current Conditions as Modeled by SacWAM, and Inflow-Based Delta Outflow Scenarios Corresponding to Sacramento River and Eastside Delta Tributary Inflows from 35 to 75 Percent of Unimpaired Flow

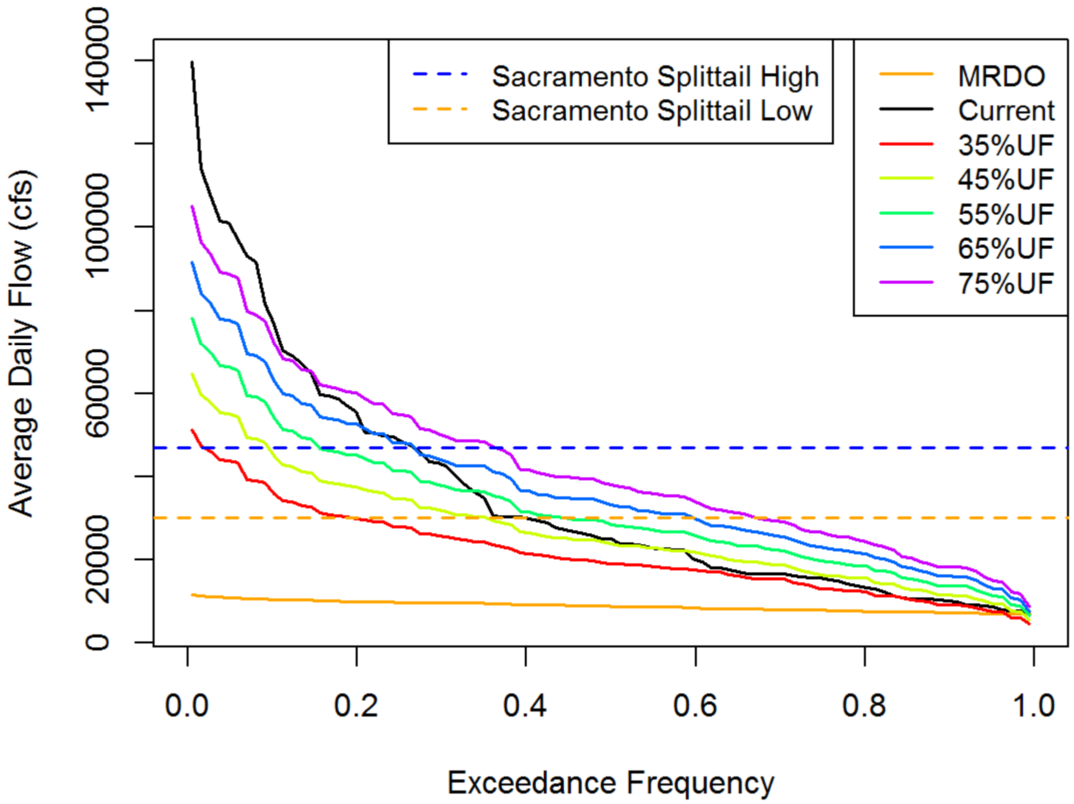

Figure 5.3-5. Frequency of Meeting February–May Delta Outflows to Benefit Sacramento Splittail for MRDO, Current Conditions as Modeled by SacWAM, and Inflow-Based Delta Outflow Scenarios Corresponding to Sacramento River and Eastside Delta Tributary Inflows from 35 to 75 Percent of Unimpaired Flow

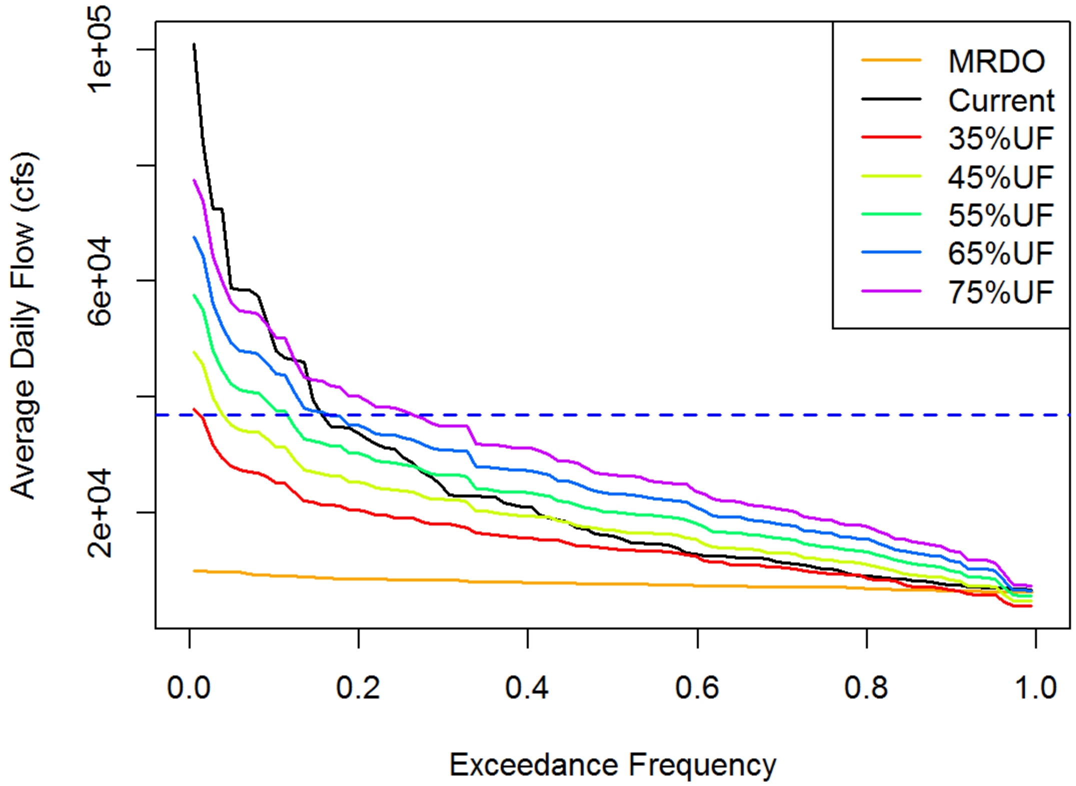

Figure 5.3-6. Frequency of Meeting March–July Delta Outflows to Benefit White and Green Sturgeon for MRDO, Current Conditions as Modeled by SacWAM, and Inflow-Based Delta Outflow Scenarios Corresponding to Sacramento River and Eastside Delta Tributary Inflows from 35 to 75 Percent of Unimpaired Flow

Table 5.3-3. Summary of Frequency of Meeting Winter-Spring Delta Outflows to Benefit Estuarine Habitat and Species. As discussed above, these frequencies would be higher for the unimpaired scenarios when accounting for unregulated flows, other regulatory flows, etc. Current conditions reflect MRDO flows plus the other regulated and unregulated flows.

Species or X2 Location	MRDO	Current	35%UF	45%UF	55%UF	65%UF	75%UF
Collinsville	86	100	95	97	99	99	100
Chipps Island	1	81	73	86	94	96	97
Port Chicago[9]	0	40	15	30	39	52	58
Bay Shrimp High	0	44	28	44	59	72	75
Bay Shrimp Low	0	53	44	61	73	82	86
Green and White Sturgeon	0	15	1	4	12	16	27
Longfin Smelt	0	28	2	6	17	28	34
Longfin Smelt Spawning	0	27	0	4	11	19	27
Sacramento Splittail High	0	27	2	10	15	27	37
Sacramento Splittail Low	0	40	19	35	45	60	68
Starry Flounder	0	45	32	46	60	72	78

The flow frequency distributions suggest that population abundance of native species will increase with increasing Delta outflows. 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 current conditions scenario (Table 5.3-4). 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. Actual outcomes will depend on future flows, management of other stressors, and factors such as stock rebuilding that cannot be accounted for without life cycle models and appropriate data to parameterize them. According to this limited analysis, estuarine species would be expected to derive limited benefits from the 35 percent or 45 percent unimpaired scenarios, though there would be substantial benefits relative to MRDO. Modest benefits would be expected from the 55 percent scenario, and more substantial benefits from 65 percent and 75 percent scenarios when compared to current conditions, with much larger benefits when compared to MRDO. Again, this analysis does not consider other uncontrolled and regulatory flows which would significantly increase the flows and assumed benefits in some years.

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[9] 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 5.3-4. Potential Percent Increase in Median Abundance Indices Relative to SacWAM Modeled Flows for Existing Regulatory Conditions Assuming No Additional Unregulated or Regulated Flows

Species	35%UF	45%UF	55%UF	65%UF	75%UF
Longfin Smelt	0	0	22	51	81
Bay Shrimp	0	6	17	27	37
Starry Flounder	0	5	16	25	34
Sacramento Splittail	0	0	13	31	48

In addition to the benefits of additional winter and spring flows, there is evidence that year-round Delta outflows are important to maintain the quantity and quality of estuarine habitat. As discussed in Chapter 3, Baxter et al. (2015) found an inverse relationship between the location of X2 in fall and larval Delta smelt abundance the following spring (Figure 3.8-4). The relationship was improved by accounting for adult stock, suggesting that both habitat quantity and quality and the number of breeding adults were important in determining recruitment (Baxter et al. 2015). As summarized in Chapter 3, the findings from the Interagency Ecological Program Management, Analysis, and Synthesis Team (IEP MAST) (Baxter et al. 2015) have confirmed the importance of the location of X2 in fall for Delta smelt larval recruitment. 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 in Chapter 3).

Finally, Delta inflow from the Sacramento River tributaries and outflow through the Delta are the primary factors (along with some regulation by salinity control gates) governing salinity in Suisun Marsh. 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 (Delta and longfin smelt in particular).

5.3.4 Conclusion and Proposed Requirements

Available scientific information supports the proposed modifications to the existing Delta outflow requirements to ensure the reasonable protection of the ecosystem and fish and wildlife beneficial uses, including the natural production of viable native estuarine species populations rearing in and migrating through the Delta, and to better integrate inflow and outflow requirements in a comprehensive framework for environmental flows. 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. In addition, there is evidence that native species benefit from flows that place the LSZ downstream of the confluence of the Sacramento and San Joaquin Rivers during summer and fall.

Proposed changes to the Delta outflow requirements include the addition of a new narrative objective and a new numeric objective and maintenance of some existing requirements. The Delta outflow narrative objective is proposed to describe the outflow conditions that reasonably protect native anadromous and estuarine fish and aquatic species populations. Specifically, it requires maintenance of Delta outflow sufficient to support and maintain the natural production of viable native fish and aquatic species populations rearing in or migrating through the Bay Delta.

The proposed new narrative outflow objective is as follows:

> *Maintain Delta outflows sufficient to support and maintain the natural production of viable native anadromous fish, estuarine fish, and aquatic species populations rearing in or migrating through the Bay-Delta estuary. Delta outflows that reasonably contributes toward maintaining viable native fish and aquatic species populations include, but may not be limited to, flows that connect low salinity pelagic waters to productive tidal wetlands and flows that produce salinity distributions that more closely mimic the natural hydrographic conditions to which these species are adapted, including the relative magnitude, duration, timing, quality and spatial extent of flows as they would naturally occur. Indicators of viability include population abundance, spatial extent, distribution, productivity and genetic and life history diversity. Viability is dependent on maintaining migratory pathways, sufficient quantities of high quality spawning and rearing habitat, and a productive food web.*

In order to ensure that minimum quantities of Delta outflow are provided to the estuary in all months and all years, base Delta outflows from the current Bay-Delta Plan would be maintained. Specifically, the existing Delta outflow requirements that are included in Table 3 of the Bay-Delta Plan that range from 3,000 cfs to 8,000 cfs based on water year type from July through January would be maintained.

In addition, base February through June flows of 7,100 cfs would also be maintained (Footnote 11 to Bay-Delta Plan Table 3). Under the existing Bay-Delta Plan, this requirement may be met by achieving a salinity (as measured by electrical conductivity) level of 2.64 millimhos per centimeter, or X2 location, at Collinsville. The methods by which this objective may be met are proposed to be reevaluated in the program of implementation to ensure that intended protections are provided, while providing flexibility to reduce water supply impacts.

The remaining existing Delta outflow requirements included in Table 4 of the Bay-Delta Plan that require flows of 11,400 cfs and 29,200 cfs (or equivalent salinity) for a specified number of days based on the ERI are proposed to be replaced with an inflow-based Delta outflow objective that is expected to better achieve the proposed new narrative Delta outflow objective in an integrated fashion with the proposed new inflow requirements. The proposed new inflow-based Delta outflow objective specifies that the required inflows from the Sacramento and San Joaquin Rivers and their tributaries and the three Delta eastside tributaries are provided as outflows with appropriate adjustments for depletions and accretions, including adjustments for floodplain inundation flows and other side flows. Like the inflow requirements, the outflow requirements are not proposed to be lower than existing conditions.

The proposed new numeric inflow-based outflow objective is as follows:

> *The inflow-based Delta outflow shall be the inflows required below [Sacramento River and its tributaries and the Delta eastside tributaries], including Lower San Joaquin River flows, with adjustments for downstream depletions and accretions as specified in the program of implementation.*

In addition, the fall Delta outflow requirements from the USFWS BiOp would to be incorporated in the Bay-Delta Plan. These requirements include additional Delta outflow requirements in September through December when the preceding hydrologic period was a wet or above normal year, according to the Sacramento Valley water year hydrologic classification as defined in Figure 2 of the Bay-Delta Plan. Specifically, in September and October of or following wet years, X2 would be required to be at or west of Chipps Island and in above normal water years, X2 would be required to be at or west of Collinsville. In November, inflows would be required to be bypassed from SWP and

CVP reservoirs in the Sacramento basin up to the X2 targets. In December, any increase in storage in SWP and CVP reservoirs in the Sacramento basin would be required to be released to augment December base Delta outflow requirements.

Together the Delta outflow, inflow, and other requirements are proposed to provide comprehensive protection for fish and wildlife from natal streams through the Delta and Bay and nearshore ocean while providing necessary flexibility and adaptive management provisions to address the complexities of providing Delta outflows from the watershed in a reasonable and protective manner. Like the inflow requirements, the inflow-based Delta outflow requirements would allow for adaptive management and sculpting of flows and would require the development of a plan that addresses implementation measures by Delta users, including the Projects, as well as monitoring, evaluation, and reporting measures. The program of implementation would address accounting measures for the existing and new requirements, including integration with tributary plans, accretions and depletions, and evaluation of the existing and new methods of compliance with Delta outflows to ensure they are protective, including the compliance methods for the base flows discussed above. The program of implementation would also address development of biological goals for Delta outflows; and provisions for coordination with inflows and biological opinion requirements.

5.4 Cold Water Habitat Below Reservoirs

5.4.1 Introduction

A new narrative cold water habitat objective is proposed 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. Cold water habitat conditions in the tributaries will differ and the mechanisms for best implementing the narrative objective will vary among the tributaries; thus flexibility is needed to best achieve the objective. Depending on the specific conditions of a tributary, the narrative may be implemented through cold water storage requirements, TCDs, flow provisions, passage to cold water habitat, or other measures.

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 has been eliminated or substantially reduced to the detriment of salmonid populations. Remaining populations that would otherwise migrate to upstream habitat are now dependent on maintenance of suitable conditions in the downstream reaches below dams. During the summer and fall when air temperatures exert a strong influence on river temperatures, the release of cold water from reservoirs is thus critically important for maintaining suitable cold water habitat during these periods. Consequently, effective management of cold water will continue to be a critical component of the conservation and recovery strategies for native salmonids, especially in view of the challenges posed by increasing water demands and climate change.

5.4.2 Existing Cold Water Habitat Requirements

The current Bay-Delta Plan does not include an express requirement to protect cold water habitat downstream of reservoirs; however, there are existing requirements and ongoing efforts that help to protect cold water habitat in the Delta watershed. Fish and Game Code section 5937 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 Water Board's Basin Plan includes general and specific temperature objectives. With the exception of the specific temperature objective discussed below for the Sacramento River, it is not clear whether these general requirements have been applied to any tributaries in the Phase II area to date.

5.4.2.1 Upper Sacramento River

The Sacramento River downstream of Shasta Reservoir is currently the only existing habitat for endangered winter-run Chinook salmon which are entirely dependent on adequate cold water releases below Shasta Reservoir for their persistence. Spring-run and fall-run also inhabit the upper Sacramento River and are affected by Shasta Reservoir operations. In part to protect these species, the Central Valley Water 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." In addition, 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 TCD 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 BiOp (NMFS 2009a) 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 incubation during fall months. The management of Shasta Reservoir during the summer and early fall to protect winter-run Chinook salmon is a high priority 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 DSP conducted an Independent Review Panel (IRP) to assess the effectiveness of the NMFS (and USFWS) BiOp Shasta Reservoir temperature management actions (these actions were taken in coordination with the State Water Board's implementation of Order 90-5) in 2013, 2014, and 2015. In particular, the IRP reviewed the recommendation by NMFS to use a 55°F 7DADM water temperature requirement for the Sacramento River instead of the 56°F daily average recommended by USEPA (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 resulting in increasing impacts on survival and fry production. 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). Based on deficiencies in monitoring and modeling tools that are currently available to inform managers and operators, the IRP encouraged improvements in data collection technology and 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, temperature management actions could be based on protecting areas known to be used for spawning rather than areas that have potential to support spawning but have never been used (Anderson et al. 2015).

After very high temperature-related mortality of winter-run eggs in the drought years of 2014 and 2015, NMFS and the State Water Board used the 55°F 7DADM along with other recommendations of the IRP in 2016 (in which there was a much greater quantity of cold water) to reduce uncertainty in meeting temperature needs for winter-run on the Sacramento River to avoid significant mortality for a third year, which was largely successful (at least in part due to the additional cold water supplies). Current efforts are underway by NMFS[10] and the other fisheries agencies, Reclamation, the State Water Board, and water users to improve temperature modeling and management on the Sacramento River, including implementation of IRP recommendations.

5.4.2.2 Lower American River

The State Water Board's Decision 893 (D-893), which established minimum instream flow requirements on the American River in 1958, is outdated and not considered sufficiently protective of fishery resources in the lower American River (NMFS 2014a). Currently, reservoir operations are managed in accordance with the NMFS BiOp (Reasonable and Prudent Alternative [RPA] Action II.1-II.4) which incorporates the recommended actions of the 2000 Water Forum Agreement (American River Water Forum 2004), including new flow and water temperature requirements, annual operations forecasting and temperature management planning, and evaluation of new structural technologies to improve water temperature management capabilities.[11] The proposed alternatives include replacement or enhancement of Folsom Dam's existing TCD, a number of structural and

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[10] NMFS is developing a temperature forecasting and decision-support tool (River Assessment for Forecasting Temperature [RAFT]) that couples a series of watershed, reservoir, and river temperature models to more effectively manage the reservoir's limited cold water pool for winter-run protection (Danner et al. 2012; Danner 2015).

[11] The Water Forum Agreement has not been reviewed, approved, or incorporated into any water right permit or license by the State Water Board.

operational alternatives to improve cold water transport through Lake Natoma, and a proposed El Dorado Irrigation District TCD (NMFS 2009a). Studies conducted by Reclamation have evaluated several alternatives to improve transport of cold water through Lake Natoma, including installation of temperature control curtains in Lake Natoma, removing submerged debris in front of the Nimbus Dam powerplant intakes, dredging the old river channel in Lake Natoma, and modifying Folsom Dam's powerplant peak loading operations (Reclamation 2007).

Maintaining suitable water temperatures for all life history stages of steelhead in the American River is a chronic issue because of operational (e.g., meeting Delta water quality and other downstream water demands) and structural (e.g., limited reservoir water storage and cold water pool) limitations (NMFS 2009a). Only under wetter hydrologic conditions is the volume of cold water sufficient to meet the temperature requirements of over-summering steelhead and fall-run Chinook salmon spawning and incubation in the fall. Currently, annual operation strategies are formulated to manage the available cold water pool in consideration of other water demands and tradeoffs (NMFS 2009a). Because the CVP is operated as an integrated system, conflicts in temperature management on the American River often arise due to other CVP operations for water supply and salinity and flow control purposes, including conflicts between Shasta Reservoir and Folsom Reservoir storage management.

5.4.2.3 Feather River

The existing hydroelectric power license issued by FERC in 1957 for the Oroville Facilities Hydroelectric Project (Hydro Project) expired in 2007 and DWR is currently seeking a new license. Hydro Project operations continue to build on interim measures implemented by DWR during the relicensing effort, including: measures continued under the 1983 Agreement concerning the Operation of the Oroville Division of the State Water Project for Management of Fish and Wildlife (including operations of the Feather River Fish Hatchery); select measures identified during consultation with the USFWS (USFWS 2007); and ramping rates for the Low Flow Channel (LFC) in the 2016 NMFS BiOp (NMFS 2016).

As part of the Hydro Project relicensing effort agencies have developed conditions for the new FERC license. Additional requirements in the State Water Board's 2010 water quality certification (Order WQ 2010-0016) and 2016 NMFS BiOp will be integrated into the new FERC license for the Hydro Project. The water quality certification identified inadequate protection of downstream cold water beneficial uses. DWR's studies showed that water temperatures in the LFC and the High Flow Channel (HFC) were contributing to adverse conditions for anadromous salmonids. Studies have shown that conditions are inhospitable to spawning and rearing in the Feather River below the Thermalito Afterbay Outlet (HFC). 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, in-vivo egg mortality, and temporary cessation of migration could occur due to elevated water temperatures in some areas of the lower Feather River.

In 2006 DWR signed a Settlement Agreement, which contains interim water temperature targets and a framework for developing final temperature requirements based on implementation of facility modifications to improve cold water management capabilities in the Feather River (DWR 2006). The State Water Board's 2010 water quality certification includes more than 20 elements of Settlement Agreement. The 2010 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. As part of the Settlement Agreement and under the water quality certification, DWR is required to develop a Feasibility Study and Implementation Plan (FSIP) for Facility Modification(s) to improve temperature conditions for spawning, incubation, rearing, and holding of anadromous fish within 3 years of FERC license issuance. Key design objectives are to improve accessibility to the cold water pool in Lake Oroville, minimize heat gains from the dam to targeted downstream locations in the Feather River, and reduce cold and warm water mixing in Thermalito Afterbay (NMFS 2016). The FSIP will include a recommended alternative, which may include both structural and operational modifications, will be designed to meet specific temperature objectives in the LFC and HFC subject to monitoring and evaluation of the feasibility of achieving these objectives under severe dry year hydrologic conditions as defined by the Oroville Temperature Management Index (DWR 2006). The FSIP will include a proposed implementation schedule, fisheries monitoring program, and adaptive management framework. The water quality certification also includes temperature requirements for the Feather River Fish Hatchery to aid in managing disease outbreaks. The State Water Board's water quality certification includes interim and final deadlines for completing the FSIP and any required facility modifications to meet interim and final temperature requirements in the LFC, HFC, and Feather River Fish Hatchery.

5.4.2.4 Lower Yuba River

The lower Yuba River is defined as the 24-mile section of the river between Englebright Dam and the confluence with the Feather River south of Marysville. State Water Board Decision 1644 (D-1644), adopted in 2003, contains revised instream flow requirements, flow fluctuation (ramping) requirements, and specific actions to provide suitable water temperatures and other protective measures (fish screens at water diversion facilities) for all life stages of Chinook salmon and steelhead in the lower Yuba River. D-1644 concluded that compliance with CDFW- and NMFS-recommended water temperature objectives for the lower Yuba River was not feasible prior to the construction and operation of the Yuba River Development Project's (YRDP's) New Bullards Bar Reservoir. The State Water Board retained continuing authority to establish water temperature requirements for the lower Yuba River, and required Yuba County Water Agency (YCWA) to make reasonable efforts to operate the YRDP to maintain suitable water temperatures in the lower Yuba River for fall-, late-fall-, and spring-run Chinook salmon and steelhead.

The Lower Yuba Accord, approved by the State of California in 2008, is a multi-stakeholder partnership that was formed to resolve instream flow issues associated with operation of the YRDP, and establish a collaborative process to protect and enhance lower Yuba River fisheries while ensuring the reliability of water for hydropower, irrigation, flood control, and recreation. Water Right Order 2008-0014 amended YWCA's water right permits to include the flow schedules and other specified terms and conditions of the Lower Yuba Accord's Fisheries Agreement. These include provisions for regular planning and coordination by the River Management Team (RMT) to implement flow and water temperature management actions, including planned operation of the upper and lower outlets at New Bullards Reservoir and any TCDs that might be built at Englebright Dam. Water Right Order 2008-0014 includes provisions for review and approval of recommended RMT actions by the fisheries agencies and State Water Board. As noted in the Order, water temperature data from the lower Yuba River indicate that operations under the Yuba Accord flows do not meet CDFW's and NMFS's maximum water temperature requirements for anadromous fish in the months of May through September, even in wet years. In addition, wet year Yuba Accord flows did not meet the index temperature of 60° F in August and September.

5.4.2.5 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 cold water 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.

