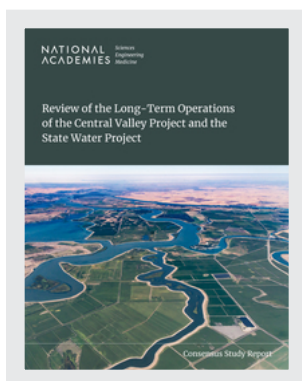


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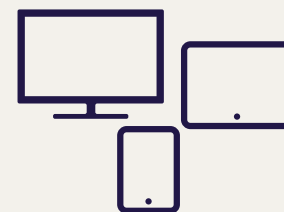
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Review of the Long-Term Operations of the Central Valley Project and the State Water Project

Committee to Review the Long-Term Operations
of the Central Valley Project and the State
Water Project

Water Science and Technology Board

Ocean Studies Board

Division on Earth and Life Studies

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NOTE: See Appendix F, Disclosure of Unavoidable Conflict(s) of Interest.

Reviewers

This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report:

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Preface

Water management in California includes two of the largest multipurpose water management projects in the world—the federal Central Valley Project (CVP), operated by the U.S. Bureau of Reclamation (USBR), and the State Water Project (SWP), operated by the California Department of Water Resources (CDWR). The water harnessed by these projects stems from the Sacramento and San Joaquin River watersheds. Much of that water flows through the area—known as the Delta or, in combination with the adjacent bays, as the Bay-Delta—created at those rivers’ confluence and then exits to San Francisco Bay and the Pacific Ocean. But a substantial amount also is diverted by the CVP and SWP. At least two thirds of California's population and more than 4 million acres of California farmland rely in whole or in part on water delivered by these projects, which transfer billions of gallons per day on average from northern California to drier Central and Southern California.

These water deliveries are complicated by several factors. More than 750 fish and wildlife species (including dozens that are now listed under state and/or federal law as threatened or endangered) and commercial fishery species rely on a functioning Bay-Delta ecosystem to thrive. The area also is an internationally significant ecosystem because of its importance for migratory bird species. The Delta’s tributary rivers provide important ecological and recreational value as well as water for diversion to cities and farms. Yet the area is also a hotspot for invasive species, many of which have dramatically altered the system.

The Delta’s economic and ecological significance has led to a complex management regime. California water management involves more than 230 federal, state, and local agencies and water contractors, as well as dozens of California tribes whose culture is intricately tied to the land, fish, and other wildlife resources that have evolved in this unique system.

The Delta, its watershed, and California as a whole have undergone almost two centuries of land use change and population growth, now compounded by more recent threats associated with a warmer and increasingly variable atmosphere, accelerating sea level rise, emerging contaminants, invasive species, dramatic declines in multiple native species, and more frequent harmful algal blooms. The increasing variability and intensity of precipitation, droughts, and wildfires will challenge California’s management of its water supplies into the foreseeable future.

In order to inform and guide the management of this complex and dynamic ecosystem, a highly skilled science and engineering community has evolved representing federal and state agencies, tribes, water delivery and power companies, agricultural interests, academia, local government, and consultants. This highly skilled and productive community is underpinned by high quality data, diffuse yet innovative modeling, and fundamental scientific research that has led to application of these advances throughout California and beyond. The leadership role of the USGS in designing, implementing, and making available state-of-the-science monitoring in the Delta, Bay and watershed is the bedrock of this exemplary science and research endeavor.

Since the last National Academies review of the Bay-Delta in 2012, there have been extensive advances in the science and technologies deployed to monitor, model, manage, and understand this complex system. This Committee's charge focuses on the science used to inform three actions that the USBR and CDWR carry out as they manage the CVP and SWP, respectively. These three actions are Shasta Coldwater Pool Management, Old and Middle River Flow Management, and the Summer-Fall Habitat Action. Because of this specific focus, the Committee did not review many elements of CVP and SWP water management, and readers should not interpret this report to be expressing opinions on those other actions. That is, this review is not intended to be an exhaustive and critical evaluation of the extensive published and gray literature on California water.

Perhaps most importantly, the Committee's review overlapped with the Endangered Species Act reconsultation process leading to the 2024 biological opinions of the U.S. Fish and Wildlife Service and the National Marine Fisheries Service, the 2024 Incidental Take Permit from the California Department of Fish and Wildlife, and USBR's final Environmental Impact Statement for the Long-term Operation of the projects. Despite this overlap, the Committee was not asked to review the reconsultation process. Indeed, the reconsultation activities prevented the Committee from interacting fully with all of the relevant state and federal agency scientists. The Committee did use reconsultation-related documents to inform its understanding of how USBR and other agencies define the relevant actions and as part of its literature review. However, this report is not a review of the biological opinions, the incidental take statement, or the environmental impact statement.

In addition, although the Committee studied the information provided by USBR and participants at the Committee's public meetings, derived from the peer-reviewed scientific literature, and provided in the 2024 reconsultation documentation, this review is not exhaustive of all recent studies and programs. Other important activities were completed or nearing completion during the Committee's tenure, but fell outside of the scope of the Committee's charge, including the following:

- the Healthy Rivers and Landscapes Initiative, previously referred to as Voluntary Agreements, used to satisfy water quality standards for the Bay-Delta and tributary waters;
- the State Water Resources Control Board update to the Bay-Delta Plan, which is due in late 2025; and
- the many current review activities of the Delta Science Program.

Some topics presented to the Committee during its public meetings were also beyond the scope of this review. Hence, although this report briefly mentions some ways in which the actions might affect hydropower generation, hydropower operations were not a focus of the review. Similarly, some presenters questioned USBR's and CDWR's use of water-year classifications to guide management. Although such questions might be explored in a future report, USBR requested that the Committee not investigate that topic in this review cycle. Related topics such as forecast-informed reservoir operations (FIRO), while not addressed in this report, could be explored in future work. Finally, the Committee considered existing legal frameworks as given.

The Committee was established under the auspices of the Water Science and Technology Board of the National Academies. The Committee included 18 individuals whose joint expertise covered the diversity of disciplines relevant to the study. Over the course of 15 months and eight committee meetings, five of which included sessions open to the public, the Committee heard from local, state, and federal experts about project operations and the three actions. The Committee acknowledges and appreciates the many individuals within USBR, CDWR, the Delta Science Program, other state and federal agencies, tribes, and other institutions and organizations who have endeavored to keep the National Academies staff and Committee apprised of science developments and have provided thoughtful input. The Committee would especially like to acknowledge the following individuals for their support throughout this project: Dave Mooney, Josh Israel, and Lillian McCormick (USBR); Lenny Grimaldo and Britt Davis (CDWR); and Dylan Stern, Delta Science Program. The Committee also thanks the many individuals who spoke during open-mic sessions or submitted written comments during the course of the study.

Peter Goodwin, *Chair*
Committee to Review the Long-term Operations of the
Central Valley Project and the State Water Project
October 2025

Acronyms and Abbreviations

ANN	Artificial Neural Network
ADCP	Acoustic Doppler Current Profile
CDFW	California Department of Fish and Wildlife
CDWR	California Department of Water Resources
C-C	Clausius-Clapeyron
CCV	California Central Valley
CEQA	California Environmental Quality Act
CESA	California Endangered Species Act
cfs	Cubic feet per second
CMIP	Coupled Model Intercomparison Project
COA	Coordinated Operating Agreement
CPUV	Catch per unit volume
CSAMP	Collaborative Science and Adaptive Management Program
CV	Central Valley
CVP	Central Valley Project
CVPIA	Central Valley Project Improvement Act
CWA	Clean Water Act
CWEMF	California Water and Environmental Modeling Forum
CWT	Coded-wire tag
DCC	Delta Cross Channel
DCD	Delta Channel Depletion
DCG	Delta Coordination Group
DIDSON	Dual-frequency identification sonar
DJFMP	Delta Juvenile Fish Monitoring Program
DPIIC	Delta Plan Interagency Implementation Committee
DSM	Decision Support Model or Delta Simulation Model
DSM2	Delta Simulation Model II
DSM2-GTM	Delta Simulation Model 2-General Transport Model
DTS	Distributed temperature sensing
DU	Demand Units
ecoPTM	Ecological particle tracking model
EDSM	Enhanced Delta Smelt Monitoring
EIS	Environmental Impact Statement
EOS	End-of-September
ePTM	Enhanced Particle Tracking Model
ESA	Endangered Species Act
ESU	Evolutionarily Significant Unit
ET	Evapotranspiration
FMWT	Fall Midwater Trawl Index
FNU	Formazin Nephelometric Units

GCID	Glenn Colusa Irrigation District
GCMs	Global Climate Models
HABs	Harmful Algal Blooms
HEC	Hydrologic Engineering Center
HEC-HMS	Hydrologic Engineering Center-Data Support System
HSI	Habitat Suitability Index
IEP	Interagency Ecological Program
ITP	Incidental Take Permit
JPE	Juvenile Production Estimate
LCMG	FWS Delta smelt Life-Cycle Model
MAF	Million acre-feet
MSE	Management Strategy Evaluation
MSL	Mean Sea Level
NASEM	National Academies of Sciences, Engineering, and Medicine
NEPA	National Environmental Policy Act
NMFS	National Marine Fisheries Service
OBAN	Oncorhynchus Bayesian Analysis Network
OMR	Old and Middle River
OMRI	OMR Index
PDSI	Palmer Drought Severity Index
ppt	parts per thousand
PSMFC	Pacific States Marine Fisheries Commission
R2R	Reorienting to Recovery
RAFT	River Assessment for Forecasting Temperature
RBDD	Red Bluff Diversion Dam
RM	River Mile
ROD	Record of Decision
RST	Rotary Screw Trap
SAC-SMA	Sacramento Soil Moisture Accounting
SaMT	Salmon Monitoring Team
SCHISM	Semi-implicit Cross-scale Hydroscience Integrated System Model
SDM	Structured Decision Making
sDPS	Southern distinct population segment
SFE	San Francisco Estuary
SFHA	Summer-Fall Habitat Action
SGMA	Sustainable Groundwater Management Act
SHOT	Shasta Operations Team
SIT	Science Integration Team
SJR	San Joaquin River
SKT	Spring Kodiak Trawl
SLS	Smelt Larva Survey

Acronyms and Abbreviations

xxi

SMT	Smelt Monitoring Team
SMSCG	Suisun Marsh Salinity Control Gates
SR	Sacramento River
SRG	Sacramento River Group
STARS	Survival, Travel time, and Routing Simulation
STN	Summer Townet
SWP	State Water Project
SWRCB	California State Water Resources Control Board
TCD	Temperature Control Device
TDM	Temperature-dependent Mortality
TMP	Temperature Management Plan
USACE	U.S. Army Corps of Engineers
USBR	U.S. Bureau of Reclamation
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
VIC	Variable Infiltration Capacity
WOMT	Water Operations Management Team
WRIMS	Water Resources Integrated Modeling System
WRLCM	Winter-Run Life Cycle Model
WTMP	Water Temperature Modeling Platform
WUA	Wetted Usable Area
ZOI	Zone of Influence

Summary

The Sacramento-San Joaquin Delta (the Delta) is formed by the confluence of two of California's largest rivers: the Sacramento, flowing south from its headwaters near Mount Shasta, and the San Joaquin, flowing north from its origins in the southern Sierra Nevada mountains. These rivers and their tributaries carry about half of the state's total annual runoff. Freshwater from the rivers mixes with saltwater from the San Francisco Bay and Pacific Ocean, forming one of the largest estuaries on the west coast of North America. The Delta, which spans about 738,000 acres in Northern California at the western edge of the Central Valley, is home to more than 627,000 people as well as 750 animal and plant species and 55 fish species.

Precipitation in California generally occurs between October and April, while municipal and industrial water demands are year-round, with agricultural demand at its highest during the growing season from April through August. To support growing demands for water supply development in California in the 20th century, two massive and interconnected systems of reservoirs, dams, and levees were constructed on the Sacramento and San Joaquin rivers: the Central Valley Project (CVP), overseen by the U.S. Bureau of Reclamation (USBR), and the State Water Project (SWP), overseen by the California Department of Water Resources (CDWR). The CVP can capture and store nearly 12 million acre-feet of water and it delivers, on average, 7 million acre-feet of water a year from Northern California and the Sierra Nevada to support about 3 million acres of farmland, about 2 million people in urban centers, and 19 wildlife refuges, most of them in the Central Valley. The SWP can capture and store about 4.2 million acre-feet of water and it delivers water to 750,000 acres of farmland, mostly in the southern San Joaquin Valley, and to households (including 27 million Californians) and businesses throughout much of the state.

The CVP and SWP (referred to collectively as “the Projects”) rarely deliver their full contracted amount of water. Some of this is inherent in the operation of large water projects with diverse demands in a dry and highly variable climate. A growing, complex regulatory environment of state and federal laws, some of which were created to protect fish species endemic to the Delta, has further restricted CVP and SWP operations.¹ These fish include the southern distinct population segment of North American green sturgeon, California Central Valley steelhead, Central Valley spring-run Chinook salmon, Sacramento River winter-run Chinook salmon, longfin smelt, and Delta smelt. Operating the Projects while trying to prevent species extinction can be a source of conflict if the actions to prevent extinction reduce the amount of water that can be exported. Project operation into the future will likely become more challenging as changes in various climatic factors push the listed species closer to their thresholds of survivability. Hence, in late 2023 USBR contracted with the National Academies of Sciences, Engineering, and Medicine (NASEM) to form an expert committee that could serve as an independent review for the CVP and SWP as they operate into the future. The Committee's statement of task appears in Box S-1. The three actions chosen for the study—the Shasta Coldwater Pool Management Action, the Old and Middle River Flow Management Action, and the Summer-Fall Habitat Action for Delta Smelt—are perceived as consequential for species survival and controversial for their effects on water deliveries to contractors.

Chapters 2 through 4 discuss the three specific actions, providing a description of the action; evaluating the monitoring, modeling, and decision support tools relevant to the action; and identifying science challenges including how certain climate impact drivers will affect the action. Chapter 5 explores the organization of the science enterprise in the Delta region, overarching modeling issues, and the action agencies' plans to address the increasing variability in precipitation and intensity of droughts as the

¹ As discussed in Chapter 3, salinity and flow requirements control project exports to a greater extent than Endangered State Act requirements.

actions are implemented into the future. Each chapter ends with conclusions and recommendations, the most important of which are compiled in this summary. Five appendices provide relevant background information on California climate and hydrology (A), the history of California water resources development and major features of the Projects (B), the regulatory framework under which the CVP and SWP operate (C), the monitoring networks and modeling used in CVP and SWP operations (D), and a general overview of the seven fish species endemic to the Delta region that are listed as threatened or endangered under the Endangered Species Act (E).

BOX S-1

NASEM Committee's Statement of Task

At the request of the USBR, an *ad hoc* committee of the National Academies of Sciences, Engineering, and Medicine will conduct a biennial review of the monitoring, modeling, and other relevant scientific activities and initiatives that support the long-term operations of the CVP. Along with the State Water Project, the CVP consists of coordinated federal-state water operations that annually move millions of acre-feet of water via dams, canals, tunnels, pumps, power plants and transmission lines from Northern California to a wide variety of water users throughout the state, including municipalities, agriculture, industries and wildlife refuges. Operation of the CVP affects species protected under the ESA such as the southern distinct population segment of North American green sturgeon, California Central Valley steelhead, Central Valley spring-run Chinook salmon, Sacramento River winter-run Chinook salmon, and Delta smelt.

In the first cycle of the study, the committee will:

1. Assess the state of science for the following topics as they relate to long-term operations of the CVP:
 - a. Old and Middle River (OMR) flow management
 - Salmonid route selection and survival
 - Delta smelt entrainment and recruitment
 - b. Shasta cold-water pool management
 - c. Summer–fall Delta smelt habitat
2. Provide recommendations on how modeling and monitoring strategies and decision-support tools can be changed, improved, or replaced to more accurately assess the impacts of the CVP operations described above.

SHASTA COLDWATER POOL MANAGEMENT

Shasta Reservoir, the largest storage reservoir in the CVP, is managed so that water is released to maintain flood conservation space, meet downstream flow and water delivery requirements, generate hydropower, and provide cold water to support populations of migrating winter-run Chinook salmon. Winter-run Chinook salmon historically migrated through the Delta and up the Sacramento River to spawn in the stable, cold, spring-fed headwaters of the Sacramento, Pit, and McCloud rivers during the summer. These historic spawning habitats were blocked by the construction of Shasta Reservoir, such that nearly all adult holding and spawning, as well as egg incubation and rearing, now takes place in an approximately 20 kilometer (km) reach of the Sacramento River below Keswick Dam, where summer water temperatures are much warmer. The Shasta Coldwater Pool Management Action aims to ensure that water cold enough to support winter-run Chinook adult holding and spawning and egg incubation is present in the reaches downstream of Keswick Dam over the summer months. To achieve this aim, USBR retains cold water in Shasta Reservoir until the summer and then operates a Temperature Control Device to blend water from warmer and colder layers within Shasta Reservoir during the appropriate summer months. The action is supported by a wide range of planning, monitoring, and modeling activities that assess physical and ecological conditions within the reservoir/river system. Finally, the action depends on

the winter-run Chinook salmon hatchery program to supplement natural recruitment, particularly in drought years.

As explained in Chapter 2, the existing scientific understanding supports a three-pronged approach to Shasta Reservoir management: (1) continuing to improve temperature management downstream of Keswick Dam, which currently is where the only significant population of spawning winter-run Chinook salmon can be found; (2) continuing hatcheries management; and (3) reintroducing winter-run Chinook salmon above Shasta Dam and in Battle Creek, which will be essential to the protection and eventual recovery of the species. Over the long term, the third approach should increase operational flexibility as well as create diverse ecological benefits supportive of multiple species and life history stages. The following specific conclusions and recommendations are made.

Recommendations 2-1 and 2-2: USBR should enhance the monitoring of (1) Shasta Reservoir and (2) rivers relevant to the coldwater pool management action.

Temperature sensors for rivers and lakes are inexpensive to install and maintain. Additional sensors in key locations could provide information that enhances the predictive accuracy of the Water Temperature Modeling Platform, which USBR created to modernize the analytical tools that it uses to support activities and decision making for water temperature management in CVP reservoirs for fishery species protection in downstream river reaches. The installation of four to six Lake Diagnostic Systems throughout Shasta Reservoir would help operators better understand how high-frequency physical dynamics within the reservoir (such as seiching and internal waves) affect the thermocline depth and generate more accurate estimates of the coldwater pool volume.

Recommendation 2-3: High levels of “unattributed mortality” of winter-run Chinook salmon eggs must be better understood, through research that defines specific pathways for reducing said mortality, in order to develop management actions that can increase confidence in the use of egg-to-fry survival as the principal focus for coldwater pool management.

The focus on temperature dependent mortality, interactive effects of multiple-stressors, and fine tuning of releases from the Shasta coldwater pool may increase survival, but even in years when temperature-dependent mortality is minimal, high mortality can still occur. Additional management actions supportive of winter-run survival can only be identified through an understanding of the influence of factors such as temperature, flow, habitat, substrate, pathogens, predation, and food quality and availability across all life stages. Ongoing studies investigating the temperature, dissolved oxygen levels, and flow through redds could evaluate the potential benefits of larger scale actions such as channel and floodplain restoration, gravel augmentation, and pulse flows in sustaining pool-riffle sequences and other geomorphic features conducive to spawning.

Recommendation 2-4: As tribes, CDWR, and other groups continue feasibility studies, USBR should develop an actionable plan to facilitate and support the reintroduction of winter-run Chinook salmon to historic spawning and rearing habitat above Shasta Reservoir and in Battle Creek.

The challenges to and operational constraints on coldwater pool management presented by rising air temperatures, reduced snowpack, and increased drought intensity place winter-run Chinook salmon at increasing risk. The only way to mitigate that risk, especially the risk of a catastrophic population crash associated with a more than three-year drought, is to safeguard some portion of the population in existing coldwater habitats.

OLD AND MIDDLE RIVER FLOW MANAGEMENT

The Projects divert large quantities of freshwater from the San Joaquin and Sacramento rivers, with some of the largest diversions occurring through the South Delta pumps: the C. W. “Bill” Jones Pumping Plant, operated by the San Luis & Delta-Mendota Water Authority for USBR, and the Harvey O. Banks Pumping Plant, operated by the CDWR. Operation of the pumps can promote water flow away from the Sacramento and San Joaquin rivers and toward the South Delta, leading to entrainment of the listed fish species at both pumping facilities (“take”)², meaning they are drawn toward water intakes for the pumps along with flowing water. Other impacts to fish caused by the pumps include changes to Delta channel flow patterns that reroute fish to places where habitat conditions are less optimal for survival, prevent fish from completing their natural migration, and make fish increasingly subject to predation. Salvage of some entrained fish occurs at both pumping plants, and the salvaged fish are trucked to one of six locations near the confluence of the Sacramento and San Joaquin rivers.

The Old and Middle River (OMR) Flow Management Action seeks to maximize the export of water while minimizing the adverse effects of pumping to fish populations when fish are rearing in and migrating through the Delta (December through June). The strategy is to limit exports during the migration season to control the magnitude of reverse flows in the Old and Middle River corridor just north of the pumps, based on real-time evaluation of environmental surrogates for Delta and longfin smelt and detections in salvage for winter-run and spring-run Chinook salmon and steelhead.

Chapter 3 makes three primary points. The OMR Flow Management Action, which uses fish “take” at the pumps, flow levels, and turbidity levels as triggers for placing limitations on pumping, has a reasonable scientific basis, although there are substantial uncertainties about how well each trigger correlates with fish protection. Reducing those uncertainties would require changes to monitoring and modeling. The most profound change would involve the development of a Delta-wide hydrodynamic model that enables mapping of the spatial and temporal influence of pumps, which in turn would allow water managers to move beyond management strategies that focus primarily on take at the pumps. The following specific conclusions and recommendations are made.

Recommendation 3-1: The underlying scientific bases of the thresholds and corresponding export reductions used in OMR flow management should be made available so that their use can be appropriately reviewed.

Although it did not thoroughly analyze each threshold value, the Committee noted examples of thresholds that are not scientifically defensible. More thorough use of validated hydrodynamic models and particle tracking models could help defend or refine these values.

Recommendation 3-3: To move OMR flow management beyond the use of salvage as a proxy for impacts on fish in the Delta, the monitoring and modeling in support of the action should evolve to address four questions:

- (1) What is the zone (or sphere) of influence of operations?
 - (2) What proportion of any given fish population is under that influence?
 - (3) What is the impact to fishes in these regions?
 - (4) What are the consequences of these impacts at the full population level?
- Several recommendations stem from adherence to this strategy.
- a. Fish spatial distribution and abundance throughout the Delta should be better assessed, using the latest technologies (e.g., underwater acoustics using both fixed and moving sensors, nocturnal aimed/instrumented midwater trawling) at higher temporal and spatial resolution than currently done.
 - b. Expanded modeling efforts should build upon USBR’s zone of influence analysis to study changes in key factors such as temperature, submersed aquatic vegetation, salinity and other

² See Appendix C for a more complete legal definition of “take.”

- water quality conditions across regions under a variety of Delta flow conditions, spanning dry to wet years, and under a range of pumping rates, using dimensionless flow ratios.
- c. Ultimately, higher resolution, expanded domain, and multi-parameter integrated modeling is required for full assessment of the Delta-wide impacts of exports on hydrodynamics, water quality, and fish.

Recommendation 3-4: Improvements in Delta channels, forebays, infrastructure, and operations might help to reduce Delta-wide native fish losses and should be studied for their potential to reduce the ecological impacts of pumping.

Hydrodynamic models could help USBR and CDWR explore opportunities to both dampen tidal dispersion and reduce the pumps' zone of influence via more effective Delta channels, forebays, fish screens, and tidal gates. USBR could assess the effects of building a separate forebay for the CVP, CDWR could assess ways to improve SWP forebay management, or the agencies could explore a joint forebay such as a flooded island.

SUMMER-FALL HABITAT ACTION FOR DELTA SMELT

Although the Delta smelt was once considered one of the most abundant fishes in the Delta, they are now extremely rare, with zero caught in most catch indices in recent years. The Summer-Fall Habitat Action (SFHA) seeks to address a seasonal bottleneck for juvenile Delta smelt survival by providing more low salinity habitat in the Suisun Marsh area during the summer and fall. The underlying hypothesis is that improving Delta smelt habitat by optimizing salinity, turbidity, temperature, and prey conditions, and by creating connectivity to food supplies, will support Delta smelt recruitment and population growth.

In its current form, the SFHA consists of three primary components: (1) management of the location of X2 (the 2 parts per thousand bottom salinity isohaline) in the fall and thereby the areal extent of the low salinity conditions that favor Delta smelt, (2) operation of the Suisun Marsh Salinity Control Gates to adjust salinity in Suisun Marsh (and secondarily in Grizzly Bay) and possibly enhance food provision in the summer, and (3) an additional supplemental release of 100,000 acre feet (100 TAF) of freshwater.

Chapter 4 concludes that the greatest uncertainty about the SFHA is the inability to detect a response to the action in fish populations. Several targeted lines of research could accelerate better implementation of the SFHA and increase understanding of the effectiveness of various SFHA components, including genetic analyses (e.g., eDNA, DNA of predator guts), laboratory and field studies to analyze the species of zooplankton consumed by smelt, and mark-recapture technology for improved smelt detection. As with the other two actions reviewed by the Committee, it is unlikely that the SFHA will be sufficient to lead to Delta smelt persistence and recovery. Many more components of the SFHA, and other actions systemwide, will be needed to prevent extinction of this endemic Delta fish. The following specific conclusions and recommendations are made.

Conclusion 4-1: USBR and CDWR are to be commended for embracing an ecosystem-based approach to protecting Delta smelt that attempts to overlay Delta smelt distribution with food supplies and the favorable habitat conditions of the low salinity zone.

However, over time some components of the SFHA believed to be necessary to generate food for resident native Delta fishes have been stopped. The action agencies are encouraged to pursue the identified special studies related to food and to commit to implementing the Suisun Marsh Salinity Control Gate component of the SFHA over multiple years in sequence.

Recommendation 4-1: Development of a process-based Delta smelt model in a spatial food-web context could greatly accelerate better implementation of the SFHA and increase understanding of the effectiveness of various SFHA components.

Ideally, this process-based model for Delta smelt and its prey would be linked to existing models on estuarine hydrodynamics and water quality, which would enable evaluation of how the SFHA ultimately affects Delta smelt reproduction, growth, mortality and seasonal movement. To achieve this level of prediction and analysis, monitoring may need to include the measurement of rates (e.g., zooplankton production) and not just static variables (e.g., standing crop) and should also examine zooplankton responses to action-mediated changes in water residence time. The Committee acknowledges that acquiring this modeling capacity will require targeted data collection and experimentation and possibly multi-year development horizons and investment across agencies.

Recommendation 4-3: An annual decision process for the SFHA founded on a series of environmental triggers that encompass more than water year type should be considered.

Lessons from previous SFHA implementation, such as the 2017 Fall X2 action, show that the response of Delta smelt may be determined by environmental conditions that are unrelated to water year type, including water temperature and antecedent conditions. The success of Fall X2 in a wet or above normal year may be dependent on the conditions in the previous year. A set of triggers (for example, related to temperature and food resources) for the Suisun Marsh Salinity Control Gate could be established based on expectations developed early in the year, identifying under what conditions the action would proceed and how. Closer to the time of the action, monitoring data based on the triggers could be used to adjust SFHA implementation.

OVERARCHING ISSUES

Cross-cutting issues that emerged from the Committee's analyses of Shasta coldwater pool management, OMR flow management, and the SFHA include the need to (1) enhance collaborative science to improve the pace and effectiveness of Bay-Delta watershed science efforts; (2) improve the modeling enterprise, with a focus on CalSim and ecological model integration; and (3) more strongly consider how changes in climate impact drivers will affect long-term operations. The following specific conclusions and recommendations are made.

Recommendation 5-1: A formal feasibility study should be undertaken to assess the potential for a Science Hub for the Bay-Delta and its watershed.

This hub must be fit-for-purpose and grounded in the needs and culture of the science community. It should be designed to develop solutions to problems that are difficult to address within existing agency or academic silos, without interfering with agency mandates or diminishing internal capacity. It should enhance institutional expertise by creating a collaborative environment where new approaches can be developed and tested, monitoring can be better coordinated, and cross-agency training can be implemented. It would also facilitate better coordination across the science that supports CVP and SWP activities.

Recommendation 5-2: Finer scale models are needed for water and ecosystem management in the Delta and its watershed.

In particular CalSim (which is now widely used to evaluate ecosystem impacts) would benefit from a finer time step (perhaps one week) coupled with explicit or empirical disaggregation to still finer

ecologically relevant time steps. With such capability, CalSim (or some other model) could then provide systematic hydrologic information for the more fully coupled hydrodynamic and population models needed for ecosystem management. Innovative ecosystem-wide approaches and quantitative life-cycle models could help to identify management actions that can contribute to species recovery. Monitoring should be tailored and managed to provide data at the spatial and temporal scales needed by the models.

Recommendation 5-3: CDWR and USBR should coordinate more closely and develop shared standards and protocols for modeling climate change impacts on the CVP and SWP.

Consistent protocols are essential for minimizing uncertainty in projected climate change impacts, particularly those arising from two sources: future greenhouse gas emission scenarios and model-related uncertainties (e.g., climate sensitivity). Moreover, CDWR and USBR should regularly update their modeling protocols to ensure alignment with current best practices in climate impact assessment. Finally, given the increasing evidence of more frequent compound events (i.e., multiple extreme events occurring simultaneously) and cascading events (i.e., extremes occurring in sequence), there is a pressing need for more detailed modeling studies to assess how such events may affect the Projects.

The three actions reviewed in this report are important elements of a broader effort to protect listed fish species while maintaining water-project operations. Each action has limitations and would benefit from improvements in related monitoring, modeling, and scientific understanding. In the near term, and perhaps for the long-term, maintaining and fine-tuning these actions will be necessary for achieving key CVP and SWP goals. Nonetheless, taken in isolation the individual actions will be insufficient to achieve species recovery; rather, ecosystem-wide thinking on the part of action agencies will be imperative.

1

Introduction

The State of California has the fourth largest economy in the world, behind only the United States, China, and Germany (Rao, 2025). California's economic success is heavily dependent on water, much of which comes from Northern California and flows through the Sacramento-San Joaquin Delta (the Bay-Delta or Delta), with a substantial portion diverted to the Central Valley and more heavily populated Southern California. Given California's highly variable precipitation, both within and across years, managing the water that moves through the Delta is a critically important state and federal responsibility. The fundamental challenge in the Delta of how to provide and distribute water to human, agricultural, and ecosystem needs is keenly dependent on science, particularly adequate monitoring and modeling.

BACKGROUND

The Sacramento-San Joaquin Delta is formed by the confluence of two of California's largest rivers: the Sacramento, flowing south from its headwaters near Mount Shasta, and the San Joaquin, flowing north from its origins in the southern Sierra Nevada mountains. These rivers and their tributaries carry about half of the state's total annual runoff. Freshwater from the rivers mixes with saltwater from the San Francisco Bay and Pacific Ocean, forming one of the largest estuaries on the west coast of North America. The Delta, which spans about 738,000 acres in Northern California at the western edge of the Central Valley, is home to more than 627,000 people as well as 750 animal and plant species and 55 fish species.¹ Indeed, Myers et al. (2000) highlighted the California Floristic Province, of which the Bay-Delta is a critical part, as one of the world's 25 priority hotspots of ecological diversity.

Precipitation in California generally occurs between October and April, while municipal and industrial water demands are year-round, with agricultural demand peaking during the growing season from April through August (see Appendix A for a complete discussion of California climate). To support growing demands for water supply development in California in the 20th century, two massive and interconnected systems of reservoirs, dams, and levees were constructed in the Sacramento and San Joaquin river basins (Figure 1-1). These are the Central Valley Project (CVP), overseen by the U.S. Bureau of Reclamation (USBR), and the State Water Project (SWP), overseen by the California Department of Water Resources (CDWR). The region also contains many other smaller water systems owned and operated by water utilities, power companies, and water management agencies.

The CVP can capture and store nearly 12 million acre-feet of water, and it delivers, on average, 7 million acre-feet of water a year from Northern California and the Sierra Nevada to about 3 million acres of farmland, about 2 million people in urban centers, and 19 wildlife refuges (Johnson, 2024), most of them in the Central Valley. In addition, the CVP provides hydropower for 650,000 people, as well as flood protection, navigation, and recreation benefits. The SWP can capture and store about 4.2 million acre-feet of water and it delivers an average of 2.5 million acre-feet of water a year (CDWR, date unknown). The SWP extends more than 705 miles (two-thirds the length of California) and delivers water to 750,000 acres of farmland, most of it in the southern San Joaquin Valley, and to households (including 27 million Southern Californians) and businesses throughout much of the state². A recent study found that the SWP supports 8.7 million fulltime jobs and 800,000 businesses, including 160,000 farmworkers, and provides water to 8.2 million people in disadvantaged communities (Sunding et al., 2023). The water

¹ See <https://deltacouncil.ca.gov/frequently-asked-questions>.

² See <https://water.ca.gov/programs/state-water-project>.

supply commitments of the CVP and SWP (collectively referred to as “the Projects”) are outlined in hundreds of contracts (as described in Appendix B).



FIGURE 1-1 Map of California showing the Delta and the major features of the Central Valley Project and State Water Project.

SOURCE: Chapter 3 of DSC (2018).

Operational Context

The Projects were originally proposed to send surplus fresh water to the Central Valley and Southern California, and to help recharge groundwater, all while preventing salinity intrusion into the Delta and the water intakes. The operations of the CVP and SWP are coordinated by the USBR and CDWR. The two agencies must account for climatic conditions; water supply commitments of the CVP and SWP contracts; infrastructure limits (e.g., reservoir capacities, pumping constraints); flood operations and preparations; multiple statutes including the Endangered Species Act (ESA), the Clean Water Act (CWA), the National Environmental Policy Act (NEPA), and state versions of these federal laws; water rights; and licensing requirements for dams. The coordination of CVP and SWP operations occurs in a framework established in a Coordinated Operating Agreement (COA), approved in 1986 and amended in 2018 by California and the United States (DOI and CA Resources Agency, 1986). The 2018 COA (USBR and CDWR, 2018) updates and formalizes earlier agreements dating back to 1960.

Daily calculations are made to determine whether the Delta is in so-called “balanced conditions,” which occur when releases from upstream reservoirs plus unregulated flow approximately equal the water supply needed to meet Sacramento Valley in-basin uses, plus exports (USBR and CDWR, 2018). Excess water conditions are periods when it is agreed that releases from upstream reservoirs plus unregulated flow exceed Sacramento Valley in-basin uses, plus exports. Whether the Delta is experiencing balanced or excess conditions determines how much water the CVP and SWP are responsible for releasing from reservoirs or are allowed to pump. The COA specifies how much of the water stored in CVP and SWP facilities must support Sacramento Valley in-basin water uses and how Delta export capacity is to be shared. The COA also specifies the flow and storage measurements and forecasts to be made for each project, as well as repayments for expenses when one project’s facilities are operated to benefit the other project.

To allocate water, USBR and CDWR use annual assessments of water availability. They adjust those assessments as each water year develops. They also convene periodic operational meetings to help coordinate and adjust operations, with adjustments informed by the COA, water supply and flood control needs, and various environmental requirements. Flood management is a shared responsibility of multiple federal, state, and local agencies, including the U.S. Army Corps of Engineers. Operators of both the CVP and SWP are housed at a joint operations center in Sacramento. Coordination meetings are held at daily to quarterly intervals, depending on the topic, and involve staff from key state and federal agencies (see Table 1-1).

Both the CVP and the SWP draw water from heavily allocated river systems, and water supplies are often insufficient to meet all the demands of users that have contracts with the Projects for water deliveries. Factors that impact the ability of the Projects to deliver water for agricultural, municipal, and industrial uses include variability in precipitation, upstream diversions from the Delta’s tributary basins, and environmental mandates for such things as Delta outflows, water quality, fish migration pathways, and entrainment prevention at the pumps. Future climate conditions, characterized by warmer temperatures, more intense winter precipitation, prolonged droughts, reductions in snowpack, and increasing demand due to rising temperatures are expected to exacerbate these challenges by further reducing water availability or altering the times when water is available.

Environmental Context

The construction and operation of the CVP and SWP have had major effects on fish native to the Bay-Delta watershed. Many of those fish species are now listed as threatened or endangered, by both state and federal agencies (Box 1-1; Appendix E). These listed species include the Sacramento River winter-run Chinook salmon, Central Valley spring-run Chinook salmon, Delta smelt, longfin smelt, California Central Valley steelhead trout, and the southern distinct population segment of North American green sturgeon. (White sturgeon has threatened status at the state level, pending a review in 2025.)

TABLE 1-1 CVP and SWP Operations Teams

Meeting/Event	Frequency	Participants	Purpose
Daily Operations Coordination Meetings	Daily	USBR, CDWR, Joint Operations Center staff	Coordinate current reservoir releases, Delta pumping, and forecast-based adjustments.
Meeting of the Smelt Monitoring Team, Salmonid Monitoring Team, Delta Monitoring Workgroup	Weekly during OMR season (more frequent in critical periods) or as needed	CVP and SWP staff from CDWR and USBR, NMFS, USFWS, CDFW, SWRCB, stakeholders	Review real-time Delta conditions, fish presence, and water quality, and coordinate pumping/fish protections.
Meeting of the Sacramento River Group and JPE Subteam, American River Group, Stanislaus Watershed Team, Clear Creek Technical Team, Trinity River Temperature Task Group, Delta Coordination Group, DRY Team	Monthly, or as needed	Same as above	Ensure operational endangered species protection and regulatory compliance
Meeting of the Water Operations Management Team	Weekly during OMR season or as needed	Senior agency representatives from USBR, CDWR, NMFS, USFWS, CDFW, SWRCB	Make strategic decisions, resolve conflicts elevated from other teams.
Meeting of the Shasta Operations Team	Monthly, or as needed	Senior agency representatives from USBR, CDWR, NMFS, USFWS, CDFW	Make strategic decisions, resolve conflicts elevated from other teams, manage assets for voluntary agreements
Quarterly Outages, Operations and Maintenance Coordination Meeting	Quarterly	USBR, CDWR, WAPA, and SLDMWA	Plan for long-term maintenance, equipment outages, and infrastructure coordination.

NOTES: WAPA= Western Area Power Administration; SLDMWA= San Luis and Delta-Mendota Water Authority.

Dams and levees built around the rim of the Central Valley floor have prevented many fish species from reaching their historical habitats and spawning grounds, limiting their reproductive success (Hanak et al., 2011). Water diversions for agricultural, industrial, and municipal uses have also impaired passage for both returning adult fish and outmigrating juveniles, partly by altering the hydrodynamics of the Delta (Hassrick et al., 2022; Perry et al., 2015; Sturrock et al., 2020; Brown et al., 2024). Warm water conditions caused by the construction and operation of the Projects and exacerbated by a warming climate are less compatible with spawning, incubation, and rearing requirements of the listed fish species (Slater, 1963; Willis et al., 2021; see Appendix E).

BOX 1-1 Declines in Fish Abundance in the Bay-Delta

Six fish species in the Bay-Delta have seen dramatic declines in abundance in the last few decades and are listed as threatened or endangered under the Endangered Species Act. Brief descriptions of these declines and relevant abundance data are presented below for three of the fish: Delta smelt, longfin smelt, and Sacramento River winter-run Chinook salmon. Appendix E provides a lengthier description of the life history of each listed fish, along with information on species monitoring, conceptual models and quantitative life cycle models for the species, how the Projects and other major stressors affect the species, the role of hatcheries in maintaining the population, and key uncertainties.

Delta smelt (*Hypomesus transpacificus*) experienced a major decline during the early 1980s, followed by substantial fluctuations during the 1990s. This was followed by an abrupt decline in the early 2000s that was part of the pelagic organism decline (Sommer et al., 2007). In 2022, the Spring Kodiak Trawl abundance index was 1.7, which is the fourth lowest on record (USBR, 2024a). The 2023 actual abundance was estimated to be 4,656 adults (95% CI: 1,178–12,730), which is the lowest since that survey began in 2002 (see Figure 1-2A).

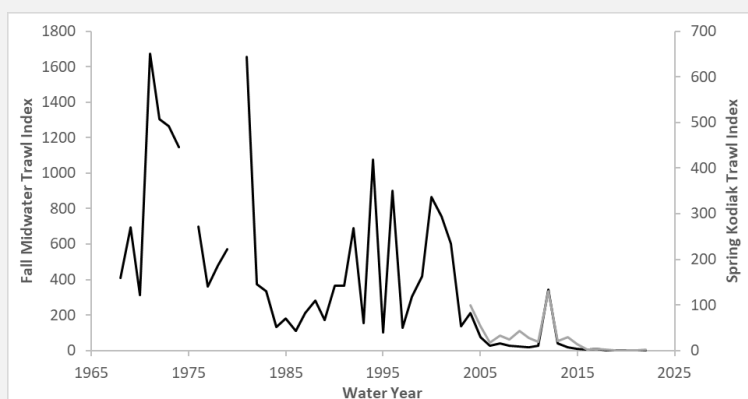


FIGURE 1-2A Abundance indices for Delta smelt. The black line shows the time series of the Fall Midwater Trawl (water years 1968–2023) and the gray line shows the time series of the Spring Kodiak Trawl (water years 2004–2022). SOURCE: USBR (2024a).

Longfin smelt (*Spirinchus thaleichthys*) were historically very abundant in the San Francisco Bay estuary. Over the past few decades, species abundance has progressively declined. Longfin smelt is also part of the pelagic organism decline in the Bay-Delta, having declined to about 1 percent of their former abundance, as shown in Figure 1-2B.

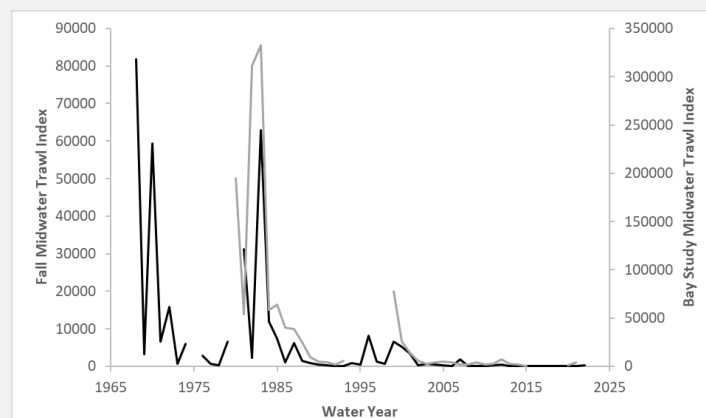


FIGURE 1-2B Abundance indices for longfin smelt. The black line shows the time series of the Fall Midwater Trawl Survey (water years 1959–2022), and the gray line shows the time series of the Bay Study Midwater Trawl Survey (water years 1995–2021). SOURCE: USBR (2024b).

continued

BOX 1-1 continued

Sacramento River winter-run Chinook salmon (*Oncorhynchus tshawytscha*) populations have declined substantially since the early 1970s. According to the National Marine Fisheries Service (NMFS; 2024a), threats to the species have changed over the years, with disease and predation adding to problems created by poor spawning habitat and migratory corridor habitat. Figure 1-2C shows annual escapement^a data for winter-run Chinook salmon from 1970 to 2021.

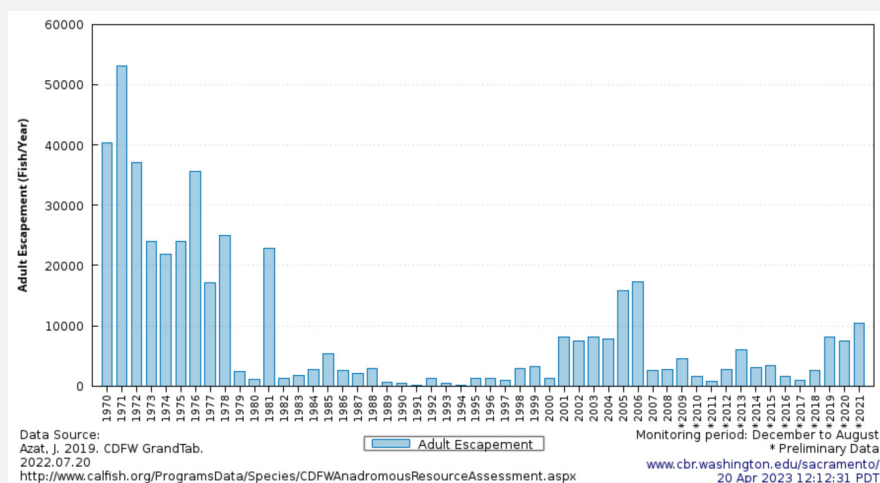


FIGURE 1-2C Winter-run Chinook salmon adult annual escapement in the Central Valley, 1970–2021. Note these data include both natural and hatchery origin Chinook.
SOURCE: USBR (2024c).

^a Escapement refers to the number of salmon that “escape” fisheries (i.e., are not harvested) and return to fresh water to spawn (<https://www.npafc.org/salmon-escapement/>).

Beyond the significant effects stemming from the Projects, other stressors adversely affect fish, including contamination from terrestrial runoff in the watersheds draining into the Sacramento and San Joaquin Rivers and the Delta (Hammock et al., 2015; Stillway et al., 2024), land use changes in the Delta region that have altered food webs and reduced vital energy pathways for fish (Moyle et al., 2011; SFEI, 2014; Whipple et al., 2012), an increase in nonnative species that thrive in the degraded Delta habitat and compete with or prey on native species (DISB, 2024; Hagani et al., 2023; Sommer et al., 2007), and the loss of genetic integrity of some listed fish species (Bert et al., 2007; Brown and Moyle, 1991; Moyle et al., 2011; Quiñones et al., 2014).

The combination of all of these stressors has led to dramatic loss of listed fish populations over the last half century (Mount et al., 2012), with particularly significant declines since 2000 for pelagic fish (Sommer et al., 2007). Indeed, the term “pelagic organism decline” was coined to describe the reduction, primarily between 2000 and 2005, in fish abundance for the four major pelagic fishes of the upper estuary (i.e., Delta smelt, longfin smelt, striped bass, and threadfin shad). These fish vary widely in their life histories and estuary use, suggesting the presence of systemic ecological problems.

The environmental stressors outlined above have been exacerbated by hot and dry periods over the past few decades that are likely to intensify in the coming years. As discussed in greater detail in Appendix A, average annual precipitation varies greatly both interannually and spatially among California’s 11 climate regions. Although no long-term trend in California statewide precipitation is apparent (OEHHA, 2022), the interannual variability in precipitation amounts has increased, with a steep increase in variability occurring during the mid-1970s (Figure 1-3). Indeed, compared to the first half of the 20th century, many fewer years in the past 80 years reflect so-called average conditions. Along with

sea level rise, warming of air temperature, and an increasing intensity of both droughts and atmospheric rivers, this rise in variability of precipitation is expected to further challenge efforts to maintain and enhance populations of listed fish species.

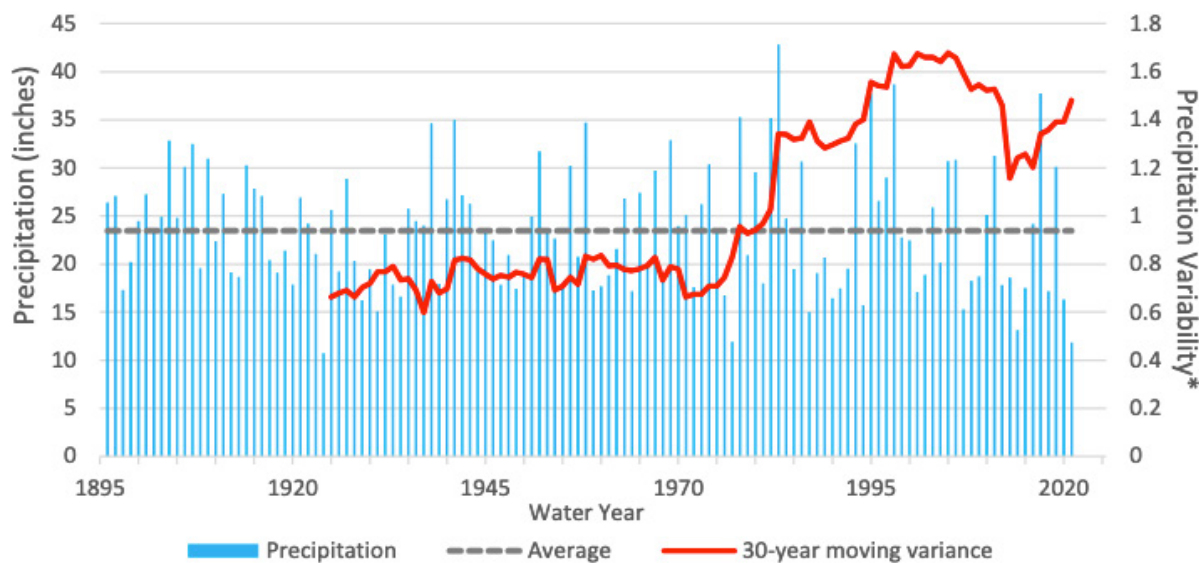


FIGURE 1-3 Annual precipitation variability in California, 1895–2020.

NOTE: Annual variability is the ratio of the variance for the 30-year period ending in that year to the variance over the entire period. A ratio above 1 means precipitation was more variable; below one, less variable.

SOURCE: OEHHA (2022).

California's generally dry, strongly seasonal hydrology, with frequent droughts and high and diverse water demands, brings perennial water management challenges and controversies. When and where water is naturally available in California's Central Valley is poorly matched with when and where water is needed for agricultural and urban uses, as depicted in Table 1-2. That is, most precipitation and streamflow occur in winter, while the water demands of cities and agriculture are highest in the summer. This mismatch had led to the development and operation of major federal, state, and local water projects in California and throughout the American West.

Because California's precipitation varies greatly from year to year, and within each water-year, water operations, contractual deliveries, and other aspects of water supply also vary from year to year according to a coarse classification adopted by state and federal agencies. Each water year, which spans from October 1 to the following September 30, is classified by type: Wet (W), Above Normal (AN), Below Normal (BN), Dry (D), or Critically Dry (C) (CDWR, 1989, 1991). These classifications are assigned based on a water-year index, which is calculated using estimates of unimpaired streamflow for the year and sometimes unimpaired flow from the previous year.

The water-year-type classifications were originally developed for water allocation and environmental purposes relevant to CVP and SWP operations, and they affect each of the three actions reviewed in this report differently. The coarse classification of five water-year types does not reflect seasonal dynamics, regional and subbasin conditions, the availability of stored water, or other factors often important for both water allocation and environmental water management. More fine-grained or multi-dimensional classifications might be useful for implementing environmental protections (e.g., water-year types that also account for temperature, fish populations, tides, or other state variables).

(Murdoch 2024; Null and Viers, 2013), but the Committee did not consider alternative classifications in detail.

The ecosystems of the Delta, along with the operations of the water supply projects, are particularly complex because the Delta is a seasonally and tidally flushed network of rivers, sloughs, canals, and channels. Indeed, most internal Delta flows are driven by the 6-foot tides that occur twice daily. For most of the year and for most years, tidal flows are responsible for the mixing and transport of salts, nutrients, particulate matter, and many organisms within the Delta (Brown et al., 2024). Large seasonal, interannual, and operational fluxes in freshwater flows are important in modifying the effects of these underlying tidal flows.

TABLE 1-2 Seasonality of California Hydrology, Infrastructure Capacity, Water Demands, Actions, and Fish Life Histories Relevant to the California Bay-Delta

	October	November	December	January	February	March	April	May	June	July	August	September
Hydrology	Wet Season - precipitation, floods						Dry season - rarely significant precipitation					
	No snow	Snow accumulates					Snow melts			Snow mostly gone		
	Twice-daily tides of 4-7 feet that drive Delta mixing, flows, and inundation of wetlands											
Infra-structure	Low storage	Reservoirs fill as they can							Reservoir storage withdrawals			
Delta pumping	Pumping variously limited by Delta salinity, pumping capacity, downstream storage, water demands, and environmental regulations											
Water demands							Main irrigation season for agriculture and urban areas					
	Indoor residential, commercial, and industrial water uses											
	Middling hydropower prices				Lowest hydropower prices			Highest hydropower prices				
Actions							Shasta coldwater pool management					
			OMR flow management									
									SFHA			
Winter-run salmon			Returning adults									
							Spawning					Holding
	Holding		Juveniles out-migrate									
Spring-run salmon						Returning adults					Spawning	
	Spawning	Holding	Juveniles out-migrate									
Delta smelt	Adults									Adults		
			Spawning, eggs, and larvae									
			Juveniles									
Longfin Smelt	Returning adults						Juveniles out-migrate; spend 1½ years at sea					
	Spawning with peak in February; adults die; eggs											
Steelhead	Returning adults											
			Spawning, egg emergence									
			Juveniles out-migrate									
Green Sturgeon					Returning adults		Spawning					
	Adults outmigrate mainly fall and winter; juveniles rear in Delta year-round for 1-4 years											

NOTES: OMR – Old and Middle River; SFHA – Summer-Fall Habitat Action.

Regulatory Context

The challenges of operating the Projects have grown since the 1960s, partly because of the promulgation of laws that require water quality protection and protection of native fish species, which evolved in extensive pre-development habitats and in the variable flows of the watershed's natural hydrology. Growing water demands and water diversions from groundwater pumping also have made Project operations and how they respond to environmental regulations more complex over time. The current governing legal frameworks are discussed in Appendix C of this report in great depth. What follows is an initial and general overview.

General Administrative Law Principles

The CVP and SWP are managed by USBR and CDWR, respectively, both of which are administrative agencies. Under federal and state law, agencies obtain their authority through legislation, and that authority is also bounded by governing legislation. As the U.S. Supreme Court has stated, “an agency literally has no power to act... unless and until Congress confers power upon it.”³ That general principle means that USBR and CDWR have management discretion only to the extent that it is conferred upon them by state and federal statutes. USBR and CDWR are also bound by both federal and state laws. Under Section 8 of the Reclamation Act of 1902, USBR obtains and exercises its water rights “in conformity” with state law,⁴ which means that the California State Water Resources Control Board (SWRCB) has regulatory authority over USBR’s water rights and that USBR operations are constrained by some state-law provisions.⁵ The Supremacy Clause of the U.S. Constitution gives the federal government regulatory authority over states, and while some key provisions of federal statutes apply only to federal agencies, others apply more generally.

Project management decisions are also based on water rights and contracts. USBR and CDWR obtain their water rights through California’s water-rights system, which is based partly on principles of “prior appropriation.” In a prior appropriation system, older or “senior” water rights receive their water before newer or “junior” rights do.⁶ Because irrigated agriculture was well established in the Central Valley before the CVP and SWP were built, each project’s water rights are relatively junior, and more senior water users’ rights must be satisfied before the Projects are allowed to divert water. The CVP and SWP serve several groups of contractors who had water rights before the Projects existed. As discussed in Appendix B, these “settlement” and “exchange” contractors have priority within the system. California’s water rights system also recognizes riparian rights, which allow water diversions by waterfront landowners, and project exports are generally subordinate to the water uses of the many riparian-right holders in the Bay-Delta watershed.⁷ For these reasons, and also because “area of origin” laws have limited water exports,⁸ CVP and SWP operations are especially vulnerable to drought conditions, because earlier-established water users have priority when water is allocated.

The CVP and the SWP both deliver water to end users, and those end users have contracts for CVP and SWP water rather than hold the water rights themselves.⁹ The contracts are complex and include water shortage provisions. Both federal and state contracts specify maximum delivery amounts but do not require delivery of those amounts. Instead, USBR and CDWR deliver water to the extent that it is available, accounting for not only the limits of precipitation and storage and the needs of senior water

³ Louisiana Pub. Serv. Comm’n v. FCC, 476 U.S. 355 (1986).

⁴ See 43 USC §383, which states: Nothing in this Act shall be construed as affecting or intended to affect or to in any way interfere with the laws of any State or Territory relating to the control, appropriation, use, or distribution of water used in irrigation, or any vested right acquired thereunder, and the Secretary of the Interior, in carrying out the provisions of this Act, shall proceed in conformity with such laws, and nothing herein shall in any way affect any right of any State or of the Federal Government or of any landowner, appropriator, or user of water in, to, or from any interstate stream or the waters thereof.

⁵ See, e.g., *California v. United States*, 438 U.S. 645, 650, 678 (1978); *Natural Resource Defense Council v. Patterson*, 333 F.Supp.2d 906, 913-14 (E.D. Cal. 2004). Section 101(b) of Public Law 99-546, enacted in 1986, also requires the Bureau of Reclamation to manage the Central Valley Project consistently with state water quality standards.

⁶ See https://www.waterboards.ca.gov/waterrights/board_info/faqs.html.

⁷ An exception to this general principle arises if the freshwater that riparian-right holders hope to divert would not be present if not for project operations. This could happen in the late summer and fall or dry years, when releases of stored water from the projects is responsible for maintaining freshwater conditions in parts of the Delta.

⁸ See Craig M. Wilson, *California’s Area of Origin Laws* (2013), https://www.waterboards.ca.gov/board_info/agendas/2013/oct/100813_7origin.pdf.

⁹ Some of the contractors have separate water rights to non-CVP and non-SWP water.

users but also constraints imposed by environmental laws and the need to prepare for future dry years.¹⁰ Some of those laws, such as the Central Valley Project Improvement Act, are specific to the Projects; some, like California's Delta Protection Act, apply regionally; and others, such as NEPA, apply nationally. A summary of these laws appears in Appendix C.

For the elements of CVP and SWP operations addressed in this report, two of the most important laws are the federal and state Endangered Species Acts.¹¹ Both ESAs are designed to prevent extinction¹² and facilitate recovery of species, as described in Box 1-2. They require implementing agencies—the U.S. Fish and Wildlife Service (USFWS) and the National Marine Fisheries Service (NMFS or National Oceanic and Atmospheric Administration [NOAA] Fisheries), for the federal statute, and the California Department of Fish and Wildlife (CDFW), for the state statute—to list species that are in danger of going extinct. Once listed, those species receive several protections (Box 1-2). Most importantly, the federal ESA prohibits federal agencies from actions likely to jeopardize the continued existence of listed species or to adversely modify their critical habitat [16 USC §1536(a)(2)]. It also prohibits unauthorized takes of endangered and some threatened species, and the definition of “take” includes acts that unintentionally kill, wound, or harm protected species (16 USC §1538)—a requirement echoed by California's ESA (CA Fish & Game Code §2080). Many operating constraints on CVP and SWP operations stem from these legal prohibitions. The federal operating constraints are often contained in documents called biological opinions, to which the remainder of this report will often refer.

Although the ESAs are perhaps the most prominent environmental laws that apply to the Projects, many other laws are important. Under the federal Clean Water Act and California's Porter-Cologne Water Quality Control Act, the State of California sets water quality standards, including requirements for salinity control (33 USC §1313; CA Water Code 13241). For much of a typical year, those standards are the primary controls on CVP and SWP pumping levels (Gartrell et al., 2017). The SWRCB's Decision D-1641 is the rulebook for implementing the 1995 Water Quality Control Plan, and D-1641 assigns responsibility for meeting flow, salinity, and Delta outflow standards to USBR and CDWR. The Central Valley Project Improvement Act specifies environmental flow requirements and establishes goals for the recovery of salmonid populations.¹³ NEPA and, for state projects, the California Environmental Quality Act (CEQA) require analysis of discretionary new agency actions, and although many elements of the CVP and SWP predate NEPA and CEQA, both statutes can apply to significant changes in the projects.¹⁴ California Fish and Game Code section 5937 requires operators of dams to maintain below-dam fish populations “in good condition.”¹⁵ Furthermore, all surface water rights in California are subject to the state's public trust doctrine and to California's constitutional requirement that limits water rights to

¹⁰ See *O'Neill v. United States*, 50 F.3d 677, 684 (9th Cir. 1995) (“We conclude that the contract's liability limitation is unambiguous and that an unavailability of water resulting from the mandates of valid legislation constitutes a shortage by reason of ‘any other causes.’”).

¹¹ The committee acknowledges that salinity control drives most restrictions on exports. However, for the three actions that this report evaluates, the state and federal Endangered Species Acts are critical, and hence this report focuses on the controls brought about by the ESA.

¹² Biologists sometimes distinguish “extinction,” which involves the complete loss of a species (as a biologist would use the term “species”), and “extirpation,” which involves the loss of some distinct population of the species. In contrast, the federal ESA does not use the term “extirpation,” and it defines a species as being in danger of extinction if it might disappear in “all or a significant portion” of its range. Thus, the Act treats the term “extinction” as including situations where a biologist might use “extirpation.” This report uses the term “extinction” in the ESA sense because of the importance of the ESA to agency decision-making for the three actions.

¹³ See *San Luis & Delta Mendota Water Auth. v. U.S.*, 672 F.3d 676, 684-85 (9th Cir. 2012) (summarizing the act's requirements).

¹⁴ 42 USC §4332(C); *Cleveland Nat'l Forest Found. v. San Diego Ass'n of Gov'ts*, 397 P.3d 989, 992 (Cal. 2017) (describing CEQA).

¹⁵ *Natural Resource Defense Council v. Patterson*, 333 F. Supp. 2d at 913-14.

reasonable uses.¹⁶ Both of these doctrines can be somewhat vague in their requirements, but they both apply to the CVP and SWP, and both can be the basis for environmentally motivated restrictions on project operations.

BOX 1-2

ESA for Species Recovery Versus Prevention of Extinction

A question for agencies as they strive to comply with the ESA is whether the end goal is species recovery or merely prevention of extinction. The latter goal is obvious from the statute's text, and sometimes commentators and implementing agencies can assume that extinction prevention is the statute's sole focus—or, at least, is the sole focus of its regulatory provisions.

Nevertheless, the ESA is concerned with *both* survival and recovery. The Act opens with a statement of purpose, which refers to “conserving” and the “conservation” of species. The next section states that “[t]he terms ‘conserve’, ‘conserving’, and ‘conservation’ mean to use and the use of all methods and procedures which are necessary to bring any endangered species or threatened species to the point at which the measures provided pursuant to this chapter are no longer necessary.” In other words, the statute's core goal is to recover species.

Multiple other sections of the statute specifically focus on recovery. Section 4 governs species listings and requires recovery plans. Sections 5 and 6 authorize federal land acquisitions and cooperation with state programs, respectively, and speak of the need to “conserve” species. Section 7(a)(1) states that “[a]ll ... Federal agencies shall, in consultation with and with the assistance of the Secretary, utilize their authorities in furtherance of the purposes of this chapter by carrying out programs for the conservation of [listed] species.” Section 7 also requires federal agencies to avoid taking actions that adversely modify the critical habitat of listed species, defined as habitat that is “essential to the conservation of the species.”

Recent Changes to the Biological Opinions

In late 2024, USFWS and NMFS issued new biological opinions for endangered and threatened fish in the Bay-Delta region (NMFS, 2024b; USFWS, 2024). Both agencies' biological opinions also contained “incidental take statements,” which conditionally authorize takes of listed species, and CDFW also issued an incidental take permit (CDFW, 2024). These documents have substantial impacts on CVP and SWP operations because they limit the number of fish that can be taken as the Projects supply water to their contractors and specify a range of operating conditions designed to limit takes. Biological opinions for this system have been produced about every ten years, although in the recent past reconsultation has become more frequent. In response to each biological opinion/incidental take permit, USBR and CDWR produce a revised plan of operations for the CVP and the SWP (e.g., USBR EIS, 2024). These operations have multiple components, most of which fall under the category of reservoir and system operational changes and flow-related actions, including altering reservoir storage, managing system flows, and managing temperature regimes to benefit listed species. Other components include habitat restoration projects, facility improvements, use of hatcheries, and special scientific studies. These components are supported by real-time biological and physical monitoring and modeling of the Projects, the results of which are used in decision making.

¹⁶ See *Northern Cal. Water Ass'n v. State Water Resources Control Bd.*, 230 Cal. Rptr. 3d 142, 166 (Cal. Ct. App. 2018). As the court explained, “the USBR operates the CVP and allocates CVP water *subject to* a comprehensive scheme of environmental statutes and regulations, and various state and federal regulations. . . . Moreover, the CVP contractors take their interest in the USBR's water rights subject to these legal obligations... and the USBR cannot give away more than it has.”

SIZE AND SCOPE OF THE DELTA SCIENCE ENTERPRISE

Numerous parties in the Delta region have contributed to the overall science enterprise that informs management of the Projects, including USBR, CDWR, USFWS, NMFS, CDFW, SWRCB, the U.S. Geological Survey (USGS), the Delta Stewardship Council (including the Delta Science Program), electrical utilities, Native American tribes, environmental nongovernmental organizations (NGOs), water contractors, researchers from many universities, consultants, and others. Table 1-3 lists many of the organizations that have a stake in Project operations and also conduct or fund research relevant to the Delta science enterprise, each with different missions and combinations of expertise. These organizations are often aided by a large number of specialized and general consulting firms that are important to maintaining scientific activities and disseminating ideas among agencies. Long-term success for managing such a complex and controversial system as the CVP and SWP will be more likely if the scientific activities of the many federal, state, local and regional, nongovernmental, and academic institutions are coordinated and organized. The effectiveness and improvement of this broad enterprise are addressed in Chapter 5.

The public meetings that informed this review underscored the strong scientific and engineering expertise of California state agencies and sister federal agencies staff. Furthermore, collaborative relationships exist among these entities, as evidenced by the Delta Plan Interagency Implementation Committee, the Interagency Ecological Program, the independent coordination and review role of the Delta Science Program, the Collaborative Science and Adaptive Management Program (CSAMP), and many other efforts. Innumerable scientific discoveries and technological advances have benefited the management of the Projects and informed understanding of the Delta ecosystem. Benefits of the agency commitment to the application of best science and collaboration, many of which are cited throughout this report, include the improved understanding of fish life cycles (Hendrix et al., 2014, 2019), the role of nutrients and contaminants in ecosystem health (Brown et al., 2024; Dahm et al., 2016; DISB, 2018), and the development and application of new modeling tools (Abrahamsson, 2023; MacWilliams et al., 2016; Wang et al., 2024). These and many other advances have informed laws and policies, guided water operations, protected human health, and led to a substantial knowledge base to guide the recovery of the Delta and its watershed. Sustaining and continuing this legacy of interagency science collaboration is essential to meeting the long-term goals of the Projects.

REQUEST FOR THE STUDY AND STATEMENT OF TASK

The previous sections have outlined the complexities of CVP and SWP operations. Inherent to the operation of large water projects with diverse demands in a dry and highly variable climate, the Projects rarely deliver their full contracted amount of water or completely fulfill all their mandated and contractual expectations. Furthermore, the Projects function within a complex regulatory environment of state and federal laws created to protect water quality and prevent fish species native to the Delta and estuary from going extinct. This task will become more challenging as rising temperatures and changing precipitation patterns complicate water quality protection and push the listed species closer to their thresholds of survivability. Presently, despite USBR and CDWR's efforts to comply with the ESA and reduce take, the abundance of listed species continues to decline, with some nearing extinction (Box 1-1; Hobbs et al., 2017). There is disagreement about whether and how much to hold the Projects responsible for the observed fish population collapses, and what should be the future obligation of the action agencies to prevent further species decline and to recover fish populations.

TABLE 1-3 Examples of Organizations Contributing to the Science Enterprise That Informs Water Management and Policy in the Central Valley and Delta

California Agencies	
Water project action agencies	California Department of Water Resources ^a
Regulatory agencies	California Department of Fish and Wildlife, ^a State Water Resources Control Board, ^a Delta Stewardship Council, ^a Central Valley Regional Water Quality Board, ^a San Francisco Bay Regional Water Quality Board, ^a Delta Protection Commission, Delta Conservancy, Delta Watermaster
Federal Agencies	
Water project action agencies	U.S. Bureau of Reclamation, ^a U.S. Army Corps of Engineers ^a
Regulatory agencies	National Oceanic and Atmospheric Administration National Marine Fisheries Service, ^a U.S. Fish and Wildlife Service, ^a U.S. Environmental Protection Agency
Nonregulatory agencies	U.S. Geological Survey ^{a,b}
Local and Regional Agencies	
Water supply organizations	Metropolitan Water District of Southern California, ^a State Water Contractors, ^a Sacramento River Settlement Contractors, East Bay Municipal Utility District, Turlock Irrigation District, Modesto Irrigation District, Westlands Water District, Kern County Water Agency, Contra Costa Water District, Santa Clara Valley Water District, Central Delta Water Agency, Valley Water, ^a San Luis & Delta-Mendota Water Authority, San Joaquin River Exchange Contractors Water Authority, American River agencies
Flood control agencies	Sacramento Area Flood Control Agency, Reclamation districts, regional water authorities.
Hydropower	Northern California Power Agency, Western Area Power Authority, Roseville Electric Utility, City of Palo Alto Electric Utility, Trinity Public Utilities District, Yuba County Water Agency
Wastewater Dischargers	Sacramento Regional County Sanitation District
Tribes	Winnemem Wintu, Yurok, Karuk, Shingle Springs Rancheria, Hoopa, Miwok
Universities	University of California campuses, ^a California State University campuses, ^a Stanford University, ^a others
Nongovernmental Organizations	Coalition for a Sustainable Delta, Pacific Coast Federation of Fishermen's Associations, Institute for Fisheries Resources, Golden State Salmon Association, Save California Salmon, Friends of the River, Defenders of Wildlife, California Trout, The Nature Conservancy, ^a The Bay Institute, American Rivers, Center for California Water Resources Policy and Management
Non-advocacy Science Organizations	Public Policy Institute of California, ^a San Francisco Estuary Institute ^a

NOTE: This table is not exhaustive.

^a Groups with major science and technical staff.^b USGS provides the 'gold standard' for generating water and ecological data as well as the field experience and logistics to advise other entities on supplemental studies or monitoring.

It was in the midst of grappling with this complicated scientific, regulatory, and sociopolitical environment that USBR engaged in nearly two years of planning discussion to finally contract, in late 2023, with the National Academies of Sciences, Engineering, and Medicine (NASEM) to form an expert committee that could independently review the science supporting CVP and SWP operations. Similar to the National Academies' review of the Greater Everglades Restoration Program (e.g., NASEM, 2021, 2023, and 2024), this Committee was tasked to produce biennial reports that assess the progress of the Projects to meet various operational and other goals. This first report focuses on the underlying science—as well as the monitoring, modeling, and decision making—relevant to three actions (out of about 27) that make up the long-term operations of the CVP and SWP: the Shasta Coldwater Pool Management Action, the Old and Middle River Flow Management Action, and the Summer-Fall Delta Smelt Habitat Action. The NASEM Committee's statement of task appears in Box 1-3.

BOX 1-3
NASEM Committee's Statement of Task

At the request of the U.S. Bureau of Reclamation, an *ad hoc* committee of the National Academies of Sciences, Engineering, and Medicine will conduct a biennial review of the monitoring, modeling, and other relevant scientific activities and initiatives that support the long-term operations of the Central Valley Project (CVP). Along with the State Water Project, the CVP consists of coordinated federal-state water operations that annually move millions of acre-feet of water via dams, canals, tunnels, pumps, power plants and transmission lines from Northern California to a wide variety of water users throughout the state, including municipalities, agriculture, industries and wildlife refuges. Operation of the CVP affects species protected under the ESA such as the southern distinct population segment of North American green sturgeon, California Central Valley steelhead trout, Central Valley spring-run Chinook salmon, Sacramento River winter-run Chinook salmon, and Delta smelt. In the first cycle of the study, the committee will:

1. Assess the state of science for the following topics as they relate to long-term operations of the CVP:
 - a. Old and Middle River (OMR) flow management
 - Salmonid route selection and survival
 - Delta smelt entrainment and recruitment
 - b. Shasta cold-water pool management
 - c. Summer–fall Delta smelt habitat
2. Provide recommendations on how modeling and monitoring strategies and decision-support tools can be changed, improved, or replaced to more accurately assess the impacts of the CVP operations described above.

The Shasta Coldwater Pool Management Action, the Old and Middle River Flow Management Action, and the Summer-Fall Habitat Action for Delta Smelt were chosen for consideration in Phase 1 of this study because they are consequential and controversial, for both scientific and nonscientific reasons (Mooney, 2024; USBR, 2024d). These three actions are described briefly below.

Shasta Coldwater Pool Management (Chapter 2). USBR manages Shasta Reservoir to maintain flood conservation space and to meet downstream flow and water delivery requirements. Those downstream needs include meeting minimum instream flows, satisfying senior water rights on the Sacramento River, meeting Delta salinity and outflow requirements; providing for water service contract diversions at the Red Bluff Pumping Plant; and fulfilling contracts for exports from the Delta. USBR operates a Temperature Control Device (TCD) within Shasta Reservoir to maximize the use of available cold water to support Sacramento River winter-run Chinook salmon spawning and incubation just downstream of Keswick Dam over the summer months. The TCD is used when Shasta Reservoir is stratified (typically starting in late April or early May). It blends water from warmer and colder layers

within Shasta Reservoir to preserve the lowest and colder water for later in the season; hence, the action extends from May through October. Because of a warming climate, meeting the required temperatures below Keswick will become increasingly difficult, as recent droughts have demonstrated.

Old and Middle River (OMR) Flow Management (Chapter 3). This action aims to maximize the export of water while minimizing pumping's adverse effects on fish populations, particularly when fish are rearing in and migrating through the Delta. The strategy is to close the Delta Cross Channel and to limit exports from the state and federal pumping stations during the migration season (December through June), thus controlling the magnitude of OMR reverse flows, and then to further control such flows based on detections (in salvage) of winter-run and spring-run Chinook salmon and steelhead and on surrogate measures for Delta and longfin smelt. The OMR flow management action is of interest because it curtails the amount of water pumped south, limiting the CVP's and SWP's ability to deliver water to their contractors, and because those limits on pumping are a core element of USBR's strategy to minimize project impacts on species. Yet, disagreement exists about the effectiveness of both the triggers and the corresponding flow restrictions on protecting the listed fish populations.

Summer-Fall Habitat Action (SFHA) for Delta Smelt (Chapter 4). SFHA seeks to address a seasonal bottleneck for juvenile Delta smelt survival, which has been identified based on analysis and interpretation of historical monitoring data and life-cycle models. The action responds to this problem by providing more low-salinity habitat in the Suisun Marsh area during the summer. The underlying hypothesis is that improving Delta smelt habitat by optimizing salinity, turbidity, temperature, and prey conditions and by creating connectivity to food supplies will support Delta smelt recruitment and population growth. Some aspects of the action are costly in terms of water use. Furthermore, over the relatively short time period that the action has been implemented, evaluating its effectiveness for improving the population viability of Delta smelt has been challenging.

Subsequent cycles of this NASEM review will each address up to three new scientific topics selected after consultation with USBR (and with input from other agencies and stakeholders) that are timely for potentially improving Project operations. For each topic, the Committee will consider the best available science along with relevant monitoring and synthesis, modeling and decision support tools, and adaptive management strategies, and it will recommend the highest priorities for improvement. Subsequent reports will also evaluate progress toward meeting the Projects' long-term operational goals and discuss significant accomplishments of the Projects during the biennial report period.

Previous Reviews of Science Relevant to Agency Actions in the Bay-Delta

This report is not the first time that NASEM has reviewed science in the Bay-Delta region. In 2010, Congress and the Departments of the Interior and Commerce asked NASEM to review the scientific basis of actions that have been taken and that could be taken for California to achieve an environmentally sustainable Bay-Delta ecosystem and a reliable water supply. Specifically, a committee was convened to:

- Identify the factors that may be contributing to the decline of federally listed species and other significant at-risk species in the Delta.
- Identify future water-supply and water-delivery options that reflect a proper consideration of climate change and compatibility with the objectives of maintaining a sustainable Bay-Delta ecosystem.
- Identify gaps in available scientific information and uncertainties.

- Advise on the degree of restoration of the Delta system likely to be attainable, given adequate resources.

That Committee and the resulting reports (NRC, 2010, 2011, 2012) offered recommendations and identified a variety of ecosystem stressors, including those not directly related to operation of the CVP and SWP, that interact in different ways to influence at-risk and other species. That Committee also noted that meeting the two “co-equal goals” of providing a more reliable water supply for California and protecting, restoring, and enhancing the Delta ecosystem (from the Delta Reform Act of 2009) requires clarity on how the inevitable trade-offs between the goals will be managed when water is in short supply.

Beyond consulting the past work of NASEM, this Committee reviewed the extensive literature that supported the development of regulatory documents such as the 2024 biological opinions and incidental take permits for endangered and threatened fish in the Bay-Delta region (CDFW, 2024; NMFS, 2024b; USFWS, 2024). NMFS conducts five-year reviews that describe whether recovery is on track in the context of the recovery plan, explain what the most significant accomplishments have been over the previous five years, and identify the greatest immediate challenges for species recovery. A review of California coastal Chinook salmon was produced in 2024 (NMFS, 2024a). Many other agencies active in the Delta have also produced syntheses and reviews of recent work (e.g., Brown et al., 2024; DISB, 2015, 2022, 2024). Several relevant Delta Science Program reviews coincided with the timing of this study. Whenever possible, the Committee used these reports, many of which became available well after it began its work, for this review. The vast amount of material available, which grew even as this report was being drafted, posed a challenge for this and similar reviews.

REPORT ROADMAP

To be of immediate relevance to the study sponsors and other decision makers working in the Bay-Delta region, this report relegates substantial background material to five appendices. The first three appendices provide scientific, technical, and legal context for understanding the long-term operations of the CVP and SWP. Appendix A provides an overview of California climate and hydrology, including the impacts of recent and projected future climate change on several physical metrics such as precipitation, air and water temperature, streamflow, and sea level rise. Appendix B provides the history of California water resources development before outlining the major features of the CVP and SWP, including descriptions of the relevant infrastructure and the ways in which that infrastructure and its operations have altered flow paths in the upper Sacramento River and the Delta. Appendix B also describes the water users that rely on CVP and SWP water and their contracted allocations. Finally, Appendix C describes the regulatory framework under which the CVP and SWP operate, providing more detail than in Chapter 1.

Appendix D describes many of the monitoring networks and models used in CVP and SWP operations. This includes the monitoring of physical, chemical and biological parameters conducted by various state and federal agencies, with a particular spotlight on the many fish surveys throughout both the Delta and the upper Sacramento River. Appendix D covers models of physical processes such as CalSim3 and DSM2, along with many biological models, including quantitative life cycle models for the listed fish species. Finally, Appendix E provides a general overview of the seven fish species in the Delta that are listed as threatened or endangered under the federal ESA. It discusses the species’ life histories, fish monitoring networks for these species, abundance data, available life cycle models, and major stressors on the individual species.

Chapters 2 through 4 discuss the three specific actions that are the focus of this first report: the Shasta Coldwater Pool Management Action, the Old and Middle River Flow Management Action, and the Summer-Fall Habitat Action for Delta smelt. Each chapter describes the action; evaluates monitoring, modeling, and decision support tools relevant to the action; and considers how certain climate impact drivers will affect the action. Each chapter also outlines science challenges for each action. Finally, Chapter 5 explores overarching issues such as the organization of the science enterprise in the Delta

region, systemwide monitoring and modeling issues, and action agencies plans to account for the increasing variability in precipitation and intensity and frequency of droughts. Each chapter ends with conclusions and (when appropriate) recommendations, the most important of which are compiled in the report summary.

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2

Shasta Coldwater Pool Management

The Committee's statement of task requires it to assess the state of science for the Shasta Coldwater Pool Management Action as it relates to long-term operations of the Central Valley Project (CVP) and, where applicable, the State Water Project (SWP). In addition, the Committee was asked to recommend how modeling, monitoring, and decision-support strategies and tools can better support Shasta coldwater pool management. Hence, the focus of this chapter is on winter-run Chinook salmon, which is the target of the coldwater pool management action.

Winter-run Chinook salmon historically migrated through the Delta and up the Sacramento River to spawn in the stable, cold spring-fed headwaters of the Sacramento, Pit, and McCloud rivers, as well as in Battle Creek. The historic spawning habitats in the first three rivers lie upstream of Project dams, such that nearly all adult holding and spawning, as well as egg and alevin incubation and rearing, now takes place in a ~20 km reach of the Sacramento River below Keswick Dam (NMFS, 2014; Windell et al., 2017). The isolation of the current winter-run Chinook salmon population from reliable historic spawning and rearing habitats has placed the population at risk, and keeping the current spawning grounds cold enough for optimal spawning is a substantial management challenge. Indeed, the status of the Sacramento River winter-run Chinook salmon population has declined in the last five years, with the single spawning population below Keswick Dam having a high risk of extinction (NMFS, 2024a). The Shasta Coldwater Pool Management Action aims to ensure that water cold enough to support adult holding and spawning and egg incubation is present in the reaches downstream of Keswick Dam at the appropriate times of year so that that winter-run can reproduce with enough success for the species to survive.

This chapter first provides background on the Shasta Coldwater Pool Management Action, including descriptions of the infrastructure used to provide cold water and the seasonal timeline for decisions. It then discusses the roles of physical and biological monitoring data and the use of models related to the action. Finally, the chapter highlights aspects of the action where improved scientific understanding could significantly affect how the action is conducted and supported.

The existing scientific understanding supports a three-pronged approach to Shasta management: (1) improving conditions downstream of Keswick Dam, (2) continuing propagation and supplementation including hatcheries management, and (3) reintroduction of winter-run Chinook salmon above Shasta Dam and in Battle Creek. Improving conditions downstream of Keswick Dam and continuing propagation and supplementation will be necessary for winter-run Chinook salmon's survival for as long as the species depends on that reach as its primary spawning habitat. Incremental improvements to each approach are possible, as discussed in the chapter. Nevertheless, approaches (1) and (2) will likely be insufficient to sustain and recover the species. The most promising longer-term alternative is reintroduction of winter-run Chinook salmon to their historic spawning habitats.

DESCRIPTION OF THE SHASTA DIVISION AND THE COLDWATER POOL MANAGEMENT ACTION

Figure 2-1 shows the geography of the Shasta Division of the CVP. Shasta Dam, located about 10 miles north of Redding, was completed in 1945 and is the CVP's principal storage facility. The dam impounded the upper Sacramento River and created Shasta Reservoir, which is the largest water storage facility in California and the ninth largest storage facility in the United States¹. The reservoir has a surface

¹ See <https://npdp.stanford.edu/largestusreservoirs>.

area of about 30,000 acres at full pool and a maximum depth of 517 feet. The dam is 0.6 miles wide and 600 feet tall. It is one of the ten highest dams in the United States, and it has a maximum capacity of 4.5 million acre-feet of water². It receives runoff from a 6,665 square mile drainage basin. Shasta Dam was primarily constructed to provide irrigation water to the Central Valley, flood control, and hydropower generation. Water released through the turbines at Shasta Dam provides hydropower with an average value of \$50 million annually³.

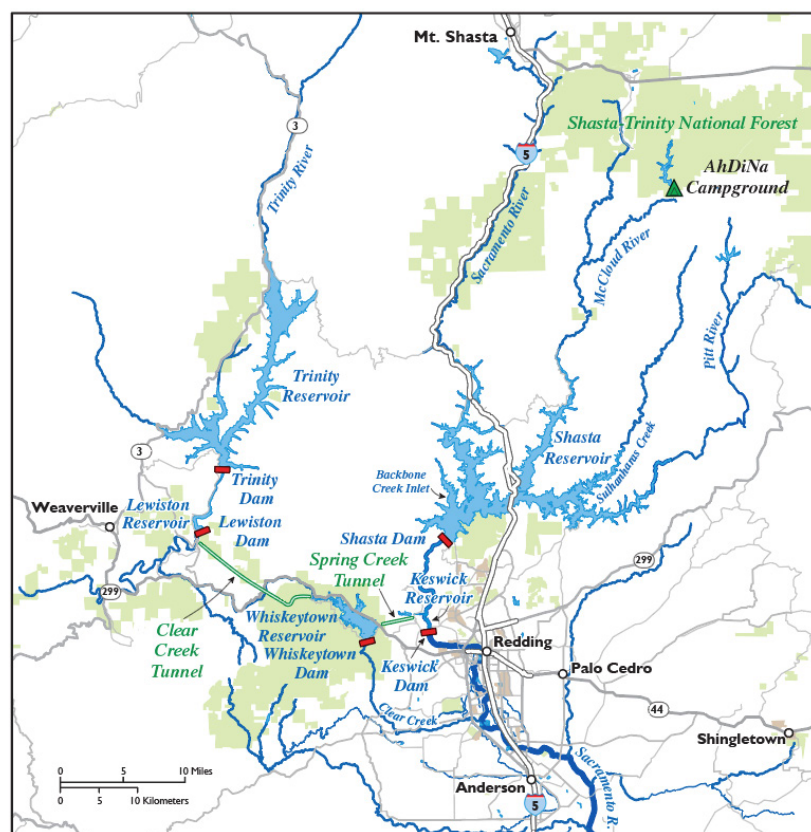


FIGURE 2-1 Geography of the Shasta Division of the CVP.

SOURCE: Kevin Lear, International Mapping Associates.

The Shasta Division of the CVP also includes Trinity Reservoir, which is large and deep, with 2.45 million acre-feet of storage. Because of the altitude of its catchment, its water is colder than that of Shasta Reservoir (Patton, 2024; USBR, 2024a). Water released from Trinity Dam flows a short distance to Lewistown Reservoir, which serves as a re-regulating reservoir for Trinity Dam. From Lewistown, water can flow through its powerhouse and/or spillway and then downstream, meeting demands and requirements for in-basin Trinity River flows, or it can be diverted through Clear Creek Tunnel into Whiskeytown Reservoir. (A powerhouse is located at the end of this tunnel.) Whiskeytown Reservoir also receives some inflow from the upper Clear Creek catchment. Some releases from Whiskeytown Dam flow south down Clear Creek to meet environmental requirements and fisheries; Clear Creek eventually flows into the Sacramento River near the I-5 crossing below Keswick Reservoir. However, most water

² See <https://www.usbr.gov/mp/mpr-news/docs/factsheets/shasta-dam.pdf>.

³ See <https://www.usbr.gov/projects/index.php?id=552>.

from Whiskeytown Reservoir exits through Spring Creek Tunnel and its powerhouse into Keswick Reservoir. This is the primary route for cold water in Trinity Reservoir to reach the Sacramento River to meet CVP water demands; hydropower is generated as it passes through three power houses. Keswick Reservoir is large enough to regulate highly variable flows from Shasta's powerhouse and thus to modulate releases down the Sacramento River, except during flood operations.

Shasta Reservoir is fed by rivers and streams that feed into five major arms: the Pit River, Sulanharas Creek⁴, the McCloud River, the Sacramento River, and Backbone Creek Inlet. The longest arm of the reservoir stretches approximately 35 miles from the dam. Shasta Reservoir stratifies annually, resulting in warm surface waters (i.e., epilimnion) sitting above deeper, colder waters (hypolimnion). The thermocline is the boundary between the layers where water density and temperature change rapidly. During drought years, when the thermocline is at a low elevation, delivering cold water from Shasta Reservoir to Keswick Dam can be challenging. Furthermore, the water downstream of Keswick Dam can warm rapidly during summer conditions, further contracting the downstream extent of coldwater habitat needed for spawning of winter-run Chinook salmon in summer. The drought years (1976–1977, 2007–2009, 2012–2016, 2020–2022) significantly affected reservoir and river temperatures and are believed to have caused sharp declines in the winter-run population (USBR, 2024b).

Although coldwater pool management affects only a portion of the many habitats that winter-run Chinook salmon use throughout their life, the area and time frame targeted by the action is critical to the species' survival. To support winter-run Chinook salmon, stream habitats need suitable temperature and flow conditions for spawning, egg incubation and fry emergence during the period from May to October. A stream temperature in the low- to mid-50s F has been considered necessary for reproductive success and survival of winter-run Chinook salmon (McCullough, 1999). In addition, clean, well-oxygenated gravel substrates (often located on riffles) are necessary for spawning, although their availability can be limited in the portion of the system where winter-run spawning occurs under current conditions. After hatching, juveniles rely on instream cover, such as woody debris, submerged aquatic vegetation, and riffle–pool sequences, to provide refuge from predators and to facilitate foraging. Habitat complexity in this region of the Sacramento River has been reduced by channelization, channel incision, bank armoring, and levee construction, which has subsequently reduced access to floodplain and wetland rearing habitats (Herbold et al., 2018; San Francisco Estuary Partnership, 2019). The remaining habitat is of poor quality (Lindley et al., 2009; NMFS, 2014, 2016, 2024a). Although restoration efforts, such as gravel augmentation and riparian habitat improvements, aim to enhance spawning and rearing habitats, a combination of poor habitat quality downstream of Keswick Dam and limited coldwater availability have limited the effectiveness of these actions in restoring salmon populations, necessitating ongoing dependence on the Livingston Stone National Fish Hatchery to maintain winter-run populations via artificial propagation and supplementation. This chapter focuses on the coldwater management aspect of winter-run Chinook salmon survival and recovery.

Components of Coldwater Pool Management

The Shasta Coldwater Pool Management Action includes several key components. The main component is releasing water of a certain temperature and flow rate by operating the Temperature Control Device (TCD) within Shasta Reservoir and via diversions from Whiskeytown Reservoir (which receives water from the Trinity Reservoir). The action is supported by a wide range of planning, monitoring, and modeling activities that assess physical and ecological conditions within the reservoir/river system. For example, every year in February, the U.S. Bureau of Reclamation (USBR) develops a seasonal temperature management plan that establishes target releases from Shasta Reservoir based on climatological projections and estimates of the anticipated coldwater pool volume in the Shasta and Trinity reservoirs. Hence, modeling water temperature within the reservoir and predicting the available

⁴ Renamed in 2022 by the Board of Geographic Names.

coldwater pool volume over time are central to the action. Finally, the winter-run Chinook salmon hatchery program to supplement natural recruitment is mentioned, given its role in maintaining fish populations alongside coldwater pool management.

Flow Releases and Use of the Temperature Control Device

Water temperatures within Shasta Reservoir typically range from approximately 6–27°C (42.8–80.6°F) annually across the volume of the reservoir, reaching a seasonal minimum in late winter or early spring before warming to a summer maximum. As with many large lakes and reservoirs, during spring and summer Shasta Reservoir undergoes vertical thermal stratification, which causes water temperature to vary significantly with depth, with colder denser water overlain by warmer surface waters (Boehrer and Schultz, 2008; Ford and Johnson, 1983). During the stratified period, surface waters frequently exceed 22°C (71.6°F), while bottom waters typically remain below 10°C (50°F), with a steep thermal transition that defines the top of the coldwater pool (Daniels et al., 2018; Lieberman and Horn, 1998). The coldwater pool itself is defined as the volume of water between the thermocline and dead pool elevation⁵. To take advantage of this stratification, in 1997 the USBR installed a TCD on Shasta Dam to enable selective withdrawals from different reservoir elevations and hence different temperatures (Box 2-1). The installation of the TCD was a major step in optimally using the cold water from Shasta Reservoir to provide a specified minimum water temperature for fish habitat downstream of Keswick Dam.

BOX 2-1

The Temperature Control Device at Shasta Reservoir

Shasta Dam was retrofitted with a TCD at a cost of \$80 million to enhance USBR's ability to regulate the temperature of releases, primarily for sustaining viable downstream fish habitat while avoiding loss of hydropower generation (Hanna et al., 1999). At the time of completion in February 1997, this was one of the most innovative and large-scale structural adaptations to a large dam in the United States. The TCD is a 250-ft wide and 300-ft high structure that consists of upper, middle, and lower gates (Figure 2-2). There is a separate unit for each of the five penstocks. For a given unit, the upper, middle, and lower gates can be opened individually or in combination to withdraw water from specific thermal layers in the reservoir. Below the gates, each unit is also equipped with a side gate located at an even lower elevation that enables access to deeper hypolimnetic water not available through the main gates. This design enables temperature blending across a broad vertical range of the reservoir, which is especially valuable during drought or low-storage conditions when cold water is in short supply.

Operators can reposition the TCD gates vertically to align with the desired thermal layer, and transitions between gate settings can be made within a few hours. Each penstock is instrumented with temperature and flow measurement devices with values recorded every 15 minutes. These devices inform hydropower operations and temperature management decisions. However, no continuous temperature sensors are embedded within or on the TCD structure itself, limiting real-time vertical profiling capability at the intake face.

The TCD's difficulties with temperature releases and stabilization of water temperatures in the river downstream of Shasta could be related to leakage around the gates. To remedy this situation, particularly under severe drought conditions and low reservoir water surface elevations, USBR has considered installing impermeable curtains on the middle TCD gates. The curtains could help reduce leakage of warm water and provide greater control of the temperature of water releases (NMFS, 2024b, Section 7.9.3). The decision to temporarily install these curtains would depend on many factors, including the lake surface elevation, depth of the thermocline, duration of the drought, prevailing ambient conditions, and the estimated reduction in downstream temperatures. Internal mixing processes and circulation in the reservoir also could play a role in the observed temperature fluctuations. For example, as water is entrained into the TCD, the vertical temperature profile is likely

continued

⁵ Dead pool elevation is the lowest elevation in the reservoir below which water cannot be released.

BOX 2-1 *continued*

to be altered locally (Hannah et al., 1999). Seiche within the reservoir can create vertical fluctuations over a period of hours to days (as discussed in a later section).

Managing Shasta Dam in general, and operating the TCD in particular, to achieve a downstream target temperature is not trivial and relies heavily on the skill and experience of the dam operators, who must balance several factors (USBR, 2017). They must determine the volume of water to be released, taking into account hydropower operations, and they must decide how many and which turbines to use. The net temperature downstream of the dam is affected by the blending of water from multiple different pathways including from Spring Creek Tunnel. In addition, the operator needs to anticipate water temperature changes during river transit between Shasta and Keswick, during the period the water is resident in Keswick Reservoir, and after mixing with releases from Whiskeytown Reservoir via Clear Creek. To ease management somewhat, USBR could develop decision support software that incorporates the Water Temperature Modeling Platform (see modeling discussion) and measurements of the vertical reservoir temperatures. That software could guide operators on optimal ways to use releases from Shasta Reservoir to achieve downstream flow and temperature targets.

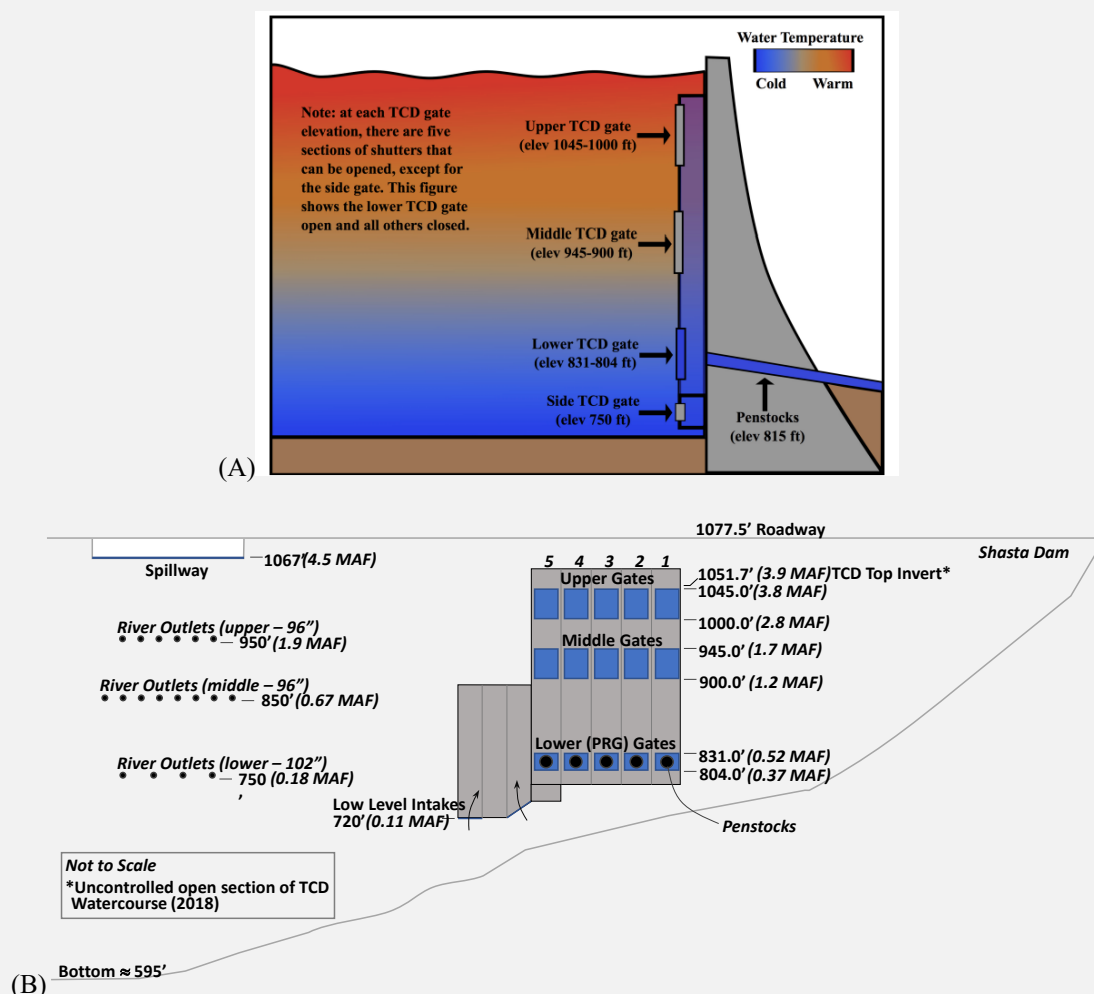


FIGURE 2-2 (A) Conceptual schematic of the temperature control device in Shasta Reservoir. (B) Shasta Dam outlet works and TCD, as if one is standing at the upstream face of the dam looking downstream.

NOTES: There are ten river release gates at three elevations, each approximately 8 feet in diameter that release directly into the Sacramento River. The TCD feeds water into the penstocks that lead to the powerhouse. Elevations are relative to mean sea level. Powerhouse units 1 through 5 are shown for reference.

SOURCE: (A) Figure 8 in Daniels et al. (2018); (B) USBR (2024c).

The use of the TCD has not been without challenges, including potential leakage around the gates (which has been blamed for difficulties in accurately delivering waters to achieve release temperature targets, USBR, 2024a). Some effort has been made to characterize the precise flow patterns into the TCD, including the actual elevations from which water is predominantly being withdrawn. Studies were conducted by Resource Management Associates (2003) to estimate the leakage around the TCD, and on occasion a remotely operated camera has also been used to assess gate closure. Currently the University of California (UC) Davis is working with USBR, with funding from the Delta Science Program, to experiment with upward-looking Acoustic Doppler Current Profilers (ADCPs) to quantify the flow behavior into the TCD under different release criteria and under different reservoir conditions. This study shows promise and was underway during the preparation of this report; no results are yet available. Furthermore, despite substantial investment in the TCD, in auxiliary screens, and in cooling systems to manage extreme drought conditions, relatively little attention has been paid to vertical temperature fluctuations that occur more frequently than the current weekly or bi-weekly monitoring can detect, such as fluctuations caused by seiching within the reservoir. These issues are discussed in the subsequent section on monitoring.

Forecasting Release Temperatures and Coldwater Pool Volume

Shasta coldwater pool management is guided by complex modeling and decision-making processes. The general goal of those processes is to balance the need to predict water availability and to prepare for future water needs with the need to maintain operational flexibility. If USBR errs on the side of retaining cold water, then deliveries may be lower, or they may be released after water users have already planned for lower delivery levels. If USBR errs on the side of early-season releases, then it may have insufficient cold water to support both winter-run and fall-run Chinook salmon through the summer and fall. Because of these stakes, and because an explanation of the decision-making processes will help readers understand some of the chapter's recommendations, the following paragraphs describe the decision-making criteria and steps in detail.

In 2004, USBR started to write water temperature management plans for Shasta Reservoir based on predictions of the coldwater pool volume and spring/summer climatological forecasts. Applicable to the May through October timeframe, a typical water temperature management plan establishes temperature requirements at various locations and estimates potential winter-run Chinook salmon egg mortality, dates for operation of the side gates on the TCD, and coldwater pool volume at the end of September. USBR monitors the coldwater pool, compares the projected coldwater pool with observations, tracks actual performance during implementation of the temperature management plan, and provides regular updates to the Sacramento River Group (SRG) throughout plan implementation.

In March, April, and May—prior to the temperature management season—USBR uses seasonal air temperature forecasts and historical meteorological data (USBR, 2025) to model projected inflows, estimate water availability, and evaluate end-of-April and end-of-September storage targets. In coordination with the SRG, USBR selects one of five inflow forecast scenarios, each based on a different inflow exceedance probability—a statistical representation of the likelihood that future reservoir inflows will meet or exceed a given value. A high exceedance probability (e.g., 90 percent) reflects more conservative planning because there is a 90 percent chance that inflows will reach or exceed the modeled value. In contrast, a low exceedance probability (e.g., 10 percent) reflects more aggressive planning because there is only a 10 percent chance that inflows will be as high or higher than the modeled value. High exceedance probability are more common during drier conditions and when water availability is lower, in order to reduce the risk of overcommitting cold water early in the season. A 10 percent exceedance forecast is more likely to be chosen during wetter conditions, although this increases the risk of inadequate coldwater reserves if actual inflows fall short. Use of a medium exceedance threshold (e.g., 50 percent or 70 percent) may result in higher anticipated deliveries and earlier coldwater use; however, if

inflows underperform, then end-of-September storage may fall below planning targets, reducing the ability to meet temperature objectives during late summer and fall egg incubation.

In February of each year, the SRG starts to evaluate data and discuss scenarios. Each month after February, USBR creates an operational forecast and performs a water temperature model run. In mid-April, USBR typically prepares updated projections of anticipated temperature management capability including considerations from updated hydrologic and runoff forecasts; those projections are shared at SRG meetings. In April and May, the operators evaluate the volume of coldwater pool available. They release a draft temperature management plan at the end of April or early May and finalize that plan at the end of May or early June.

The 2024 Record of Decision for the Long-term Operations of the Central Valley Project (USBR, 2024d) adopts a new approach for setting specific objectives for the Shasta coldwater pool management season. As shown in Table 2-1, under this new “Bin” approach, the overall action is classified as Bin 1, 2, or 3, along with two subcategories: A (standard) and B (drought protection). Bin number (1, 2, or 3) is defined by the projected end-of-April storage, which is primarily driven by hydrology, and it considers forecasted end-of-September storage (USBR, 2025). The letter of the Bin (A or B) is primarily driven by the expected demands on the reservoir, which are a function of hydrology, meteorology, system-wide conditions, contractual requirements, and other conditions. The “A” Bins are years when the expected demand on the reservoir is lower, with the potential of affording better drought protection if the following year is dry. The “B” Bins designate drought protection and are intended to increase the priority of storage conservation to address the possibility that the current year is likely to be a drought.

TABLE 2-1 Requirements for Various Elements of Shasta Coldwater Pool Management, by Bin

Designations	Bin 1A	Bin 1B	Bin 2A	Bin 2B	Bin 3A	Bin 3B
Estimated Frequency	80% of years		~11.5% of years		~8.5% of years	
End-of-April Storage (MAF)	≥ 3.7		3.0 – 3.7		< 3.0	
End-of-September (EOS) Storage (MAF)	≥ 3.0	≥ 2.4	2.2 – 2.4	2.0 – 2.2	> 2.0	< 2.0
Operational Goals		Increase EOS ≥ 2.4 MAF. If impossible, shift into Bin 2A	Increase EOS ≥ 2.2 MAF. If impossible, shift into Bin 2B	Increase EOS ≥ 2.0 MAF. If impossible, shift into Bin 3A	Increase EOS ≥ 2.2 MAF. If impossible, shift into Bin 3B	Increase EOS ≥ 2.0 MAF. If impossible, identify system priorities and contingencies
Biological Objective	Enhance		Recover	Maintain	Protect	
Temperature Target	Average daily water temperature 53.5°F (11.9°C) (determined by BiOps; subject to change with future scientific research)					
Compliance Point	Downstream of CCR gage		At the CCR gage		Upstream of the CCR gage	
Temperature Dependent Mortality	≤ 3%				≤ 30%	
Temperature Management for Winter-run Chinook Salmon	Manage all spawning habitat		Manage the majority of spawning habitat		Manage spawning habitat during the critical periods of spawning and egg incubation	

NOTES: CCR = Clear Creek compliance location, EOS = end-of-September, MAF = million acre-feet, SR = Sacramento River. SOURCE: NMFS (2024b).

The bin designation begins in February, with updates once per month until mid-April. During a two-week period (May 1–14) following bin determination and before the beginning of the temperature management season, uncertainty with inflows and late-spring weather conditions may impact storage volumes. The temperature management plan drafted each year by USBR (in coordination with the SRG) contains the bin-specific operational, thermal, and biological objectives for adult holding, spawning, and egg incubation, along with projected reservoir releases, assumed meteorological conditions, anticipated water temperatures and target locations, and temperature-dependent mortality estimates (see Table 2-1). USBR finalizes the temperature management plan in May or later through coordination with the SRG and the Shasta Operations Team (SHOT).

Winter-run Chinook Salmon Hatchery

Although technically not part of the Shasta Coldwater Pool Management Action, the hatchery program is discussed here because of its role in supplementing winter-run stocks, especially in years when coldwater pool management cannot or does not deliver water below the required target temperatures. The Livingston Stone National Fish Hatchery (established in 1997 by the U.S. Fish and Wildlife Service just downstream of Shasta Dam) is designed to serve as a genetic safety net, supplementing the wild population while attempting to maintain genetic diversity (NMFS, 2019). Each spring, wild winter-run Chinook salmon adults are collected from the Sacramento River and held at the hatchery until spawning occurs between June and August. After fertilization, eggs are incubated at the hatchery, and the juveniles are reared through the winter before release into the Sacramento River near Redding the following April. Increasing hatchery output in years when coldwater pool storage is insufficient to meet temperature objectives is a management lever to mitigate thermal mortality among in-river eggs and fry (USBR, 2024a).

Although the hatchery has helped buffer the population during periods of extreme environmental stress, its effectiveness in aiding long-term recovery is questionable. One concern is the potential for hatchery-origin fish to interbreed with natural-origin fish, leading to reduced reproductive success, domestication selection, and loss of locally adapted traits. Such concerns are echoed broadly among fisheries conservation ecologists (Araki et al., 2007; Bert et al., 2007; Naish et al., 2007). The proportion of hatchery-origin spawners within the winter-run population is a key indicator of this risk. Recent estimates suggest that hatchery-origin fish comprise a small enough proportion of the population to only present a moderate risk of extinction due to reduced fitness in natural spawning conditions (NMFS, 2019), but that risk can shift dramatically during successive drought years when native returns decline over a prolonged period. NMFS (2024b) identified the influence of hatchery broodstock as a key factor negatively influencing Chinook populations that remain at a high risk of extinction. Hatchery-origin fish differ behaviorally from their wild counterparts and often have lower survival, and perhaps more importantly, reduced reproductive success, which in turn imperils the wild stock with which they interbreed (Berejikian et al., 2005; CDWR and USBR, 2024).

The hatchery's role in population supplementation presents ecological and demographic tradeoffs. It provides a buffer against catastrophic recruitment failure, especially during years when coldwater pool volume is insufficient to protect natural incubating eggs, and it can be used to augment populations in historically productive coldwater streams. For example, fertilized hatchery eggs have been used to support reintroduction efforts in Battle Creek (NMFS, 2024b). However, the use of hatchery fish, as a replacement strategy, risks masking continued habitat degradation and may delay or displace investment in the restoration of thermal and hydraulic conditions essential to rebuilding a self-sustaining population (Hilborn, 1992; McMillan et al., 2023). Livingston Stone maintains a broodstock reserve as a multi-year hedge against poor adult escapement, but this buffer is only viable for about three years. Extended droughts, which are increasingly likely under a warming climate (see Appendix A), could exhaust this reserve and expose the hatchery's limits as a long-term insurance policy (NMFS, 2019).

Despite the implementation of best genetic management practices—including factorial mating schemes, temporal broodstock collection, and limits on natural-origin take—the hatchery program alone

remains a temporary mitigation measure rather than a recovery solution (Bert et al., 2007; NMFS, 2019). The broader scientific consensus cautions against relying too heavily on hatchery-based strategies, particularly when underlying habitat conditions remain impaired (Hilborn, 1992; McMillan, 2023).

Pulse Flows

Although not formally part of the Shasta Coldwater Pool Management Action, pulse flows interact with the action in operational, thermal, and ecological ways. Pulse flows are short-duration, intentional increases in river discharge designed to simulate natural variability for ecological benefits. Flow has been correlated with survival for outmigrating Chinook salmon in the Sacramento River system (Michel et al., 2021). Spring pulse flows specifically support juvenile winter-run Chinook salmon survival by providing migratory cues, accelerating their downstream transport, lowering water temperatures, and improving access to off-channel rearing habitats (CDFW, 2024; NMFS, 2019). The pulses also attract adult spring-run Chinook during their upstream migration between April and June and contribute to geomorphic processes by mobilizing fine sediment, transporting gravel, and helping sustain geomorphic features (NMFS, 2019). If the pulse flow releases are higher in magnitude, then they can also serve as flushing flows that flush fine sediments from the gravel bed, leaving behind cleaner, recently mobilized spawning gravels. USBR may release up to 150,000 acre-feet in spring pulses when conditions permit, provided this does not compromise other operational objectives (USBR, 2024e). USBR coordinates this planning through the SRG and SHOT, in alignment, when possible, with storm-driven events or tributary pulses (NMFS, 2024b).

Observational and experimental studies in the upper Sacramento River system support many of the potential ecological benefits of pulse flows discussed above. Acoustic telemetry studies indicate that pulse flows improve juvenile migration speed and survival during outmigration from the Sacramento River (Notch et al., 2024). Increased spring discharge has also been linked to reduced residence time of hatchery-origin juveniles in the upper river, altering exposure to predation and contributing to life history diversity (Hassrick et al., 2022). Flow-driven reductions in water temperature have also been shown to advance winter-run Chinook salmon spawning phenology, which may reduce the risk of thermal mortality during summer incubation (Jennings and Hendrix, 2020).

While the potential ecological benefits of pulse flows are well established, their specific effects on juvenile salmon survival remain less certain and stage-dependent. Most direct evidence comes from smolts, where telemetry studies demonstrate that higher flows are associated with greater survival (Michel et al., 2021; Notch et al., 2020). Effects on fry survival are less well understood because of constraints on tagging size, and information is limited to indirect indices and inference. Regardless of which specific early life history stage, how pulse flows translate into improved outcomes (i.e., mechanisms, or interactions with factors such as water temperature, turbidity, predation risk, or habitat access) remains uncertain. Evidence exists that, in certain circumstances, the timing and magnitude of Delta inflows affect travel time, route selection, and survival of migrating juvenile Chinook salmon (Perry et al., 2018). The timing, magnitude, and duration of pulse flows are often not optimized to support the full spectrum of juvenile development stages (USBR, 2024e) or they are constrained altogether because of coldwater pool limitations. There is limited integration of pulse flow strategies with other environmental variables such as water temperature, turbidity, through-Delta migration, and predation risk, which are critical factors influencing post-fry survival (Notch et al., 2024). Currently, pulse flows are not implemented unless Shasta Reservoir storage exceeds 4.1 million acre-feet on May 1 (NMFS, 2024b); in dry years with elevated risk of temperature-dependent mortality, pulse flows may be deferred altogether to conserve coldwater (NMFS, 2024b).

Decision Making During Shasta Coldwater Pool Management

The Coldwater Pool Management Action is implemented by three main coordination teams: the winter-run Juvenile Production Estimate (JPE) SubTeam, the SRG, and the SHOT. The Winter-run JPE SubTeam is a technical group tasked with the development of the yearly winter-run JPE (see Chapter 3) and the winter-run broodstock assessment; it is composed of staff from USBR, the California Department of Water Resources (CDWR), the National Marine Fisheries Service (NMFS), the U.S. Fish and Wildlife Service (USFWS), and the California Department of Fish and Wildlife (CDFW). The SRG discusses pulse flow shaping, temperature management, fall flow smoothing, and fall/winter base flows. It is composed of technical staff from USBR, CDWR, NMFS, USFWS, CDFW, the California State Water Resources Control Board (SWRCB), tribes, the Sacramento River Settlement Contractors, and the Western Area Power Administration. The SHOT is a policy-level team that discusses actions whose implementation may have biological, system conditions, or water supply impacts or tradeoffs. It includes management and policy staff from key management agencies, including the Sacramento River Settlement Contractors. Generally, topics will be discussed at a technical level through the SRG, with agency feedback provided prior to topics being discussed by the SHOT.

The chronology of decisions for coldwater pool management is shown in Table 2-2. The annual consultation about water allocations and water contracts occurs in February because farmers need to know how much water to expect, thereby affecting the crops to be planted. Those initial allocation decisions are made based on certain assumptions about what the water-year type will be (see Chapter 1) as an estimate of water availability and demand. As the SRG begins to develop the draft temperature management plan, it looks at weather, reservoir, and instream data and discusses potential bin scenarios. The SRG meets at least monthly throughout the temperature management season, and it may update the final temperature management plan at the request of the SHOT.

Each month, USBR operators make operational forecasts and conduct a temperature model run to be discussed during the monthly SRG meetings. In April and May, thermal stratification in the reservoir begins. The final water allocation is issued in May. By the end of May, the SRG finalizes the temperature management plan.

There is the potential for downstream target temperatures to increase beyond the 53.5°F (11.9°C) target stipulated in the biological opinions, depending on conditions. The NMFS 2024 Biological Opinion states that when conditions may “cause water temperatures to rise to concerning levels prior to the completion of the final temperature management plan, USBR will begin temperature management as early as March 1st to target water temperatures of 58°F (14.4°C) as the threshold daily average temperature at the Sacramento River Clear Creek (CCR) gage [rather than 53.5°F (11.9°C)].” It is unclear how decisions are made regarding deviations from the 53.5°F (11.9°C) threshold and deviations from the distance at which the temperature threshold must be met. As an additional challenge, the initial allocation of water to downstream contractors occurs in February, prior to the SRG evaluation of coldwater pool volumes (in March) that reveals the amount of water that must be conserved for the temperature management season.

Why Is the Action Controversial?

The controversies surrounding the Shasta Coldwater Pool Management Action stem from its impact on freshwater allocations for a wide variety of end users. Shasta Reservoir holds 41 percent of all the water in the CVP,⁶ which supplies roughly 7 million acre-feet of water annually to agricultural and urban users; CVP water irrigates about 3 million acres of farmland (~30 percent of California’s total) and provides about 2.5 million people with water for municipal and industrial uses (CRS, 2025). The hydroelectric powerplant at Shasta reservoir generates roughly 1800 gigawatt-hours of electricity

⁶ See <https://www.usbr.gov/projects/index.php?id=241>.

TABLE 2-2 Approximate Chronology of Planning, Monitoring, and Timing of Events Related to the Shasta Cold Water Pool Management Action

<i>Activity</i>	<i>Action</i>	<i>Purpose</i>	<i>Timing</i>	<i>Source</i>
Pre-Season Planning	Develop initial hydrologic forecasts based on snowpack, reservoir storage, and runoff predictions.	Assess anticipated water availability for the upcoming season, considering drought or surplus conditions.	January–March	USBR (2023a) 2022 LTO Shasta CWP Seasonal Report
Initial Temperature Management Projections	Generate early forecasts of coldwater pool volume and temperature management plan.	Determine preliminary targets for temperature compliance points and prioritize cold water conservation.	February–March	USBR (2024a) Final EIS Appendix L - Shasta CWPM
Coordination with Stakeholders and Regulatory Agencies	Convene meetings with the SRG, fishery agencies, and water users to review forecasted conditions and discuss management options.	Ensure alignment on coldwater allocation priorities and regulatory compliance.	February–November	USBR (2023a) 2022 LTO Shasta CWP Seasonal Report
Draft Initial Temperature Management Plan (TMP)	Draft TMP with target temperature thresholds at compliance points.	Consider operational goals based on early assumptions of water year type/snowpack	April	USBR (2024a) Final EIS Appendix L - Shasta CWPM
Finalize the Temperature Management Plan	Develop and submit TMP with target temperature thresholds at compliance points.	Formalize operational goals for the season, balancing environmental and water delivery needs.	May–June	USBR (2024a) Final EIS Appendix L - Shasta CWPM
Onset of Coldwater Management Season	Begin operational adjustments to manage releases from Shasta Dam using the TCD.	Regulate water temperatures to support winter-run Chinook salmon egg incubation.	May–October	USBR (2023a) 2022 LTO Shasta CWP Seasonal Report
Monthly and Weekly Operational Adjustments	Adjust reservoir releases and TCD gate operations based on real-time conditions.	Optimize cold water usage while maintaining compliance with temperature and flow targets.	Weekly or ongoing, May–October	USBR (2023a) 2022 LTO Shasta CWP Seasonal Report
Monitoring and Data Collection	Conduct temperature monitoring at compliance points and assess fish habitat conditions.	Evaluate performance of temperature management and ensure real-time responsiveness.	Year-round with varying frequency depending on the month	USBR (2024b) Chapter 5 Winter-Run Chinook Salmon
End-of-Season Assessments and Carryover Storage Planning	Evaluate the effectiveness of coldwater pool management and assess remaining storage for the next year.	Review lessons learned and plan carryover storage strategies to mitigate impacts of potential drought.	October–December	USBR (2024a) Final EIS Appendix L - Shasta CWPM
Four-Year Reviews and Independent Evaluations	Conduct comprehensive reviews of coldwater management performance.	Assess long-term efficacy of CWP management and inform future operational changes.	Every 4 years	NMFS (2019) BiOp Section 7

annually⁷. Any management decisions that reduce water availability are consequently met with opposition from a host of stakeholders and interest groups. At the same time, construction of Shasta Dam has prevented migration, in both directions, of all fish species that historically journeyed from the Pacific Ocean to the upper Sacramento River watershed, most notably winter-run Chinook salmon. The current poor condition of the winter-run Chinook salmon population (Appendix E) has led to pressure from other stakeholders for releases and diversions to be altered to benefit the fish.

Conflicting Water Use Needs and Prioritizing Allocations

Coldwater pool management affects several water end-user groups, each with specific seasonal needs. Agricultural users, particularly those in the Sacramento Valley, depend on predictable and consistent water deliveries from spring through early fall for crop irrigation. As described above, their needs are integrated into decision making for the action, which influences the development of the annual temperature management plan. Hydropower operators may face diminished power generation during spring and early summer if flows are restricted to preserve cold water for release later in the summer (see Box 2-2). Indeed, during the critically dry 2021 season, USBR was forced to bypass power generation at Shasta Dam for one month starting in April, which resulted in a reduction in power value by approximately \$5 million (USBR, 2022). In most cases, however, bypassing hydropower generation has nothing to do with coldwater pool management and is more likely to occur to avoid penalties from generating power when renewables are online (during sunny and/or windy days).

BOX 2-2

Hydropower Operations and Coldwater Pool Management

To achieve desired temperatures at compliance points below Keswick Dam, coldwater from Shasta Reservoir is released using the temperature control device on the lake side of Shasta Dam, which allows withdrawal of water from different depths. The coldwater temperature calculation also accounts for the volume and temperature of cold water from the Trinity Reservoir that enters Keswick or the Sacramento River from Clear Creek, along with an allowance for warming as water travels from the Shasta or Trinity dams to the spawning areas below Keswick (USBR, 2017). According to USBR (2017), “water temperature variations in Spring Creek Powerhouse flows typically have a relatively modest impact on Keswick Dam release temperatures because Shasta Dam discharges are much larger than Spring Creek Powerhouse flows into Keswick Reservoir.” Indeed, Shasta currently contributes on average almost 10 times more flow to the Sacramento River than does the Trinity River. Thus, rescheduling Trinity releases to control Sacramento River temperatures is likely not worth pursuing. (Keswick Reservoir is shallower, well-mixed, and with a shorter residence time than Shasta although weak stratification can occur occasionally. The mixing of waters within Keswick Reservoir is the subject of an ongoing study by the U.S. Geological Survey (USGS) using the DELFT-3D hydrodynamic model; results are pending although preliminary data are available.^a)

Figure 2-3 shows the CVP’s north-of-Delta reservoirs and power plants. It includes the major CVP reservoirs that have power plants (Folsom, Trinity, and Shasta dams) plus the stand-alone Carr and Spring Creek power plants. The figure shows the crest elevation of each reservoir and power plant locations. Figure 2-3 demonstrates the large head for hydropower generation at these CVP reservoirs. The top of Trinity Reservoir has an elevation of nearly 2,400 feet, whereas Shasta Dam’s crest is at an elevation just above 1,000 feet, and Folsom’s crest is near 500 feet. The 1,300-foot difference between Trinity and Shasta results in Trinity’s water temperature being lower than Shasta’s, and water traveling from Trinity to the Sacramento River at Keswick Dam has much more incremental hydropower potential (generated at the Trinity, Carr, and Spring Creek powerhouses). The Shasta powerplant, with a capacity of 710 megawatts, generates energy worth \$50–100 million annually.^b

continued

⁷ See <https://www.usbr.gov/projects/index.php?id=241>.

BOX 2-2 *continued*

Both Shasta and Trinity dams can schedule hydropower releases at any time of day, with downstream Lewistown and Keswick dams reregulating flows within 24 hours. Power generation is generally directed to times when power has a higher energy market value and hydropower generation is not restricted by competition from other renewable sources of energy (like wind and solar). In some circumstances, coldwater pool management requirements may delay cold-water releases in the spring and early summer so that the coldwater pool will last through the early fall. Although this withholding can delay hydropower generation, the volume of water withheld then becomes available for release in the fall. Thus, the volume of water released in different months shifts, but total power production is about the same. The value of differences in energy and spinning reserve in different months will depend on energy and reserve-power regional markets and where a facility's generation fits in those markets at different times of the day. Although there has been one documented instance where hydropower generation was diminished because the turbines were bypassed in spring to benefit adult winter-run prior to spawning (USBR, 2022), in general the economic impact of coldwater pool management on hydropower's value is expected to be small because relative to the spring, energy prices are the same or higher in the fall.

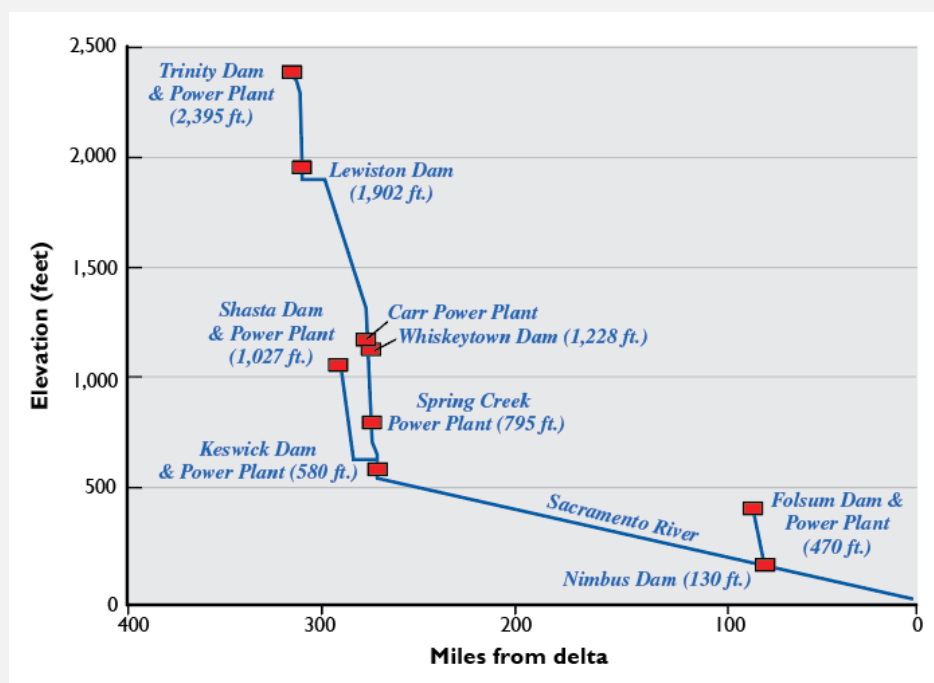


FIGURE 2-3 CVP hydropower profile.

NOTES: PP = Power plant.

SOURCE: Adapted by Kevin Lear, International Mapping Associates from Patton (2024).

^a See <https://data.usgs.gov/datacatalog/data/USGS:62e16507d34e10763b599008>.

^b See <https://www.usbr.gov/newsroom/news-release/5187>.

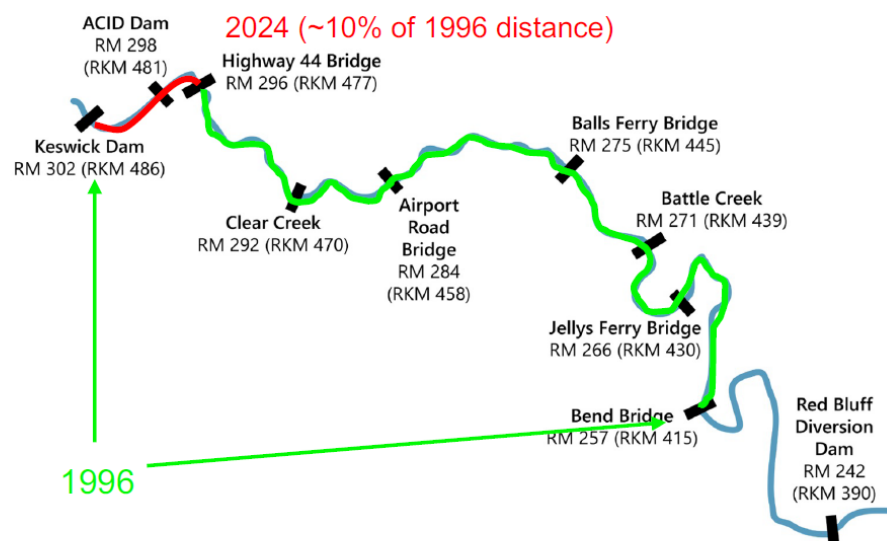
Uncertainty Around Temperature Thresholds and Compliance Points

The temperature threshold chosen for coldwater pool management is controversial because it establishes the volume of cold water needed for conservation (and consequently affects the timing of deliveries and the volume unavailable for other uses), and evidence suggests that the threshold may not be protective. The current 53.5°F (11.9°C) threshold was established based on guidelines issued by the Environmental Protection Agency (EPA Region 10, 2003) in conjunction with studies of temperature-dependent mortality that identified sharp increases in egg mortality above this temperature during incubation (Anderson et al., 2022; Martin et al., 2017). Martin et al. (2017) observed that field-based mortality rates in the Sacramento River were higher than laboratory predictions at similar temperatures, likely due to compounding and interactive effects from multiple abiotic and biotic stressors or heterogeneity at the ecosystem scale. The sensitivity of embryonic development to competing abiotic factors has been demonstrated (Del Rio et al., 2019, 2021) and suggested as a factor explaining differences in survival between lab and field studies (McCullough et al., 2001). Given the vulnerability of winter-run Chinook as exemplified by its declining population over the past 50 years (Figure 1-3C), additional research is warranted to explore the interactive effects of temperature, dissolved oxygen, and flow through redds. As discussed in a subsequent section, this research may provide valuable insight for refining the temperature threshold or managing temperature and flow more dynamically.

The spatial extent of the Sacramento River reach that is managed for temperature, which spans Keswick Dam (River Mile or RM 302) to Balls Ferry (RM 275), has changed over time. Presently, the downstream compliance point is in the vicinity of the Sacramento River confluence with Clear Creek (CCR, RM 292) (Table 2-1 and Figure 2-4A; NMFS, 2019; USBR, 2024a). There has been an ongoing upstream shift of the compliance point over the last few decades (Figure 2-4B). This shift has reduced the spatial extent of suitable spawning habitat, concentrated redds in upstream areas, and diminished genetic diversity and imprinting cues essential for long-term population resilience (NMFS, 2024b). Although upstream shifts in the compliance point can reduce temperature-related mortality in critically dry years, they risk undermining recovery objectives that depend on maintaining a broader spawning distribution (NMFS, 2024b; USBR, 2024a). For example, density dependent disturbance effects on redds may negatively impact egg survivorship (Bartholow, 2004). Figure 2-4B illustrates that over the past three decades, the compliance point has gradually moved upstream. In the 20 years prior to 2005, the compliance point was always downstream from RM275, whereas in the 20 years since 2005, the compliance point has been downstream from RM 275 only twice. Also shown in the graph is the annual mean flow in the Sacramento River, illustrating that the relationship between annual runoff and the compliance point (and therefore the reaches of river meeting suitable temperature conditions for spawning) is not simple and relies on numerous other factors such as the available volume of the coldwater pool and the timing of releases.

Limitations of Coldwater Pool Management Alone for Conserving Winter-run

Coldwater pool management, while critical for mitigating high water temperatures in the Sacramento River during spring and summer months, has inherent limitations for sustaining recovery of winter-run Chinook salmon. The species' dependence on managed flows and artificial coldwater management below Keswick Dam exposes the population to heightened risk, especially during consecutive drought years, when storage levels at Shasta Reservoir are insufficient to maintain coldwater reserves and the hatchery program is at risk of insufficient brood stock to support spawning. As discussed later, drought intensity is increasing and winter temperatures are warming—outcomes that underscore the risk of long-term management strategies that do not include natural coldwater habitats. The 2024 NMFS Five-Year Review for winter-run Chinook salmon (NMFS, 2024a) similarly concludes that the species remains at high risk of extinction due to its restricted spawning range, dependence on Shasta Reservoir coldwater pool availability, and vulnerability to increasing climate variability.

Diagram of the Upper Sacramento River with Key Spawner Survey Landmarks

(A) Redrawn from Anderson (2018). Note that the RM given for Clear Creek is for the Sacramento River Above Clear Creek gage (CCR). The confluence of Clear Creek with the Sacramento River is 3 miles downstream at RM 289.

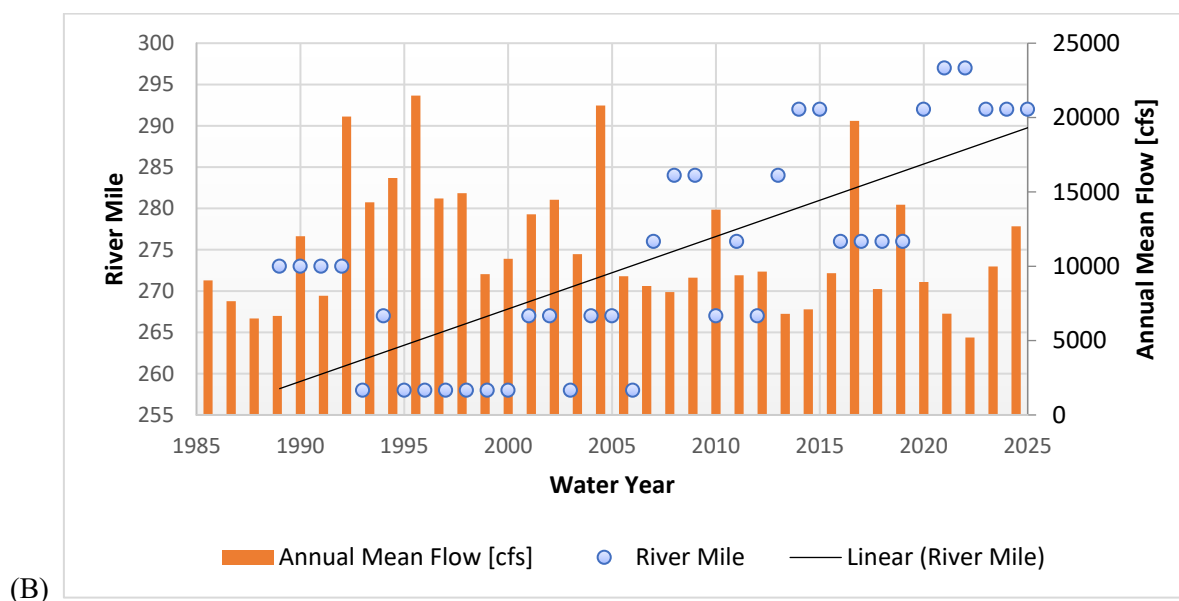


FIGURE 2-4 (A) The coldwater compliance point downstream of Keswick Dam. NOTES: The compliance point for meeting the thermal threshold for cold water in the Sacramento River has shifted between 1996 (green segment) and 2024 (red segment). RM = River Mile. SOURCE: Danner (2024) adapted from Anderson (2018). (B) Winter-run Chinook salmon spawning water temperature compliance point (shown in blue circles). NOTE: Annual mean flows (red bars) are measured at the Sacramento River near Red Bluff. DATA SOURCES: Compliance points from Sacramento River annual WY Reports 1996–2009, Sacramento River Temperature Task Group annual reports, see <https://www.usbr.gov/mp/cvo/temperature.html>, and JPE letter footnotes 2010–2024; River flows from USGS Gage 11377100.

NMFS (2024a) emphasizes continued temperature and flow management below Keswick Dam to reduce egg mortality, in particular maintaining and, where feasible, expanding the spatial extent of the temperature-managed reach beyond the Clear Creek gauge. The report also recommends developing operational tools that merge real-time environmental monitoring with temperature-dependent mortality models and seasonal hydrologic forecasts to guide decision-making. Finally, NMFS (2024a) calls for continued investment in habitat restoration and expanded biological monitoring, including disease and genetic assessments. In parallel, NMFS (2024a) recommends expanding the spatial access of winter-run to coldwater habitat by restoring connectivity to historically occupied areas—particularly above Shasta Dam and in Battle Creek—to reestablishing population structure and reduce reliance on the managed reach below Keswick. Collectively, these recommendations prioritize near-term survival while recognizing that long-term recovery depends on diversifying habitat access and buffering the population against environmental uncertainty—a theme taken up in this report as well.

Conflicting Conservation Priorities

Coldwater pool management decisions can have varying effects on several non-target fish species, some of which are listed as or expected to be listed as threatened under the Endangered Species Act (ESA). Fall-run and spring-run Chinook salmon, which spawn later in the year than winter-run, face reduced habitat availability or suboptimal temperatures if coldwater reserves are depleted by early season Shasta releases for winter-run Chinook salmon. Similarly, steelhead, which rear year-round in the Sacramento River, depend on consistently low water temperatures for juvenile development (Kershner et al., 2019; USBR, 2024a); sudden temperature or flow fluctuations may negatively impact their growth or survival during the fall and winter. Both green and white sturgeon are impacted by flow and temperatures during the spring, and during and after spawning (NMFS, 2019; USBR, 2024a). Reduced spring flows to conserve water for summer coldwater storage may hinder sturgeon spawning success by altering flow cues and increasing egg and larval exposure to warmer temperatures, potentially increasing stress, mortality, or vulnerability to predators for early-life-stage sturgeon (NMFS, 2019; USBR, 2024a). Thus, managing flows to prioritize winter-run Chinook salmon can result in suboptimal water temperatures or flow conditions for these other species during their critical life stages.

SHASTA MONITORING

Monitoring activities supporting coldwater pool management encompass a suite of physical, biological, and ecological assessments that inform decision making for water temperature management, flow volume and release timing, drought and water supply planning, and species protection. The sections below describe and then discuss improvements to the monitoring of physical parameters relevant to the Shasta Coldwater Pool Management Action, followed by biological parameters.

Monitoring of Physical Parameters

The improvements to monitoring of physical parameters discussed below focus on additional streamflow monitoring, improved temperature profiling in Shasta Reservoir, and better understanding reservoir dynamics. The overall point is that augmenting the monitoring of physical processes will facilitate more accurate determination of the coldwater pool volume and inform more effective operational decision making.

Stream Monitoring Downstream of Shasta and Keswick Dams to Support Coldwater Pool Management

Stream monitoring on tributaries to Shasta Reservoir and along the Sacramento River is conducted variously by the USGS, CDWR, USBR, USFWS, and CDFW, as well as other entities such as Pacific Gas & Electric (PG&E). At most of the USGS stream gaging stations, only stage and discharge are measured continuously, with the exception of select gages that include temperature and/or turbidity measurements. At other stations, a wider range of water quality data (e.g., nitrates, pH, salinity) are measured, in addition to temperature and turbidity. Water temperature sensors are also located in each of the penstocks of Shasta Dam and at the Livingston Stone National Fish hatchery downstream of Shasta Dam. Table 2-3 shows the monitoring locations used in the Water Temperature Modeling Platform (WTMP; discussed in a subsequent section on Modeling) along with the responsible agencies.

TABLE 2-3 Monitoring Locations in the Upper Sacramento Basin Relevant to Coldwater Pool Management Used by the WTMP

WTMP Site Abbreviation	Site Name	Agency	Site Active?	Data Frequency
Shasta Reservoir and Primary Tributaries				
<i>Flows</i>				
11342000	Sacramento River at Delta CA	USGS	Yes	15-minutes
11368000	McCloud River above Shasta Lake CA	USGS	Yes	Daily
11365500	Sulanharas C at Shasta Lake CA	USGS	No	Discontinued
11365000	Pit River near Montgomery Creek CA	USGS	Yes	Daily
DLT	Sacramento River at Delta	CDEC-USBR	Yes	15-minutes
MSS	McCloud River above Shasta Lake	CDEC-PG&E	Yes	Hourly
PMN	Pit River near Montgomery Creek	CDEC-USBR	Yes	Daily
SHA	Reservoir Elevation and Storage	CDEC-USBR	Yes	Hourly
SHA	Generation Release through 5 powerhouse units	CDEC-USBR	Yes	Hourly
SHA	Spill Release	CDEC-USBR	Yes	Hourly
SHA	Outlet Release	CDEC-USBR	Yes	Hourly
SHA	Total Release [Spill+Outlet+Power Generation]	CDEC-USBR	Yes	Hourly
<i>Water Temperature</i>				
DLT	Sacramento R at Delta	CDEC-USBR	Yes	Hourly
MSS	McCloud R above Shasta Lk	CDEC-PG&E	Yes	Hourly
PMN	Pit R near Montgomery Cr	CDEC-USBR	Yes	Hourly
SHD	Tailbay Water Temperature (Below Shasta Dam)	CDEC-USBR	Yes	Hourly
SP1	Shasta Penstock #1	CDEC-USBR	Yes	Hourly
SP2	Shasta Penstock #2	CDEC-USBR	Yes	Hourly
SP3	Shasta Penstock #3	CDEC-USBR	Yes	Hourly
SP4	Shasta Penstock #4	CDEC-USBR	Yes	Hourly
SP5	Shasta Penstock #5	CDEC-USBR	Yes	Hourly
Keswick Reservoir and Primary Tributaries				
<i>Flows</i>				
SPC	Spring Creek Debris Dam	CDEC-USBR	Yes	Hourly
WHI	Spring Creek Generation Release through 2 powerhouse units	USBR	Yes	Hourly
11371600	Spring C PH A Keswick CA	USGS	Yes	Daily
KES	Reservoir Elevation and Storage	CDEC-USBR	Yes	Hourly
KES	Generation Release through 3 powerhouse units	CDEC-USBR	Yes	Hourly
KES	Spill Release	CDEC-USBR	Yes	Hourly

KES	Fishtrap Release	CDEC-USBR	Yes	Hourly
KES	Total Release (Spill+Fishtrap+Power Generation)	CDEC-USBR	Yes	Hourly
Water Temperature				
SPP	Spring Creek Powerhouse	CDEC-USBR	Yes	Hourly
Sacramento River: Keswick Dam to Red Bluff				
Flows				
KES	Keswick Reservoir: Total Release	CDEC-USBR	Yes	Hourly
11370500	Sacramento R A Keswick CA	USGS	Yes	Hourly
11370700	Anderson-Cottonwood ID CN AT Redding CA	USGS	Yes	Hourly
11372000	Clear Creek near Igo CA	USGS	Yes	Hourly/ Daily
CCP4	Clear Creek at Phase 4 Site	Graham Mathew and Assoc.	No	Hourly
11374000	Cow Cr NR Millville CA	USGS	Yes	Hourly
11376000	Cottonwood Cr NR Cottonwood CA	USGS	Yes	Hourly
11376550	Battle Cr Fish Hatchery NR Cottonwood CA	USGS	Yes	Hourly
11377100	Sacramento R AB Bend Bridge NR Red Bluff CA	USGS	Yes	Hourly
Water Temperature				
KWK	Keswick Water Quality	USBR		Hourly
11372000	Clear Creek near Igo CA	USGS	Yes	Hourly
CCVW Confluence	Clear Creek video weir RM0.1 Clear Creek confluence RM0.5	CDFW	Yes	Hourly
NA	Cow Cr near mouth (old video station at RM1)	CDFW	Yes	Hourly
BSF	Sacramento River at Balls Ferry Bridge	CDEC	Yes	Hourly
NA	Cottonwood Cr	CDFW	YES	Hourly
NA	Battle Cr	CDFW	YES	Hourly
JLF	Sacramento River at Jellys Ferry	CDEC	YES	Hourly
BND	Sacramento River at Bend Bridge	CDEC	YES	Hourly

SOURCE: USBR (2024c) and <https://cdec.water.ca.gov/webgis/?appid=cdecstation>.

Temperature monitoring downstream of Shasta Dam between Shasta and Keswick and downstream of Keswick could be supplemented by the addition of more thermistors. Currently, measurements being made at the penstocks and at Livingston Stone occur before the water flows have mixed fully across the width of the river channel. This makes it difficult to determine whether the release temperatures used as the upstream boundary condition in the river segment of the WTMP are accurate for forecasting downstream temperatures at compliance points. If the temperature sensor downstream of the dam (which is mounted on one side of the channel before the flow is fully mixed across the channel) were moved downstream, or an additional sensor were added, a much more accurate measurement of average water temperature in the river just below Shasta Dam would be obtained.

There also appears to be limited measurement of water temperatures at tributary confluences downstream of Keswick. This information could influence assessments of whether main stem Sacramento River segments can provide appropriate spawning grounds for winter-run Chinook salmon or the effect of tributary inflows on downstream temperature targets.

Enhanced Tributary Monitoring Above Shasta Reservoir to Enable Better Estimation of the Coldwater Pool

The development of the coldwater pool in reservoirs depends on the carryover volume and water temperature from the previous year, the internal hydrologic mixing processes, and the tributary inflows. If the tributary inflow has a density less than the receiving water in the reservoir (i.e., low sediment

concentrations and warmer temperature), then the flow will be positively buoyant and the inflow will spread across the surface waters. If the reservoir is stratified, then these inflows will contribute primarily to the warmer surface waters of the epilimnion. However, if the tributary inflows are denser than the receiving waters, then the inflow can plunge beneath the surface layers and possibly along the bed of the reservoir as a density current (underflow) or as an interflow at a depth in the reservoir where the density of the inflow matches the receiving water and the motion of the inflowing plume stabilizes (e.g., Alavian et al., 1992; Fischer et al., 1979). These colder inflows can flow beneath the thermocline and contribute directly to the coldwater pool. For example, the Pit and upper Sacramento rivers enter Shasta Reservoir as density-driven interflows or underflows depending on their temperature and sediment load and can reinforce the coldwater pool without disrupting upper stratification (Lieberman and Horn, 1998).

The WTMP is well structured to capture the dynamics of these inflows, but accurate inflows and water temperatures are required close to the points where the tributaries enter the reservoir. The top half of Table 2-3 summarizes the flow and water temperature data collected from tributaries into Shasta Reservoir. The inflow from Big Backbone Creek is assumed negligible, and Sulanharas Creek⁸ is not currently monitored and a regression equation is used to predict flows based on water year type (USBR, 2024c). Although the inflow from Sulanharas Creek is significantly less than that from the Upper Sacramento River, the Committee suggests placing a low-cost temperature sensor close to the Sulanharas inflow to the reservoir. This would enable a confirmation of the accuracy of the regression equation used. Consideration should also be given to placing temperature sensors close to the point of tributary inflow to Shasta Reservoir where the current gaging is significantly upstream of the inflow point. The WTMP can be used to evaluate the importance of the inflowing tributaries in establishing the coldwater pool and the value of maintaining these low-cost gages beyond the study period.

Measurements of Reservoir Temperatures and Coldwater Pool Volume

Temperature profile data of Shasta Reservoir and the reservoir's stage-storage relationship (Figure 2-5) are used to estimate the volume of the coldwater pool. Specifically, the elevation of the thermocline is identified from the single vertical profile, and this elevation is then used in stage-storage curves to calculate the volume of water below a selected temperature threshold down to the reservoir's dead pool or other management-defined elevation (Nickel et al., 2004; NMFS, 2019). Assuming a horizontally uniform temperature distribution introduces uncertainty because stratification can vary across the reservoir and at fairly short time scales, especially in a large, multi-arm reservoir such as Shasta (Nickel et al., 2004). Furthermore, water temperature *below* the thermocline is not uniform and may vary from year to year; knowing the vertical temperature profile is key to optimally managing the TCD and water releases and projecting the amount of coldwater throughout the season. To reduce uncertainty in the Shasta coldwater pool management action, water temperature should be measured at sufficiently high spatial and temporal resolution to capture shorter time scale physical dynamics that affect the temperature distribution. Without capturing these dynamics, or at least understanding whether and when they are significant, single-profile or infrequent measurements risk mischaracterizing the extent and availability of the coldwater pool, especially during critical temperature management periods. Indeed, if the estimation of the coldwater pool is inaccurate by 1 foot in elevation, this translates, assuming an area of 15,000 acres, to the equivalent of releasing 1,000 cubic feet per second (cfs) of cold water for one week. Managers would be better positioned to plan and communicate operational decisions about Shasta if an accurate understanding of the thermal structure, prevailing mixing processes, and coldwater pool characteristics were available—all of which can be addressed with improved monitoring, as discussed below.

⁸ Renamed in 2022 by the Board on Geographic Names.