As part of the JSA, a Lower Mokelumne River Partnership was established by EBMUD, USFWS, and CDFW in 1998 to support fishery and ecosystem protection in the lower Mokelumne River, encourage stakeholder participation, and integrate Mokelumne River strategies with other programs (EBMUD et al. 2008). The Partnership Steering Committee is guided by a coordination committee that includes biologists and other technical staff from CDFW, EBMUD, USFWS, and NMFS. The coordination committee meets each year to review fisheries and water quality monitoring data, evaluate projected water year type conditions and operations plans, make recommendations for expenditure of the Partnership Fund, and develop proposed adaptive management actions to optimize habitat conditions in the lower Mokelumne River (EBMUD et al. 2008). In addition to these flow provisions, the JSA includes a number of non-flow measures, including cold water pool management to provide suitable water temperatures for all salmonid and native fish life stages. This involves integrated operation of Camanche and Pardee Reservoirs and water temperature monitoring, modeling, and forecasting to ensure sufficient storage of cold water during the winter and spring to prevent early turnover (destratification) of Camanche Reservoir, and to provide sufficient cold water for releases in the lower Mokelumne River through early November (EBMUD 2013).

5.4.2.6 Putah Creek

In 2000, the Putah Creek Council, City of Davis, and UC Davis signed a settlement agreement (Putah Creek Accord) with the Solano County Water Agency, Solano Irrigation District, and other Solano water interests to establish permanent flows in the 23 miles of Putah Creek below Lake Solano (formed by Putah Diversion Dam, the upstream limit of fish migration) and initiate a program to optimize benefits for fish, wildlife, and other resources in a manner compatible with human water and land uses in the lower Putah Creek watershed (EDAW 2005). Under the Accord, current instream flows and water releases from Lake Berryessa (Monticello Dam) are managed to provide a more natural flow regime to support native resident and anadromous fishes, including: (1) baseline flows to maintain cool water habitat for native fishes in the upper reaches of the creek; (2) a pulse flow in February-March to provide migration and spawning opportunities for native fishes in years when such flows do not occur naturally; (3) supplemental flows to attract adult fall-run chinook salmon into Putah Creek in the fall, and provide minimum flows for juvenile rearing and emigration in the spring; and (4) provisions to meet minimum flow requirements of fish during severe droughts (EDAW 2005).

Water temperature monitoring and modeling has revealed that cold water discharged from the bottom of Lake Berryessa into lower Putah Creek flows rapidly downstream to Lake Solano with minimal heating, maintaining cold water habitat and a high-quality resident trout fishery from Monticello Dam to 1 to 2 miles below Putah Diversion Dam (EDAW 2005). Among the factors that continue to limit native fish populations, including salmon and steelhead, is the lack of access to cold water habitat above Putah Diversion Dam and Monticello Dams and limited cold water habitat below Putah Diversion Dam (EDAW 2005; NMFS 2014b). Recommended actions for improvements in water temperatures and overall habitat quality for native fishes in Putah Creek include restoration of riparian and shaded riverine aquatic cover, spawning gravel augmentation, and fish passage improvements (EDAW 2005).

5.4.2.7 Calaveras River

Little information is available on cold water habitat management in the Calaveras River below New Hogan Dam. A Chinook salmon and steelhead limiting factors analysis concluded that the Calaveras River is unique among Central Valley tributaries because of high summer flows, cool temperatures, abundance of high quality juvenile rearing habitat, and presence of deep pools that provide potentially excellent conditions for resident rainbow trout, steelhead, and spring- and fall-run Chinook salmon above Bellota Weir (Stillwater Sciences 2004). Regulation of the lower Calaveras River by New Hogan Dam may have increased the consistency of suitable conditions for steelhead and Chinook salmon spawning and rearing. However, a major limiting factor for anadromous fish populations are fish passage problems associated with municipal and agricultural diversions from Bellota Weir downstream to the San Joaquin River confluence (Stillwater Sciences 2004). Recommendations for future studies include the development of a spatially explicit flow-dependent model of stream temperatures below New Hogan Dam to help identify stream reaches where water temperatures reach levels potentially stressful or lethal to salmonids, and help facilitate an adaptive management approach to managing stream temperatures in the future (Stillwater Sciences 2004).

5.4.2.8 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 cold water 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 Discussion

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 cold water pool (NMFS 2009a). Chapter 3 describes the thermal requirements for each life stage of Chinook salmon and details dam and reservoir effects on salmonids.

Adequate cold water storage is a primary factor limiting the ability of reservoirs to meet water temperature requirements for spawning and rearing, especially during droughts and critically dry periods. Temperature control management below reservoirs is dependent on ambient air temperatures, reservoir storage levels, reservoir releases and the operation of TCDs that may be present. 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 through the critical season. Flows must also be managed to avoid fluctuations that cause stranding and dewatering. In reservoirs where TCDs are present, they assist with temperature management by providing access to cold water deep within the reservoir and an ability to selectively withdraw water from varying depths to manage the available volume of cold water to meet downstream water temperature needs. Annual temperature management plans that are adjusted throughout the season based on regular monitoring and evaluation of fish distribution and timing, reservoir inflows, storage, and thermal dynamics, and meteorological conditions are also important components of temperature management.

As discussed above, 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 other demands for water and climate change that may place greater demands on available supplies. The current cold water habitat and management will need to be further evaluated in the context of an updated Bay-Delta Plan and new flow requirements to ensure the protection of salmonids in the Sacramento River and major tributaries of the Sacramento River and Delta.

There has also been increasing recognition of the need for improvements in data collection and modeling to better understand the physical processes affecting the thermal dynamics of large reservoirs, and determine the most effective strategies (including both operational and facility modifications) for meeting the downstream temperature requirements of anadromous salmonids (Anderson et al. 2015). To the extent possible, cold water management planning efforts and decision-making should be based on the application of linked physical models that propagate the thermal effects of proposed actions through the watershed, reservoir, and river system (Cloern et al. 2011). These model systems also provide a means of evaluating the potential roles of other habitat restoration measures (e.g., riparian habitat restoration, gravel replenishment, channel and floodplain rehabilitation) in enhancing cold water habitat by reducing heat inputs from other sources (e.g., tributary streams) or increasing surface-groundwater interactions (Tompkins and Kondolf 2007b). Cold water management efforts will also benefit from improved data collection and modeling efforts that provide more accurate predictions of the spatial and temporal distribution of sensitive life stages (Anderson et al. 2011) and take into account the effects of other environmental variables (e.g., intergravel oxygen) on thermal stress and tolerances of these life stages (e.g., Martin et al. 2016).

An alternative strategy for addressing increasing risks to cold water habitat protection for anadromous salmomids is the re-introduction of populations to historical habitat above the existing dams, or in the case of winter-run Chinook salmon, into other tributaries where cold water management is less challenging than on the mainstem Sacramento River. Such projects present unique technological, regulatory, and logistical challenges and require extensive pre-project feasibility studies to evaluate the potential for successful re-introductions of salmon and steelhead above the dams (NMFS 2014a) or other streams. A model for such an effort is the *Shasta Dam Fish Passage Evaluation Pilot Implementation Plan* (Reclamation 2015) which evaluates the feasibility of reintroducing endangered winter-run Chinook salmon above Shasta Lake. This plan includes an examination of the benefits, risks, and constraints of a long-term re-introduction program; potential fish passage technologies that will be evaluated as part of a pilot plan (e.g., adult and juvenile collection and transport options); and proposed pilot studies to address key uncertainties associated with re-introduction.

5.4.4 Conclusion and Proposed Requirements

Scientific information supports the proposed narrative requirement to provide reasonable protection of cold water habitat below reservoirs. Effective management of cold water supplies or alternative measures will continue to be a critical component of the conservation and recovery strategies for native salmonids in the Bay-Delta watershed. With the demands of new inflow and outflow requirements and ongoing concerns about protection of cold water for salmonids, it is important that requirements protecting cold water habitat and storage be developed to assure protection of fisheries resources in the tributaries of the Delta, particularly given existing and future climate change.

The proposed narrative objective is as follows:

> *Maintain stream flows and reservoir storage conditions on the Sacramento River and its tributaries and Delta eastside tributaries to protect cold water habitat for sensitive native fish species, including Chinook salmon, steelhead, and sturgeon. Cold water habitat conditions to be protected include maintaining sufficient quantities of habitat with suitable temperatures on streams to support passage, holding, spawning, incubation, and rearing while preventing stranding and dewatering due to flow fluctuations.*

The program of implementation would provide that the narrative be implemented on a tributary basis through the tributary plans discussed in the inflow section and would take into consideration the unique structural, operational, and hydrological characteristics of the many tributaries in the project area. The need to reserve cold water pool could justify environmental flows moving lower in the range of inflow requirements at certain times. Tributary-specific plans should use data collection and modeling tools for effective cold water management, and could contemplate alternative strategies to cold water management. Although approaches may differ among tributaries, the effectiveness of cold water management will require ongoing coordination, collaboration, and technical review among water managers, stakeholders, and technical experts to facilitate both short-term and long-term planning and decision-making efforts. In addition, because of uncertainties associated with climate change and increasing demands for water, an integrated, flexible, and adaptive management approach will be necessary to cope with the increasing risks to cold water habitat and species protection in the future.

5.5 Interior Delta Flows

5.5.1 Introduction

New and modified interior Delta flow requirements are proposed to protect native migratory and estuarine species from entrainment effects in the southern Delta associated with CVP and SWP diversion activities including new narrative requirements and numeric requirements for DCC gate closures, OMR reserves flow limits and export constraints as a function of San Joaquin River flows consistent with existing BiOp and ITP requirements in an adaptive management framework informed by monitoring and research efforts.

5.5.2 Discussion

Flow management, including the operation of the Projects in the Delta, affects salmonids, pelagic fishes 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 Sacramento River freshwater directly into the interior Delta to support CVP and SWP diversions and to meet interior 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 flows in the southern Delta are associated with increased entrainment of numerous fish species (Grimaldo et al. 2009a) and disruption of migration cues for migratory fish. Reverse flows, in combination with hydrologic alterations from upstream reservoir operations, the constraints of artificially connected Delta channels, and 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, 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

The existing Bay-Delta Plan includes DCC gate closure requirements that help to minimize risk of entrainment of juvenile Sacramento River salmonids 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 emigrating 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 (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 BiOp 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 to the Mokelumne River and reduces straying to the American River (EBMUD 2013; CDFG 2012). CDFG (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 have 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 Long-Term Operations Biological Opinions 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 proposed 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 Limits

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 BiOp (Actions 1 through 3), the NMFS BiOp (Action IV.2.3), and the CDFW ITP (Conditions 5.1 and 5.2) for the protection of Delta smelt, salmonids, and longfin smelt, respectively. (NMFS 2009a p. 648; USFWS 2008; CDFG 2009b.) These reverse flow limitations vary between -1,250 cfs and -5,000 cfs based on triggers related to entrainment risk of smelt and salmonids.

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 2.4-5 shows that under conditions with today’s channel configurations but no water supply development (1925–2000 unimpaired flow), negative OMR flow would be estimated to occur 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 2009a; 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 OMR reverse flows less negative than -1,250 cfs.
- Green and white sturgeon are vulnerable to entrainment from exports year-round.
- 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 consistent with the BiOps and ITP provisions discussed above. The requirement 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 Limits

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 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 a ratio of San Joaquin River flow to exports of 1:1 apply from April 15 through May 15 (San Joaquin River spring pulse flow period in the current Bay-Delta Plan). These constraints would be maintained. In addition, additional provisions are proposed to protect San Joaquin River flows provided for fish and wildlife purposes from export. This is proposed to be accomplished in part through the Delta outflow requirements discussed above, which require that required inflows be provided as outflow. In addition, it is proposed that the existing NMFS BiOp San Joaquin River flow to export constraints be included in the Bay-Delta Plan.

During the April to May peak outmigration period for San Joaquin basin steelhead, the NMFS BiOp (NMFS 2009a) 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. These constraints would be added to the Bay-Delta Plan along with adaptive management provisions that would allow for the export time period to be shifted based on monitoring of fish presence. Juvenile salmonids migrate out of the San Joaquin River basin during February through June (State Water Board 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, the time period for the San Joaquin River flow to export rate could be shifted 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 BiOp). The range recommended for consideration is illustrated in Figure 5.5-1.

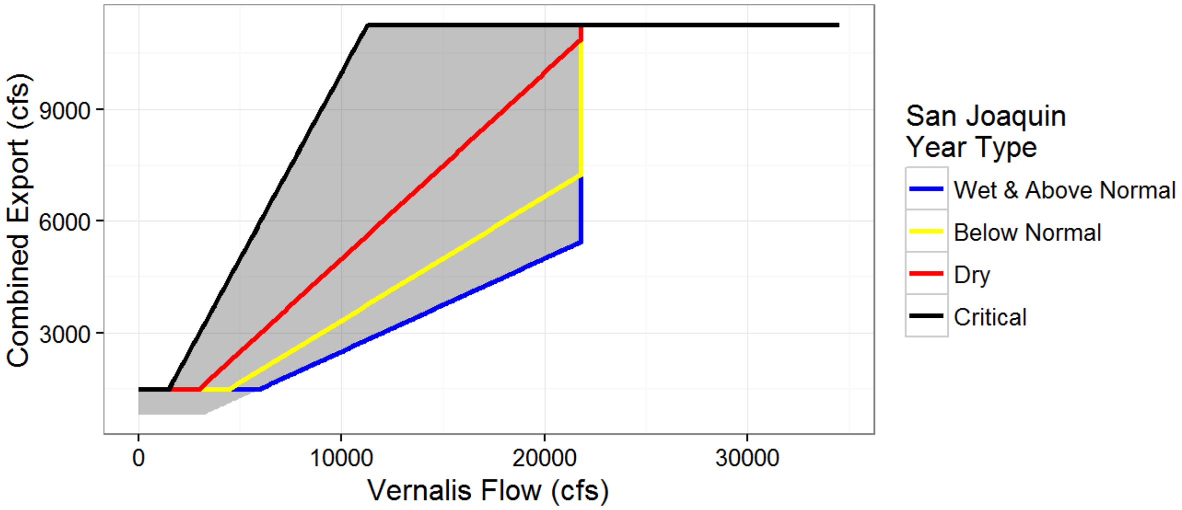

Figure 5.5-1. Range for Combined CVP and SWP South Delta Exports as a Function of Delta Inflow from the San Joaquin River at Vernalis (shaded area). The black, red, yellow, and blue lines represent the existing NMFS BiOp export constraints for critical, dry, below normal, and wet/above normal years, respectively. The grey shaded area represents the range of export constraints recommended for consideration.

5.5.6 Conclusion

New and modified narrative and numeric interior Delta flow requirements are proposed to protect resident and migratory species from entrainment and related effects. The narrative requirement would establish the overall flow conditions in the Delta to reasonably protect native fish populations migrating through and rearing in the Delta.

The proposed narrative requirement is as follows:

> *Maintain flow conditions in the interior Delta sufficient to support and maintain the natural production of viable native fish populations migrating through and rearing in the Delta. Interior Delta flow conditions that reasonably contribute toward maintaining viable native fish populations include, but may not be limited to, flows that more closely mimic the natural hydrographic conditions to which native fish species are adapted, including the relative magnitude, duration, timing, quality and spatial extent of flows as they would naturally occur. Indicators of native fish species viability include population abundance, spatial extent, distribution, productivity and genetic and life history diversity. Viability is dependent on maintaining migratory pathways, sufficient quantities of high quality spawning and rearing habitat, and a productive food web.*

Changes to the numeric interior Delta flow requirements would reasonably protect these beneficial uses and help to implement the narrative requirement. Numeric objectives would be consistent with requirements that are already included in the USFWS BiOp, NMFS BiOp, and DFW ITP including:

new Old and Middle reverse flow limitations and changes to export and DCC gate restrictions to expand the level of protection for those existing objectives. Similar to the existing process, the interior Delta flow requirements for Old and Middle River reverse flows, export limits, and DCC gate closures would be determined and based on monitoring of fish presence and a consultation process involving staff from the fisheries agencies, DWR, and Reclamation, with the addition of the State Water Board. 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.

5.6 Updates to the Program of Implementation

The State Water Board has authority to adopt statewide Water Quality Control Plans and adopts the Bay-Delta Plan because of its importance as a major source of water for the state. The State Water Board is the only state agency with authority to oversee and regulate water rights. Because California combines its water rights and water quality authorities (Wat. Code, § 174), the Bay-Delta Plan addresses water diversions and use in the water quality planning context, including the federal Clean Water Act and state Porter-Cologne Water Quality Control Act. When addressing water diversions and use, it is important to emphasize, however, that implementation of water quality objectives is pursuant to the State Water Board's water quality and water rights authorities under state law. There are a variety of water right and water quality authorities that the State Water Board may utilize to implement new and revised objectives and the State Water Board has discretion in how it chooses to implement the objectives in accordance with state law. (See, Wat. Code, § 13242 [program to achieve objectives shall include a description of the nature of the actions necessary to achieve objectives, including recommendations for appropriate action by any entity, public or private, a time schedule for actions to be taken, and monitoring to determine compliance].)

The program of implementation is still being developed as the planning process moves forward in order to allow input from other agencies, stakeholders and the public and therefore precise Bay-Delta Plan language is not provided at this time. The proposed program of implementation would include early implementation measures, including the submittal of tributary plans by potentially responsible parties. As discussed above, the tributary plans would include a flow element and cold water management and drought planning and response elements, monitoring and reporting elements, among others. In each tributary, adaptive management of the percent of unimpaired flows could allow flows to be sculpted in order to improve their functionality and provide the greatest benefits to native fish and wildlife, as well as allow for changes in flows within a range in response to changed information or conditions.

The proposed program of implementation would also include measures to ensure that water bypassed or released to meet water quality objectives is protected and actions to ensure that tributaries with flow levels that are already protective are not degraded, including updating the FAS list as appropriate and other actions.

The State Water Board recognizes that voluntary agreements can help inform and expedite implementation of flow objectives and can provide durable solutions in the Bay-Delta watershed. The tributary plan framework provides a regulatory mechanism for accepting local voluntary agreements that meet the tributary inflow narrative objective and may include alternative methods for enhancing protection for native fish and wildlife. The State Water Board encourages all stakeholders to work together to reach early voluntary agreements that may also help inform and accelerate Bay-Delta planning and implementation actions. The program of implementation could provide a schedule for stakeholders to submit implementation agreements for State Water Board review. When considering whether to approve an agreement to implement the Bay-Delta Plan, the State Water Board must satisfy its independent statutory and constitutional obligations.

Implementation of the inflow-based Delta Outflow objective would correlate to the development, approval, and implementation of tributary plans. Like the inflow requirements, the inflow-based Delta outflow requirements would allow sculpting of flows and would require the development of implementation measures for adaptive management, likely in coordination with the Projects and other in-Delta users. Delta outflow implementation measures would include monitoring, evaluation and reporting provisions, development of biological goals, and provisions for coordination with inflows. The implementation measures would address accounting methods for the existing and new requirements, including integration with tributary plans, calculation of accretions and depletions, and evaluation of the existing and new methods of compliance with Delta outflows to ensure they are protective. In addition, the program of implementation would provide flexibility to allow for continual improvements, including of NDOI calculations, salinity monitoring, and coordination with the USFWS BiOp processes for fall outflows.

The proposed program of implementation would also include monitoring and special studies necessary to fill information needs and determine the effectiveness of, and compliance with, the new requirements. The State Water Board has identified four primary goals for near and long-term monitoring in the Delta in order to: (1) evaluate compliance with specific implementation provisions by responsible parties pursuant to water right conditions, other orders and/or regulations; (2) evaluate the effectiveness of management measures, management modifications, and remediation efforts aimed at meeting water quality objectives and improving conditions for beneficial uses; (3) track whether conditions are trending toward numeric targets, water quality objectives, and beneficial use support; and (4) inform when and how to reevaluate the objectives and program of implementation.

A combination of monitoring and assessment is necessary to achieve these goals. It is anticipated that tributary plans will include a monitoring and reporting element that 1) documents whether provisions are implemented as proposed, and 2) evaluates the effectiveness of the provisions, to the extent possible. Tributary groups will be encouraged to provide reach-scale targets defining channel and habitat conditions in order to gauge progress toward meeting objectives. Tributary plans that contain restoration elements and other nonflow measures designed to complement flows must include effectiveness monitoring to assess which techniques yield the greatest benefits. Finally, monitoring and special studies may be recommended as necessary to address the resource protection goals and answer specific questions. State Water Board staff will report to the State Water Board annually on the status and progress of implementation activities. The State Water Board staff will also conduct formal assessments of the effectiveness of implementation measures on a regular basis and pursue any necessary revisions using monitoring and reporting data, other studies and any other available data, as appropriate. During reassessment, the State Water Board will consider how effective the requirements of the program of implementation are at achieving water quality objectives, and protecting the beneficial uses of water in the Bay-Delta and watersheds based on biological, water quality and other appropriate trends in the Delta and its tributaries. Ultimately, success is achieved when beneficial uses are supported.

Finally, the program of implementation will identify actions other entities should take that would contribute to achieving the overall goal of improving conditions for native fish and wildlife. The program of implementation will include recommendations for non-flow measures that are complementary to the revised objectives and that are expected to improve habitat conditions or improve related science and management within the Bay-Delta watershed.

The program of implementation will provide for active monitoring and reporting, adaptive management, and State Water Board update and review in specified time periods. The Phase II Plan Update is structured to provide for timely action, flexibility, and coordination with other planning, regulatory, and restoration efforts. This includes the integration of needed flow and nonflow actions to the extent possible, and science, monitoring, and evaluation activities. New requirements include adaptive management provisions to respond to new and changing information over the long term and in real time.

The State Water Board will collaborate and coordinate with other science efforts including the DPIIC, IEP, the CSAMP, and other groups and programs. There are various activities that are underway or currently being planned or implemented by other agencies in coordination with efforts such as: the California Water Action Plan; species recovery planning required by federal and state endangered species acts; California EcoRestore; projects financed under the Water Quality, Supply, and Infrastructure Improvement Act; and, other projects and programs. Many of these activities are expected to complement the State Water Board's water quality control planning and implementation efforts and could inform adaptive management decisions regarding needed flows and operational measures.

Chapter 6
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Appendix A
Modeling Approaches Used to Develop Unimpaired Watershed Hydrology

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 estimate represents something different than the "natural flow" that would have occurred absent human land use and infrastructure for water supply and flood control.

Previous work on unimpaired flows in the Sacramento watershed has been completed by the California Department of Water Resources' (DWR's) Division of Flood Management and Bay-Delta Office to provide estimates throughout the Central Valley. DWR's unimpaired flow estimates also termed "full natural flow" are produced by removing the effect of reservoir storage, water transfers, and diversions from historical observed flows. Land use, levees, flood bypasses, and weirs are all assumed to exist as they do now (DWR 2007, 2016a). DWR's Bay-Delta Office has produced unimpaired estimates for 24 locations in the Central Valley for October 1921 through September 2014 on a monthly basis (DWR 2016a). DWR's Division of Flood Management produces estimates of "full natural flow" on a monthly basis for 36 locations around the state and on a daily basis for 19 locations. These estimates are used 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. 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 do not explicitly account for any stream-groundwater interaction and take a simplified approach to estimating surface runoff from ungaged streams (DWR 2007, 2016a).

The methods used by 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. 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 confluences, and it is very difficult to estimate stream gains and losses to groundwater.

DWR's Bay-Delta Office has recently published estimates of the "natural flow" that would have resulted if the precipitation and valley floor inflow hydrology of the water year 1922–2014 record had occurred in a natural landscape, unaltered by humans (DWR 2016a). This involves making assumptions about pre-development groundwater accretions, distribution and evapotranspiration of wetland and riparian vegetation, channel configurations, and detention of overbank flows, all of which differ from the current physical condition and land use of the watershed (DWR 2016a).

The study described here was undertaken to better estimate unimpaired flows at the confluences of the tributaries in the Sacramento River watershed, at locations on the mainstem Sacramento River, and at the mouths of the Delta eastside tributaries. Unimpaired flows were estimated with the Sacramento Water Allocation Model (SacWAM) utilizing the "unimpaired" mode. This appendix describes the model assumptions and provides detailed unimpaired modeling results.

A.2 Methods

SacWAM version 1.05, which assumes existing conditions, was modified as described in A.2.1 – A.2.5 to generate estimates of unimpaired flow. A full description of model assumptions can be found in the SacWAM Model Documentation (State Water Board 2017).

Methods used to estimate unimpaired flows in the previous draft Phase II Update of the 2006 Bay-Delta Plan Scientific Basis Report have been overhauled based on comments received and newly available models; however, the basic monthly mass balance approach remains. The improvements include further development of upper watershed unimpaired inflows, improved estimates of stream gains/loss to groundwater, dynamic calculation of valley floor rainfall runoff, and the use of SacWAM for network calculations.

The upper watershed unimpaired rim inflows account for the largest component of the unimpaired flows at the tributary confluences. These flows developed by DWR and their consultants have been extended through 2015 and have been further refined since the previous draft. These methods are described in Chapter 6 of the SacWAM Documentation (State Water Board 2017).

The stream gains/losses have been updated to include a dynamic calculation based on streamflow and season. Previously the stream gain/loss was estimated as a preprocessed time series based on results from a C2VSIM "current conditions" run. SacWAM uses relationships of stream gains/losses to streamflow which are based on a C2VSIM "current conditions" simulation (State Water Board 2017). The updated method results in greater seasonal variation in stream gains and losses and a slight overall reduction in losses across the entire valley. These methods are described in Chapter 6 of the SacWAM Documentation (State Water Board 2017).