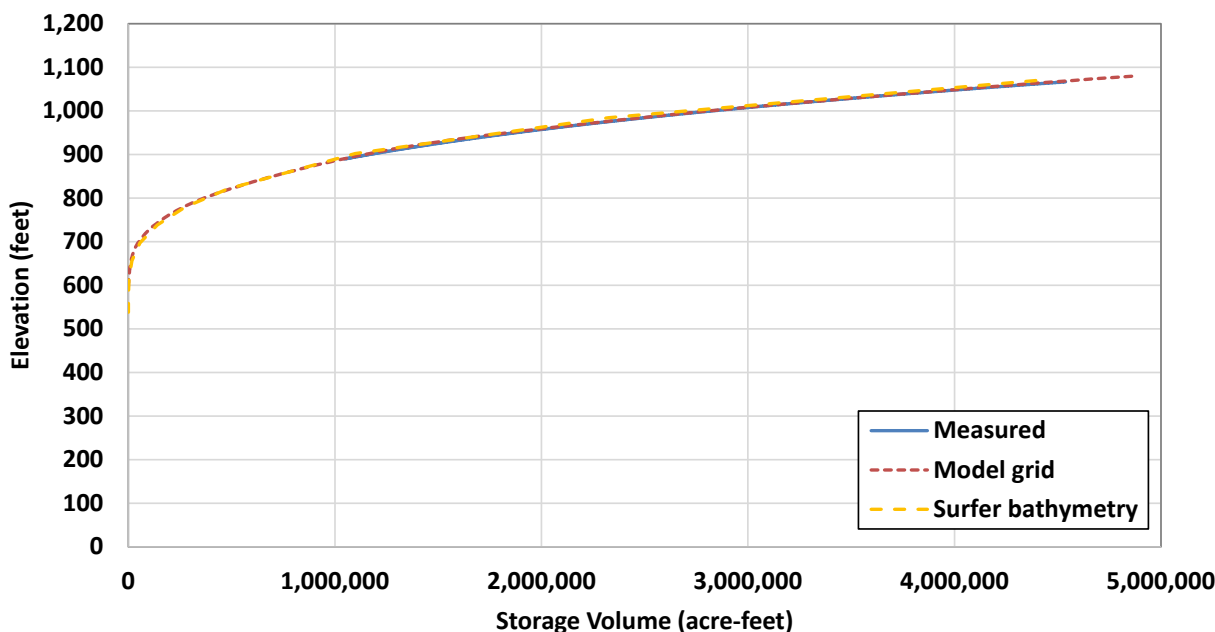


FIGURE 2-5 Stage-storage curves for Shasta Reservoir used in the WTMP.

NOTE: The volume is based on bathymetry measured in a 2019 survey, “Surfer” interpolation from bathymetric maps, and calculated from the model grid.

SOURCE: USBR (2024c, Figure 5.3).

Vertically discrete measurements of water temperature from within Shasta Reservoir are necessary to estimate and validate the depth and volume of the coldwater pool. A few different approaches have been implemented in the past, described in greater detail below: (1) water temperature profile measurements manually collected from a boat, (2) continuous measurements of water temperature made at discrete intervals throughout the water column using a thermistor chain, (3) a short-term temperature study conducted from 2015 to 2016 using fiber-optic distributed temperature sensing, and (4) a USGS study that evaluated the spatial distribution of water temperature from 1995 to 1997 (Lieberman and Horn, 1998). The profilers used in (2) and (3) are usually attached to a surface buoy or platform and can be linked directly to other water quality sensors. Micro-meteorology stations can be mounted on the buoy or platform with capability to transmit data real-time through cell phones, satellites, or cables. These comprehensive systems go by different names; this report uses the generic term Lake Diagnostic System (LDS; Imberger, 2004) without preference for any specific fiber-optic or thermistor technology.

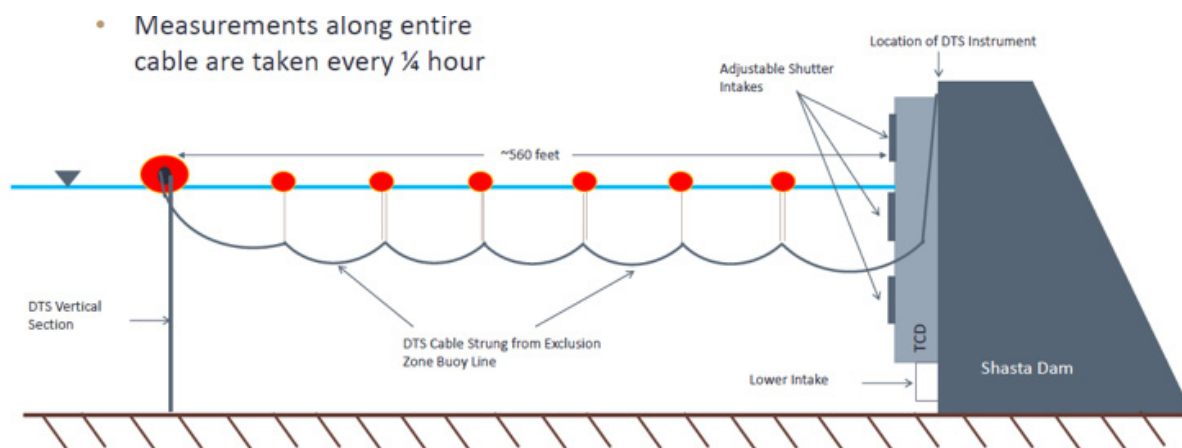
First, manual water temperature profiles are collected year-round via boat on a weekly to monthly basis. The highest frequency (weekly) measurements are made from April through mid-November at a vertical resolution of 5 feet (ft). During the winter months (December to March) sampling is done only monthly and at a lower vertical resolution of 25 ft. In the two short intervals between those periods (March and the latter two weeks of November) sampling is done every two weeks at a vertical resolution of 25 ft. The exact location of the profile varies depending on prevailing conditions, but for safety reasons it is generally about 75 meters (m) (246 ft) from the dam face.

Second, continuous monitoring of temperature throughout the water column has been temporarily conducted at one location in the reservoir, on a seasonal basis, and only for the purposes of validating the WTMP implemented by USBR. This was done using a series of HOBO® water temperature loggers deployed in a vertical array as a thermistor chain. Neither real-time telemetered nor manually downloaded high frequency measurements of water temperature are part of the existing monitoring program in Shasta Reservoir.

Third, a short-term high-resolution monitoring effort was conducted from August 2015 to July 2016. During that period, the National Oceanic and Atmospheric Administration (NOAA) and USBR deployed a combined micro-meteorology station and continuous fiber-optic distributed temperature sensing (DTS) cable, which was installed in a vertical array to measure water temperature at high-resolution over the vertical length of the cable. Figure 2-6 illustrates the monitoring setup; weather data are recorded hourly and water temperature is measured at 1-ft intervals over the water column every 15 minutes (Daniels et al., 2024). Although equipment was acquired to continue this more detailed real-time monitoring, it has not been deployed since 2018 because of safety concerns for recreational boaters and potential risks posed to the TCD and other dam infrastructure.



A. Plan View



B. Side View

FIGURE 2-6 Vertical temperature profile monitoring setup used from 2015 to 2016. NOTE: Data presented in this report is for the DTS vertical section only. DTS = distributed temperature sensor. SOURCE: Daniels et al. (2024).

Investment in continuous, high-resolution monitoring infrastructure—such as the vertically distributed thermistor chains or fiber-optic DTS systems (mentioned as approaches #2 and #3 above)—would provide more accurate inputs for coldwater pool modeling and more defensible operational decisions. The addition of LDS or similar technology will supplement previous studies by USBR, NMFS, and USGS and provide continuous recording with the ability to download data either in real-time or via a daily download. One of these stations should be permanently deployed within 1 km of the dam. Other LDS stations could be located to provide the best representation of the flow and meteorological conditions in the arms of the reservoir and to capture the interactions between the various parts of the reservoir. Ideally, WTMP modelers could run scenarios and determine the optimum number and location of these LDS stations. The deployment should last for as many seasons as required to ensure the WTMP team and SHOT have confidence in the model projections (typically 2-3 years), after which fewer monitoring stations (perhaps only one) would be needed. Deployment of these technologies has several advantages over the status quo including continuous data at 5- to 15-minute intervals that are capable of capturing shorter time scale vertical mixing processes (including seiching), less staff time to collect measurements by boat if coupled with telemetry (maintenance is only required when the data transmission indicates a problem), and information can be collected during adverse weather conditions when significant changes may occur. The detailed vertical temperature profiles provided by LDS will provide a better understanding of the coldwater pool, how it is likely to develop throughout the year, and how water may be blended within the TCD and river outlets to maximize the ecological benefits of this finite resource.

Thermal Regime and Mixing Dynamics in Shasta Reservoir

The mixing regime of Shasta Reservoir is warm monomictic, meaning it never cools to the point of freezing and only experiences one period of vertical mixing a year. However, in many years, vertical mixing in the fall and winter is incomplete, reaching only a depth of 50–60 m below the surface, and the reservoir is considered merimictic (Lieberman and Horn, 1998). The extent of this vertical mixing depends on the water temperature profile and the associated density differences that develop over the year. Figure 2-7 shows the seasonal thermal stratification of Shasta Reservoir over the last five years. As previously mentioned, stratification usually develops in April or May, the onset of which is defined as the point when surface waters warm 2°F (1.1°C) above the normal spring surface water temperature of 52°F (11.1°C). The thermocline typically deepens through early summer before stabilizing in mid-summer. In dry or critically dry years, stratification may begin earlier and persist longer, often with a thinner coldwater pool and greater risk of mid-summer hypolimnetic warming (see Figure 2-7). Conversely, in wet years, colder inflows from high-elevation tributaries such as the McCloud and Upper Sacramento rivers sustain colder hypolimnetic temperatures and a larger coldwater pool.

In addition to inflow temperatures and volumes, seasonal air temperatures (Nickel et al., 2004), and vertical mixing processes, the thermal structure of reservoirs is further shaped by complex mixing dynamics that include wind-driven turbulence, seiching, and internal waves—especially in the multi-arm, mountainous morphology, and microclimatology of Shasta Reservoir. A potential role for seiching was suggested from the Daniels et al. (2018) modeling study that was trying to better understand leakage around the TCD gates. Some leakage around the gates in the TCD is inevitable due to the scale of the TCD structure and high pressures. Estimates of gate leakage have been made in the past (Resource Management Associates, 2003), and a current UC Davis study aims to improve these estimates. Daniels et al. (2018) predicted the temperature of water releases with and without estimated TCD leakage (Figure 2-8). Accounting for leakage around the TCD improved the projections of water temperatures but failed to account for the high frequency fluctuations of about 2°C (3.6°F) observed in the releases and the significant fluctuation at the end of June 2012 that persisted for a few days. Box 2-3 explores whether these temperature fluctuations might have been caused by seiching. The current monitoring of Shasta's vertical water temperature profiles at a weekly to biweekly cadence during the coldwater pool

management season does not have a fine enough temporal resolution to detect such physical mixing dynamics as seiches.

A final, complex factor affecting Shasta coldwater pool development is the volume and temperature of carryover storage. Higher end-of-September storage does not necessarily result in a greater volume of coldwater the following season if the reservoir turns over with a large volume of warm water.

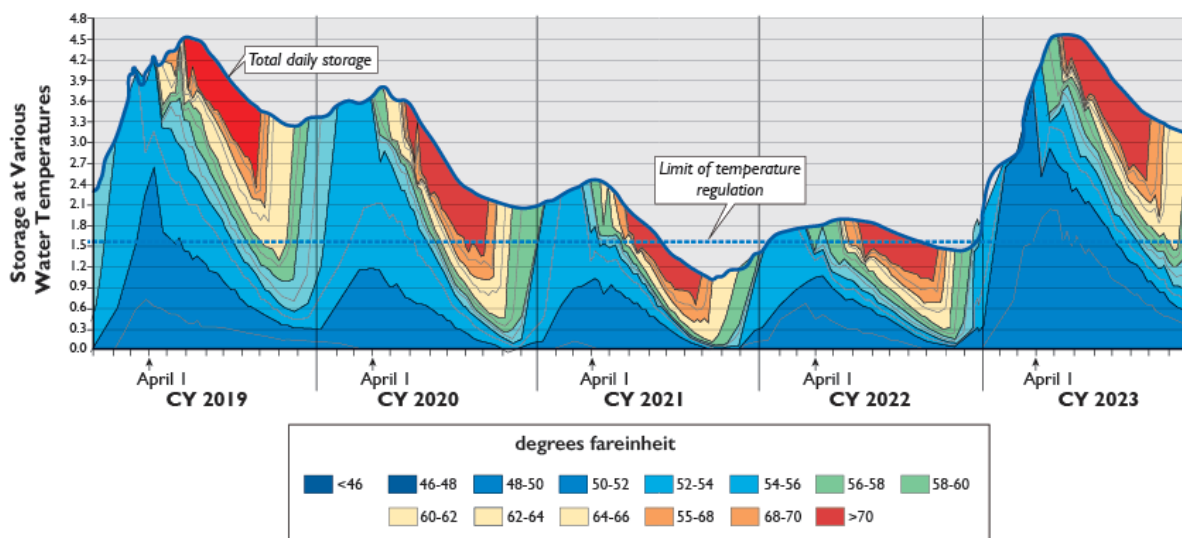


FIGURE 2-7 The seasonal variation in the thermal structure of Shasta Reservoir from 2019 through 2023.

SOURCE: <https://www.usbr.gov/mp/cvo/temperature.html>.

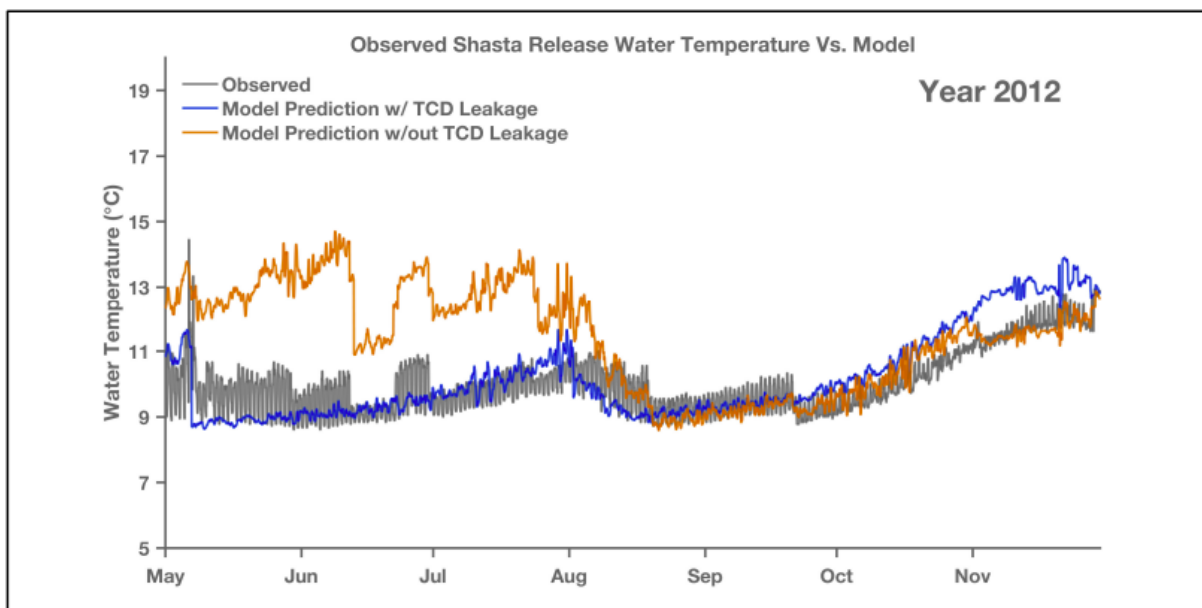


FIGURE 2-8 Comparison of observed (grey line) and CE-QUAL-W2 model simulations for 2012 with (blue line) and without (orange line) leakage around the TCD gates.

SOURCE: Daniels et al. (2018).

BOX 2-3 Seiching in Shasta Reservoir

Seiching, a potentially important physical process affecting the coldwater pool, cannot be detected by the current reservoir monitoring. Seiching can be initiated by severe wind events or by gate or turbine operations, as well as external disturbances such as landslides or major inflows creating density currents. Seiching is not the only form of internal mixing phenomenon and other mechanisms such as Kelvin waves could also play an important role (Wuest and Lorke, 2003).

Seiching is established when wind blows across the surface of a lake, the water surface at the leeward shore becomes elevated relative to the windward shore. As the wind stops or changes direction, there is a counterflow to restore a horizontal water surface and, because of the nature of water waves, this usually occurs as a series of diminishing oscillations. This process may become significant and relevant to reservoir operations if it occurs during a period of stratification. In this case, the epilimnion will deepen on the leeward shore and diminish on the upwind (windward) shore, and a counterflow will restore the horizontal thermocline when the wind subsides. These series of oscillations at the density interface are termed internal seiches (Fischer et al., 1979). The height of the internal seiche can be much larger than the surface oscillation, and the internal seiche can significantly affect the temperature of releases if the point of withdrawal is close to the thermocline or if a temperature gradient exists in the hypolimnion. The amplitude and period of the seiche depends on the wind speed, direction and duration, the fetch, atmospheric stability, density difference and wavelength (Chen et al., 2016). Shasta Reservoir has five arms and mountainous topography that will create local meteorology and a complex interaction of seiches. NOAA and USBR conducted detailed continuous monitoring of the meteorology and vertical temperature profile from August 2015 to July 2016. During this period the peak sustained wind speed recorded was over 30mph and a typical diurnal air temperature and wind pattern, as illustrated in Figure 2-9 for the month of April 2016. These wind events contribute to vertical mixing of the surface layers in the reservoir and have the potential to initiate seiching.

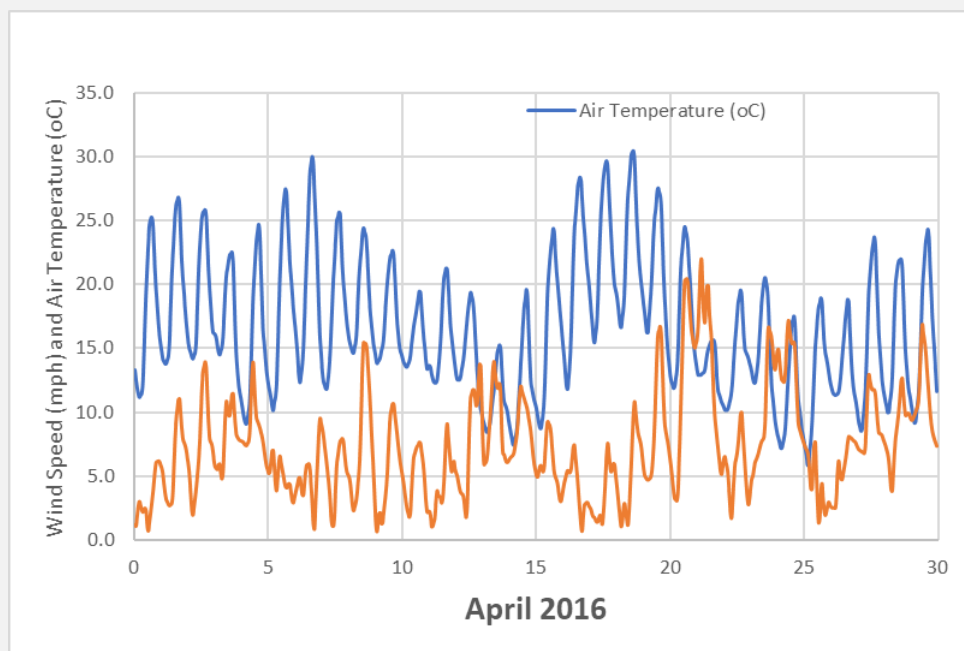


FIGURE 2-9 Air temperature and local wind speed at Shasta Dam in April 2016.
SOURCE: Graphed by the Committee with data sourced from Daniels (2024).

continued

BOX 2-3 *continued*

Observed vertical temperature profiles at Shasta Dam are shown in Figure 2-10 for August 28 and September 20, 2015. The air temperatures are cooling during this period and the water temperature in the well-mixed surface layer of the reservoir drops by about 2°C (3.6°F). During this period the reservoir was drawn down by 2.75 m and the mixing layer in the epilimnion and upper hypolimnion increased by about 10 m. Mixing by turbulence from convective heat loss and diurnal wind activity does not account for the entire deepening of the warmer epilimnion (and reduction in the coldwater pool). The upper layers of the hypolimnion are also warming significantly during this period because of the transfer of warmer water across the thermocline. Strong winds can help explain the additional reduction in the coldwater pool, and further investigation is warranted using the new WTMP and associated reservoir monitoring.

There are two effects during this period. First, there was an abrupt deepening of the epilimnion. For example, at elevation 276 m, the water warmed to the same level as the epilimnion almost immediately and did not recover for the rest of the season (Figure 2-11). Second, there is evidence of a seiche at the thermocline (Elevation 273m) with a period of about 25 hours. The difference in wind speed and direction in the different arms of the reservoir and how the internal seiche propagates within such a complex geometry is unknown, but the WTMP can be used to determine when and whether these mixing processes will affect reservoir operations and enhance the ability to optimally manage the coldwater pool. Additional monitoring data can be used to better assess the effect of short-time scale dynamics on coldwater pool volume estimates.

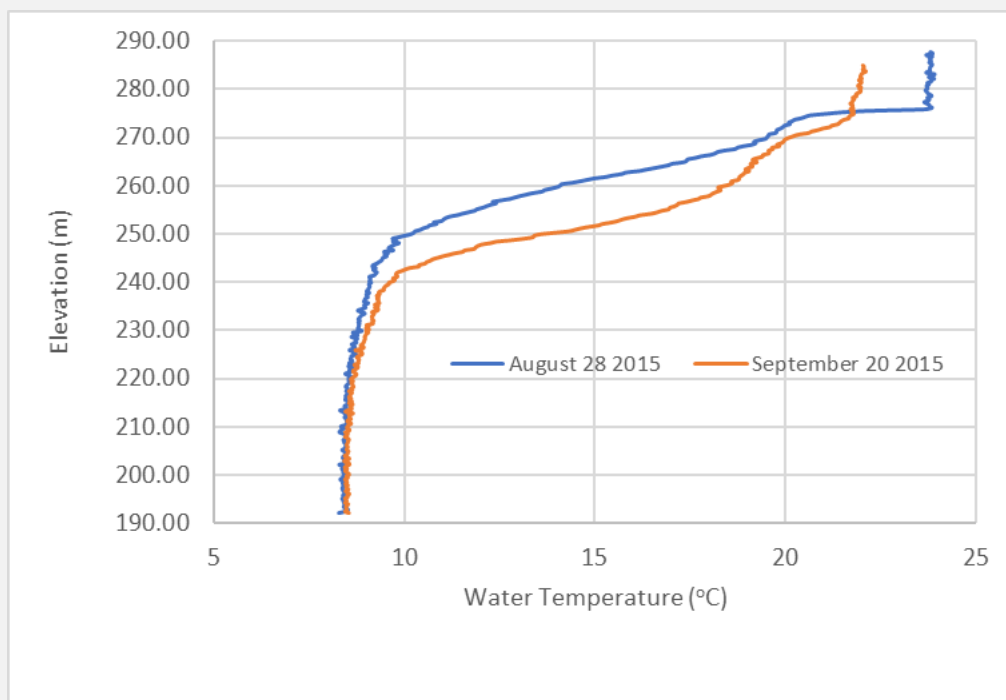
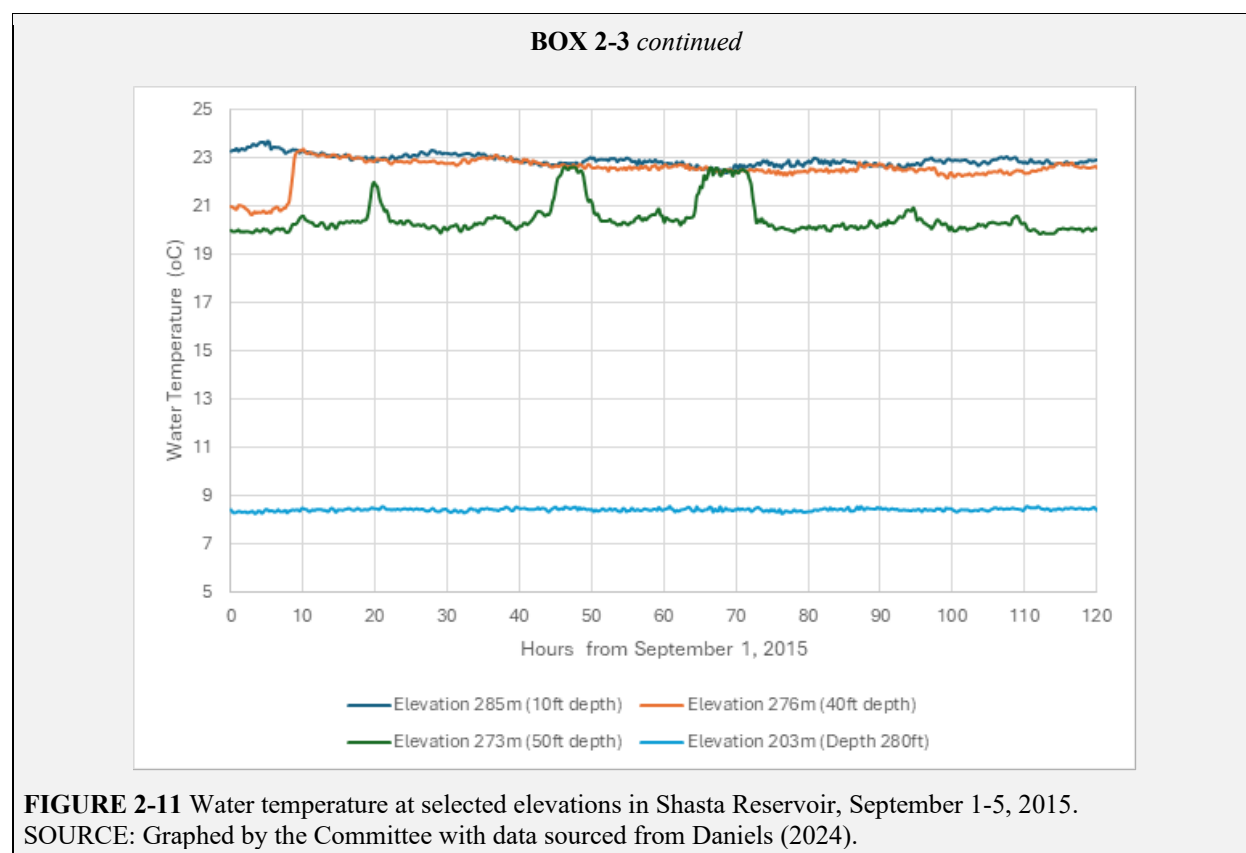


FIGURE 2-10 Water temperature profile at Shasta Dam on August 28 and September 20, 2015.

SOURCE: Graphed by the Committee with data sourced from Daniels (2024).

continued



All of these factors suggest that additional monitoring of the vertical thermal structure within Shasta Reservoir, if coupled with the WTMP, will provide greater insights and predictions regarding the development and dissipation of the coldwater pool. It was mentioned previously that NOAA and USBR deployed a combined micro-meteorology station and continuous vertical profiler DTS from August 2015 to July 2016, with weather data recorded hourly and water temperature measured at 1-ft intervals over the water column every 15 minutes (see Figure 2-6). Since that one effort, NOAA and USBR have not deployed such a monitoring system again. However, more detailed examination of this valuable dataset and the long-term use of such an LDS set-up would provide valuable information about physical processes in Shasta Reservoir. If deployed over a two-year period, a Lake Diagnostic System linked with the reservoir model CE-QUAL-W2 (see Modeling section below) could be evaluated for its ability to simulate and predict the formation of stratification, the internal mixing processes affecting the coldwater pool, and the influence of different TCD operational rules. Some of this equipment could be used for other special studies after the two-year deployment. The additional meteorological information close to the water surface will supplement the new meteorological station on Shasta Dam and provide a better understanding of conditions throughout the complex topography of Shasta Reservoir and the influence of internal mixing processes. Such enhanced monitoring would help Shasta operators understand and predict why the coldwater pool can vary significantly for water years with approximately the same total annual runoff, as well as help to clarify the roles of carryover, seiche, and leakage around the TCD.

Biological Monitoring

Biological monitoring activities inform both operational decision-making for coldwater pool management and long-term protection of winter-run Chinook salmon. The short-term operational

priorities are to ensure temperature compliance during critical spawning and egg incubation periods and mitigate risks of redd dewatering or juvenile stranding. The longer term priority is to enhance population resilience by tracking population dynamics and habitat conditions over time.

In support of these goals, many monitoring activities track critical indicators of winter-run Chinook salmon abundance and development, as well as characterize key aspects of habitat availability and quality. Biological monitoring activities supporting the Shasta Coldwater Pool Management Action include annual assessments of returning adult salmon populations through carcass and redd surveys, which provide essential data on escapement trends and spawning success. Juvenile outmigration is monitored using rotary screw traps at strategic locations along the Sacramento River, enabling managers to evaluate fry survival rates, migration timing, biological condition (an index of size and weight), and year-class strength. Habitat surveys help assess the distribution, quality, and availability of redd areas, while rearing habitat assessments examine in-stream and floodplain conditions critical for juvenile growth and survival. Although not technically monitoring, hatchery production is a component of long-term conservation efforts, and hatchery-origin fish are monitored to assess their contribution to salmon recovery efforts and their relative contribution to the overall genetic pool of the wild population. These monitoring programs are described in Appendix D of this report. What follows is a brief summary and evaluation of activities.

Redd Monitoring

Redd surveys along critical reaches of the Sacramento River document the location, depth, and surrounding flow conditions of redds. Those surveys directly inform flow release schedules from Shasta Reservoir to ensure that water levels remain adequate to protect redds during critical incubation periods. Real-time or near real-time monitoring of redds could be done by increasing the frequency of redd monitoring activities and equipping field teams with tools to input redd data directly into centralized databases, ensuring rapid processing and immediate availability for operational managers. Surveys could be conducted more frequently in areas at high risk of dewatering or sedimentation, which would allow for faster adjustments to flow releases when dewatering risks are identified.

Redd survey data could support proactive, rather than reactive, management strategies by being integrated with predictive tools such as temperature and flow models to forecast future risks to redd viability under various hydrological scenarios. Redd surveys could be used to identify areas with recurring dewatering or habitat degradation, guiding targeted restoration efforts such as gravel augmentation, sediment removal, or riparian improvements that mitigate sedimentation, improve gravel quality, and reduce warming. Egg-to-fry survival estimates derived from redd surveys could be correlated with long-term population data to refine recovery goals and evaluate the effectiveness of coldwater pool management.

Carcass Surveys

Carcass surveys provide data on adult salmon escapement and inform evaluation of spawning success from spawning reaches downstream of Keswick Dam. They contribute to validation of longer-term coldwater pool management actions and they are used to assess the relative contribution of hatchery-origin fish to the total population. Current surveys are concentrated primarily in spawning reaches near Keswick Dam, leaving gaps in data from secondary habitats or underutilized areas that could be critical for improved escapement estimates. Expanding spatial coverage to include under-surveyed areas could provide a more comprehensive understanding of spawning activity.

Monitoring to Understanding Juvenile Survival, Residence Time, and Habitat Use

Coldwater pool management actions support the broader survival and habitat utilization of winter-run Chinook salmon throughout the Sacramento River system. Flows interact with physical and biological cues in the environment to influence juvenile outmigratory behavior, with important implications for growth rates and survivorship. To that effect, multiple agencies justifiably expend considerable effort to characterize movement and habitat accessibility or utilization of juvenile winter-run Chinook salmon (NMFS, 2014, 2017; 2024a).⁹

Juvenile outmigration monitoring involves rotary screw traps, acoustic tagging, and environmental data collection to track juvenile salmon as they migrate downstream. In the short term, the data inform operational managers about the timing and magnitude of juvenile outmigration, allowing for flow adjustments to enhance migration conditions. In the long term, these data are used to assess the effectiveness of coldwater pool management strategies on juvenile survival, evaluate population trends, and guide habitat restoration efforts aimed at improving rearing and migration conditions. Rearing habitat surveys evaluate the quality and availability of habitats critical for juvenile growth and survival by assessing off-channel habitats, floodplains, and mainstem river areas to determine their suitability for rearing during key life stages. These surveys typically involve field assessments of water depth, temperature, turbidity, flow velocity, and cover availability, including vegetation, woody debris, and overhanging banks—factors that influence juvenile survival by providing refuge from predators, maintaining optimal temperatures, and supporting prey availability. Augmenting monitoring to improve estimates of mortality and develop a more detailed spatial-temporal understanding of movement and habitat utilization may help to increase survivorship of those individuals that have already cleared the upstream egg-to-fry survival hurdle.

Our assessment of the limitations in biological monitoring is consistent with NMFS (2024a). That report identified deficiencies in current monitoring as (1) limited spatial and temporal coverage, (2) inadequate integration of hatchery data including genetic monitoring, (3) insufficient study of the long-term impacts of hatchery-origin fish on wild populations, (4) a lack of comprehensive habitat assessments, and (5) insufficient climate preparedness including a lack of predictive tools to evaluate future changes in hydrology and their impacts on coldwater pools.

SHASTA MODELING

A suite of numerical models supports coldwater pool management, including operations, hydrologic, hydrodynamics, water quality, and fish models. Although USBR presented the Committee with a complex schematic of the models used in the CVP and SWP (see Figure D-1, Sumer, 2024), many of which are indicated as particularly relevant for the three actions reviewed in the report, the Committee favors the simpler schematic of the models relevant to the long-term operation of the projects in Figure 2-12 (NMFS, 2024b). In Chapters 2 to 4, the Committee describes almost all of the models shown in Figure 2-12, focusing on those models where further consideration would lead to improved project operations. For this chapter on Shasta coldwater pool management, the primary focus is the WTMP, newly developed by USBR to encompass the reservoir and streamflow hydrologic models currently used in coldwater pool management. Temperature-dependent mortality, egg-to-fry survival models, and life-cycle models for winter-run Chinook salmon are also discussed.

⁹ See <https://www.fisheries.noaa.gov/resource/document/recovery-plan-evolutionarily-significant-units-sacramento-river-winter-run>; see <https://repository.library.noaa.gov/view/noaa/15458>.

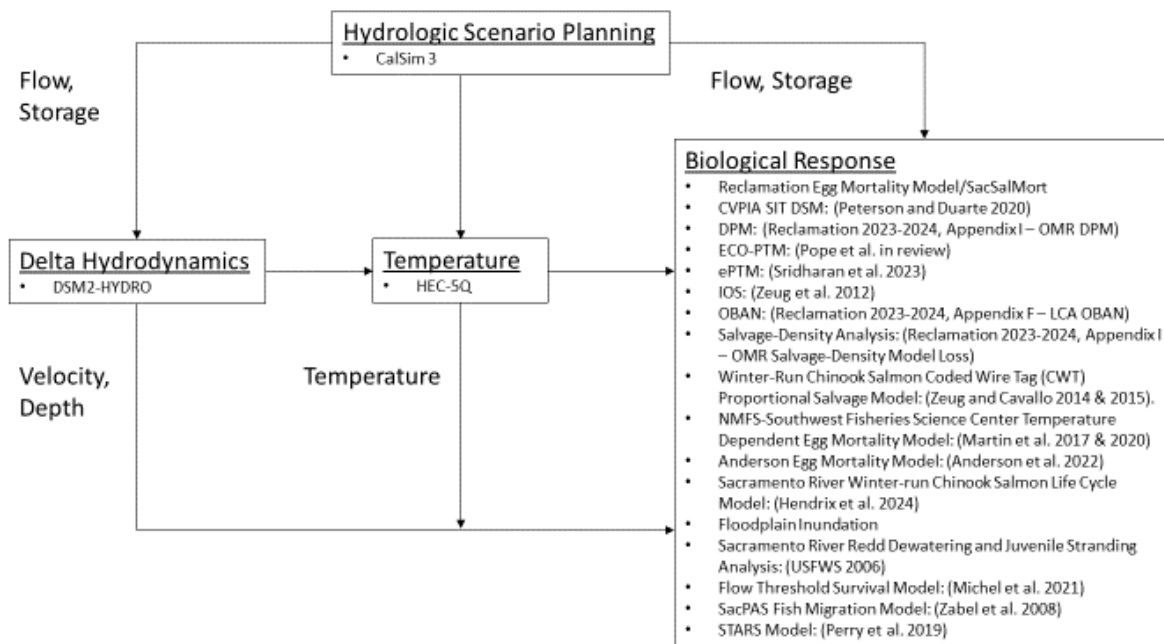


FIGURE 2-12 Main models used in the analysis of operations in the 2024 NMFS Biological Opinion and the flow of information with respect to the modeling output necessary to run subsequent models. Water temperature modeling for operational purposes used HEC-5Q prior to 2025; in 2025 the WTMP, including HEC-ResSim and CE-QUAL-W2, was adopted to replace HEC-5Q, as discussed elsewhere in this report.

SOURCE: Figure 8 in NMFS (2024b).

Many of the models relevant to coldwater pool management were critically reviewed by the Delta Science Program during the past two years. This includes an independent review of many models used for the Long-Term Operations for the Central Valley Project and State Water Project Fish and Aquatic Effects Analysis (Rose et al., 2024), a review of the WTMP (Delta Science Program, 2023), and a review of the HEC ResSim model (Wells et al., 2025). When appropriate, conclusions from those reviews are mentioned here, although the charge to those panels differed significantly from the charge to this Committee.

Numerical Modeling of Physical Processes

Estimating the Coldwater Pool

As the year progresses, stratification of water temperatures over the depth of the reservoir occurs. The coldwater pool is defined as the volume of water stored in the reservoir below the 52.5°F (11.39°C) isotherm (or other selected reference temperature) and, as previously discussed, can be estimated from the measured vertical temperature profiles and the stage–storage curves maintained by USBR.¹⁰ This estimate provides the volume of available cold water at the time of measurement but is not sufficient for SRG planning or for USBR operations because there is at least a 3-day lag between inflows, releases, and Sacramento River water reaching critical downstream reaches. In addition, the coldwater pool evolves throughout the summer depending on the ambient weather conditions, inflows, and reservoir withdrawals,

¹⁰ The most recent bathymetric survey of Shasta Reservoir was conducted in 2019 (Berry et al., 2021) and the stage–storage curves were updated in 2024 (USBR, 2024c).

which affect the rate at which the thermocline and surface warm water layers deepen. For these reasons, the models that USBR has used are undergoing significant upgrades to enhance the accuracy of predictions of water temperatures throughout the reservoirs and downstream reaches of the Sacramento River. Physical models are critical for understanding how far downstream of Keswick dam threshold temperatures can be achieved and provide insights into flow conditions and the risk of dewatering reaches.

Water Temperature Modeling Platform

USBR is updating its flow and temperature models by establishing a water temperature modeling platform (WTMP) based on the software models CE-QUAL-W2 and HEC-ResSim. USBR initiated this project to modernize the analytical tools that it uses to support activities and decision making for water temperature management in CVP reservoirs aimed at protecting fish species in downstream river reaches. USBR intends to use the WTMP consistently for both CVP real-time operations and seasonal and long-term planning purposes.¹¹ The scoping, development, and implementation of the WTMP has undergone a rigorous peer-review process (Delta Science Program, 2023) that will not be replicated in detail herein.

The WTMP has been developed with the intent of establishing a model user group to foster understanding and guide future model development, as well as to enable stakeholders to explore scenarios for managing flows and water temperatures. Although WTMP development includes three areas (Sacramento River, American River, and Stanislaus River), this report focuses on the region covered by the Trinity-Shasta system in the Sacramento River basin. The integrated river-reservoir model, CE-QUAL-W2, and the reservoir systems model, HEC-ResSim, are desktop software/physically based models that have been widely used for similar systems. Both models are in the public domain, supported by the Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers (USACE). HEC-ResSim is not open source, but it was developed so that a user can add a specific algorithm in certain limited situations.

HEC-ResSim was developed by the USACE HEC to simulate and optimize the behavior of one or more reservoirs (in terms of water storage, releases, and flows) for a variety of hydrologic and operational conditions. The model simulates reservoir operations for a variety of purposes, from flood management to water supply. Depending on the chosen time step, the model can simulate single runoff events or a full period of record. Water temperature modeling capabilities were recently incorporated into HEC-ResSim.

The June 2025 Delta Science Program Independent Peer Review of HEC-ResSim (Wells et al., 2025) provides valuable insights into the model. The review acknowledges the considerable effort to link observations with model simulations across the Upper Sacramento and Trinity river basins. The Shasta application of HEC-ResSim is still under development, and several important suggestions were made to guide the evolution of the model, including:

- Conduct a sensitivity analysis to understand which parameters are most important and how uncertainties in these key parameters can be reduced.
- Clarify whether the initial conditions to run the model are at the onset of stratification in the spring. Also unclear is whether multi-year projections can be made from a “hot start” based on conditions simulated in the previous 12 months, or if the model can be used to simulate planning horizons beyond a few months.
- Incorporate an algorithm that can track whether mass and energy are conserved.

¹¹ See <https://www.usbr.gov/mp/bdo/cvp-wtmp.html>.

The management of the WTMP and USBR's efforts to build a modeling community around this new platform provides an excellent forum to explore the issues raised in Well et al. (2025). Bringing together modeling experts from USACE HEC, USBR, CDWR, consulting groups, and academia would allow HEC-ResSim to be configured and compared to CE-QUAL-W2 and other models to ensure that it is state-of-the-art. Currently, it is unclear when HEC-ResSim will be used within the WTMP rather than the more computationally intensive CE-QUAL-W2, and what the differences in model accuracy might be for the questions being asked.

CE-QUAL-W2 is a two-dimensional (2-D) water quality and hydrodynamic code supported by the USACE Waterways Experiments Station (Cole and Buchak, 1995) and last updated on February 28, 2025. The model has been widely applied to stratified surface water systems such as lakes, reservoirs, and estuaries. It simulates water levels, horizontal and vertical velocities, temperature, and 21 other water quality parameters (e.g., dissolved oxygen, nutrients, organic matter, algae, pH, the carbonate cycle, bacteria, and dissolved and suspended solids). The 2-D model captures vertical and longitudinal processes but laterally averages across the width of the river, reservoir, or estuary. CE-QUAL-W2 Version 4.5 can simulate the flow processes in sloping riverine sections and can model entire river basins with rivers and inter-connected lakes, reservoirs, and/or estuaries.

Within the WTMP, the more computationally efficient HEC-ResSim is used to evaluate operations of Keswick Reservoir and upstream facilities including Shasta Reservoir for long-term planning scenarios, develop annual operational plans, and rapidly assess any modifications required as the water year progresses. The more computationally intensive CE-QUAL-W2 model is used to provide greater spatial and temporal detail of the findings from HEC-ResSim, and to validate the results. Because the two models use different algorithms and assumptions, comparing simulations from the two can allow better understanding and quantification of potential sensitivities and uncertainties. CE-QUAL-W2 encompasses more of the physical and biogeochemical processes and is therefore a useful tool to enhance basic understanding of this complex system of reservoirs and rivers. It can also be used to evaluate the importance of internal seiching and mixing to the operation of the TCD, whereas it is not apparent that HEC-ResSim has this capability.

The WTMP includes a Graphical User Interface, which was the desired model format for users at USBR, to facilitate and standardize applications of CE-QUAL-W2 and HEC-ResSim. River segments are modeled using a one-dimensional (1-D) longitudinal model, whereas reservoirs are modeled with a 1-D vertical model or a 2-D transversally averaged model depending on the simulation objectives. The modular approach offers the advantage of using models of different spatial and temporal resolutions and scales for selected elements, for example, rivers and reservoirs. The modeling platform allows flexibility to change modeling elements to address processes at different temporal and spatial scales.

The WTMP accounts for three features related to Shasta operations: (1) the TCD at Shasta Dam, (2) thermal curtains in Lewiston Lake and Whiskeytown Reservoir, and (3) tunnels in the Trinity-Sacramento system (USBR, 2023b). Operators of Shasta Reservoir do not yet use the WTMP. USBR plans a public rollout and training of the WTMP in fall 2025.

In the conceptual planning of the WTMP, USBR wanted to create an open system that could be used by interested parties within and beyond USBR—thereby establishing a diverse community of modelers and allowing the application of other models or new algorithms. This approach is akin to that of the National Weather Service, which has more than 70 weather models. However, in the current software modeling framework, it would be very difficult for a model user to modify the code in order to update the governing equations, the calculations of heat transfer coefficients, and the equations that represent important heat transfer processes. Although these constraints offer consistency for day-to-day USBR users, they limit updating of the model to reflect the best available science. Recent stream temperature models have made substantial advances in predicting river temperatures by (1) developing a detailed full-spectrum radiation balance for calculating the heat energy balance (e.g., FLUVIAL-EB; Bray et al., 2017, 2025), and (2) focusing on the advection component of the energy balance (e.g., RAFT; Daniels et al.,

2020; Pike et al., 2013). To incorporate new equations or computational components, an external modeler would need to write code for a plug-in for other models and then conduct an objective model comparison. This substantial computational effort effectively limits other interested parties from readily testing different algorithms or assumptions within the WTMP.

Two approaches could be adopted to achieve USBR's objective: (1) codes could be developed to be modular or source code could be offered to users through structured source code version control, or (2) initial conditions, boundary conditions, scenarios and other data could be made available to different modeling groups. Under both situations, USBR and USACE would require adequate resources for managing the WTMP.

The WTMP provides an excellent foundation for outreach and communication of conditions within Shasta Reservoir and for predicting how conditions evolve during a given year and why. This important communication component of the WTMP should not be underestimated and should be resourced accordingly, particularly in the February to May period between initial allocation and final decisions on water deliveries.

The WTMP is not a real-time flow and temperature forecasting model, primarily because of the difficulty in assimilating temperature observations from across multiple entities with different protocols for data checking and time of reporting. However, it can be used to make short-term predictions if values of flows and temperatures at tributary inflows (Table 2-3) and monitoring stations are assimilated in a timely manner.

The WTMP represents a major initiative by USBR to enhance transparency and accelerate the generation of water temperature predictions along the Sacramento River. The success of this nascent initiative is dependent on adequate support and continued commitment to fostering a community of modelers that can refine and enhance the solid foundation achieved during the past two years.

HEC-5Q

The HEC-5Q model is used by USBR to predict river temperature, but it will soon be replaced with the WTMP because HEC-5Q is considered a legacy model by USACE and is no longer supported. This reservoir routing and temperature model uses meteorological data and flow data, and it employs lumped heat exchange coefficients at the water-atmosphere interface, which tend to be highly calibrated with adjustable parameters. Model outputs (temperature time series) serve, along with empirical daily water temperature data collected near redds, as input to egg-to-fry survival models, such as those produced by Martin et al. (2017) and Anderson et al. (2022). Although HEC-5Q is run at hourly or 6-hour timesteps, the reported output is a daily average. HEC-5Q logic informs the management of the TCD on Shasta Reservoir.

River Assessment for Forecasting Temperature Model

CE-QUAL-W2 is computationally expensive and requires many inputs. Therefore, only a limited number of simulations or longer term planning scenarios can be assessed in a given year. Furthermore, the early river temperature models that informed the biological opinions used a weekly time step. To gain a deeper understanding of the response of fish to sub-diurnal time intervals, NMFS developed the River Assessment for Forecasting Temperature (RAFT; Pike et al., 2013) model to have sub-hourly capacity to predict river temperatures below Keswick Dam. RAFT is a simplified version of CE-QUAL-W2 that can run thousands of combinations of operational scenarios. Also embedded in RAFT is the HEC-5Q logic that determines how to manage the TCD for certain objectives. RAFT does not represent operations of Trinity and Whiskeytown reservoirs. Despite these features, RAFT is not currently an integral part of the WTMP and is not used by USBR to guide reservoir operations. Rather, it was used to inform the 2024 NMFS Biological Opinion.

Using the Water Temperature Modeling Platform to Better Understand Physical Processes in Shasta Reservoir

The complex configuration of Shasta Reservoir creates local meteorology and winds that result in different hydraulic mixing within and between the major arms of Shasta Reservoir. CE-QUAL-W2 and the enhanced temperature and water quality monitoring proposed in the earlier section on monitoring can simulate this internal flow structure and anticipate the potential influence on releases, as well as impart greater real-time understanding for the operators responsible for controlling releases. Now that the WTMP is functional, a focused study using the optical temperature chains (DTS) and micrometeorology stations coupled with the reservoir model is recommended to quantify the relative roles of gate leakage (building on the findings of Daniels et al., 2018; Resource Management Associates, 2003) and short-term fluctuations in the vertical temperature profile in the reservoir. Furthermore, the innovative current study by UC Davis and USBR to use upward-looking ADCP technologies has great potential to help USBR understand the flow structure into the TCD under different reservoir elevations, flow releases, and gate manipulations. These modifications and studies will elucidate more precisely the temperature of water releases into the Sacramento River, and these predictions can be confirmed by relocation of the temperature sensor downstream of the dam to a site where the water is fully mixed across the channel. This knowledge, combined with the WTMP and near real-time data feeds, will (1) enhance the information available to operators who are making short-term decisions on gate operations to help stabilize temperature of releases, (2) better inform the monthly SRG report, and (3) enable operators to communicate with the myriad parties interested in the actions outside the SRG.

To implement the full potential of the WTMP, the Shasta modeling team should:

1. Evaluate the importance of storms or high wind events in changing the available coldwater pool as is illustrated in Box 2-3. The study could identify under what conditions these events are important to operations.
2. Design an enhanced monitoring system using a Lake Diagnostic System (combined DTS and micro-meteorology technologies). This system would be optimized through model simulations and would build on the experience of NOAA, USGS, and USBR. The additional data can be assimilated into the WTMP to ascertain near real-time current conditions throughout the reservoir and to generate updated projections of the expected conditions for that water year. This technology could also reduce the need for manual sampling, although routine maintenance and service would be required in the event of sensor or transmission failure.
3. When the WTMP is fully functional, expand on the recent sensitivity analyses (USBR, 2024c) to determine whether additional monitoring of tributary inflows and temperatures would significantly improve the predictive accuracy of the WTMP. The study should determine which tributaries to Shasta and tributaries to the Sacramento River between Shasta and Red Bluff, if any, should be monitored and whether both flow and temperature need to be measured. The study could also recommend whether a full gaging station is needed or whether simple low-cost temperature gages that can be downloaded infrequently would be provide adequate information.
4. Use the riverine component of the WTMP to conduct a hindcast of the past year to understand the consequences of operational decisions given the changing hydrologic and meteorologic conditions. When running the river model of the WTMP in predictive mode, the results should not be restricted to whether compliance was achieved at selected points along the river. Instead, the WTMP should generate longitudinal temperature profiles to enable ecologists to interpret temperature and flow habitat suitability criteria spatially.

5. Use drone technologies to supplement existing manned flights of selected areas of concern in the Sacramento River. Drones equipped with thermal sensors could map fine-scale variation in downstream surface water temperatures in the river with respect to substrate, presence of redds, and zones of mixing, as well as locate where redds are created during the season.
6. Continue validation exercises of the WTMP, with specific attention to the transition from HEC5Q to HEC-ResSim.
7. Ensure achievement of the full potential of the WTMP by fostering model enhancements, testing and integrating new models, and upgrading algorithms. These actions are important because current models based on existing or historic information may become less robust because of changes in climate. For example, modelers should pay attention to the air–water interface as longwave radiation and air temperatures increase over time. In recent years, understanding of air–water interfaces has improved substantially (Bray et al., 2025), and this knowledge can be folded into future discussions on temperature management.

USBR is to be commended for having taken the steps to build a community of modelers around the WTMP through the selection of open software, regular communication with the science and engineering community through forums such as the California Water and Environmental Modeling Forum, and open events hosted by USBR. USBR should continue to ensure that data used in the WTMP and the details of scenario model runs are easily accessible, enabling modelers to test algorithms and next-generation models in parallel with the industry-standard models that are already deployed.

Biological Modeling for the Shasta Coldwater Pool Action

A suite of biological tools and models informs decisions related to Shasta coldwater pool management. They range from simple risk assessment tools and empirically derived statistical relationships to process-based simulation models. They are used to forecast or evaluate outcomes such as egg-to-fry survival, juvenile passage, temperature-dependent mortality, floodplain habitat accessibility, and vulnerability to stranding or dewatering. The development and calibration of some of these tools are coupled with field monitoring and hydrologic simulation platforms such as CalSim3, HEC-5Q, and HEC-RAS to support both near-term operations and long-term scenario planning.

Model or tool outputs are used to guide seasonal temperature targets, determine coldwater pool storage targets, assess the feasibility and trade-offs of pulse flows and release schedules, and project egg-to-fry survival under different temperature regimes. They also help to quantify cumulative biological risks under extended drought conditions or alternative management strategies. Managers typically weigh modeling results alongside other lines of evidence—including recent empirical observations, seasonal forecasts, and regulatory thresholds—as part of a broader deliberative process (USBR, 2024a). Although some models include ensemble runs or sensitivity analysis, uncertainty in both parameter estimates and structural assumptions remains a limiting factor for predictive precision and transparent risk communication (Rose et al., 2010) and the mechanisms through which model outputs are incorporated into decision making are often indirect or nontransparent (Rose et al., 2024; USBR, 2024f).

The following tools and models are described in Appendix D, starting with the simpler tools and empirical relationships and ending with the mechanistic life-cycle models of winter-run Chinook salmon.

- Redd dewatering tools
- Juvenile stranding tools
- Floodplain inundation and habitat models

- Temperature-dependent models of egg-to-fry mortality
- Quantitative winter-run Chinook salmon life-cycle models
 - Interactive Object-Oriented Simulation (IOS) model (Zeug et al., 2012) and its update, Zeug+
 - Oncorhynchus Bayesian Analysis Network (OBAN) (USBR, 2024f)
 - Winter-Run Life Cycle Model (WRLCM) developed by NMFS’s Southwest Fisheries Science Center (Hendrix et al., 2024)
 - CVPIA Science Integration Team Winter-run Life-cycle Model (Peterson and Duarte, 2020) as well as the more expansive R2R Decision Support Model derived from it.

This section focuses on models of egg-to-fry survival—a key transition for winter-run Chinook salmon and the subject of much recent scientific effort—and the quantitative winter-run life-cycle models.

Modeling Egg-to-Fry Survival and Unattributed Mortality

Egg-to-fry survival is a sensitive life stage for winter-run Chinook. For the purposes of informing coldwater pool management, it is computed using estimates of the number, timing, and distribution of eggs based on redd surveys and carcass mark-recapture surveys, combined with modeled temperature-dependent mortality during egg development and estimates of the number of fry that reach Red Bluff Diversion Dam (RBDD). The number of eggs that hatch and survive to become fry directly contributes to the number of winter-run Chinook that eventually reach RBDD, thus affecting the calculation of the yearly winter-run JPE—see Chapter 3. The section below reviews the models and methods used to determine egg-to-fry survival as well as highlights focal areas that may be critical for reducing the existing uncertainty. Reducing the uncertainty around the relative importance of factors contributing to but not currently accounted for in estimates of egg-to-fry survival may hold greater potential for managing temperature than seeking a universally optimal threshold.

Several abiotic and biotic processes can contribute to mortality during the period from spawning through early alevin and fry life history stages. Sources of mortality include inhospitable water temperature and dissolved oxygen concentrations, suboptimal redd composition and location, in-stream and hyporheic flow dynamics, predation, toxicity from contaminants, poor food availability, and pathogens and disease, such as thiamine deficiency (Mantua et al., 2021; NMFS, 2017). Of these, temperature-dependent mortality is the only cause that is routinely quantified through mechanistic models. Two detailed quantitative simulation studies highlight many of the complexities associated with determining optimal temperature requirements and flow regimes needed to support winter-run egg-to-fry survival (Anderson et al., 2022; Martin et al., 2020). These models estimate egg and alevin survival as a function of river temperatures during development, linking thermal exposure to mortality risk through either cumulative or stage-specific mechanisms. While these egg-to-fry mortality models attempt to capture temperature dependence, they do not resolve the full set of mechanisms affecting survivorship (e.g., interstitial flow rates, gravel structure, substrate quality) and are thus imperfect representations of dynamics within redds.

NMFS Temperature Dependent Egg Mortality Model. The Martin model (Martin et al., 2020) applies a dose–response approach, assuming that thermal stress accumulates when daily temperatures exceed a threshold. Mortality is modeled as a function of the magnitude and duration of temperature threshold exceedance. Although grounded in oxygen-limitation theory, the model does not explicitly resolve oxygen supply and demand; instead, it uses cumulative thermal metrics as a proxy for metabolic stress. Monte Carlo sampling enables exploration of how uncertainty in thermal thresholds, metabolic scaling, and developmental timing influences survival, which makes the model especially useful for stress testing and scenario planning.

Anderson Egg Mortality Model. The Anderson model uses a stage-specific framework based on mass transfer theory. It identifies a critical window near the end of egg development when oxygen demand increases sharply because of embryo growth and oxygen diffusion remains constrained. Mortality results when oxygen demand exceeds supply during this period. The model functionally uses temperature as a proxy for oxygen, and scales oxygen flux and metabolic demand with egg mass and development rate; it is calibrated to winter-run Chinook salmon survival data from 2002 to 2020 in the upper Sacramento River (Anderson et al., 2022). Empirical and experimental studies support the biological premise that diffusion limits oxygen supply during later stages of development, making embryos vulnerable to temperature-induced hypoxia (Del Rio et al., 2019, 2021). Although the Anderson model improves biological realism and provides a physiological foundation, its current implementation uses fixed parameter values for background and density-dependent mortality and does not quantify uncertainty in model outputs (USBR, 2024a).

Although the effects of water temperature on egg-to-fry survival have been well-studied in this system (Alderdice and Velsen, 1978; Anderson et al., 2022; Del Rio et al., 2019, 2021; Martin et al., 2017), uncertainty around temperature thresholds remains. Much of the debate about optimization of temperature thresholds neglects the broader ecosystem context of uncertainty for any given threshold. The physical environment that developing salmon eggs experience within redds varies across the entirety of the spawning reach because of differences in features such as channel shape, gravel size, sediment composition, and the movement of water through the riverbed (known as hyporheic flow). This spatial variability means that eggs in different locations may respond differently to the same water temperature. Any individual temperature threshold is unlikely to be optimal everywhere because of variation in localized conditions. Thus, reducing the uncertainty around the relative importance of those factors in mediating the temperature-survivorship response across the entirety of the spawning grounds may hold greater potential for managing temperature than seeking a universally optimal threshold. In fact, a universally applied threshold would likely need to be more conservative (i.e., colder) to guarantee the minimum functional effect in the face of spatial variability in responses across the spawning reach.

The relative importance of all the other factors contributing to mortality, currently bundled under the category of “unattributed mortality” in calculations done by USBR, remains unclear. According to Buttermore (2024), the contributions from any specific non-temperature dependent source of mortality can be substantial, with unattributed mortality determined to be greater than temperature-dependent mortality in 17 of the past 20 years. Characterizing and quantifying the relative importance of several of these factors is a critical and rapidly developing area of research, one that is a priority focus of USBR and other agencies. For example, artificial redd experiments have occurred or are getting underway to assess critical factors affecting redd habitat quality as a function of environmental and managerial drivers, including temperature, dissolved oxygen, gravel quality, and river flow. Laboratory flume experiments using synthetic salmon redds have demonstrated that the roughness of the redd surface and the permeability of the egg pocket strongly influence the delivery of oxygenated water to incubating embryos (Hilliard et al., 2025). On the Sacramento River, artificial redd experiments have been planned (Cavallo, 2024; Plumb, 2024) but not yet executed; they will assess critical factors affecting redd habitat quality as a function of environmental and operational drivers.

To translate findings from these experiments into practical management tools, coordination across studies is essential. For example, results from artificial redd experiments could be systematically integrated with spatially explicit redd survey data and temperature modeling outputs to identify reach-specific drivers of mortality. A coordinated effort could involve standardizing field protocols, aligning experimental variables (e.g., flow treatments or gravel composition), and establishing a shared data platform to enable comparison across systems and years. This effort would allow researchers to link laboratory and field studies to predictive models, improving the attribution of observed egg-to-fry losses to specific mechanisms and guiding bin selection and coldwater allocation more precisely.

Developing a clearer mechanistic understanding of interactions between flow, redd physical structure, dissolved oxygen concentrations, and temperature may enable refinement of temperature thresholds and the range of resulting management strategies, and the Committee agrees that such efforts are warranted. Moving forward, coordination across studies and an evaluation of the science involved in relation to existing redd and spawning surveys will be vital to translating newly developing scientific understanding into useful management tools. Moreover, the most important questions warranting exploration center on other important factors that may contribute to unattributed mortality, such as the following:

- How do habitat availability, access, and quality relate to food availability and predatory pressure under different flow and temperature regimes?
- How does variability in hyporheic flows and redd structure relate to concentrations of contaminants?
- To what extent might interactive effects among factors contributing to mortality result in nonlinear increases in mortality, and how might that inform management decision-making?

Other studies have considered taking a broader focus across other life history stages (Corzier et al., 2021; Dahlke et al., 2020; Hendrix et al., 2014; Mertz et al., 2013). Wohner et al. (2022), for example, highlight the potential for integrating monitoring and optimization modeling to inform flow decisions that increase success for outmigrating Chinook salmon smolts.

Better Use of Quantitative Life Cycle Models

Shasta coldwater pool management is not having the intended impact on winter-run Chinook salmon recovery. The action tends to focus effort on narrow and incremental improvements, rather than evaluations of other actions—or collections of actions—that could be more effective. A broader focus would be greatly aided by the fish life-cycle models that simulate biological and ecological processes and their relationship to environmental and managerial factors in the upper Sacramento River watershed/Bay-Delta region (see Appendix D for model descriptions). There are only two quantitative life-cycle models for winter-run Chinook—WRLCM and the CVPIA Science Integration Team Model (more recently expanded into the R2R Decision Support Model). They are not used in regular Shasta operations, including coldwater pool management. Rather, they are used intermittently to support long-term planning and the Endangered Species Act reconsultation by enabling managers to explore the impacts of different operational choices. Differences in model structure, calibration methods, and treatment of uncertainty mean that no single model provides a definitive forecast. Instead, these models have been employed as complementary tools offering different perspectives on how operations may affect population viability (Rose et al., 2024; USBR, 2024a).

Chinook salmon life-cycle models (e.g., CVPIA SIT, WRLCM, R2R DSM) could be used to systematically investigate how combinations of stressors interact to influence both egg-to-fry survival and juvenile growth and survival in a spatially explicit context. A proactive approach will facilitate comparison of the effects and relative potential population benefits of both individual actions and suites of actions (as is being done in CVPIA SIT restoration planning, Reorienting to Recovery, and winter-run drought management). For example, a multi-scenario model run could compare the outcomes of coldwater pool-only management to integrated strategies that combine temperature control with gravel enhancement, habitat restoration designed to improve food abundance or reduce predatory pressure, or thiamine treatment of spawners. With this approach, managers could quantify trade-offs and identify which combinations offer the best gains in survival for a given water year type.

Another activity to consider is using the quantitative life-cycle models to identify and comprehensively examine a series of alternative management actions to evaluate the system-wide tradeoffs. In many areas of marine fisheries management, assessment models that estimate the abundance

and production of fish and the quality and availability of other resources in the system (e.g., habitat, food, aquatic environment) can be used interactively and even in real time to identify and implement reasonable sets of actions. One approach is known as management strategy evaluation (MSE), in which the methods of monitoring and assessment are established and modeled to interact with and produce results under a variety of quantifiable management actions known as control rules. Such approaches can be automated to explore a number of control rules, but once a set of optimal control rules are identified, a set of actions can be made available to explore the consequences of taking such actions in real time (e.g., annually or even on a monthly or weekly basis). Such an approach could be implemented in the upper Sacramento and Delta system in a stepwise fashion by taking existing quantitative integrated life-cycle models and simulating one by one the consequences of different managerial options under different environmental conditions. An MSE approach might, for example, guide hypothesis development and steer efforts to understand unattributed mortality in the egg-to-fry stage, helping to answer some of the questions posed in the section above. Likewise, it would contribute to a better understanding of the extent to which targeted restoration efforts between RBDD and the Delta, or different flow management strategies, might improve survivorship.

Others have made similar recommendations. The recent five-year review of winter-run Chinook salmon (NMFS, 2024a) indicates that options exist, beyond coldwater pool management, to promote the survival and recovery of the species inhabiting this system including evaluating the benefits of non-natal rearing habitats in the context of different functional flow regimes, investigating sources of early life-stage mortality beyond temperature effects, and enhancing monitoring activities and juvenile abundance estimates to better inform both model simulations and management decision-making.

There is value in exploring the ways in which the existing quantitative life-cycle models could be more broadly utilized and integrated to understand the consequences of different simulated scenarios. Life-cycle modeling can help to operationalize recommendations by estimating which of the options are most likely to reduce unattributed mortality and by how much, under realistic environmental constraints. Rather than treating unattributed mortality as a residual loss, it can be treated as a solvable problem—partitioned, modeled, and reduced through targeted, scenario-based exploration. If their use became more regular and interactive, these integrated life-cycle models, in conjunction with existing hydrological and climatological models, could help to drive alternative management actions, rather than examining actions only occasionally and retrospectively.

Quantitative models can also be used to optimize the allocation and timing of monitoring efforts. Imagine that multiple elements of the ecosystem are being monitored, such as egg survival, juvenile passage through pumping stations, juvenile survival at downstream locations, proportion and genetic makeup of hatchery-reared versus natural adult returns, habitat use by different life stages, and habitat maintenance. A life cycle model could be used to comprehensively identify all of the bottlenecks to survival in the system, including those currently categorized as unattributed mortality during the egg-to-fry stage, and then to determine the sampling effort needed to reduce uncertainty at each stage. For example, if the model identifies early alevin or fry mortality in specific reaches as a significant driver of population loss, then targeted monitoring could be deployed to assess habitat quality and predation pressure. Prioritization could then be done to focus on those actions that will have the greatest value in promoting overall survival. In this way, life-cycle models can be used in conjunction with ongoing monitoring efforts to guide the hydrologic actions as opposed to evaluating the actions post hoc.

In summary, USBR and its partners are encouraged to further develop the quantitative life-cycle models along with their associated monitoring data requirements and then employ the models to explore the consequences of alternative actions, with the goal of optimizing the survival and recovery of winter-run Chinook salmon. Many of the modeling concepts, and even the models themselves, already exist. Needed are efforts to use the existing life-cycle models more effectively and in an interactive, comprehensive, and adaptive way. To capture additional sources of mortality across life history stages, model structures would need to include functions that explicitly link survival to measured environmental drivers (e.g., sediment load, predation pressure, habitat quality), allowing those factors to vary dynamically. Developing such functions would require empirical data from targeted field studies that

quantify how these drivers affect survival under different conditions. By linking mortality attribution, monitoring design, and management action within a single simulation framework, life-cycle models can help to prioritize management actions that will have the greatest value in improving survival. In this way, life-cycle models can be used not only to predict biological outcomes, but also to guide and optimize hydrological operations.

ADDITIONAL SCIENCE TOPICS

The discussion that follows recommends improvements to the Shasta Coldwater Pool Management Action that go beyond monitoring and modeling. In providing these recommendations, the Committee has assumed that temperature management in the Sacramento River below Keswick Dam will be a primary strategy for preventing extinction of winter-run Chinook salmon over the short term. But, for reasons explained below, the Committee also recommends restoring winter-run Chinook salmon to historic coldwater habitats both upstream of Shasta Reservoir and in Battle Creek. For the foreseeable future, both approaches, along with the maintenance of the winter-run hatchery, will likely be essential to the protection and eventual recovery of winter-run Chinook salmon populations.

Improvements to Flows and Geomorphology Immediately Downstream of Keswick Dam

The physical and ecological changes that occur in river channels downstream of large dams is well documented (e.g., USGS, 1996), and the Sacramento River downstream of Keswick Dam has not been immune to these changes. Changes to physical conditions can include reductions in sediment transport, armoring of the channel bed, altered hydrographs that influence geomorphic characteristics and biological cues, channel incision, reduced connectivity to floodplains, loss of gravels suitable for spawning, reduction in the topography of pool–riffle sequences, armored banks that can reduce refuge habitat and inhibit meandering, reduction in hyporheic flows, altered seasonal water temperatures, loss of riparian vegetation and associated shading, and widening and shallowing of the cross-section that can contribute to enhanced warming of the water. There is an extensive literature on these changes as well as remedial measures taken to overcome them (e.g., Palmer and Ruhi, 2019; Poff et al., 1997). For example, pulse flows are sometimes used to sustain diversity of channel morphology and initiate biological cues.

The reach just downstream of Keswick Dam is where most winter-run Chinook salmon spawning currently occurs because water temperatures are maintained at levels conducive to spawning (Figure 2-4). Yet this reach tends to lack geomorphic diversity (Cavallo, 2024; Plumb, 2024), and the less pronounced and less frequent pool–riffle sequences in this reach are likely to restrict hyporheic flow through redds compared to reaches with well-defined riffles (Tonina and Buffington, 2007, 2011). Ongoing studies by consultants (Cavallo, 2024) and USGS and USBR (Plumb, 2024) aim to better understand the functioning of redds under a range of flow and channel conditions (varying such parameters as flow rate, water temperature, oxygen and sediment fines) as a way to further explore egg-to-fry mortality. It would be beneficial if these field studies could be supplemented with a detailed geomorphic study of the lengthy reach below Keswick Dam to identify locations where restoration or augmentation activities would be the most effective and sustainable overall. A geomorphic study might develop explicit predictions regarding the potential tradeoffs of certain channel restoration actions in different locations. Examples of the actions or combination of actions in the reaches downstream of Keswick Dam that could be evaluated include the following:

- The benefits and persistence of riffles resulting from gravel augmentation;
- The location, scale, and benefits associated with river and floodplain restoration actions;

- The role of pulse flows in establishing and sustaining channel morphology conducive to functioning redds, accelerating outmigration of smolts, and triggering biological cues that enhance spawning and egg-fry survivability.

Winter-run Chinook Salmon Reintroduction

The Sacramento River winter-run Chinook salmon historically occurred in the upper reaches of the Sacramento River, its largest upper elevation tributaries (the McCloud River and the Pit River), and Battle Creek. Sacramento River winter-run is the only known Chinook sub-species exhibiting this run timing, which is presumed to be an adaptation to the long migratory pathways and perennially cold waters associated with those ancestral habitats. The construction of Shasta Dam flooded Winnemem Wintu villages and sacred ceremonial sites and displaced the Tribe and their *Nur*¹² (Chinook salmon) from the cold, spring-fed waters of the *Winnemem Waywaket* (McCloud River) where the Winnemem Wintu and the salmon had lived synergistically since time immemorial, as well as from the Sacramento River's other largest tributaries (Johnson, 2023a). In the nearly 80 years since the completion of Shasta Dam, the winter-run population has reproduced in the hotter, lower-elevation Sacramento River, and has dwindled to the point of being listed as endangered. Box 2-4 makes clear the myriad of environmental stressors affecting winter-run Chinook salmon in the Sacramento River watershed, which are not limited to the effects of the Projects. The winter-run stressors presented in Box 2-4, along with similar considerations for the other Chinook runs, are examples of components that could be included in the previously discussed lifecycle model-based framework to inform operations and support decision making.

BOX 2-4

Key Stressors for Sacramento River Winter-Run Chinook Salmon

The geographic and temporal diversity and extent of their freshwater habitat use has resulted in winter-run Chinook salmon being susceptible to impacts from a commensurately diverse range of landscape and ecosystem changes through time. In thinking about their protection beyond coldwater pool management, the Committee considered the impacts of 12 stressors on winter-run juveniles and adults, based on a review of relevant literature. The stressors are listed in the rows of Table 2-4, while the columns rank (1) impact of the stressor on fish, (2) the proximity of those impacts to the Projects (e.g., linked either directly or indirectly via a well-established driver-linkage-outcome relationship), and (3) potential for impact reduction via reoperation of the Projects [based on the Committee's best professional judgment and informed by (1) and (2)]. "Operation" (alone or in the context of reoperation) is defined as presence or use of existing infrastructure, the resulting hydrology and hydrogeomorphic dynamics, and manipulation of exports. Stressors categorized as medium or high rank across all three columns for a given life stage indicate a potential opportunity for stressor reduction through changes in Project operations. Justifications for the rankings are given in the text below and elsewhere throughout this report. For example, Appendix E describes certain stressors to winter-run Chinook salmon in greater detail, Chapter 3 describes entrainment of winter-run Chinook in the pumps and the South Delta, and the role of hatcheries in supporting winter-run populations is discussed in Chapter 2.

continued

¹² *Nur* is the Winnemem word referring to the ancestral salmon of the McCloud River and their progeny. It encompasses those individuals/ populations commonly referred to as winter-run Chinook salmon, as well as those Sacramento River and its tributaries salmon species established in New Zealand and elsewhere.

BOX 2-4 continued**TABLE 2-4** Assessment of Key Stressors for CV Winter-Run Chinook Salmon Juvenile and Adult Life Stages, including (1) extent (i.e., severity of impact from the stressor), (2) CVP proximity (direct or indirect), and (3) potential for stressor reduction through CVP operational changes (alone or in combination with other actions)

Stressor Assessment Key				
Magnitude	Low 	Med 	High 	Unknown or N/A 
Impact – The stressor severity and/or extent (spatial, temporal) of impact to the species	Results in sublethal effects and/or contributes to individual mortality indirectly; not considered a population level threat.	Results in direct mortality to individuals and/or population level impacts when paired with another stressor of similar magnitude	Results in population level impacts	Level or extent (spatial/ temporal) of impact unknown or poorly understood
CVP Proximity – The extent to which the stressor is a direct effect of CVP operations or infrastructure	Related to CVP only indirectly or via weak or inconsistent driver-linkage-outcome relationship(s)	Related to CVP indirectly via consistent driver-linkage-outcome relationship; or directly with weak or inconsistent effect	Related to the CVP via strong and/ or consistent direct effect	No or unknown relationship to the CVP
Reoperation potential – The extent to which the stressor can be reduced through changes to CVP operations	Unlikely to be improved or resolved through changes to CVP; requiring non/ extra CVP related actions for improvement	May be somewhat improved through changes to CVP alone and/ or significantly improved or resolved through a combination of CVP and other actions	May be significantly improved or resolved through changes to the CVP alone	Changes to CVP likely to have no effect and/ or other factors expected to render effect of CVP changes inconsequential

Stressor	Life Stage	Impact Extent	CVP Proximity	Reoperation Potential
Loss of habitat access/ area (due to physical alteration, infrastructure)	Juv			
	Adlt			
Degradation in habitat quality/ suitability (due to hydrodynamics, ecosystem condition)	Juv			
	Adlt			
Disease (exacerbated by high water temperatures)	Juv			
	Adlt			
Stranding/ false pathways (due to flow changes and/ or human infrastructure)	Juv			
	Adlt			
Interspecies competition (including Chinook)	Juv			
	Adlt			
Entrainment in agricultural diversions (including CVP and SWP Delta pumping facilities)	Juv			
	Adlt			
High predation rates (human mediated)	Juv			
	Adlt			
Degraded water quality (from agricultural and urban runoff)	Juv			
	Adlt			
Hatchery biological (genetic introgression, competition)	Juv			
	Adlt			
Hatchery management (cultivation and supplementation)	Juv			
	Adlt			
Overfishing	Juv			
	Adlt			
Climate Change	Juv			
	Adlt			

continued

BOX 2-4 continued

Loss of habitat access/area (due to physical alteration, infrastructure). At least 1,057 miles of the stream lengths historically available to salmon (or 48 percent of the total habitat, greater than 72 percent of the spawning habitat) have been lost as a function of dams from the original total of 2,183 miles in the Central Valley drainages (Yoshiyama et al., 2001). As much as 80 percent of the floodplain habitat historically accessible to Chinook salmon has been lost as a function of levees and reduced flows during critical portions of the outmigration window (Katz, 2012). Of the remaining portions, the vast majority for the Sacramento drainage is located within the Yolo and Sutter Bypasses and activated primarily during flood events. Winter-run Chinook salmon are disproportionately affected by lack of access to higher elevation portions of the habitat which provide the cold spring and snowmelt-fed conditions they require for over-summering and the yearling life-history strategy. Hence, for both juveniles and adults, the level of impact related to loss of habitat access/area, along with the proximity to CVP/SWP operations, is ranked high.

Reoperation opportunities include (but are not limited to) passage for adults into the upper watershed and release of additional flows to inundate floodplain habitats along the channel margin and in the bypasses during critical outmigration windows, potentially in combination with floodplain habitat restoration. Reoperation potential is ranked medium because of other confounding stressors (e.g., climate change) that are less amenable to being resolved through reoperation.

Degradation in habitat quality/suitability (due to hydrodynamics, ecosystem condition). The abundance and accessibility of food and the energetic consequences of foraging vary among habitats and through time, providing a shifting mosaic of growth opportunities for fish in rivers (Rossi et al., 2024). The disruption of longitudinal connectivity in the river continuum caused by dams, the disruption of latitudinal connectivity with floodplains caused by levees, and changes to seasonal hydrodynamics caused by both of those physical structures, by diversions, and by managed flows has resulted in alteration, degradation, and disruption of ecosystem and food-web processes (Henery et al., 2010; Jeffres et al., 2008; Johnston et al., 2018; Limm and Marchetti, 2009; Michel et al., 2021; SST, 2017; Sommer et al., 2001; Takata et al., 2017). For both juveniles and adults, the impact of the Projects on habitat degradation, and the proximity to Project operations, are ranked high.

Reoperation opportunities include (but are not limited to): passage for adults into the significantly less impacted upper watershed habitat, release of additional flows to inundate floodplain habitats along the channel margin and in the bypasses during critical outmigration windows, and release of additional flows to improve juvenile survival during outmigration in the Sacramento mainstem and Delta. As above, reoperation potential is ranked medium for juveniles due to other stressors (e.g., climate change downstream of Shasta) that exacerbate the level of impact and would not be resolved through reoperation. Reoperation potential is ranked low for adults because (1) CVP operations do not significantly influence habitat quality or suitability in the historic above-dam habitats and (2) flexibility to create improved habitat conditions for adults downstream of Shasta through changed operations is currently limited.

Disease (exacerbated by high water temperatures). A range of different disease types (e.g., bacteria, parasites) posing risk to Chinook salmon are exacerbated by high water temperatures (Antonio and Hendrick, 1995; Holt et al., 1989). In the Sacramento River specifically, evidence suggests that pathogen-infected juveniles have lower outmigration success (Mauduit et al., 2022). Lack of access to historic habitat about Shasta Dam, along with increased demands on limited water resources, warmer seasonal air temperatures, and more frequent droughts increase the likelihood of winter-run Chinook salmon in the Sacramento River encountering less favorable temperatures. In part, as a result, the risk to winter-run from disease has been increasing. Emerging concerns include the advent of a thiamine deficiency complex, which has been observed to cause increased mortality in the early life stages of the winter-run Evolutionarily Significant Unit (NMFS, 2024a). CVP proximity is ranked high for adults due to both (1) CVP infrastructure preventing access to perennially cold historic upper watershed habitats and (2) the primary role that operations play in determining temperatures and creating or alleviating associated thermal stress that adult salmon experience in the current habitat downstream of Shasta Dam. CVP proximity for juveniles, on the other hand, is low because factors beyond CVP operations contribute to the temperatures juveniles experience.

continued

BOX 2-4 continued

Because the impacts from disease, as well as when and under what conditions impacts occur, is unknown for adults, reoperation potential to address this stressor is considered unknown. Reoperation potential is ranked low for juveniles because temperature conditions for juveniles can only be controlled to a limited extent via (1) translocation, which only fixes temperatures for a limited time/area of their outmigration or (2) downstream temperature management which even under the best circumstances is limited.

Stranding/ false pathways including Delta routing (due to flow changes and/or human infrastructure). Chinook salmon in the Central Valley evolved to take advantage of the heterogeneity of the habitat both in terms of landform and hydrology. Human alteration of the landscape, migration corridors, and the hydrograph has created the potential for species impacts from stranding (due to hydraulic variation) and false pathways to detrimental routing, especially in the Delta (Perry et al., 2018; SST, 2017). Impact extent is ranked medium for both juveniles and adults as both experience direct mortality from stranding and/or false pathways.

CVP proximity and reoperation potential are greater (ranked medium) for juveniles than for adults (ranked low) as operations have a larger relative influence on the extent to which the juvenile life stage is impacted (e.g., via Delta routing) versus the adult life stage (e.g., via stranding in the Yolo Bypass).

Interspecies competition. Interspecies competition between juvenile winter-run and other species and other Chinook run-timings primarily results from winter-run rearing in non-historic habitat, which is a function of Project operations (hence the high rank for proximity). The extent and severity of these impacts, however, is poorly understood. For adults, the impact is ranked low because spawning habitat availability and allocation of flow to support both fall-run and winter-run are known challenges (Jason Robers, CDFW, personal communication, 2024) and is actively being managed for. Reoperation potential is accordingly unknown for juveniles and ranked low for adults.

Entrainment in diversions (including CVP and SWP Delta pumping facilities). Water export operations contribute to juvenile salmonid mortality in the Delta via direct mortality at the pumps. Direct mortality (at the facilities) is a combination of pre-screen and within-facility mortality (including mortality during salvage and transport) and entrainment into the pumps and water conveyance canals. However, direct mortality does not account for the majority of juvenile Chinook salmon mortality in the Delta (see Box 3-3) (hence the low ranking for impact and reoperation potential). The mechanisms and associated magnitudes of specific indirect effects of water project operations on juvenile Chinook mortality in the Delta but outside the facilities is poorly understood (SST, 2017).

High predation rates (human mediated). Hypothesized factors contributing to the observed flow-correlated survival rates in the Sacramento River (Michel et al., 2021), and low Delta survival of juvenile Chinook salmon include (1) increased abundance and metabolic rate of predatory fish such as striped bass and largemouth bass in the Delta; (2) water project operations affecting the magnitude and timing of flow resulting in increased juvenile salmonid predation mortality; and (3) changes in Delta habitat including expansion of non-native submerged aquatic vegetation and increased water clarity (NMFS, 2024a; SST, 2017). Given the many causes of habitat degradation in the Delta, reoperation potential is ranked medium.

Degraded Water Quality. While there is evidence for both agricultural products (e.g., pesticides) and urban runoff (e.g., 6PPD) negatively affecting Chinook salmon (Anzalone et al., 2022; Lo et al., 2023) as well as the relationship between those effects and hydrogeomorphic dynamics in the Sacramento River system (Anzalone et al., 2022; Fuller et al., 2022), the extent of the impact of degraded water quality to winter-run in the Sacramento River system specifically is poorly understood. Proximity of these effects to CVP operations is limited for both juveniles and adults, resulting in unknown potential for remediation through reoperation.

continued

BOX 2-4 *continued*

Hatchery effects both biological (genetic introgression, competition) **and management related** (cultivation and supplementation effects). Hatchery supplementation remains a key conservation strategy for Central Valley Chinook salmon generally and winter-run Chinook salmon specifically. Competition between hatchery-produced Chinook and in-river spawning winter-run Chinook exists. However, the relatively small population size and extent of reliance on hatchery supplementation as a mechanism for conservation results in competition or introgression related impacts being relatively minor and difficult to pinpoint. That said, the influence of hatchery broodstock has been identified as a key reason that winter-run populations remain at a high risk of extinction (NMFS, 2024a), and preliminary evidence suggests that a range of negative impacts associated with prolonged reliance on hatchery production are detectable in winter-run (Steven Lindley, former NMFS, personal communication, 2024).

Reoperation actions that provide an alternative to reliance on hatchery propagation and/or increase the potential for natural spawning and successful in-river juvenile rearing (principally reintroduction above dams and to a lesser extent coldwater pool management) may significantly reduce reliance on hatcheries, especially in years when adult escapement is low and hatchery supplementation has a disproportionately large effect on the recovering population.

Overfishing. Harvest of winter-run has the potential to occur in years when commercial and recreational fisheries for fall-run Chinook salmon are open. Conservation and management measures to prevent harvest of winter-run include closures and non-retention periods for specific areas in the Sacramento River, as well as timing and location restrictions for ocean commercial and recreational fisheries (CDFG, 2004). Some estimated spawner reduction rates have ranged from 0.26 in 1988 to 0.23 in 1999 (CDFG, 2004). Total bycatch in any given year, however, is not well understood. Additionally, the primary risk for bycatch occurs in the ocean fishery with minimal proximity to CVP/SWP operations, hence the unknown rankings for this stressor for both CVP proximity and reoperation potential.

Climate Change. Specific individual and multiple consecutive drought years are already measurably affecting the condition of California salmon populations, directly, indirectly, and in combination with other stressors. Effects include but are not limited to direct impact on the extent, availability, and quality of habitat, ecosystem productivity and food-web dynamics, and predator-prey dynamics, as well as potential indirect impacts on fish behavior. For adults specifically, spawning already occurs in a significantly different, less suitable, lower elevation, more climate-vulnerable habitat—in close proximity to Shasta Dam. Stream warming that might jeopardize adult spawning (for example) can be mitigated to some extent through coldwater pool management. Other opportunities include reintroduction to more climate resilient habitat above dams (assuming the infrastructural challenges can be overcome), as well as restoration of physical and ecological processes and associated habitats that support species condition and resilience within their existing ranges (e.g., floodplain restoration and gravel augmentation).

During the past several decades, interest in reintroducing winter-run into their historic habitat above Shasta Dam has grown. Preliminary investigations by USBR and others were initiated in the early 2000s and have progressed, carried forward by state and federal agencies, nongovernmental organizations, tribal representatives, universities, private landowners, and timber and valley water interests. In 2014 the NMFS Recovery Plan for Sacramento River Winter Run and Central Valley Spring Run Chinook Salmon specifically identified reintroduction above the valley rim dams as a critical need (NMFS, 2014).

In parallel, a number of key efforts exploring the possibility of winter-run reintroduction began to take form, including: (1) an assessment by USBR of habitat condition to support winter-run above Shasta Dam, which identified suitable conditions in both the McCloud and upper Sacramento rivers (USBR, 2014); (2) a suite of investigations into potential approaches for the capture and transport of juvenile outmigrating salmon before or during entrance into Shasta Reservoir; and (3) an investigation initiated and led by the Winnemem Wintu into the possibility of bolstering imperiled winter run populations by

reintroducing Sacramento River-origin Chinook salmon historically translocated to New Zealand back into the Sacramento River system (Winnemem Wintu, 2016). Despite these efforts, successful reintroduction and translocation or passage of winter-run Chinook salmon around Shasta Dam was perceived as physically unachievable, cost-prohibitive, or politically infeasible, with few examples from other areas that were models of success. Key activities currently advancing winter run reintroduction are discussed below.

Juvenile Collection. In February 2022, CDWR received \$1.5 million for the Juvenile Salmonid Collection System (JSC) Pilot Project in the upper McCloud arm of Shasta Reservoir, with the goal of evaluating the viability of juvenile salmon collection during emigration from the McCloud River. The project was specifically initiated to test an experimental, mobile guidance and capture system designed to collect out-migrating salmon and to determine whether it creates the desired conditions for fish, water temperatures, and debris management. The initial project was a collaborative effort between CDWR, CDFW, NMFS, and the Winnemem Wintu Tribe and construction is now complete (CDWR, 2022) with ongoing collection occurring as a component of the reintroduction efforts using a combination of the JSC and other collection methodologies. Overall, juvenile collection has continued to improve each year, with efficiencies reaching 75 percent in 2024 and greater than 13,000 juveniles transported downstream of Keswick Dam to continue their journey to the ocean (Rachel Johnson, NMFS, personal communication, September 2025). The measured collection efficiencies have been incorporated into preliminary lifecycle modeling. The modeling results suggest that, at current levels of collection efficiencies and outmigrant survival, the addition of upper watershed rearing has the potential to increase the likelihood of outmigrant success and survival to adulthood, especially in those years with dry or critically dry conditions in the lower Sacramento River (Noble Hendrix, QEDA Consulting LLC, personal communication, September 2025).

Drought Response. In 2022, in response to near unprecedented drought at a time when winter-run numbers were hovering around their lowest in history, NMFS and CDFW initiated a suite of emergency drought actions that included (1) increasing production of winter-run Chinook salmon at Livingston Stone National Fish Hatchery; (2) relocating a portion of adult winter-run Chinook salmon trapped at Coleman National Fish Hatchery and the Keswick Trap to Battle Creek, upstream of Eagle Canyon Dam; (3) relocating spring-run Chinook salmon collected incidentally at the Keswick Trap to Clear Creek; (4) initiating a secondary captive brood-stock of winter-run Chinook salmon; and (5) incubating a portion of winter-run Chinook salmon eggs from Livingston Stone National Fish Hatchery along the McCloud River (Johnson, 2023b). While these measures appear to have been effective at averting some potential drought impacts for winter- and spring-run populations, both populations continue to hover at critically low levels.

Experimental Reintroduction of Winter-run Chinook Salmon from New Zealand. The Winnemem Wintu Tribe is working to reintroduce winter-run Chinook salmon, which are currently reproducing naturally in New Zealand, back into the McCloud River. They have been collaborating with New Zealand biologists and Māori peoples to secure eyed eggs for broodstock cultivation in the United States, as part of a larger plan to restore the salmon population (Winnemem Wintu, 2016). Funding is needed to continue these efforts and to synthesize the data and information already gathered so that co-managers can make recommendations about a path forward. Additionally, concerns over the potential introduction of both known and unknown foreign pathogens continue to challenge advancement of an experimental introduction in the McCloud (Sisk, 2024).

Passage Investigations. In spring 2023, the Winnemem Wintu Tribe, CDFW, and NMFS entered into historic salmon management and stewardship agreements. The coalition of “co-managers” comprised of CDFW, NMFS and the Winnemem Wintu Tribe, with support from USGS and environmental consultants Anchor QEA and HDR and Associates, are developing a plan for studying volitional passage

of winter-run Chinook salmon around Keswick and Shasta dams that includes the following core components (John Ferguson, Anchor QEA, personal communication, 2024):

1. Gather critical biological and physical information needed to inform the development of engineering alternatives for fish passage volitional or otherwise and assess data gaps.
2. Determine the feasibility of volitional passage, including development and analysis of alternatives using existing data.
3. Advance design of the preferred alternative from concept to a level of engineering analysis and project description sufficient to prepare environmental compliance documents and estimate construction costs.

Additionally, subsequent to launching the passage investigation for Shasta, a separate but related effort was initiated to explore potential removal of McCloud dam and reservoir to facilitate access to significant additional historic winter-run habitat upstream.

The four run timings of Central Valley Chinook salmon and their diverse life stages and life histories co-evolved with one another and benefit from many of the same hydro-physical and hydro-ecologic conditions. Changes to those underlying conditions resulting from the construction and operation of the CVP and SWP have also forced novel management actions, like coldwater pool management for winter-run spawning, incubation, and emergence below Keswick Dam. Actions narrowly tailored to the preservation of a single run-timing and/or specific life stages risk not only negatively impacting the other Chinook run timings and native aquatic species broadly, but also reducing the magnitude and diversity of conservation benefits resulting from the management of California's water—pitting water management actions for species needs against one another. A number of key stressors for winter-run Chinook salmon specifically are sufficiently proximate to CVP infrastructure and operations that their impact could be mitigated through re-operation of Shasta releases and coldwater pool management (as shown in Box 2-4). In the absence of the constraints resulting from coldwater pool management, both re-operation potential and other potential flow-associated benefits for the aquatic ecosystem and native species (including other Chinook run-timings) could expand. Therefore, the Committee encourages further progress in reintroducing of winter-run Chinook salmon into their ancestral spawning grounds in the McCloud River, Battle Creek, and upper Sacramento River a reality. If possible, these efforts could also consider the establishment of spring-run Chinook salmon populations above Shasta Reservoir, coupled with passage approaches for adults and juveniles (McCloud/upper Sacramento rivers) and habitat restoration (Battle Creek) that support success for those populations, in a life-cycle context, beyond what they are experiencing under current conditions. In the meantime, the Committee recommends maintaining the three-pronged approach to preventing winter-run extinction that combines reintroduction of winter-run Chinook salmon above Shasta Dam with improving conditions downstream of Keswick Dam and continuing artificial propagation, supplementation, and hatchery management.

Climate Impact Drivers Relevant to Coldwater Pool Management

Climate impact drivers are physical climate conditions—such as average states, events, or extremes—that affect human or natural systems (IPCC, 2021). The sections that follow discuss how climate impact drivers may affect the Shasta Coldwater Pool Management Action, beginning with the most critical drivers.

Drought. Drought episodes that result in decreased inflow to Shasta Reservoir will affect the size of the coldwater pool (Hallnan et al., 2020; USBR, 2022). While seasonal (1–3 months) and year-long droughts can impact the system, the main concern regarding Shasta coldwater pool management is the occurrence of multi-year droughts such as the 2007–2009 drought and the 2012–2015 megadrought in

California. Chen et al. (2025) show that there has been an increase in the occurrence and severity of multi-year drought events at the global scale. This is consistent with findings that show increased drought duration in a warmer climate (Gu et al., 2020). Furthermore, the probability of hot droughts (i.e., dry conditions associated with anomalously warm temperatures) is also projected to increase in a warmer climate (Chen and Sun, 2017). These events could have significant impacts on Shasta coldwater pool management and USBR's ability to provide favorable conditions downstream of Keswick Dam.

Critically dry years have resulted in reduced total storage in Shasta Reservoir and a significantly diminished coldwater pool. For example, in 2014 and 2015, exceptionally low coldwater pool volumes contributed to downstream temperatures that exceeded survival thresholds, resulting in estimated egg-to-fry mortality rates of greater than 75 percent (NMFS, 2019; USBR, 2022). Similarly, in 2021–2022, below-average runoff and minimal carryover storage led to severely constrained thermal management, with operational forecasts indicating minimal ability to meet target temperatures through the end of the management season (USBR, 2024a). In addition to spring storage and other factors such as seasonal air temperature, radiative heating, the volume and temperature of runoff, and reservoir releases, the size of the coldwater pool is affected by prior-year carryover. This storage effect is particularly important in back-to-back drought scenarios, when biological risk compounds due to prolonged exposure to inadequate thermal conditions (USBR, 2024a). Moreover, the three-year brood stock reserve maintained by the Livingston Stone National Fish Hatchery is vulnerable to extended droughts (NMFS, 2019), and a prolonged period of critical drought could result in a population crash (NMFS, 2024a).

Average Annual and Seasonal Temperature. Projections of average annual temperatures clearly show an increase both globally and at local scales in the Bay-Delta region (see Appendix A). Higher air temperatures throughout the year—especially during the summer—can lead to higher downstream water temperatures at compliance points, which may require increased water releases. Empirical evidence showed that spring's seasonal temperature is negatively correlated with the size of the coldwater storage (Nickel et al., 2004). Together with the magnitude of the preceding year's late summer hypolimnetic releases, these two factors were found to explain 64 percent of the variability in the size of the coldwater pool (Nickel et al., 2004).

Snowpack. In a warmer climate, the transition from snow to rain leads to several changes in the snowpack, including reduced overall accumulation, an earlier peak, and a shorter snow season. These changes—both individually and collectively—can impact the size and timing of development of the coldwater pool. An earlier snowmelt peak and shorter snow season present unique challenges for system operations, particularly because temperature management occurs from May to October, directly following the start of the snowmelt period.

Streamflow. The impacts of global warming on streamflow are most evident in changes to the timing of flow (Han et al., 2024). In many snow-dominated river basins, shifts in streamflow timing have been observed over the past few decades (Han et al., 2024; Wang et al., 2024). However, shifts in streamflow timing are expected to be small (on the order of days), and their effect partially mitigated by the relatively large size of Shasta Reservoir.

Annual Precipitation. When it comes to trends in annual precipitation in California, it is difficult to observe effects that might be associated with warming, due to natural variability (Dettinger et al., 2011). Furthermore, climate model projections for annual precipitation show significant disagreement, with little consensus on either the direction (increase vs. decrease) or the magnitude of change (see Appendix A). Annual precipitation in the western U.S. has decreased between 2002 and 2021 compared to the long-term average (1901–1960) (see Figure A-3), and if annual precipitation began to trend consistently downwards, there could be substantial impacts to Shasta's ability to store a sufficiently large pool of cold water in drier years.

Interannual variability in precipitation is expected to increase in a warmer climate (see Figure 1-3). This is particularly relevant for California, where a substantial portion of annual precipitation comes from atmospheric rivers (Dettinger, 2015).

Heatwaves. Heatwaves can significantly affect downstream conditions through the impact of riverine heatwaves (Tassone et al., 2023), often necessitating increased releases of cold water to meet environmental requirements. However, because heatwaves are transient, the Shasta system is expected to be resilient and generally tolerant of these short-term disturbances.

Wildfires. There is growing scientific consensus that wildfires alter the partitioning of water fluxes at the watershed scale (Williams et al., 2022), typically leading to increased runoff and reduced evapotranspiration. These effects can persist for several years following a wildfire, often resulting in temporarily higher inflows—which can, in turn, expand the coldwater pool. Unlike other climate-influenced disturbances, increased wildfire activity may have a beneficial effect on coldwater pool management at Shasta Reservoir by increasing coldwater inflows and reducing rates of warming by reflecting incoming solar radiation (Farruggia et al., 2024). However, more detailed projections of wildfire activity in the upper Sacramento River basin are needed to fully assess the range of potential impacts.

Of the climate impact drivers discussed above, those that affect stream temperatures downstream of Shasta and Keswick dams are likely to be the most important to the future of the Shasta Coldwater Pool Management Action. Indeed, understanding the mechanisms and response of river temperatures to warming atmospheric conditions is a key challenge to be addressed globally in the management of water resources in large river basins.

Bray et al. (2025) showed that many of Earth’s climate variables, including incoming shortwave radiation, net longwave radiation, atmospheric emissivity, and air temperature, along with the fundamental optical properties of water, control the heating of rivers. Although air temperature and river temperature are *correlated*, air temperature warming is not the primary mechanism that is driving warming of river temperatures, especially downstream of dams. Rather, the sensitivity of river temperatures to atmospheric factors likely to change under future climates also depends on the radiation that is absorbed by the water column and the bed, the rate at which energy is added or removed through atmosphere–water surface interactions, and the rate at which the river flow transports and accumulates energy in the water (see Figure 2-13; Bray et al. 2017). Thus, climate coupled with advective and diffusive flow processes determines the along-stream temperature of the rivers downstream of dams.

Physically based modeling studies that employ future climate data to the year 2100 under high-emissions scenario (RCP8.5) suggest that anticipated climate conditions may weaken the cooling benefits of managed flow releases from dams in the Central Valley, especially along rivers that experience a reduction in streamflow due to diversions. This reduction in streamflow results in shallower river depths, making the river more vulnerable to the net absorption of shortwave radiation, and higher temperatures, especially downstream of large diversions as the river becomes shallower and dominated by atmospheric heating fluxes (Rojas-Aguirre et al, 2024). Furthermore, water operators may experience increasing difficulty maintaining adequate coldwater pool volume in reservoirs through hotter summer months, and even extreme reductions in reservoir outflows may not be enough to mitigate the result of warmer release temperatures (Hallnan et al., 2020).

The implications of the above for Shasta coldwater pool management are that the action may not provide sufficiently cold stream temperatures for winter-run Chinook salmon downstream of Keswick Dam into the future. The watersheds that provide runoff and inflows to Shasta Reservoir will likely be subjected to more intense drought, decreased tributary inflows, higher rates of evapotranspiration and evaporation due to higher air temperatures, decreased snowpack, earlier peak snowpack, and a shorter

snowpack season. Historical data already show that the thermally suitable river habitat has contracted from about 40 miles in 1996 to about 5 miles in 2022 (see Figure 2-4).

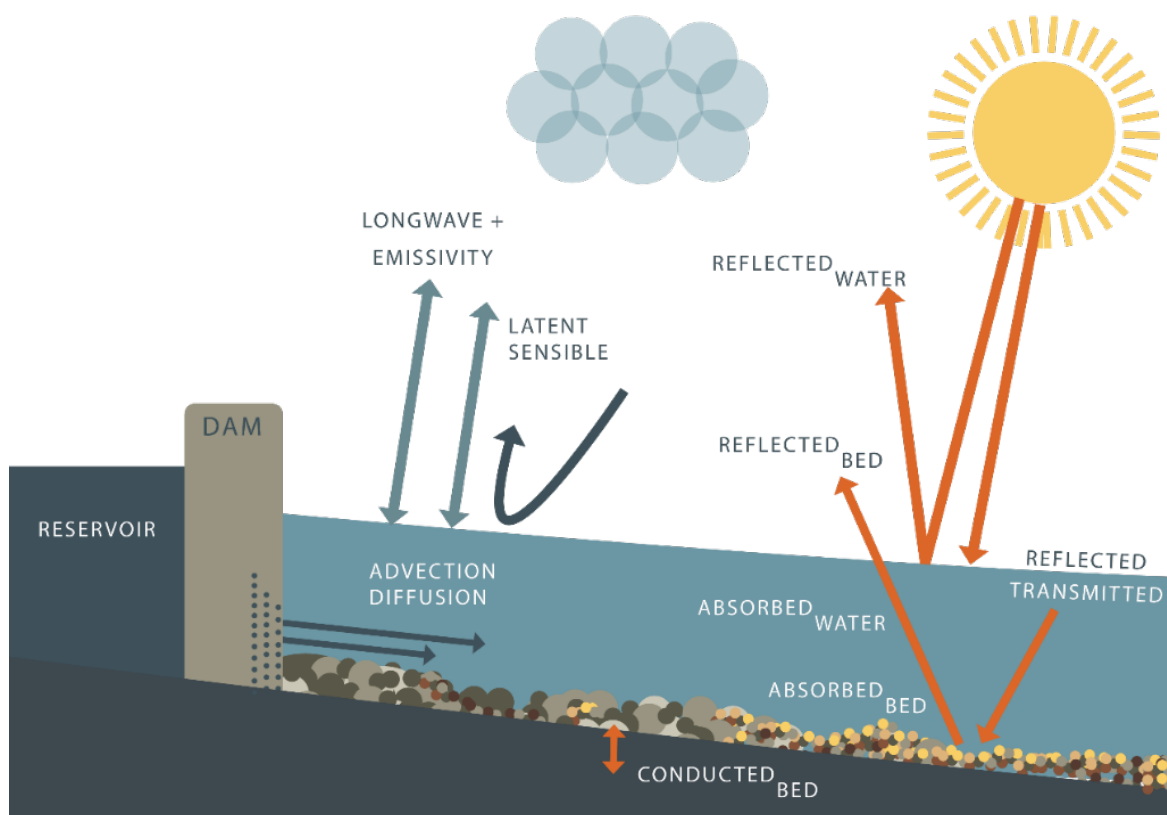


FIGURE 2-13 Heat energy balance along a river downstream of a dam, including atmospheric heat exchanges, along-stream heat exchanges and at the bed.
SOURCE: Bray et al. (2025).

A related consideration for coldwater pool management is that the percentage of years falling into each of the six available bins is likely to shift as climate factors change. Each bin corresponds to a range of storage values and is associated with a historical frequency of occurrence—for example, Bin 1 has occurred in about 80 percent of years historically (see Table 2-1). However, climate change is expected to lead to sustained reductions in flows into Shasta Reservoir. As a result, the frequency of Bin 1 conditions will likely fall below the historical 80 percent, while the frequency of years falling into Bin 2 and Bin 3 will increase. In addition, climate change is amplifying variability between wet and dry years, which reduces the number of years with “normal” conditions. These shifts are not currently reflected in the existing bins framework, which is based on fixed, absolute storage thresholds.

To fully address climate-related impacts to Shasta Reservoir, management approaches should consider projects that provide fish passage to upstream habitats in the McCloud, Pit, and upper Sacramento rivers in addition to continued improvements in forecasts of the coldwater pool volume and flow releases downstream of Keswick Dam during the summer management season.

CONCLUSIONS AND RECOMMENDATIONS

A three-pronged approach to Shasta management that focuses on improving conditions downstream of Keswick Dam, continuing artificial propagation and supplementation via hatchery management, and reintroducing winter-run Chinook salmon in natal coldwater habitats will be essential to the protection and eventual recovery of winter-run. Some of the recommendations that follow are based on continued coldwater pool management, including monitoring improvements that can lead to better estimates of the volume of coldwater annually and a better understanding of the potential role of seiching and vertical mixing in Shasta Reservoir. Continuing efforts to improve temperature management downstream of Keswick Dam are essential because that is currently where the only significant population of spawning winter-run Chinook salmon can be found. Reintroducing winter-run Chinook salmon to other habitat areas (above Shasta Reservoir and to Battle Creek) will take time, with uncertain prospects of success, such that supporting the salmon population below Keswick Dam will be an important bridge to the future. Ultimately, an ecosystem approach to coldwater pool management, focused on optimization for a range of species, will create greater operational flexibility as well as diverse ecological benefits supportive of multiple species and life history stages.

Recommendation 2-1: USBR should enhance the monitoring of temperature and mixing in rivers relevant to the coldwater pool management action.

Temperature sensors for rivers are inexpensive to install and maintain and could provide important information to enhance the predictive accuracy of the WTMP. USBR should use the WTMP to determine which tributaries—particularly in the reach downstream of Keswick Dam—and locations for which additional temperature data will reduce uncertainty in simulations and increase accuracy of modeled boundary conditions. Evidence shows that the Sacramento River quickly mixes across the channel width eliminating any significant lateral variations; the main exception is the temperature gage at Shasta Dam, which should be relocated (or a secondary gage installed) downstream to a point of full lateral mixing.

Recommendation 2-2: USBR should install four to six Lake Diagnostic Systems (micro-meteorology stations mounted over a fiber-optic distributed temperature sensing system) throughout Shasta Reservoir for two years to better understand how high frequency physical dynamics within the reservoir (such as seiching and internal mixing) affect the thermocline depth and to generate more accurate estimates of the coldwater pool volume.

Over this two-year period, the adequacy of a single Lake Diagnostic System linked with CE-QUAL-W2 could be evaluated for its ability to simulate and predict the formation of stratification, the internal mixing processes affecting the coldwater pool, and the influence of different TCD operational rules. This enhanced monitoring will support the WTMP and help to explain and predict why the coldwater pool can vary significantly for water years with approximately the same total annual runoff.

Recommendation 2-3: High levels of “unattributed mortality” of winter-run Chinook salmon eggs must be better understood through research that defines specific pathways for reducing said mortality, in order to develop management actions that can increase confidence in using egg-to-fry survival as the principal focus point for management.

The focus on temperature dependent mortality, interactive effects of multiple-stressors, and the fine tuning of releases from the Shasta coldwater pool may increase survival, but even in years when temperature dependent mortality is minimal, high mortality can still occur. Additional management actions supportive of winter-run survival can only be identified based on understanding the influence of factors such as temperature, flow, habitat, substrate, pathogens, predation, and food quality and

availability across all life stages. Ongoing studies investigating the temperature, dissolved oxygen, and flow through redds could evaluate the potential benefits of larger scale actions such as channel and floodplain restoration, gravel augmentation, and pulse flows in sustaining pool-riffle sequences and other geomorphic features conducive to spawning.

Recommendation 2-4: As tribes, CDWR, and others continue feasibility studies, USBR should develop an actionable plan to facilitate and support the reintroduction of winter-run Chinook salmon to historic spawning and rearing habitat above Shasta Reservoir and in Battle Creek.

The challenges and operational constraints posed on coldwater pool management by warming air temperatures, reduced snowpack, and increased drought frequency and duration place winter-run Chinook salmon at increasing risk. The only way to mitigate that risk, especially the risk of a catastrophic population crash associated with a more than three-year drought, is to safeguard some portion of the population in existing coldwater habitats.

Recommendation 2-5: Life-cycle models should be applied to develop a long-term strategy for winter-run Chinook salmon conservation and recovery, in the context of CVP and SWP operations.

Although temperature-dependent mortality has received the most focus as a factor in winter-run Chinook salmon mortality, the relative importance of other factors throughout the system remains unclear, especially in the context of interannual variability in climate and resulting variation in streamflow and water temperature. Chinook salmon life-cycle models (e.g., CVPIA SIT, WRLCM, R2R DSM) could be used to systematically investigate how combinations of stressors interact to influence both egg-to-fry survival and juvenile growth and survival in a spatially explicit context. Model comparisons could be done to quantify system-wide trade-offs in management decisions, including impacts to other Chinook run timings and native aquatic species, and to identify which combinations offer the best gains in survival for a given water year type.

Conclusion 2-1: Hatchery supplementation offers critical near-term support for both winter- and spring-run Chinook salmon populations but may become increasingly nonviable over the long-term.

Conservation-focused hatchery production and supplementation has and continues to be a critical tool for the conservation of both winter-run and spring-run Chinook salmon populations, especially in drought years. However, mounting evidence suggests that the benefits of hatchery actions are coupled with associated impacts to the species genetics, life history diversity and reproductive fitness. In addition, increasing constraints on instream habitat conditions, reduced availability of clean cold water for hatchery production, and the increasing intensity of dry years are, collectively, likely to accelerate the decline of naturally reproducing populations, increase the frequency of hatchery interventions, and magnify harmful impacts from hatcheries.

Recommendation 2-6: Shasta Reservoir operations, and the models and inputs used to inform them, should more fully consider the effects of climate impact drivers on coldwater pool management.

In future years with anomalously warm temperatures, diminished snowpack, and more intense droughts, total winter-run survival is likely to drop meaningfully if current operations continue, particularly as these climate conditions worsen over time. Importantly, biophysical model predictions based on historical relationships with climate variables may become unreliable, because those

relationships may no longer reflect underlying physical mechanisms. In addition, the historical pattern of wet, dry, and normal years is expected to shift, making it necessary to adopt a more refined framework for coldwater pool management. Additional modeling could create an expanded set of operational rules targeted at extreme years (or even just those that are hotter and drier than considered by current management).

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3

Old and Middle River Flow Management

The Committee was charged with assessing the state of science for Old and Middle River (OMR) flow management and recommending ways that modeling and monitoring strategies and decision-support tools can be changed, improved, or replaced to more accurately assess the impacts of OMR flow management. This chapter first describes the OMR Flow Management Action, including the specific actions taken during a typical wet and dry OMR season and of the thresholds that, if crossed, lead to constraints on exports. It also assesses whether existing OMR management practices are grounded in reasonable scientific concepts, whether existing scientific information supports those concepts, and how better information might be obtained.

The chapter makes three primary points. First, existing OMR flow management, which uses takes at the pumps, flow levels, and turbidity levels as triggers for limitations on pumping, does have a reasonable scientific basis, although significant uncertainties exist about how well each trigger correlates with fish protection. Second, because of those uncertainties, OMR management could be improved, though such improvements would require changes to monitoring and modeling approaches. Third, the most promising changes would involve, first, more robust monitoring to better assess fish abundances, distributions, and movements within the Delta and, second, the application of a Delta-wide hydrodynamic model that enables mapping of the spatial and temporal influence of pumps. With these advances, water managers could move beyond management strategies that focus primarily on takes at the pumps.

OMR DESCRIPTION

The Central Valley Project (CVP) and the State Water Project (SWP) (sometimes referred to collectively as the Projects) divert enormous quantities of freshwater from the San Joaquin and Sacramento rivers, with some of the largest diversions taking place through the south-Delta pumps. The Projects deliver water from those pumps to contractors, primarily in the San Joaquin Valley and Southern California. The C. W. “Bill” Jones Pumping Plant (the Jones pumping plant), operated by the San Luis & Delta-Mendota Water Authority for the U.S. Bureau of Reclamation (USBR), generally limits maximum pumping to 4,600 cubic feet per second (cfs) due to subsidence in the Delta-Mendota canal (USBR, 2024a); otherwise, the pumping capacity could be 5,200 cfs. The Harvey O. Banks Pumping Plant (Banks pumping plant), operated by the California Department of Water Resources (CDWR), has a capacity of 10,300 cfs (CDWR, 2024a). Figure 3-1 shows the generalized, highly simplified flow paths created by opening of the Delta Cross Channel and operation of the pumps, promoting water flow away from the Sacramento and San Joaquin river channels and toward the South Delta.

OMR flow management occurs in a highly complex, tidally affected inland delta. Freshwater inputs to the OMR reaches of the Delta are primarily from the Sacramento and San Joaquin rivers (about 75 and 25 percent of inflow, respectively), both of which are regulated by upstream dams. However, semi-diurnal mixed tides also affect flow in the OMR reaches, with effects dependent on tidal phase, meteorological conditions, and freshwater inflows. Saltwater (greater than 2 parts per thousand [ppt]) can intrude into the Delta, depending on tides and freshwater flows, and water quality standards are designed to prevent salt from degrading the quality of exported water.

Adding to these challenges is the need to protect the six listed fish species that both pumping facilities can directly entrain, meaning the fish are drawn into water intakes for the pumps. Exports can also cause fish to become trapped in the OMR corridor or in Clifton Court Forebay prior to reaching the Banks pumping plant, thereby failing to complete their natural migration and becoming increasingly

subject to predation (ESA, 2018; NOAA, 2013). Other more indirect impacts to fish occur across the Delta because pumping changes the flow patterns within channels, sometimes rerouting fish to places where habitat conditions are poorer (NMFS, 2024; Section 7.5). Both direct and indirect effects of pumping cause fish mortality. Salvage of entrained fish occurs at both pumping plants, and the salvaged fish are trucked to one of six locations near the confluence of the Sacramento and San Joaquin rivers.

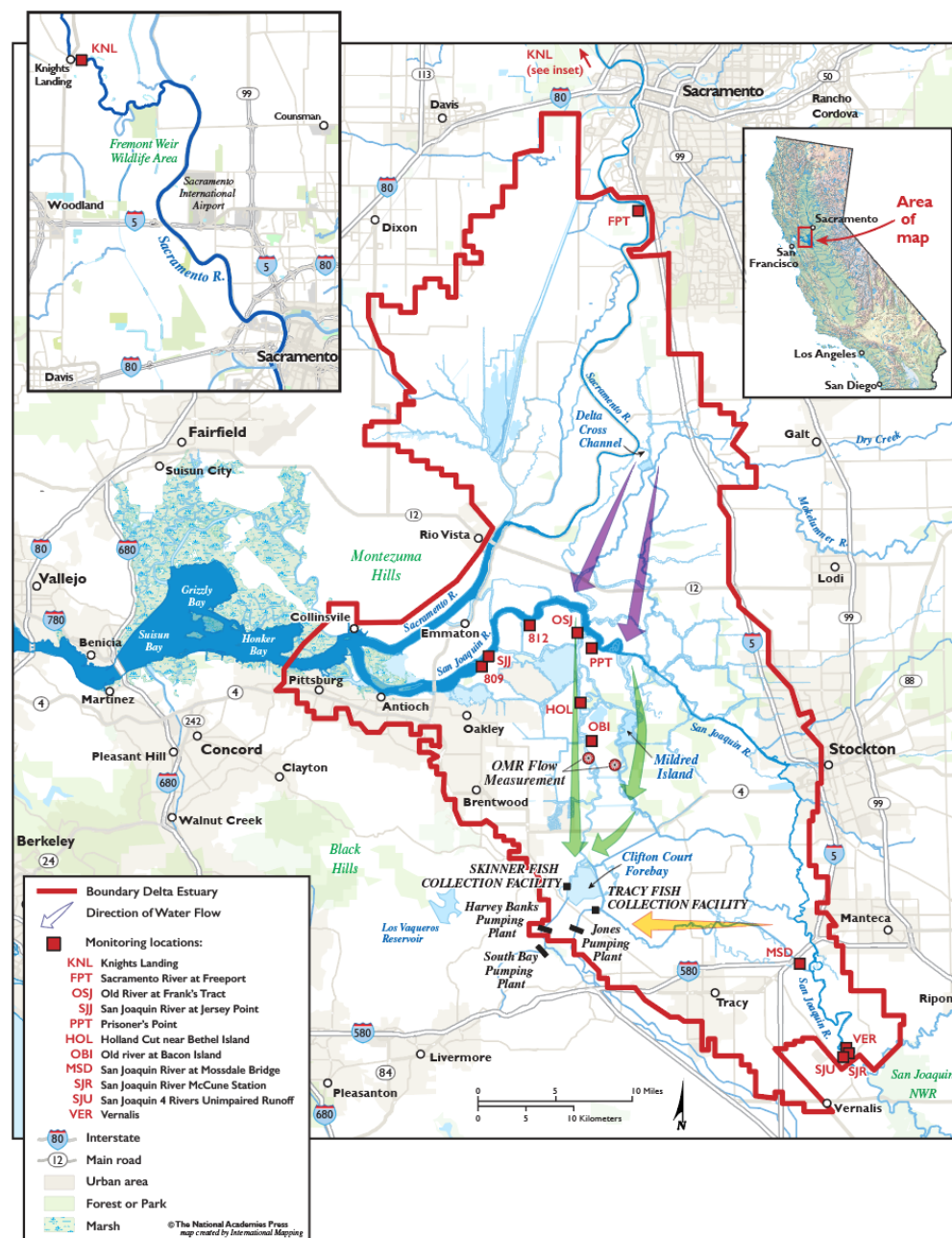


FIGURE 3-1 Features and monitoring locations relevant to OMR.

NOTE: Purple arrows indicate direction of water flow when the DCC is open, while green and yellow arrows indicate direction of water flow from the Sacramento and San Joaquin rivers, respectively, when the pumps are running.

SOURCE: Kevin Lear, International Mapping Associates.

The objectives of OMR flow management are to ensure that water delivery obligations are met while minimizing the negative effects of exports on protected fish species (NMFS, 2019, p. 476). Over the years, the U.S. Fish and Wildlife Service (FWS) and the National Marine Fisheries Service (NMFS) biological opinions have set forth specific steps to meet these broader goals. The OMR Flow Management Action began in 2009 as part of those biological opinions, with pumping rates reduced in accordance with constraints imposed by the federal and state Endangered Species Acts (ESA), and the action has continued to be part of subsequent biological opinions. A primary means by which USBR and CDWR comply with the biological opinions is by managing tidally averaged flows in the OMR corridor just north of the pumps (so-called “OMR flow”). These flows can range from -12,000 to 13,000 cfs in each channel near the two OMR flow measurement sites (Figure 3-1), where negative flow indicates net flow to the south. Without pumping, both positive (downstream) and negative (reverse) flows would be expected to occur over the course of a day in the channels during ebb and flood tides, respectively, with the net daily flow being positive. Depending on the time of year, CVP and SWP exports can result in a negative net daily [reverse] flow in portions of these channels. OMR flow management regulates the amount of freshwater pumped by the Jones and Banks pumping plants during a period that generally extends from December through June, which is the period when sensitive life stages of the listed fish species are found in the Delta (Figure 3-2).

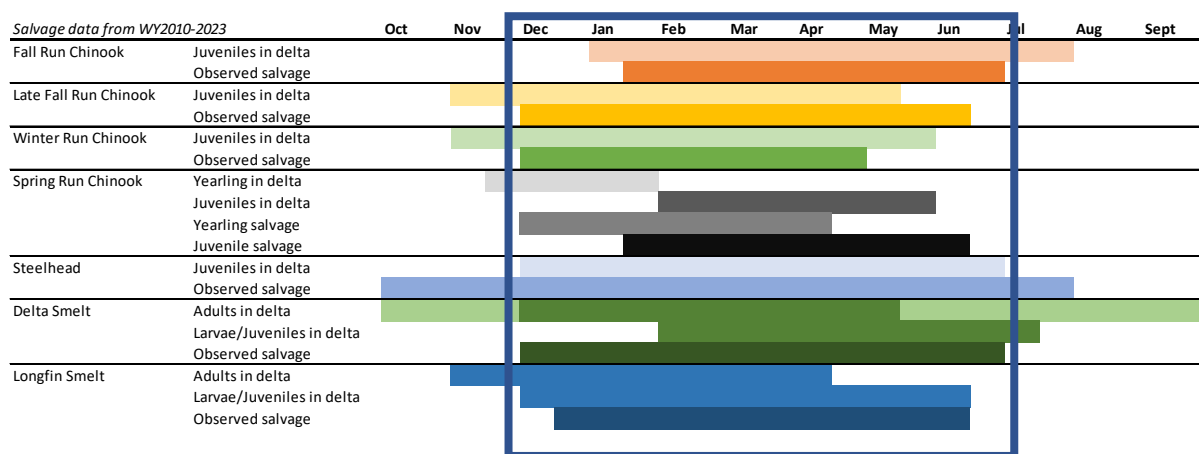


FIGURE 3-2 Overlap between fish presence in the Delta and their various life stages and the OMR flow management season.

NOTE: fall-run and late-fall-run Chinook are not ESA-listed species. Sturgeon is not included in the graphic.

SOURCE: Schreier et al. (2024).

The biological opinions that govern OMR flow management are part of a broader set of laws and physical constraints that affect pumping levels. The general conditions and legal constraints—including but not limited to biological opinions—that limit exports during the period of OMR flow management are listed below¹:

¹ Not every possible constraint is listed; rather, the focus is on those constraints highlighted by the USBR and CDWR as central to OMR flow management at the Committee’s Meeting 2. For example, the list does not mention constraints stemming from the voluntary agreements, such as limiting exports to half of the San Joaquin River inflow (Hutton, 2008), which, even in wet years, can be low due to substantial diversions in that basin.

- Infrastructure capacity: The reservoirs, pumps, and canals have capacity limits and sometimes these limits control the pumping levels.²
- Water quality and flow standards, of which there are dozens,³ as outlined in Water Rights Decision D-1641⁴ (State Water Resources Control Board, 2019).
- Biological opinions from USFWS and NMFS: The 2024 biological opinions restrict 14-day running averaged OMR flow to values between -2,000 and -5,000⁵ cfs to reduce entrainment of smelt and salmonids.
- Incidental Take Permit (ITP) from the California Department of Fish and Wildlife (CDFW) for longfin smelt, Delta smelt, and spring-run and winter-run Chinook salmon: The ITP restricts OMR flows to values between -1,250 and -5,000 cfs.
- The need for a minimum export of 1,500 cfs to meet health and safety needs.
- Contractual obligations for Project water: the highest priorities are senior water right holders and wildlife refuges (see Appendix B), and delivery to those right holders may limit the amounts of water flowing into the Delta, thus reducing the amount of water available for export.
- Storm-flex, which allows exports to exceed normal thresholds during storm conditions in the Delta, e.g., allowing the 14-day average OMR flow to reach -6,250 cfs under certain criteria (USBR, 2024b, pg. 3-66 to 3-67).
- Emergency drought operations (e.g., California Water Boards, 2016, and Temporary Urgency Change Orders).⁶

Of the aforementioned constraints, a primary control is D-1641, which defines water quality conditions that must be met at different parts of the Delta and establishes constraints designed to make sure those conditions are attained. Hence, D-1641's requirements govern Delta outflows, salinity levels, and export-to-inflow ratios. D-1641 also establishes a framework for adjusting these requirements. The decision specifies automatic relaxations, which are tied to water year type; those relaxations derive from a recognition that some water quality objectives may be too difficult to attain in dry or critically dry years. CDWR and USBR also may file Temporary Urgency Change Petitions with the State Water Resources Control Board, which may grant those petitions through Temporary Use Change Orders (TUCOs), which can allow short-term modifications to D-1641 requirements beyond the automatic water-year-type relaxations. TUCOs typically include measures like reduced outflow requirements, movement of compliance points further upstream, and adjustments to export restrictions—especially in dry years.

The particular condition and/or legal requirement that ultimately controls exports depends on the water year type and the time of year, and it can vary from week to week. The importance of D-1641 as a constraint in wet versus dry years is shown in Figure 3-3. In late 2021, a dry fall meant that D-1641 standards, likely for salinity, were controlling exports. Around January 1, 2022, a “first flush” trigger caused by a storm event (labeled “OMR” in Figure 3-3 and described below) became controlling. However, overall dry conditions that winter led to a return to D-1641 standards as the overall controlling factor for the remainder of the OMR flow management period. In contrast, in late 2022 a dry fall again preceded the OMR flow management period, and D-1641 controlled exports. However, December 2022 storms ushered in a very wet winter, which led to a different set of controlling factors in 2023, including infrastructure capacity, that varied throughout the OMR season.

² For example, in some wet years pumping is curtailed when the San Luis Reservoir is full, as there is no place to put the water.

³ See https://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/deltaflow/docs/closing_comments/dwr_closing_attachment.pdf.

⁴ See <https://cawaterlibrary.net/document/water-rights-decision-1641-d-1641/>.

⁵ The -5000 cfs baseline for OMR flow is based on Grimaldo et al. (2009), which suggested an increase in Delta smelt salvage at OMR flows more negative than -5000 cfs.

⁶ See https://www.waterboards.ca.gov/drought/tucp/docs/2016cpmarnovadd1_update.pdf.

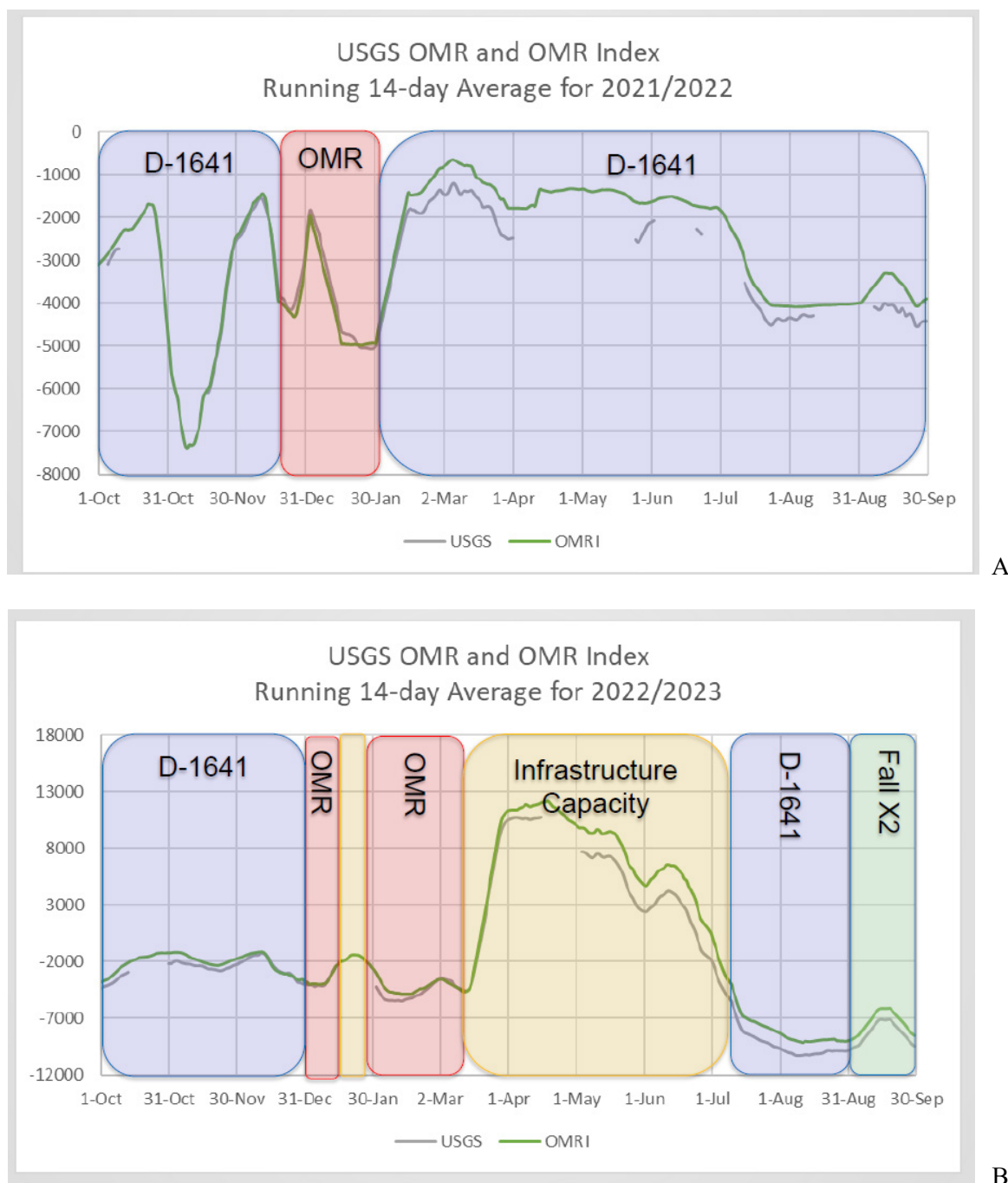


FIGURE 3-3 Controlling regulations on OMR flow management during (A) a dry season (2021–2022) and (B) a wet season (2022–2023). During the 2021–2022 season, the exact water quality and/or flow regulations from D-1641 that controlled exports varied and are not explicitly shown in (A). Furthermore, in March 2022, due to the challenges in meeting certain D-1641 standards, a TUCO was requested and received to (1) reduce the minimum Delta outflow, (2) move the Emmaton compliance location upstream, and (3) reduce San Joaquin River minimum flow requirements from April to June. NOTE: the difference in scales on the y axis. SOURCE: Schreier et al. (2024).

Actions in an OMR Season

The three main phases of OMR management—onset, duration, and offramp—are described below.

OMR Onset

The 2024 Record of Decision (ROD) for the Long-Term Operation of the Central Valley Project and State Water Project (USBR, 2024c) governs the actions that constitute OMR flow management, including onset. The first condition that controls onset, which can start on or after December 1, is called “first flush.” First flush is defined as when the running 3-day average of the daily flow at Freeport (8 miles south of Sacramento on the Sacramento River) is greater than or equal to 25,000 cfs and when the running 3-day average of daily turbidity at Freeport is greater than or equal to 50 Formazin Nephelometric Units (FNU)⁷. During “first flush,” listed fish are more likely to be moving through the system, and entraining these fish is undesirable, hence the on-ramping of OMR flow management during such conditions. The second condition that controls onset is the salvage of adult longfin smelt (Adult Longfin Smelt Entrainment Protection Action) or crossing a turbidity threshold indicative of adult Delta smelt entrainment (Adult Delta Smelt Entrainment Protection Action). If none of those conditions is met, OMR flow management automatically starts January 1.

Actions During the OMR Season

OMR flow management during the December–June period is layered and imposes a variety of constraints on exports. The constraints can stem from water quality conditions that occur during the management season or the presence of fish in the Delta. For example, “turbidity bridge avoidance” refers to reducing exports to maintain daily average turbidity to be below 12 FNU at three water quality monitoring stations (OBI, HOL, and OSJ—see Figure 3-1). The rationale behind this control is that a continuous area of turbid waters from the San Joaquin River Shipping Channel to the south Delta fish facilities could attract pre-spawning adult Delta smelt to the pumps (Brown et al., 2024). When it is controlling exports, turbidity bridge avoidance restricts the OMR Index (OMRI)⁸ to no more negative than -3,500 cfs.

Constraints on exports are also imposed if certain environmental or biological thresholds that might indicate entrainment are breached during the management season. Environmental triggers used as surrogates for smelt protection include temperature, turbidity, and Secchi depth, each of which is measured at various locations in the Delta. Biological triggers include a certain number of listed fish salvaged at the pumps, specifically larval, juvenile, and adult Delta smelt and longfin smelt; winter- and spring-run Chinook salmon; and steelhead. Depending on which fish and life stage have been detected above a trigger, and at what time during the season (and only when the incidental take permit or the biological opinions are controlling), OMR flows cannot be more negative than a certain value, which ranges between -5,000 and -2,500 cfs. For example, if the natural winter-run Chinook loss in salvage exceeds some percentage of the juvenile production estimate (JPE), then exports must operate to achieve an OMR flow of no more negative than -3,500 cfs for seven consecutive days. As another example, if salvage of adult longfin smelt exceeds a threshold based on prior months San Francisco Bay Study index,

⁷ Turbidity can be measured using metrics of Formazin Nephelometric Units (FNU) or Nephelometric Turbidity Units (NTU). Instream turbidity is typically measured by equipment that uses FNU based on infrared or monochrome light source, while most laboratory equipment uses NTU measured with white or broadband light. <https://pubs.usgs.gov/sir/2007/5178/section4.html>.

⁸ OMRI is defined subsequently and is similar to flow in the OMR corridor.

exports must be reduced to maintain a seven-day average OMR flow no more negative than -3,500 cfs. The specific triggers that are compared to environmental and fish salvage data are presented in Table 3-1 and discussed subsequently in greater detail.

OMR Offramp

According to the 2024 ROD (USBR, 2024c), the OMR management period will end prior to June 30 (1) for smelt when water temperature at Clifton Court Forebay exceeds 77°F (25°C) for three consecutive days and (2) for salmonids when daily mean water temperature at Mossdale and Prisoner's Point exceeds 72°F (22.2°C) for any seven days in June. If temperature cutoffs have not occurred, OMR management ends on June 30.

Other Components of OMR

Calculation of OMR Flows

OMR flows are quantified as the sum of daily averaged tidally filtered flow at two U.S. Geological Survey (USGS) monitoring stations. The USGS operates gauges on both the Old (station ID 1313405) and Middle (station ID 11312676) rivers, where velocity and water level are measured. These observations are then converted to flow based on a rating curve. Because flows in the OMR corridor are tidally affected, USGS provides a net flow at each site through the application of a Godin filter to the hourly observations; this is standard practice for calculating net flow at tidally affected sites (Walters and Heston, 1982). However, the Godin filter requires 72 hours of observations beyond the current time to estimate a flow and does not perform well when wind and atmospheric pressure changes affect water levels and the direction and magnitude of flow.

Because of the limitations of the time-delayed Godin-filtered net flows, CDWR proposed the use of an OMR index (OMRI) for OMR management. Conceptually, the OMRI is a water balance using measured riverine inflows, measured exports by water projects and estimates of other diversions, channel depletions, and precipitation (CDWR, 2017; Hutton, 2008; Sandhu et al., 2016)⁹. An analysis by CDWR (2017) demonstrated a very close correlation between the USGS tidally filtered measured flows and the OMRI over long averaging periods; the correlation was higher for wetter years compared to drier years. (For an example of OMR flow and OMRI, see the gray and green lines in Figure 3-3, which also shows intervening missing periods of tidally filtered flow filled in by the OMRI). CDWR recognizes the need for additional work to help close the water balance, including additional instrumentation, improved estimates of consumptive water use and evapotranspiration, and a better understanding of groundwater and channel depletion (CDWR, 2017). Nevertheless, the OMRI is the flow metric currently used for management.

Delta Cross Channel

The Delta Cross Channel (DCC) is a controlled diversion channel between the Sacramento River and Snodgrass Slough, north of the Delta. Operation of the DCC is part of OMR flow management because the DCC improves the efficiency of conveying water from the Sacramento River to both export facilities. By moving water from the Sacramento River to pumping plants, opening the DCC can improve water quality in the central and southern Delta and reduce salinity intrusion from the west. The gates are closed to protect out-migrating Sacramento River salmonids from entering the interior Delta where

⁹ See https://www.cbr.washington.edu/sacramento/data/metadata/method_omr.html.

mortality is expected to be high. Fish monitoring data from Knights Landing and Sacramento are used to determine the presence of juvenile salmonids that may enter the Delta (USBR, 2023). In addition, whenever flows in the Sacramento River at Sacramento reach a sustained flow 20,000 to 25,000 cfs, the gates are closed to reduce potential scouring and flooding that might occur in the channels on the downstream side of the gates (USBR, 2021). Between December 1 and January 31, the DCC gates are closed unless there is a risk of exceeding water quality standards. For the bulk of the OMR flow management season (February 1–May 20), the DCC gates are closed. From May 21 to June 15, the DCC gates are closed for 14 days (generally weekdays to accommodate recreation on the weekends), after which time the gates open permanently until fall.

Decision-Making During OMR Management

Major decisions about OMR flow management are made by the Water Operations Management Team (WOMT) on a weekly basis (see Table 1-1). The WOMT considers summaries of water operations, operational outlooks, and notes provided by other participating teams, including the Salmon Monitoring Team (SaMT) and Smelt Monitoring Team (SMT). These teams consider a myriad of factors such as data on hydrology, flow requirements of the incidental take permit and biological opinions to meet specific water quality and entrainment criteria, water quality (salinity, temperature, Secchi depth/turbidity at specific locations), and smelt and salmonid presence and fish distribution. The WOMT also receives input from the Delta Monitoring Workgroup, which consists of water contractors and other stakeholders. In all, export decisions consider regulatory constraints, risk assessments, historic and real-time data, and model outputs from water quality experts, biologists, water contractors, and operators. Many of the data sets about current conditions on Delta smelt, operational data, onset and offramp conditions, and other metrics relevant to OMR management are compiled and visualized daily at the SacPas website¹⁰. If the WOMT cannot agree on a path forward, the issues elevate to agency directors. Decisions to change the export rate can take several days to implement due to CDWR/USBR administrative protocols for coordinated operations, facility (e.g., pumps, gates) adjustments and reaction times, and other factors.

Table 3-1, compiled by the Committee from multiple documents, lists the many hydrologic, water quality, and biological triggers that currently play a role in OMR flow management, organized by management phase. For each trigger, Table 3-1 shows the location of the measured parameter, the threshold value(s) of the measured parameter, and the operational consequence of exceeding the threshold. Since implementation of the 2024 ROD, these triggers and their corresponding thresholds have taken on greater importance in OMR flow management because other criteria that used to be part of OMR flow management, such as estimating the percentage of salmonid populations affected by a change in export rate, have been removed from the decision-making process. Now, decisions about changing the export rate (when the biological opinions or the incidental take permit are “controlling”) are almost entirely based on the exceedance of such thresholds.

Over the years, triggers and thresholds have been revised with each subsequent biological opinion. Those laid out in the 2024 incidental take permit for the SWP and in the 2024 biological opinions that govern the CVP pertain to Delta smelt, longfin smelt, winter-run Chinook salmon, spring-run Chinook, and steelhead. The typical response to threshold exceedance involves reducing the export rate so that the OMRI is no more negative than ($\geq$ in Table 3-1) some value, ranging from -5,000 to -2,500 cfs. Reductions in exports brought about by crossing these thresholds are in place until conditions change to bring measured data below the thresholds or until some other factor takes over control of the export rate.

¹⁰ See https://www.cbr.washington.edu/sacramento/workgroups/delta_smelt.html.

TABLE 3-1 Triggers in OMR Flow Management Stemming from the Biological Opinions

Component	Trigger	Location	Threshold Value	Operational Action
Winter-Run Early season migration	Genetically verified 7-day rolling sum of salvage loss exceeds threshold	At the pumps	Calculated similar to JPE; start with RBDD brood-year totals, use unique multipliers for Nov./Dec.	7-day average OMRI $\geq$ -5,000 cfs for 7 days
<i>Onset of OMR</i>				
<u>First Flush</u> Between Dec 1 and Feb 28/29	Turbidity	Sacramento R. at Freeport	3-day running average turbidity ≥ 50 FNU	OMR management starts; exports reduced such that 14-day OMRI $\geq$ -2,000 cfs for 14 consecutive days
	Flow	Sacramento R. at Freeport	3-day running average flow $\geq 25,000$ cfs	
<u>Adult LFS Entrainment Protection Action</u> (Dec 1 to start of OMR season)	Salvaged fish ≥ 60 mm	At the pumps	Threshold is calculated from Age 1+ LFS index from Aug-Dec SFBS catch (Equation on p. 3-59 of USBR, 2024b)	7-day average OMRI $\geq$ -5,000 cfs for 7 consecutive days; the WOMT may then decide to onramp OMR after action concludes
<u>Adult DS Entrainment Protection Action</u> (After First Flush action or Dec 20, which-ever occurs first)	See below for turbidity threshold	OBI, HOL, OSJ	≥ 12 FNU	DS action onramps (see below) OMR management onramps (after Dec 20)
<u>Date Cutoff</u>	Jan 1, if none of the above actions have occurred			OMR management onramps
<i>During OMR Season</i>				
<u>Adult DS Entrainment Protection (Turbidity Bridge Avoidance)</u>	Turbidity	OBI, HOL, OSJ	≥ 12 FNU	5-day average OMRI $\geq$ -3,500 cfs, assessed on the 7 th day, until the daily-average turbidity is < 12 FNU for one of three stations for 2 consecutive days
	Flow (High flow temporary action offramp)	San Joaquin R. at Vernalis	Daily average flow $> 10,000$ cfs. Action resumes when Vernalis flow $< 8,000$ cfs	OMRI $\geq$ -5,000 cfs on a 14-day average
	Temperature	Jersey Point or Rio Vista	≥ 53.6 F (3-day continuous)	Ends the action period (can no longer occur during water year)
<u>Adult LFS entrainment protection</u> (Onset of OMR season until the end of Feb)	Exceed threshold of salvaged fish ≥ 60 mm	At the pumps	Threshold is calculated from Age 1+ LFS index from Aug-Dec SFBS catch (Equation on p. 3-59 of USBR, 2024b)	7-day average OMRI $\geq$ -3,500 cfs for 7 consecutive days, to be assessed on the 7 th day of action whether to continue the action
<u>Larval/Juvenile DS Protection Action</u> (End of Adult DS Protection action to end of OMR management)	Secchi depth	SLS and 20-mm survey locations	< 1 m average Secchi depth for all south Delta stations	7-day average OMRI $\geq$ -3,500 cfs until the Secchi depth has increased to > 1 m; 7-day average OMRI $\geq$ -5,000 cfs at other times
	Flow (High flow temporary action offramp)	SR at Rio Vista SJR at Vernalis	Daily average $> 55,000$ cfs or Daily average $> 8,000$ cfs Action resumes when Rio Vista flows $< 40,000$ cfs or Vernalis flows $< 5,000$ cfs	OMRI $\geq$ -5,000 cfs on a 14-day average

<u>Larval/Juvenile LFS Protection Action</u>	Flow	QWEST	7-day QWEST < 1,500 cfs	7 day average OMRI ≥ -3,500 cfs for 7 days, assessed on the 7 th day
	Larvae and juvenile LFS catch	SLS or 20-mm at stations 809 and 812	Catch exceeds threshold from Table 3-9 in USBR (2024b)	
	Salvage Juvenile LFS	At the pumps	Cumulative total salvage of 50% (75%) of average annual salvage from 2009 to previous Water Year	7-day average OMRI ≥ -3,500 (-2,500) cfs for 14-days; WOMET may request assessment after 14 days
	Flow (High flow temporary action offramp)	Identical to DS Protection Action (above)	Identical to DS Protection Action (above)	Identical to DS Protection Action (above)
<u>Winter-Run Annual Loss</u>	WR Chinook in salvage	At the pumps	If cumulative loss > 50% (or 70%) of annual loss thresholds	7-day average OMRI ≥ -3,500 (or -2,500) for 7 consecutive days, assessed on 7 th day, machine learning model results may trigger -2,500 OMRI
	Natural WR: Annual loss of = 0.5% of JPE			
	Hatchery WR: Annual loss of = 0.12% of JPE		Cumulative loss exceeds 100% of annual loss thresholds	CDWR/USBR immediately convene SaMT to review and provide advice to WOMET
<u>Winter-Run Weekly Loss</u>	WR Chinook in salvage: natural	At the pumps	Weekly loss threshold: Weekly percentage of natural WR in Delta (from Table 3-10 in USBR, 2024b), <i>times</i> 50% Natural WR annual loss threshold	If weekly distributed loss threshold is exceeded on any single day by the 7-day rolling sum of WR loss, then 7-day average OMRI ≥ -3,500 cfs for 7 consecutive days.
<u>Spring-Run Loss via Salvage</u> <i>Waiting for a JPE to use as a threshold</i>	Counts of SR surrogates (e.g., yearling LFR and young-of-year FR release groups)	At the pumps	Surrogate cumulative loss threshold for coded wire tagged SR is 0.25% for each release group	7-day average OMRI ≥ -5,000 cfs in Nov/Dec; ≥ -3,500 cfs beginning Jan 1 or after the start of OMR management.
<u>Steelhead detection via salvage</u> <i>Waiting for a JPE to use as a threshold</i>	Cumulative count of unclipped juvenile steelhead	At the pumps	Annual threshold is 3,000 fish	SaMT would meet and discuss and elevate information and/or recommendations to WOMET.
	7-day rolling sum of steelhead salvage, calculated daily		Weekly loss threshold = 120 fish.	7-day average OMRI ≥ -3,500 cfs for 7 days
<i>Offramp of OMR</i>				
<u>Smelt offramp</u>	Temperature	Clifton Court Forebay (Station CLC)	Daily mean > 25 C at CFF for 3 consecutive days	OMR management for smelts ends
<u>Salmonid Offramp</u>		Mossdale and Prisoner’s Pt.	> 22.2 C for any 7 days at each station in June	OMR management season for salmonids ends
<u>Date cutoff</u>	June 30, if temperature cutoffs have not occurred			OMR management season for both salmonids and smelts offramps

NOTES: CCF = Clifton Court Forebay; FMWT = Fall Midwater Trawl Index (see Appendix D); HOL = Holland Cut near Bethel Island; JPE = Juvenile Production Estimate (see Box 3-1); LFR = Late-fall run Chinook salmon; OBI = Old River at Bacon Island; OSJ = Old River at Franks Tract near Terminous; QWEST = net flow at Jersey Point; RBDD = Red Bluff Diversion Dam; SLS = Smelt Larval Survey (see Appendix D); SFBS = San Francisco Bay Study; SR = Spring-run Chinook salmon; WR = Winter run Chinook salmon.

Threshold Approach for Salmonids

For the three main salmonids, three different approaches are taken to develop thresholds, although the primary biological data collected are fish salvage data at the pumps. For winter-run Chinook, there are thresholds for both natural and hatchery-derived fish based on exceeding some percentage of the JPE. As explained in Box 3-1, measurements of fish at Red Bluff Diversion Dam along with empirical relationships are used to develop a JPE for natural winter-run Chinook and a JPE for hatchery winter-run Chinook. The 2024 biological opinions designate an annual loss threshold of genetic winter-run as 0.5 percent of the JPE—a reduction in the threshold from the 2019 biological opinions.

For spring-run Chinook an OMR threshold is set based only on a percentage of the number of fish released from the hatchery. This involves measuring fall-run and late-fall-run hatchery fish as surrogates for spring-run. Development of a JPE for spring-run Chinook is a high priority for USBR and CDWR.

Finally, for steelhead an OMR threshold has been set based on historic salvage numbers (the greatest loss from 2010 to 2018), although the thresholds are now single numbers (e.g., 3,000 fish). Both approaches are flawed because the salvage trigger should be influenced by the size of the population, and neither past nor current thresholds are. As for spring-run, USBR intends to develop a JPE for steelhead within the next few years to replace the current threshold (Beakes et al., 2024).