Surface runoff estimated by SacWAM is dynamically calculated based on climate conditions, vegetation, and soil moisture, whereas previous estimates used in the unimpaired flow calculations were preprocessed based on results from CalSim Hydro. In the unimpaired simulation in SacWAM, the surface runoff is lower than in the current conditions. During summer months, this is due to the reduction in applied water because no water is being diverted from the rivers and streams and groundwater pumping has been limited to the existing conditions scenario. During winter months, in the unimpaired scenario, more rainfall infiltrates into the ground due to the drier soil conditions at the end of the growing season. This is the result of drier soil due to less water being applied to the fields because no water is being diverted from the rivers and streams. In the unimpaired scenario, more rainfall is applied to the soil moisture deficit than in the existing conditions simulation resulting in less runoff to the rivers. Previous estimates did not account for changes in soil moisture and, therefore, likely overestimated surface runoff. Additionally, previous estimates did not account for runoff covering a large ungaged area surrounding the Delta. Runoff from this region is now included in the estimates of Delta inflow using SacWAM.

A.2.1 SacWAM "Key Assumptions"

The "key assumptions" in SacWAM are settings that the user can easily modify to change the type of hydrologic simulation. More detail about "key assumptions" can be found in Chapter 9 of the SacWAM Documentation (State Water Board 2017). To simulate unimpaired flows, the two changes to "key assumptions" were to turn off operations, and to limit groundwater pumping.

A.2.1.1 Turn off Simulation of Operations

The "key assumption" called "simulate operations" was set to 0 for the unimpaired simulation. By turning off operations, SacWAM does not allow any diversions to occur or any storage in reservoirs with two exceptions. These exceptions include storage in Clear Lake, discussed below in Section A.2.3, and diversions to some Delta islands, discussed below in Section A.2.4. By setting the simulate operations switch to 0, unimpaired San Joaquin inflows at Vernalis are assumed by default. More details about unimpaired San Joaquin flows are discussed in Section A.2.5.

A.2.1.2 Limits on Groundwater Pumping

The "key assumption" called "Constrain GW Pumping" limits the maximum flow through each transmission link from a groundwater source to a demand site. The maximum limit can be set by the user as a time series for each transmission link defined in a comma separated value (csv) input file. For this unimpaired flow study, the maximum groundwater pumping for each transmission link was set equal to the result from the Existing Conditions simulation. This ensured that groundwater pumping would not increase in response to a reduced surface water supply. The only effect this assumption has on stream flow is to prevent the relatively small amount of return flows associated with groundwater pumping from increasing.

A.2.2 SacWAM User Defined Linear Programming Constraints

The user defined linear programing constraints (UDCs) in SacWAM are hard constraints primarily used to simulate operational logic such as the Coordinated Operations Agreement and Old and Middle River reverse flows. For the unimpaired flow simulation, all of the UDCs are turned off except for the flow splits at the all of the weirs, Knights Landing Ridge Cut, and Georgiana Slough.

A.2.3 Clear Lake Evaporation

Clear Lake on Cache Creek is a large, natural, shallow lake that has relatively high evaporative losses when compared to the mean annual inflow to the stream. Because Clear Lake is a natural lake with very little control on the reservoir elevation, minimal storage in this lake has been included in the unimpaired flow simulation. Initial storage, top of conservation, and top of inactive were all assumed to be 840 thousand acre-feet (TAF), which is the minimum operable level of storage in the existing conditions simulation. This constraint on Clear Lake will not allow storage to increase above 840 TAF but it will allow evaporation to reduce storage below 840 TAF. During dry periods when Clear Lake storage is reduced below 840 TAF, no water leaves the lake until storage has increased to 840 TAF.

A.2.4 Delta Depletions

Many Delta islands are below sea level, causing seepage from Delta channels into the islands. In these areas, water is continuously pumped out of the islands even when diversions are not occurring. Even with unimpaired conditions, seepage water would be available for consumptive use by vegetation. To account for depletions in areas below sea level, some Delta diversions were included in the unimpaired simulation. Figure A-1 shows the percentages of each Delta demand unit that is below sea level. These percentages were applied to each month of the preprocessed Delta Depletion time series, resulting in a total annual average Delta depletion of 31 percent of existing conditions.

A.2.5 Unimpaired San Joaquin Inflow at Vernalis

Assumptions for unimpaired inflow from the San Joaquin River came from DWR unimpaired flow report 4th Edition and expanded to 2015 (DWR 2007, 2016a). The San Joaquin Valley unimpaired runoff estimate using these methods suffers from the issues similar to those discussed above for 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.2.6 Additional Model Assumptions

Land use was assumed to be the same as under existing conditions. Because there are no surface water diversions in the unimpaired flow simulation and groundwater pumping is not assumed to increase, the crop demand for water may not always be met.

Stream-groundwater interaction is a dynamic calculation based on streamflow and season; therefore, the stream gains/losses associated with the unimpaired simulation differ from those associated with existing conditions. For example, losses to groundwater are generally higher in the spring in the unimpaired flow simulation due to higher flows.

A.2.7 Model Limitations

There are currently no abstractions of water from streams due to riparian vegetation. Many river channels in the Sacramento Valley are lined with levees and rip rap to manage erosion and floods. This flood development reduces the riparian vegetation demands; however, there are many channels in the Sacramento Valley where riparian vegetation could theoretically be reducing the streamflow, and these areas have not been explicitly considered in this study.

Consideration has been made to route surface runoff and return flows to the correct watershed as accurately as possible. This results in flow estimates being considered most accurate at the confluences of each tributary (locations listed below). Along each tributary, unimpaired flows may not be accurate due to the spatial resolution and the consolidated representation of small stream and surface runoff arcs.

SacWAM calculates unimpaired flows on a monthly time step which underestimates flood peaks and can overestimate flows in severely dry conditions by averaging flows over an entire month. This should be considered especially when examining the unimpaired flow results of flood bypasses and weir spills.

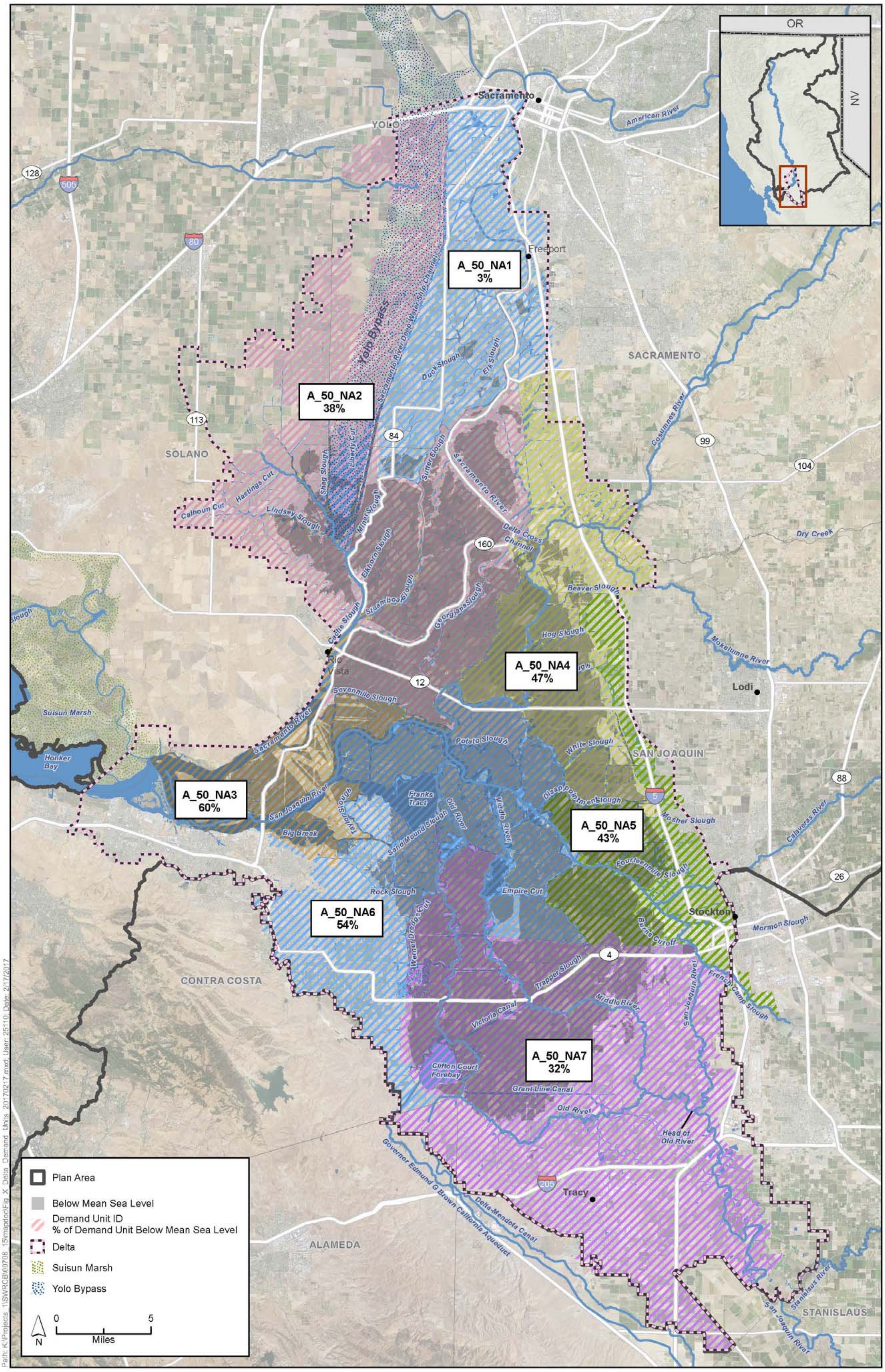


Figure A-1. Demand Units within the Delta

A.3 Results

The following bar charts show the monthly average unimpaired results by tributary broken up by flow component (Figures A-2 through A-27, presented in alphabetical order). The flow components include rim inflow, surface runoff, tributary inflow, accretions, depletions, evaporation, groundwater gain/loss, weir outflow, and outflow at tributary confluences. Table A-1 presents the annual average unimpaired results by water year type.

Figures for the Feather River, the Sacramento River at Freeport, and the Yolo Bypass (Figures A-16, A-22, and A-26, respectively) provide examples of how flow from multiple tributaries may contribute to unimpaired flows at some locations. Tributary inflow for the confluence of the Feather River shown in Figure A-16 comes from the Bear River (Figure A-5), Yuba River (Figure A-27), Honcut Creek, and Jack Slough. Tributary inflow for the Sacramento River at Freeport (Figure A-22) comes from all the upstream tributaries and includes outflow from the Sutter Bypass. “Inflows” (rim inflows) in this figure are the Lake Shasta rim inflows. The weir spills, such as to the Yolo Bypass, shown for the Sacramento River at Freeport (Figure A-22) are negative because they represent water that leaves the Sacramento River system upstream of Freeport and does not return until downstream of Freeport. Note that the Yolo Bypass flows shown in Figure A-22 are of smaller magnitude than the Yolo Bypass flows shown in Figure A-26 because the Yolo Bypass flows in Figure A-22 do not include water from Putah and Cache Creeks, whereas the Yolo Bypass flows shown in Figure A-26 include Putah and Cache Creeks. Urban return flows are minimal in the unimpaired scenario and have been included in the tributary inflow component.

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-2), the Feather River (Figure A-16), the Mokelumne River (Figure A-18), and the Yuba River (Figure A-27). 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-22). Almost all streams show substantially reduced unimpaired flow during July–October compared to other months. However, Battle Creek (Figure A-4) and Mill Creek (Figure A-17) show relatively high inflows during these dry months, which may indicate contribution from springs in the upper watershed.

The valley rim inflows are by far the largest contribution to the unimpaired tributary outflows; however, for some locations, surface runoff has a large influence on the unimpaired tributary outflow, such as Butte Creek (Figure A-7) and Natomas East Main Drain (Figure A-19). In the case of Natomas East Main Drain, most of its inflow comes from surface runoff.

Almost all tributaries have stream gains or losses. 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-15), Paynes Creek (Figure A-20), and Thomes Creek (Figure A-25).

For all watersheds represented in Figures A-2 through A-27 (Sacramento Valley and Delta eastside tributaries excluding the Delta), the total average annual rim inflow is approximately 22,800 TAF per year (TAF/yr), whereas the net stream-groundwater interaction (gain/loss) is an average net loss of approximately 880 TAF/yr (3percent of the rim inflow), and the surface rainfall runoff from the valley floor is approximately 1290 TAF/yr (5 percent of the rim inflow). There is very little change in unimpaired hydrology through the Delta, as shown in Figure A-28. Nearly all of the unimpaired Delta outflow originates from its tributary inflows and a relatively small amount comes from Delta accretions and is lost to depletions.