As can be inferred from Table 3-1, the OMR Flow Management Action is complicated, resource intensive, and dependent on a variety of regular field observations and modeling results. It involves many people with expertise in field data collection, laboratory analyses, computational modeling, and fisheries management. As a consequence, the decision-making process is not readily explainable.

BOX 3-1
Juvenile Production Estimate for Sacramento River Winter-run Chinook

The Juvenile Production Estimate (JPE) is used to determine the annual allowable incidental take of ESA listed winter-run Chinook salmon at the state and federal pumps in the South Delta. If take is exceeded, then pumping rates must be reduced. Separate natural and hatchery-derived forecasts of JPE are made. O’Farrell et al. (2018) and CDWR (2024b) provide straight-forward descriptions of these estimates, summarized below.

The natural-origin JPE is defined as the number of winter-run Chinook salmon juveniles produced from natural spawning areas that enter the Delta (O’Farrell et al., 2018). The approach is a simple accounting method that adjusts for fry-to-smolt and subsequent smolt-to-ocean survival rates.

The JPE for *natural salmon* is calculated as follows:

$$\widehat{JPE}_{n,t} = \widehat{PI}_{t-1} * \hat{f} * \hat{s}_n$$

where

$\hat{f}$ is a forecast of the fry-to-smolt survival rate in fry equivalent units

$\hat{s}_n$ is a forecast of the smolt survival rate of natural-origin fish

$\widehat{PI}_{t-1}$ is a point estimate of the number of fry-equivalent juveniles that pass the Red Bluff Diversion Dam (RBDD) from calendar year $t-1$

In the example provided in O’Farrell et al. (2018), $\hat{f} = 0.59$ and $\hat{s}_n = 0.5129$, which is the variance-weighted mean of survival rates estimated from acoustic tagging studies performed on hatchery-origin winter-run Chinook salmon conducted from 2013 to 2017 (NMFS, 2018). Figure 3-4 shows the natural-origin JPE for the past 20 years.

continued

BOX 3-1 *continued*

A similar calculation is done to determine JPE estimates for *hatchery-derived salmon*, with smolt survival estimated as above:

$$J\widehat{P}E_{h,t} = P_t * \hat{s}_n$$

where

P_t is the number of hatchery-derived pre-smolts released in year t in the upper Sacramento River (typically at Caldwell Park in Redding, O'Farrell et al., 2018).

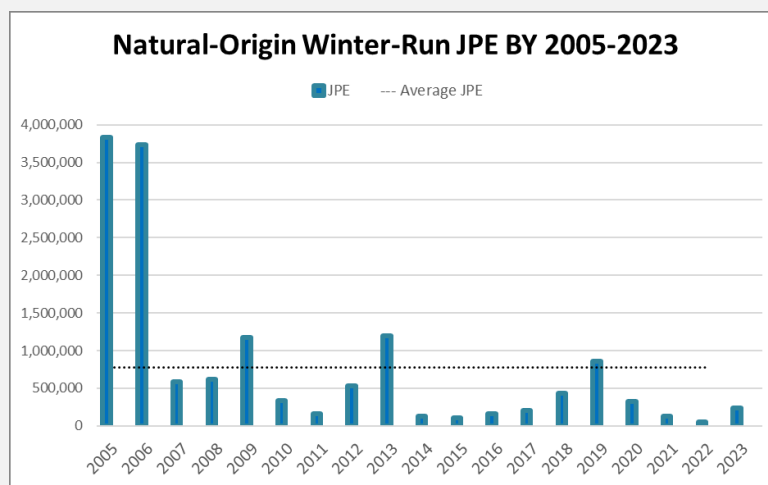


FIGURE 3-4 Natural-origin winter-run Chinook salmon JPE for brood years (BY) 2005 through 2023. SOURCE: NOAA, 2023, <https://www.fisheries.noaa.gov/s3/2024-01/jpe-letter-2023.pdf>.

Two other methods that attempt to account for statistical uncertainty in the JPE are proposed by O'Farrell et al. (2018):

“Method 2 follows the same basic model structure as Method 1 but (1) introduces a new approach for forecasting the fry-to-smolt survival rate ($\hat{f}$), (2) uses external survival estimates to forecast the smolt survival rate ($\hat{s}_n$), and (3) quantifies observation error for the model components and thus the JPE itself. Observation error represents the error in estimation for a particular year; it is the variation between the true value and its estimate. Method 3 accounts for observation error in the JPI estimate and uses the same approach to forecast $\hat{f}$ as Method 2, but uses a Bayesian approach to forecasting $\hat{s}_n$ that accounts for both observation and process error. Process error is the variation in true abundances or rates (not their estimates) across years from endogenous or exogenous forces. Both observation and process error can be important when making forecasts.”

Methods 2 and 3 result in JPE forecasts that are lower than the original method by 24% and 18%, respectively. The variance weighting and the use of the Cormack-Jolly-Seber model to account for detection probability contribute to the reduction in the estimate of $\hat{s}_n$ and consequently in the estimates of JPE. Both Methods 2 and 3 hold merit in terms of sophistication and likely greater accuracy; however, technical challenges remain in terms of data availability and greater computational complexity. Even if these methods were not adopted for regular use, they could be used to validate and cross-check the parameter values, methods, and prediction made by other methods.

Two considerations remain: (1) How good are the techniques used to obtain these annual measurements? (2) How good are the estimates of survival ($\hat{f}$ and $\hat{s}_n$)? Answering these questions and improving the JPE calculations is doable. However, whether doing so would be of greatest overall value to understanding system limitations is unclear, considering the broader set of processes influencing winter-run Chinook salmon in the system (see Chapter 2).

continued

BOX 3-1 *continued*

To improve the JPE, USBR and others could consider gathering *in vivo* estimates. O’Farrell et al. (2018) mention estimating winter-run smolt survival using acoustic tagging studies on hatchery origin fish. *In vivo* survivorship could be accomplished starting with simple mark-recapture methods (e.g., fin clips, coded wire tags—see later discussion). Then, to facilitate more sophisticated and informative approaches, they could consider seeding the previously tagged population with ultrahigh frequency or radio frequency identification tags to track the location of the population through their different life stages in different parts of the Delta. A pilot study applied to hatchery-origin fish could help to overcome hurdles associated with sampling intensity and timing and to develop statistically appropriate measures of uncertainty for the estimates. Regular annual estimates would be best to monitor changes in the system. Adopting such changes could potentially produce much more information than just a JPE estimate, including survivorship at different life stages, where the bottlenecks are occurring, and the role of size, condition, or growth in overall survivorship.

Why is OMR Management Controversial?

The OMR Flow Management Action is controversial for three related reasons. First, it curtails the amount of water pumped south, limiting the CVP’s and SWP’s ability to deliver water to their contractors. Second, there is disagreement about how effective OMR restrictions on exports are at delivering ecological benefits. Finally, there are ongoing debates about whether the thresholds for OMR export restrictions (Table 3-1) are well-grounded scientifically or are set in ways that match the environmental goals of the action.

Salvage as a Proxy

An underlying premise of OMR flow management is that the triggers (particularly salvage levels at the pumps) and the consequences of exceeding the triggers (limiting negative OMR flows) serve as proxies for fish species’ protection within the Bay-Delta.¹¹ The focus on salvage at the pumps arises from a mix of legal and practical reasons. The legal reason is that any act of capturing or killing a protected fish at the pumps is a take, as that term is defined by the federal and state ESAs. Those takes must be addressed by an incidental take statement or permit. The practical reason is that takes at the pumps are easy to see, quantify, and assign responsibility for, while undocumented takes elsewhere in the system are not. Therefore, it is relatively easy to develop clear operating rules based on at-pump salvage; it would be much more difficult to tie operational changes to estimates of Project-caused in-Delta mortality as a whole. Similarly, triggers such as exceeding certain values for turbidity and temperature are easy to monitor, and it is legally possible to use them as proxy measures of take.

Although tying rules to a simple and measurable metric has important benefits, it also creates potential problems. The most important problem arises if the things being measured are poor proxies for the overall level of take and the extent of other negative impacts caused by pumping. If, for example, project operations are creating hazardous conditions for fish well before those fish arrive at the pumps, then salvage levels again would be a poor proxy. Similarly, salvage levels may be a poor proxy of fish mortality if a high percentage of the salvaged fish survive capture and release (see Box 3-2). Modeling has suggested that Delta smelt behavior is much more complex than previously thought, such that single covariates like salinity or turbidity provide poor fits to abundance data and may not be good proxies (Gross et al., 2021a).

¹¹This is gleaned from the following statements about OMR in USBR (2024d) p. I-1: “Net flows in OMRs provide a surrogate for how exports influence hydrodynamics in the Delta...The management of exports for OMRs reverse flows, in combination with other environmental variables, can minimize or avoid adverse effects on the migration of fish and reduce or avoid entrainment at the export facilities.”

The poor-proxy problem could be persistent or arise temporarily and under particular flow and pumping conditions. In either circumstance, the problem is likely widespread, especially because at-pump salvage is probably a small percentage of overall take levels. Indeed, several papers agree that for salmon and steelhead, direct mortality at the pumps is not the primary mechanism of their decline. Estimates of direct mortality at the pumps for juvenile Chinook salmon that have been coded with wire tags are typically less than 1 percent (SST, 2017a). Another estimate of direct mortality at the pumps as a proportion of total migration mortality has been as high as 5.5 percent for winter-run Chinook salmon (SST, 2017a; Zeug and Cavallo, 2014).

Much of the controversy around OMR flow management arises from concerns that this poor-proxy problem is real and may pose significant costs to water users, the environment, or both. However, flawed proxies are often unavoidable in environmental management, and a weak proxy that is available and usable is often better in practice than a theoretically perfect proxy that would depend on nonexistent monitoring data. Adherence to the system of proxies suggests that three issues should be addressed: (1) whether the current suite of thresholds is reasonably grounded in current scientific knowledge; (2) whether improved scientific knowledge will lead to more accurate threshold *values*; and (3) whether improved scientific knowledge could enable development of new and better thresholds.

BOX 3-2 **Survivability of Salvaged Fish**

Survival rates after salvage for salmonids and smelt vary widely. Page 89 of the 2024 USFWS Biological Opinion (USFWS, 2024) says that “FWS estimates the loss of entrained smelt to be ‘essentially 100 percent’ because of several factors, including the limited efficacy of salvage.” The NMFS 2009 Biological Opinion (NMFS, 2009) anticipates that 10–30% of salvaged fish are lost to predators at the Delta release sites and that more die after release because of stress or injury associated with the handling process. Below is an abbreviated summary of the literature on this topic for salmonids, drawn largely and paraphrased from NMFS (2024, pp. 634–635).

During normal operations, salvaged fish are transported and released at one of two currently operational USBR release sites near the confluence of the Sacramento and San Joaquin rivers (Antioch Fish Release Site and Emmaton Fish Release Site). With the permission of CDWR, fish may also be released at any of four SWP-owned release sites. USBR transports salvaged fish to release sites with injected oxygen and 8 ppt salt solution to reduce stress. Upon arrival at release sites, operators measure water quality parameters such as dissolved oxygen, salinity, and temperature prior to releasing fish to verify that water quality parameters remained acceptable during fish transport. Salmon losses due to handling and trucking are generally low—assumed to be 2 percent for salmon smaller than 100 millimeters (mm) and 0 percent for salmon larger than 100 mm (Aasen, 2013). Fullard et al. (2018) estimated that the “survival of salvaged fish at Delta release sites is likely dependent on water temperature, seasonal predator and prey assemblage variability, diurnal behavioral changes, frequency of site-specific releases (e.g., number of releases per day), tides, river discharge, and total abundance of fish in each release.”

Miranda et al. (2010) conducted a release site predation study from 2007 to 2008, which concluded mortality of salvaged fish is due to predatory fishes remaining near the release sites when the number of fish being released is consistently high. In addition, salvaged fish were also vulnerable to bird predation when released during daylight hours. Overall, predation at release could have a substantial effect on salvaged fish survival. Estimates of post-release predation rates given by CDWR range from 10 to 30 percent for juvenile salmonids, depending on the density of predators at the release site and the number of fish released per episode (Earley et al., 2010; Orsi, 1967; Pickard et al., 1982). Estimates are crude and several potential biases in the earlier studies are present, including net sampling efficiency, susceptibility of predators to capture, and estimation of predator populations within the study area. Recent evidence obtained using acoustic imaging equipment (DIDSON cameras) has shown that predators are quickly attracted to the discharge pipelines upon the startup of the priming water flow, indicating a learned response to the discharge of salvaged fish at the release sites. Hammen et al. (2021) reported that altering the frequency from a salvage release every day (perhaps more predictable to local predatory fish) to a salvage release every fifth day did not reduce relative predation rates, but that relative predation rates were lower during dawn and dusk and with deeper water releases.

Are Export Reductions to Protect Fish Grounded in Reasonable Scientific Premises?

In the Committee's view, OMR flow management is reasonably consistent with current scientific understanding, but improvements in that understanding are possible and could lead to changed approaches to the action. The basic assumptions are that the listed fish are likely to be influenced, often negatively, by flow patterns; that those flow patterns are meaningfully affected by the pumps; and that take levels at the pumps are reasonable indicators of when fish are close to the pumps and therefore susceptible to pumping-related effects. Each element of that understanding makes sense. For species that move somewhat passively, such as Delta smelt, or that migrate downstream, such as juvenile salmonids, flow directions matter, and flows toward the pumps could divert species from better habitat areas or from pathways to the ocean. The pumps clearly influence flow patterns and material transport, although the magnitude and extent of that influence is not known with any great clarity (see later discussion of the zone of influence). In addition, levels of take at the pumps are possible indicators of when and where protected fish species are in the Delta.

However, there are also plausible reasons to question some of the scientific concepts underlying OMR flow management. The literature presented in Box 3-3 does not present unequivocal evidence that limiting exports benefits the listed fish species, for which there could be many explanations. The effects of pumping could be masked by the overwhelming influence of tides or high inflows. Perry et al. (2018) found that Chinook salmon survival was positively related to inflow in reaches that transitioned from bidirectional tidal flows to unidirectional flow with increasing inflows. Food web effects or predation could be much stronger controls than the effects of pumping-related flow changes, at least for some fish populations. Factors specific to fish size and run-timing, environmental conditions, and chosen migratory pathways could affect survival rates. For example, fish size was found to be a stronger indicator of ocean recovery rate than hydrologic variables (inflow, exports) for coded-wire-tagged fall-run Chinook salmon released in the Delta (SST, 2017a; Zeug and Cavallo, 2013). Finally, it is possible that takes at the pumps are actually poorly correlated with impacts elsewhere, either because takes at the pump occur well after impacts elsewhere evolve or because relationships between takes in one part of the Delta and impacts miles away are weak. The studies that could clearly elucidate these issues would involve comparing fish metrics in high-inflow years with pumping to fish metrics in high-inflow years without pumping, and in low-inflow years with pumping to low-inflow years without pumping.

BOX 3-3**Indirect Effects of Pumping on Fish in the Delta**

What is known about the indirect effects of pumping on flows and fish migration in Delta channels? The extent to which management actions such as limiting negative OMR flows affect salmonid survival and route selection in the Delta outside of the facilities has been subject to limited analysis (SST, 2017a,b). In 2015, the Delta Independent Science Board concluded that the exact mechanisms of how flows affect fishes is still poorly understood (DISB, 2015). The evidence for a negative effect of altered flows on fish survival is summarized below, followed by scientific studies that are equivocal about flow–survival relationships.

Studies showing a negative impact of pump-altered Delta flows on fish:

- Juvenile Chinook salmon may experience a diminished ability to navigate out of the south Delta because of confusing navigational cues from altered hydrology and water quality gradients, the highly altered channel network configuration, and impairments to sensory systems from contaminants (Windell et al., 2017).
- A negative correlation between water exports and survival probabilities has been demonstrated, although the mechanism is not well documented (Newman and Brandes, 2010).

continued

BOX 3-3 *continued*

- Juvenile outmigrants from the Sacramento River experience higher survival when riverine inflows are higher (Buchanan et al., 2018, 2021; Kjelson et al., 1982). Outmigrants from the Sacramento River experience lower survival when they route through the central and south Delta instead of remaining in the mainstem Sacramento River (Brandes and McLain, 2001; Newman and Brandes, 2010).
- Out-migration survival of salmonid smolts in riverine waterways increases with increasing flow for Chinook salmon and steelhead from both the Sacramento (Henderson et al., 2019; Michel et al., 2021; Notch et al., 2020) and San Joaquin (Buchanan et al., 2018, 2021) river basins.
- Delta inflow, tidal flows, and diversions influence outmigrating steelhead route selection by altering hydrodynamics around channel junctions along the lower San Joaquin River (Anchor QEA, 2022). These changes in flows can attract fish entering the Delta out of the San Joaquin River (with low-moderate survival) into the interior Delta (with extremely low survival) and pumping facilities (with low-moderate survival).
- All fish migrating from the San Joaquin basin (including threatened California Central Valley steelhead and SJRRP Central Valley spring-run Chinook salmon) necessarily transit the South Delta. In a study of loss of coded-wire-tagged release groups at the export facilities, Zeug and Cavallo (2014) found that the relative loss of San Joaquin River releases was “more than double that of Sacramento River releases at both facilities [...] although relative loss was less than 5% for most releases; this value ranged as high as 17.5%.”

Studies showing contradictory or confounding evidence:

- Since longfin smelt can spawn farther seaward than previously thought, entrainment from the SWP and CVP pumps does not appear to have a substantial effect on the population (Gross et al., 2022).
- In tidally reversing channels of the interior Delta, many covariates (e.g., Delta inflow, exports, routing, predation) may affect the survival of salmonids and the evidence for a relationship with flow is more equivocal (Buchanan et al., 2018, 2021; Buchanan and Skalski, 2020). Studies are hampered by correlation between environmental covariates, complicated routing, little experimental control, and (for Chinook salmon) overall low survival.
- The Salmon Technical Working Group (2024) states that “after many years of intensive scientific investigation, we have not observed significant survival improvements for San Joaquin River-origin salmonids, nor have we seen an adverse impact from water export rates on survival under the range of regulatory and environmental conditions studied (e.g., OMR flow no more negative than -5,000 cfs).”
- Some study results seem to be Project-dependent. For example, Buchanan et al. (2021) found that the direction of effect on steelhead survival from the head of Old River to Chipps Island was positive for CVP exports but negative for SWP exports or combined SWP and CVP exports. However, in Buchanan and Skalski (2020), a similar analysis on Chinook salmon survival found a positive direction of effect on Chinook survival from the head of Old River to Chipps Island (again, within the range of variation beyond regulatory constraints) for both a CVP export term and a combined SWP and CVP export term.

No experiments have tested dramatically lower pumping levels in non-extreme-drought conditions to see how the system responds because conducting such studies would limit water deliveries. Absent such information it is difficult to know the strength of relationships between pumping levels, at-pump takes, overall levels of take, and adverse modification of critical habitat. Sommer et al. (2020) and Grimaldo et al. (2021) have suggested that OMR flow management might not be the critical factor in the health of the listed fish species. Since 2002, through-Delta survival¹² rates for juvenile salmon have been

¹² Through-Delta survival is generally the percentage of fish entering the Delta that then exit the Delta over a given time frame. What specific geographic location constitutes “Delta entry” depends on the study and the source

consistently low and seemingly independent of variations in both export rates and Delta inflows (SST, 2017a, STWG, 2024), despite the implementation of actions specifically intended to reduce through-Delta mortality (SST, 2017a). Cavallo et al. (2015) also noted that it would be very difficult to influence route selection along the lower San Joaquin River by managing SWP and CVP exports. It could be that survival rates in the South Delta are so low that any protection afforded by an OMR flow restriction of greater than -5,000 cfs will likely be undetectable until background survival rates improve (SST, 2017a,b, 2024). In summary, although the assumptions underlying OMR flow management may make sense, available scientific research is mixed in its conclusions and contains important gaps.

OMR MONITORING AND MODELING

Unlike in Chapter 2 where the Committee observed gaps in monitoring that, if addressed, would improve Shasta coldwater pool management, that is not the case for OMR flow management as currently practiced. So long as salvage, flow, and turbidity levels are the key triggers for action, monitoring to ensure compliance is straightforward and adequate. Nonetheless, the Committee encourages the OMR scientists and decision-makers to consider options beyond the use of salvage as a proxy and to resolve some of the unanswered questions about the effects of exports on fish populations as a whole. Doing so will require more comprehensive fish population monitoring across the Delta.

The models used for OMR flow management have been developed over decades and are adequate for current operations. Because the Committee's suggestions for improving those models are not specific to the OMR action, they appear in Chapter 5. After a brief description (and a comprehensive table) of the relevant models, this chapter outlines a combined monitoring and modeling strategy that could advance OMR management. This holistic OMR monitoring and modeling strategy is based on the USBR's recent zone of influence analysis combined with more comprehensive population estimates for all the listed fish species and their various life stages. The modeling part of the strategy—to be able to simulate the hydrologic zone of influence of the pumps—will require the further development of Delta Simulation Model II (DSM2) or an existing multidimensional model. The hope is that the combination of a reinvigorated zone of influence modeling exercise with new fish population monitoring data will advance OMR flow management beyond the reliance on salvage metrics and reveal critical underlying relationships on how exports affect fish.

Monitoring

The OMR Flow Management Action is supported by multiple monitoring networks in the Delta and in the upper Sacramento and San Joaquin rivers, too numerous to discuss individually. Indeed, USBR (2022) lists 35 separate data streams that could potentially support this action. In the 2023 Seasonal Report for OMR Flow Management (USBR, 2023), 44 fish monitoring sampling locations/data sets are listed in Figure 10 as being used for OMR flow management. To prioritize and highlight the most important networks, Mahardja and Pien (2024) grouped these data into three broad categories (that correspond to triggers and thresholds shown in Table 3-1). First, data that informs the *onset of the OMR season* include flow and turbidity measurements (as surrogates for Delta smelt) and data on longfin smelt. Second, data used to *control exports* during the OMR season include (1) turbidity, flow, water temperature and Secchi depth, along with the presence and location of fish for smelt and (2) weekly and cumulative loss measured as salvage for salmonids. The data used to develop JPEs for the salmonids would also be considered critical to OMR flow management. Third, data used to *offramp the OMR action*

population/migratory pathway (different for Sacramento River fish vs. San Joaquin fish vs. Mokelumne River fish). “Delta exit” also varies but is typically considered to be at entry to the bay, however, it often ends up effectively being where the fish are measured either by trawl or tag. See Perry et al. (2010) and Buchanan et al. (2018).

in June include water temperature and flow. Although salvage monitoring of fish at the pumps is designed to directly inform OMR flow management, the other monitoring for fish in the Delta and monitoring of surrogates for fish presence (e.g., temperature, Secchi depth, and turbidity) use networks designed for other purposes.

Two main questions stem from this brief description of the monitoring programs that feed into OMR flow management. First, are the data that are needed for comparison with thresholds available? The answer to this question is yes. Second, should the existing focus on exceeding thresholds, many of which are determined by an estimate (like the JPE), be augmented by other monitoring that more directly assesses fish presence and population abundance in the system? The use of OMR thresholds is a reasonable approach, but there are reasons to believe that OMR flow management could be based on more scientifically robust metrics, starting with the development of a more tailored set of fish-population monitoring systems at locations across the Delta and its tributaries. Having absolute measurements of fish abundance by year and potentially by different life-history stages and consequently in different parts of the system would advance the science. With better fish data throughout the Delta, combined with salvage data, one would have a better chance of elucidating the proportion of the population that salvaged fish represent. Delta-wide fish data might also suggest alternative proxies beyond salvage. Finally, Delta-wide fish data are central to the Committee's suggestion for a new, more holistic strategy for OMR monitoring and modeling. As discussed below, an array of relatively new monitoring techniques would make that broader monitoring network possible.

Direct Assessment of Abundance and Distribution of Fish

Improvements could be made in the detection of fish in the Delta prior to reaching the pumps. Current smelt data are gathered from the Enhanced Delta Smelt Monitoring (EDSM), the Fall Midwater Trawl, the Smelt Larval Survey, and the 20-mm surveys (see Appendix D for a full description of these surveys)—large-scale programs designed to look at the overall distribution of fish and interannual variability in relative fish abundance. The net surveys provide an abundance index at monthly intervals and do not provide measures of absolute abundances because catchability is unknown, particularly for pelagic species and for daytime sampling.

Salmonid data used to compare to thresholds come from a variety of sources including the Sacramento regional Beach Seines, lower Sacramento rotary screw trap (RST), Sacramento trawls, Chipps Island trawls, and Mossdale Kodiak trawl. Additional monitoring for Chinook occurs via salvage data from the Tracy and Skinner Fish Facilities and via seasonal fish assemblage trawls and the Delta Juvenile Fish Monitoring Program (DJFMP) (including the Sacramento, Mossdale, and Chipps Island trawls and beach seines that monitor Sacramento River salmonids migrating to the Delta, through the Delta, and exiting the Delta to assist with resource management).

Fish tagging is a standard approach to assess fish abundances (e.g., numbers of fish per unit volume or surface area), mortality, growth, and movement. Common tags include the classical fin clip, Floy tags, PIT (Passive Integrated Transponder), and coded-wire tags.¹³ These types of tags can be considered point-to-point tags since data (e.g., fish species, size, location) are only collected at the beginning and end points of fish handling. Tags are retrieved when tagged fish are caught during commercial or recreational fishing or active sampling. Population abundances can be assessed through a number of mark-recapture or multiple mark-recapture methods (e.g., Cormack, 1964; Jolly, 1965).

Acoustic tagging of individual fish is a more sophisticated approach to track movements of individual fishes. Acoustic tags are largely implanted into a fish (or attached to its outside) and transmit an acoustic signal that is unique to the individual fish and is detected by a fixed receiver. The receivers have a range on the order of a few hundred meters. Generally, the receivers are in a fixed location and

¹³ A coded wire tag is a tiny magnetic numbered tag and is usually injected into the nose of the fish.
<https://www.nmt.us/cwt/>

monitor fish within a particular volume of water over time. The information received can be converted to fish densities and sizes through sophisticated analyses. Tracking fish using acoustic tags and stationary receiving arrays has been used widely in the Delta for two decades, as evidenced by many studies tagging juvenile salmon and steelhead (Buchanan, 2019a,b,c, 2021; Buchanan and Skalski, 2020; Clark et al., 2009; Perry et al., 2010, 2018) and dozens of examples of Chinook salmon tagging as part of the Central Valley Enhanced Acoustic Tagging Project¹⁴. The sensor locations have been chosen to help estimate the number of fish entering and exiting the Delta, fish distribution within the Delta, and when fish are at risk of being entrained into the South Delta. For example, the fixed array in place to detect winter-run Chinook salmon that have been acoustically tagged at the Livingston Stone National Fish Hatchery include the Butte City Bridge array (halfway between Redding and Sacramento), Tower Bridge array (in downtown Sacramento), and Benicia Bridge array (just east of Suisun Bay). At least 16 sensor locations have been used to detect acoustically tagged San Joaquin River salmonids including Mossdale and other release sites along the river, Chipps Island (to determine exit from the Delta), and 12 sensor locations in between (Buchanan et al., 2018).

Although the use of acoustic tags can be limited by the size of the tag relative to the size of the fish, acoustic tagging of fish down to 30-80 mm size is now possible (Liss et al., 2019, 2021). An unexplored possibility is the extension of the array of fixed stations to track acoustic-tagged hatchery-origin Delta smelt, although their small size, especially at the juvenile life stage, could make this challenging. Nonetheless, this has been contemplated in other systems.¹⁵

Active Acoustic Assessment. Active acoustics involves the transmission of a continuous series of sound pulses into the water through a transducer, which also receives the echoes bounced off of the fish. Those echoes contain information on depth (or range) of the fish from the transducer and can be used to assess fish density, size, and swimming speed through sophisticated analyses and use of specialized equipment such as a split-beam transducer. Such echo sounding can be applied through the use of mobile acoustics whereby the transducer is towed across the surface of the water or through stationary or fixed transducers. Quantitative acoustic techniques cannot identify the species of fish directly and therefore require alternative means to help identify the fish, such as midwater trawling. Mobile acoustics directly measure the fine scale distributions and absolute densities of fishes under the transducer and are best applied where larger areas must be covered in a relatively short period of time. Population assessment is one such common application of mobile acoustics (e.g., Higgs et al., 2025; Rudstam et al., 2009)¹⁶. Assessment of habitat, fish preferences, and fishery availability are other common applications of mobile acoustical methods (Abukawa et al., 2013; Jones et al., 2021; Trenkel et al., 2011; Winfield et al., 2015). Although acoustic stock assessments can be more challenging in shallower systems, they have been successfully applied in small shallow lakes (Unger and Brandt, 1989) and large estuaries (e.g., Boswell et al., 2007) as well as the San Joaquin River to assess abundances of salmon smolt predators (Cutter et al., 2017).

Fixed location echo sounding is best used to monitoring densities and distributions of fish within a specific volume of water through time. Depending on the sensor locations, such arrays can reveal movement of fish into, through, and out of the Delta as well as movement into at-risk locations and/or flow junctions. Fixed acoustic arrays could be used to continuously monitor fish abundances to get a baseline relative to entrainment. These data can be used to not only gain a more accurate understanding of fish response to complex channel flows but also to validate particle tracking models (Appendix B5 in SST, 2017).

¹⁴ See <https://oceanview.pfeg.noaa.gov/CalFishTrack/index.html>.

¹⁵ See <https://www.smithsonianmag.com/innovation/a-new-generation-of-tiny-tracking-tags-offers-a-fresh-look-at-the-lives-of-little-fish-180987011/>.

¹⁶ See <https://acousticsunpacked.echoview.com/acoustics/AcousticsUnpacked.asp>.

In addition, in the last decade, CDFW has also been using imaging acoustic technology (e.g., the DIDSON) that consists of extremely high frequency, rapid pulse acoustics with limited range on the order of tens of meters that provide enough echoes so that individual fish might be identifiable.¹⁷

Genetic Assessment. Salvage monitoring for both the CVP and SWP is moving toward being able to distinguish between natural and hatchery-produced fish by including more genetic testing of a subset of salvaged fish to confirm that they are in fact winter-run Chinook salmon (USBR, 2023; Whitman et al., 2024). Close-kin mark-recapture methods may also prove valuable in assessing abundance and other demographic parameters of species by use of genetic tags from inherited genes (Sévêque et al., 2025; Waples and Feutry, 2021). Genetic-based methods are advancing quickly and should at least be given some consideration because a virtual census of the population can sometimes be derived. Other genetic-based methods include parental-based tagging, classic mixed-stock evaluation, and genetic assignment of individuals to a population of origin.

These methods were originally focused on species that had passed through some reproductive bottleneck and thus they relied on the use of the narrower genetic makeup of the population to provide insights. Genetic assessment has since greatly expanded (Casas and Saborido-Rey, 2023). Samples may be taken with a simple fin clip and can be applied to a broad range of species. A major consideration is sample size which is typically proportional to the square root of the true population size (Casa and Saobrido-Rey, 2023, citing Bravington, 2014). Because the extant natural populations of Delta smelt, or even winter run, are likely small, the genetic sample sizes needed to support such studies should not be overwhelming.

Image and Video Analysis. Another quickly growing automated method for determining fish abundance and observing fish behavior is image and video analysis (Nalmpanti et al., 2023; NASEM, 2015). This method can be coupled with other methods specifically for species identification, but it is also extremely useful for monitoring behavior in and around dams and pump intakes and for assessing gear avoidance while conducting surveys. For example, a video device stationed near a population to be trawl sampled can assess the degree of avoidance by fish of the sampling gear (Fréon et al., 1993; Nunnallee, 1991). Feyrer et al. (2013) used an underwater video camera codend in a trawled net to observe that Delta smelt positioned themselves differently in the water column during flood tides compared to ebb tides, presumably to maintain a position in favorable habitats. Wilson et al. (2015) found some success using video analysis when conducting fish abundance estimates in areas with high-density submersed aquatic vegetation. Mollenhauer et al. (2024) used video traps to monitor the imperiled Comanche Springs Pupfish (*Cyprinodon elegans*) using both point observations to get counts and time interval observations to get detectability. Video analysis could be challenging in the Delta in areas of high turbidity, although water clarity in general is increasing over time.

Improvements to the JPE Calculation

Assuming that a JPE will be determined for spring-run Chinook salmon and steelhead in the near future, improvements to the JPE method for winter-run Chinook salmon would be fruitful. Survival estimates are based in part on mark/recapture methods coupled with methods for assessing catches in traps. These methods have inherent assumptions (e.g., catchability, handling mortality) that should be explicitly stated. The JPE could be improved by using the more sophisticated estimation procedures proposed by O’Farrell et al. (2018) as described in Box 3-1. It is important to regularly update the “fixed” parameter estimates with the JPE such as $\hat{f}$, the forecast of the fry-to-smolt survival rate in fry equivalent units, and $\hat{s}_n$, the forecast of the smolt survival rate of natural-origin fish. Growth rate (or smolt size/condition) is not currently part of the JPE calculation, yet it should be considered an important

¹⁷ See <https://wildlife.ca.gov/Conservation/Fishes/Sturgeon/DIDSON>.

component of the JPE because size and condition do influence mortality rates. It will be critical to understand the uncertainty in the various estimates through error propagation using, for example, Monte Carlo methods as well as forecasting. The methods outlined above for assessing and tracking abundance, mortality, and movement will assist in this effort.

Modeling of OMR Flow Management

Although a variety of 1-D, 2-D, and 3-D numerical models have been used for Delta simulations, only a few numerical models are routinely used for OMR flow management. Some of these models are used for short-term operations (e.g., DSM-2), some are used for long-term planning and evaluations (e.g., the salmon life-cycle models), and some are used for both operations and long-term planning with appropriate simplifications (e.g., DSM-2 and CalSim3 with Artificial Neural Networks).

Use of DSM2 and Biological Models for Operations

A key model is DSM2 developed by CDWR (currently version 8.2.1), consisting of 1-D hydrodynamics (DSM2-HYDRO), water quality (DSM2-QUAL), and particle tracking (DSM2-PTM) models that can be applied for historical simulations and real-time forecasting, with suitable adaptations for long-term simulations. DSM2-HYDRO (DWR-DSM2, 2019) provides 1-D flow, velocity, depth, and water surface elevations and is the prime input for DSM2-QUAL and DSM2-PTM (Bogle, 1997; CA DWR, 2002; Kimmerer and Nobriga, 2008). DSM2-QUAL is a 1-D fate and transport model of conservative and non-conservative constituents. It simulates salinity, dissolved oxygen, temperature, and ecological parameters. DSM-PTM simulates the pseudo 3-D transport of (individual) neutrally buoyant particles in DSM2 flow fields, modified to include vertical and lateral velocity profiles. It considers the inert particles to be surrogates of eggs and larvae, which do not swim well.

For OMR purposes, DSM2-HYDRO and DSM2-QUAL are run weekly with a 21-day forecast period. A three-week run can be completed within minutes, with the first-week forecast being the most reliable. Based on model runs, combined with weather forecasts and anticipated operational changes, CDWR develops weekly flow and salinity distributions using their best judgment. At times, upon request, a DSM-PTM run is done with specific particle injection points.

For biological models, two winter-run Chinook salmon models that use weekly time steps are used regularly: (1) the Tillotson et al. (2022) regression forest model to predict the winter-run Chinook salmon distribution and natural Central Valley steelhead numbers at the salvage facilities, and (2) the Salvage Machine-Learning Tool that predicts salvage as a function of various environmental drivers. The former is being phased out in favor of the latter. The biological model STARS (Survival, Travel time, and Routing Simulation; Perry et al., 2019) was regularly used during the 2023 OMR season to evaluate effects on fish from changing the export rate (USBR, 2023). STARS was also used in the 2019 and 2024 biological opinions to evaluate alternatives. The other biological models listed in Table 3-2 have not been used routinely except for agency planning, development of new regulations (as was the case for the recent reconsultation), or special projects.

Use of CalSim3

Long-term planning involves many iterations covering dozens of scenarios, each requiring integration time over a long time period. DSM2 is too computationally demanding (~ several hours/iteration) for long-term planning, so the complex water accounting model CalSim3 is used. CalSim, developed by CDWR and USBR over the past three decades, has become fundamental to much Delta planning. It provides boundary conditions for high-resolution models of hydrodynamics, fish lifecycles, routing, and survival.

TABLE 3-2 Models Used in OMR Flow Management

Model Name	Description	Used in Operations	Used in Long-term Planning
<i>Hydrologic Models</i>			
CalSim3 Jointly developed by CDWR and USBR (Draper et al., 2004)	This water operations planning model for long-term operations (LTO) provides input to other CVP/SWP models. It simulates planning decisions using linear optimization and weights, within the general-purpose simulation environment Water Resources Integrated Modeling System developed by CDWR in 2000. CalSim3 simulates LTO for multi-year periods on a monthly time step, over a 100-year time period. Output from CalSim is used directly in many other models.		X
DSM2 DSM2-HYDRO, DSM2-QUAL DSM-PTM (CDWR, 2019)	DSM2-HYDRO is a 1-D hydrodynamic model for Delta water stages, flows and velocities. DSM2-QUAL employs the mathematical flow-salinity relationship model of Denton (1993) and Denton and Sullivan (1993). DSM2-HYDRO output is water stage, flow, and velocity. DSM2-QUAL simulates salinity, dissolved oxygen, temperature, trihalomethane formation potential, and ecological parameters. DSM2-PTM calculates pseudo-3D trajectories of individual neutrally buoyant particles.	X	X
ANN (Jayasundara et al., 2020)	This ANN is used as an alternative to direct CalSim3-DSM2 integration by training ANN using DSM2 salinity output. ANN output is salinity in monthly time steps.		X
Delta Island Consumptive Use Model (Mahadevan and Hutton, 1995)	The DICU model is used to develop channel-island interaction inputs to DSM2. It calculates monthly land-use-based consumptive use for 142 subareas within the Delta. An ANN used for OMR management, DICU has been replaced by the Delta Channel Depletion (DCD) model (Liang and Suits, 2018).		X
Delta Evapotranspiration of Applied Water (Kadir, 2006)	The DETAW model estimates daily consumptive water demands for 168 subareas within the Delta Service Area. It can be used for flow and salinity estimates in the Delta.		X
Delta Channel Depletion Model (CDWR, 2018)	An extension of DETAW that also considers subsurface water from Delta lowlands, groundwater from uplands, deep percolation, runoff, irrigation efficiency, and leach water. It estimates the actual daily Delta hydrology and channel depletions, including diversions, drainage, and seepage.		X
<i>Particle Tracking Models</i>			
DSM2-PTM (Bogle, 1997; CDWR, 2002; Kimmerer and Nobriga, 2008)	Simulates routing of pseudo 3D transport of [individual] neutrally buoyant particles in DSM2 flow fields, modified to include vertical and lateral velocity profiles. It provides a Lagrangian description of inert particles as a surrogate of eggs and larvae (with negligible physiology), with visualization capabilities. The PTM computes the location of an individual particle at any time step within a channel based on input from DSM-HYDRO.	X	X
ecoPTM (Ecological Particle Tracking Model) (Wang et al., 2024)	This enhanced PTM includes swimming behavior of simulated neutrally buoyant particles, including upstream or downstream movement, holding, and swimming velocity every 15 minutes. Behaviors parameterized by calibrating ecoPTM to observed travel time data through reaches in the Delta from acoustic telemetry studies on late fall–run smolts, Dec-Mar (2006–2014).		X

Model Name	Description	Used in Operations	Used in Long-term Planning
ePTM (Enhanced Particle Tracking Model) (Sridharan et al., 2023)	This model of juvenile salmonid migration through the Delta uses outputs of system scale hydrodynamic models and acoustically tagged late-fall-run Chinook data with plans to use fall-run data in the future. ePTM has been developed to improve the lifecycle model estimates for survival effects from Delta flows.		X
<i>Biological Models</i>			
STARS (Survival, Travel time, and Routing Simulation) (Perry et al., 2019)	STARS simulates travel time, routing, and survival of individuals in a daily cohort as they migrate through eight unique reaches of the Delta. A daily cohort is defined as all fish that enter the Delta on a given day at Freeport. The model calibrated to historic movement of acoustically tagged late-fall-run Chinook from 2007 to 2011. It was used regularly during the 2023 OMR season to evaluate the effects on fish of changes to the export rate. It was used in the 2019 and 2024 biological opinions to evaluate the alternatives.	X	X
Salvage Density Model (USBR, 2024d)	This models entrainment into the south Delta pumps as a linear function of export flows based on 2009-2022 salvage data, without considering spatial distribution of fish populations. This method can be used to compare the salvage index calculated from one alternative to another. It was used in the 2024 biological opinion to predict what month more salvage would occur in.		X
Delta Passage Model (Cavallo et al., 2011)	This model simulates migration and mortality of Chinook Salmon smolts entering the Delta from the Sacramento, Mokelumne, and San Joaquin rivers through a simplified Delta channel network and provides quantitative estimates of relative Chinook salmon smolt survival through the Delta to Chipps Island. It is based on releases of acoustically tagged Chinook salmon from 2007 to 2017. It uses a daily time step. DPM was used in the reconsultation to evaluate the alternatives.		X
Negative Binomial Salvage Model (USBR final EIS, 2024)	The model is used to predict daily average salvage of salmonids for each month from 1922 to 2021 by water year type using modeled exports (combined Jones and Banks pumping), San Joaquin River flow at Vernalis, and winter-run Sacramento trawl catch per unit effort (CPUE). Monthly historic values from water years 1993 to 2020 were used to generate an average monthly winter run CPUE chosen as representative of recent salvage patterns. It was used in 2024 biological opinion.		X
Winter-Run Chinook Salmon Coded Wire Tag Salvage Model (Cavallo et al., 2015)	This model estimates the fraction of juvenile winter-run Chinook salmon in the Delta predicted to be salvaged based on hydrologic conditions and fish size. It assumes the relationship developed with hatchery-origin winter-run Chinook salmon are applicable to natural-origin winter-run Chinook salmon. It was used in the reconsultation to compare alternatives.		X
Winter-Run Chinook Salmon Lifecycle Model (Hendrix et al., 2014, 2019)	This is a spatially and temporally explicit stage-structured simulation model that estimates the number of winter-run Chinook salmon at each geographic area and timestep for all stages of their life cycle.		X
CVPIA SIT Winter-Run Model (Peterson and Duarte, 2020)	This is the other major quantitative life-cycle model for winter-run and spring-run Chinook salmon, after the Hendrix model above.		X

Model Name	Description	Used in Operations	Used in Long-term Planning
FWS Delta Smelt Life-Cycle Model (LCMG) (Polansky et al., 2021, 2023)	This statistical state-space model was developed to assess past and future population status and predict the outcome of management actions to recover Delta smelt. It was fit to data collected from 1990 to 2015 from multiple long-term fish surveys in the upper San Francisco Estuary. It models reproduction and survival of Delta smelt as a function of ecosystem conditions since the 1990s. It is used to develop annual take limits, entrainment management strategies and supplementation strategies.		X
FWS Delta Smelt Life-Cycle Model with Entrainment (Smith et al., 2021)	This state-space life cycle model is finer resolution than LCMG and enables specific isolation of entrainment as a cause of mortality. It was originally fit to data from 1995 to 2015. It was used extensively in the 2024 USFWS Biological Opinion to determine the effects of OMR flow management on 4 non-overlapping Delta smelt life stages.		X
Maunder and Deriso model (MDR) (Maunder and Deriso, 2011)	This model is conceptually similar to the LCMG in that entrainment effects are indirectly accounted for through entrainment covariates rather than directly. USBR used the same abundance and covariate data in the MDR that Polansky et al. (2021) used in the LCMG. Like the LCMG, it was superseded by LCME in the USFWS 2024 Biological Opinion.		X
FWS Delta Smelt Individual-Based Model (Rose et al., 2013a,b)	This is an individual-based simulation model of Delta smelt processes of growth, survival, movement, and reproduction. It currently supports the Collaborative Adaptive Management Team's Structured Decision-Making Model, which evaluates Delta smelt management strategies. It was not used by USBR for the reconsultation.		X
Longfin Smelt Salvage OMR Relationship	This is a model of salvage at south Delta facilities as a function of flow based on historical salvage data. Following Grimaldo et al. (2009), the method uses data from 1993 to 2005, reflective of historically high periods of juvenile salvage at the CVP/SWP collection facilities.		X
Tillotson Model (Tillotson et al., 2022)	This is a hurdle quantile regression forest model that predicts winter-run Chinook salmon and natural Central Valley steelhead numbers at the salvage facilities one week in advance. It does not account for fish behavior in response to environmental conditions. This model was built to be a risk forecasting tool to inform adjustments of water export in the Delta based on real-time conditions. This is being replaced by the Salvage Machine-Learning Tool.	X	X
Salvage Machine-Learning Tool Jeremy Gaeta (CDFW), Trinh Nguyen (CDFW), and Brian Mahardja (USBR)	This model takes a machine learning approach (extreme gradient boosting dropout multiple additive regression trees) for winter-run Chinook salmon occurrence at the salvage facilities as a function of potential environmental drivers. It can incorporate daily flow data from the Sacramento and San Joaquin rivers as well as export-level values from the pumping facilities. It is an improvement of the Tillotson et al. (2022) model and is designed to predict winter-run Chinook salmon occurrence prior to any salvage. USBR did not use this model for evaluating OMR alternatives in the reconsultation.	X	X

Discussed in greater detail in Chapter 5 and Appendix D, CalSim3 inputs consist of surface hydrology, storage and conveyance capacities, water delivery quantities and priorities, and upstream flow releases. Its output consists of information on many parameters such as river, tributary, subsurface, urban, and agricultural flows; exports; storage and deliveries; water quality; power generation; fish salvage; and routing on monthly time scales. A typical CalSim3 run (which often has several internal cycles) may take 3–4 hours.

Because making many complex model runs with CalSim3 is computationally prohibitive for routine OMR management, modelers have been developing flow-parameter relationships (so-called parsimonious models) that can be integrated into CalSim3 to incorporate environmental factors and for faster execution. These parsimonious models often consist of artificial neural networks (ANNs) that predict salinities and other water quality parameters based on given export rates. The ANNs were trained with an ensemble of DSM2 or other high-resolution simulations to develop flow-parameter (e.g., salinity) relationships. Execution of parsimonious models occurs within CalSim3 such that within a given (monthly) time step, daily regulatory constraints are met (e.g., meeting standards in D-1641).

To this end, the ANN of Jayasundara et al. (2020) is currently used in CalSim3 to estimate salinity at four locations (Emmaton, Jersey Point, Collinsville, and Rock Slough) based on seven input variables, including water control gate operations, water exports, tidal stage and flow, and salinity boundaries. Recent variants of ANNs (not yet implemented in CalSim3) are those of Qi et al. (2021, 2022) that simultaneously predict salinity at twelve regulatory water quality monitoring stations (the first four plus Antioch, Mallard Island, Old River at Highway 4, Martinez, Middle River Intake, Victoria Intake, CVP Intake, and Clifton Court Forebay Intake) and the ANN of Namadi et al. (2023, 2025) that estimates ion constituents based on salinity at several intake locations. The Committee encourages continued development of these ANNs.

Other Numerical Models Used in OMR Flow Management

Although DSM2 is the primary hydrodynamic model for operational (real-time) decision making and CalSim3 is mostly used for long term planning, a host of other models are also used in various OMR management projects and planning depending on the context. Table 3-2 lists key models that have been applied for OMR flow management, either for operational or planning purposes, and describes their use.

Critique of Models Used in OMR Flow Management

Because the Delta's hydrologic and ecological systems are so complex, and because OMR decision making must occur daily to weekly through consensus, the development of modeling tools to support this process is imperative. DSM2 is considered a sound and robust platform that works well for high space-time resolution simulations and field data. It can be readily coupled with Delta water quality (DSM2-QUAL), particle tracking (DSM-PTM), channel depletion (DICU, DCD), and hydrologic models (e.g., Hutton et al., 2021) and can be extrapolated to estimate 2- and 3-D flow fields via reasonable approximations. As such, DSM2 appears to be a robust tool for simulating flow fields, salinity distributions, particle tracks, and other water quality parameter distributions for evaluating compliance and making routine water export decisions. CDWR has also developed algorithms to predict lateral and vertical flow profiles from DSM2 to enhance 3-D particle tracking. However, computational limitations of DSM2 render it less useful for longer-term planning, which involves evaluating multiple alternatives over longer timescales. DSM2 is also less well suited to some non-routine situations requiring more detailed 3-D flow fields and processes for some ecological and water quality applications, especially under conditions that vary from its current calibration (due to sea level rise, changed channel and island geometries, island flooding, and large operational changes).

Although CalSim3 is an important planning tool for OMR management, the Committee's suggestions for improving CalSim3 are not specific to OMR flow management and hence are discussed in Chapter 5. These suggestions address the needs for (1) better transparency to overcome the lack of version control that has created confusion over the years and (2) a smaller time step because the monthly resolution of CalSim3 is too coarse to capture biological effects.

One criticism of both DSM2 and CalSim3 specific to OMR flow management is the need to include representation of additional physical processes. Both CalSim3 and DSM2 lack turbidity and sediment transport capabilities, which precludes simulations that could be pertinent to turbidity bridge avoidance and requires the use of measured turbidities at specific locations for OMR management. Delta sediment/bed erosion models have been in development over past decades: for example, the Delta Simulation Model 2-General Transport Model (DSM2-GTM) for real-time operations; and long short-term memory (LSTM) artificial neural network suitable for CalSim3 based planning (Abrishamchi and Nam, 2019; Kim et al., 2022). Their operational or planning use to benefit OMR flow management await further development.

A More Holistic Strategy for OMR Monitoring and Modeling

OMR flow management is currently based on whether salvage and other chemical or physical thresholds are exceeded (see Table 3-1), and if they are exceeded, exports rates are reduced. If the action agencies choose to expand OMR flow management beyond using salvage as a proxy, then they will need a strategy to determine how to monitor the effects of OMR flow management on Delta-wide fish populations. This section describes such a strategy, which relies on more holistic thinking about the effects of project operations, updated and redesigned monitoring, and further model development.

An overarching strategy for OMR management could be based on the four simple questions below to better understand knowns and unknowns and to help set overall scientific/monitoring priorities:

1. What is the (geographic) zone of influence of operations related to entrainment and habitat conditions?
2. For any given fish population, what proportion of that population is influenced by Delta pumping?
3. What are specific impacts to fishes in the zone of influence?
4. What are the consequences of these impacts to the full population?

Zone (or Sphere) of Influence of Water Exports

Pumping operations can affect fishes through direct entrainment or alteration of flows nearby and far afield. Flow patterns, in turn, can have first-order effects on habitat conditions important to fishes including water temperature, water depth and velocity, turbidity, temperature, dissolved oxygen, submersed aquatic vegetation (SAV), and food supply/food-web interactions. In addition, fish may relocate or migrate their habitats under sustained changes in flow conditions from water exports (Kimmerer, 2011). Understanding and predicting the zone of influence of the pumps remain a basic, understudied scientific question for OMR flow management. The following section refers to a *zone* because current modeling capabilities could further refine this area. Ideally, defining a 3-D *sphere* of influence would be the modeling goal, although this effort would be resource intensive. Existing 3-D models such as SCHISM and to a lesser extent UNTRIM (see Appendix D) could be evaluated for their ability to fulfill this requirement for a 3-D hydrodynamic model that could elucidate a sphere of influence of the pumps.

Given the complexity of flow, fish behavior, and fish-flow relationships, answering the zone of influence question requires a comprehensive modeling effort including application of a suitable Delta-

wide hydrodynamic model to map this region of significant flow modification for a variety of Delta inflow and outflow conditions, spanning dry to wet years, and under a range of pumping, gate, and barrier operations. USBR's Zone of Influence (ZOI) analysis (USBR, 2024e), which uses DSM-HYDRO, maps changes in water velocity and is a start that could be built on, as described in Box 3-4. These types of models have been used in other large ecosystems (DeMutsert et al., 2016; Maicu et al., 2018; Zhang et al., 2023). Once influence on flow is determined, the impact on fish and other habitat conditions could be explored using behavioral particle tracking approaches, water quality models, or other surrogates for movement, mortality, and habitat utilization.

BOX 3-4

USBR Zone of Influence Analysis: Description and Recommendations for Further Study

The relative effects of SWP and CVP exports on flows in the Delta are greatest in channels located near the water export facilities and decreases with distance both upstream and downstream (Castillo et al., 2012; Salmonid Scoping Team, 2017a,b). Hence, USBR initiated a project to evaluate the spatial extent of hydrodynamic alteration caused by pumping, described as the Delta export zone of influence (ZOI; USBR, 2024e), with the goal of mapping ZOI more precisely as a function of the OMRI.

The analysis used DMS2-HYDRO to estimate changes in the probability distributions of hourly average velocity at various nodes in the Delta from changing operations (pumping rates). At a given node, two velocity distributions (kernel density estimate) were generated: one under an export that coincides with a given OMRI value like -5000 cfs and one with zero export. If the overlap of the two distributions is 70% or less, then the export was considered to have had an effect, from which ZOI was estimated. An example is shown in Figure 3-5 with contour lines corresponding to where overlap between the export and no-export scenarios was less than 70%.^a Four export scenarios were tested that correspond to the following OMRI: -2,000, -3,500, -5,000, and more negative than -5,000 cfs. In addition to different export rates, nine combinations of inflows are considered in the analysis, hence the nine graphs.

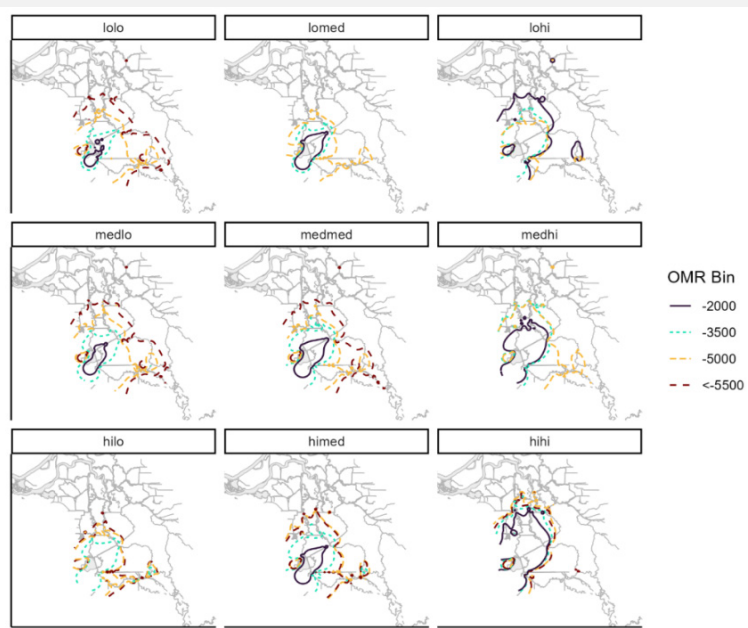


FIGURE 3-5 Results from the ZOI analysis for the case of Preferred Alternative 2 version 2 of the proposed action. NOTE: “hilo” means that inflow from the Sacramento River was high and that inflow from the San Joaquin River was low.

SOURCE: USBR (2024e).

continued

BOX 3-4 *continued*

The maps illustrate the spatial extent of changes to velocity throughout the Delta. The results suggest that ZOI depends highly on inflows from the Sacramento (SR) and the San Joaquin (SJR) rivers. Some qualitative results, such as those for low SR and SJR inflows (lo lo) and those for high SR and SJR inflows (hi hi), were expected (Josh Israel, USBR, personal communication, 2025), while others were less intuitive. Even for the highest negative OMRIs, the contours and ZOI velocity effects appear to be limited to the south Delta and do not reach Frank's Tract.

The Delta is a complex hydraulic basin with networks of highly engineered canals, diversions, water export pumps, sloughs and open water connected distinct water sources from the SR, SJR, agricultural drainage (particularly from SJR basin), and the San Francisco Estuary (SFE). Variability of natural and managed hydrologic inputs, tidal forcing from the SFE (the most prominent source), turbulence contributed by canal and channel junctions, and engineered operations (e.g., water exports through pumping in south Delta and diversions) determine the local hydraulic pathways. These, in turn, drive mixing of distinct water masses and hence the spatial distribution of water quality (e.g., salinity, temperature, dissolved oxygen, minerals) that impacts ecosystem health.

Although water operations (e.g., pumps, gates) are localized, their effects can have Delta-wide consequences. Disturbances in shallow flows (e.g., due to pumps) propagate at the shallow-flow wave speed that is on the order of 10 m/s for the Delta (Sridharan et al., 2018). Therefore, a change of pumping rate at the Banks pump (SWP) is felt at Clifton Court Forebay 4 kilometers (km) away in 1 minute, and at the head of the Old River or at the north intake of OMR/SJR junction (25–30 km) in about 40–50 minutes. These disturbances may produce disproportionate responses during their travel through the channel network by producing local amplification or suppression in channels, which, in turn may produce water velocity, quality and fish responses that are difficult to determine by simple calculations. Numerical models could help in this regard, for example, DSM-QUAL to understand water quality and DSM-PTM/Eco-PTM to understand both non-swimming and swimming species.

USBR's ZOI analysis estimated changes in the probability distribution function of hourly averaged velocity as well as the proportion of channel lengths influenced by a change of Delta exports. The expectation was that larger exports, which should correspond to more negative OMR flows (cfs), would have larger ZOIs (or longer channel length of influence), but this was not always the case. In some cases, larger OMR flows produced shorter lengths of influence and vice versa. Although coarse space-time resolution and model deficiencies are partly to blame, it is also possible that the investigations omitted other governing parameters.

The ZOI can depend on multiple parameters, volumetric export rate (Q_{EX}) being only one of them. Several inflows supply the pumps, for example, Old River and Middle River flows and direct supply from the SJR to Clifton Court via Great Line Canal. The (reverse) Old River and Middle River flows, in turn, are supplied from the north by both the SJR and SR (via north-south Mokelumne River supplying SR water to the SJR). Numerical results from the TRIM3D hydrodynamic model (Delta TRIM) based on inputs from the SJR, the SR, and tidal exchange show that flows in Delta channels are drastically dependent on a myriad of factors (Monsen et al., 2007). When pumping rates are high, the Old and Middle rivers become the major north-south freshwater corridor of SR-derived water from the northern entrance (near the location of former Mildred Island). During curtailed pumping, the structure of water routing also changes: Old River flow becomes SR-derived whereas Middle River inflow becomes SJR-derived, the latter being drawn in from a channel in the southeast corner of Mildred Island. This points to the importance of the relative roles of the SR (Q_{SR}) and the SJR (Q_{SJR}) suitably averaged volumetric rate inputs to the Delta in determining the ZOI, in addition to exports (Q_{EX}). To the first order, the apportionment of SR and SJR water to the Old and Middle rivers can be considered a function of the dimensionless flow ratios Q_{EX}/Q_{SJR} and Q_{EX}/Q_{SR} . So, the change of flow structure at the headwaters of Old River and Middle River and the ZOI is expected to be determined by hydraulic adjustments in channel junctions, decided by the above two parameters.

It is important to separately consider ZOIs of water quality and fish passage impacts, because their responses depend on additional parameters pertinent to a complex mix of bio-chemo-physical processes. In Monsen et al. (2007), simulations show how the exports generate an extended (regional) response, wherein curtailment of pump exports generated a rapid salinity response at the northern Old River and Middle River inlets (25–30 km away) near Mildred Island. The salinity increase was due to increased share of the (more saline) SJR water distributed heterogeneously. To the north of Old River/Middle River junction, the flow is mainly tidal and hydraulic adjustments are relatively weaker, but salinity adjustments may extend well beyond the region of velocity adjustments because of changes in mixing. Adjustments of fish migration routes are anticipated to be more complex.

continued

BOX 3-4 continued

In summary, literature suggests that changes in water exports cause rapid hydraulic adjustment of (1) circulation, (2) channel flow distribution, and (3) composition of exported water masses as well as changing water quality and fish migration routes in the proximity of the pumps (i.e., in the ZOI). The ZOI as a function of OMRI and water exports (Q_{EX}) has been studied by USBR using DSM2-HYDRO (USBR, 2024e). Although the study noted interdependence between Q_{EX} , the OMRI, and the ZOI, no clear correlation between ZOI, OMRI, or pumping rate could be established. It is recommended that USBR use both Q_{EX}/Q_{SJR} and Q_{EX}/Q_{SR} (dimensionless flow rate ratios) as parameters to map ZOI correlations instead of using Q_{EX} alone.^b It should also be highlighted that ZOIs for water quality and fish passages may not coincide with the ZOI for hydraulics. In addition, ZOIs do not consider local effects of different space-time scales that may potentially have disproportionate effects on survival within the Delta, accounting of which requires consideration of factors such as tidal amplitude (relative to total flow), residence time, flow velocity, vorticity, barriers, predator densities, and habitat conditions. **Hence, a comprehensive study is warranted given the ZOI's importance in managing fish species and water quality. As a first step, in addition to 1-D hydrodynamics and water quality models, particle tracking models with and without fish behavior can be used. Such a study would be valuable for developing science-based guidelines for improved OMR flow management.**

^a 70% was chosen to be consistent with an exposure analysis in the 2024 NMFS Biological Opinion (NMFS, 2024, p. 88). “The frequency of exposure is categorized as high (very frequent; occurring in more than 75 percent of years), medium (moderately frequent; occurring in 25 to 75 percent of years), and low (infrequent; occurring in fewer than 25 percent of years).” Josh Israel, USBR, personal communication, 2025.

^b This follows from a straightforward similarity analysis that shows that ZOI (as defined, but simplified into one length scale based on the area of influence) can be expressed as $ZOI = \mathcal{L} \mathcal{F}(Q_{EX}/Q_{SJR}, Q_{EX}/Q_{SR})$, where $\mathcal{L}$ is a characteristic length scale for the channel network, which is a constant, and $\mathcal{F}$ is a function to be determined via hydrodynamic simulations or experimentation (which is impractical). $\mathcal{F}$ could be developed via simulations and the model ($ZOI = \mathcal{L} \mathcal{F}$) output could be validated using voluminous flow data available from CDWR and USGS monitoring sites.

A goal of the modeling would be to elucidate how changes in velocities affect habitat factors important to fish growth, survival, or reproductive rates. The environmental factors that directly affect fishes include salinity, temperature, dissolved oxygen concentrations, turbidity, and water velocity. Additional factors indirectly affect fishes through food web processes (e.g., nutrient concentrations, the presence and type of SAV, phytoplankton and zooplankton production, and predation consumption rate—DISB, 2024). Furthermore, there can be important second-order effects, because changes in flow, temperature, and turbidity can alter SAV, which could impact fish habitats and assemblages (Christman et al., 2023; Smits et al., 2025). In some cases, the relationships of these environmental factors to a fish's vital rates are well established or could be directly assessed using particle tracking models and biological models. The degree of influence on the fishes will vary by fish as well as spatially and temporally, and focused studies and research are needed to identify where and when the influence of the pumps is unduly impactful.

Proportion of the Fish Population Affected

For each fish species of interest, at any given time a proportion of that fish population is within the dynamic reach of the zone of influence and thus potentially affected by exports. This proportion is best estimated for the relevant life stage(s) of the fish and would vary throughout the year. Some populations may not reside in the zone of influence whereas some species may be more concentrated there seasonally. The primary science needed to do this would be to assess or model the species spatial distribution across the Delta and determine the proportion of the population within the zone of influence.

Current fish monitoring programs may provide an initial first-order assessment. More likely is that the quantitative measures of fish densities recommended previously, derived from the latest technologies (e.g., active acoustic assessment, genetic assessment, nocturnal aimed/instrumented midwater trawling; image and video analysis), will be needed to obtain high-resolution data for these analyses. Assessing the distribution of fish across the Delta is a significant endeavor that could happen incrementally, but will require a systematic change in the monitoring programs.

Defining Impact

Once the overlap of the species distribution with the regions being altered by operations are defined, specific impacts to fish must be assessed. The impact of entrainment is likely mortality, except for fishes that are salvaged, captured, and released (see Box 3-2). Entrainment is directly measured in the field or modelled with particle-tracking models run in the context of a 3-D hydrodynamic model (e.g., Gross et al., 2022).

Defining impacts to fish will require understanding the sphere of influence of pumping on salinity, water temperature, dissolved oxygen, turbidity, water velocity, SAV abundance, and food web processes (e.g., predator distributions, predator feeding rates, zooplankton production), because these are the factors that directly affect fishes' vital rates. For example, temperature is a key driving force affecting fish growth and feeding rates. If pumping changes water temperatures in a region, then the impact of those temperature changes on individual growth rates can be assessed through bioenergetic modeling (Deslauriers et al., 2017; Hartman and Brandt, 2011; Rose et al., 2013) or direct assessments. Spatially and temporally explicit bioenergetic models can be further developed by linking the models to hydrodynamic models as has been done in the Delta and elsewhere (e.g., DeMutsert et al., 2018; Rose et al., 2013; Zhang et al., 2023).

In general, how exports change habitat conditions and how those changing conditions affect fish is complicated to assess, but ripe for scientific inquiry. Habitat suitability indices for many of the key species have been developed (e.g., Smith and Nobriga, 2023), and those indices define some of the key habitat characteristics of fish related to water quality, but they often do not define the functional relationship between habitat change and fish growth, survival, or movements. This is a fundamental area where detailed science synthesis can better define the knowns, unknowns, and assumptions and where experimentation is useful.

Population Level Changes

The final step of the holistic strategy is to determine the consequences of these impacts at the population level. Once the impacts on the portion of the population within the zone of influence have been assessed, the impact on overall population growth, mortality, distribution, and reproductive success can be estimated, if we assume that fish movement in and out of this zone is minimal for the time period of the assessment. These types of analyses have been done for assessing proportional entrainment (e.g., Kimmerer, 2008; Miller, 2011). Needed science includes a life cycle/population dynamics model that can simulate population responses to processes occurring at different rates in different portions of the population. Indeed, as described in Appendix E, quantitative life-cycle models and bioenergetics models exist for some of the listed species; whether they are spatially explicit enough to assess the variable impacts brought about by OMR flow management (see DISB, 2015), or have the needed functional relations among habitats and fish vital rates, is unclear. Understanding fish movements into and out of the zone of influence will be critical to these analyses.

In summary, moving beyond the comparison of salvage data to thresholds that currently characterizes OMR flow management will require a commitment to higher resolution, expanded domain, and multi-parameter integrated modeling to fully assess the Delta-wide impacts of exports on hydrodynamics, water quality, and ultimately fish. Above we outline a first-order approach for defining the impacts of operations on individual species. Mapping the pumps' zone of influence on fish will necessitate evaluating the suitability of currently deployed 1-D hydrodynamic models; invoking 2-D and 3-D models if required; developing model chains that calculate fish/ecosystem response to governing variables through an integrated succession of suitable models; and validating models, to the extent possible, using available Delta flow and fish population and routing data.

ADDITIONAL SCIENCE TOPICS

Biological Relevance of the Triggers and Their Associated Export Reductions

The impacts of pumping on the listed species can be direct through entrainment or indirect through flow-driven changes in habitat factors (e.g., temperature, turbidity, water velocity, transport) or food webs that affect individuals and ultimately populations. These impacts have been operationalized in OMR flow management as a complex set of triggers that, if exceeded, lead to reductions in exports during the OMR season. Presumably, each of these many triggers and their associated reductions in the pumping rate are based on current scientific understanding of the relevant processes at work. However, if so, this information is not catalogued in any easily identifiable source, making it difficult for the Committee to assess the underlying science.

Some notable thresholds are not based on reliable, reproducible science. For example, the salvage threshold for steelhead is currently based on comparing salvage data to historically salvaged steelhead (the threshold being the highest observed salvage value for the time period 2010–2018). Although there is a stated desire to transition to the use of a JPE as the steelhead threshold, which would rightly be based on some percentage of the estimated steelhead population in the Delta, this transition may be years from fruition. A second and more complex example is the reduction in exports to achieve an OMRI greater than -5,000 cfs when specific thresholds are crossed—a value which the Committee was informed was based on an observed bend in Delta smelt salvage data at OMR flows greater than -5,000 cfs from Grimaldo et al. (2009). Having reviewed that publication, the Committee does not agree with certainty that the -5,000 cfs export rate represents some type of “break” below which fish entrainment becomes more severe. In addition, research is warranted to better understand the relative effects of the required OMR flows found in Table 3-1 on fish survivability in the Delta. For example, does a OMRI of -2,000 cfs compared to -5,000 cfs result in better survivability (via a reduction in salvage) and is this offset by flow-related factors that could reduce survivability, such as an increase in residence time in the Delta? More robust development of the zones of influence analysis (Box 3-4) combined with particle tracking models could be used to refine these values and better elucidate fish routing in the Delta.

As long as the OMR Flow Management Action is based primarily on the exceedance of thresholds to downregulate pumping levels, USBR and CDWR are encouraged to make the scientific basis of the thresholds and the corresponding pumping rates available to the scientific community, and to conduct further studies to provide more certainty around the use of those values.

Could Changing the Delta Infrastructure Help the Ecosystem?

OMR flow restrictions are intended to reduce impacts to native fish populations caused by pumping. Water export users often maintain that environmental flow regulations, particularly OMR flow regulations, significantly reduce water export volumes. The long-term average economic value of water exports will likely increase in the future, especially with the Sustainable Groundwater Management Act

ending roughly 2 million acre-ft (MAF)/year in southern Central Valley groundwater overdraft as a source of irrigation water. The effects of OMR regulation on water export reduction vary greatly seasonally and from year to year, but are substantial on average (CRS, 2015; Gartrell et al., 2017, 2022)—implying lost revenues and economic productivity with a substantial capitalized value. It might be economically and ecologically desirable to consider whether and how modifying the Delta’s channels and gates might reduce the reliance on flow restrictions for fish protection.

It may be possible to modify Delta pumping intake structures, forebays, channels, and gates and their operations, to reduce pumping’s interference with the larger Delta ecosystem. The tides dominate internal Delta flows most of each year, such that fish movement is primarily controlled by tidally driven advection and dispersion (Brown et al., 2024). Ways to dampen the tidal dispersion of fish into the Delta and reduce some environmental impacts of pumping, by modifying Delta channels, forebays, fish screens, and tidal gates and how they work with tidal flows and harmonics, could be explored.

Recent decades have seen great improvements in modeling hydrodynamics, salinity, and water quality operations in the Delta, particularly from several 3-D hydrodynamic and water quality models, including SCHISM and UnTRIM. The particle tracking capabilities of these models improve our understanding of and abilities to model fish and food movements and behavior and to hypothesize and test ideas about fish behavior and management. New approaches to guiding and preventing fish from entering junctions are also being tried in parts of the Delta (such as Georgiana Slough) and elsewhere in the world (Sager et al., 1987).

Combining this understanding of flows, tides, and Delta ecosystems with these new analytical tools should enable exploration and evaluation of a wider range of new Delta ecosystem management solutions, especially when combined with traditional solutions such as improved rearing habitat. Such solutions could involve small local improvements, but could also involve grander schemes to move and configure channels, pumping operations, and forebays to be less harmful for the Delta’s native species while improving in-Delta and export water quality. First, Clifton Court Forebay lacks a fish screen on its intake. Second, USBR could consider building a separate forebay for the CVP, CDWR could improve the SWP forebay, or they could design a joint forebay on a flooded island. Altering forebays might enable the agencies to run the pumps more reliably. The effect would be to draw water from the Mildred Island area or further afield and reduce the pumps’ zone of influence. The hydrodynamics (and other implications) of such infrastructure modifications could be explored through modeling, similar to the study of fish entrainment risk in the forebays of dams (e.g., Williston Reservoir, Li et al., 2024) and the study related to pump inflow regimes with forebays (Lv et al., 2025).

Climate Change and OMR Flow Management

Of the changes in climate affecting the Bay-Delta, rising temperature, drought, and potential changes in the flood regime have both direct and indirect implications for OMR flow management. A short summary of relevant changes is provided below, with more details provided in Chapter 5 and Appendix A.

Climate Changes Most Relevant to OMR Management

Climate change is projected to pose challenges to OMR management. By mid-century, the Bay-Delta region is expected to see four to ten times more extreme heat days annually, with average air temperatures rising 2.0–3.5°C (3.6–6.3°F) and water temperatures increasing by up to 5°C (9°F), threatening native aquatic species (CDWR, 2024c; Cloern et al., 2022; Ficklin et al., 2013; Vroom, 2017). The region will likely face more intense storms, longer droughts, and greater winter precipitation, and sea-level rise will increase saltwater intrusion, potentially reducing freshwater supplies and export capabilities (Dettinger, 2016; Schwarz et al., 2020; Swain et al., 2018).

These climate-driven changes in temperature, precipitation, and sea level are also projected to impact Delta water supply reliability. CDWR analyses (Figure 3-6) indicate that changes in climate could reduce combined CVP and SWP Delta exports by approximately 11 percent (500,000 acre-ft/year) compared to the 1981–2010 levels (Schwarz et al., 2018). The 2023 State Water Project Delivery Capability Report (CDWR, 2024d) estimates that, without adaptation, climate change and sea level rise could reduce SWP Table A deliveries by 13 to 22 percent by 2043, depending on scenario assumptions for temperature, precipitation, and sea level rise. Sea level rise—about 1 foot (30 centimeters [cm]) by 2050—could decrease water exports by 10 percent annually (CDWR, 2016).