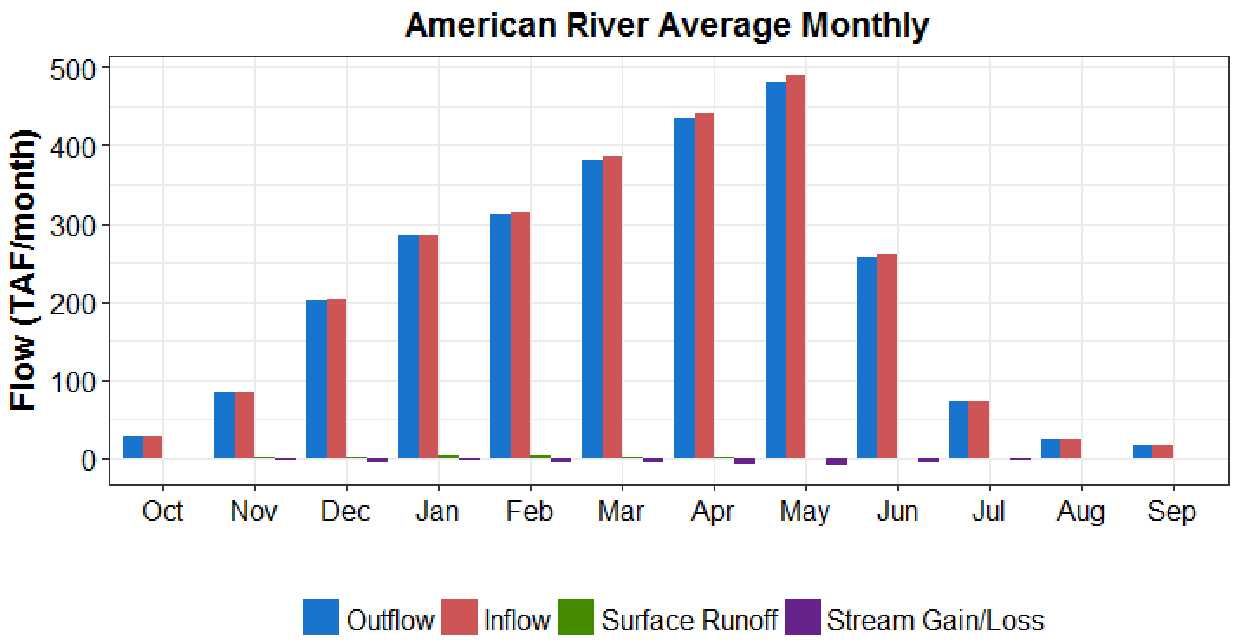


Figure A-2. Monthly Average Unimpaired Flow Components for the American River

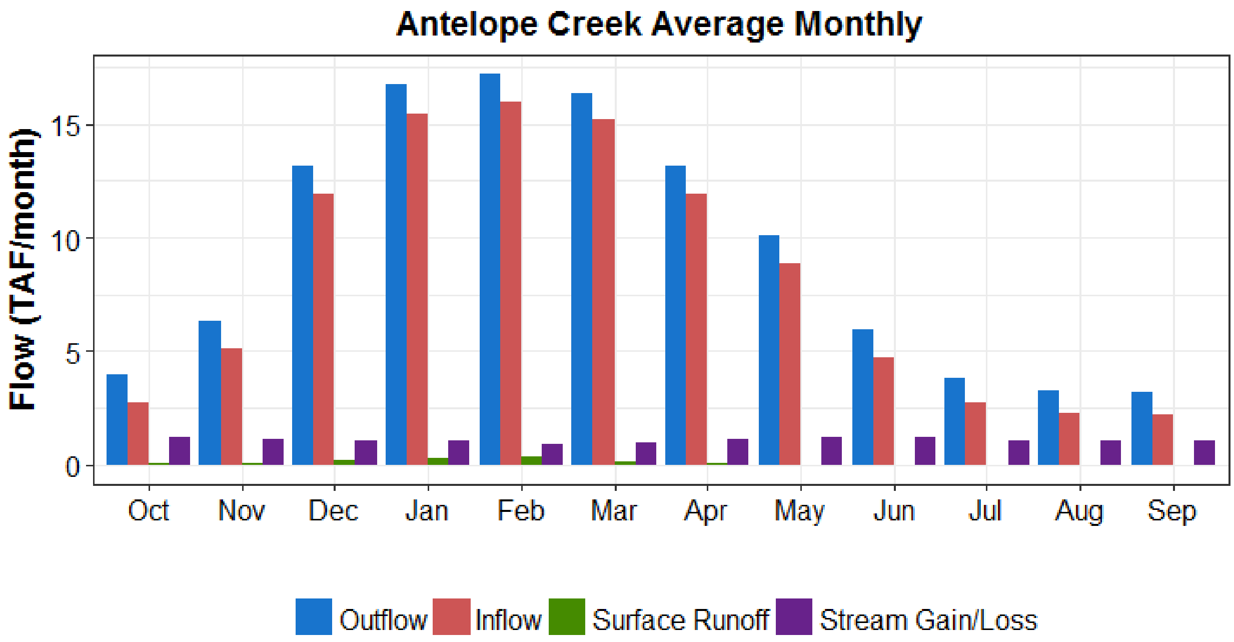


Figure A-3. Monthly Average Unimpaired Flow Components for Antelope Creek

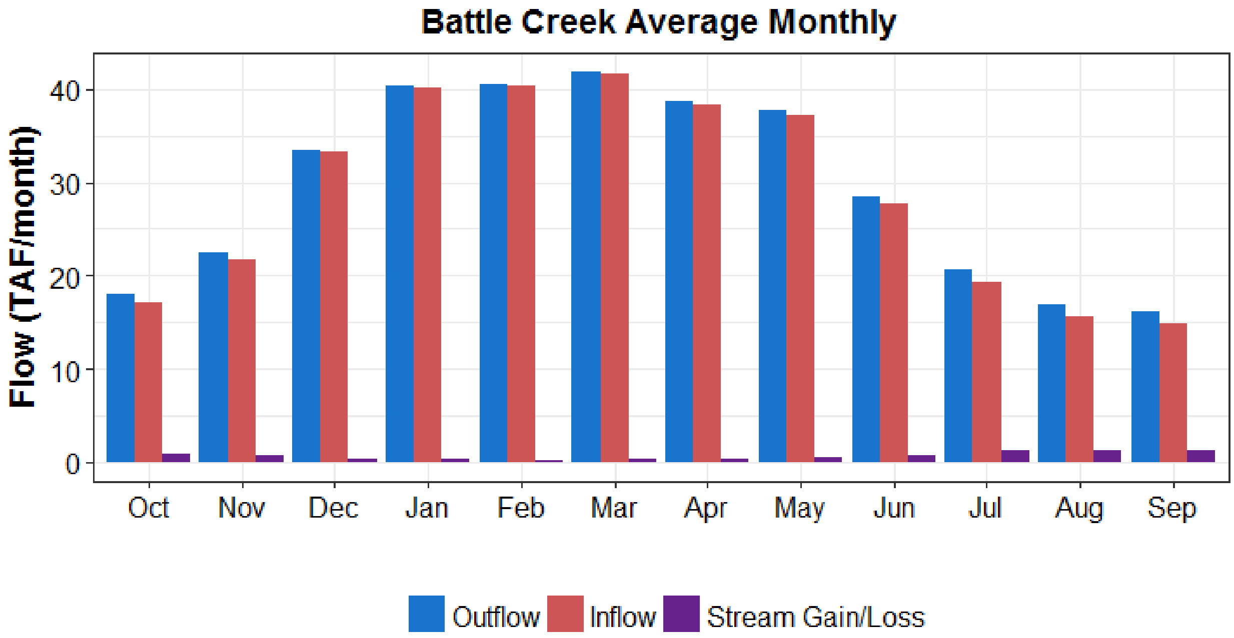


Figure A-4. Monthly Average Unimpaired Flow Components for Battle Creek

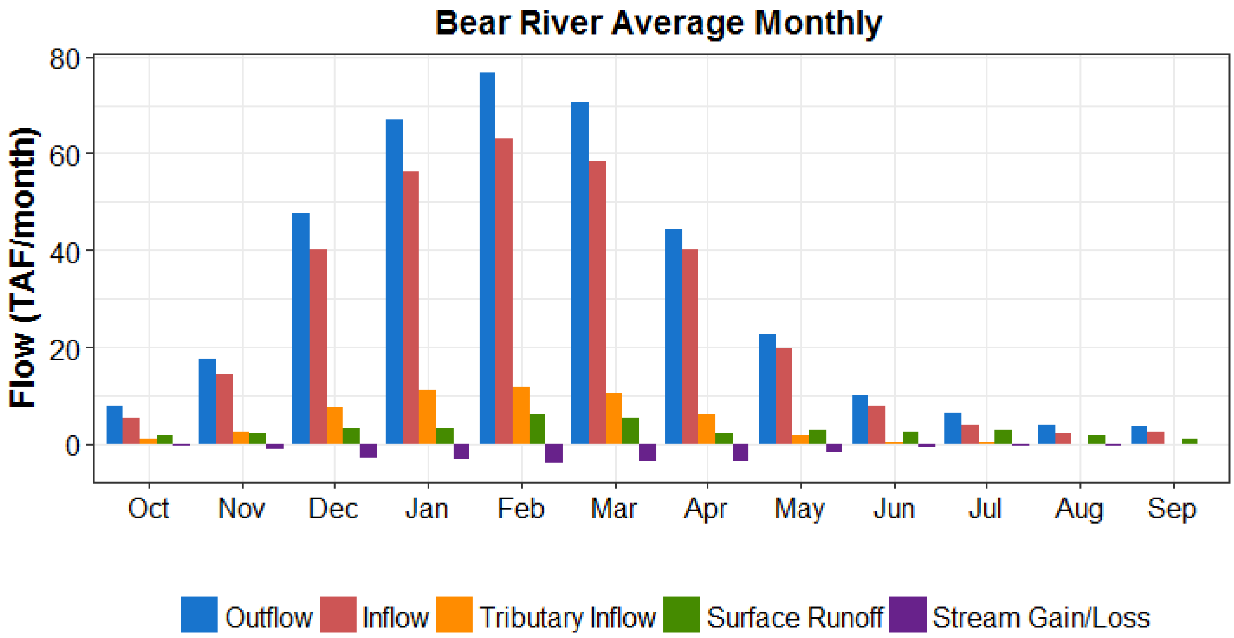


Figure A-5. Monthly Average Unimpaired Flow Components for Bear River

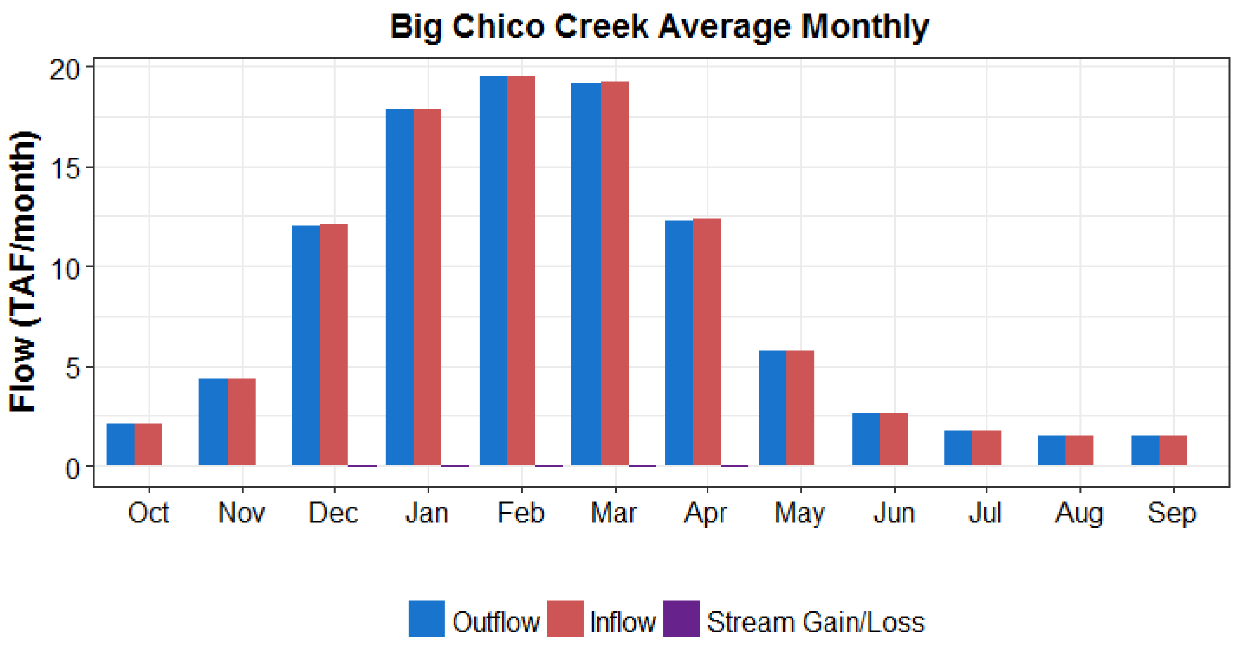


Figure A-6. Monthly Average Unimpaired Flow Components for Big Chico Creek

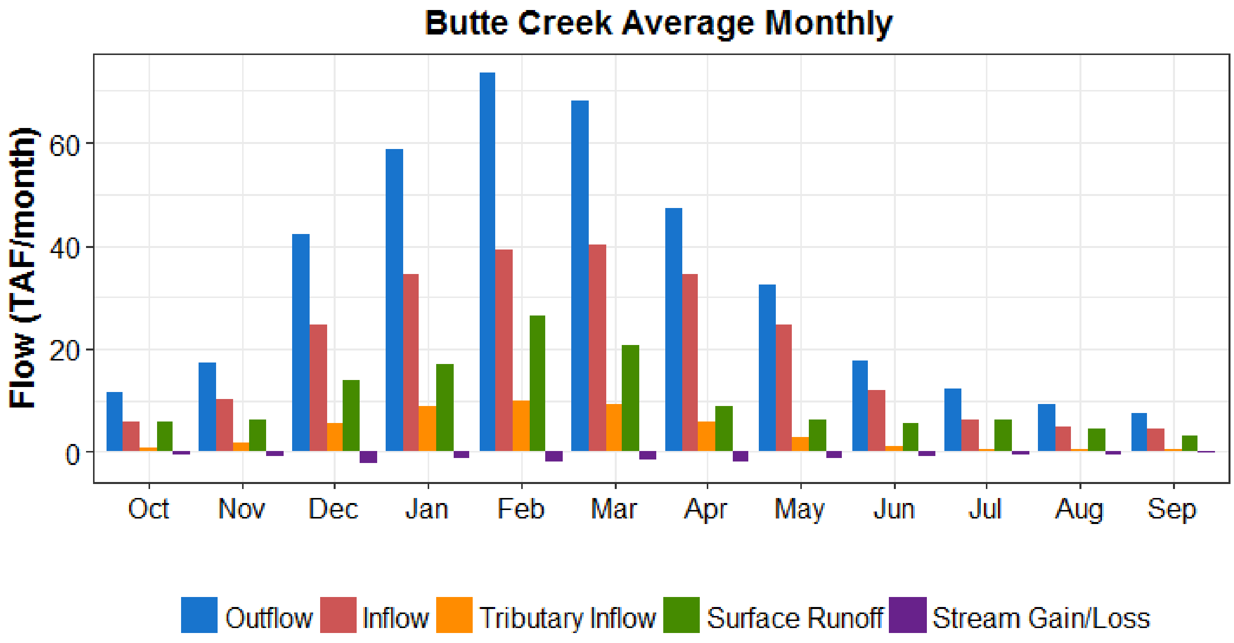


Figure A-7. Monthly Average Unimpaired Flow Components for Butte Creek

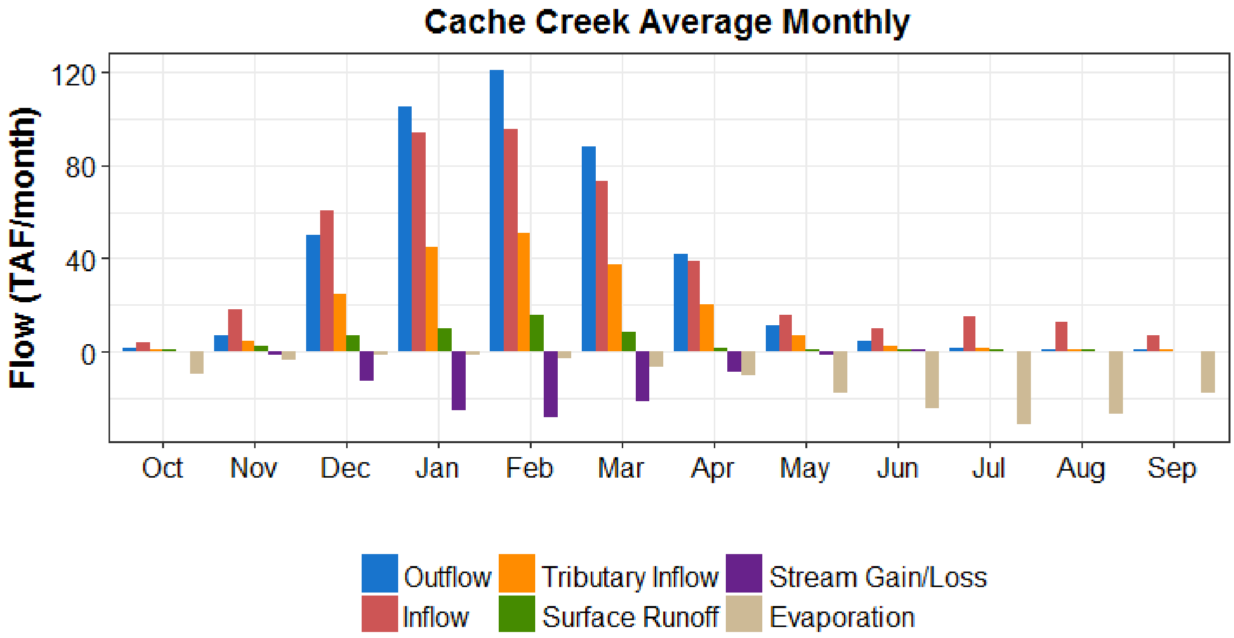


Figure A-8. Monthly Average Unimpaired Flow Components for Cache Creek

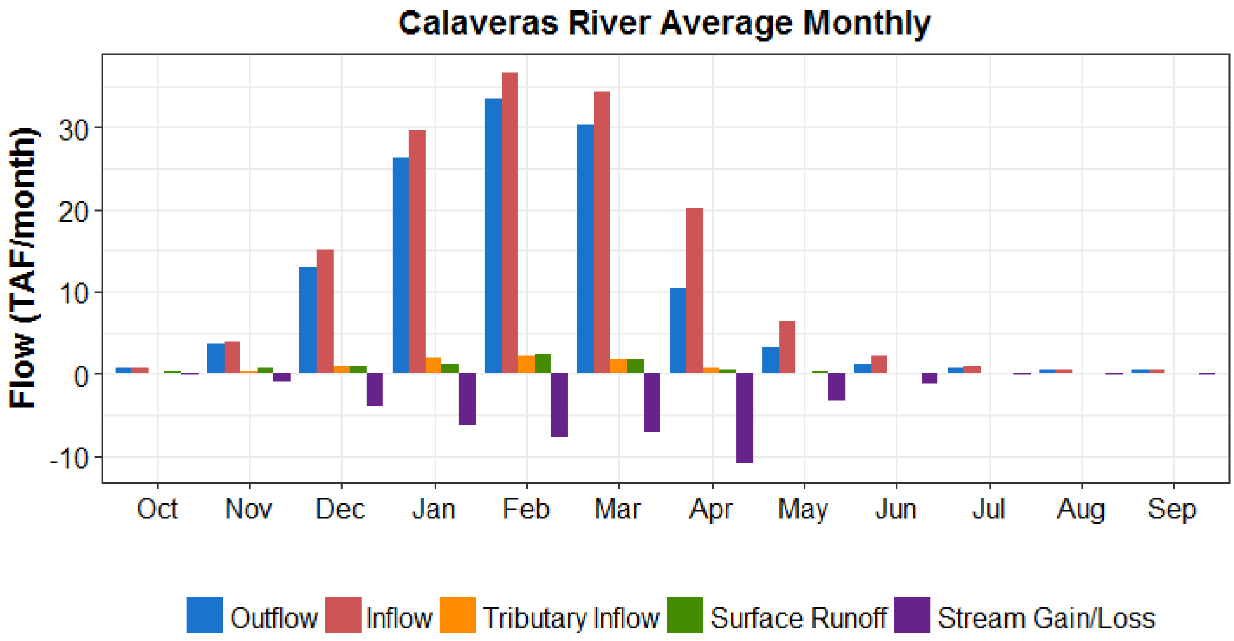


Figure A-9. Monthly Average Unimpaired Flow Components for Calaveras River

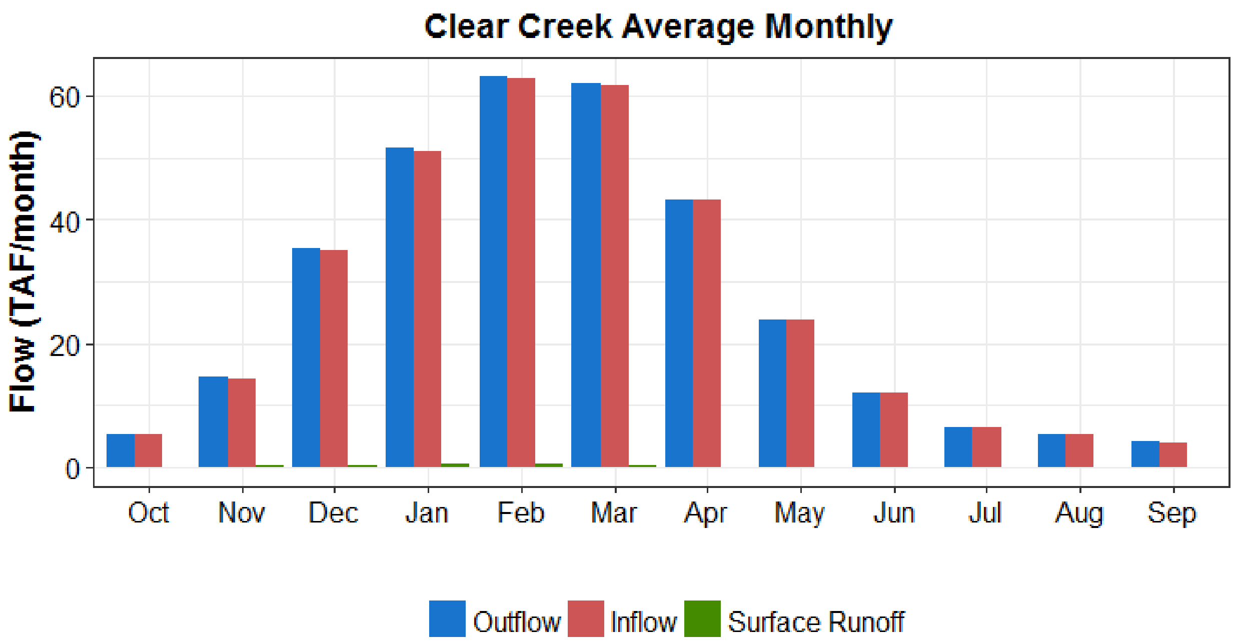


Figure A-10. Monthly Average Unimpaired Flow Components for Clear Creek

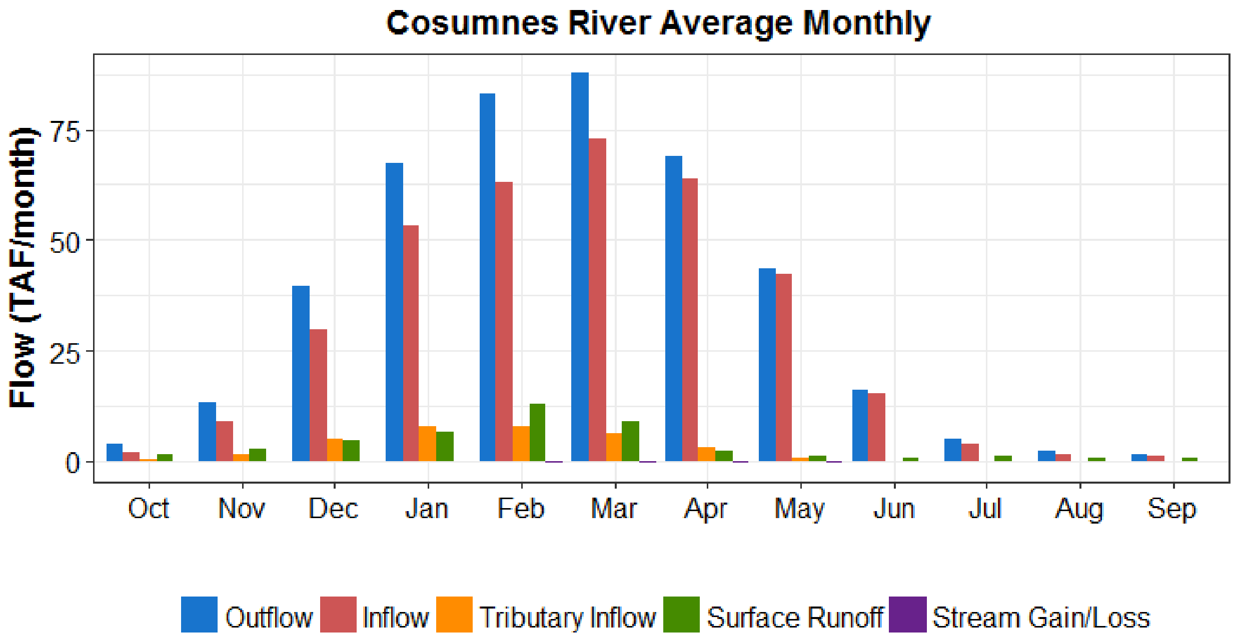


Figure A-11. Monthly Average Unimpaired Flow Components for Cosumnes River

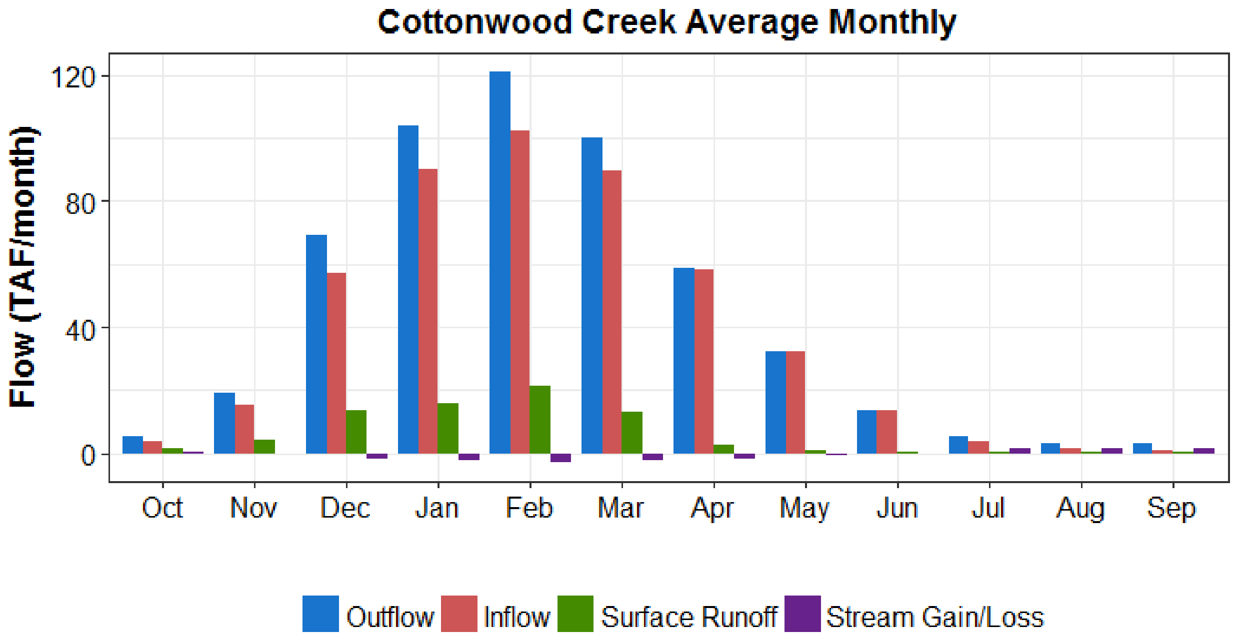


Figure A-12. Monthly Average Unimpaired Flow Components for Cottonwood Creek

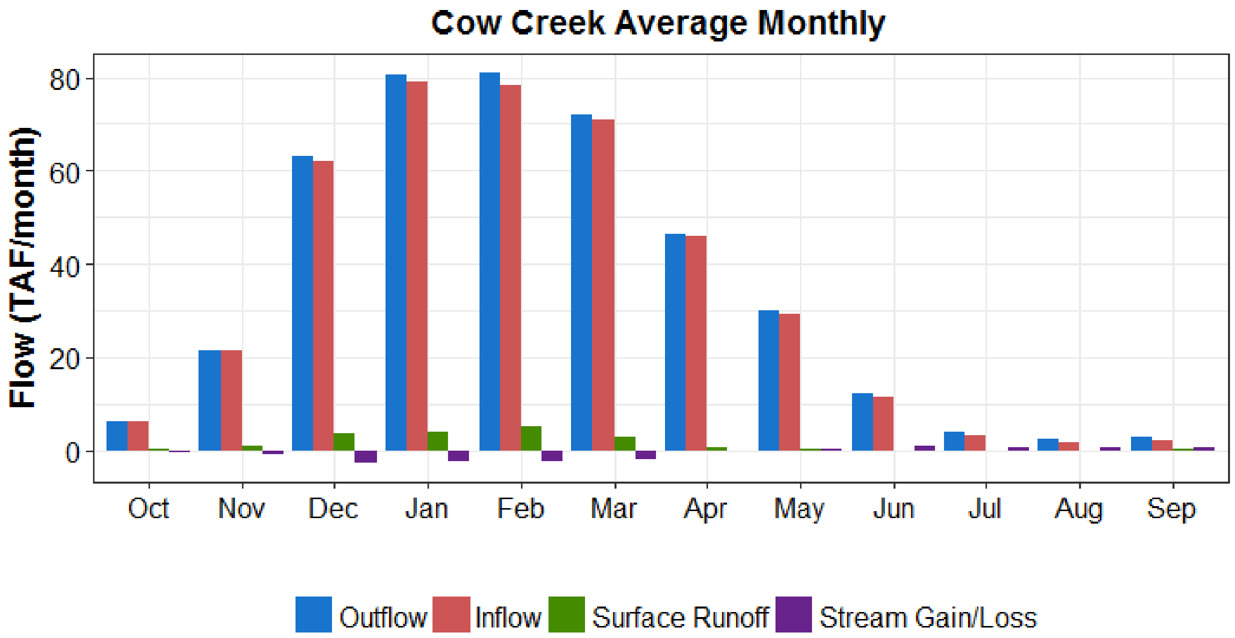


Figure A-13. Monthly Average Unimpaired Flow Components for Cow Creek

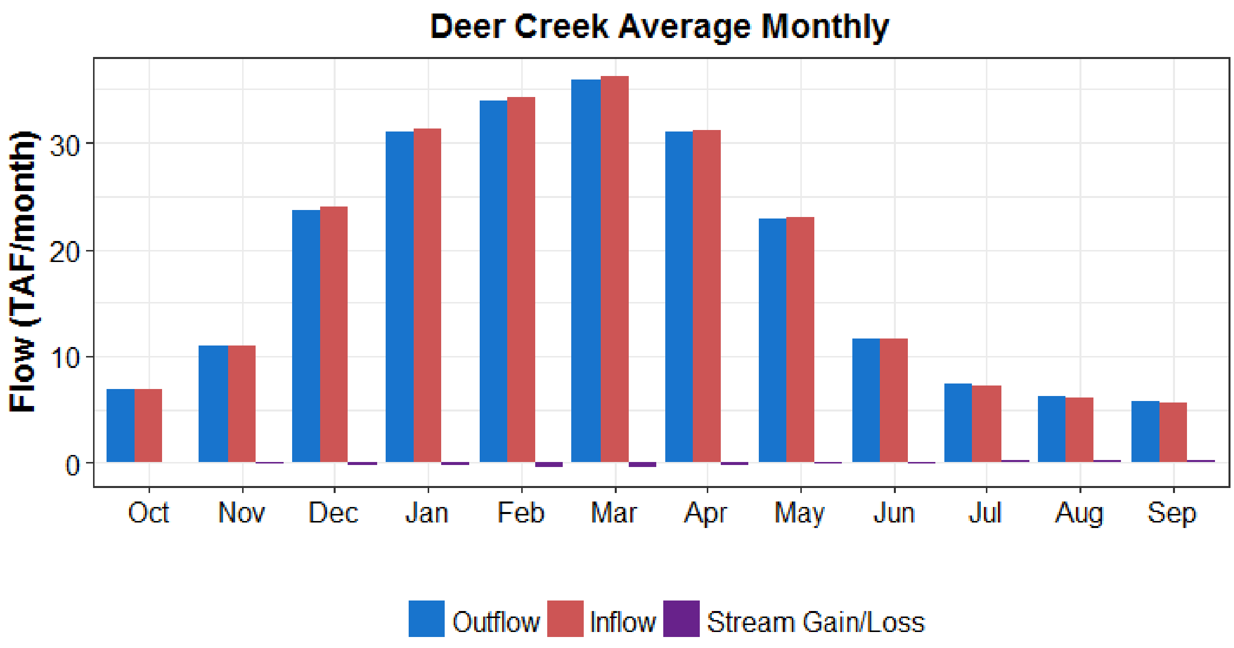


Figure A-14. Monthly Average Unimpaired Flow Components for Deer Creek

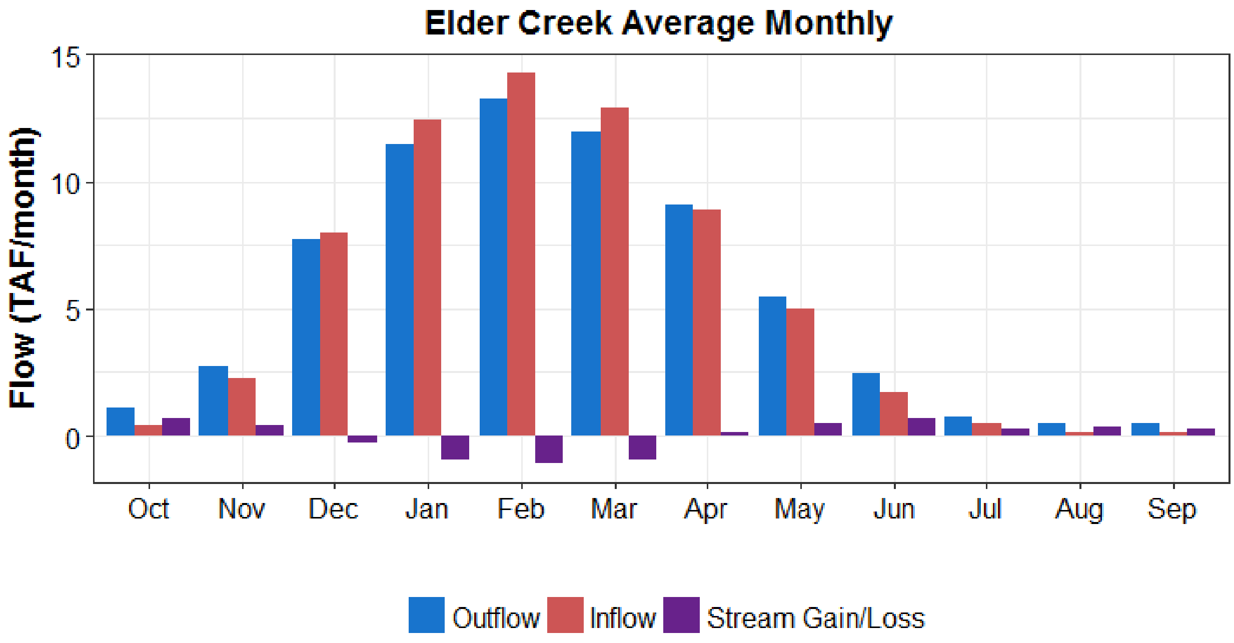


Figure A-15. Monthly Average Unimpaired Flow Components for Elder Creek

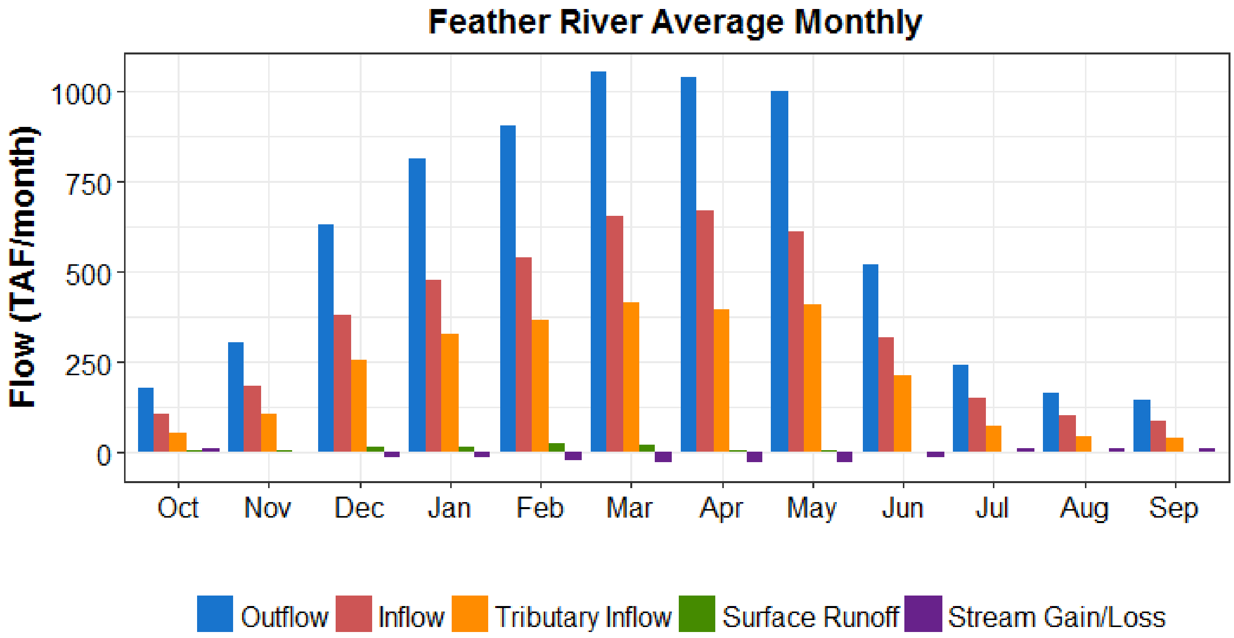


Figure A-16. Monthly Average Unimpaired Flow Components for Feather River

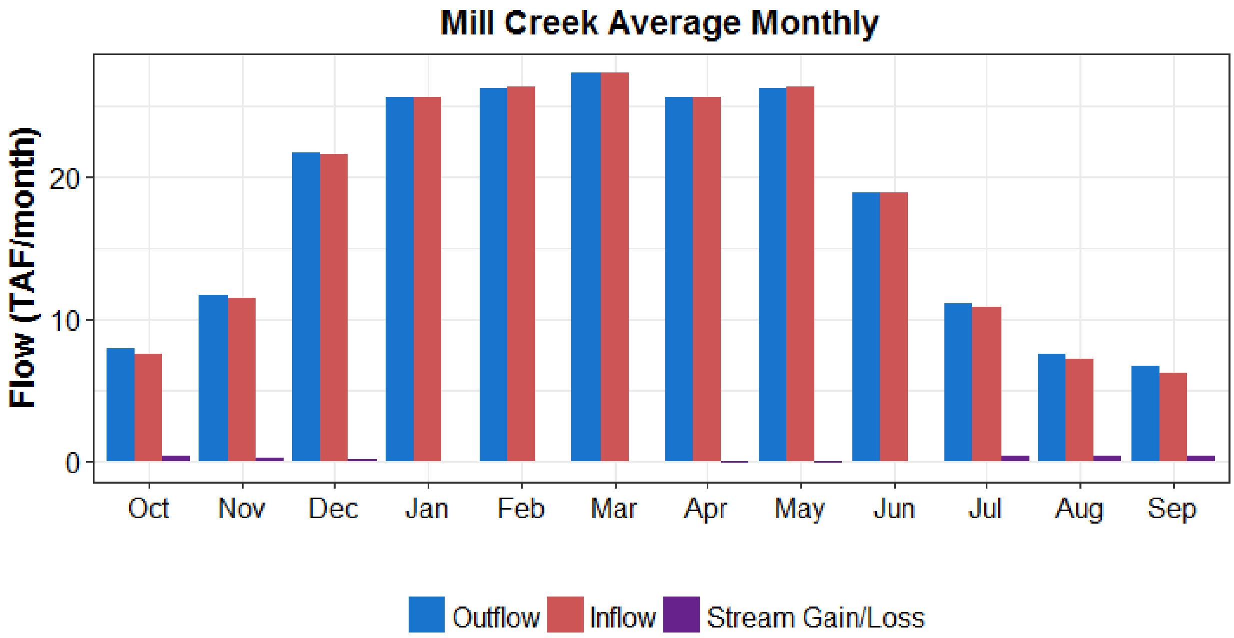


Figure A-17. Monthly Average Unimpaired Flow Components for Mill Creek

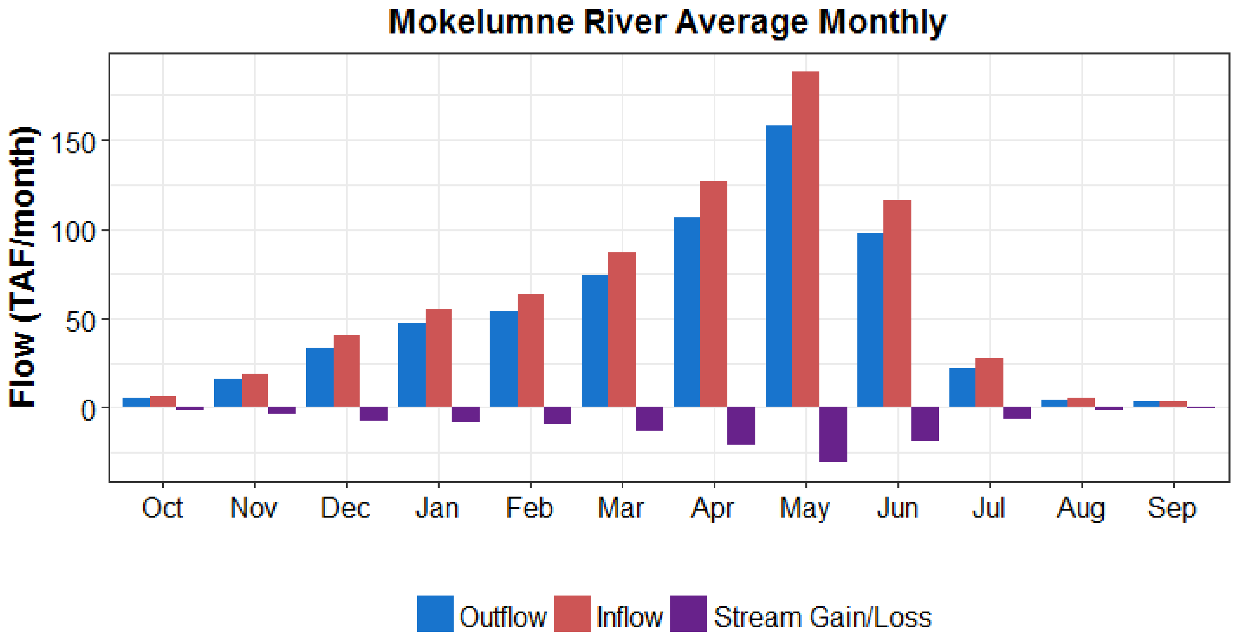


Figure A-18. Monthly Average Unimpaired Flow Components for Mokelumne River

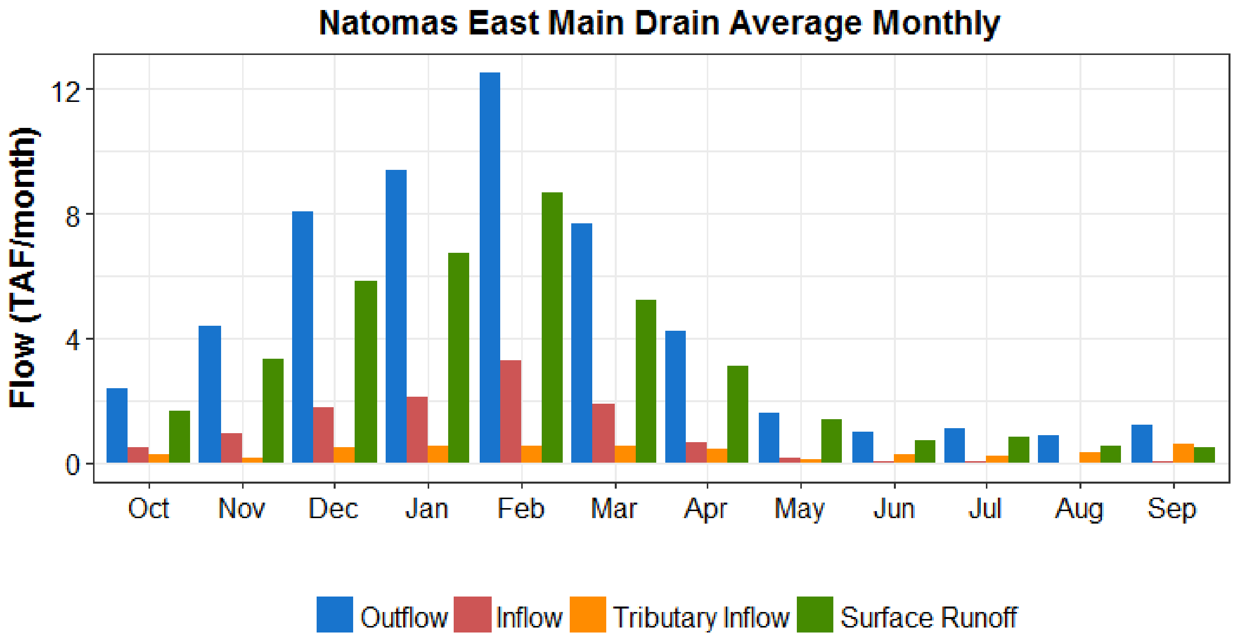


Figure A-19. Monthly Average Unimpaired Flow Components for Natomas Main Drain

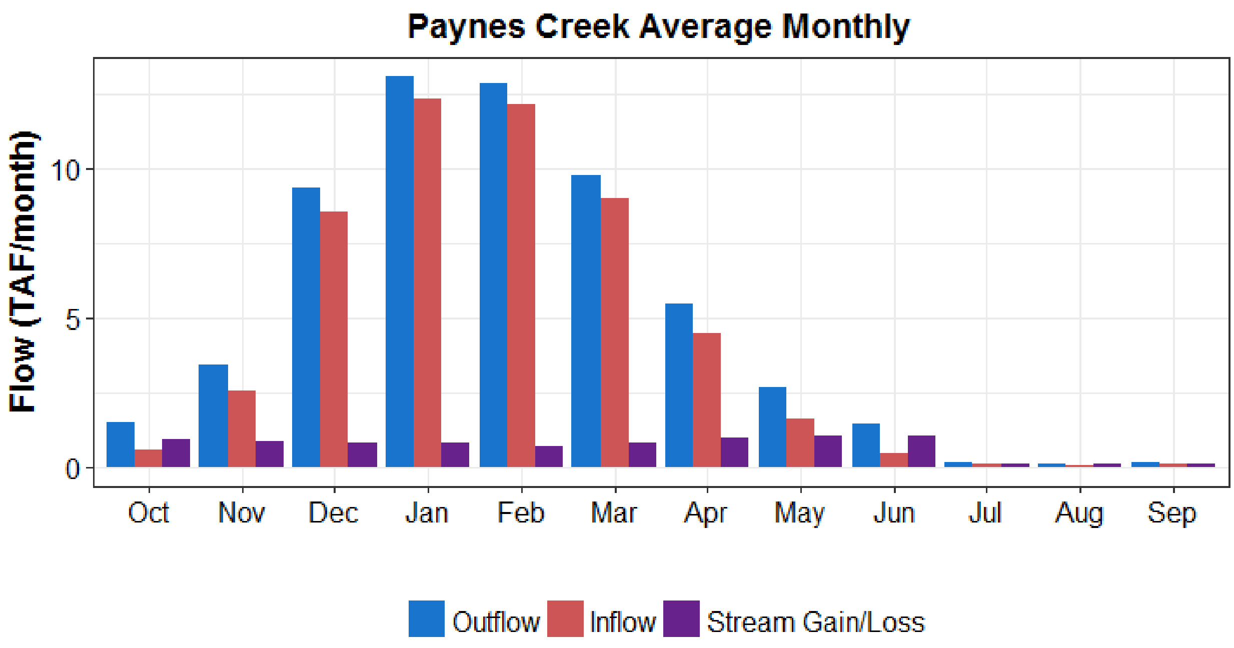


Figure A-20. Monthly Average Unimpaired Flow Components for Putah Creek

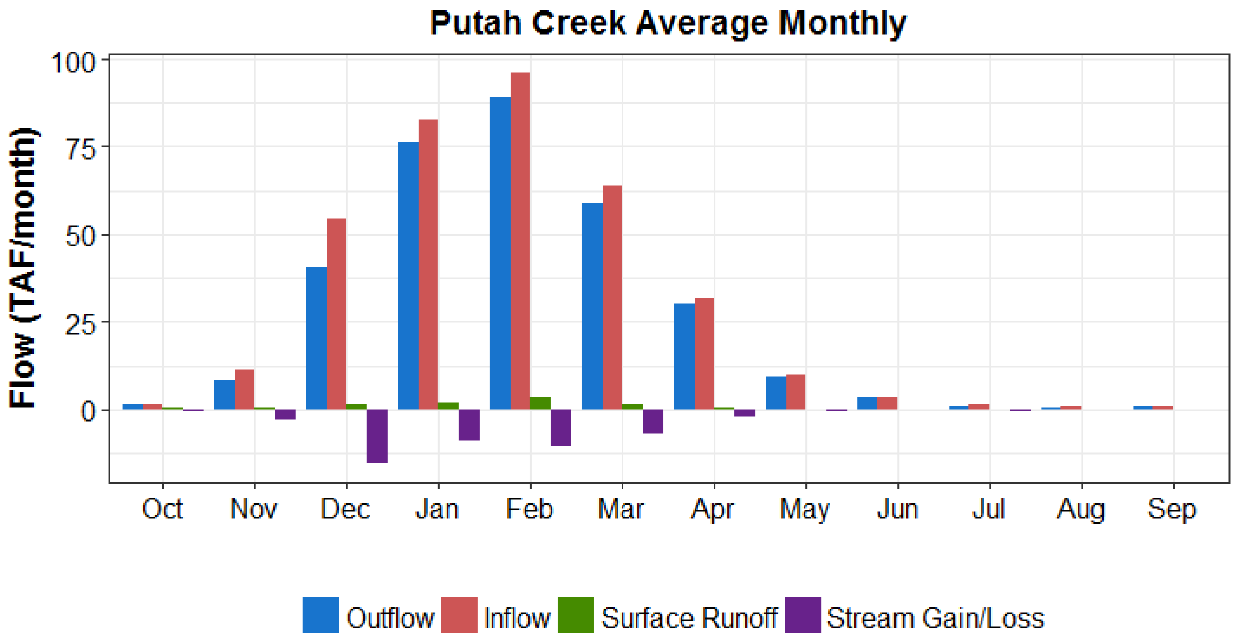


Figure A-21. Monthly Average Unimpaired Flow Components for Putah Creek

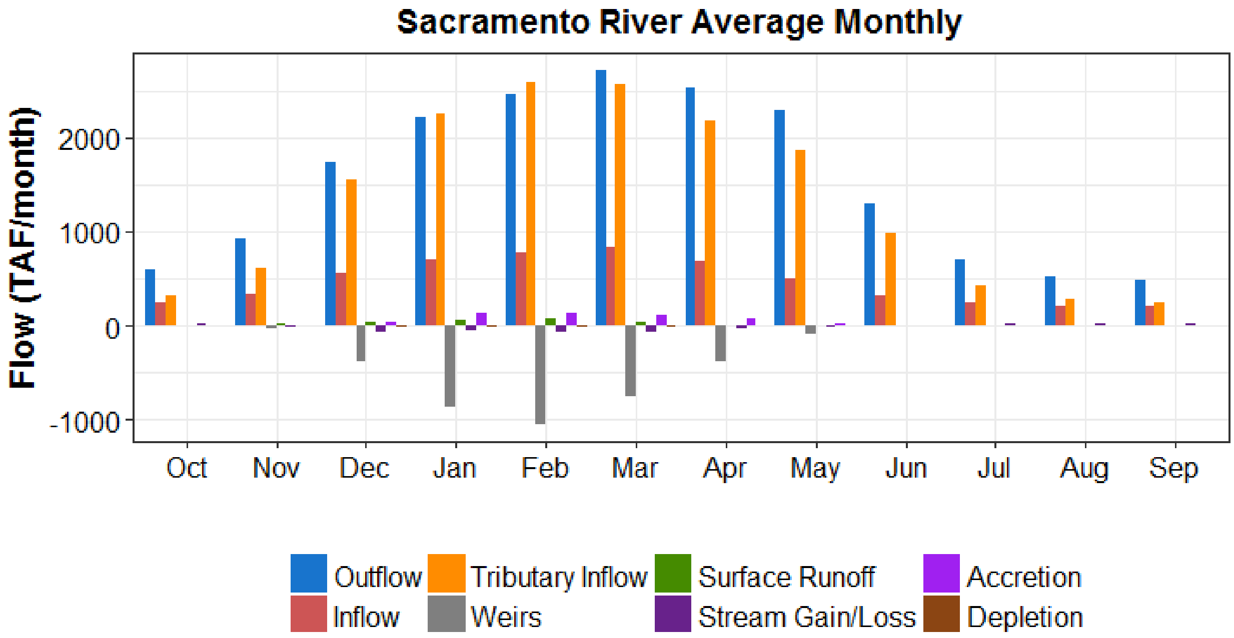


Figure A-22. Monthly Average Unimpaired Flow Components for Sacramento River

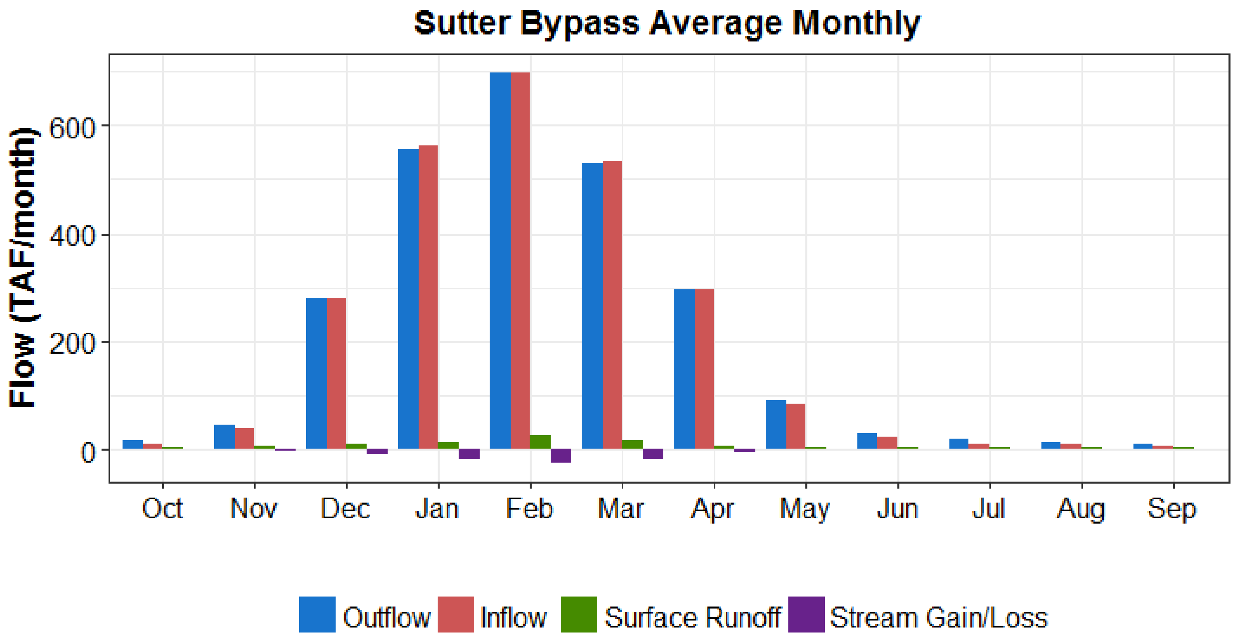


Figure A-23. Monthly Average Unimpaired Flow Components for Sutter Bypass

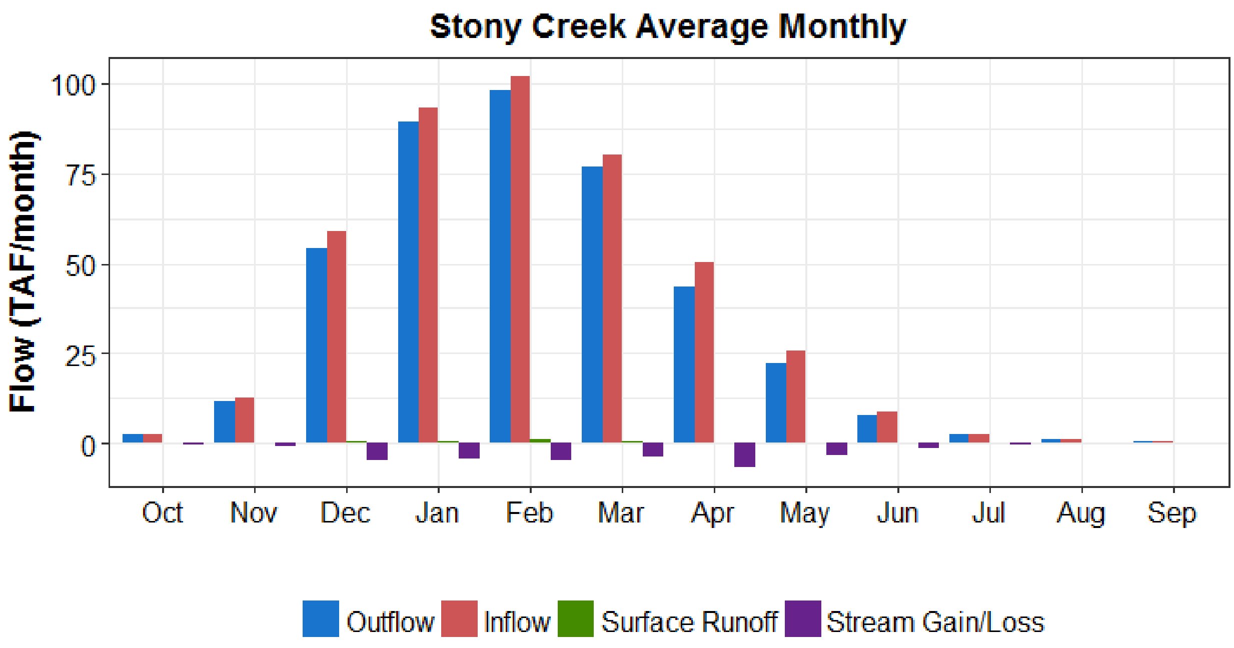


Figure A-24. Monthly Average Unimpaired Flow Components for Stony Creek

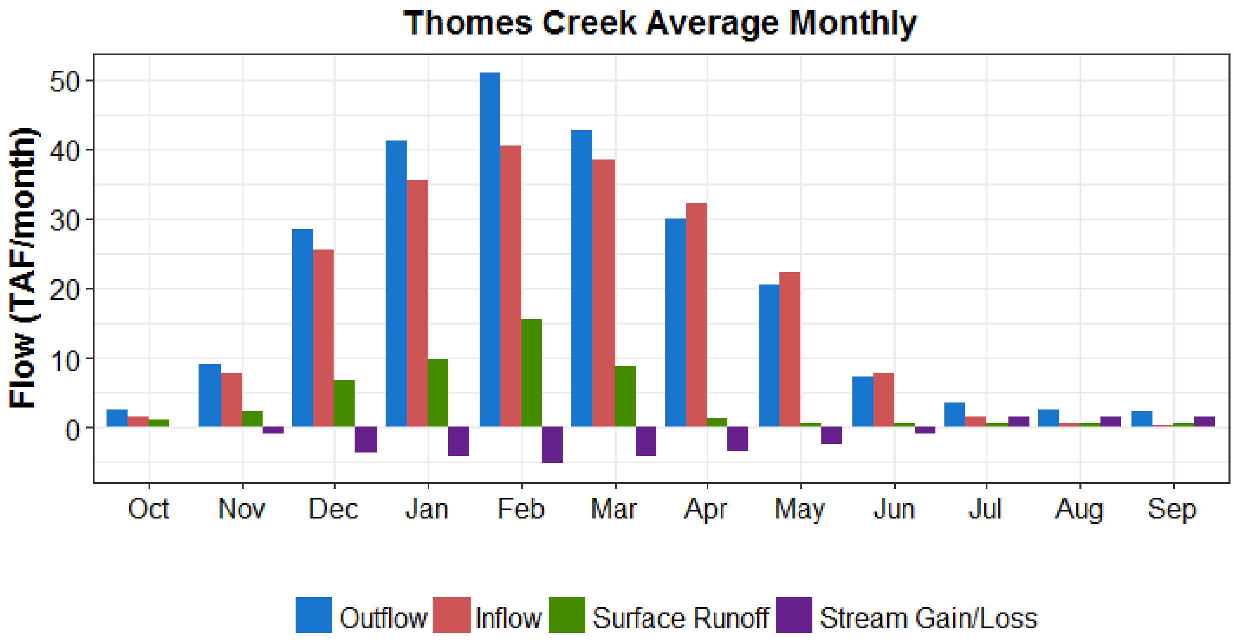


Figure A-25. Monthly Average Unimpaired Flow Components for Thomes Creek

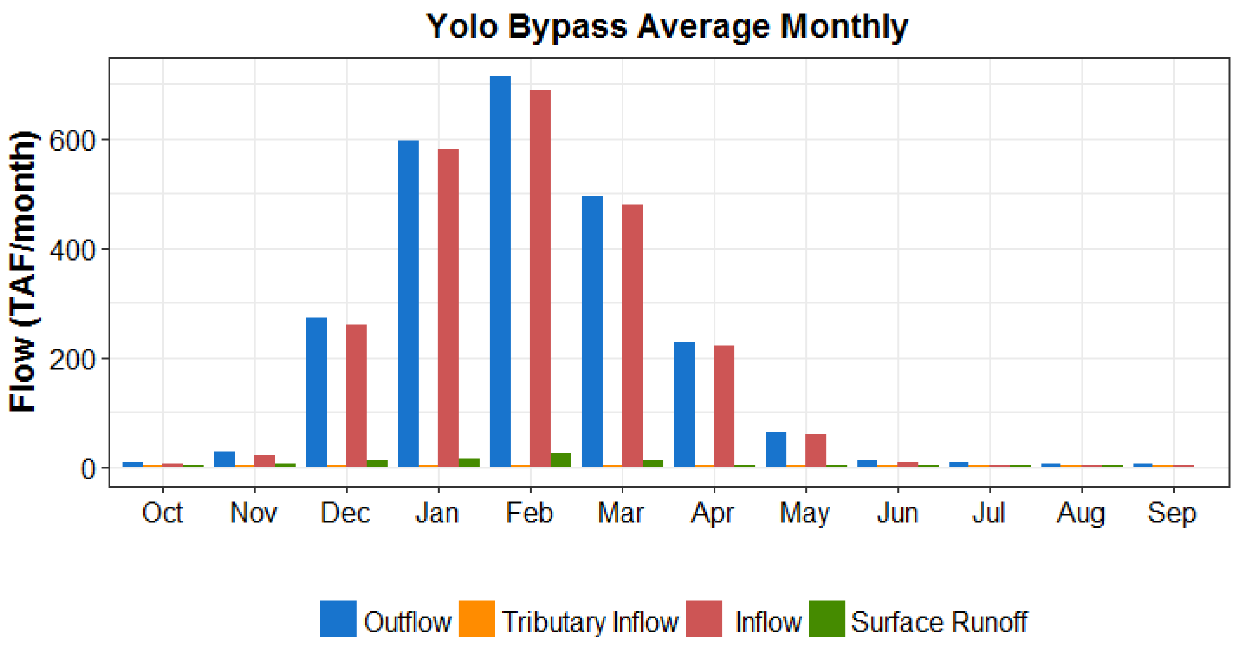


Figure A-26. Monthly Average Unimpaired Flow Components for Yolo Bypass

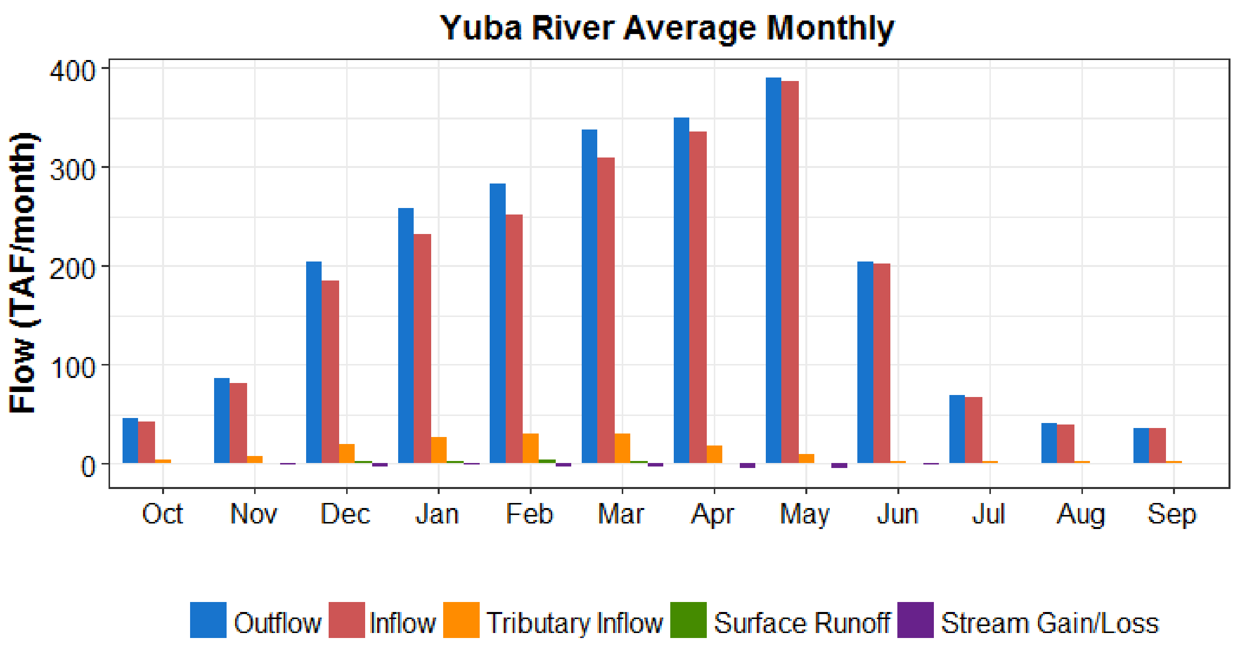
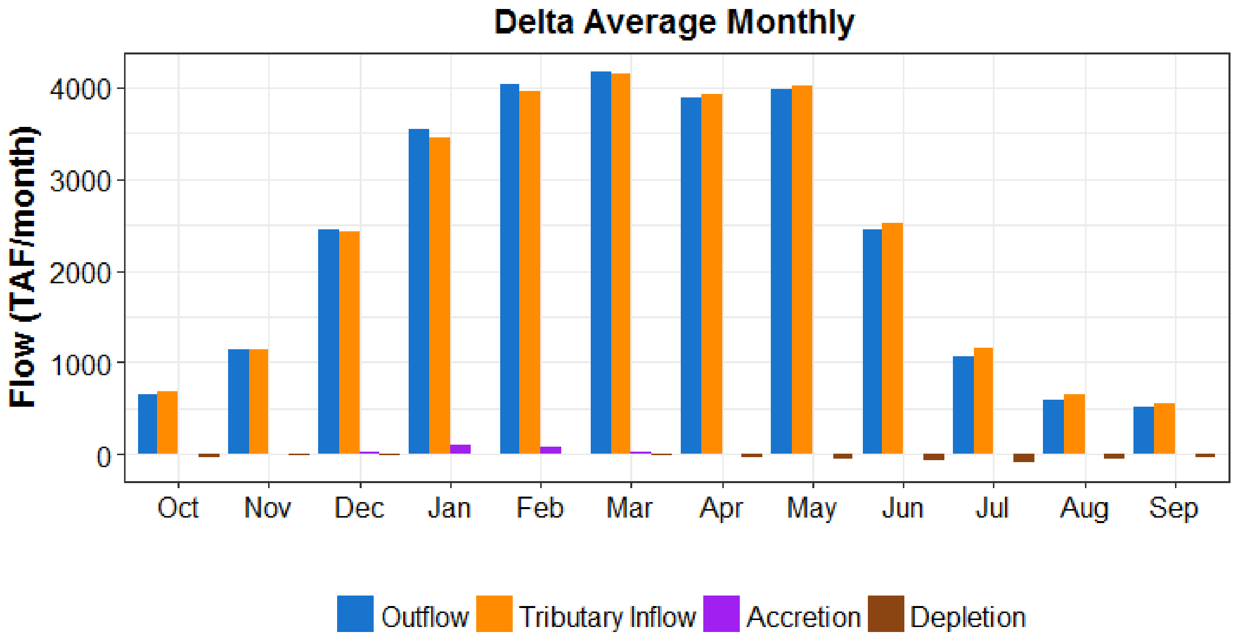


Figure A-27. Monthly Average Unimpaired Flow Components for Yuba River



Note: surface runoff and return flows included in tributary inflow

Figure A-28. Monthly Average Unimpaired Flow Components for the Delta

Table A-1. Average Annual Values per Water Year Type

Unimpaired Flow Component	All	W	AN	BN	D	C
American River Inflow	2,609	4,264	3,082	2,213	1,643	945
American River Outflow	2,580	4,213	3,050	2,187	1,625	939
American River Stream Gain/Loss	-41	-67	-47	-35	-26	-15
American River Surface Runoff	18	28	24	14	11	11
Antelope Creek Inflow	99	161	117	82	62	40
Antelope Creek Outflow	113	176	132	97	76	51
Antelope Creek Stream Gain/Loss	13	13	13	14	14	10
Antelope Creek Surface Runoff	1	2	1	1	1	1
Battle Creek Inflow	347	494	375	302	267	211
Battle Creek Outflow	355	499	383	313	278	219
Battle Creek Stream Gain/Loss	8	5	8	11	12	8
Bear River Inflow	313	520	383	259	189	106
Bear River Outflow	377	622	462	308	229	139
Bear River Stream Gain/Loss	-23	-37	-27	-19	-14	-8
Bear River Surface Runoff	34	46	40	27	26	27
Bear River Tributary Inflow	52	93	66	40	28	14
Big Chico Creek Inflow	101	173	119	78	58	35
Big Chico Creek Outflow	100	173	118	78	58	35
Big Chico Creek Stream Gain/Loss	0	0	0	0	0	0

Unimpaired Flow Component	All	W	AN	BN	D	C
Butte Creek Inflow	241	391	286	198	150	101
Butte Creek Outflow	397	629	472	326	251	188
Butte Creek Stream Gain/Loss	-14	-22	-16	-12	-9	-7
Butte Creek Surface Runoff	123	177	141	104	87	81
Butte Creek Tributary Inflow	47	83	61	36	24	13
Cache Creek Evaporation	155	-151	-155	-155	-158	-160
Cache Creek Inflow	444	731	524	349	274	190
Cache Creek Outflow	433	817	550	301	199	104
Cache Creek Stream Gain/Loss	-99	-196	-126	-66	-41	-18
Cache Creek Surface Runoff	48	74	62	37	28	28
Cache Creek Tributary Inflow	195	365	251	132	91	50
Calaveras River Inflow	150	279	183	120	69	32
Calaveras River Outflow	123	224	154	98	59	29
Calaveras River Stream Gain/Loss	-42	-80	-49	-34	-19	-9
Calaveras River Surface Runoff	8	11	10	6	5	5
Calaveras River Tributary Inflow	8	14	10	6	3	1
Clear Creek Inflow	324	522	424	244	202	138
Clear Creek Outflow	326	525	426	245	203	139
Clear Creek Surface Runoff	2	3	2	1	1	1
Cosumnes River Inflow	358	645	437	292	177	84
Cosumnes River Outflow	433	771	532	351	219	116
Cosumnes River Stream Gain/Loss	-2	-3	-2	-1	-1	0
Cosumnes River Surface Runoff	45	68	55	34	29	27
Cosumnes River Tributary Inflow	32	60	42	26	15	5
Cottonwood Creek Inflow	469	843	601	314	248	147
Cottonwood Creek Outflow	535	943	684	369	294	183
Cottonwood Creek Stream Gain/Loss	-9	-19	-12	-4	-2	-1
Cottonwood Creek Surface Runoff	76	119	95	59	48	37
Cow Creek Inflow	412	674	497	336	258	159
Cow Creek Outflow	423	686	511	346	268	166
Cow Creek Stream Gain/Loss	-7	-15	-9	-4	-2	-1
Cow Creek Surface Runoff	18	28	23	14	12	9
Deer Creek Inflow	228	370	260	185	146	100
Deer Creek Outflow	227	367	258	185	146	100
Deer Creek Stream Gain/Loss	-1	-3	-2	-1	0	0
Delta Accretion	244	407	340	185	122	99
Delta Depletion	365	-348	-355	-378	-369	-383
Delta Outflow	28,456	45,026	33,592	23,857	18,540	12,510
Delta Tributary Inflow	28,596	44,985	33,626	24,069	18,807	12,816
Elder Creek Inflow	67	117	91	45	36	22
Elder Creek Outflow	67	113	90	47	39	24
Elder Creek Stream Gain/Loss	0	-4	-2	2	3	2

Unimpaired Flow Component	All	W	AN	BN	D	C
Feather River Inflow	4,275	6,894	4,850	3,516	2,816	1,829
Feather River Outflow	6,999	11,109	8,041	5,857	4,674	3,046
Feather River Stream Gain/Loss	-90	-244	-127	-26	5	20
Feather River Surface Runoff	109	164	130	85	74	65
Feather River Tributary Inflow	2,693	4,315	3,185	2,254	1,745	1,096
Mill Creek Inflow	215	319	245	185	154	115
Mill Creek Outflow	216	319	246	188	157	117
Mill Creek Stream Gain/Loss	2	0	1	2	3	2
Mokelumne River Inflow	740	1,178	875	646	479	288
Mokelumne River Outflow	620	986	733	542	402	241
Mokelumne River Stream Gain/Loss	-120	-192	-141	-104	-77	-46
Natomas East Main Drain Inflow	11	18	15	8	7	6
Natomas East Main Drain Outflow	54	81	68	42	35	34
Natomas East Main Drain Surface Runoff	38	58	49	29	24	23
Natomas East Main Drain Tributary Inflow	5	5	5	4	4	4
Paynes Creek Inflow	52	88	60	43	31	16
Paynes Creek Outflow	60	97	69	51	40	23
Paynes Creek Stream Gain/Loss	8	8	8	9	9	6
Putah Creek Inflow	358	652	441	252	183	111
Putah Creek Outflow	319	578	396	225	161	99
Putah Creek Stream Gain/Loss	-48	-89	-57	-32	-26	-15
Putah Creek Surface Runoff	9	15	12	6	4	4
Sacramento River Accretion	506	1,136	689	256	126	0
Sacramento River Depletion	87	-190	-138	-36	-24	0
Sacramento River Inflow	5,599	8,018	6,372	4,856	4,206	3,260
Sacramento River Outflow	18,447	26,725	21,859	16,499	13,467	9,445
Sacramento River Stream Gain/Loss	-253	-615	-372	-84	-9	-15
Sacramento River Surface Runoff	299	440	363	245	206	174
Sacramento River Tributary Inflow	15,856	26,789	18,760	12,235	9,521	6,097
Sacramento River Weirs	3,559	-8,981	-3,919	-1,043	-616	-121
Stony Creek Inflow	438	791	569	299	220	138
Stony Creek Outflow	410	740	534	279	207	131
Stony Creek Stream Gain/Loss	-31	-56	-38	-22	-16	-10
Stony Creek Surface Runoff	3	5	4	3	2	3
Sutter Bypass Inflow	2,555	5,657	3,221	1,205	736	309
Sutter Bypass Outflow	2,596	5,639	3,256	1,274	809	390
Sutter Bypass Stream Gain/Loss	-67	-171	-90	-19	-5	3
Sutter Bypass Surface Runoff	109	153	125	88	78	79
Thomes Creek Inflow	213	357	265	158	130	83
Thomes Creek Outflow	241	397	299	181	148	102
Thomes Creek Stream Gain/Loss	-21	-38	-26	-13	-10	-7
Thomes Creek Surface Runoff	48	77	61	36	28	26

Unimpaired Flow Component	All	W	AN	BN	D	C
Yolo Bypass Inflow	2,329	5,659	2,354	828	571	257
Yolo Bypass Outflow	2,433	5,803	2,480	914	644	331
Yolo Bypass Surface Runoff	79	120	102	61	49	49
Yolo Bypass Tributary Inflow	25	25	25	25	25	25
Yuba River Inflow	2,166	3,428	2,538	1,836	1,436	911
Yuba River Outflow	2,302	3,662	2,704	1,938	1,514	960
Yuba River Stream Gain/Loss	-25	-40	-29	-21	-17	-11
Yuba River Surface Runoff	16	23	19	12	11	11
Yuba River Tributary Inflow	146	252	176	112	85	48

A.3.1 Unimpaired Stream Gains/Losses to Groundwater

Stream gains and losses are difficult to estimate because they cannot be directly measured. Additionally, in most cases they cannot be calculated using mass balance about each tributary, because very few of the tributaries to the Sacramento River have stream gages at the confluence with the Sacramento River.

Although there is uncertainty in the estimation of this component of unimpaired flows, for most tributaries, the stream losses are estimated to be less than 10 percent of the tributary inflow with the exception of Antelope Creek, Cache Creek, Putah Creek, Calaveras River, and the Mokelumne River (Table A-2). Results for these tributaries are consistent with other studies that have shown large stream-groundwater interactions on the lower reaches (Yolo County 2006; Thomasson et al. 1960; DWR 2016b). Since stream gains/losses are estimated as a function of streamflow, the unimpaired losses are larger than the losses under the existing conditions simulation because the streamflows are higher. For example, East Bay Municipal Utility District (EBMUD) estimates the loss on the lower Mokelumne River to be about -45 TAF/yr (EBMUD 2017), which is consistent with the SacWAM estimates in the current conditions simulation (-57 TAF/yr-below normal to -32 TAF/yr-dry). However, the unimpaired outflow for the Mokelumne River is much larger in the unimpaired simulation (620 TAF/yr) than the current conditions simulation (327 TAF/yr); therefore, the losses are greater in the unimpaired simulation.

The total annual average estimated unimpaired stream loss for the Sacramento River, its tributaries, and the eastside Delta tributaries is about -880 TAF/yr but averages -1,888 TAF/yr in a wet year and -123 TAF/yr in a critical year (Table A-3). When compared with the total Delta outflow, the estimated system-wide stream loss is an annual average of 3.1percent across all years. In critical years, the gain is only 1.0% of Delta outflow and in a wet year the loss is nearly 4.1percent of the total Delta outflow.