To understand the effect of these changing climate dynamics on OMR flows, CDWR performed a climate sensitivity analysis of OMR flows. This modeling effort found that climate change will be the primary driver of future OMR flow changes. CalSim3 modeling suggests that long-term average OMR flows will be slightly less negative compared to the current climate, as shown in Table 3-3 below. It also shows that flows will be an average of 10 percent less negative during the months of July to November, for all water year types (CDWR, 2024c). This suggests a slight improvement in OMR flow rates.

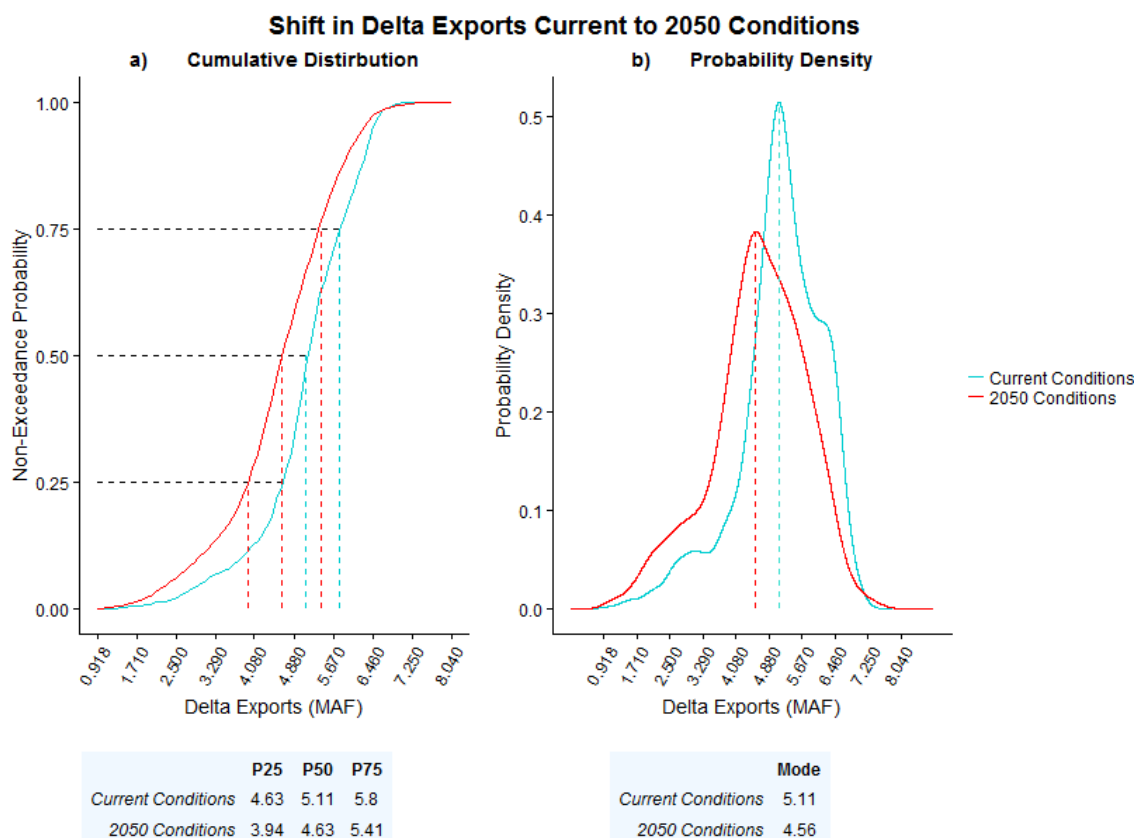


FIGURE 3-6 Shift in annual Delta exports, current to mid-century conditions.
SOURCE: Schwarz et al. (2018).

The above estimates, including Figure 3-6 and Table 3-3, should be interpreted with caution. Most current models assume both static bathymetry and inundation, but sea level rise will alter channel depths and inundated areas. Increased channel depths can worsen salinity intrusion and may require greater outflow to maintain salinity control, reducing exports and tidal velocities, but sedimentation—especially in wet years—may offset some deepening. Furthermore, future dredging practices are

uncertain. The spatial pattern of inundation, such as flooding specific islands, can either worsen or improve salinity, depending on location. Additionally, Delta channels tend to self-adjust, with increased depth potentially reducing velocities and increasing sedimentation—feedbacks that are not fully captured in most models. Improved, dynamic modeling that accounts for these factors is needed for more reliable projections of salinity intrusion and water supply reliability under future climate scenarios.

TABLE 3-3 Baseline OMR Flows Under Current and Future Climate

Water Year Type	OMR Flows under Current Climate and Operations	OMR Flows under Future Climate and Operations
Wet	-5,017 cfs	-4,744 cfs
Above Normal	-5,395 cfs	-5,137 cfs
Below Normal	-5,283 cfs	-5,015 cfs
Dry	-4,539 cfs	-4,312 cfs
Critically Dry	-2,958 cfs	-2,951 cfs

SOURCE: CDWR (2024c).

A number of specific components or metrics of OMR flow management are either directly or indirectly affected by the changes described above. They are organized below by certain climate impact drivers (see Chapter 5 for a full description of these drivers).

Droughts and Extreme Precipitation. The severity of both extreme precipitation and droughts are expected to increase in the future, which could alter the conditions that are controlling exports at any given time. Dry year conditions that often feature D-1641 as the primary control on exports will likely become more prominent as reduced freshwater inflows lead to elevated salinity levels. More extreme precipitation events in the winter and spring could mean that the San Joaquin River will flood more frequently, relaxing OMR constraints or allowing for maximum pumping, which could further complicating export management. These dynamic conditions could have significant implications for the distribution and survival of both native and invasive species in the Delta.

Average Annual and Seasonal Temperature. Warmer water temperatures could potentially make the listed fish more sensitive to OMR reverse flows than they are at present. The seasonal onset and duration of warmer temperatures could have direct effects on biological rates and timing of activities such as spawning. Generally, Delta smelt spawn optimally at temperatures between 15–20°C (59–68°F) (Brown et al., 2013). As temperatures increase, Delta smelt will require more food to survive. By 25°C (77°F), water temperatures are lethal (Bennett, 2005). In addition, the off-ramping of the OMR action could shift earlier if water temperatures rise consistently in Clifton Court Forebay, Mossdale, or Prisoner’s Point, contracting the overall OMR season.

Seasonal Streamflows and Average Annual and Seasonal Temperature. The OMRI is based on a water balance that accounts for the inputs, outputs, and changes in storage within a defined hydrologic system. A critical component of this balance is evapotranspiration (ET). However, accurately estimating ET remains challenging, particularly under dynamic and changing climatic conditions. Traditional ET estimation methods used in models such as the OMRI often rely on empirical relationships or static parameters that may not fully capture the nonlinear responses of vegetation and soil moisture to increasing temperatures, elevated atmospheric demand, and shifts in precipitation patterns. As a result, these models may systematically underestimate ET, particularly under increased aridity or during extreme heat events. Furthermore, as streamflow becomes more sensitive to ET changes under warming scenarios, even small errors in ET estimation can lead to large discrepancies in projected flow regimes. This situation creates a compounding risk: inaccurate representation of ET not only affects water availability

estimates but also undermines the ability of the OMRI and similar tools to assess ecological health, water allocations, and system reliability under future conditions. ET estimation may need to evolve to use more physically based, dynamic methods, including those that leverage remote sensing (Zhang et al., 2016), energy balance models (Rahman and Zhang, 2019), or machine learning approaches that can adjust to evolving climate and land cover conditions (Chia et al., 2020).

OMR management that relies on historical hydrologic and fish migration information may become increasingly inadequate under climate change. OMR flow targets are set based on analysis of historical data and are intended to protect species such as Delta smelt during key life cycle periods. However, climate-driven shifts in precipitation, snowmelt timing, air and water temperatures, and estuarine salinity gradients are altering hydrologic and ecological processes across the Delta. As a result, OMR flow criteria based on fixed seasonal windows or past fish patterns may fail to provide effective protection under future conditions. For example, warming winter temperatures can lead to earlier runoff and changes in flow pulse timing, which may decouple fish migration cues from protective OMR flow actions. Similarly, increased water temperatures and altered salinity dynamics can shift the spatial and temporal distribution of sensitive species, rendering historically derived flow targets misaligned with current habitat needs. Under current operations and management, the combination of future drought conditions and increased incidence of water temperatures above 20°C (68°F) could reduce the feasibility and efficacy of OMR management actions to limit impacts on listed fish species.

The OMR Flow Management Action can better incorporate climate change through the development of indicators that signal when conditions have shifted enough to necessitate a change in management (e.g., if water temperatures increase by a set number of degrees, then the model that simulates daily fish migration is deemed no longer valid). This approach suggests relying more heavily on recent trends and less on historical records. Long-term planning based on the OMRI may need to better represent plausible future changes in the components of the water balance such as evapotranspiration, or at a minimum conduct climate sensitivity testing of the OMRI components.

CONCLUSIONS AND RECOMMENDATIONS

USBR asked the Committee to consider the state of the science of OMR flow management and to recommend ways to improve monitoring and modeling in order to better understand the impacts of the action on fish. One motivation for this request was the central role of OMR flow management in trying to meet the co-equal goals of water delivery and species protection in the Delta. Another motivation was the continued decline of the listed fish species in the recent decade, despite export restrictions. The following conclusions and recommendations address these concerns.

Conclusion 3-1: Current OMR management practices are grounded on a reasonable understanding of existing science, even though salvage is a limited and contested proxy for impacts to fish.

The basic assumptions underlying OMR are that (1) pumping causes adverse effects on protected fish species, not just at the pumps but farther afield in the Delta; (2) the level of take at the pumps is a reasonable proxy for overall levels of impact to protected species; and (3) maintaining certain flow rates in Old and Middle rivers is a reasonable way to reduce those adverse impacts. There are other plausible drivers of impacts on the listed fish, including invasive species, temperature effects, predation, and food web issues (which are themselves modulated by exports). Nonetheless, based on currently existing information, and on the absence of an obvious alternative, identifying controls on pumping levels as important to species protection is reasonable.

Recommendation 3-1: The underlying scientific bases of the thresholds and corresponding export reductions used in OMR flow management should be made available so that their use can be appropriately reviewed.

Although it did not thoroughly analyze each threshold value, the Committee noted examples of thresholds that are not scientifically defensible. More thorough use of validated hydrodynamic models and particle tracking models could help defend or refine these values.

Recommendation 3-2: Improvements are needed for the JPE.

Survival estimates are based on fixed survival rates and methods for assessing catches in traps that have inherent assumptions (e.g. catchability, handling mortality) that should be explicitly stated. The JPE could be further improved by using more sophisticated estimation procedures, regularly updating the fixed parameter estimates, and understanding estimation uncertainty through the use of the methods of O'Farrell et al. (2018) and others.

Recommendation 3-3: To move OMR flow management beyond the use of salvage as a proxy for impacts on fish in the Delta, the monitoring and modeling in support of the action should evolve to address the following four questions: (1) What is the zone (or sphere) of influence of operations? (2) For any given fish population, what proportion of that population is under that influence? (3) What is the impact to fishes in these regions? (4) What are the consequences of these impacts at the full population level?

Several recommendations fall out of adherence to this strategy.

- a. Fish spatial distribution and abundance throughout the Delta should be better assessed, which is not possible with the currently employed fish monitoring networks based on netting. The use of a combination of the latest technologies (e.g., underwater acoustics using both fixed and moving sensors, nocturnal aimed/instrumented midwater trawling) at higher temporal and spatial resolution would lead to better detection of fish at time and space scales more appropriate to OMR operations.
- b. Expanded modeling efforts should build upon the USBR's zone of influence analysis to study changes in key factors such as temperature, SAV, salinity, and other water quality conditions across regions under a variety of Delta flow conditions, spanning dry to wet years, and under a range of pumping rates, expressed in terms of dimensionless flow ratios (see Box 3-4) including those that can account for local effects.
- c. Ultimately, higher resolution, expanded domain, and multi-parameter integrated modeling is required for full assessment of the Delta-wide impacts of exports on hydrodynamics, water quality, and fish. This will necessitate simulating fish response to governing variables through an integrated succession of suitable models. New approaches to link 3-D hydrodynamic models to fish vital rates have been used in other large ecosystems (DISB, 2015) to better assess the spatial complexities of interactions and define the most sensitive drivers and should be considered here.

Recommendation 3-4: Improvements in Delta channels, forebays, infrastructure, and operations might help to reduce Delta-wide native fish losses and should be studied for their potential to reduce ecological impacts of pumping.

Hydrodynamic models could help USBR and CDWR explore opportunities to both dampen tidal dispersion and reduce the pumps' zone of influence via more effective Delta channels, forebays, fish screens, and tidal gates. USBR could assess the effects of building a separate forebay for the CVP;

CDWR could assess ways to improve SWP forebay management; or the agencies could explore a joint forebay such as a flooded island.

Recommendation 3-5: The OMR Flow Management Action should evolve to better anticipate changing climate impact drivers.

One means of doing this is to develop indicators that signal when climate conditions have shifted enough to necessitate a change in management (e.g., if water temperatures increase by a set number of degrees, the model that simulates daily fish migration is deemed no longer valid). Long-term planning based on the OMRI may need to better represent plausible changes in the components of the water balance such as evapotranspiration, or at a minimum conduct climate sensitivity testing of OMRI components.

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4

Summer/Fall Habitat Action

The Committee's statement of task calls for assessing the state of science for the Summer-Fall Habitat Action (SFHA) and providing recommendations about ways to change, improve, or replace modeling, monitoring, and decision-support tools to more accurately assess the impacts of the SFHA. To that end, this chapter describes the components and evolution of the SFHA; describes the monitoring and modeling that support the action; outlines the structured decision-making process and decision support tools that have been used to govern implementation of the actions; highlights key science and engineering challenges of the action; and makes relevant conclusions and recommendations.

The ecological disruptions experienced by Delta smelt and other native fishes of the Delta and Central Valley have been extreme, especially in the summer and early fall, such that a management effort focusing on enhancing Delta smelt summer-fall habitat is scientifically reasonable. The SFHA attempts to address a variety of factors impacting habitat suitability and ultimately Delta smelt through manipulations of flow to influence salinity and food availability. The chapter concludes that the greatest uncertainty about the SFHA stems from the inability to detect a response to the action in fish populations because of their small numbers. Several targeted lines of research, including the development of a process-based Delta smelt model, could accelerate better implementation of the SFHA and increase understanding of the effectiveness of various SFHA components.

DESCRIPTION OF THE DELTA SMELT SUMMER-FALL HABITAT ACTION

The Delta smelt is a small, short-lived fish endemic to the upper Sacramento - San Joaquin Delta. It was considered an abundant species, until it started to decline in the early 1980s (Moyle et al., 1992). Now, Delta smelt are extremely rare (zero caught in most catch indices in recent years; USBR, 2024, Figures 9-1 and 9-2) and listed as endangered under the California Endangered Species Act (CESA) and threatened under the federal Endangered Species Act (ESA). Delta smelt life history is described briefly in Box 4-1, with a more in-depth exploration provided in Appendix E.

The overall goal of the SFHA is to improve the growth, survival, and recruitment (i.e., fitness) of Delta smelt within Suisun Bay by improving critical habitat and food availability through coordinated water flow management actions aimed at mitigating human-driven habitat modifications (CDWR and USBR, 2023). The action focuses on the summer and fall seasons, because multiple lines of evidence indicate that decreases in habitat suitable for juvenile and subadult Delta smelt during this window have resulted in these life stages becoming a bottleneck for Delta smelt (Moyle et al., 2016; Smith et al., 2021; USBR, 2023; Woo, 2024).

In its current form, the SFHA consists of three primary components: (1) management of the location of the 2 parts per thousand (ppt) bottom salinity isohaline in the fall (Fall X2) and thereby the areal extent of the low salinity conditions that are considered to favor Delta smelt; (2) operation of the Suisun Marsh Salinity Control Gates (SMSCG) to adjust salinity in Suisun Marsh (and secondarily in Grizzly Bay) and possible food provision in the summer; and (3) an additional supplemental release of 100,000 acre feet (100 TAF) of freshwater. In the past, the mix of specific components comprising the SFHA has varied. Components of the SFHA have been identified by the U.S Fish and Wildlife Service (USFWS) as a "reasonable and prudent action[s]" (i.e., necessary or appropriate to minimize the impacts of the incidental take on the species) or within the U.S. Bureau of Reclamation's (USBR's) Proposed Action for long-term operations of the Central Valley Project (CVP) for more than a decade. Figure 4-1

shows key SFHA locations within the San Francisco Bay Estuary, including Suisun Bay, the Suisun Marsh Salinity Control Gate, and the Delta.

BOX 4-1 **Delta Smelt Life History and Stages**

The Delta smelt (*Hypomesus transpacificus*) is a small (60–70 millimeter [mm]), translucent fish in the family Osmeridae. Delta smelt are endemic to the Sacramento–San Joaquin Delta, where they were historically found from the San Pablo Bay upstream into the Central Valley. They are adapted to a broad range of environmental conditions and use a wide variety of Delta habitats to complete their different life stages (reviewed in USBR, 2024). However, the conditions of the Delta ecosystem have been altered to such a degree that Delta smelt are no longer detected in routine monitoring surveys. They may be, locally, functionally extinct,^a meaning that a few individuals may still be living, but the species is no longer able to produce healthy offspring because of low numbers and is no longer playing a significant role in the ecosystem (e.g., Jørgensen, 2002). In 1991, the USFWS proposed to list the Delta smelt under the ESA as threatened with proposed critical habitat; the threatened listing occurred in 1993 (USFWS, 1993) and designated critical habitat listing for the species occurred in 1994 (USFWS, 1994). From 2004 until the present, the Delta smelt’s status has been reviewed multiple times. The species is now listed as endangered under CESA but still threatened under the ESA.

The Delta smelt is primarily an annual species that completes its life cycle in one year, beginning in approximately March to the following March, a window that varies by one to two months (Moyle et al., 2016). The Delta smelt has been described as a semi-anadromous species that rely on a range of habitat types during different stages of their relatively short lifespan, including tidal freshwater habitats within the Delta and brackish low-salinity (1–6 psu^b) habitats, although studies have also identified two additional life-history phenotypes: freshwater resident and brackish-water resident (Hobbs et al., 2019). Under the system’s current flow regime, the low-salinity zone occurs downstream of the confluence of the Sacramento and San Joaquin rivers. During the dry seasons (summer and fall, June to September/October), the location of the low salinity zone and its overall size are strongly influenced by the Delta outflow (e.g., Dege and Brown, 2004). The zone has been changing in areal magnitude and physical characteristics (e.g., turbidity, salinity, food quantity and/or quality, and temperature) in ways that appear to be detrimental to Delta smelt (USBR, 2024).

Historically, most Delta smelt spawning was believed to occur in upstream freshwater areas that are tidally influenced backwater sloughs and low-velocity channel edgewater. However, Hobbs (2010) suggests that the range of life histories includes freshwater spawning/freshwater rearing, freshwater spawning/brackish rearing, and brackish spawning/brackish rearing with multiple variations in the specific timing. The eggs are adhesive and are believed to be batch-released over firm substrates or sand. The adult fish generally migrate upstream to spawn in the winter, following the first flush of turbid freshwater from precipitation.

Delta smelt are primarily planktivores, feeding on small, free-floating (pelagic) crustaceans and also sporadically on insect larvae and even larval fish. Traditionally, the main prey of Delta smelt was a copepod (*Eurytemora affinis*) that was likely introduced from the mid- to late-19th century, as well as cladocerans and mysid shrimp (*Neomysis mercedis*; reviewed in USBR, 2023).

^a <https://www.watereducation.org/western-water/delta-smelt-all-gone-wild-first-ever-hatch-and-release-effort-aims-save-them>

^b One psu (practical salinity unit) is generally considered equal to 1 ppt or 1 gram per kilogram (g/kg) of salt.

The SFHA aims to improve habitat conditions and food supply for Delta smelt by maintaining more low-salinity habitat in Suisun Marsh and Grizzly Bay when water temperatures are suitable, managing the low-salinity zone to overlap with turbid water and available food supplies, and establishing contiguous low-salinity habitat from the Cache Slough Complex to Suisun Bay. The target biotic and abiotic criteria to create Delta smelt habitat that maximizes recruitment include (Brown et al., 2014):

- low salinity (0–6 ppt)
- low temperature ($< 24^{\circ}\text{C}$ [75.2°F]; although recent evidence suggests $< 20^{\circ}\text{C}$ [68°F]; Lewis et al., 2021)
- turbidity of at least 12 NTU
- high food availability in open water habitats

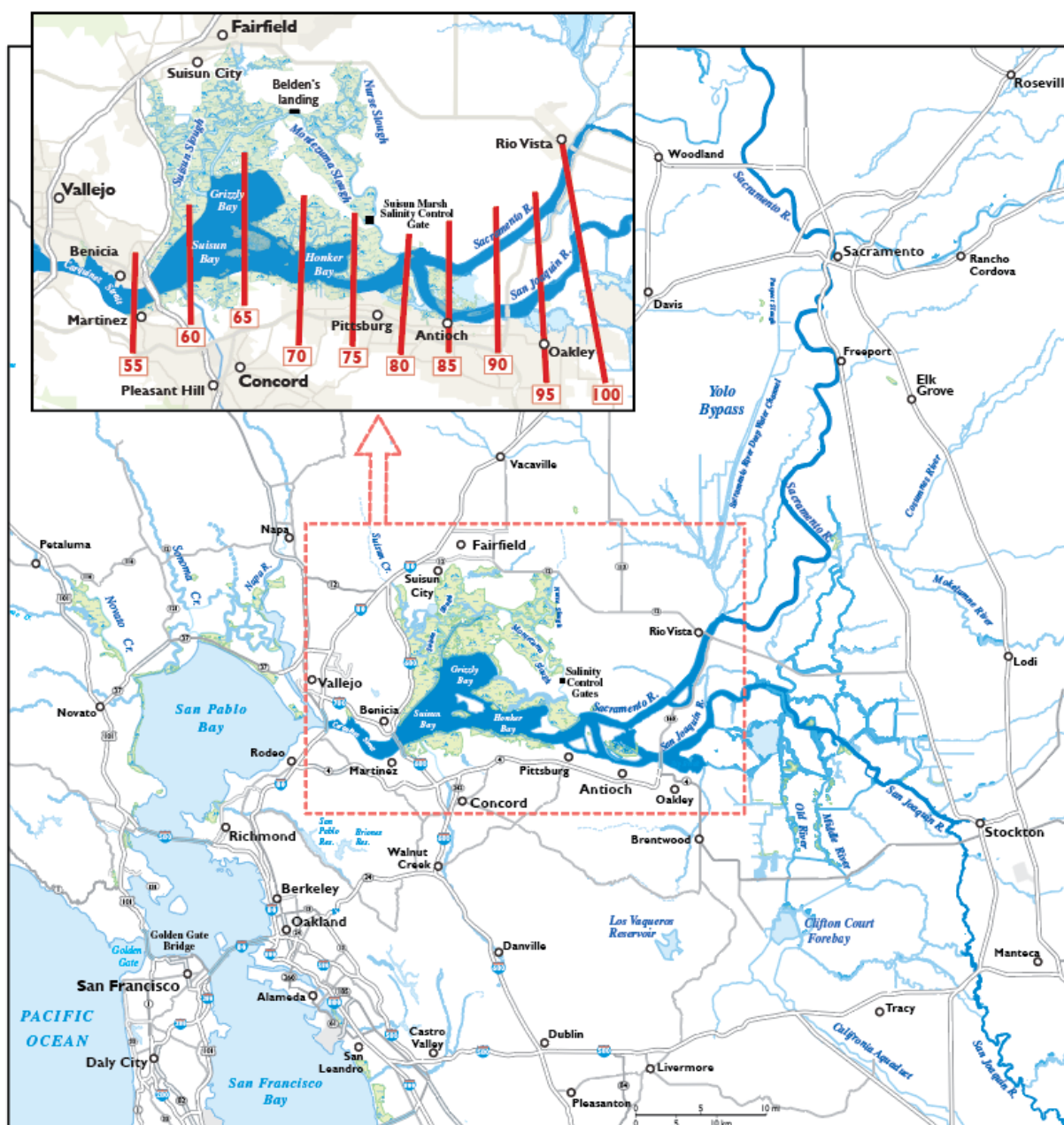


FIGURE 4-1 San Francisco Bay Estuary highlighting Suisun Bay and the Delta.

NOTES: The boxed area is the primary focus of the SFHA. The inset shows the distance in kilometers from the Golden Gate Bridge, which is used to measure the position of X2 (2 ppt bottom salinity isohaline).

SOURCE: Kevin Lear, International Mapping Associates.

Overall, the objective of the SFHA is to increase the spatial and temporal overlap of the distribution of Delta smelt with the low salinity zone and high-quality habitat including turbidity and available food. Because the highest quality habitat in the Bay-Delta are areas with complex bathymetry, in deep channels close to shoals and shallows, and in proximity to extensive tidal or freshwater marshlands and other wetlands (Bever et al., 2016; CDWR and USBR, 2023; Hammock et al., 2019), Suisun Bay and Marsh are the key focal areas of this action.

Rationale for the Action

The rationale for the SFHA's design is that managing flows can help maintain adequate physical habitat while simultaneously ameliorating potential food limitation for Delta smelt. In trying to address the many factors affecting habitat suitability and the Delta smelt, this action takes an ecosystem-based approach (e.g., Link, 2002). The SFHA is supported conceptually by the match-mismatch hypothesis, which was originally developed specifically for larval (first-feeding) fish stages and has a firm grounding in fisheries science. For over a century, fishery scientists have attempted to predict populations of future year classes of fishes, largely for managing commercial fisheries (e.g., Ferreira et al., 2023; Hjort, 1914). Under this umbrella of recruitment theory, successful new populations are based on maximizing the overlap (match) between consumers and peaks in abundance of their prey, with a mismatch resulting in low new year-class populations. Several trophic levels can be involved (e.g., Kristiansen et al., 2011). Many of the fishes known to suffer from the match-mismatch hypothesis (e.g., cod, Kristiansen et al., 2011; herring, Ferreira et al., 2023) are those with life histories similar to Delta smelt or are similar to Delta smelt during their larval stages with a reliance on zooplankton, which prey on phytoplankton, which in turn can demonstrate large boom and bust cycles.

For the SFHA, it is not unreasonable to suggest a current mismatch in the geography and timing of Delta smelt and their food resources (e.g., zooplankton) and other key abiotic factors (e.g., turbidity), given the dramatic anthropogenic changes to the hydrology, habitats, and biology of the Bay-Delta ecosystem, and given the reliance of Delta smelt on pelagic zooplankton. As just one example of these changes, food limitation for Delta smelt has been strongly linked to the invasion of the overbite clam (*Potamocorbula amurensis*), as it greatly reduces biomass of phytoplankton and zooplankton nauplii (Kimmerer et al., 1994; Moyle et al., 2016), sequestering much of the remaining primary production from the pelagic to the benthic part of the food web (Cloern and Jassby, 2012; Durand, 2015).

The SFHA aims to provide suitable habitat in the summer and fall so that sufficient numbers of juvenile fish will grow and survive through the winter (thereby increasing their recruitment success) and then successfully spawn in the early spring. Because of the substantial and diverse alterations to the upper Sacramento River system and the Delta resulting from a century of land use change and water resources project development (see Appendix B), it is not surprising that a misalignment of optimal habitat conditions for sustaining Delta smelt (including food availability) and their preference for the low salinity zone during certain life stages. Although it is the goal of the SFHA to help mitigate some of those misalignments, the action is not designed or intended to restore pristine conditions. Rather, it is focused on what is thought to be one of the important bottlenecks (summer/fall food limitation) to Delta smelt survival. For this approach to be effective, there must not be other limiting factors that result in high mortality (e.g., predation or entrainment). Given the scale and complexity of the ecosystem and its natural variability, uncertainty remains regarding whether recruitment would actually increase because of the SFHA.

Components of the Action

The SFHA components included in the 2024 USFWS Biological Opinion (USFWS, 2024a, p. 133) and the 2024 California Department of Fish and Wildlife (CDFW) Incidental Take Permit (CDFW,

2024, p. 101) are summarized below, with key details captured in Box 4-2. Hence, implementation of the SFHA is a shared responsibility between the CVP and the State Water Project (SWP).

Fall X2

X2 is a metric developed to characterize the geographic distribution of fresh, brackish, and saline waters across the Delta and eastern San Francisco Bay (primarily Suisun and San Pablo bays). The numeric value of X2 identifies the location along the deep channel where the daily-averaged bottom salinity is 2 ppt, measured in kilometers (km) from the Golden Gate Bridge. X2's position varies over time, primarily in response to freshwater flow from the Delta over the preceding days to weeks. Higher freshwater flows shift X2 west or seaward (decreasing X2). Although X2 is presented as a distance (see the inset in Figure 4-1), its location determines the spatial extent (area, volume) of low salinity zone habitat, a critical seasonal habitat for juvenile Delta smelt in summer and fall as well as other biota.

The Fall X2 action calls for maintaining a 30-day average $X2 \leq 80$ km from September 1 through October 31 in wet and above normal water years. Achieving freshwater flows into Suisun Bay to sustain X2 at ≤ 80 km during this time period usually requires sustained additional upstream reservoir releases and/or reductions in CVP and SWP exports (on the order of 200 TAF for the period)¹.

The Fall X2 action has occurred five times—in 2011, 2017, 2019, 2023, and 2024. There is some evidence that the increase in freshwater discharge required for $X2 \leq 80$ km can result in increased fluxes of zooplankton from the Delta into Suisun Bay (e.g., Hassrick et al., 2023). Years with such flow augmentation (2017 and 2019) were shown to have higher total zooplankton abundance and altered community composition in Suisun Bay and Suisun Marsh compared to years without the flow augmentation (2018 and 2020) (Lee et al., 2023), suggesting that freshwater flows can influence foraging habitat and prey availability for Delta smelt.

Starting in 2025, the Fall X2 component is subject to reevaluation annually to biannually by technical teams according to the 2024 Biological Opinion Appendix 2: Proposed Action (USFWS, 2024b). This Appendix assigns action into “bins” depending on the frequency with which data regarding performance is to be assessed and considered. Indeed, the Fall X2 action was curtailed in October 2024. There is no specific expectation that the Fall X2 component of the action will continue in the future.

Suisun Marsh Salinity Control Gate Operation

Operation of the Suisun Marsh Salinity Control Gate is the second component of the SFHA and has some overlapping objectives with Fall X2, because both aim to expand low salinity habitat. A key difference is that the gate operation focuses on Suisun Marsh and seasonally re-establishes low salinity conditions in this area. This targeted freshening is achieved by operating flow control gates near the river confluence on Montezuma Slough to open the gates and allow freshwater to flow northwest directly into Suisun Marsh on the ebb tides and then close the gates on the flood tide to retain more freshwater in Suisun Marsh. The gate action has both low-salinity and food-supply objectives by creating the low-salinity habitat in the potentially food-rich Suisun Marsh (Colombano et al., 2021).

In above-normal and below-normal water years, and in dry years following wet or above-normal years, the Suisun Marsh Salinity Control Gate is operated for 60 days to maximize the number of days at Belden's Landing with 3-day average salinity ≤ 4 psu between June and October. In dry years following below-normal years, the gate is operated for 30 days to maximize the number of days at Belden's Landing with 3-day average salinity ≤ 6 psu between June and October. The Suisun Marsh Salinity Control Gate component of the SFHA has occurred four times, in 2018, 2023, 2024, and 2025.

¹ $4.3 \times 10^6 \text{ m}^3/\text{day}$ relative to $X2 @ 85 \text{ km}$ (Andrews et al., 2017) $\times 1 \text{ AF}/1233.5 \text{ m}^3 \times 60 \text{ days} = 209 \text{ TAF}$.

According to the 2024 USFWS Biological Opinion Appendix B: Proposed Action (USFWS, 2024b), the Suisun Marsh Salinity Control Gate component of the SFHA has been assigned to Bin 3.²

Supplemental Water Release of 100,000 Acre-Feet

For the 2025 water year only, the 2024 ITP allows for a third component of the SFHA: the supplemental release of 100,000 acre-feet (acre-ft) of additional freshwater to further enhance and enlarge the low salinity zone. This release is achieved by adjusting CVP releases and export rates from the Delta and can be implemented in conjunction with the Suisun Marsh Salinity Control Gate Operation or as an independent supplemental outflow. In water year 2025, the 100,000 acre-ft release of stored water may be released to supplement Delta outflow from June to September, but is subject to spill from the Oroville Reservoir, according to an agreed plan (CDFW, 2024, p. 101). 100,000 acre-ft of water is equivalent to increasing average Delta outflows by about 400 cubic feet per second (cfs) during this four-month period³. (This is a small change in the average Delta outflow and would be difficult to detect in the field.) It is unclear if the supplemental 100,000 acre-ft component will be part of the SFHA going forward.

Box 4-2 outlines the history of the SFHA as implemented over two decades, including how the suite of SFHA components has changed over time. Formerly, the SFHA included a North Delta Food Subsidies component that involved either diverting water from the Sacramento River to the Yolo Bypass or releasing pulses of agricultural runoff within the Yolo Bypass/Cache Slough region. The augmented flow pulses during low-flow months would ideally transport productive water from upstream to food-limited habitats downstream. Similarly, the SFHA also included a Sacramento Ship Channel Special Study, which considered whether pulses from the highly productive Sacramento Deep Water Channel might serve as a food subsidy for Delta smelt habitats downstream. With this latter approach, fertilizers could be applied to further stimulate production, and a pilot study assessed this potential in 2019 (Loken et al., 2022). Finally, the concept of using managed wetlands as a source of productivity for Delta smelt has also been considered as a potential component of the SFHA. However, these three elements were not included in the 2024 SFHA. Rather they are included as special studies as described in the 2024 USFWS Biological Opinion (USFWS, 2024a).

The alterations to habitat and flow that result from the SFHA, while aiming to benefit Delta smelt, may affect other fish species' use of habitat. The 2024 USFWS Biological Opinion evaluated the potential effects of the SFHA on several other species of concern (winter-run and spring-run Chinook salmon, steelhead, and green sturgeon). That evaluation identified straying or delayed migration as the primary potential stressors and estimated the magnitude of effect to be "low" (USFWS, 2024a). Similarly, CDWR (2023) discussed whether the redistribution of stored water to support the SFHA might affect stranding of juvenile spring-run Chinook salmon in the Feather River and egg mortality of winter-run Chinook salmon below Keswick Dam. Concern was expressed about the potential impact of ramping rates from release of 100 TAF from Oroville on spring-run Chinook salmon in the Feather River. However, there could also be benefits to imperiled juvenile fishes rearing in the area, such as more food and more suitable temperatures. Overall, the potential impacts of the SFHA on other fishes are generally assumed to be minor (USFWS, 2024a) and likely extremely difficult to detect.

² For items in Bin 3, evaluation and potential refinement occur less frequently, on the order of 10–15 years, and may inform the next ESA Section 7 consultation and development of a new ITP.

³ This is a unit conversion. 100,000 af = 50,000 cfs in one day. Average additional cfs outflow = 50,000/(4*30) = 416 cfs averaged over 4 months.

BOX 4-2**Recent Consideration of the Summer-Fall Habitat Action**

The concepts behind the SFHA developed over more than a decade, and details of these actions have evolved through various regulatory processes related to the CVP and SWP. Legal details about the biological opinions and incidental take permits cited below are provided in Appendix C.

2008 USFWS Biological Opinion (USFWS, 2008) on the coordinated operations of the CVP and SWP included a Reasonable and Prudent Alternative (RPA) to “improve fall habitat for Delta smelt through increasing Delta outflow during fall. Increase in fall habitat quality and quantity will both benefit Delta smelt.” Under the action, subject to adaptive management, USBR and CDWR were to provide, during September and October in years when the preceding precipitation and runoff period was wet or above normal, sufficient Delta outflow to maintain monthly average X2 at 74 km from the Golden Gate in wet water years and at 81 km in above-normal years. The rationale was that Fall X2 had a measurable correlation with recruitment of juveniles the following summer since the introduction of the overbite clam (*Potamocorbula amurensis*) around 1987 (Cloern and Jassby, 2012). Although a broad relationship between the Fall Midwater Trawl (FMWT) index, which indicates relative Delta smelt abundance (Appendix D), and turbidity and salinity had been established, the relationship was not strong or simple (NRC, 2010). When the action occurred in 2011, an increase in the FMWT index occurred when September–October X2 was at 75 km, near the objective of X2 at 74 km identified in the RPA.

2016 Delta Smelt Resiliency Strategy (CNRA, 2016) included an Outflow Augmentation action. Conceptual models suggested that seasonally augmented outflows could improve turbidity and hydrology to the benefit of Delta smelt. The strategy also identified North Delta Food Web Adaptive Management Projects, reoperation of the Suisun Marsh Salinity Control Gates, Roaring River Distribution System Food Production, and Coordination of Managed Wetland Flood and Drain Operations in Suisun Marsh as promising actions.

2019 USFWS Biological Opinion (USFWS, 2019) includes, as part of the proposed action, “Summer-Fall Delta Smelt Habitat.” USBR and CDWR proposed to operate the Suisun Marsh Salinity Control Gates in the summer and fall to create habitat for Delta smelt in Suisun Marsh, in combination with various actions to generate food from the Colusa Basin Drain, Roaring River Distribution System, and Sacramento Deepwater Ship Channel. In addition, in years when the infrastructure operation was unable to create sufficient habitat, USBR and CDWR would operate to maintain X2 at 80 km from the Golden Gate Bridge, a location considered key for possible low salinity habitat in Suisun Marsh. USBR also proposed a monthly average X2 of 80 km in September–October in above-normal and wet years as an operational backstop to provide a specific acreage of low salinity habitat.

2020 CDFW Incidental Take Permit (CDFW, 2020) for the long-term operation of the SWP also included a Delta smelt Summer-Fall Habitat Action. It requires that each year CDWR and USBR develop a Summer-Fall Action Plan that considers actions to improve key aspects of Delta smelt habitat including turbidity and food availability and facilitation of downstream transport of phytoplankton and zooplankton in the North Delta and Suisun Marsh. It requires the establishment of the Delta Coordination Group (DCG) and the use of Structured Decision Making (SDM).

2024 CDFW Incidental Take Permit (CDFW, 2024) calls for the annual development of a plan to implement and report on the SFHA for use in adaptive management. The SFHA spans June 1 to October 31. A 30-day average X2 $\leq$ 80 km is to be maintained from September 1 through October 31 in wet and above-normal years. The Suisun Marsh Salinity Control Gates will be operated to increase habitat and food access for Delta smelt in summer and fall (June through October) in Suisun Marsh and Grizzly Bay during above-normal and below-normal years, and dry years following wet or above-normal years. The duration of the operation and the target salinity are reduced in dry years. There is also a one-time water commitment of 100,000 acre-ft of water in year 2025 from Oroville.

2024 USFWS Biological Opinion (USFWS, 2024a) includes Fall X2 and operating the Suisun Marsh Salinity Control Gates. Monitoring plans are to be based on a schedule determined by the Adaptive Management Steering Committee. Food subsidy measures, including Managed Wetland reoperation in Suisun Marsh and the Sacramento Deepwater Ship Channel Food Subsidy Action, are considered Special Studies to the SFHA.

The Role of Hatchery Fish in the SFHA

The SFHA can benefit from the hatchery-raised Delta smelt supplemented into portions of the river systems; such “supplementation” has been ongoing for a few years for a variety of purposes. The need for supplementation stems from the extremely low densities (mostly zero) of Delta smelt in the data from multiple monitoring programs including the Enhanced Delta Smelt Monitoring (EDSM, see Appendix D). USFWS (2024a) referred to the original supplementation efforts as “experimental releases” for two reasons: (1) whether fish grown at the University of California (UC) Davis Fish Conservation and Culture Laboratory (FCCL) would survive when released into the wild was unknown, and (2) the numbers initially released were too small to be considered a full-fledged supplementation program. There is now a Delta Smelt Supplementation Strategy for supplementation that includes production, tagging, transport, and release of cultured adult fish into the wild. The goal is to ramp up production numbers over the next few years to reach 200,000 in water year 2026. USBR and CDWR also expressed an ongoing commitment to helping USFWS and CDFW continue to plan for the construction of facilities that could produce 400,000 to 500,000 Delta smelt by 2030. Notably, cage deployments and tethering of fish have been attempted as part of monitoring for the SFHA, but these techniques introduce problems with fouling, artificial surroundings, and lack of exposure to real-world factors such as predation (Baerwald et al., 2023; Enos et al., 2022) that constrain interpretations and are not considered further.

Why the Action Is Controversial

Economic Cost

The SFHA is considered controversial because it can be costly in terms of water released to the estuary that could have otherwise been exported or stored for later use (including environmental uses). With prices for agricultural uses south of the Delta of roughly \$300 per acre-foot, reductions of water exports of 100 TAF per year to support the SFHA would imply an economic loss of roughly \$30 million/year for water export uses. Partly because of such considerations, in late 2024 the Fall X2 action was reduced in scope after petitioning from various stakeholders.

Lack of Evidence for Effectiveness

Another issue is the difficulty in measuring and attributing a fish response to the SFHA, which is caused by several factors. First, the ultimate endpoint of the action (Delta smelt) is difficult to detect because they are a short-lived, small-bodied fish in a large heterogeneous system; the habitat is complex and requires many gear types to sample exhaustively; and perhaps most importantly, they are now at such low abundances that any response is likely impossible to detect at this time, especially for wild Delta smelt. However, the use of specifically deployed tagged or marked hatchery Delta smelt to enable detection of effects might overcome some of these challenges. Because deploying hatchery fish into warm summer waters may be stressful, their utility in relation to detecting a response to this action should be carefully considered.

Second, the system is highly variable in environmental conditions over diel, seasonal, and interannual scales, which makes detection of responses to discrete interventions more challenging. The targeted biotic and abiotic factors that are the focus of this action would have naturally fluctuated widely interannually, because of ocean influences and climate variability, as well as spatially within subregions of the estuary, due to extremely heterogeneous hydrodynamics (Brown et al., 2024). Within a given year, phytoplankton and other carbon sources are typically higher in areas of the estuary where flood tides dominate ebb tides. This natural temporal and spatial variability in the interactions between physical processes and the landscape, which ultimately creates high quality habitat for Delta smelt, is described in

detail in Brown et al. (2024). As a consequence, for example, it could be difficult to detect an increase in zooplankton in the low salinity zone, because the zone is large in spatial scale and very dynamic, zooplankton are notoriously patchy, and both the water and the zooplankton are moving with the tide.

Third, this action takes an ecosystem-based approach and seeks to affect a whole food web. Although this approach is scientifically robust and ambitious, food-web dynamics are often difficult to distinguish from individual species dynamics (e.g., DeAngelis et al., 1989; Polis and Strong, 1996). This could be particularly true in a food web that has been “rewired” by numerous invasions, including by indirect competitors such as the overbite clam (*Potamocorbula amurensis*), which appeared shortly before Delta smelt started to decline and is presumed to have reduced primary production five-fold (Cloern and Jassby, 2012). The fact that other planktivorous fishes also declined in abundance over this time frame (Colombano et al., 2022) further suggests that these indirect interactions may be important (Moyle et al., 2016) and could introduce uncertainty in the action by preventing increases in pelagic production from benefitting pelagic consumers such as the Delta smelt.

Fourth, it may be difficult to attribute any observed changes in phytoplankton or zooplankton density or other targeted abiotic conditions to a specific flow management action (and not to climatic variability, annual hydrology, or some other factor). Evidence is emerging that other stressors, such as temperature, can confound the success of actions such as Fall X2 (Hammock et al., 2022). In addition, although studies exposing Delta smelt to agricultural drainage water collected during SFHA-like actions found no acute toxicity, negative effects were found in the livers of Delta smelt exposed to agricultural water from the Toe Drain and Cache Slough during a 2019 pulse flow action, which coincided with higher detections and concentrations of organic pesticides (Hammock et al., 2015; Stillway et al., 2024). The lack of consistent response of Delta smelt to flow related actions suggests a need to further understand the role of additional stressors, and their interaction with flow actions.

Finally, because the components of the SFHA are designated for implementation only in some water-year types and not repeatedly across years, conditions may change in the estuary from one implementation to the next, making it difficult to detect a consistent response.

MONITORING FOR THE SFHA

Although direct measures of Delta smelt abundance would be the ultimate metric for the SFHA, monitoring and analysis currently target the amount and quality of habitat that have been identified as critical for improved Delta smelt growth and survival (CDWR, 2023; CDWR and USBR, 2024a; USBR and CDWR, 2023). These variables serve as primary indicators of SFHA effects for two key reasons. First, improved Delta smelt growth and survival are the end-products of a multi-step set of ecological processes that would be difficult to detect under the best of circumstances because of natural variability. Second, it is unlikely that the response produced by a single favorable action would be readily detectable given the extremely low current populations of Delta smelt.

This section focuses on evaluating responses to two of the current components of the SFHA: Fall X2 and Suisun Marsh Salinity Control Gate operation. CDWR and USBR (2024a) summarizes the approach to monitoring for SFHA responses as primarily utilizing monitoring data collected through long-term monitoring programs, which were not designed specifically to detect Delta smelt or Delta smelt response to management perturbations, and the Enhanced Delta Smelt Monitoring program, and supplementing those efforts as needed. Table 4-1 summarizes the monitoring activities, environmental variables, and analyses used to test for and quantify ecosystem responses to the two components, with each row corresponding to a hypothesized response. Figures 4-2 to 4-4 provide the sampling locations for the monitoring.

The hypotheses set forth in the SFHA 2024 Comprehensive Monitoring Plan (CDWR and USBR, 2024a) include:

- *Hypothesis #1*: Decreasing X2, and/or operating the SMSCG during summer or fall, will increase the area and duration of habitat with appropriate temperatures, turbidity, and salinity for Delta smelt.
- *Hypothesis #2*: Decreasing X2 and/or operating the SMSCG during summer or fall will increase biomass of calanoid copepods in the low salinity zone, through their increased transport from upstream areas.
- *Hypothesis #3*: Operating the SMSCG will increase the area of appropriate Delta smelt habitat in Grizzly Bay.
- *Hypothesis #4*: Better habitat and increased food availability will improve Delta smelt growth and survival.

The first three hypotheses focus on measuring indicators of habitat. The 2023 Comprehensive Monitoring Plan (CDWR, 2023) calls for testing Hypotheses #1 and #3 using data from the existing networks of continuous sensors (15-minute data) that measure temperature, salinity, and turbidity. CDWR and USBR (2024a) also proposed using three-dimensional (3-D) hydrodynamic models in combination with (or calibrated using) mooring data to estimate the area that reached suitable conditions (i.e., salinity < 6 psu and temperature < 22 C), or to hindcast conditions during earlier time periods that pre-date establishment of the sensor network. The difference between Hypotheses #1 and #3 is that #1 considers conditions over a wide spatial extent (Suisun Bay and Marsh, Grizzly Bay, and the Sacramento River) while #3 focuses specifically on Grizzly Bay using data from a subset of locations.

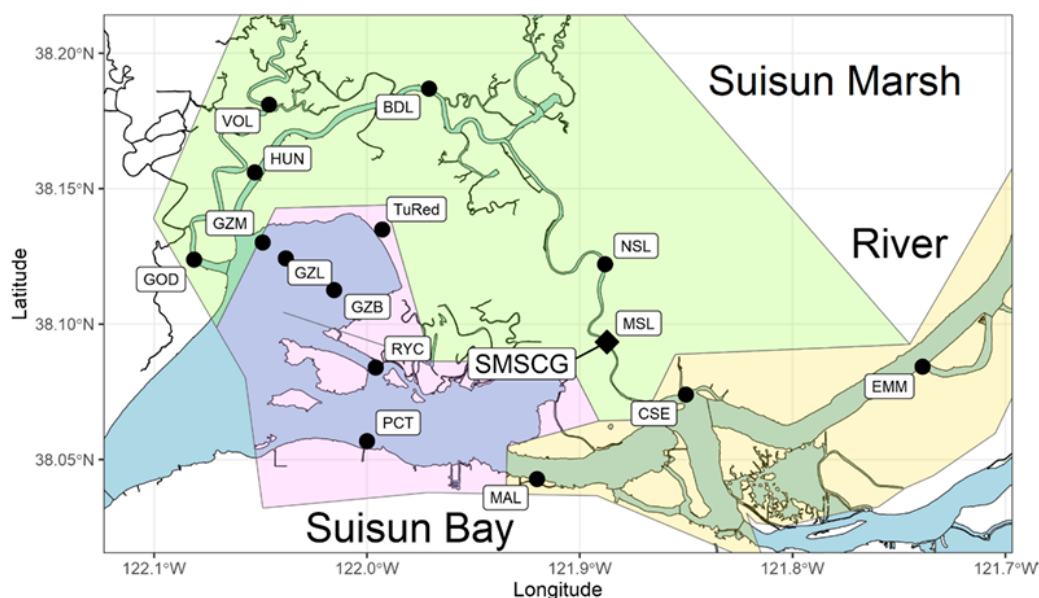


FIGURE 4-2 Locations of continuous water quality moorings (15-minute data) in the lower Sacramento River, Suisun Bay and Suisun Marsh. NOTES: Salinity, temperature, dissolved oxygen, and turbidity are measured at all locations. Sensors for additional parameters (pH; chlorophyll and phycocyanin fluorescence) are included at a subset of the stations (CSE, MSL, NSL, BDL, HUN, GZL, GZB, GZM, TRB); periodic discrete samples (biweekly or monthly) are also collected at these locations for measuring chlorophyll-*a* and nutrient concentrations. The three regions used for major comparisons are shown in yellow (lower Sacramento River), green (Suisun Marsh), and pink (Suisun Bay). SOURCE: CDWR (2023).

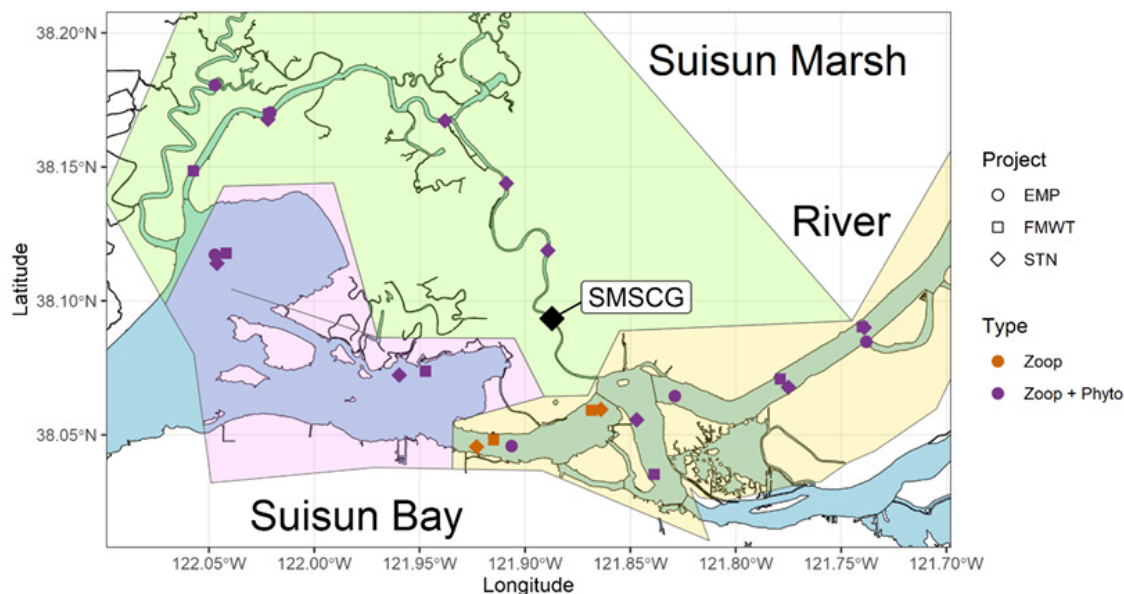


FIGURE 4-3 Zooplankton and phytoplankton sampling locations. NOTES: The three regions used for major comparisons are shown in yellow (lower Sacramento River), green (Suisun Marsh), and pink (Suisun Bay). EMP = Environmental Monitoring Program, FMWT = Fall Midwater Trawl, STN = Summer Townet Survey (see Appendix D).

SOURCE: CDWR (2023).

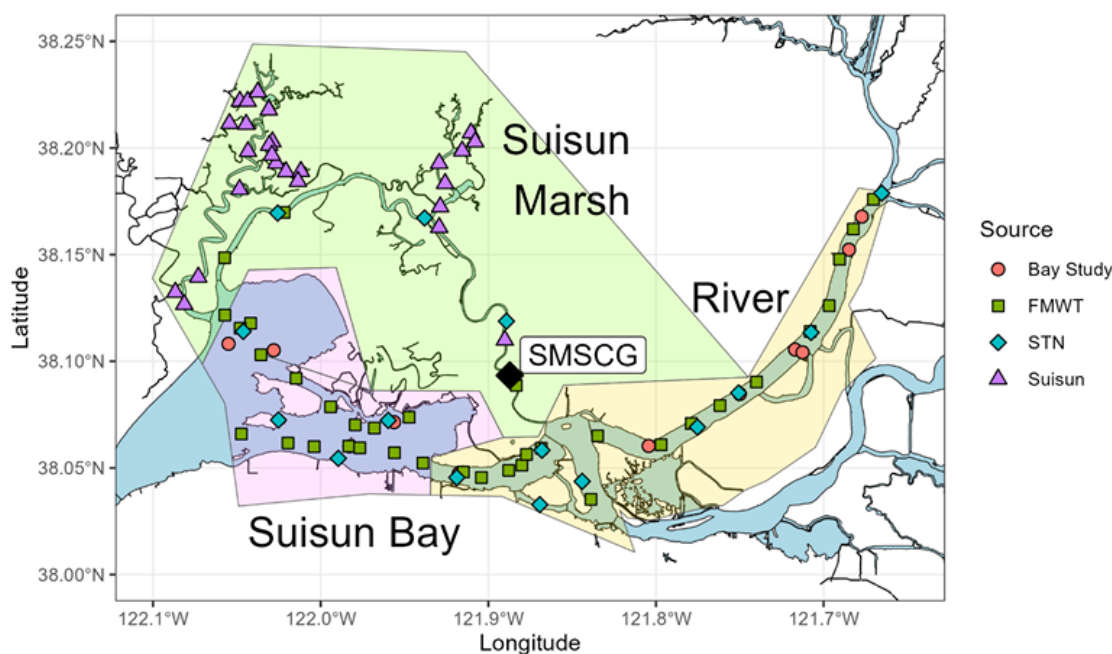


FIGURE 4-4 Sampling sites for long-term fish monitoring surveys in the lower Sacramento River, Suisun Bay, and Suisun Marsh. NOTES: The three regions used for major comparisons are shown in yellow (lower Sacramento River), green (Suisun Marsh), and pink (Suisun Bay). FMWT = Fall Midwater Trawl. STN = Summer Townet Survey, Bay Study = CDFW San Francisco Bay Study, Suisun = UC Davis Suisun Marsh Fish Survey.

SOURCE: CDWR (2023).

Testing of Hypothesis #2 relies primarily on zooplankton data from three on-going monitoring programs (Summer Townet Survey, FMWT, and the Environmental Monitoring Program—see Appendix D). The Environmental Monitoring Program conducts year-round monthly sampling, while the other two programs sample monthly within seasonal windows (Summer Townet Survey: June–August; FMWT: September–December). The study plan notes that additional sampling will also be performed related to these actions, to increase sampling spatial and temporal resolution. However, this hypothesis would be best tested by estimating zooplankton production rates (e.g., from enclosure experiments before and after the action, along a gradient of action influence) (Poff, 2018; Vanni, 1987). Zooplankton biomass or counts are an imperfect proxy for production (or actual “food availability”) because they only reflect the uneaten portion, and because production/biomass relationships may be affected by the action itself (e.g., as a consequence of changing water temperature and thus zooplankton growth rates).

Delta smelt responses to the SFHA (Hypothesis #4) are tested primarily through analyzing fish abundance data from existing surveys (see Table 4-1 and Figure 4-4), with the science and monitoring plans highlighting two limitations to this approach. First, of the six fish monitoring surveys being used, only one, the Enhanced Delta Smelt Monitoring (EDSM), has been catching Delta smelt regularly. Second, multiple action years may be required (and results combined) before statistical analyses can be reliably performed to assess the effects of the SFHA. Because all of the existing monitoring programs extend over larger areas than the SFHA regions of interest, each survey has only a few relevant stations or limited seasonal sampling windows (CDWR, 2023).

None of the routine monitoring plans includes direct measurements of vital rates (e.g., growth, survival), which limits the ability to detect the effectiveness of the action on Delta smelt. While such measurements for wild Delta smelt are currently limited by low abundance, the lack of such information on key response variables further confounds understanding of the action.

The SFHA science and monitoring plans are described in more detail in two recent technical reports (CDWR, 2023; USBR and CDWR, 2023) that underwent technical review through a 2024 peer-review process led by the Delta Stewardship Council (DSC, 2024a). The SFHA science and monitoring plans are explored further in the section on Additional Science Topics.

SFHA MODELING

A range of computer models of various physical, chemical, and biological processes are (or can be) employed in the SFHA (Table 4-3). The routinely used models rely mostly on operations, hydrodynamic, and water quality models that grew from modeling needs for Delta water supply operations and are discussed below. Table 4-3 also lists other research models that have been used infrequently and provide some innovations and insights into the SFHA. Several of these studies are mostly statistical estimations of Delta smelt habitat suitability indices (Bever et al., 2016; Hamilton and Murphy, 2020; Manly et al., 2015; Nobriga et al., 2008; Nobriga and Rosenfeld, 2016; Sommer et al., 2011).

The hydrology of the Central Valley and operations of its major water projects is simulated using CalSim3 (see Chapter 3 and Appendix D), which outputs monthly flows into the Delta and Delta pumping and outflow boundary conditions to be used in other Delta hydrodynamic and water quality models. Also discussed in Chapter 3, internal Delta hydrodynamics and salinity are routinely represented by the faster 1-D DSM2 model. This model is used to manage most Delta water supply operations and regulations and serves as a foundation for the Delta smelt model IBMR, which can estimate effects on Delta smelt populations from flow, salinity, and broader habitat conditions.

TABLE 4-1 Overview of Monitoring and Other Data Used for Assessing Responses to the SFHA

Hypothesized Response	Long-Term Monitoring	Special Studies and/or Analyses to Quantify Response
	Parameters, Region(s), # of stations, Sampling Frequency	
1. Increased overlap of temperatures, turbidity, and salinity	• <i>Parameters:</i> in-situ sensors for temperature, salinity, and turbidity • <i>Regions:</i> Suisun Marsh: 5 slough sites; Suisun Bay and Grizzly Bay: 6 sites; Sac River: 3 sites. • <i>Frequency:</i> continuous (15 min)	• Analysis: # suitable habitat days per year, for each parameter, comparing action and no-action years (2017–2023) • Hindcast modeling of temperature and salinity: comparison of action to no-action scenarios
2. Increased food abundance for Delta smelt (calanoid copepods), including through increased transport of freshwater species from upstream	• <i>Parameters:</i> zooplankton biomass and community, phytoplankton, chl-<i>a</i>; • <i>Regions:</i> Suisun Marsh: 6 slough sites; Suisun Bay and Grizzly Bay: 2 to 3 locations sampled by multiple programs; Sac River: 6 sites, some sampled by multiple programs • <i>Frequency:</i> monthly	• Analysis of long-term monitoring data on zooplankton biomass and community; phytoplankton biomass (chl-<i>a</i>); comparing action and no-action years (2017–2023)
3. Increased area of appropriate Delta smelt habitat in Grizzly Bay	• <i>Parameters:</i> in-situ sensors for temperature, salinity, and turbidity • <i>Regions:</i> Grizzly Bay, 3 sites (Montezuma Slough, Center of Grizzly Bay, and the mouth of the Tule Red restoration site). • <i>Frequency:</i> continuous (15 min)	• Analysis of long-term monitoring data: Suitable habitat days per year, for each parameter and overlapping • Hindcast modeling of temperature and salinity
4. Improved Delta smelt growth and survival	• Summer Townet Survey, Fall Midwater Trawl, San Francisco Bay Study (monthly), UC Davis Suisun Marsh Survey, Enhanced Delta Smelt Monitoring • <i>Parameters:</i> abundance, distribution, health metrics, stomach fullness • <i>Regions:</i> Suisun Marsh: 1 slough site; Suisun Bay and Grizzly Bay: 3 sites; Sac River: 5 sites; Sac Deep Shipping Channel, 1 site • <i>Frequency:</i> weekly to monthly	• Analysis of data from long-term monitoring and EDSM: inter-year comparisons of abundance, distribution, health metrics, stomach fullness • Enclosure Studies: Locations: Rio Vista and Suisun Marsh, after 6 weeks measured: growth, survival, liver glycogen, critical thermal maxima, diets

SOURCE: CDWR and USBR (2024a).

SCHISM, a 3-D model of Delta hydrodynamics and salinity, is the main model used to assess the likely extent of suitable salinity habitat from the SFHA, using upstream freshwater inputs from CalSim3. SCHISM and UnTRIM (another 3-D Delta model) calculate water depths, flows, and salinities over small time scales and over a relatively fine 3-D grid of the Delta and San Francisco, extending outside the Golden Gate Bridge and upstream to the extent of tidal influence. Both models are computationally intensive, with much greater spatial resolution than both DSM2 and the fast empirically trained artificial neural network models of salinity at specific locations (see Chapter 3). These 3-D models also display good skill in predicting water surface elevation, velocity, and salinity. Delta smelt habitat indices are estimated from 3-D model results, mostly using the habitat suitability method of Bever et al. (2016) (described in more detail below).

The water surface elevation, flow speed, and salinity predictions from these models (DSM2, SCHISM, and UnTRIM) are fairly accurate and reliable, based on well-known physics. Estimates of Delta smelt habitat suitability and populations are far less mature, less accurate, and calculated over coarser spatial scales. The prognosis for developing more accurate Delta smelt models is greatly hindered by the lack of wild Delta smelt available for improving these models. Yet, the precarious position of Delta smelt makes developing mechanistic life-cycle models for this species urgent, in order to help inform Delta environmental and water policies and operations.

The modeling summarized in Table 4-3 was an application of the information available when the SFHA was being planned for Water Year 2022. Ideally, annual planning would be supported by predictions of how the SFHA will affect the suitability of habitat, and ultimately Delta smelt, for different environmental conditions and management strategies. However, although a few of the models currently available contain components necessary for modeling the likely effects of the SFHA, none contain all the components. Life cycle-specific models for Delta smelt are described in Appendix E. Most of them, including Maunder and Deriso (2011) and Polansky et al. (2021), are based on statistical analysis, meaning they cannot be reliably applied to conditions not represented in the data used to build the statistical relationships. Those that are process based, such as Rose et al. (2013a,b), are driven in part by existing field data and therefore are limited in their application to future conditions for which representative data are unknown.

Models that could potentially be used to evaluate the environmental impacts of the CVP and SWP on listed fishes were reviewed in detail in the 2024 USFWS Biological Opinion (USFWS, 2024a), where the following criteria were used to consider model suitability: (1) models are accessible and model output can be reproduced by an independent party, (2) model structure is well documented including model assumptions, (3) model functions are responsive to changing operations such as flow, and (4) model output informs performance metrics. With regard to modeling Delta smelt habitat, food, and growth potential, USFWS (2024a) considered a common bioenergetics approach (e.g., Rose et al., 2013a,b; Smith et al., 2021) but determined that CalSim outputs were inappropriate as inputs into these models, a common issue with coupling CalSim with other models that operate on a finer time scale than one month (Chapter 5). Regarding the evaluation of different water project alternatives, the Kimmerer Copepod Box Model (Hassrick et al., 2023; Kimmerer et al., 2019) requires empirical field data that are not available for planned management actions, limiting its application. The RMA Copepod BPUE Model⁴ remained under review at the time of the 2024 Biological Opinion and therefore was not considered in detail but was believed to be limited in scope.

⁴ Calanoid copepod analysis addendum; see https://dshh.rmanet.app/overview/rma_calibration_reports/USBR_LTO_copepod_addendum.pdf.

TABLE 4-2 Summary of Models/Tools Used in SFHA in Water Year 2022

Model	Inputs	Outputs	Notes on Model Use for the SFHA
CalSim3 (2022)	Hydrology from and within watersheds; Delta flow requirements	Monthly inflows into the Delta, water exports from the Delta	Delta operations and Delta model boundary conditions (monthly inflows and outflows) affecting internal Delta flows and water quality
SCHISM (3-D) ^a Ateljevich et al. (2021)	Flow boundary conditions from CalSim3	Salinity distribution, temperatures, habitat metrics based on acreage/frequency	Used to assess extent of salinity habitat from SFHA. Generally good predictions, conditioned on wind and air temperature, salinity, and water temperature assumptions. Turbidity is less well predicted. ^a
DSM2 (1-D) CDWR (2019)	Hydrology from CDWR studies and CalSim3	Salinity, water export cost	Only simulations of salinity are used for the SFHA. The biggest limitation is the uncertainty in hydrologic forecasts.
IBMR Rose (2013a,b) Kimmerer and Rose (2018)	Hydrodynamics, prey density, Secchi depth, smelt distribution, temperature, turbidity	Simulated population growth rate; can also produce simulated individual growth rates, or growth potential	Individually based model for Delta smelt written in R. Includes reproduction, growth, mortality, and movement of individual Delta smelt and prey over their entire life cycle on a DSM2 grid. Field validation not possible.
RMA Bay-Delta model ^b (2-D), RMA San Francisco Estuary UnTRIM ^c (3-D) RMA (2021)	Wind velocity, air temperature, solar radiation and cloudiness; salinity and water temperature from data and DSM2; Secchi depth data	Salinity, temperature, turbidity, water velocity for input to a habitat suitability index	Coupled hydrodynamic, water quality, and habitat suitability modeling. Did not include different implementation scenarios for the Suisun Marsh Salinity Control Gate action. Relies on historical conditions.
<i>Various Habitat Suitability Index Estimation Studies</i>			
Bever et al. (2016) ^d	UNTRIM/SCHISM outputs and historical FMWT data	Habitat Suitability Index used in the 2022 Structured Decision Making	Uses UNTRIM/SCHISM hydrodynamic and water quality outputs and historical FMWT data to estimate Delta smelt preferences for different types of habitat
Nobriga et al.(2008) ^e	Temperature, turbidity, salinity	Habitat Suitability Index	Statistical analysis of water quality suitability for Delta smelt
Manly et al. (2015) ^f	Salinity and turbidity	Habitat Suitability Index	Low predictive accuracy for presence of Delta Smelt
Hamilton and Murphy (2020) Smelt Habitat	Field data: depth, copepod biomass, temperature, turbidity, and prey	Habitat Suitability Index	Copepod biomass is only food source
<i>Other Coupled 3-D Hydrodynamics, Water Quality, and Zooplankton Biomass</i>			
Kimmerer copepod box model; Kimmerer et al. (2019) ^g ; Hassrick et al. (2023) ^h	3-D hydrodynamic model for velocity, salinity, volume, and particles moving per day	3-D temperature, salinity, turbidity, and zooplankton biomass	Assumes copepod densities and reproductive rates are similar to historical levels. Only models <i>Pseudodiaptomus forbesi</i>

^a See <https://data.cnra.ca.gov/dataset/methodology-for-flow-and-salinity-estimates-in-the-sacramento-san-joaquin-delta-and-suisun-marsh/resource/c64349eb-397a-47c1-b516-b3f522528c00>.

^b See <https://dshm.rmanet.app/overview/>.

^c See https://dshm.rmanet.app/overview/rma_calibration_reports/USBR_LTO_Summer_Fall_Delta_Smelt_Habitat.pdf.

^d See <https://escholarship.org/uc/item/2x91q0fr>.

^e See <https://escholarship.org/uc/item/5xd3q8tx>.

^f See <https://link.springer.com/article/10.1007/s12237-014-9905-3>.

^g See <https://escholarship.org/uc/item/4b1433j7>.

^h See <https://link.springer.com/article/10.1007/s12237-022-01142-1>.

The Bever et al. (2016) Habitat Suitability Index (HSI) for Delta smelt is perhaps the most promising statistical approach for modeling the effects of the SFHA. The approach uses a 3-D hydrodynamic model in combination with long-term data from the FMWT, in order to develop a statistical relationship between Delta smelt catch and (1) salinity (percent of time < 6 psu), (2) velocity (maximum depth-averaged current speed over a 4-month period), and (3) turbidity (0.5 meter Secchi depth threshold). Based on these relationships, Bever et al. (2016) predicted a catch station index (relative ranking of FMWT stations) based on Delta smelt catch. This index was also validated with Delta smelt data from the Bay Study survey, and general agreement throughout the Delta was determined. Bever et al. (2016) used the UnTRIM Bay-Delta Model, but the statistical relationships can be applied using SCHISM. Although informative, this modeling approach is not process based and cannot predict how the SFHA will operate mechanistically under different scenarios.

DECISION SUPPORT TOOLS

Decision support tools can enable the integration of field data, available model results, and technical, scientific, and management expertise to inform decision makers. Decision tools, data, and models co-evolve over time with decision concerns, options, and processes. Unlike the Shasta Coldwater Pool Management Action and the OMR Flow Management Action, the SFHA has used a structured decision-making (SDM) approach to determine how the SFHA will be implemented each year. This approach considers information about the state of the system during each water year and how it can be used to inform the planning and execution of either Fall X2 or the operation of the SMSCG, as described in greater detail below.

The Annual Decision Process for the SFHA

The Delta Coordination Group determines how the components of the SFHA are implemented each year. The determinations are based on available projections and information about the hydrologic conditions reflected in the water-year type and use a so-called Structured Decision Making (SDM) tool. Documentation made available to the Committee to inform its understanding of the SDM approach for water years 2022 and 2023 (DSC, 2024b,c) had been previously compiled for a 2024 Delta Science Program review of the science and monitoring plans and decision approach for the SFHA (DSC, 2024a). No specific documentation of the SDM approach was available for water year 2024, but the 2024 Action Plan for the SFHA notes, “The 2024 recommendation was based on (1) previous SDM iterations developed by the Delta Coordination Group, (2) new analyses of low salinity zone habitat, temperature, and food (i.e., *Pseudodiaptomus forbesi*) for scenarios, and (3) a series of collaborative discussions within the Delta Coordination Group of predicted benefits to Delta smelt” (CDWR and USBR, 2024b). Of note, the SFHA for water years 2022 and 2023 included actions that are no longer part of the SFHA in the 2024 Biological Opinion (e.g., North Delta Food Subsidy).

SDM was used in water year 2023 to answer the question “What suite of actions should the Delta Coordination Group recommend for the SFHA period (June to October), given the likely water year types?” This question encompasses not only whether the action involves Fall X2 or operation of the SMSCG, but also how to implement the action. The SDM approach was designed to cover as many water-year types as feasible given time and data. Water-year types are initially set by first-of-month runoff forecasts beginning in February. The final determination is based on the May 1 forecast of conditions that have a greater than 50 percent chance of occurring. SDM meetings begin earlier in the year; hence, the Delta Coordination Group met in January and February 2022 to consider updates from the approach used in water year 2021, and therefore had to consider several water-year types to develop plans that could be implemented once the final water year was determined in May.

The stepwise SDM process considers:

1. Decision Objectives—the factors important enough for the Delta Coordination Group to consider when determining the nature of the SFHA in that year
2. Performance Measures for each decision objective—the metrics that will be used to characterize the Delta Coordination Group’s predictions of an alternative’s performance relative to a decision objective
3. Alternatives—management actions as well as science actions or monitoring
4. Consequences of each alternative for each decision objective by predicting performance using methods agreed on by the Delta Coordination Group.

Figure 4-5 presents an example of the influence diagram developed to support the SDM in water year 2022. At the far right-hand side of the diagram are fundamental objectives such as Delta smelt recruitment (in a white box)—the outcomes identified through the SDM process that Delta Coordination Group members care about and that can be affected by the decision. Increased Delta smelt recruitment is supported by increased Delta Smelt growth and survival (DCG, 2024b). Because many efforts beyond those covered by the SFHA are geared toward increasing Delta smelt recruitment, and because the broader system is complex and poorly understood, Delta smelt recruitment is unlikely to be useful as a decision objective. Thus, Delta smelt growth and survival are shown as decision objectives (in blue boxes). The grey box on the left-hand side of the diagram contains the main categories of management actions that the Delta Coordination Group considered in the water year 2022 SDM process. The central part of the influence diagram shows how changes in management levers influence different aspects of the system that ultimately influence Delta smelt growth and survival. Of note, the SDM process includes documentation of how the relationships on the influence diagram are commonly understood by the Delta Coordination Group.

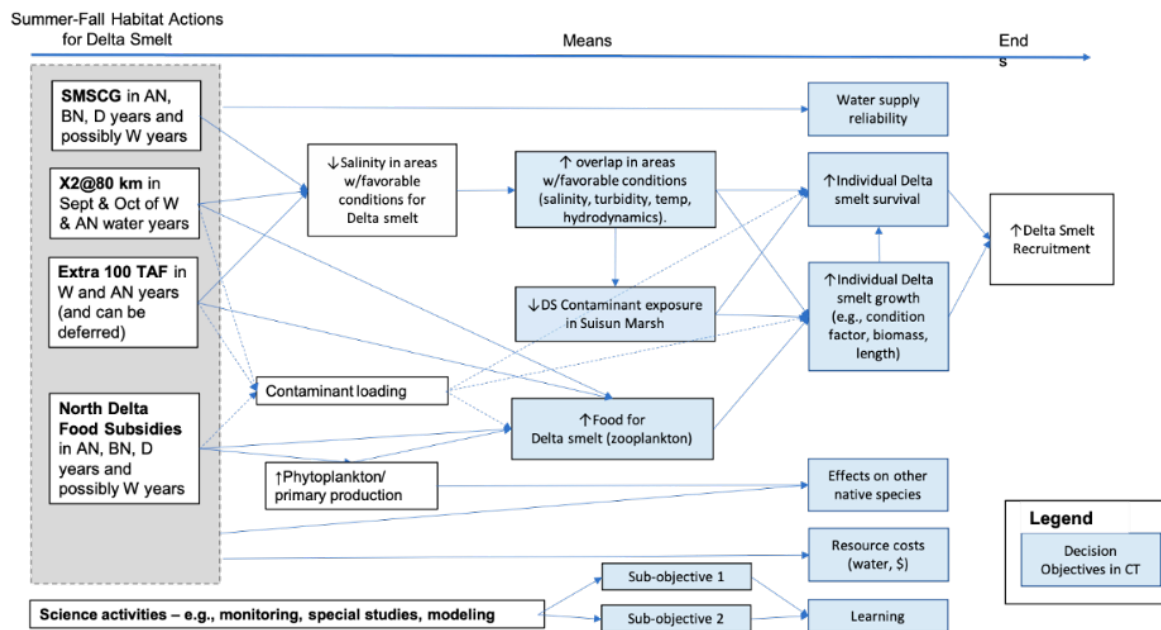


FIGURE 4-5 Influence diagram of the Summer-Fall Habitat Action developed by the Delta Coordination Group illustrating the hypothesized relationships (e.g., mechanisms) between the SFHA action and the objectives.

NOTE: The North Delta Food Subsidy is no longer part of the SFHA.

SOURCE: CDWR and USBR (2023).

The consequences analysis, both quantitative and qualitative, determines the effects of the SFHA on the various decision objectives. Fact sheets are developed based on predictive models and expert elicitation. Some performance measures are assessed using models (e.g., a bioenergetics model) and habitat suitability indices, while others are assessed using expert elicitation, whereby experts rate alternatives relative to “No Action” using a predetermined scale (e.g., to assess exposure to contaminants). The consequences of each alternative action are then compared, and consequences and tradeoffs are explored by the Delta Coordination Group using Compass Resource Management’s online Altaviz tool.

Figure 4-6 shows an example of the display from Altaviz for a below normal (BN) water year. In the left panel, color coding (brown to green for less effect to more effect) is used for the outcomes that are impacted by two different options for SMSCG operation, i.e., achievement of either ≤ 4 psu or ≤ 6 psu at Belden’s Landing versus not undertaking the action. The table on the right of Figure 4-6 shows the details of the table on the left but displayed in a more simplified way. Here, performance is categorized as better or worse than a selected option.

In water year 2022, consensus on the selected approach for the SFHA was reached through negotiation. For water year 2023, the Delta Coordination Group used an optimization approach to tradeoffs. The selected optimization method, Simple Multi-Attribute Ranking Technique with Swings, worked as follows:

- Prior to meeting to decide on SFHA recommendations, each Delta Coordination Group member weighed growth, food, and contaminant subobjectives in terms of their relative importance to the overall Delta smelt objective, and then weighed the four top-level objectives (Delta smelt, Effects to Other Species, Costs, and Learning) in terms of overall importance. Each member also directly ranked alternatives.
- Scores for each performance measure were normalized to a 0 to 1 scale.
- Normalized, weighted scores were summed for each alternative to create a single gross utility score for each Delta Coordination Group member.

These results were then used to facilitate the Delta Coordination Group’s discussion. This approach provides a way of depicting how close or far apart the different group members are in their thinking. However, as information is scored and normalized, some nuances of members’ individual preferences may be less obvious than if they were revealed through negotiation.

Suggestions for Improving the SFHA Decision Process

Because the SDM process was reviewed in detail by the Delta Science Program (DSC, 2024a), this Committee did not repeat that review. DSC (2024a) expressed concerns about ambiguity in the definition of objectives and a lack of clear framing of the process, including the scope. Regarding participants, the review noted “that group members from state and federal resource management agencies and the state and federal water contractors, who have had long involvement in the water projects, can introduce a status quo bias and discourage insightful questions and the development of new alternatives.” Finally, the review noted a lack of focus on uncertainties, tradeoffs and priorities:

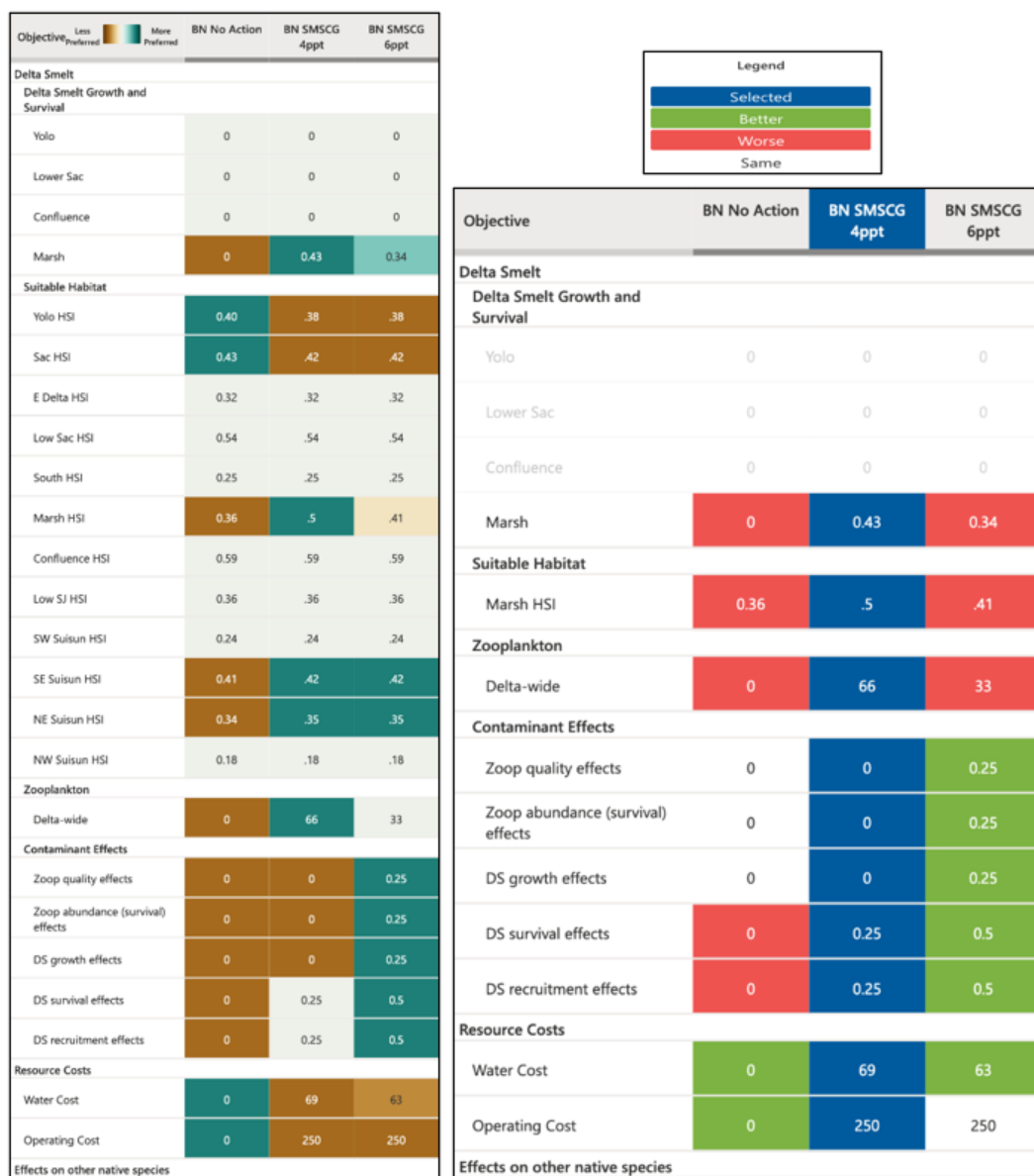


FIGURE 4-6 Screenshots of unsimplified (left) and simplified consequence table (right) for below-normal water year type SMSCG actions from Altaviz program actions.
SOURCE: DSC (2024b).

“SDM is decision-based and thus requires simplification: when an Objectives by Alternatives consequence matrix grows large, it no longer provides an easy path to insights for making better management decisions. An SDM process achieves simplification by highlighting uncertainties (with respect to the consequences of actions), tradeoffs (with respect to the achievement of objectives), and priorities (in terms of what is most important to the decision at hand). These reports describe the modeling results and provide convincing documentation that reducing extinction risks to Delta Smelt is a complex task.”

Presently, whether the Fall X2 component of the SFHA will occur is based on water-year type. However, water-year type may not be an appropriate way to characterize the conditions under which X2 will be most successful. For example, even in “wet” years, spring conditions (such as temperatures) could be so unfavorable that they would preclude success of the X2 component. Furthermore, planning for the SFHA occurs early in the year so that agencies and water users can plan for and coordinate water needs. However, water-year type may not be clear until early May. Although water users should have reasonable expectations of how water deliveries may change, a set of triggers for moving forward with various components of the SFHA could be established based on expectations developed early in the year. For example, this might include information on antecedent conditions, temperature, and availability of food resources, with the goal of identifying under what conditions the action’s components would proceed and how. Closer to the time of the action, monitoring data could be used to adjust SFHA implementation based on the triggers. There is sufficient flexibility in how the SFHA is described in regulatory documents to allow for year-to-year adjustments. Taking advantage of this within-year flexibility could achieve a more efficient and effective use of water, staff, and field data collection resources.

If implemented collaboratively including a range of stakeholders, SDM should improve the transparency, efficiency, and hopefully the effectiveness of regulated operations (e.g., Peterson et al., 2024). The 2024 biological opinions and incidental take permit do not require the use of SDM for annual planning of the SFHA. However, the adaptive management approach described in Appendix 2 of the USFWS 2024 Biological Opinion (USFWS, 2024b) states that Adaptive Management Teams will use “decision-analytic tools or a structured decision-making process to define relevant uncertainty, develop action alternatives, estimate expected consequences of the alternatives, and evaluate trade-offs and preferences when making choices between alternative courses of action.”

ADDITIONAL SCIENCE TOPICS

The SFHA is complex and ambitious in the changes it seeks, and by its nature it will be difficult to unambiguously trace response variables back to the SFHA. The complexity of the system and confounding factors make it difficult to isolate the impacts of the action from those attributed to other system dynamics. Further, the relationships among the action, food availability, and Delta smelt recruitment, are not fully understood. Low Delta smelt abundance poses additional challenges, and questions remain about the potential role of experimental releases of cultured fish. Finally, opportunities exist to explore the potential role of tidal modifications in the system to support the delivery of food for Delta smelt. These multiple challenges facing the SFHA could be addressed with new science as discussed below.

Isolating the Action from Other System Dynamics

As mentioned previously, a major challenge to implementing the SFHA is the extreme difficulty in isolating the effects of the action from the other system dynamics to identify direct effects. It is necessary to rule out the effects of other stressors on either Delta smelt individuals or their food resources. Factors that may be important are predation (either of Delta smelt or their prey) and other food web interactions, the effects of contaminants, and warming water temperatures.

Predation and Food Web Interactions

Several studies have examined the potential effects of predation on Delta smelt in general (Nobriga and Smith, 2020), and Mississippi Silversides have been identified as predators, especially

in clearer water (Schreier et al., 2016), with less evidence of a clear role for striped bass (Brandl et al., 2021). Genetic analysis (e.g., eDNA) of potential predators in the areas where Delta smelt are proposed to benefit from the SFHA could help to identify the potential for predation to counter expected benefits.

The Delta Independent Science Board recently released a report (DISB, 2024) with a goal of advancing food web science to better inform a broad range of management decisions, including the SFHA. If food-web models were updated and improved, they could support planning of the SFHA by predicting and understanding the effects of the SFHA on (1) other fishes (e.g., longfin smelt and salmonids), (2) non-native competitors of Delta smelt, and (3) predators of Delta smelt.

Contaminants

Some components of the SFHA increase flows in areas or at times of the year when they would otherwise be low. This increase in flows has the potential to mobilize and transport contaminants to the areas where the Delta smelt are expected to benefit from the action. Hammock et al. (2015) demonstrated that Delta smelt from the Suisun Marsh region had better morphometric and histopathological condition and higher short-term nutrition and growth indices. In contrast Delta smelt from the freshwater regions of the estuary, particularly Cache Slough, demonstrated the greatest histopathological signs of contaminant exposure.

Stillway et al. (2024) similarly conducted laboratory experiments with Delta smelt exposing them to field water from six sites in the estuary that encompass the freshwater and low-salinity habitat of Delta smelt. No acute toxicity was observed during any exposure, but negative effects were observed in the livers of Delta smelt exposed to agricultural water from the Toe Drain and Cache Slough during the 2019 pulse flow action, which coincided with elevated detections and concentrations of organic pesticides. Clearly, understanding whether potentially toxic contaminants are mobilized by the components of the SFHA needs to be monitored. Changing the patterns of exposure to contaminants as a result of the SFHA could be a potential stressor confounding the response of Delta smelt to the action.

Spawning Habitat

Availability of suitable spawning habitat for Delta smelt is another potentially important constraint on their recovery. Dense invasive submersed aquatic vegetation can physically block access to shallow channel margins, alter local flow and dissolved oxygen conditions, and reduce the availability of suitable substrate for egg deposition. Monitoring programs and recent syntheses have documented rapid expansion of invasive SAV over the past two decades, particularly during drought years when water clarity increases (Christman et al., 2023; Smits et al., 2025). In tidal freshwater sloughs of the northern Delta, vegetation cover increased dramatically—by factors of six (e.g., Lindsey Slough) to nearly one thousand (e.g., Cache Slough) over the last decade (Smits et al., 2025), coincident with large increases in water clarity. These vegetation-driven changes not only obstruct spawning access but also modify light regimes, decrease turbidity, and create habitat for non-native predators, compounding other stressors on Delta smelt (Moyle et al., 2016).

Temperature

High temperature is a well-established stressor for Delta smelt (e.g., Davis et al., 2019), and therefore high temperatures in some years could negate potential positive effects of the Fall X2 action. For example, although 2017 was one of the wettest years on record, the Delta smelt population

did not demonstrate a corresponding increase with the Fall X2 action during the fall or the following spring (2018), in comparison to the action in 2011 (Brown et al., 2014). Although the specific reason is unclear (Schultz et al., 2019), the 2017 Delta smelt year class began with poor recruitment in spring 2017 and below average survival for spring to summer and summer to fall. Thus, low production and low survival led to low abundance of all life stages. One reason could have been water temperature, which in 2017 approached or passed levels (≥ 22 – 23 C or 71.6 – 73.4 F) where physiological stress for Delta smelt has been shown to occur (FLOAT-MAST, 2020), especially in the more landward regions of the study area. As discussed previously, adjusting the decision process for the SFHA so that information about within-year conditions can be considered may enable better tuning of the action to the conditions at hand, or a decision that the action is unlikely to be effective in a given year.

When they reach certain levels, each of these stressors individually could limit the ability to detect a response of Delta smelt to the SFHA. Their interactions may produce even more complex results. The use of laboratory experiments has advanced our understanding of Delta smelt response, such that continued studies of interacting effects, such as the Davis et al. (2019) study of temperature and predation, could provide insight, especially if the potential beneficial effects of the SFHA such as food and turbidity are also interactively examined. Otolith analyses (Lewis et al., 2021) of wild fishes captured between 2011 and 2019 have been insightful and have shown how growth of Delta smelt varies with environmental conditions. In the future, if Delta smelt were to increase in abundance and/or using supplemented fish, additional studies of this type may provide greater insight into environmental conditions that should be targeted. This information would be complementary to statistical analysis of Delta smelt catches in long-term monitoring programs (such as the data relied on in Feyrer et al., 2007).

Will Increasing Food Supply Help Delta Smelt Persist?

This chapter began by stating that the SFHA was a way of better aligning Delta smelt distribution, their preferred low salinity habitat, and available food. Several aspects of the SFHA seek to increase the availability of food resources in the low salinity zone, but the links between these actions and Delta smelt abundance are not fully understood. Although zooplankton *growth rate* and reproductive output is positively related to chlorophyll concentration (Gearty et al., 2021; Owens et al., 2019), the link to zooplankton *biomass* is sometimes weak because of highly variable mortality. In addition, most analyses of zooplankton as food for Delta smelt have examined a limited number of taxa that may individually compose a large proportion of Delta smelt prey, but may not be important locally or under specific conditions. Detailed species-specific data on zooplankton distributions and abundance are available (Bashevkin et al., 2022). The importance of species-specific feeding could be revealed by a more thorough analysis of species consumed by Delta smelt in relation to prey availability, for example, through laboratory studies.

Studies have shown that Delta smelt caught in the vicinity of tidal wetlands have greater stomach fullness than those more remote from wetlands (Hammock et al., 2019). Therefore, it may be difficult to detect the impact of new food advected to the low salinity zone, as many of the SFHA components are close to wetlands. Opportunities to identify the food sources of Delta smelt could be found by using stable isotopes during deployment of cultured Delta smelt in association with SFHA operations. Carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$) have been used in studies in the Delta examining the use of various food sources by fish (e.g., Grimaldo et al., 2009; Schroeter et al., 2015). Identifying which food sources are utilized by cultured Delta smelt (e.g., those tethered before, during, and after the SFHA) may enable verification of the utilization of food brought to the low salinity zone from the Central Delta via flow releases.

The original food-supply goals of the SFHA were not to increase food supply along pelagic pathways (i.e., phytoplankton to zooplankton and zooplankton to Delta smelt) while bypassing benthic grazing, but rather to move the zooplankton to where the Delta smelt are. Two invasive clam species are dominant primary consumers in Delta-Suisun freshwater (*Corbicula*) and saline/low-salinity (*Potamocorbula*) habitats (see Appendix E), with the latter being a particularly strong food-web disruptor. It is reasonable to hypothesize that both species are food limited in their respective ranges: thus, their densities and spatial distributions could increase in response to food availability. The Committee is not aware of studies conducted to test this hypothesis. This basic uncertainty about clam responses to food availability remains but may be irrelevant. If more food is available for fish and clams, then fish may still benefit.

If there is agreement that the provision of food in turbid waters of an appropriate salinity will benefit Delta smelt, then the question of “how much is enough” still remains. Some SFHA components require large amounts of water, but how much and how often is needed to achieve a meaningful response in the Delta smelt population is unclear. An additional unexplored complication is that as additional flows and the gate action freshen Suisun marsh, the pelagic food-supply might be advected out of the marsh at approximately the same rate.

A number of statistically based approaches to fish modeling are available, and there have been efforts to simulate vital rates, i.e., growth, mortality, movement, and reproduction (e.g., Rose et al., 2013a,b). However, tests of how much flow is needed and how often, and when/where SFHA components need to be conducted in concert, will require a process-based model of Delta smelt that incorporates changing physical conditions in the system, the dynamics of food resources, and vital rates for the fish (e.g., as proposed in Reed et al., 2021). Ideally, this modeling would incorporate complex hydrodynamics and operations that reflect tidal dynamics over a range of hourly, weekly, seasonal, and longer time scales. Extensive developments in Delta smelt science in recent years (Baerwald et al., 2023; Huntsman et al., 2024; Korman et al., 2021; Lewis et al., 2025) provide an increasingly solid platform for developing such a model. Such a model might also enable exploration of fundamental constraints on the provision of habitat conditions. For example, can a less turbid Delta (Hestir et al., 2016) even support Delta smelt and does this fundamentally constrain efforts to benefit the species? Furthermore, biological and ecological process-based modeling, including food-web models, will need to become more compatible with the impressive 3-D hydrodynamic modeling capabilities for the Delta.

There may be opportunities to learn more about the relationship between food availability and fish abundance by extending the Bever et al. (2016) habitat suitability approach and completing a retrospective statistical analysis of previous annual estimates of zooplankton abundance and catch of Delta smelt and long-fin smelt (the Committee is not aware of such an analysis).

Tidal Modifications to Enhance Food Supply

The intent of the SFHA is to improve the production, transport, and accumulation of food for native fish species in the western Delta and Suisun Marsh. Before development, the Delta’s extensive and diverse tidally dominated wetlands and internal flows provided many opportunities for higher levels of production, with tidal transport moving this larger production throughout the Delta where it was available to support fishes. Suitable conditions existed somewhere in the Delta for all its fishes under the historical range of extremes (Moyle et al., 2012).

Because most freshwater and brackish Delta flows that distribute and circulate water, salt, nutrients, and organisms are caused by tides, varying tidal flows and elevations could be key to (1) inundating wetlands to improve their productivity and provide fish habitat, (2) moving flows through wetlands to make biological productivity available outside wetlands, (3) transporting fish food to other locations in the Delta with native fishes, and (4) sometimes retaining and accumulating (rather than dispersing) food at these locations (Brown et al., 2024).

Tidal elevations, flows, and mixing might be altered through a combination of levee elevation and coverage changes, changes in channel geometries and lengths, tide gates, modifying island drainage discharges, and changes in Delta inflows and pumping. These ideas could be explored through a series of focused modeling studies, combined with field studies needed to improve model representations of these processes.

Ramifications of Low Delta Smelt Abundance

A fundamental uncertainty with the SFHA is that low abundance makes it extremely difficult to quantify the actual direct benefits of the SFHA to Delta smelt. Therefore, the effectiveness of the action should be first assessed based on whether or not desired physical habitat conditions (in terms of temperature, turbidity, and salinity) and food availability levels (i.e., zooplankton biomass or production) were achieved, regardless of whether a fish response is observed. Temperature, turbidity, and salinity are the three dimensions that, when combined, constitute suitable habitat (Bever et al., 2016).

If a process-based model (as described above) were developed using a hydrodynamic model to predict how flow releases affect physical habitat conditions (such as temperature, turbidity, and salinity), and how those conditions affect zooplankton production and Delta smelt survival and growth, then planning for the SFHA could greatly improve. Such a model could be used for sensitivity analyses of the mechanisms and assumptions influencing the abiotic and biotic endpoints of the action (i.e., physical habitat, zooplankton production, and Delta smelt fitness). A sensitivity analysis would help to inform understanding of which responses are robust versus which are sensitive to context, as well as the size of the response that could be reasonably expected. This exercise could help to elucidate which responses are associated with more uncertainty and the extent to which a lack of detected response may reflect low sample size (i.e., a type II error) as opposed to true unresponsiveness. It could also determine the numbers of “deployed” juvenile fishes needed to assess success of the action (see below) and support refinement of the action.

Given the current extremely low Delta smelt abundances, even if the SFHA improves Delta smelt growth or survival, increased abundance may not be detectable in the near term. This argues not only for having realistic expectations about assessing the action, but also for implementing the SFHA over multiple years and conducting special studies (including process-based model development) that will eventually enable detection of a response.

The Potential Role of Hatchery Delta Smelt in Evaluating the Likely Effectiveness of the Action

The growing numbers of hatchery Delta smelt being raised for supplementation offer the opportunity to deploy small numbers of these fish to aid in detecting the effects of SFHA. If possible, released fish should be tagged or marked in some way, with extensive attempts to recapture the fish using high-frequency local sampling or acoustic surveying. Although hatchery Delta smelt may not grow and reproduce exactly as do wild Delta smelt (Chase et al., 2024; Finger et al., 2018), they are the most appropriate available surrogate for wild Delta smelt. Given their limited time reared in captivity, both within and across generations, it is fair to assume a considerable component of their wild genome is still present (reviewed in Fraser, 2008). Captured fish would enable evaluation of their food sources, recent growth, and any adverse effects resulting from components of the action.

Climate Change Impacts to the SFHA

Climate change will directly affect the Delta ecosystem through rising sea levels, increasing temperatures, and altered freshwater inflows. Over the next half century, sea level rise has the potential to reshape the Delta, by increasing open water and wetland habitats through flooding and perhaps promoting upstream salinity migration and levee failures. According to Fleenor et al. (2008), maintaining salinity controls will require additional Delta outflows, potentially up to half a million acre-feet per year. Nonetheless, although sea-level rise poses long term challenges to the Bay-Delta and the SFHA, temperature increases and reduced inflows due to drought will likely have greater short-term impacts on the SFHA.

Temperature trends in the Bay-Delta region show warming and drying over 30-year averages, alongside increasing extremes that prolong dry spells (see Appendix A). Delta smelt populations, which thrive in cooler, wetter years, are particularly vulnerable to these shifts because of their restricted geographic range and specialized ecological requirements (Moyle et al., 2016). Their thermal tolerance lies between 15–20°C (59–68°F) (Komoroske et al., 2014), below projected temperature increases for the region. Komoroske et al. (2014) identified juvenile smelt as the most susceptible life stage to warming, noting that higher maximum temperatures could render otherwise suitable habitats uninhabitable. Likewise, Brown et al. (2016) projected that under severe climate scenarios, suitable habitat availability for Delta smelt (particularly considering temperatures for all life stages) could resemble conditions seen during the worst recorded droughts.

The severity of extreme precipitation events and droughts is also increasing, amplifying California's already high hydrologic variability (see Figure 1-3 and Appendix A). In the Delta, drier years will reduce freshwater inflows, while wetter years will bring short-term surges in inflows, concentrated over periods of weeks and not over the entire wet season. These events will bring greater swings in Delta pumping and internal Delta flows, especially in upstream areas with less tidal influence. Climate model projections of temperature and precipitation conditions consistent with drought in California (Diffenbaugh et al., 2015) suggest that future drought incidence could reduce freshwater flows and increase salinity intrusion, pushing the low-salinity zone critical for Delta smelt reproduction and early life stage development east (Brown et al., 2013, 2016). This eastward shift of the low-salinity zone, combined with higher temperatures found in the eastern Delta, could further degrade habitat conditions for Delta smelt if they encounter warmer waters, compounding the challenges for their reproduction and early development.

Additional climate-related stressors compound challenges for Delta smelt. Altered precipitation regimes are modifying seasonal flow patterns crucial for spawning cues (Hobbs et al., 2017), while reduced turbidity resulting from changing sediment transport dynamics decreases the protective cover that historically shielded Delta smelt from predation (Hasenbein et al., 2013).

When the SFHA was conceived, it assumed that a small population of Delta smelt existed in the targeted areas and could benefit from habitat improvements. However, current catch data suggests that Delta smelt are no longer reliably detectable in these locations during the summer and fall. If conditions become increasingly inhospitable due to higher water temperatures and degraded habitat quality, then they may limit the benefits of continuing the action in its original form. Process-based modeling could provide insights for preparing for and managing such conditions.

CONCLUSIONS AND RECOMMENDATIONS

The ecological disruptions experienced by Delta smelt and other native fishes of the Delta and Central Valley have been extreme, especially in the summer and early fall, such that a management effort focusing on Delta smelt summer-fall habitat is scientifically reasonable. The SFHA attempts to address a variety of factors impacting habitat suitability and ultimately Delta smelt through manipulations to flow and food availability. The following conclusions and recommendations

offer feedback and suggest improvements to the action. However, as with the other two actions reviewed by the Committee, it is unlikely that the SFHA will be sufficient to lead to Delta smelt persistence and recovery. Many more components of the SFHA, and other actions systemwide, will be needed to prevent extinction of this endemic Delta fish.

Conclusion 4-1: USBR and CDWR are to be commended for embracing an ecosystem-based approach for protecting Delta smelt that attempts to overlay Delta smelt distribution with food supplies and the favorable habitats conditions of the low salinity zone.

However, over time some components of the SFHA believed to be necessary to generate food for resident native Delta fishes have been stopped. The action agencies are encouraged to pursue the identified special studies related to food and to commit to implementing the Suisan Marsh Salinity Control Gate component of the SFHA over multiple years in sequence.

Conclusion 4-2: The greatest uncertainty of the SFHA is the inability to detect a response in fish populations.

Evaluation of SFHA effectiveness is hampered by natural variability and variability in anthropogenic stressors, the size and complexity of the ecosystem, the dynamics of trophic interactions including those potentially affected by the action, and perhaps most importantly the current low abundance of Delta smelt. In addition to evaluating the effectiveness of the action based on achievement of a suite of abiotic and biotic conditions, which is already done, the health of any targeted fishes collected in monitoring could be systematically assessed. Indices such as condition, gut fullness, isotopic position, and diet can be informative with a much smaller sample size relative to the large numbers necessary for estimating true vital rates (e.g., growth, survival) or population level metrics (e.g., population growth rate). Finally, opportunities for field experimentation exist, including tightly monitored experiments involving large-scale releases of tagged, cultured fish. A sensitivity analysis could be completed to help guide this experimentation by asking how many fish, where, and when. Only if Delta smelt populations start to recover, or if sufficient quantities of hatchery fish are used, will SFHA effectiveness be measurable via fish vital rates and population level viability metrics.

Recommendation 4-1: Development of a process-based Delta smelt model in a spatial food-web context could greatly accelerate better implementation of the SFHA and increase understanding of the effectiveness of various SFHA components.

Ideally, this process-based model for Delta smelt and its prey would be linked to existing models on estuarine hydrodynamics and water quality, which would enable evaluation of how the SFHA ultimately affects Delta smelt reproduction, growth, mortality and seasonal movement. To achieve this level of prediction and analysis, monitoring may need to include the measurement of rates (e.g., zooplankton production) and not just static variables (e.g., standing crop) and should also examine zooplankton responses to action-mediated changes in water residence time. The Committee acknowledges that acquiring this modeling capacity will require targeted data collection and experimentation and possibly multi-year development horizons and investment across agencies.

Recommendation 4-2: Exploring new scientific research areas (through special studies) would enhance understanding of factors limiting Delta smelt and support the implementation of the SFHA.

These research areas include genetic analyses (e.g., eDNA, DNA of predator guts), which could offer insight into the role of predators in determining the effectiveness of the SFHA. Using

cultured Delta smelt, laboratory and field studies could be completed to analyze the species of zooplankton consumed by smelt (short term diet), and stable isotopes could be used to understand long-term diet and trophic position. This information in combination with other critical information (e.g., bioenergetics) could be used to update food-web models in order to better predict and understand the effects of the SFHA on other lower trophic levels, on other imperiled fishes (e.g., longfin smelt and salmonids), and on non-native competitors and predators. Finally, mark-recapture technology, and the tags specifically, are advancing rapidly and may offer opportunities for much stronger monitoring and the ability to tag smaller fishes such as Delta smelt.

Conclusion 4-3: Climate change, in particular future drought, may reduce number of the years in which the SFHA can be implemented.

It may also reduce the efficacy of the SFHA when it does occur, given the sensitivities of Delta smelt to warm temperatures and increased salinity. Eastward shifts of the low-salinity zone, combined with higher temperatures, could further degrade habitat conditions for Delta smelt. As a consequence, the mixture and magnitude of components that compose the action and the targeted regions may require adjustment over time.

Recommendation 4-3: An annual decision process for the SFHA founded on a series of environmental triggers that encompass more than the water year type should be considered.

Lessons learned from previous implementation of the SFHA, including the 2017 Fall X2 action, have shown that the response of Delta smelt may be determined by environmental conditions that are unrelated to water year type, including water temperature and antecedent conditions. The success of Fall X2 in a wet or above normal year may be dependent on the conditions in the previous year. A set of triggers (for example, related to temperature and food resources) for the SMSCG could be established based on expectations developed early in the year, identifying under what conditions the action would proceed and how. Closer to the time of the action, monitoring data based on the triggers could be used to adjust SFHA implementation.

Recommendation 4-4: The SFHA should be developed and adapted using a more coherent and transparent longer-term science program, where a broader range of experts explore, develop, and preliminarily evaluate integrated actions, and agency managers and scientists adapt these more comprehensively considered actions for regulatory and operational implementation.

A successful combination of SFHA components is unlikely to be developed by the current method of internal agency professional judgement and partial consensus alone.

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5

Overarching Issues

This chapter considers cross-cutting issues arising from the Committee’s analyses of Shasta coldwater pool management, Old and Middle River (OMR) flow management, and the Summer-Fall Habitat Action (SFHA). These issues include the needs to (1) enhance collaborative science to improve the pace and effectiveness of Bay-Delta watershed science to inform management efforts; (2) improve the modeling enterprise, with a focus on integrating water management, hydrodynamic, water quality, and ecological models, and (3) continue incorporating climate change into long-term operations.

THE SCIENCE ENTERPRISE AND THE BAY-DELTA WATERSHED

As discussed in Chapter 1, the overall enterprise of science and technical support for California water management (especially for the Bay-Delta watershed) is extensive. This enterprise employs more than 1,000 professionals with a total budget of more than \$100 million per year,¹ with people and money distributed across more than a dozen agencies and research organizations. Adding to the complexity, these government agencies often contract work out to consulting firms. California’s many universities are also deeply involved in aspects of water-related research. This distributed scientific and technical workforce both reflects and reinforces the fragmentation of authority and missions across a wide range of agencies at local, state, and federal levels. Yet, the operational success of these organizations requires shared access to quality information and science.

The following discussion provides the Committee’s recommendations for ways to sustain and improve shared scientific efforts for management of the Bay-Delta watershed. Although the discussion offers a specific suggestion—the creation of a Science Hub—the most important point is simple, irrespective of whether or not agencies pursue the Science Hub concept. Shared science efforts are crucially important to each agency’s individual missions and the overall effectiveness of the community of water project and regulatory agencies. Maintaining and enhancing shared scientific and technical efforts should be a management and strategic science priority.

The Need for, and Challenges of, Coordinated Science

The idea that management of complex environmental systems should draw on collaborative science is not new. Terms such as team science, interdisciplinary research, transdisciplinary research, convergence research, and collaborative science are often used to describe collective efforts to tackle complex scientific or societal problems (Hall et al., 2012; Lyall et al., 2011; Stokols et al., 2013). Such efforts emphasize the importance of collaboration across disciplines, institutions and sectors to tackle problems that are too intricate for any single field or entity to resolve.

Collaborative approaches often improve the relevance and usability of science for decision-making, particularly for problems involving conflicts (Cash et al., 2003; Kirchhoff et al., 2013). Similarly, interdisciplinary research teams can better address complex problems by integrating diverse perspectives and expertise, thus creating solutions that are both scientifically robust and socially relevant (Hall et al., 2012; Stokols et al., 2013). Strengthening interagency and cross-disciplinary collaborations enhances the

¹ See <https://www.deltacouncil.ca.gov/pdf/dpiic/meeting-materials/2024-10-28-fy-2022-2023-delta-crosscut-budget-report.pdf>.

ability to translate scientific knowledge into practical solutions in a timely and defensible way, creating more effective bridges between science and policy and across stakeholders.

Despite these benefits, coordinating scientific efforts and bringing that science to managers is challenging. That challenge exists partly because some fragmentation across agencies and programs is necessary. In some cases, science in agencies is focused on mission-specific priorities, and in other cases questions require interactions among disciplines and across agencies and other interested parties. If everything science-related happened through coordinated, interdisciplinary, multi-agency initiatives, hardly anything could get done. In a system as complex as the Bay-Delta watershed, the ideal of holistic decision-making is unattainable; no person can know, and no model can address, or even consider, every important facet of the system. Fragmentation also sometimes enables innovation; groups independently working on similar problems often introduce fresh ideas. Fragmented management also can be easier to budget, because it reduces the “transaction costs” of sharing funds or personnel across agencies and can clarify the assignment of responsibilities and accountability. Contracting work out to consultants may sometimes save money and can bring in distinctive expertise not immediately available within agencies, and contracting can sometimes expedite the process. For these reasons, the pressures towards fragmentation are constant—and in some ways valuable.

But fragmentation also can create problems when scientists and system operators are drawing on different assumptions, bodies of information, and models or versions of models while trying to manage the same system. That can easily lead to situations where different managers and regulators talk past each other, act at cross-purposes, or make mistakes that other entities’ knowledge or collaboration could have helped avoid.

Coordinated Science and the Bay-Delta Watershed

The need for shared knowledge and for advancing scientific and technical understanding of the Central Valley’s water problems remains pressing. A warming climate, more extreme events, and invasive species are changing underlying conditions for ecosystems, water supply, and flood control. Traditional monitoring is growing in expense while new monitoring techniques are expanding the range of information and insights available, but require coordinating expertise, instrumentation, and planning to realize these benefits and control costs. Political dysphoria has increased skepticism of facts and science, making it both more difficult and more valuable to develop common understandings.

The value of collaborative, coordinated, and science-informed decision-making has long been recognized in California. Agencies responsible for managing California water have taken important actions grounded in that recognition. For the Bay-Delta and its watershed, several organizations are already important in supporting collaborative science—including the U.S. Geological Survey (USGS), the Delta Science Program, the San Francisco Estuary Institute, the California Water and Environmental Modeling Forum (CWEMF), and the Interagency Ecological Program (IEP). Box 5-1 summarizes some key achievements of these entities.

In the Committee’s view, efforts such as those listed in Box 5-1 are crucial and should be expanded. These efforts could be bolstered by creating a centralized organization with a broad mandate, as described herein—the Committee uses the term the Bay-Delta Science Hub, or just the Hub. Its work should encompass the Delta and its watershed as well as relevant inter-connections to San Francisco Bay. Such centralized science organizations have been broadly useful to all entities involved, with several examples listed below.

1. Southern California Coastal Water Research Project²
2. National Center for Ecological Analysis and Synthesis³

² See <https://www.sccwrp.org>.

³ See <https://www.nceas.ucsb.edu>.

3. Delta Science Program⁴
4. USGS John Wesley Powell Center for Analysis and Synthesis⁵
5. Chesapeake Bay Program Office⁶ and the companion Chesapeake Research Consortium⁷
6. California Water Data Consortium⁸
7. San Francisco Bay Estuary Institute (SFEI)⁹
8. University of California COEQWAL project¹⁰
9. U.S. Bureau of Reclamation (USBR) and California Department of Water Resources (CDWR) collaboration on the CalSim model.

BOX 5-1

Selected Examples of the Outcomes of Collaborative Science in California

Pelagic Organism Decline. The IEP led one of the first synthesis activities linking experts, data, and information from across agencies and other entities to identify the primary causes of the dramatic reduction in several fish species in the upper estuary of San Francisco Bay and the Delta (Sommer et al., 2007). The IEP provides a forum to generate and integrate ecological information for management of the San Francisco Bay-Delta ecosystem and the water that flows through it. The IEP has been providing monitoring data and scientific information for more than 60 years (Herrgesell, 2012).

The Baylands Goals Project.^a This comprehensive project was coordinated by the California Coastal Conservancy and the San Francisco Estuary Institute in 2015. Comprehensive restoration goals for the San Francisco Bay estuary were produced by a collaborative of 21 management agencies working with a multi-disciplinary team of more than 100 scientists.

Delta Science Fellows Program.^b This program administered by the California Sea Grant Program and Delta Science Program is an example of an initiative that builds links between academia, community partners and agencies. This competitive program provides funding for early career researchers to work with academic, community, and agency mentors. Awards are given to those research questions that contribute to solving priority management issues and informing decision making.

State of Bay-Delta Science Reports.^c Since 2013, the Delta Science Program has convened multiple experts across the science enterprise spectrum to generate periodic updates of the state-of-the-science in the Bay-Delta and its watershed with findings published in the open access *San Francisco Estuary & Watershed Science* journal.

Water Temperature Modeling Platform (WTMP). As discussed in Chapter 2, USBR has invested considerable resources and staff to develop the WTMP with an objective of building a diverse community of experts around a suite of models that is easily accessible. The WTMP has been the subject of rigorous peer review and is expected to be launched to interested experts in fall 2025.

Training Workshops for CalSim 3 and Other Central Valley Project (CVP) and State Water Project (SWP) Models. Among many current efforts directly related to CVP and SWP is that CDWR and USBR have worked with CWEMF to offer training sessions in CalSim 3 and to build a virtual community of experts beyond CDWR and USBR.^d

^a See <https://www.sfei.org/projects/baylands-ecosystem-habitat-goals-project>.

^b See <https://caseagrants.ucsd.edu/funding/2025-delta-science-fellowship>.

^c See <https://sbds.deltacouncil.ca.gov>.

^d See <https://cwemf.org/wp/services/workshops/>.

⁴ See <https://deltacouncil.ca.gov/delta-science-program/>.

⁵ See <https://www.usgs.gov/centers/john-wesley-powell-center-for-analysis-and-synthesis>.

⁶ See <https://www.chesapeakebay.net>.

⁷ See <https://chesapeake.org>.

⁸ See <https://cawaterdata.org>.

⁹ See <https://www.sfei.org>.

¹⁰ See <https://live-coeqwal-ca.pantheon.berkeley.edu>.

The scientific research that supports and stimulates more informed management is complex and crosses agency boundaries, with different agencies emphasizing different aspects of issues. Even when consensus exists on the underlying science, less consensus exists on priorities and approaches that guide decision making (Luoma et al., 2015). This tension is reflected in two recurring critiques of the science enterprise: (1) science is often underutilized in policy and management, in part because of inadequate science communication; and (2) management entities struggle to employ scientific knowledge in developing timely, relevant and actionable solutions.

A Bay-Delta Watershed Science Hub

This discussion of a Bay-Delta Watershed Science Hub is an exploration—not a detailed blueprint. A feasibility study, as proposed below, could flesh out the conceptual framework, or at least provide a forum for major project and regulatory agencies to discuss their common science needs. The Committee envisions the Hub as a coordinating entity for shared science and technical efforts supporting multiple agencies. Its work could include the following:

1. Developing and sustaining coordinated monitoring to address specific topics, fundamental conditions, or long-term trends; developing and maintaining common multi-agency data sets; and performing synthesis of existing knowledge and data
2. Developing and maintaining modeling capabilities (e.g., expanding joint CVP-SWP operations modeling to include ecosystems, developing a common water accounting framework for the Central Valley; and applying machine learning) needed by multiple agencies and programs
3. Reviewing existing models and structured model comparisons to enhance the algorithms and data used, improve estimates of risk and uncertainty; and better integrate physical, biogeochemical, and life-cycle models
4. Coordinating multi-agency studies and technical consensus efforts on broadly important scientific questions
5. Developing and vetting ambitious new ideas, such as enhancing migration of species or inhibiting salinity intrusion through altered flow patterns and timing of tidal flows across the Delta
6. Offering joint training for models, data analysis and mining, AI, visualization, monitoring technologies and other activities that support agency needs and professional development for staff working in the system
7. Recruiting and educating the next generation of scientists and engineers through opportunities provided by the Delta Science Fellows program and other agency-academia partnership programs
8. Supporting and strengthening current long-term scientific and technical planning initiatives, such as the Delta Science Plan

Regarding 2 and 3 above, there is a temptation to build the most complicated models to represent complex systems. Such modeling has high cost in time and funding and can lead to over-fitting and over-confidence in modeling results and over-dependence on these expensive models for new and changing problems. Conversely, simpler models are quicker and cheaper to develop, more easily understood (in terms of strengths and weaknesses) and could provide better simulations beyond the training data. The Hub organization, with the engagement of capable experts, could help guide the right balance between simplicity and complexity in model selection and development, as well as identification and prioritization of modeling improvements. This could improve the transparency and robustness of decision-making that use models.

Many of the activities listed above are done independently by individual organizations. The community of agencies (and their missions) would benefit from more collaborative activities across the board. The various modeling groups are primarily focused on the objectives of a single agency or department within an agency. There is little time or direction for these experienced modelers to interact with other agencies or even across programs within the same organization particularly when planning or developing innovations or the next generation of a model or method (refer to Section on Siloing). The Hub could provide a forum and resources for key individuals to engage across boundaries through mechanisms such as dedicated Sea Grant Fellows and postdoctoral researchers to work within modeling teams, enhanced communications such as collaborative online communication tools and CWEMF or other in-person activities. Some activities likely to reap the largest benefits from coordination across institutions include: routine syntheses of existing data and research; identifying and testing new monitoring approaches; stewardship of existing models and identifying and supporting new modeling initiatives; and planning and executing integrated scientific studies that could include field, laboratory, and modeling initiatives focusing on major confounding issues such as those highlighted in Chapters 2-4.

A small core staff, which might include a program manager and technical staff, could manage the Hub. The technical staff would have skills in areas such as data science and modeling and would be able to work with experts across the Bay-Delta watershed on key issues such as model interoperability or new monitoring approaches. Some staff could be assigned on a project basis, either full-time or part-time, from contributing organizations (including agencies, tribes, nongovernmental organizations [NGOs], consultants, and academia). Specific project leadership would be identified by agencies or entities with particular interest in the action(s) that will be informed by the science or study outcome.

The Hub would need a physical location and a virtual presence, a modest funding base to support these assets and staff, and access to computational resources (e.g., by agreement with agencies and/or universities). Specific project activities coordinated by the Hub could access funding from additional sources, such as agencies, research programs, foundations, the private sector, and other entities. Projects could be funded as directed research or through a competitive grant process with clearly articulation of the contribution to management actions. This process could be facilitated through existing avenues such as the Delta Science Program and California Sea Grant, but would need more involvement from other major project and regulatory agencies.

The Hub's priorities could be developed from the Delta Science Plan (which includes the watershed and connections to the Bay), previous work by the Coordinated Science and Adaptive Management Program, the Sacramento River Science Partnership, agency/tribal priorities, and other sources. The Hub would also have flexibility to coordinate and mobilize scientific activities in response to episodic events such as an earthquake, unanticipated levee break, contaminant spill, or a newly identified invasive species determined to significantly influence the ecosystem and Project operations. An effective governance structure is critical if the concept of a Hub, however it is constituted, is to be successful.

Feasibility Study

The Committee recommends a multi-agency feasibility study to explore improvements to the management of science for water and ecosystems in the Central Valley, including specifically the concept of a Hub. The feasibility study should consider earlier assessments and concepts and describe:

1. The basic organizational structure of the Hub: What, Why, How and Who
2. A governance structure to ensure that the Hub is agency-led and enhances the in-house agency expertise and mission of agencies. Careful consideration should be given to a governance structure that ensures the primary users of the science (including the State Water Resources Control Board, CDWR, and USBR) receive the information they need, develop shared scientific knowledge, and support complementary collaborative tools. The Delta Science Program is widely respected for facilitating, coordinating, reviewing and working

- across agency and interest boundaries to identify common science priorities. However, this role does not currently extend to having responsibility to coordinate or implement a comprehensive interagency science program. Similarly, effective engagement with California's academic institutions should also be explored within this feasibility assessment
3. How priority activities would be selected and governed (expanding from the efforts of DPIIC and the Delta Science Plan)
 4. The (a) staffing, (b) how experts would be engaged (particularly those representing underserved communities, tribes, NGOs, academia and groups with limited resources), (c) how computational resources would be accessed, (d) how data would be accessed and managed from different repositories, and (e) the tools and expertise that would be available to investigative teams
 5. A base budget for sustaining the Hub, and source of base funding support
 6. Additional funding mechanisms for supporting specific projects
 7. How problems to be addressed would be selected, scoped, prioritized and implemented
 8. How this entity would ensure meaningful engagement of experts from interested parties and how results are communicated
 9. Performance metrics, review process, and renewal cycle
 10. A potential charter, which would also examine any need for legislative establishment

A well-scoped feasibility study of the Hub concept would provide agency leaders and policy makers with a pragmatic, structured framework to evaluate this opportunity. A feasibility study could be completed in less than 12 months and the approach could be piloted by pursuing two or three demonstration problems with a timeline, adequate funding and other resources, and clearly specified deliverables. This approach would allow the concept to evolve, building on what has worked. The science hub is not a new concept and the feasibility could build on past ideas and include a review of other frameworks and their effectiveness, successes, and failures—including assessments done by the National Center for Ecological Analysis and Synthesis, the National Socio-Environmental Synthesis Center, the Southern California Coastal Water Research Project, and the John Wesley Powell Center for Analysis and Synthesis.

MODELING

California water management draws upon a broad array of numerical models, and the Committee is impressed with the quality and sophistication of the agencies' modeling work. Nevertheless, the models have been developed by different agencies and different groups within agencies, academia, and other organizations. Some models have been repurposed for uses other than those for which they originally were developed, and some models were originally developed when computational science was less advanced. Most models have their origins in periods when California's climate, water management issues and technologies, and water demands were significantly different than they are today or will be in the future. All of these limitations suggest that better integration of new data into models (rather than reliance on the historic record), better integration among models, development of new models that can outperform their predecessors, and better management of the modeling enterprise as a whole are key to better linkage of scientific knowledge and management decisions.

Computer modeling of aquatic systems and water management for the Central Valley has developed since the 1970s to be among the best in the world. Yet, the Central Valley and its modeling enterprise face new challenges from the diversification and intensification of water demands including higher evaporative demand; competition between native species that have adapted to a historical climate and nonnative species, some of which are better adapted to current conditions; and the targeted end of groundwater overdraft by 2040, which currently supports a large proportion of water use. The following

sections specifically discuss higher level issues with CalSim applicable to all three actions reviewed in the previous chapters (and other actions).

Issues with CalSim

CalSim (and its predecessor DWRSIM) was designed to develop and compare alternative infrastructure designs for expanding the SWP, because building statewide infrastructure was the principal mission of CDWR at that time. CalSim is foundational for much of the Bay-Delta modeling and remains useful for many purposes, but it can be a misfit for other purposes, such as ecosystem management.

Time Step

When CalSim was first developed, computational limitations made a monthly model a reasonable compromise between temporal resolution, accuracy, and computability. However, in the past 35 years, the power of modern computers, software, and storage have exploded. But even with these improvements, major CalSim model runs, because of their more detailed spatial and institutional representation, are slower than their predecessors. Interest is growing in modeling ever finer-scale operations, which include OMR operations in the Delta, fish habitat, environmental and ecosystem performance indicators, coldwater pool management, flood risk management and operations, and hydropower operations and benefits. Simple or statistical disaggregation of results from monthly to daily values, or finer, is now used. For some purposes, this use is reasonable. However, there could also be value in reducing the main time-step of CalSim to reduce temporal extrapolations (as discussed below and in Rose et al., 2024).

The monthly timescale resolution of CalSim3 is too coarse for representing biological effects, which occur over much smaller time scales to capture diurnal and other processes. Not surprisingly, a reduction of the simulation timestep for CalSim without prohibitively increasing the computation time has been a topic of discussion among CalSim users. The smallest model time step should be determined by the appropriate transport time scale (Monsen et al., 2002), which appears to be the advection time of water parcels to the Delta, estimated at about five to eight days. A reduction of timescale will help reduce errors introduced by the large impedance encountered due to mismatch of time scales when downscaling flow variables from monthly to daily or hourly values. Conversely, Delta Simulation Model II (DSM2) solves the shallow water equations for which the computational times step is determined by the Courant and Wave Resolution Factor criteria. Currently, DSM2 uses 15-minute timesteps with inputs provided at a commensurate time scale. Sridharan et al. (2018) argued¹¹ that this timestep may not satisfy the above criteria for numerical consistency. Where modeling must couple processes at large and smaller time scales, three approaches are available: disaggregate large time step results into smaller time steps (by

¹¹ This is the time scale where a perturbation in the Delta is felt systemwide and flow is adjusted accordingly. This is the minimum timestep that the model could run capturing the changes within. The model time step should be determined by the processes that need to be resolved: (1) For DSM2 that solves the cross-sectionally-averaged Saint-Venant equations for shallow flows, the time step ought to satisfy the Courant–Freidrichs–Lewy criterion so that disturbances are contained within a grid during one time step. Because disturbances satisfy the shallow-water disturbance speed $c \sim \sqrt{gh} \sim 10$ m/s, h being the averaged fluid depth ($h = 10$ m; Sridharan et al., 2018), within 15 minutes the disturbances cover a good distance within the Delta ~ 10 km (compared to 1.0–1.5 km grid size used). Hence, we recommend a reduction of the time step for DSM2, which is the same recommendation as Sridharan et al. (2018). A reduction of grid sizes is also recommended, say to ~ 300 m, considering that nonhydrodynamic disturbances (e.g., salinity) travel at lower speeds ~ 0.3 – 0.5 m/s. (2) For CalSim3, which does not depend on shallow water theory, this time step would be the advection time of a water parcel moving through the Delta, ~ 200 km/ $(0.3$ – 0.5 m/s) ~ 5 – 8 days. (The average speed was estimated using Ramon et al., 2018). Therefore, the CalSim3 time step could be reduced significantly to a week or so.

simple averaging or statistical methods), use empirical models (such as artificial neural networks [ANNs] in CalSim to fit short-term compliance to longer simulation steps), or explicitly model on the smaller time-steps. A modeling strategy would consider (and perhaps use) all three of these approaches.

Although daily models are used for some large water system operations models (e.g., New York City), a weekly CalSim model would suffice if followed by reasonable disaggregation methods for finer time periods (by simple or statistical disaggregation or explicit nesting of long and short time-step process-based or empirical models). However, such methods cannot be used for transient (dynamic) calculations such as those required for pulsed flows and sudden barrier closures for which dynamic models such as DSM2 need to be used.

The types of hydrologic information needed for relevant biological models that utilize CalSim output directly or derivatives of CalSim simulations include peak winter flows, spring recession peak and duration, fall pulse duration and peak, ramping rates and accurate minimum instream flows within reaches (Yarnell et al., 2015; Poff et al., 1997; CEFWG, 2021). These examples of hydrologic output that cannot currently be generated from CalSim's monthly average inflow. Reducing the CalSim time step would help encompass these metrics.

Moving to a weekly-time-step version of CalSim may seem major, but it need not happen all at once. This will require more detailed data sets including hydrologic inflows, and reformulation of the operational description of some parts of the system. Different approaches to providing finer time-step results for ecological and flood management purposes could be explored.

Transparency

CalSim3 is an important planning tool, although there is much room for improvement. Although CalSim3 has been reasonably well documented (CalSim, 2002), some details on its usage and inner workings need better transparency—a difficult chore given the many agencies, consultants, model developers and researchers that have provided upgrades for CalSim3. In addition, resources to train modelers across the wide swath of CalSim3 operations, and continuous training of a new generation of CalSim 3 modelers should be a priority. The CWEMF/CDWR efforts to run training sessions for CalSim3 for the modeling community are a step in the right direction.

Additional Processes

In recent years, higher resolution hydrodynamic models and innovations in particle tracking have provided greater insight into many ecological processes. Examples include the work of Holleman et al. (2022), who combined telemetry of tagged hatchery fish with a high-resolution hydrodynamic model to quantify the range of swimming behavior of emigrating salmon smolts at a tidal junction. They found that smolts moved through the area more slowly than the mean flow velocity, which may have important implications for flow management in the Delta. Similarly, movement behavior for Delta smelt was investigated using behavior movement models that included high resolution hydrodynamics and population models by Korman et al. (2022) to explore proportion entrainment loss. They found that behavioral rules based on concepts such as tidal surfing, movement toward more turbid water, or movement toward less saline water did not, on their own, explain the temporal and spatial variability in trawl catches or the temporal variation in salvage. Similar types of analyses that seek to understand species movement in response to management action using high-resolution hydrodynamic models have examined longfin smelt (Kimmerer and Gross, 2022) and the movement of copepods (Hassrick et al., 2023). Numerical experiments using high-resolution coupled models to test actions can reveal insights about local processes or short-term effects that are not captured in ecological models driven with DSM2 outputs. Such three-dimensional water flow, water quality, and ecological modeling capability can also expand the horizons of Delta management actions to include modifications of tidal flows in the Delta to

support biological productivity and transport of food and organisms to desirable locations, and reduce movement of native species into unsuitable parts of the Delta.

Both CalSim3 and DSM2 lack turbidity and sediment transport capabilities that could enhance their use in OMR flow management. This deficiency precludes calculations pertinent to turbidity bridge avoidance, requiring use of measured turbidities at specific locations for OMR management. Scour is another major issue at some flow junctions (divergence regions), and sediment transport models coupled with hydrodynamic models such as DSM2-HYDRO or DSM2-PTM could simulate when excessive scour could harm fish (Bowen et al., 2012). Delta sediment/bed erosion models have been in development over past decades: for example, Delta Simulation Model 2-General Transport Model (DSM2-GTM) for real-time operations; and long short-term memory ANN suitable for CalSim3 based planning (Abrishamchi and Nam, 2019; Kim et al., 2022). Their operational or planning use await further developments. To this end, development of parsimonious models such as ANN salinity-flow relationships in CalSim3 would be useful.

CalSim's origin as an operation planning model for the SWP and CVP has hindered its ability to represent the coordinated operations of many local resources and decisions within the larger California water system. The model misses much of the more sophisticated water banking, market, and exchange decisions made locally and regionally to integrate a broader portfolio of local, regional, and groundwater supplies, and many water demand management activities are largely absent from state and federal modeling. These local and regional decisions are increasingly relied on statewide and greatly reduce the costs of shortages, droughts, Sustainable Groundwater Management Act compliance, and climate adaptation.

Siloing

Developing and upgrading models in an operational setting with many participants and stakeholders is difficult. There is a high degree of inertia in advancing modeling for the Bay-Delta system. Some of this inertia is because of the convenience of using models (and monitoring networks) already accepted and more usable in one's agency or program (because of staffing, accessibility, or ease of internal communication, or agency missions). Some is perhaps due to the fear, expense, or risks of an agency having to master an additional model or modify existing models for additional missions outside their normal operations. Furthermore, creating new monitoring to support new models can be expensive. This can be compounded by separation, within agencies, between model developers, system operators, and decision-makers. All of these factors can lead to institutional modeling "silos" that provide comfort and expertise within individual agencies. However, such "silos" of modeling also impede communications, collaboration, and the development of common explorations and understandings of problems and solutions, which increasingly span several state and federal agencies. Modeling should help to bring together agencies and interests for common understanding, knowledge, and perhaps trust, both among agencies and across the entire stakeholder community. However, modeling currently often reinforces separation of agencies (and programs within agencies) and creates barriers to common analyses, discussions, and knowledge. The proposed Hub could help break down these silos and lead in the coordinated development and strategic application of models (new or existing) to controversial problems involving multiple agencies.

WATER MANAGEMENT IN A CHANGING CLIMATE

Each of the previous three chapters has discussed how various climate impact drivers (CIDs) will affect the three actions reviewed by the Committee. This section provides an overview of the CIDs, reiterates their effects on the actions, and recommends ways to improve the integration of climate-related impacts into modeling and project operations and planning. CDWR and USBR have adopted two

different approaches. Increased coordination and a detailed comparison of these approaches would offer additional insights about uncertainties and avoid confusion or conflicting planning decisions resulting from divergent methodologies and predictions.

CIDs are defined as physical conditions of the climate system—such as average states, events, or extremes—that affect human or natural systems (IPCC, 2021). The eight drivers considered by the Committee are described below, along with their relevance to the three actions. This information is also summarized in Table 5-1, which includes three rankings (A, B, or C) that reflect whether the impact is direct or indirect, whether observed changes are statistically significant, whether there is consensus among models on projected changes, and whether the impact is positive or negative. Furthermore, because changes in CIDs can involve different characteristics—such as magnitude, intensity, frequency, duration, or timing—Table 5-1 specifies which characteristic is relevant for each driver. For example, streamflow changes refer specifically to shifts in the *timing* of streamflow, not its magnitude. For additional information on observed and projected changes associated with these climate impact drivers, see Appendix A and Chapters 2, 3, and 4.

TABLE 5-1 CIDs and Their Influence on the Long-Term Operation of the Three CVP Actions

<i>Climatic Impact Driver</i>	<i>Shasta Cold Water Pool Management</i>	<i>Old and Middle River Flow Management</i>	<i>Summer-Fall Habitat Action</i>
Annual Precipitation (Magnitude)	B	B	B
Annual and Seasonal Temperature (Magnitude)	C	C	C
Snowpack (Magnitude, Timing)	C		
Sea Level Rise* (Magnitude)		A	B
Streamflow (Timing)	B	B	B
Heatwaves (Magnitude, Frequency, Intensity)	B	B	B
Droughts (Frequency, Intensity, Duration)	C	C	C
Extreme Precipitation (Intensity, Frequency)		A	A
Wildfire (Frequency and Magnitude)	A		
Symbol	Importance	Definition	
A	Moderate or Uncertain	CIDs that have an indirect impact on the action, unlike the other two categories, the impact can either be negative or positive.	
B	Important	CIDs that have a direct impact on the action but are not statistically significant or their direct effects are less significant for management decisions.	
C	Critical	CIDs that have a direct negative impact on the action and there is sufficient evidence of statistically significant change in their characteristics (e.g., magnitude, intensity, duration, frequency).	

NOTES: Each driver is characterized by changes in magnitude, intensity, frequency, duration, or timing but only certain aspects are considered here (indicated in parentheses). Blank cells indicate drivers not considered to have a direct or substantial impact on a given action.

*Sea level rise effects are not considered to be an important factor until after 2050.

Annual Precipitation. Annual precipitation in this context refers to the long-term average of total yearly precipitation, typically calculated over a 30-year period or longer. Changes in annual precipitation are considered in terms of magnitude only. Observations indicate that California’s annual precipitation has decreased over the period 2002–2021 compared to the long-term average; however, future projections are highly uncertain, with models suggesting either a slight increase or decrease in annual precipitation (see Appendix A). The rankings in Table 5-1 are based on recent decreasing trends (2002-2021) in annual precipitation and their potential impacts on the three CVP actions.

Annual and Seasonal Temperature. Annual and seasonal temperatures in this context refer to long-term average air temperatures, calculated over a 30-year period or more. Only changes in magnitude are considered. Both observational data and model temperature projections show an upward trend across California (see Appendix A pg. 14). Table 5-1 shows that, along with drought, this CID is critical for all three actions, mainly due to the impacts of higher water temperatures on fish health. Rising temperatures alone could jeopardize the existence of wild cold-water species in the Delta and the Central Valley (Brown et al., 2016).

Snowpack. Changes in snowpack involve both decreases in snow depth and snow water equivalent (magnitude), as well as shifts in the timing of peak snowpack and snowmelt events (timing), both of which are discussed in detail in Appendix A. A decrease in snowpack is a critical CID only for the Shasta Coldwater Pool Management Action due to its impacts on formation and maintenance of the coldwater pool.

Sea Level Rise. Only changes in the magnitude of sea level rise, and not timing, were considered in evaluating the impact of this CID to the three CVP actions. According to OPC (2024), by the year 2100 sea levels in California may rise by 1 to 6.6 feet (0.3 to 2.0 meters) depending on emissions levels. Continued sea level rise is only expected to be important for the Summer-Fall Habitat Action due to the eastward shift of the low salinity zone such that it no longer overlaps with Suisun Marsh and Suisun Bay. OMR flow management might also be affected if sea level rise and associated salinity increases mean that pumping rates would have to be decreased in order to prevent salinity intrusion into the Delta. Both effects are anticipated to only be important over very long time frames (after 2050).

Streamflow. Although streamflow can change in volume (magnitude) or frequency, this discussion (and the Table 5-1 entries) focuses specifically on changes in timing—that is, consistent shifts toward earlier or later peak flows. There is growing evidence that timing shifts are most pronounced in snow-dependent regions, including parts of California (see Appendix A). As discussed in Chapter 2, shifts in the timing of streamflow could affect the development of the coldwater pool at Shasta, and it could also affect fish health in the upper Sacramento and San Joaquin rivers and the Delta by altering the timing of spawning cues for fish.

Heatwaves. A heatwave is a period of unusually high temperatures, defined relative to a local or historical threshold, lasting from several days to weeks. Changes in heatwaves may include higher peak temperatures during events (magnitude), more events per year (frequency) and longer-lasting heatwaves (duration). Table 5-1 addresses all three of these aspects, which are projected to increase in the future (see Appendix A). Common indices used to characterize heatwaves include the annual maximum of daily maximum temperature and the number of days exceeding a defined threshold. This area of study is emerging, with new analyses showing significant increases in the frequency and duration of both air and water temperature heatwaves in the Bay-Delta region, although the trends may become even clearer with longer-term datasets and further research (Mahardja et al., 2025). Heat waves are expected to have wide-ranging implications for ecological and human health in the region and to affect all three actions reviewed in this report, so understanding their effects remains a developing scientific priority.

Droughts. Changes in droughts include increased intensity (greater water deficits), longer duration, and greater frequency, which are typically driven by both reduced precipitation and increased evapotranspiration. As Table 5-1 shows, all three actions could be critically affected by drought, from the action being suspended (Summer-Fall Habitat Action) to the inability to develop a sufficient volume of cold water at Shasta reservoir, to growing inaccuracies in the estimation of evapotranspiration that plays a role in OMR flow management.

Extreme Precipitation. Extreme precipitation refers to short-duration events of unusually high rainfall or snowfall. Changes in extreme precipitation may be more intense individual events (intensity), more frequent occurrences (frequency), and longer or more persistent events (duration) or over a more extensive area. Here, the discussion focuses on the first two types of changes.

In California, climate model projections indicate a likely increase in the intensity of precipitation, even in regions where total annual precipitation may remain stable or decline (see Appendix A). Table 5-1 outlines the potential impacts of changes in extreme precipitation on the CVP actions. While these extreme high precipitation events could be disruptive to many aspects of the entire system, whether they will positively or negatively affect the three actions is unclear.

Wildfires. Wildfires are unplanned fires that burn natural vegetation. Along with forest management practices and increased human activity, wildfire occurrence is influenced by multiple climatic and environmental factors, including temperature, precipitation, humidity, wind, and vegetation amount and dryness. Changes in wildfire activity include more frequent fire events (frequency) and larger areas burned (extent or magnitude) among many others. In California, observational data show increased frequency and extent of wildfires in recent decades, driven by such climate factors as higher temperatures, reduced snowpack, earlier spring onset, and prolonged dry periods (see Appendix A). Table 5-1 shows that the implications of increased wildfire activity are most relevant to Shasta coldwater pool management, but the exact impacts have not yet been well studied.

Recent efforts to incorporate climate change into long-term operational planning and modeling for the CVP and SWP emphasize the importance of adapting water resource management to account for shifting hydrological patterns, rising temperatures, and increased variability in precipitation. According to the Delta Stewardship Council's modeling report (2024), climate change scenarios are integrated into hydrological models such as CalSim and the Variable Infiltration Capacity (VIC) model to project future water availability and demand. Other models, such as DSM2, have been updated to include projections for sea level rise and upstream hydrological changes, thus enabling simulation of water quality, flow dynamics, and salinity intrusion for a range of climate scenarios. The Delta Stewardship Council's Fish and Aquatic Effects Analysis report (Rose et al., 2024) reviews the USBR efforts to integrate climate projections into ecological models to evaluate the effectiveness of operational strategies aimed at mitigating these impacts, such as adjusting flow releases or improving habitat connectivity.

CDWR and USBR are incorporating climate change modeling efforts into their respective operational frameworks for long-term operations. CDWR's approach, detailed in the 2024 Delivery Capability Report (CDWR, 2024) and described in more detail in Box 5-2, uses multiple climate scenarios to capture uncertainties in future impacts. This approach includes system stress testing with historical and simulated hydrological data, downscaled climate projections from 15 global climate models (GCMs), and the integration of sea-level rise scenarios into CalSim3 using ANNs. USBR employs a cascading modeling approach for long-term operational planning, beginning with emission scenario selection and progressing through climate simulations, spatial downscaling, hydrologic modeling, and operational assessments. Results from these analyses drive hydrodynamic models to assess circulation, salinity, and water quality and habitat impacts, ensuring that USBR's long-term planning accounts for both global trends and regional hydrological challenges. USBR's approach is further detailed in Box 5-3.

BOX 5-2 California Department of Water Resources Climate Modeling for SWP Operations

CDWR's climate planning for the SWP is primarily carried out through two efforts – the Delivery Capability Report (CDWR, 2024) and the SWP Climate Adaptation Plan. The latter effort, to be released in 2025, will outline how innovative and planned strategies can influence future water deliveries and mitigate the risk of reductions in average annual supply. In the 2024 update to the Delivery Capability Report, CDWR has taken a new approach to generating climate scenarios. Previous reports relied on a single future scenario to estimate SWP delivery capability, representing a central tendency of climate impacts. This approach was deemed insufficient for capturing the full range of uncertainties associated with climate change. Developing multiple scenarios provides a broader understanding of potential risks and enables planning that aligns with varying user risk tolerances and objectives. The 2024 update utilizes a range of climate scenarios, but holds operations and infrastructure constant. CDWR plans to align the scenarios developed in this report with other State efforts to account for climate change.

Future conditions for temperature, precipitation and sea-level rise are characterized by their “Level of Concern”, or the “percent of model-informed climate outcomes that would result in better system performance” (Schwarz, 2024). Conditions with “more challenging outcomes” are higher concern and conditions with “less challenging outcomes” are lower concern. Figure 5-1 below illustrates the three scenarios—a 95th, 75th, and 50th percentile Level of Concern. These scenarios include projections for sea level rise, average annual temperature, average annual precipitation, and extreme precipitation events. Projections extend to 2085.

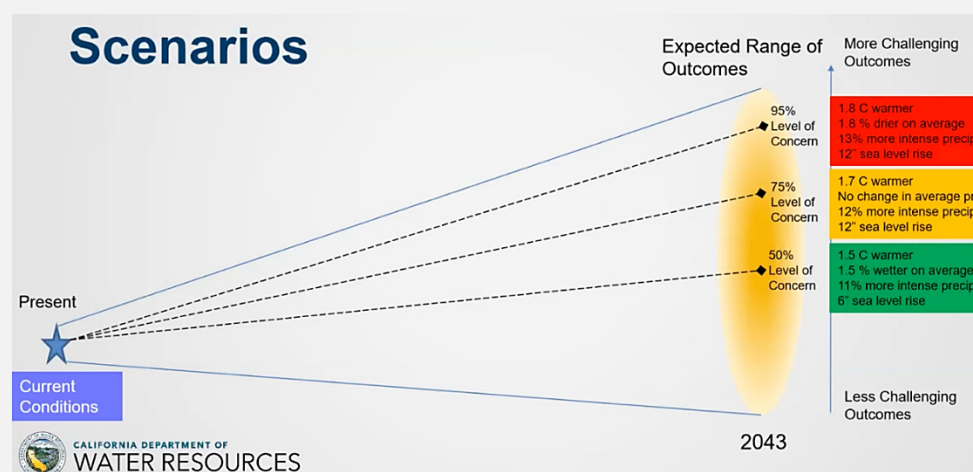


FIGURE 5-1 Climate scenarios for the Delivery Capability Report.
SOURCE: Schwarz (2024).

The scenario development process involves five key steps:

1. System Stress Test. CDWR stress-tested the SWP using historical and simulated hydrological data from a weather generator with the goal to simulate SWP operations over a range of climate conditions—from warming 0 to 5°C and from -25 to 25 percent change in average annual precipitation, resulting in 26 different simulations. This stress test was performed on the Sacramento soil moisture accounting model and the CalLite model. The outputs of these simulations enable CDWR to select which performance metric was most appropriate to use for a larger modeling effort. The Eight River Index April-to-July flow^a was selected as the most representative metric for modeling.

continued

BOX 5-2 *continued*

2. Climate Model Output. Climate model projections for precipitation and temperature were obtained from 15 GCMs available from the most recent release of global GCM output, the Coupled Model Intercomparison Project Phase 6 (CMIP6). Of the available set of climate scenarios that characterize future emissions and global development pathways, CDWR utilized Shared Socioeconomic Pathway (SSP) 2-4.5 (Middle of the Road), SSP3-7.0 (Regional Rivalry) and SSP5-8.5 (Fossil-Fueled Development) (IPCC, 2021).

Because GCM output from CMIP6 is available at a spatial resolution too coarse for modeling and analysis within California, CDWR used the 3-kilometer (km) downscaled LOCA2 dataset, which is specific to the California domain. LOCA2 employs a hybrid downscaling approach that combines statistical methods with output from dynamically downscaled GCM-Weather Research Forecasting (WRF) runs, which are bias corrected to ERA5 reanalysis data (Pierce et al., 2023). Using gridded GCM outputs from LOCA2, CDWR averaged daily temperature (minimum and maximum) and daily precipitation outputs to monthly for the entire period of record (1950–2100) and then aggregated spatially to the 20 major watersheds within the CalSim3 domain. Monthly precipitation and temperature values for each watershed were then averaged to the entire CalSim3 domain, using two approaches: an area-weighted and flow-weighted average. The flow-weighted average was ultimately used.

The final step in climate output processing was to estimate change factors, or changes in millimeters per year (mm/yr) or degrees, from the 30-year baseline climate period (1992–2021) to the future climate period (2028–2057, the future 30-year climate period centered at 2043). From these change factors (based on each GCM/SSP combination), a bivariate probability density function was fit and a 100,000-member sample was drawn. From this information, the percentile “Levels of Concern” were established. The 50th, 75th, and 95th percentiles provided a meaningful spread in the Eight River April-to-July Index values and would sufficiently stress the system.