To get a sense of how sensitive the unimpaired flow estimates are to the stream gains/losses, the last row of Table A-3 shows that if you double the stream gain/losses, the effect on Delta outflow is a decrease of 3.1%. Strictly this is not correct, however, because if the losses were increased on a tributary to the Sacramento River, the resulting inflow to the Sacramento River would be reduced, resulting in less loss along the Sacramento River. To do a formal sensitivity analysis on the stream gains/loss, the entire model would need to be recalibrated which would affect other areas of the model. Overall, there is some uncertainty in the stream gain/loss estimates, but the tributaries with the largest losses are consistent with other studies and the total gains/losses are small in terms of total Delta outflow.

Table A-2. Average Stream Gain/Losses as Percentage of Rim Inflow by Tributary

Tributary	Stream Gain/Loss as Percentage of Inflow
American River	-1.6%
Antelope Creek	13.1%
Battle Creek	2.3%
Bear River	-7.3%
Big Chico Creek	0.0%
Butte Creek	-5.8%
Cache Creek	-22.3%
Calaveras River	-28.0%
Cosumnes River	-0.6%
Cottonwood Creek	-1.9%
Cow Creek	-1.7%
Deer Creek	-0.4%
Elder Creek	0.0%
Feather River	-2.1%
Mill Creek	0.9%
Mokelumne River	-16.2%
Paynes Creek	15.4%
Putah Creek	-13.4%
Sacramento River	-4.5%
Stony Creek	-7.1%
Sutter Bypass	-2.6%
Thomes Creek	-9.9%
Yuba River	-1.2%

Table A-3. Total System-Wide Annual Average Stream Gain/Losses

	All	W	AN	BN	D	C
Total Unimpaired Stream Gain/ Loss (TAF/yr)	-880	-1,888	-1,163	-476	-243	-123
Percentage of Delta Outflow	-3.1%	-4.2%	-3.5%	-2.0%	-1.3%	-1.0%
200% Total Stream Gain/ Loss as Percentage of Outflow	-6.2%	-8.4%	-6.9%	-4.0%	-2.6%	-2.0%

A.3.2 Clear Lake Evaporation

The effect of including evaporation from Clear Lake in the calculation of unimpaired flows reduces the unimpaired outflow from Cache Creek by an average of 128 TAF/yr. The annual average evaporation for Clear Lake with the limited operations described in Section A.2.3 is 155 TAF/yr. When evaporation in Clear Lake is included, the streamflow below Clear Lake is reduced, resulting in less stream loss on Cache Creek; therefore, the effect on the unimpaired outflow from Cache Creek is less than the volume of evaporation.

The limited reservoir operation at Clear Lake results in streamflows that are not always uniformly lower due to evaporation. When inflows are very low, such as in the summer of 1984, evaporation reduces storage below the lake outlet elevation, which results in zero outflow (Figure A-29). Zero outflow is maintained until storage rises to 840 TAF. This type of response is similar to what would be expected if there was no dam controlling releases at Clear Lake.

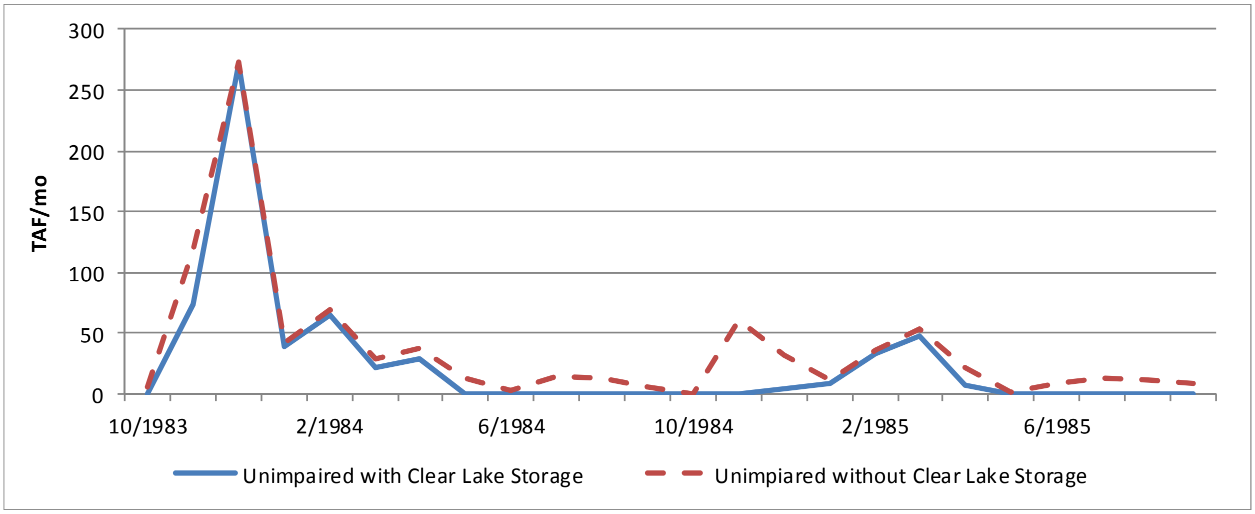


Figure A-29. Monthly Unimpaired Flow on Cache Creek below Clear Lake for Water Years 1984-1985

A.3.3 Delta Depletions

SacWAM does not include any stream gains/losses to groundwater in the Delta. This interaction is assumed to be included in the net channel depletions term described above in Section A.2.4. The unimpaired Delta depletions are -365 TAF/yr on average (Table A-1) with an average monthly pattern shown in Figure A-30. The unimpaired Delta depletions are approximately 31 percent of the Delta depletions assumed under existing conditions (State Water Board 2017).

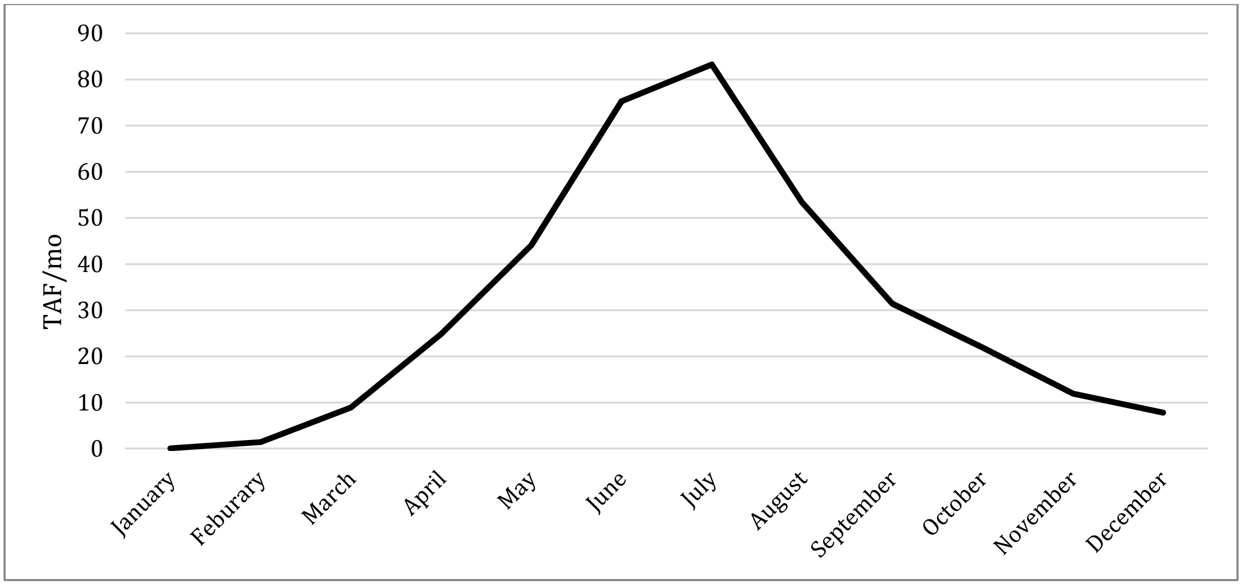


Figure A-30. Monthly Average Delta Depletion

A.4 Citations

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Errata

This errata sheet summarizes any minor typographical/editorial and model result changes that were made after the Scientific Basis Report was submitted to Health and Safety peer review in April, 2017. The Scientific Basis Report submitted to Health and Safety peer review, together with the errata, constitute the final Scientific Basis Report.

Typographical and Editorial Changes

Summary of Edits by Chapter

Chapter	Basic Editing/Formatting Corrections
Chapter 1	Corrected year the working draft version of the Science Report was released (2016, not 2017); spacing; capitalization; punctuation; abbreviations
Chapter 2	Punctuation, spacing, capitalization, abbreviations, spelling typos
Chapter 3	Spacing, punctuation, capitalization, typos, table and figure cross-references
Chapter 4	Spacing, punctuation, figure cross-references, typos, abbreviations
Chapter 5	Punctuation, figure cross-references, typos, abbreviations, spacing, capitalization
Appendix A	Spacing, punctuation, capitalization, corrected figure number cross-references, abbreviations

Updated Hydrological Model Results

The model used to develop flow estimates for the Report represents the existing water supply infrastructure in the watershed. When estimating unimpaired flows, this water supply infrastructure should not be operational (see Appendix A for a full description of unimpaired flow methods). In the unimpaired flow results that were included in the Scientific Basis Report submitted to peer review, several canals and tunnels connecting the upper watersheds of the Yuba and Bear Rivers were operational, resulting in an error that affected estimates of unimpaired flows and impairment of current condition flows on those rivers. To correct this issue, the figures, tables, and text for the Yuba and Bear Rivers have been updated in Chapter 2 and Appendix A of the final Scientific Basis Report with corrected values that eliminate the flows through the tunnels and canals. All of the changes made to Chapter 2 and Appendix A are identified below in strikeout (to show deletions) and underline (for the updated text) for all text, tables, and affected entries in Figure 2.1-10.

Additionally, one of the Delta depletion terms (A_50_NA7) was reduced to zero in the unimpaired flow model run, rather than to 32% of the current conditions depletion, which is correctly described in section A.2.4 and shown in Figure A-1 (Appendix A). Updating this value in the model run does not substantially change the results reported in the body of the Report, so the associated figures and tables in the Report were not updated to reflect this change. All summaries of hydrological data estimated using SacWAM will be updated in any future documentation associated with the proposed Bay-Delta Plan revisions.

Chapter 2 Hydrology

Section 2.1.2 Watershed Overview

Figure 2.1-10 on pp. 2-13 and 2-14 was replaced as shown below to include updated values for the Yuba River and Bear River.

WY	WYI	Water Year Type	Bear River		Yuba River	
1977	3.11	C	~~31%~~	112%	~~79%~~	57%
1931	3.66	C	~~21%~~	68%	~~43%~~	32%
1924	3.87	C	~~25%~~	74%	~~51%~~	37%
2015	4.01	C	~~21%~~	72%	~~42%~~	31%
1992	4.06	C	~~27%~~	53%	~~44%~~	36%
1934	4.07	C	~~17%~~	44%	~~28%~~	22%
2014	4.07	C	~~18%~~	46%	~~33%~~	25%
1991	4.21	C	~~21%~~	41%	~~36%~~	30%
1933	4.63	C	~~16%~~	40%	~~24%~~	19%
1988	4.65	C	~~17%~~	40%	~~47%~~	37%
1990	4.81	C	~~29%~~	64%	~~34%~~	28%
1994	5.02	C	~~29%~~	77%	~~47%~~	37%
2008	5.16	C	~~20%~~	46%	~~33%~~	27%
1929	5.22	C	~~16%~~	37%	~~27%~~	22%
1976	5.29	C	~~22%~~	80%	~~58%~~	47%
1932	5.48	D	~~29%~~	58%	~~47%~~	42%
1939	5.58	D	~~32%~~	77%	~~30%~~	24%
1947	5.61	D	~~26%~~	62%	~~31%~~	25%
1961	5.68	D	~~18%~~	47%	~~23%~~	18%
1926	5.75	D	~~41%~~	70%	~~37%~~	30%
2001	5.76	D	~~22%~~	51%	~~43%~~	34%
2009	5.78	D	~~28%~~	63%	~~51%~~	43%
2013	5.83	D	~~24%~~	68%	~~46%~~	36%
1987	5.86	D	~~35%~~	79%	~~46%~~	37%
1930	5.9	D	~~32%~~	68%	~~55%~~	45%
1949	6.09	D	~~38%~~	71%	~~41%~~	35%
1989	6.13	D	~~48%~~	88%	~~51%~~	45%
1955	6.14	D	~~21%~~	45%	~~29%~~	24%
2007	6.19	D	~~31%~~	78%	~~49%~~	39%
1960	6.2	D	~~24%~~	53%	~~47%~~	39%
1981	6.21	D	~~33%~~	75%	~~34%~~	28%
1944	6.35	D	~~32%~~	61%	~~32%~~	27%
2002	6.35	D	~~35%~~	71%	~~48%~~	40%
1925	6.39	D	~~34%~~	65%	~~44%~~	38%
1964	6.41	D	~~32%~~	72%	~~38%~~	31%
1985	6.47	D	~~31%~~	70%	~~35%~~	29%
1950	6.62	BN	~~39%~~	74%	~~58%~~	50%
1962	6.65	BN	~~37%~~	68%	~~55%~~	47%
1979	6.67	BN	~~50%~~	87%	~~47%~~	40%
1959	6.75	BN	~~29%~~	71%	~~28%~~	23%
1945	6.8	BN	~~43%~~	82%	~~60%~~	51%
1937	6.87	BN	~~50%~~	80%	~~48%~~	42%
2012	6.89	BN	~~48%~~	85%	~~45%~~	39%
1935	6.98	BN	~~51%~~	83%	~~60%~~	54%
1923	7.06	BN	~~48%~~	89%	~~58%~~	50%
2010	7.08	BN	~~37%~~	70%	~~49%~~	42%
1948	7.12	BN	~~39%~~	76%	~~53%~~	46%
1966	7.16	BN	~~35%~~	77%	~~41%~~	34%
1968	7.24	BN	~~43%~~	96%	~~44%~~	36%
1972	7.29	BN	~~27%~~	71%	~~50%~~	42%
2004	7.51	BN	~~44%~~	91%	~~57%~~	47%
1946	7.7	BN	~~38%~~	86%	~~61%~~	52%
1936	7.75	BN	~~56%~~	94%	~~67%~~	59%
1957	7.83	AN	~~40%~~	84%	~~51%~~	43%
2003	8.21	AN	~~45%~~	92%	~~69%~~	59%
1928	8.27	AN	~~62%~~	107%	~~66%~~	59%
2005	8.49	AN	~~50%~~	88%	~~65%~~	57%
1954	8.51	AN	~~49%~~	90%	~~55%~~	47%
1993	8.54	AN	~~58%~~	94%	~~67%~~	60%
1973	8.58	AN	~~68%~~	100%	~~73%~~	66%
1978	8.65	AN	~~53%~~	84%	~~61%~~	54%
1940	8.88	AN	~~58%~~	93%	~~68%~~	60%
2000	8.94	AN	~~54%~~	89%	~~62%~~	54%
1922	8.97	AN	~~70%~~	101%	~~71%~~	66%
1980	9.04	AN	~~67%~~	109%	~~76%~~	68%
1951	9.18	AN	~~66%~~	120%	~~73%~~	61%
1975	9.35	W	~~62%~~	95%	~~60%~~	55%
1927	9.52	W	~~64%~~	102%	~~77%~~	69%
1953	9.55	W	~~47%~~	97%	~~64%~~	56%
1963	9.63	W	~~66%~~	116%	~~80%~~	70%
1943	9.77	W	~~64%~~	109%	~~78%~~	68%
1999	9.8	W	~~61%~~	101%	~~74%~~	65%
1986	9.96	W	~~69%~~	107%	~~79%~~	71%
1984	10	W	~~47%~~	106%	~~70%~~	59%
1965	10.15	W	~~61%~~	120%	~~80%~~	69%
1967	10.2	W	~~69%~~	106%	~~77%~~	70%
1996	10.26	W	~~66%~~	112%	~~75%~~	68%
1971	10.37	W	~~49%~~	97%	~~72%~~	63%
1970	10.4	W	~~65%~~	105%	~~74%~~	67%
2011	10.54	W	~~73%~~	109%	~~81%~~	73%
1997	10.82	W	~~63%~~	108%	~~81%~~	72%
1969	11.05	W	~~71%~~	104%	~~80%~~	73%
1942	11.27	W	~~68%~~	109%	~~79%~~	71%
1956	11.38	W	~~65%~~	118%	~~81%~~	71%
1941	11.47	W	~~66%~~	104%	~~76%~~	67%
1958	12.16	W	~~67%~~	102%	~~79%~~	72%
1952	12.38	W	~~75%~~	108%	~~80%~~	74%
1938	12.62	W	~~71%~~	107%	~~83%~~	76%
1982	12.76	W	~~75%~~	110%	~~86%~~	78%
1995	12.89	W	~~72%~~	105%	~~79%~~	73%
1974	12.99	W	~~71%~~	114%	~~82%~~	74%
2006	13.2	W	~~75%~~	114%	~~84%~~	76%
1998	13.31	W	~~72%~~	105%	~~78%~~	70%
1983	15.29	W	~~80%~~	109%	~~84%~~	78%

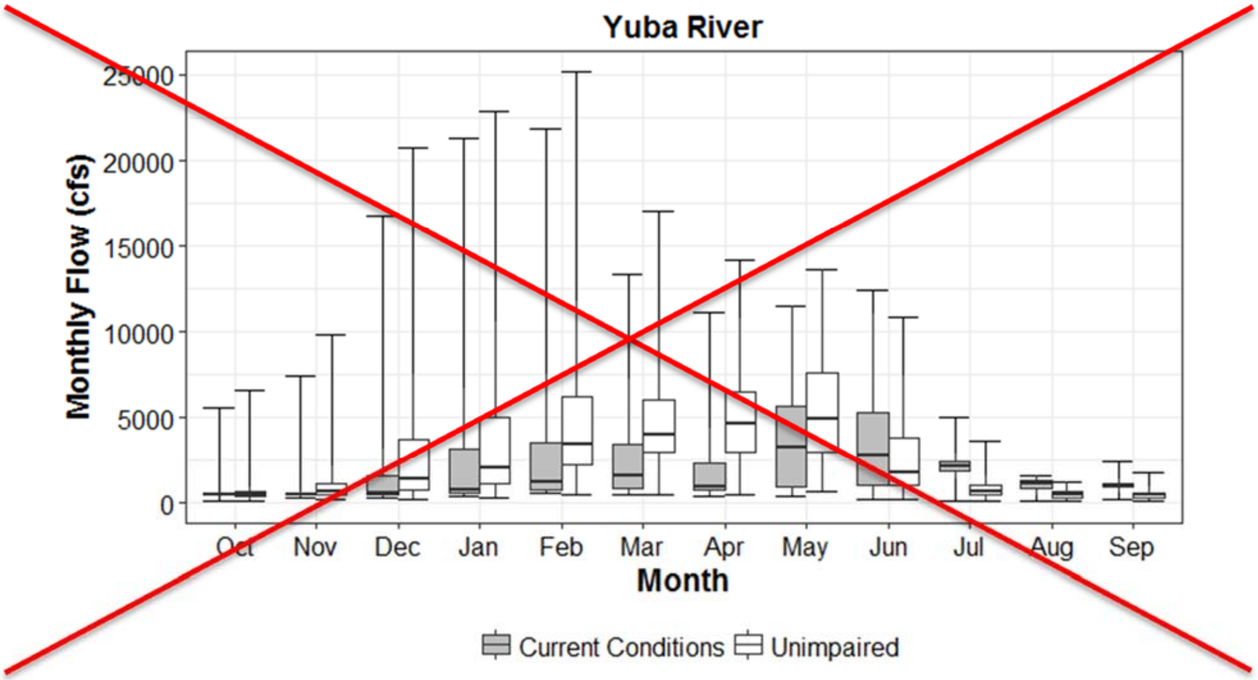
Figure 2.1-10. Simulated Impaired Flows as a Percentage of Unimpaired Flows Ranked by Water Year Index for the Sacramento River, Its Major Tributaries, and Eastside Tributaries to the Delta for January–June—Errata

Section 2.2.6.2 Yuba River

The final paragraph starting on p. 2-39 was edited to read:

> 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 Dam. Reservoir storage and diversions on the Yuba River have greatly reduced flows on the Lower Yuba River 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 ~~23~~ 18 to ~~86~~ 78 percent and is less than ~~57~~ 47 percent half of the years. Flows in all months except September are also significantly reduced in some years, but are generally reduced in the wet season and increased in the dry season (Table 2.2-12).

Figure 2.2-15 was updated as shown below:



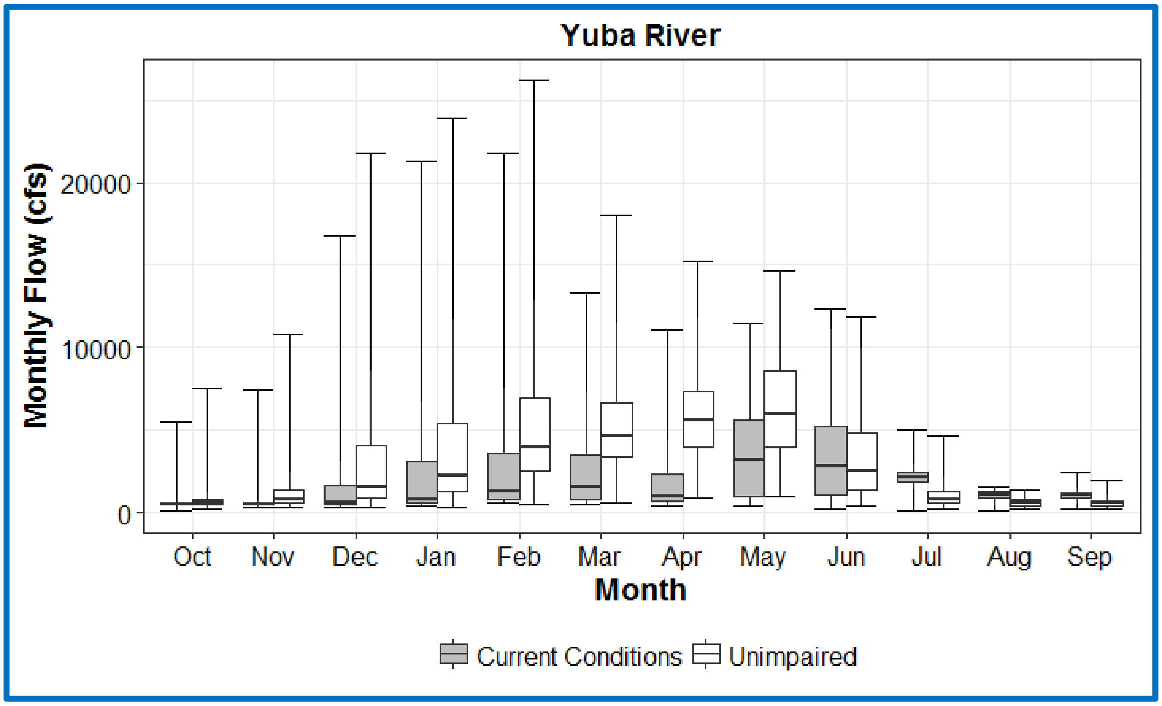


Figure 2.2-15. Yuba River Simulated Current Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-12 was updated as shown below:

Table 2.2-12. Cumulative Distribution of Current Conditions as Percent of Unimpaired Flow in Yuba River

	~~Oct~~	~~Nov~~	~~Dec~~	~~Jan~~	~~Feb~~	~~Mar~~	~~Apr~~	~~May~~	~~Jun~~	~~Jul~~	~~Aug~~	~~Sep~~	~~Jan–Jun~~	~~Jul–Dec~~	~~Annual Total~~
~~0%~~	~~56~~	~~34~~	~~20~~	~~23~~	~~20~~	~~21~~	~~12~~	~~9~~	~~14~~	~~39~~	~~62~~	~~104~~	~~23~~	~~52~~	~~44~~
~~10%~~	~~63~~	~~47~~	~~35~~	~~31~~	~~29~~	~~27~~	~~18~~	~~27~~	~~60~~	~~129~~	~~151~~	~~166~~	~~33~~	~~91~~	~~52~~
~~20%~~	~~71~~	~~51~~	~~40~~	~~38~~	~~34~~	~~29~~	~~21~~	~~42~~	~~95~~	~~156~~	~~171~~	~~180~~	~~41~~	~~96~~	~~57~~
~~30%~~	~~77~~	~~60~~	~~45~~	~~44~~	~~38~~	~~33~~	~~22~~	~~49~~	~~114~~	~~196~~	~~179~~	~~191~~	~~46~~	~~99~~	~~61~~
~~40%~~	~~83~~	~~66~~	~~53~~	~~48~~	~~46~~	~~36~~	~~25~~	~~60~~	~~125~~	~~228~~	~~186~~	~~199~~	~~50~~	~~104~~	~~65~~
~~50%~~	~~93~~	~~74~~	~~58~~	~~60~~	~~52~~	~~43~~	~~28~~	~~68~~	~~135~~	~~254~~	~~202~~	~~213~~	~~57~~	~~115~~	~~68~~
~~60%~~	~~100~~	~~83~~	~~67~~	~~66~~	~~62~~	~~48~~	~~34~~	~~73~~	~~150~~	~~287~~	~~210~~	~~224~~	~~62~~	~~126~~	~~73~~
~~70%~~	~~108~~	~~94~~	~~72~~	~~76~~	~~69~~	~~57~~	~~38~~	~~79~~	~~159~~	~~314~~	~~221~~	~~239~~	~~72~~	~~138~~	~~78~~
~~80%~~	~~115~~	~~105~~	~~79~~	~~82~~	~~77~~	~~63~~	~~48~~	~~84~~	~~176~~	~~339~~	~~236~~	~~260~~	~~78~~	~~153~~	~~82~~
~~90%~~	~~132~~	~~128~~	~~96~~	~~88~~	~~84~~	~~72~~	~~57~~	~~88~~	~~196~~	~~376~~	~~260~~	~~289~~	~~80~~	~~171~~	~~84~~
~~100%~~	~~291~~	~~178~~	~~189~~	~~198~~	~~146~~	~~95~~	~~90~~	~~94~~	~~331~~	~~538~~	~~351~~	~~403~~	~~86~~	~~214~~	~~88~~

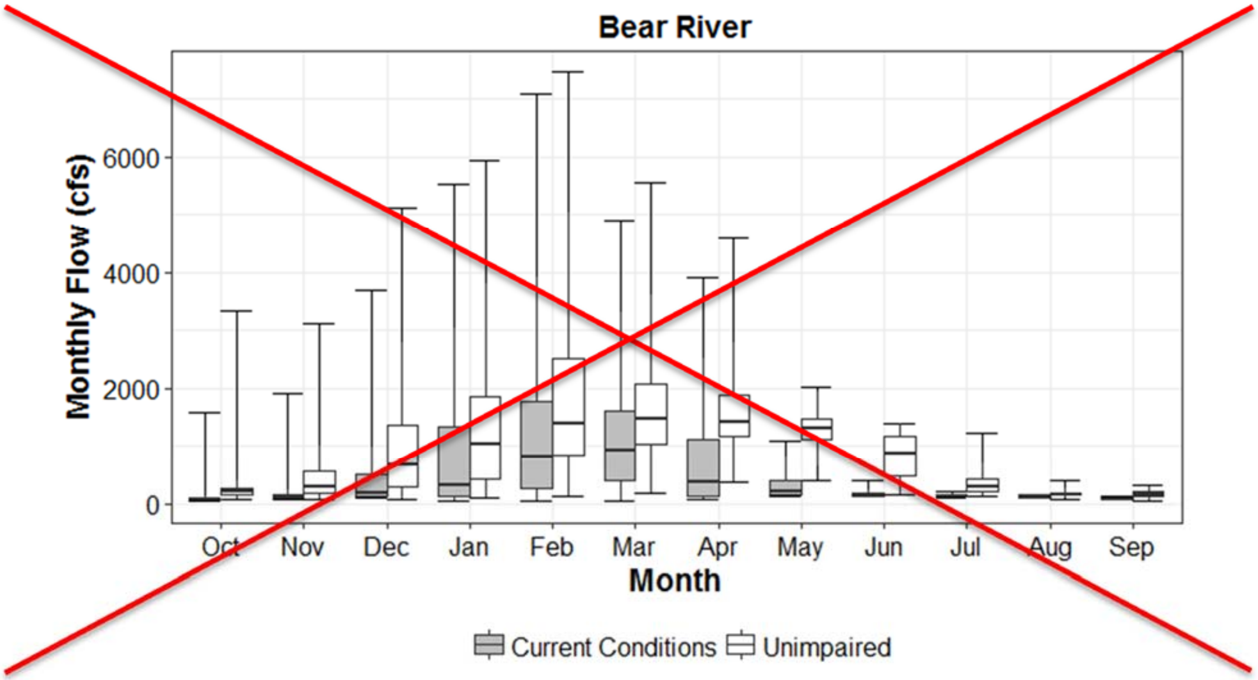
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan–Jun	Jul–Dec	Annual Total
0%	35	28	17	21	18	18	10	8	10	26	37	82	18	43	34
10%	52	39	31	29	26	24	14	20	37	98	128	135	27	79	42
20%	58	44	36	34	31	25	17	30	67	116	140	150	33	82	47
30%	63	49	40	39	34	29	18	37	101	149	148	155	37	85	50
40%	70	56	46	42	39	33	19	45	104	168	157	163	42	87	55
50%	76	63	51	53	47	38	23	53	107	200	163	170	47	94	58
60%	82	69	58	59	56	42	25	60	112	218	171	177	55	105	64
70%	88	78	65	69	64	52	32	65	115	244	179	190	60	113	69
80%	93	90	71	73	70	57	40	72	124	267	186	200	68	125	72
90%	106	106	83	80	77	65	49	78	138	298	205	229	72	139	76
100%	196	131	140	185	129	79	73	84	226	387	269	269	78	173	79

Section 2.2.6.3 Bear River

The second paragraph on p. 2-41 was edited to read as follows:

> 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 (State Water Board 1955; James 1989; NID 2008, 2010, 2011; NMFS 2014b). 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 2014b), with flows frequently below ~~20~~ 50 percent of unimpaired in winter-spring months (Table 2.2-13; Figure 2.2-16).

Figure 2.2-16 was updated as shown below:



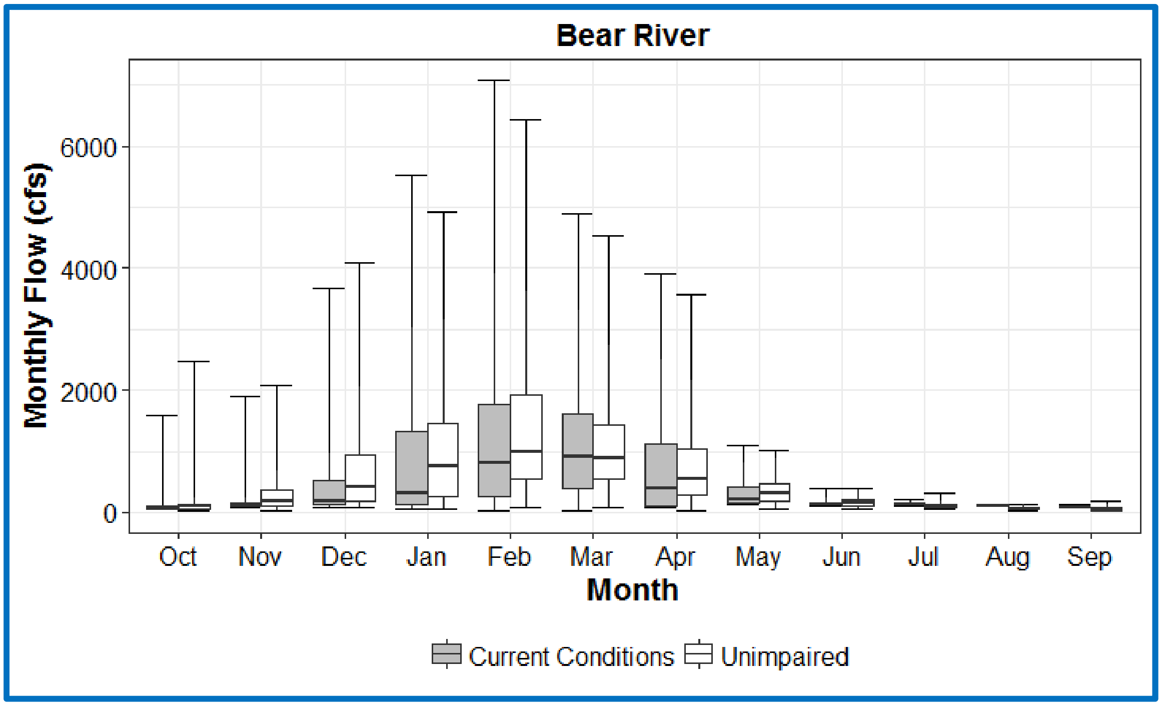


Figure 2.2-16. Bear River Simulated Current Conditions (gray) and Unimpaired (white) Monthly Flows

Table 2.2-13 was updated as shown below:

Table 2.2-13. Cumulative Distribution of Current Conditions as Percent of Unimpaired Flow in Bear River

	~~Oct~~	~~Nov~~	~~Dec~~	~~Jan~~	~~Feb~~	~~Mar~~	~~Apr~~	~~May~~	~~Jun~~	~~Jul~~	~~Aug~~	~~Sep~~	~~Jan–Jun~~	~~Jul–Dec~~	~~Annual Total~~
~~0%~~	~~18~~	~~15~~	~~16~~	~~12~~	~~9~~	~~8~~	~~8~~	~~10~~	~~11~~	~~10~~	~~30~~	~~30~~	~~16~~	~~22~~	~~24~~
~~10%~~	~~24~~	~~22~~	~~24~~	~~18~~	~~17~~	~~17~~	~~9~~	~~12~~	~~13~~	~~22~~	~~45~~	~~37~~	~~21~~	~~31~~	~~29~~
~~20%~~	~~27~~	~~26~~	~~29~~	~~25~~	~~23~~	~~29~~	~~11~~	~~13~~	~~14~~	~~25~~	~~54~~	~~40~~	~~28~~	~~37~~	~~33~~
~~30%~~	~~30~~	~~35~~	~~33~~	~~28~~	~~40~~	~~43~~	~~13~~	~~15~~	~~15~~	~~35~~	~~57~~	~~45~~	~~32~~	~~41~~	~~35~~
~~40%~~	~~33~~	~~38~~	~~37~~	~~34~~	~~53~~	~~58~~	~~20~~	~~19~~	~~17~~	~~41~~	~~63~~	~~50~~	~~37~~	~~44~~	~~39~~
~~50%~~	~~35~~	~~40~~	~~41~~	~~45~~	~~59~~	~~67~~	~~27~~	~~21~~	~~20~~	~~48~~	~~70~~	~~52~~	~~44~~	~~46~~	~~45~~
~~60%~~	~~40~~	~~46~~	~~49~~	~~58~~	~~68~~	~~71~~	~~44~~	~~24~~	~~22~~	~~57~~	~~79~~	~~55~~	~~50~~	~~51~~	~~50~~
~~70%~~	~~43~~	~~53~~	~~57~~	~~70~~	~~79~~	~~76~~	~~51~~	~~28~~	~~25~~	~~65~~	~~83~~	~~61~~	~~61~~	~~54~~	~~58~~
~~80%~~	~~45~~	~~57~~	~~67~~	~~78~~	~~83~~	~~82~~	~~61~~	~~34~~	~~34~~	~~77~~	~~92~~	~~68~~	~~66~~	~~58~~	~~61~~
~~90%~~	~~54~~	~~68~~	~~79~~	~~84~~	~~93~~	~~89~~	~~70~~	~~43~~	~~47~~	~~86~~	~~105~~	~~80~~	~~70~~	~~65~~	~~65~~
~~100%~~	~~75~~	~~151~~	~~103~~	~~95~~	~~101~~	~~98~~	~~92~~	~~56~~	~~80~~	~~133~~	~~191~~	~~140~~	~~80~~	~~85~~	~~74~~

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Jan–Jun	Jul–Dec	Annual Total
0%	31	28	24	16	15	24	24	33	48	55	94	65	37	40	53
10%	51	36	34	29	27	36	36	50	75	85	121	88	51	61	63
20%	55	48	42	36	38	61	42	67	82	93	140	105	68	70	71
30%	63	59	48	44	55	84	52	82	86	111	161	118	71	75	77
40%	71	66	58	55	74	95	62	89	92	124	179	133	77	84	83
50%	78	79	69	61	87	104	82	93	98	145	200	153	85	92	87
60%	87	84	78	85	97	108	92	97	104	162	225	183	92	99	91
70%	102	94	86	95	105	111	102	99	115	182	260	221	101	105	97
80%	112	112	97	103	108	113	113	110	147	207	295	242	107	117	101
90%	132	139	113	112	112	122	125	124	199	260	335	340	109	133	104
100%	305	378	144	135	138	142	210	232	299	300	406	592	120	175	128

Section 2.4.6 Delta Outflow and X2

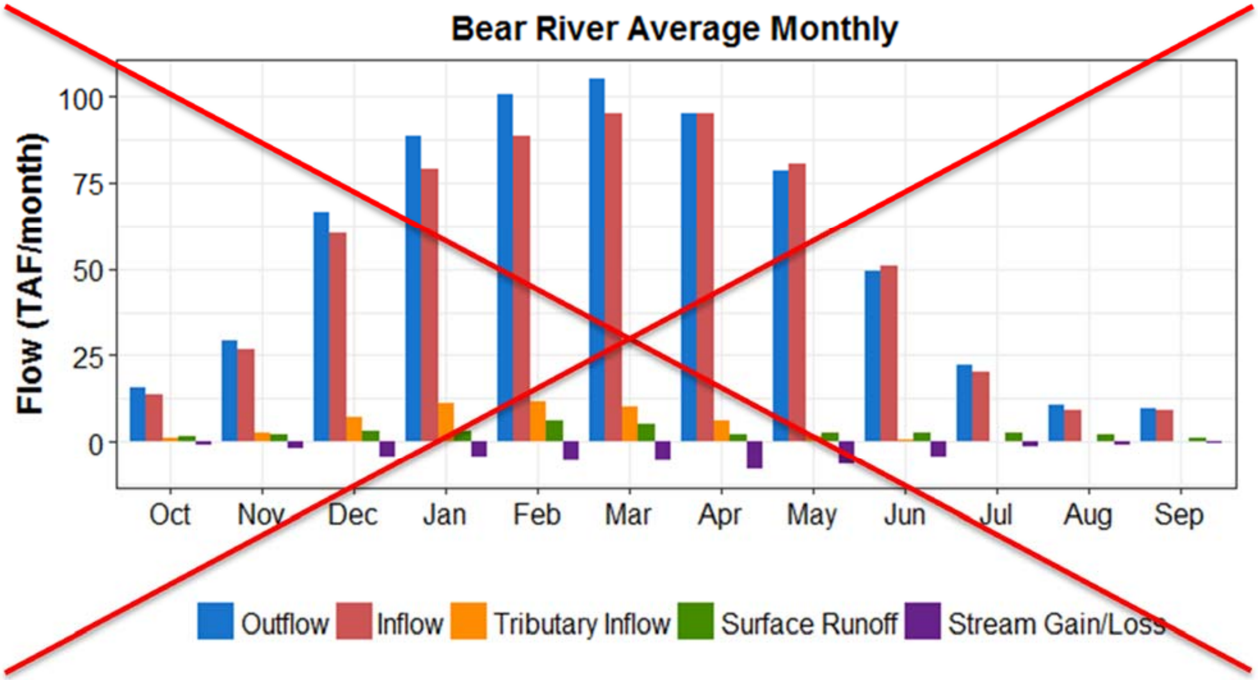
Table 2.4-4 on pp. 2-78 and 2-79 was updated to replace the entries for the Yuba River and Bear River, as shown below:

Table 2.4-4. Simulated Unimpaired Contributions to Total Delta Outflow from Various Locations in the Project Area (percent of Delta outflow)

Location	Jan–Jun	Jul–Dec	Annual Total
Sacramento River below Keswick	17.4	27.7	19.7
Sacramento River at Freeport	61.2	77.1	64.8
Cow Creek at Confluence with Sacramento River	1.5	1.6	1.5
Battle Creek at Confluence with Sacramento River	1	2	1.2
Butte Creek near Durham	1.4	1.5	1.4
Antelope Creek at Confluence with Sacramento River	0.4	0.5	0.4
Deer Creek	0.8	0.9	0.8
Mill Creek	0.7	1	0.8
Paynes Creek	0.2	0.2	0.2
Clear Creek	1.2	1.1	1.1
Big Chico Creek	0.4	0.4	0.4
Feather River at Confluence with Sacramento River	24.2	25.9	24.6
Feather River above Confluence with Yuba River	15.1	17	15.5
Yuba River	~~7.2~~ 8.3	~~6.4~~ 7.6	~~7~~ 8.1
Bear River at Confluence with Feather River	~~2.3~~ 1.3	~~2.4~~ 1.4	~~2.4~~ 1.3
American River at Confluence with Sacramento River	9.7	6.7	9.1
Mokelumne River above the confluence with Cosumnes	2.4	1.3	2.2
Cosumnes River at confluence with Mokelumne	1.7	1	1.5
Calaveras River	0.5	0.3	0.4
Stony Creek	1.5	1.1	1.4
Cottonwood Creek	2	1.6	1.9
Thomes Creek	0.9	0.8	0.9
Elder Creek	0.2	0.2	0.2
Cache Creek	1.7	1	1.5
Putah Creek	1.2	0.8	1.1
Sutter Bypass Outflow	10.1	6.1	9.2
Yolo Bypass	9.6	5.1	8.6
San Joaquin River at Vernalis	22.7	15.9	21.2
Delta Outflow	100	100	100

Appendix A Modeling Approaches Used to Develop Unimpaired Watershed Hydrology

Figure A-5 was updated as shown below:



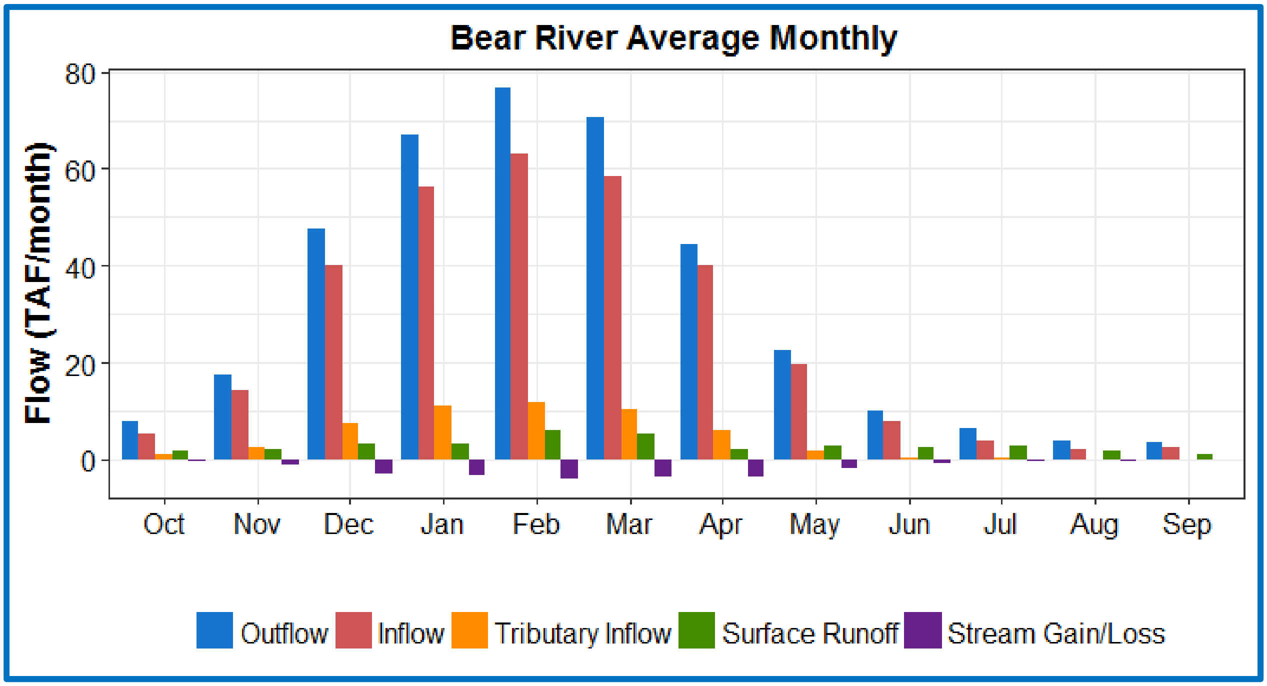
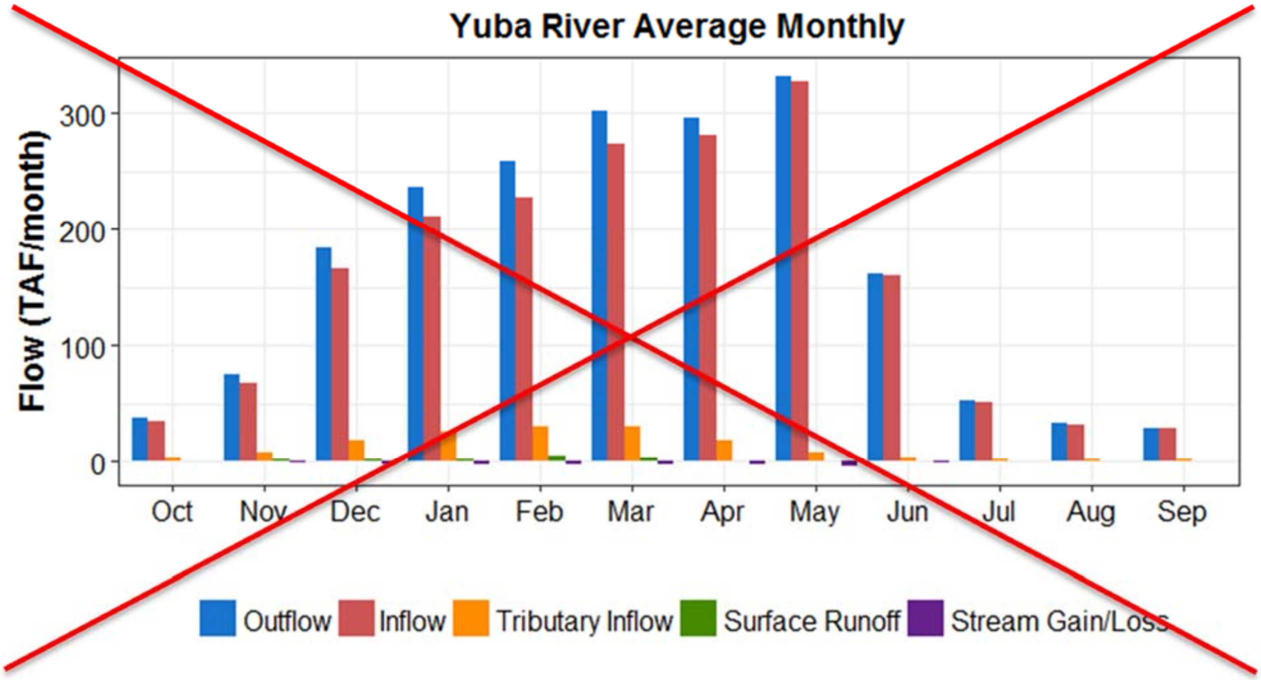


Figure A-5. Monthly Average Unimpaired Flow Components for Bear River

Figure A-27 was updated as shown below:



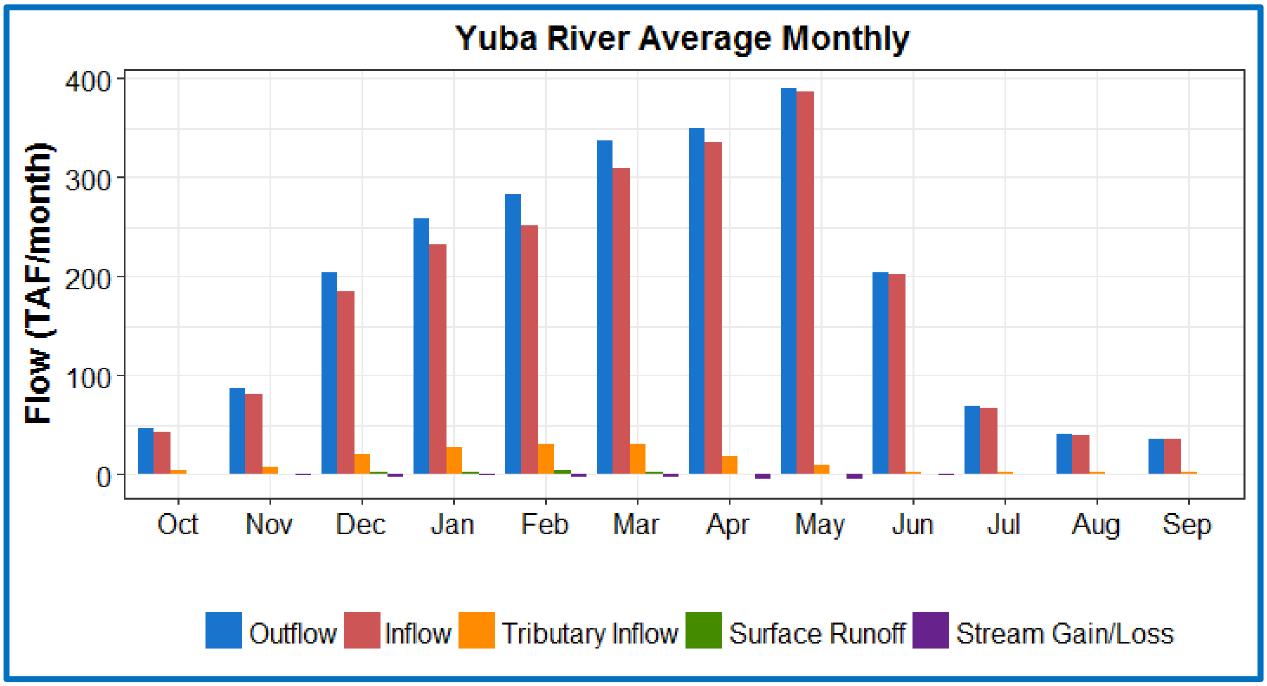


Figure A-27. Monthly Average Unimpaired Flow Components for Yuba River

Table A-1 on pp. A-22 and A-26 was updated to replace the entries for the Yuba River and Bear River, as shown below:

Table A-1. Average Annual Values per Water Year Type

Unimpaired Flow Component	All	W	AN	BN	D	C
American River Inflow	2,609	4,264	3,082	2,213	1,643	945
American River Outflow	2,580	4,213	3,050	2,187	1,625	939
American River Stream Gain/Loss	-41	-67	-47	-35	-26	-15
American River Surface Runoff	18	28	24	14	11	11
Antelope Creek Inflow	99	161	117	82	62	40
Antelope Creek Outflow	113	176	132	97	76	51
Antelope Creek Stream Gain/Loss	13	13	13	14	14	10
Antelope Creek Surface Runoff	1	2	1	1	1	1
Battle Creek Inflow	347	494	375	302	267	211
Battle Creek Outflow	355	499	383	313	278	219
Battle Creek Stream Gain/Loss	8	5	8	11	12	8
Bear River Inflow	~~628~~ 313	~~933~~ 520	~~738~~ 383	~~554~~ 259	~~451~~ 189	~~304~~ 106
Bear River Outflow	~~671~~ 377	~~1,007~~ 622	~~793~~ 462	~~583~~ 308	~~473~~ 229	~~323~~ 139
Bear River Stream Gain/Loss	~~-44~~ -23	~~-64~~ -37	~~-51~~ -27	~~-39~~ -19	~~-32~~ -14	~~-22~~ -8
Bear River Surface Runoff	34	46	40	27	26	27
Bear River Tributary Inflow	52	93	66	40	28	14
Big Chico Creek Inflow	101	173	119	78	58	35
Big Chico Creek Outflow	100	173	118	78	58	35
Big Chico Creek Stream Gain/Loss	0	0	0	0	0	0
Butte Creek Inflow	241	391	286	198	150	101
Butte Creek Outflow	397	629	472	326	251	188
Butte Creek Stream Gain/Loss	-14	-22	-16	-12	-9	-7
Butte Creek Surface Runoff	123	177	141	104	87	81
Butte Creek Tributary Inflow	47	83	61	36	24	13
Cache Creek Evaporation	155	-151	-155	-155	-158	-160
Cache Creek Inflow	444	731	524	349	274	190
Cache Creek Outflow	433	817	550	301	199	104
Cache Creek Stream Gain/Loss	-99	-196	-126	-66	-41	-18
Cache Creek Surface Runoff	48	74	62	37	28	28
Cache Creek Tributary Inflow	195	365	251	132	91	50
Calaveras River Inflow	150	279	183	120	69	32
Calaveras River Outflow	123	224	154	98	59	29
Calaveras River Stream Gain/Loss	-42	-80	-49	-34	-19	-9
Calaveras River Surface Runoff	8	11	10	6	5	5
Calaveras River Tributary Inflow	8	14	10	6	3	1
Clear Creek Inflow	324	522	424	244	202	138
Clear Creek Outflow	326	525	426	245	203	139

Unimpaired Flow Component	All	W	AN	BN	D	C
Clear Creek Surface Runoff	2	3	2	1	1	1
Cosumnes River Inflow	358	645	437	292	177	84
Cosumnes River Outflow	433	771	532	351	219	116
Cosumnes River Stream Gain/Loss	-2	-3	-2	-1	-1	0
Cosumnes River Surface Runoff	45	68	55	34	29	27
Cosumnes River Tributary Inflow	32	60	42	26	15	5
Cottonwood Creek Inflow	469	843	601	314	248	147
Cottonwood Creek Outflow	535	943	684	369	294	183
Cottonwood Creek Stream Gain/Loss	-9	-19	-12	-4	-2	-1
Cottonwood Creek Surface Runoff	76	119	95	59	48	37
Cow Creek Inflow	412	674	497	336	258	159
Cow Creek Outflow	423	686	511	346	268	166
Cow Creek Stream Gain/Loss	-7	-15	-9	-4	-2	-1
Cow Creek Surface Runoff	18	28	23	14	12	9
Deer Creek Inflow	228	370	260	185	146	100
Deer Creek Outflow	227	367	258	185	146	100
Deer Creek Stream Gain/Loss	-1	-3	-2	-1	0	0
Delta Accretion	244	407	340	185	122	99
Delta Depletion	365	-348	-355	-378	-369	-383
Delta Outflow	28,456	45,026	33,592	23,857	18,540	12,510
Delta Tributary Inflow	28,596	44,985	33,626	24,069	18,807	12,816
Elder Creek Inflow	67	117	91	45	36	22
Elder Creek Outflow	67	113	90	47	39	24
Elder Creek Stream Gain/Loss	0	-4	-2	2	3	2
Feather River Inflow	4,275	6,894	4,850	3,516	2,816	1,829
Feather River Outflow	6,999	11,109	8,041	5,857	4,674	3,046
Feather River Stream Gain/Loss	-90	-244	-127	-26	5	20
Feather River Surface Runoff	109	164	130	85	74	65
Feather River Tributary Inflow	2,693	4,315	3,185	2,254	1,745	1,096
Mill Creek Inflow	215	319	245	185	154	115
Mill Creek Outflow	216	319	246	188	157	117
Mill Creek Stream Gain/Loss	2	0	1	2	3	2
Mokelumne River Inflow	740	1,178	875	646	479	288
Mokelumne River Outflow	620	986	733	542	402	241
Mokelumne River Stream Gain/Loss	-120	-192	-141	-104	-77	-46
Natomas East Main Drain Inflow	11	18	15	8	7	6
Natomas East Main Drain Outflow	54	81	68	42	35	34
Natomas East Main Drain Surface Runoff	38	58	49	29	24	23
Natomas East Main Drain Tributary Inflow	5	5	5	4	4	4
Paynes Creek Inflow	52	88	60	43	31	16
Paynes Creek Outflow	60	97	69	51	40	23
Paynes Creek Stream Gain/Loss	8	8	8	9	9	6
Putah Creek Inflow	358	652	441	252	183	111

Unimpaired Flow Component	All	W	AN	BN	D	C
Putah Creek Outflow	319	578	396	225	161	99
Putah Creek Stream Gain/Loss	-48	-89	-57	-32	-26	-15
Putah Creek Surface Runoff	9	15	12	6	4	4
Sacramento River Accretion	506	1,136	689	256	126	0
Sacramento River Depletion	87	-190	-138	-36	-24	0
Sacramento River Inflow	5,599	8,018	6,372	4,856	4,206	3,260
Sacramento River Outflow	18,447	26,725	21,859	16,499	13,467	9,445
Sacramento River Stream Gain/Loss	-253	-615	-372	-84	-9	-15
Sacramento River Surface Runoff	299	440	363	245	206	174
Sacramento River Tributary Inflow	15,856	26,789	18,760	12,235	9,521	6,097
Sacramento River Weirs	3,559	-8,981	-3,919	-1,043	-616	-121
Stony Creek Inflow	438	791	569	299	220	138
Stony Creek Outflow	410	740	534	279	207	131
Stony Creek Stream Gain/Loss	-31	-56	-38	-22	-16	-10
Stony Creek Surface Runoff	3	5	4	3	2	3
Sutter Bypass Inflow	2,555	5,657	3,221	1,205	736	309
Sutter Bypass Outflow	2,596	5,639	3,256	1,274	809	390
Sutter Bypass Stream Gain/Loss	-67	-171	-90	-19	-5	3
Sutter Bypass Surface Runoff	109	153	125	88	78	79
Thomes Creek Inflow	213	357	265	158	130	83
Thomes Creek Outflow	241	397	299	181	148	102
Thomes Creek Stream Gain/Loss	-21	-38	-26	-13	-10	-7
Thomes Creek Surface Runoff	48	77	61	36	28	26
Yolo Bypass Inflow	2,329	5,659	2,354	828	571	257
Yolo Bypass Outflow	2,433	5,803	2,480	914	644	331
Yolo Bypass Surface Runoff	79	120	102	61	49	49
Yolo Bypass Tributary Inflow	25	25	25	25	25	25
Yuba River Inflow	~~1,858~~ 2,166	~~3,026~~ 3,428	~~2,192~~ 2,538	~~1,547~~ 1,836	~~1,178~~ 1,436	~~715~~ 911
Yuba River Outflow	~~1,998~~ 2,302	~~3,265~~ 3,662	~~2,361~~ 2,704	~~1,653~~ 1,938	~~1,260~~ 1,514	~~766~~ 960
Yuba River Stream Gain/Loss	~~-22~~ -25	~~-36~~ -40	~~-26~~ -29	~~-18~~ -21	~~-14~~ -17	~~-8~~ -11
Yuba River Surface Runoff	16	23	19	12	11	11
Yuba River Tributary Inflow	146	252	176	112	85	48

Table A-2 on pp. A-27 was updated to replace the entry for Bear River, as shown below:

Table A-2. Average Stream Gain/Losses as Percentage of Rim Inflow by Tributary

Tributary	Stream Gain/Loss as Percentage of Inflow
American River	-1.6%
Antelope Creek	13.1%
Battle Creek	2.3%
Bear River	~~-7.0%~~ -7.3%
Big Chico Creek	0.0%
Butte Creek	-5.8%
Cache Creek	-22.3%
Calaveras River	-28.0%
Cosumnes River	-0.6%
Cottonwood Creek	-1.9%
Cow Creek	-1.7%
Deer Creek	-0.4%
Elder Creek	0.0%
Feather River	-2.1%
Mill Creek	0.9%
Mokelumne River	-16.2%
Paynes Creek	15.4%
Putah Creek	-13.4%
Sacramento River	-4.5%
Stony Creek	-7.1%
Sutter Bypass	-2.6%
Thomes Creek	-9.9%
Yuba River	-1.2%