3. Weather Generator Climate Inputs. CDWR employed a weather generator approach to create gridded daily meteorological conditions for each Level of Concern scenario that would be fed into the VIC hydrological model. The weather generator was designed to generate conditions by incrementally adjusting temperature and precipitation. It does this by applying step changes to the baseline daily maximum and minimum temperature data uniformly across the entire spatial domain. This means that the climate conditions used for the Delivery Capability Report analysis were grounded in historical weather patterns but have altered temperature and precipitation characteristics that represent plausible long-term climate change.

4. Hydrologic Modeling. The weather generator outputs, as well as baseline historical conditions, were fed into the VIC model. A change factor was calculated by taking the difference between VIC outputs for each weather generator time series and the baseline conditions. These change factors were then applied to CalSim3 inputs. CalSim3 is then run under these climate-adjusted input time series.

5. Incorporation of Sea-Level Rise. CalSim3 uses an ANN to generate sea level rise data that is an input to the model. CDWR aligned a sea level rise scenario to each Level of Concern based on existing ANNs used for CalSim3. Ultimately, a 0.98-ft sea level rise (for the 75th and 95th percentile Level of Concern) and a 0.49-ft sea level rise (for the 50th percentile Level of Concern) were used.

^a The Eight River Index includes flows from: (1) Sacramento River at Bend Bridge, (2) Feather River inflow to Lake Oroville, (3) Yuba River at Smartville, (4) American River inflow to Folsom Lake, (5) Stanislaus River inflow to New Melones Lake, (6) Tuolumne River inflow to New Don Pedro Reservoir, (7) Merced River inflow to Lake McClure, and (8) San Joaquin River inflow to Millerton Lake.

BOX 5-3
USBR Approach to Long-term Operations Climate Change Modelling

The USBR long-term operations climate change modeling follows a cascade approach with the following stages (USBR, 2021):

1. **Selection of an Emission Scenario.** For example, the SSPs are a set of climate change scenarios that project how global society, economics, and demographics could change by the end of the 21st century. These scenarios dictate the level of greenhouse gas emissions in the future, which in turn affect the projected level of warming.
2. **Climate Simulations.** The emission scenarios from stage (1) are used along with a set of GCMs such as those associated with the CMIP6. The models provide projections of key physical variables, including but not limited to, temperature, precipitation, humidity and sea level.
3. **Spatial Downscaling.** The outputs of climate models in stage (2) typically have a coarse spatial resolution (approximately 100 km). Therefore, for climate change impact studies, a downscaling approach is often used to transform the outputs of climate models to a finer spatial resolution. USBR utilizes a combination of statistical, dynamical and hybrid approaches to achieve this resolution.
4. **Hydrologic Models.** Following spatial downscaling, the outputs of key variables such as precipitation and temperature are used as inputs to hydrologic models, which in turn, provide simulations of streamflow at different streams and reaches. These simulations are crucial for operation and management decisions and can be obtained using different hydrologic models, such as the VIC model and the Sacramento Soil Moisture Accounting (SAC-SMA) model, among many others.
5. **Operations Models.** The outputs of the hydrologic models (e.g., streamflow) along with those of the GCMs are used as inputs to operation models such as CalSim3.
6. **Bay-Delta Models.** The last stage of the cascading modeling approach involves using localized models at the scale of the Bay-Delta such as the Resource Management Association's (RMA) Bay-Delta model, commonly used for hydrodynamic and water quality impacts with CalSim and other models used to generate inflows and other initial and boundary conditions.

While both agencies aim to incorporate robust climate modeling into operations, differences in their approaches—such as CDWR's emphasis on percentile-based stress testing and USBR's cascading framework—may lead to divergent methods in practice. Therefore, efforts to either integrate their approaches or share findings will be challenging for the two agencies. In addition, CDWR's Delivery Capability Report scenarios assume that infrastructure and operations will remain static, which may limit the adaptability of its models to future changes in system capacity or certain management strategies. These scenarios also assume that channel bottom elevations in the Delta remain fixed—implying ongoing, extensive dredging—and that no islands in the Delta will flood. USBR's 20-year planning horizon for long-term operations is a reasonable timeframe but may not account for all long-term variability or extreme events projected beyond this period. Finally, not all CIDs—such as heatwaves and snowpack—are considered in the modeling, either by CDWR and USBR or more broadly in the region. Modeling is also not currently considering the impacts of multiple, combined CIDs, such as extreme heat coupled with drought, even though these events can occur simultaneously or sequentially.

Benefits would be realized from closer coordination between CDWR and USBR to develop shared standards and protocols for modeling climate change impacts on the CVP and SWP. Moreover, regularly updating their respective modeling protocols to ensure alignment with current best practices in climate impact assessment is warranted. This work might include, for example, following the approach used in the IPCC sixth assessment report (IPCC, 2021) of evaluating projections based on global warming levels (GWLs) rather than fixed future time periods. This approach can help to reduce uncertainty tied to climate sensitivity in CMIP6 models—often referred to as the “hot models” problem (Hausfather et al., 2022). Finally, given the evidence of more frequent compound events (multiple extreme events occurring simultaneously) and cascading events (extremes events occurring in sequence; AghaKouchak et al.,

2020), there is a need for more detailed modeling studies to assess how such events may affect the Projects and specifically the three CVP actions reviewed here. The proposed Hub could be a vehicle for improved coordination among the management agencies long-term operations related to climate trends.

CONCLUSIONS AND RECOMMENDATIONS

This chapter has outlined three overarching issues that, if addressed, should enable more effective management of the CVP and SWP into the future. Two of them, the limitations of the current Delta modeling enterprise and the need to take into account a variety of CIDs in future operations and planning, derive from the three action chapters. Although a plethora of models are available for Project operations and long-term planning, the modeling enterprise suffers from a lack of integration and coordination among models, as well as disparities in model versioning and use. All research and data also indicate a warming climate, making it more difficult to meet ongoing water demands in the future. Both issues could be addressed by a Science Hub for the Bay-Delta watershed.

Recommendation 5-1: A formal feasibility study should be undertaken to assess the potential for a Science Hub for the Bay-Delta and its watershed.

This hub must be fit-for-purpose and grounded in the needs and culture of the science community. It should be designed to develop solutions to problems that are difficult to address within existing agency or academic silos, without interfering with agency mandates or diminishing internal capacity. It should enhance institutional expertise by creating a collaborative environment where new approaches can be developed and tested, where monitoring can be better coordinated, and where cross-agency training can be implemented. It would also facilitate better coordination across the science that supports CVP and SWP activities.

Recommendation 5-2: Finer scale models are needed for water and ecosystem management in the Delta and its watershed.

In particular CalSim (which is now widely used to evaluate ecosystem impacts) would benefit from a finer time step (perhaps one week) coupled with explicit or empirical disaggregation to still finer ecologically relevant time steps. With such capability, CalSim (or some other model) could then provide systematic hydrologic information for the more fully coupled hydrodynamic and population models needed for ecosystem management. Innovative ecosystem-wide approaches and quantitative life-cycle models could help to identify management actions that can contribute to species recovery. Monitoring should be tailored and managed to provide data at the spatial and temporal scales needed by the models.

Recommendation 5-3: CDWR and USBR should coordinate more closely and develop shared standards and protocols for modeling climate change impacts on the CVP and SWP.

Consistent protocols are essential for minimizing uncertainty in projected climate change impacts, particularly those arising from two sources: future greenhouse gas emission scenarios and model-related uncertainties (e.g., climate sensitivity). Protocols will help to explain differences between projections and avoid confusion among policy makers and the public around different representations of climate change. Moreover, CDWR and USBR should regularly update their modeling protocols to ensure alignment with current best practices in climate impact assessment. Finally, given the increasing evidence of more frequent compound events (multiple extreme events occurring simultaneously) and cascading events (extremes occurring in sequence, there is a pressing need for more detailed modeling studies to assess how such events may affect the Projects.

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Appendix A

Northern California Climate, Hydrology, and Geology

This appendix provides background information on the natural system that supports the Central Valley Project (CVP) and the State Water Project (SWP). It begins with information on the hydrology and climate of Northern and Central California,¹ considering both past, current, and projected near-future conditions. It also describes the underlying geography of the region, changes in land use over time, and changes in the ecology of the Delta region over the past 150 years. The intent is for all of the appendices to support this report and subsequent reviews from the National Academies, with updates and modifications being made for each subsequent review as appropriate given the specific tasks.

INTRODUCTION

Northern California's highly varied physical geography includes coastal and inland marshes, large floodplains, high and low mountain ranges, some with cold-water springs, and large and small basins drained by a network of rivers. Its climate, with long dry summers and wetter winters, evolved about 15 million years ago (Millar, 2012). Together, this climate and the underlying geology have shaped the physical habitat in which California's ecosystems evolved over millions of years. Prior to human development, one of the most prominent features were the extensive seasonal and permanent wetlands, especially on the vast floodplains of California's Central Valley and in the Sacramento-San Joaquin Delta.

Climate has always shaped California's landscape and ecosystems. At the end of the last ice age, global sea level was about 100 meters (m) below present levels (Dolby et al., 2016; Lambeck et al., 2014; Siddall et al., 2003). The estuary for the Sacramento-San Joaquin Delta was then outside (west of) the Golden Gate Bridge near today's Farallon Islands. At that time, the inland Delta region was a non-tidal freshwater confluence of the two major rivers, probably with seasonal wetlands. Rising sea levels inundated San Francisco Bay about 9,000 years ago and started to inundate the Delta about 6,000 years ago, transforming it into a permanent tidal freshwater marsh with brackish western margins (Drexler et al., 2007; Malamud-Roam et al., 2007). This new and vast permanent marsh accreted peat soils during this period until most of the region was diked and drained for agriculture in the late 1800s and early 1900s.

The region and its habitats have evolved to endure enormous seasonal and interannual variability. Indeed, many of California's iconic native aquatic and avian species evolved, adapted, and have prospered since the end of the Ice Age (about 10,000 years ago). These species and ecosystems adapted their life histories and movements to the long, dry summer seasons by migrating, employing flows from cold water springs and groundwater, and employing the snowmelt freshet in spring and early summer. The geographic diversity of California also gave refuge opportunities to species across multi-year droughts, before extensive land and water development reduced and disconnected these habitats (see Appendix B).

¹ For the purposes of this report, California is divided into Southern, Central, and Northern regions. Southern California includes Los Angeles, Orange County, San Diego, Inland Empire, and desert areas. Northern California includes the San Francisco Bay Area up to the border with Oregon. Central California features the San Francisco Bay Area, Central Coast, Central Valley, and Gold Country.

CALIFORNIA CLIMATE

This section discusses various climate parameters, including rainfall and snowfall, temperature, sea level rise, droughts and aridity, and wildfires. Where possible both trends of the recent past and projections for the near future are provided for the regional watershed that drains to the Delta. The climate projection results reported here are mostly obtained from the sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC, 2021), and they are based on model simulations from the 6th Model Intercomparison Project (CMIP6). IPCC AR6 describes Climatic Impact Drivers (CIDs) and categorizes them into two groups: (1) changes in the average behavior of physical climate conditions, and (2) changes in extreme behavior. Both categories of CIDs are discussed in this report.

California's climate has enormous seasonal and interannual hydrologic variability, with more wet and dry years (floods and droughts) per average year than any other state (Dettinger, 2011). The long dry season (from April through September) is typically longer than any dry period seen by most of the more humid United States. The wet season runs from November through March, can be marked by occasional large storms, and provides on average 75 percent of the state's precipitation. Storms can create small to major floods in a single month or over several months from a series of atmospheric rivers. Droughts can be attributed to a delay in wet season storms, an early end to the wet season, a single "dry" wet season, or several years of "drier-than-usual" wet seasons. In medieval times,² parts of California had droughts lasting many decades, with average runoff of 40–60 percent of their historical averages (Stine, 1994).

Average Annual Precipitation

The average annual precipitation varies greatly among California's 11 climate regions, from 4.7 inches in the Sonoran Desert to 67.8 inches in the North Coast (OEHHA, 2022), as demonstrated in Figure A-1. Areas in the southern end of the Central Valley and south of the Central Valley are particularly dry and are desert in some areas (< 5 inches per year). In contrast some of the watersheds that supply the CVP and SWP, such as northeast of the Delta in the Sierras and the Trinity River watershed, can be very wet (> 50 inches per year). The spread across the entire state narrows when one considers only the Bay-Delta watershed, where annual precipitation varies from 12.9 inches in the San Joaquin portion of the Delta to 49 inches in the North Central climatic region (OEHHA, 2022).

Figure A-2 shows average monthly rainfall in five different cities in the state. Average rainfall in the more northern cities (Sacramento) is larger than in southern California (Los Angeles, Palm Springs, Bakersfield) in the winter. Figure A-2 also illustrates the seasonal pattern of precipitation present throughout the state, with rain coming in the October-to-April time period.

There has been no apparent long-term trend in total statewide precipitation over the last 60 years (Dettinger, 2024). However, an analysis of observed changes in precipitation nationwide suggests that over the 2002–2021 period, mean annual precipitation in most of California has decreased by approximately 5–15 percent relative to 1901–1960. As Figure A-3 shows, in the Sacramento-San Joaquin watersheds, the decline in mean annual precipitation is less severe compared to the southern part of the state, yet it still represents a notable decrease of around 5 percent. This decrease in mean annual precipitation over the past two decades reflects the impact of the California megadrought from 2012 to 2015 (Diffenbaugh et al., 2015; Williams et al., 2015). The period between October 2012 and October 2015 saw the lowest precipitation amount ever recorded in California in a consecutive three-year period (OEHHA, 2022).

² First, from before AD ~892 to around AD 1112, and second, from before AD 1209 to around AD 1350 (Stine, 1994).



FIGURE A-1 Average annual precipitation in California, 1961–1990.

SOURCE: National Atlas, https://maps.redcross.org/website/Maps/Images/California/pageprecip_ca3.pdf.

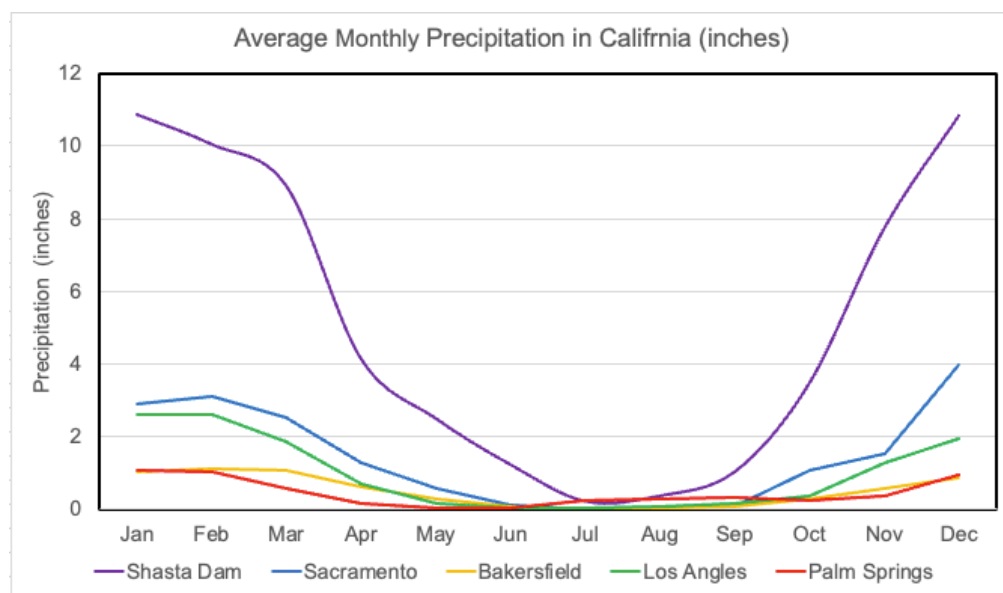


FIGURE A-2 Average monthly rainfall at five stations in California.

SOURCE: <https://weather.gov/wrh/Climate?wfo=lox>.

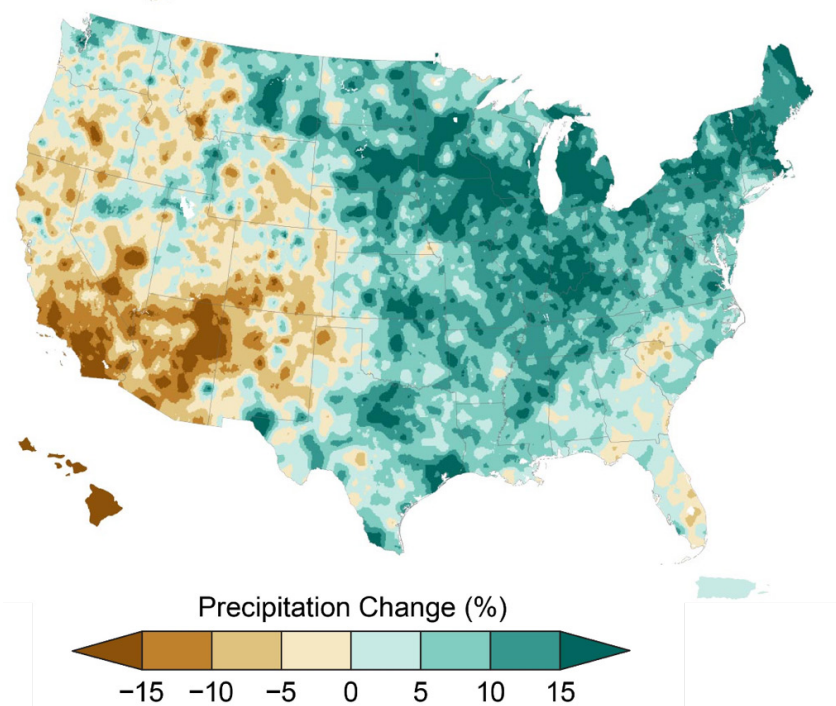


FIGURE A-3 Observed changes in mean annual precipitation for the period 2002–2021 relative to the baseline period of 1901–1960.

SOURCE: USGCRP (2023).

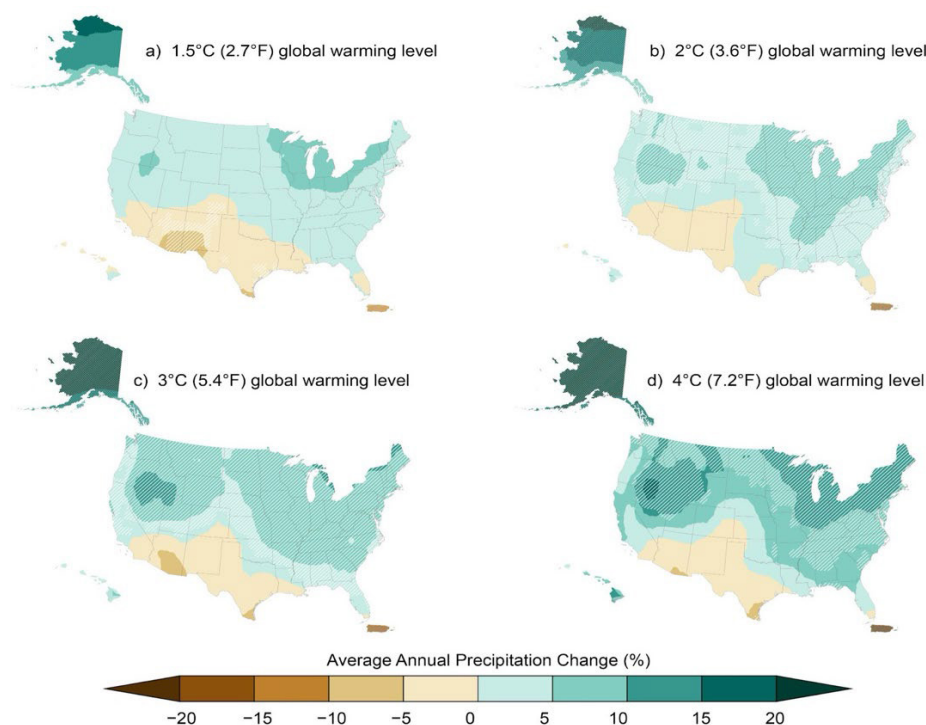


FIGURE A-4 Projected changes in mean annual precipitation as a function of different global warming levels (1.5, 2, 3, and 4 °C). NOTE: Changes are estimated relative to the baseline period 1851–1900.

SOURCE: Figure from Chapter 2 of the 5th National Climate Assessment (USGCRP, 2023).

Projected future changes in mean annual precipitation, derived from CMIP6 and shown in Figure A-4, suggest marginal variations ranging from -5 percent (in the southern part of the state) to 5 percent (in the northern and central regions of California) relative to the climatological baseline period of 1851–1900—a spatial heterogeneity that aligns somewhat with observed changes (Figure A-3). These projections are consistent with earlier analyses from CMIP5 models, as presented in California’s Fourth Climate Change Assessment (Bedsworth et al., 2018). However, model projections for future precipitation in California lack consensus compared to other regions of the United States (USGCRP, 2023). In Figure A-4, regions are marked with hatch patterns if 80 percent or more of the models agree on the direction of change. It is evident from Figure A-4 that models exhibit significant divergence regarding the anticipated change in precipitation over California, even at high global warming levels of 4°C (7.2°F).

Anthropogenic global warming influences precipitation because of the increased atmospheric water demand of a warmer climate. The Clausius-Clapeyron (C-C) relationship dictates that the atmospheric holding capacity of water vapor increases by approximately 7 percent per 1°C of warming. In wet regions where water availability matches atmospheric water demand, precipitation is expected to increase, albeit possibly less than the C-C rate. Conversely, in arid regions, increased atmospheric demand leads to greater evaporation and aridity. These effects, coupled with enhanced moisture convergence from dry to wet regions, result in distinct patterns: wet regions becoming wetter and dry regions becoming drier. However, this paradigm has faced challenges, with several studies suggesting that it does not hold true because of its failure to consider changes in atmospheric circulation (e.g., Byrne and O’Gorman, 2015). In addition, energy balance constraints also moderate the response of precipitation to global warming, resulting in an increase lower than the 7 percent per 1°C rate predicted by the C-C relationship (Allen and Ingram, 2002).

Snowpack

Because precipitation generally occurs during the October-to-April time period, while municipal and industrial water demands are year-round, and agricultural demand is largest from April to August, the need to store water from the winter is critical, either as snowpack or via CVP/SWP infrastructure, for use in the spring and summer. Indeed, snowpack plays a crucial role in water resource management by capturing, storing, and releasing water for downstream use (Immerzeel et al., 2020). Since the mid-1970s, more of the statewide precipitation generally has fallen as rain compared to snow, although there is some variability, with snowpack in 2015 being the lowest on record (for the period 1949–2020) (OEHHA, 2022). Precipitation from atmospheric rivers supplies about 40 percent of the Sierra Nevada snowpack (Guan et al., 2010).

Global warming reduces snowpacks through several mechanisms including elevated temperatures that lead to a decrease in snowpack volume (Mote et al., 2018), reduction in fraction of precipitation falling as snow (O’Gorman, 2014; Ombadi et al., 2023), altered sublimation rates (Sexstone et al., 2018), earlier snowmelt, and a reduction in the length of the snowpack season (Stewart et al., 2004). Climate change impacts on precipitation patterns can also affect the volume of snowpack; however, given the insignificant and uncertain projections of precipitation change shown in Figure A-3, it is less likely that this will be a dominant mechanism.

Figure A-5a shows that peak snowpack, as indicated by April 1 measurements, has been declining in the majority of sites across the western United States for the period 1955–2022. In the Sacramento and San Joaquin watersheds, peak snowpack has shrunk by up to 80 percent with most sites experiencing a reduction of 20–80 percent over the past seven decades. Consistent with those decreasing trends in peak snowpack, global warming is causing an earlier snowmelt, thus shifting the timing of snowpack peaks earlier in the year by up to 20 days (Figure A-5b). Furthermore, warmer winters and earlier springs lead to a shortening of the snowpack season in the majority of sites in the western United States (Figure A-5c). In parts of the Sacramento and San Joaquin watersheds, the length of snowpack season has decreased by 30–40 days since the early 1980s.

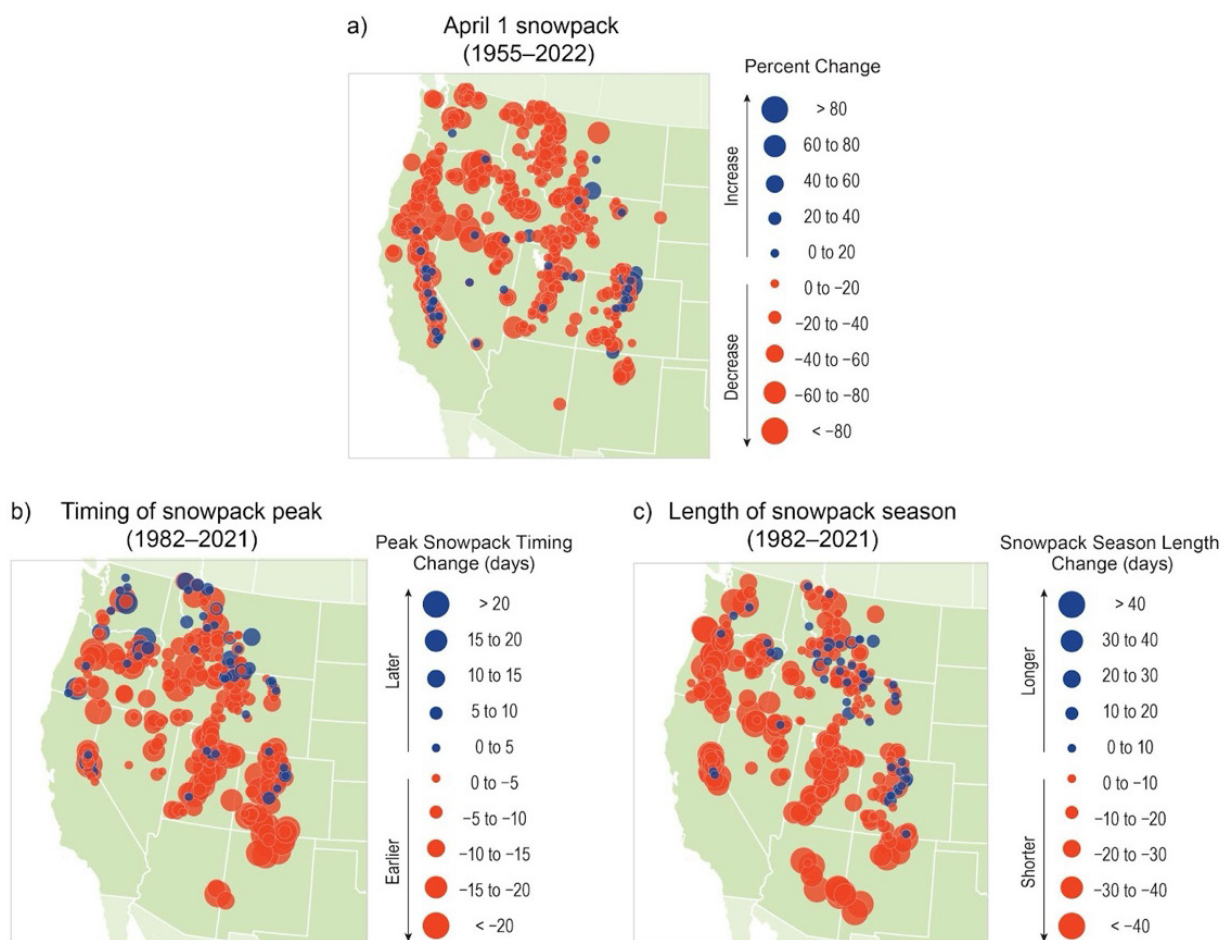


FIGURE A-5 Observed changes in April snowpack peaks (a), timing of snowpack peaks (b), and the length of the snowpack season (c). NOTE: In all panels, red markers indicate a decrease or earlier change, whereas blue markers indicate an increase or later temporal change.

SOURCE: Figure obtained from the 5th National Climate Assessment (USGCRP, 2023).

A synthesis of published literature on projected snowpack declines in the western United States show estimated decreases of $\sim 25 \pm 5$ percent by 2050, $\sim 35 \pm 10$ percent by 2075 and $\sim 50 \pm 10$ percent by 2100 (Siirila-Woodburn et al., 2021).³ The same analysis shows that projected declines in the Sierra Nevada snowpack are relatively higher than other mountain ranges in the western United States (e.g., Rockies and Wasatch/Uinta), especially for mid- and end-of-the century projections. Siirila-Woodburn et al. (2021) showed that low-to-no snow conditions, defined as years with peak snow water equivalent below the 30th percentile of historical occurrences, could become persistent within the next 35 to 60 years if global warming trends continue.

The consequences of diminishing snowpacks extend far beyond the mountain ranges. Changes in snowpack dynamics, such as earlier melting and decreased water storage, will alter groundwater and streamflow patterns, challenging effective use and management of current water infrastructure and effective use of available water, with associated economic losses. These projections underscore the urgent need for proactive measures to mitigate the effects of a low-to-no snow future.

³ This synthesis was based on time period as opposed to warming level.

Precipitation Extremes

California experiences large interannual variability in precipitation amounts (Figure A-6), and that variability has been increasing. Thus, the two left panels of Figure A-6 compare the coefficient of variation of water-year precipitation for the time periods 1941–1980 and 1981–2020. Variation is particularly acute in southern California, but all of California is experiencing more variation over time. As the section below explains, the increase in variation over time affects both droughts and extreme precipitation events.

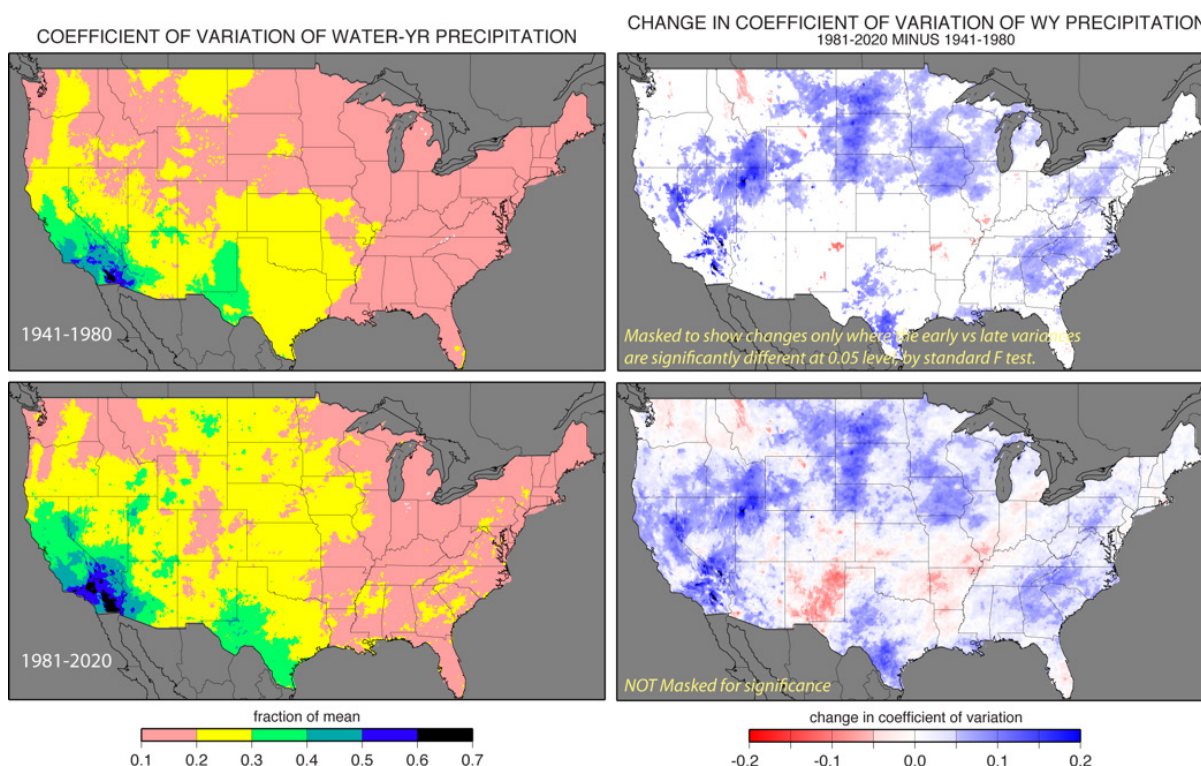


FIGURE A-6 Changes in precipitation interannual variability in the conterminous United States, 1941–2020.

SOURCE: Dettinger (2024).

Droughts

Droughts occur frequently in California, sometimes lasting four years or more. Over the past few decades, California has experienced several multi-year droughts, including in 2001–2004, 2007–2010, and 2012–2016 (Bedsworth et al., 2018). The 2012–2016 drought was the most severe on record (OEHHA, 2022) and the most extreme in the past 1,200 years (Meko et al., 2014). Williams et al. (2020) demonstrated, through analysis of tree-ring reconstructions, that the 19-year period from 2000 to 2018 was the second driest such period for the southwest U.S. including California since 800 CE. The transition toward aridity in the western United States is due not only to changes in precipitation but also to rising temperatures. These higher temperatures contribute to soil moisture loss and increased evapotranspiration rates. For example, the high air temperatures in 2014 significantly intensified drought conditions across California (Griffin and Anchukaitis, 2014; Williams et al., 2015). Studies have shown that the likelihood of precipitation deficits occurring concurrently with warm conditions has increased in

California (Diffenbaugh et al., 2015) and warming accounted for up to 27 percent of the severity of the California 2012–2015 megadrought (Williams et al., 2015). This phenomenon, often referred to as a “warm drought” or “hot drought” (Overpeck, 2013), is expected to become more frequent in a warming climate.

Another measure of dryness is the Palmer Drought Severity Index (PDSI), which combines precipitation, temperature, and soil moisture data into a single measure of dryness. As shown in Figure A-7, PDSI values in California for 1895–2020 indicate that dryness has increased in the past 50 years, likely because increased air temperatures have resulted in increased evapotranspiration (Albano et al., 2022) and thus decreased soil moisture (Cheng and Huang, 2016; OEHHA, 2022).

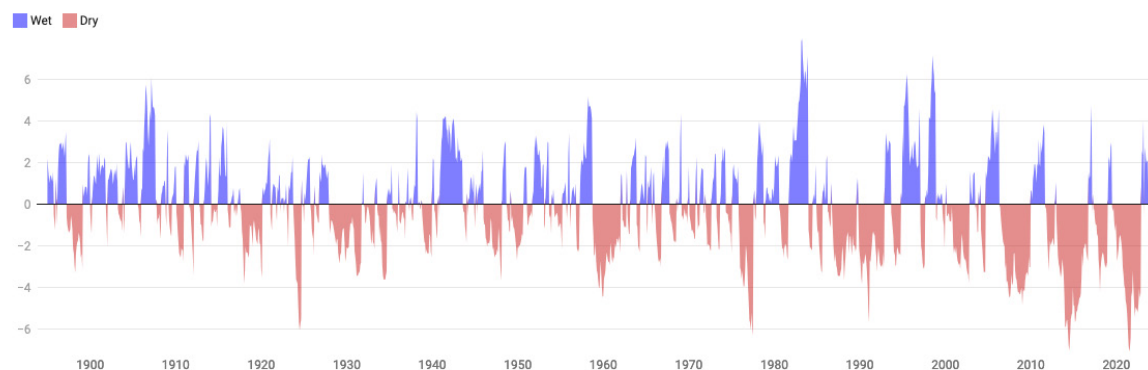


FIGURE A-7 Statewide Palmer Drought Severity Index for California, 1895–2020.

SOURCE: OEHHA (2022) from NOAA (2021).

Climate change will undoubtedly increase atmospheric evaporative demand due to rising temperatures, which means that droughts likely will become more severe and last longer in a warmer climate. A recent multi-dataset assessment of trends in evaporative demand over the past four decades revealed that increases in atmospheric evaporative demand in the western United States are already happening at a faster rate than in other regions (Albano et al., 2022). Climate model projections based on CMIP5-downscaled global climate models (GCMs), shown in Figure A-8, suggest that these increasing trends in atmospheric evaporative demand are anticipated to amplify with global warming, with an anticipated increase of 13–18 percent by the end of the 21st century (2070–2099; McEvoy et al., 2020). Overall, there is a very high certainty that future occurrence of episodic deficits in precipitation (e.g., drought events) in California will be accompanied by warmer temperatures and an increased atmospheric evaporative demand.

Atmospheric Rivers

The impact of global warming on extreme precipitation in California is quite evident, both in observations of the past and model projections of the future. The western United States, including California, has experienced an increase in both the magnitude and frequency of extreme precipitation events such as landfalling atmospheric rivers, which are concentrated bands of moisture in the atmosphere that transport large amounts of water vapor (Easterling et al., 2017; USGCRP, 2023). Large atmospheric rivers contribute approximately 30–50 percent of the annual precipitation in the western United States (Dettinger, 2011; Guan et al., 2010). Atmospheric rivers can also result in termination of droughts, and they are estimated to be responsible for terminating 33–74 percent of droughts in the western U.S., including the California megadrought of 2012–2016 (Dettinger, 2013; Payne et al., 2020; Wang et al., 2017).

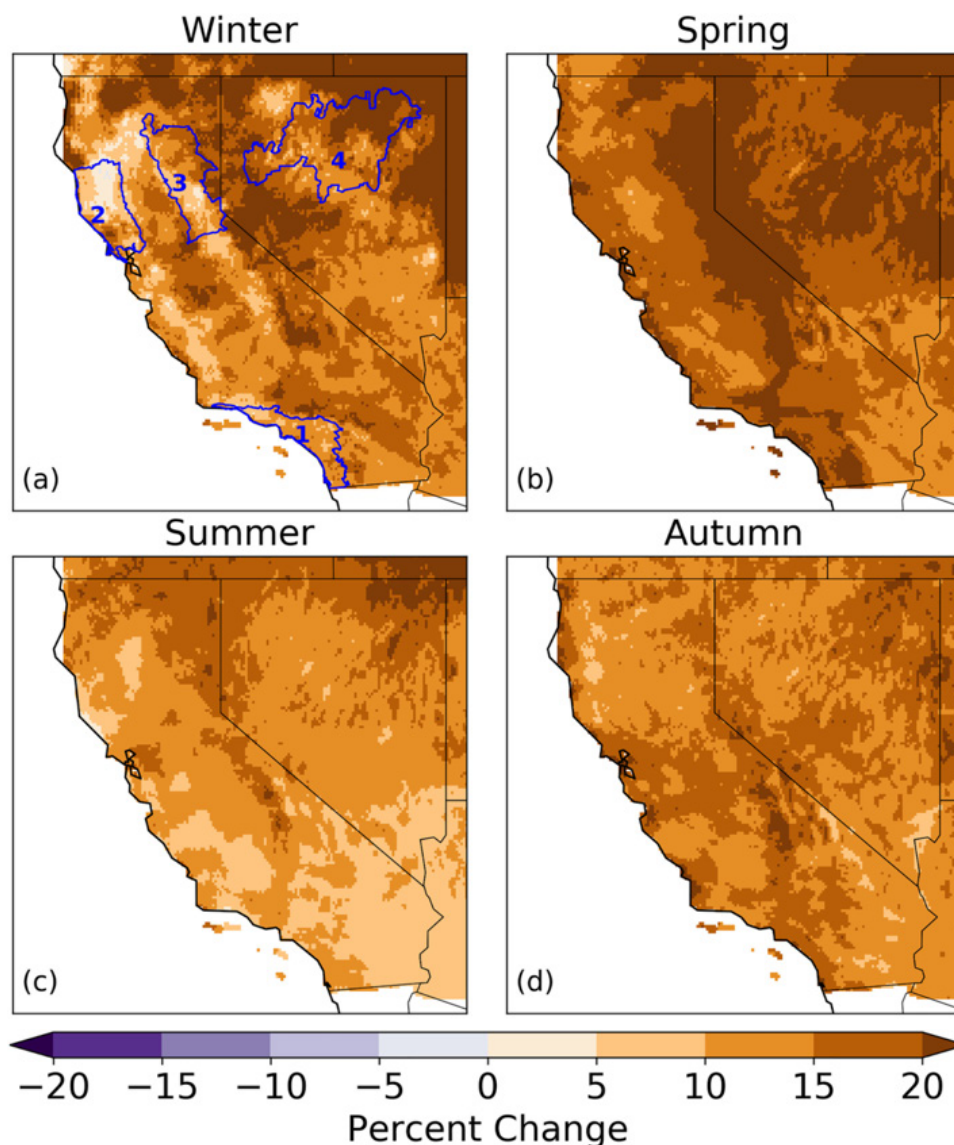


FIGURE A-8 Projected changes in reference evapotranspiration (atmospheric evaporative demand) from downscaled CMIP5 GCMs. NOTE: Projections are based on CMIP5 RCP 8.5 for the end of the century (2070–2099) relative to the baseline period (1950–2019).

SOURCE: McEvoy et al. (2020).

Atmospheric rivers drive the interannual (year-to-year) variability of precipitation in the region (Dettinger, 2016; Dettinger and Cayan, 2014). Figure A-9a shows that greater than 70 percent of interannual variability of precipitation in California can be attributed to variability in extreme precipitation amounts from one year to another. This is also clearly shown in Figure A-9b, with variability of the water-year precipitation in the Delta watershed closely matching the variability of extreme precipitation from the wettest 5 percent of days.

Overall, there is growing evidence that atmospheric rivers will intensify in a warmer climate due to thermodynamic increase in precipitation (Espinoza et al., 2018; Payne et al., 2020). In California, climate projections also indicate that concurrently with this intensification of atmospheric rivers, other storms will get smaller and less frequent. Consequently, the contribution of atmospheric rivers to annual precipitation will increase even further compared to the current climate, with estimates of a 20 percent

increase by the end of the 21st century (Gershunov et al., 2019). Climate model projections show an increase of 25–100 percent in rapid shifts from extreme dry to wet conditions (Swain et al., 2018), analogous to the rapid shift from the megadrought conditions in 2012–2016 to the wet year of 2017. Dettinger (2024) stressed the need for the CVP/SWP operations to transition to preparing for and managing extremes rather than relying solely on average conditions in order to enhance resilience in the face of increasingly unpredictable weather patterns.

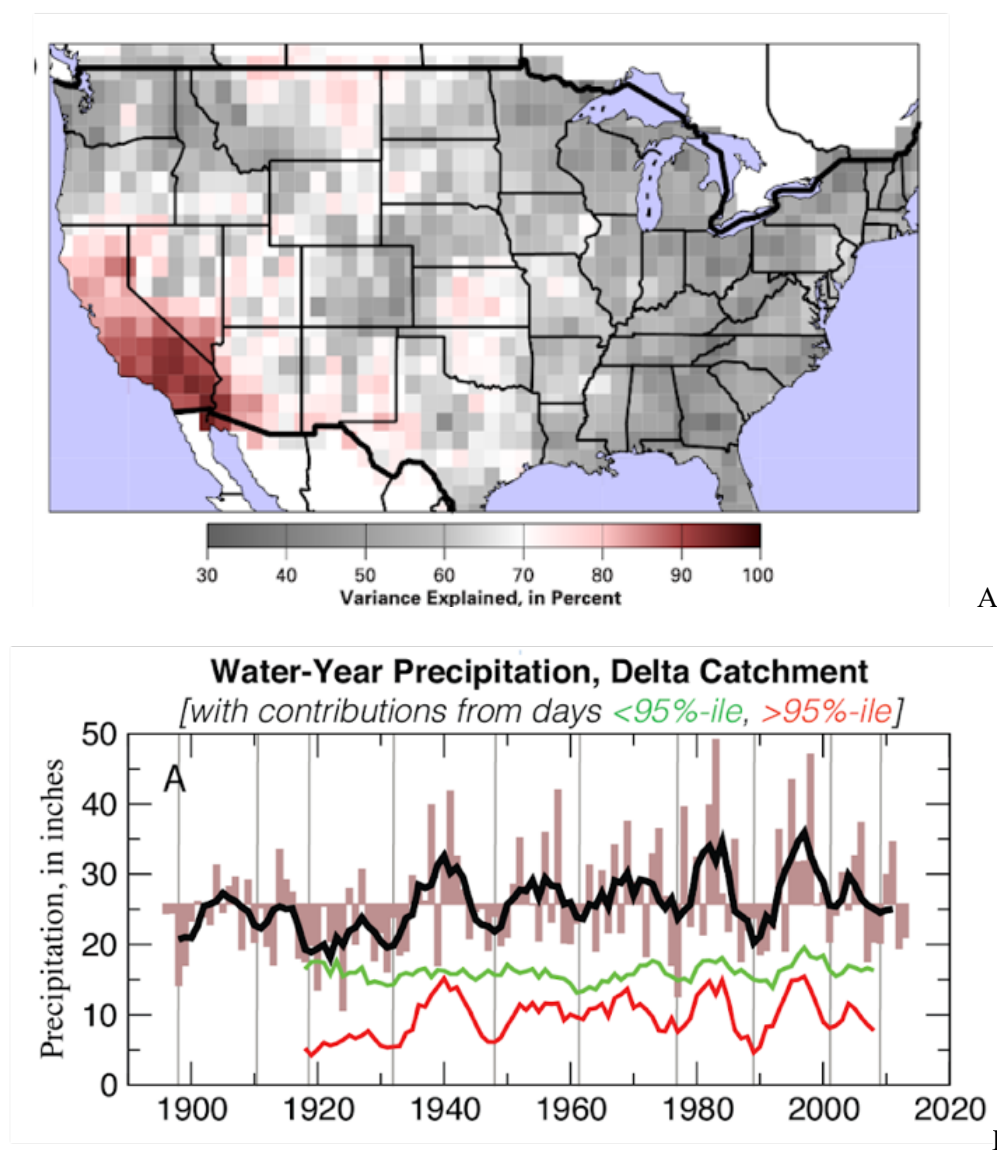


FIGURE A-9 (A) Percentages of total water-year precipitation variance explained by precipitation from the wettest days. NOTE: Wetter than a threshold exceeded by an average of 7 days per year at each 1°-latitude-longitude grid cell, water years 1951–1999. SOURCE: Dettinger (2016).

(B) Water-year precipitation totals (brown bars and black curve) in the Delta's catchment. NOTE: 1895–2014 based on updated monthly Abatzoglou et al. (2009) data, and 5-year moving averages of contributions to these totals from the wettest 5 percent of wet days (days with precipitation > 95th percentile; red curve) and all other wet days (< 95th percentile; green curve) based on updated daily Hamlet et al. (2005) data, 1916–2010.

SOURCE: Dettinger and Cayan (2014). (B) Dettinger, M., & Cayan, D. R. (2014).

Temperature

Annual average air temperature and climate in California varies widely from the hot desert in the southeast to extreme cold in a small part of east central California, depending on latitude, elevation, and proximity to the Pacific Coast. The temperature gradient between the immediate coast and the interior regions of the state can be significant, especially in the summer, when the difference can be as much as 20°F (11°C).

Since the early 20th century, the Global Mean Surface Temperature of Earth has risen by approximately 1.96°F (1.09°C) compared to the baseline of 1850–1900 (IPCC, 2021), with land areas experiencing faster warming than oceans. Earth's warmest year on record was 2024 (Tollefson, 2025). It is widely recognized that many land regions in the extratropical northern hemisphere have warmed more rapidly than the global average, notably the United States since the 1970s (USGCRP, 2023). In California, long-term average air temperature has increased about 2.5°F (1.4°C) since 1895, with an average of 55.9°F (13.3°C) in 1895 to an average of 57.4°F (14.1°C) in 2023. The highest statewide annual average temperature occurred in 2014 during the 2012–2015 drought, when the mean was 60.7°F (15.9°C; OEHHA, 2022). In general, the warmer years have occurred during the drier years, which, as previously discussed, increases the effects of drought through greater evaporative demand. Moreover, higher temperatures increase water demand for power-plant cooling (OEHHA, 2022b). Warming has been greater in the southern portion of the State than in the north, that is, the Bay-Delta watershed.

Water temperature is highly correlated with air temperature and is a key factor affecting fish health, including metabolism, predation, thermal stress, reproductive timing, development rates, and susceptibility to disease and toxins, as well as other characteristics. Bashevkin et al. (2022) examined about 50 years of water temperature data in the upper San Francisco Bay estuary, between Suisun Bay and the upstream extent of the Delta, in order to isolate the effect of ocean water on estuary freshwater temperature. They found that water temperatures have increased on average 0.017°C per year between 1970 and 2020. Temperature increases were most widespread in the late-fall to winter (November to February) and mid-spring (April to June). Warming was also fastest in the northern regions of the upper estuary. These results, particularly the long-term rate of water temperature warming, were consistent with earlier studies of rates of air temperature warming (Hoerling et al., 2013).

Projections of Extreme High Temperatures and Heatwaves

In the Sacramento Valley, downscaled climate model projections from CMIP5 show that average daily maximum temperature is projected to increase by 10°F (5.6°C) by the end of the 21st century (Figure A-10a). Moreover, the frequency of extreme heat days, defined based on daily maximum temperature exceedances of 102.2°F (39°C), is expected to increase ten-fold (from four days/year to 40 days/year; Figure A-10b). These results are based on analysis of an ensemble of high emission scenarios (RCP8.5) using downscaled climate model projections (Houlton and Lund, 2018).

For the San Joaquin Valley region, projections of high emission scenarios (RCP8.5) show an increase up to 8°F (4.4°C) in average daily maximum temperature by the end of the 21st century. The increase in temperature is associated with a 50 percent projected decline in snowpack, 13 percent more precipitation coming in extreme events, and more frequent wet and dry years by the end of the 21st century (Fernandez-Bou et al., 2021; Persad et al., 2020).

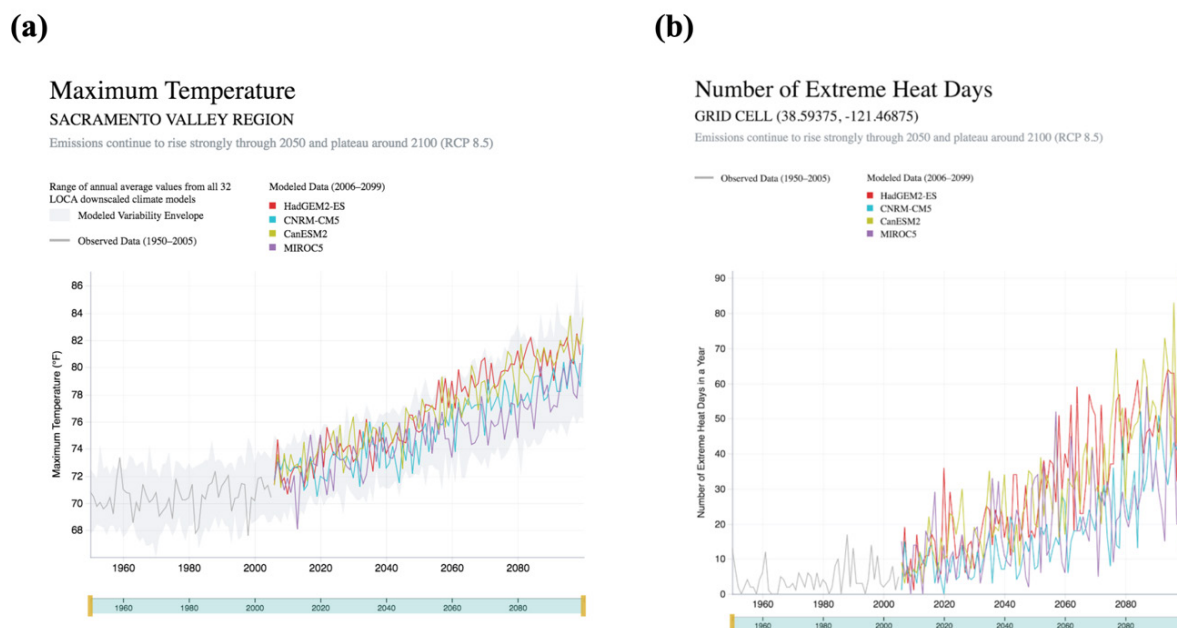


FIGURE A-10 Projected and observed changes in the magnitude and frequency of extreme temperature events in the Sacramento Valley region. NOTES: (a) Increase in average daily maximum temperature is projected to be around 10°F (5.6°C) by the end of the 21st century. (b) The frequency of extreme heat days is projected to increase from 4 days/year to 40 days/year. SOURCE: Cal-Adapt (2018); Houlton and Lund (2018).

Wildfires

The area burned by wildfires in the western United States has increased in recent years, in line with rising air temperatures and greater atmospheric evaporative demand (OEHHA, 2018). In fact, there has been a five-times increase in summer burned area in northern and central California during 1996 to 2021 compared to 1971 to 1995 (OEHHA, 2022). Statewide, there were 3,356 fires during 2009–2018, which is 1.4 times greater than the average number of fires per decade in 1979 and 2009 (Buechi et al., 2025). California lost 2.12 million hectares of tree cover because of wildfires, and another 0.80 million hectares, or 0.27 percent of the total, from other activities (Global Forest Watch, 2025). Although loss of trees generally leads to higher runoff, reduction in tree cover likely leads to snowpack reduction due to increased exposure of snow to sunlight and associated sublimation.

Observation-based studies indicate that anthropogenic global warming contributed to an additional 4.2 million hectares of forest fires between 1984 and 2015, accounting for roughly 55 percent of the observed increase in fuel aridity in the western United States (Abatzoglou and Williams, 2016). Specifically, warming-induced increases in vapor pressure deficit have played a key role in driving wildfire activity in the region (Williams et al., 2019). Model simulations suggest that, during 1971–2021, climate change resulted in, on average, 170 percent more burned area than if climate had remained stable during the period (Turdo et al., 2023).

Although the direct impacts of wildfires may not be central to the three actions outlined in the Committee's statement of task, it is important to acknowledge the cascading effects they can trigger. For example, an analysis of streamflow data from 72 forested watersheds across the western United States found that average streamflow increased by up to 20 percent of the standard deviation for as long as six years after a fire (Williams et al., 2022). Given the projected rise in wildfire-conducive conditions, wildfires are a critical CID, both for their direct and indirect effects.

HYDROLOGY OF THE DELTA REGION

The Bay-Delta watershed is a naturally complex system that has been significantly altered by humans. Figure A-11 shows an aerial view of the California Delta and its location in the northern part of California's Central Valley. At the center top of the figure, the Sacramento River flows from the north draining an area around Mount Shasta and the Sierra Nevada Mountains north of the Delta. As it flows south to the Delta, the Sacramento River is joined by several major tributaries, including the Feather River and the American River on the east side. At the bottom right corner of Figure A-11, the San Joaquin River flows northward from the southern end of the Central Valley to the Delta.



FIGURE A-11 The California Delta is a complex of channels and canals with water entering from many directions, and for the most part exiting to San Francisco Bay, or being pumped to the south.
SOURCE: Sumer (2024).

The Delta itself consists of a complex set of channels, including the areas where the Sacramento and San Joaquin rivers connect and areas where local sources of water such as the Mokelumne and Cosumnes rivers flow out of the Sierras into the Delta. The Yolo Bypass, Cache Slough, and Lindsey Slough flow into the Delta from the Coastal Range to the northwest. The Delta is the intersection of these river systems.

The following discussion addresses (1) the Sacramento River basin upstream from the Delta; (2) the San Joaquin River basin upstream from its confluence with the Sacramento River; and (3) the Sacramento River–San Joaquin River Delta.

Sacramento River Basin

The Sacramento River drainage basin (Figure A-12) is the largest river basin wholly in California. The drainage area is 27,210 square miles including tributaries north of the Cosumnes River basin, the closed basin of Goose Lake, and drainage subbasins of Cache and Putah creeks, which lie west of the Sacramento River (RWQCB, 2019). All the major rivers of the Sacramento River basin—the Sacramento, Feather, American, and Yuba rivers—have impoundments. The upper Sacramento River, the McCloud River, and the Pit River flow into Shasta Reservoir, which has a capacity of 4,552,000 acre-feet.

Oroville Reservoir, on the Feather River, has a capacity of 3,537,600 acre-feet. Folsom Reservoir, on the American River, has a capacity of 974,500 acre-feet, and New Bullards Bar Reservoir on the Yuba River has a capacity of 966,100 acre-feet. The big dams on the Sacramento River (Shasta, Oroville, Yuba Bullards Bar, Folsom) can hold about 10 million acre-feet (MAF) of water compared to an average annual runoff in the basin of 21 MAF.

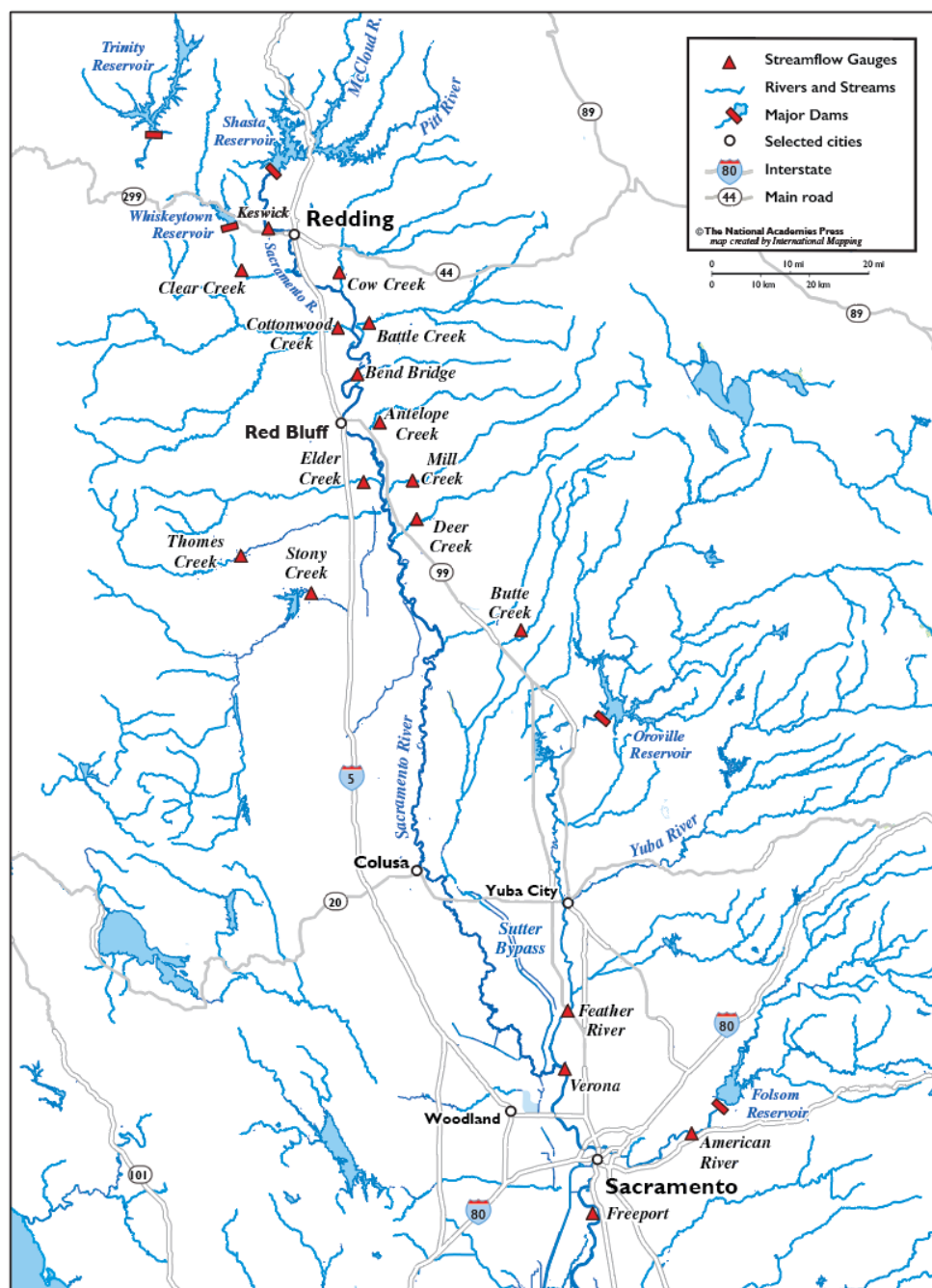


FIGURE A-12 Upper Sacramento River basin, showing major impoundments.
SOURCE: Kevin Lear, International Mapping Associates.

The effects of the Shasta Dam on flows can be seen in the record from the stream gaging station on the Sacramento River at Red Bluff (USGS station 11377100), which has a continuous record from 1891 to the present. Following the construction of the dam, overall peak flows (greater than the approximately 30th percentile) were reduced, as expected. The lowest 70 percent of flows were higher following dam construction (see flow duration curves in Figure A-13), despite the fact that the period after 1950 generally was drier than the first half of the 20th century (Figure A-7). The median flow was 9,350 cubic feet per second (cfs) following dam construction, but was 30 percent lower (6,500 cfs) prior to dam construction.

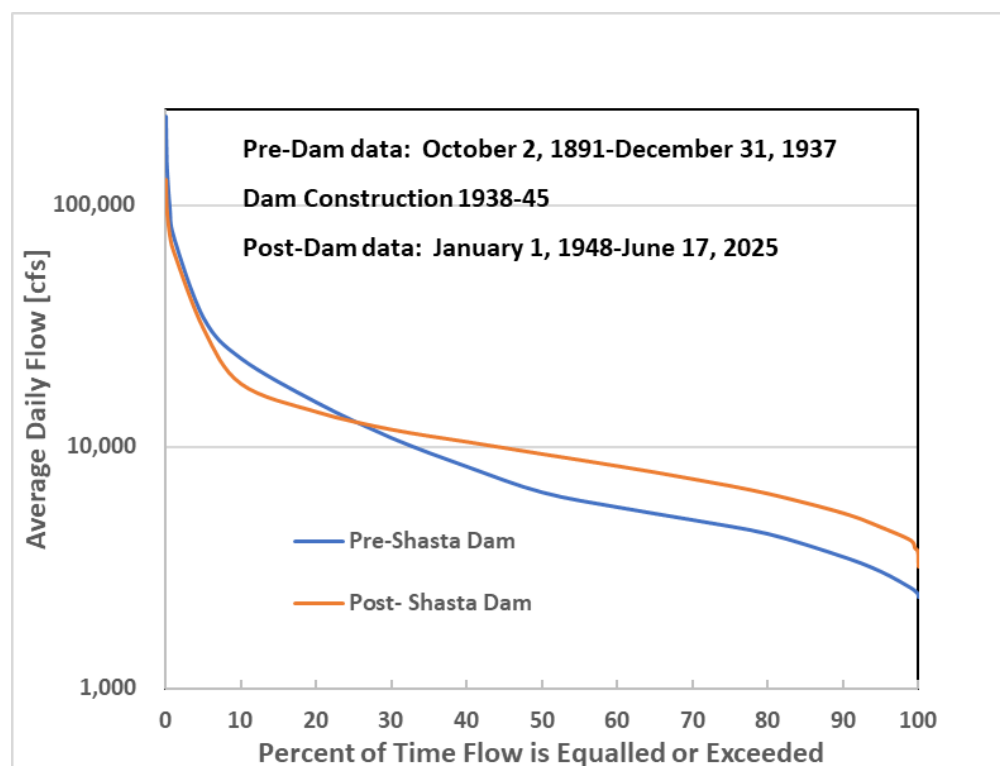


FIGURE A-13 Mean daily flow duration curves for the Sacramento River near Red Bluff, Gaging Station 11377100, for pre-Shasta Dam and post-Shasta Dam periods.

The presence of the reservoirs, as well as other flood storage areas, also have modified the annual flood hydrograph from one in which a flood peak pulse occurred in late spring to one in which the flood peak is lowered, spread over a longer period, and occurs earlier in the spring (Sommer, 2024).

Yolo Bypass

The Yolo Bypass is a leveed floodway between 1.3 and 3 miles wide and extends for 41 miles generally parallel to, and west of, the Sacramento River and northwest of the Delta. The two primary sources of water to the bypass are the Fremont Weir, located just downstream from the Sacramento River–Feather River junction at the upstream end of the bypass, and the Sacramento Weir, located just west of the city of Sacramento. The primary purpose of the bypass is to mitigate flooding in urban areas along the Sacramento River. The bypass also supports the Yolo Bypass Wildlife Area, which is an extensive marshland (California Water Library, 2025).

Delta Cross Channel

The Delta Cross Channel (DCC) is a controlled diversion channel between the Sacramento River and Snodgrass Slough. Located near Walnut Grove, California, the DCC is a short, excavated channel that diverts water from the main river to Snodgrass Slough. The water then flows through natural channels (initially the North and South Mokelumne rivers) for about 30 miles to help provide fresh water to the intakes of the state and federal pumping facilities, improves the irrigation supplies within the Sacramento-San Joaquin Delta, and pushes against the upstream movement of saline ocean water coming up the San Joaquin River. The DCC is designed to divert approximately 3,500 cfs. It also has the unintended consequence of diverting downstream migrating salmonids into the Delta rather than passing directly to San Francisco Bay and the Pacific Ocean.

Sacramento Deep Water Ship Channel

The Sacramento Deep Water Ship Channel serves the marine terminal facilities at the Port of West Sacramento by providing a passageway from San Francisco Bay. The channel joins the Sacramento River near Grand Island above Rio Vista. From Rio Vista to the Port of Sacramento, the canal serves as the eastern boundary of the Yolo Bypass. The Sacramento River flows parallel to the channel to the east. The shipping channel accommodates large ocean-going cargo vessels, with the primary cargo being agricultural products and other bulk goods. The channel, completed in 1963, is 30 feet deep, 200 feet wide, and 43 miles long, although a portion of the channel over an 8-mile reach downstream of the Port of Sacramento was deepened to 35 feet.

San Joaquin River Basin

The San Joaquin River drains about 31,200 square miles (mi²) of Central California, portions of the western Sierra Mountains, and the eastern slopes of the Coastal Range. As with the Sacramento River, the hydrology of the San Joaquin River basin has been significantly modified by the operation of reservoirs. Of the major tributaries to the San Joaquin River, only the Cosumnes River is still free flowing. Of the 25 reservoirs in the basin, 17 provide hydropower and 14 supply irrigation water (Gronberg et al., 1998). Storage in the largest San Joaquin reservoirs (New Melones, New Don Pedro, New Exchequer, and Millerton) is 6.3 MAF, which is comparable to the 6.6 MAF runoff in the basin. The presence of these reservoirs modifies the larger annual hydrograph of the San Joaquin River in a manner similar to the impacts of Sacramento River reservoirs on the Sacramento River hydrograph (e.g., Figure A-13). In dry years, the many consumptive water diversions throughout the San Joaquin watershed make the San Joaquin River very dry.

The Stockton Deep Water Ship Channel extends 41 miles west from the Port of Stockton to Antioch, California, in the counties of Contra Costa, Sacramento, and San Joaquin. The channel, which for most of its length is also the lower San Joaquin River, has an average depth of 35 feet (10.6 meters), and reaches an average of 40 feet (12.2 meters) at high tide.

The Delta

The Sacramento–San Joaquin Delta is an inland tidal freshwater delta, formed by rising sea levels over the past 6,000 years. It is east of Carquinez Strait, which is the only outlet for the Sacramento and San Joaquin rivers to San Pablo Bay and subsequently San Francisco Bay. Historically, the Delta was highly dendritic (right side of Figure A-14); however, the Delta has been altered (left side of Figure A-14) to drain tidal lands for agriculture, improve flood conveyance, reduce saltwater intrusion, allow

commercial cargo ships to reach Sacramento and Stockton, and improve opportunities for recreational boating.

The Delta is a large heterogeneous tidal region with a number of features, as shown in Figure A-15. In the west, Suisun Marsh is a large set of wetlands, managed mostly for duck hunting, which also supports some of the largest remaining brackish tidal wetlands in the region, with salinity partially managed by the Suisun Marsh Salinity Control Gates. (The gates are operated twice per day during ebb tide to direct a pulse of fresh water from the Sacramento River into the salty Bay water of the marsh.) The northern Delta is better supplied with the more abundant fresh waters of the Sacramento Valley and is shaped by that valley's flood infrastructure and bypasses (including the Yolo Bypass and Cache Slough). This section of the Delta has the most remaining tidal marshes compared to the historical coverage (Whipple et al., 2012). The Central Delta receives freshwater inflows from the Sacramento River (via the DCC, Georgiana Slough, and Three-Mile Slough), the San Joaquin River, and smaller eastside rivers and

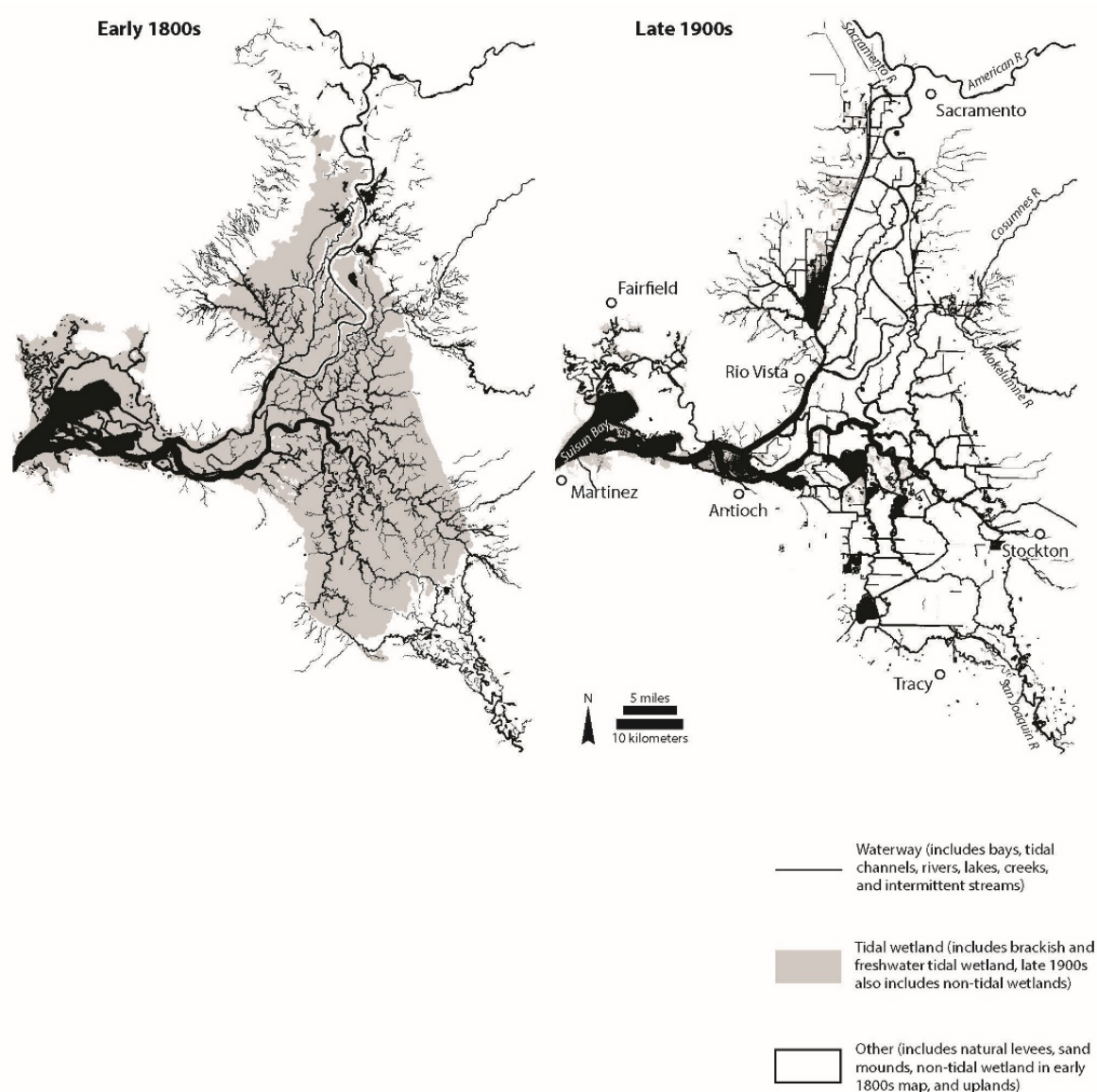


FIGURE A-14 Reconstruction of historical south Delta channels (left) and current flow network (right).
SOURCE: Robinson et al. (2014).

streams. Tidal mixing (particularly in Franks Tract) is a primary mechanism for bringing saline seawater further into the Central Delta. The Southern Delta has freshwater (and summer brackish water) inflows from the San Joaquin River and smaller streams, but most dry season freshwater inflows to the Southern Delta are drawn from the Central Delta and through the Old and Middle River corridors by pumping. Native fishes are more abundant in the Suisun Marsh and northern Delta, with non-native fishes dominating in the central and southern parts of the Delta.

There are numerous withdrawals—perhaps as many as 2,000—in the Sacramento River basin, the San Joaquin River basin, and the Delta. Temporary barriers, located primarily in the south Delta (Middle River, Head of Old River, Old River, Grantline Canal, West False River), are used for managing salinity and fish passage (Sommer, 2024).

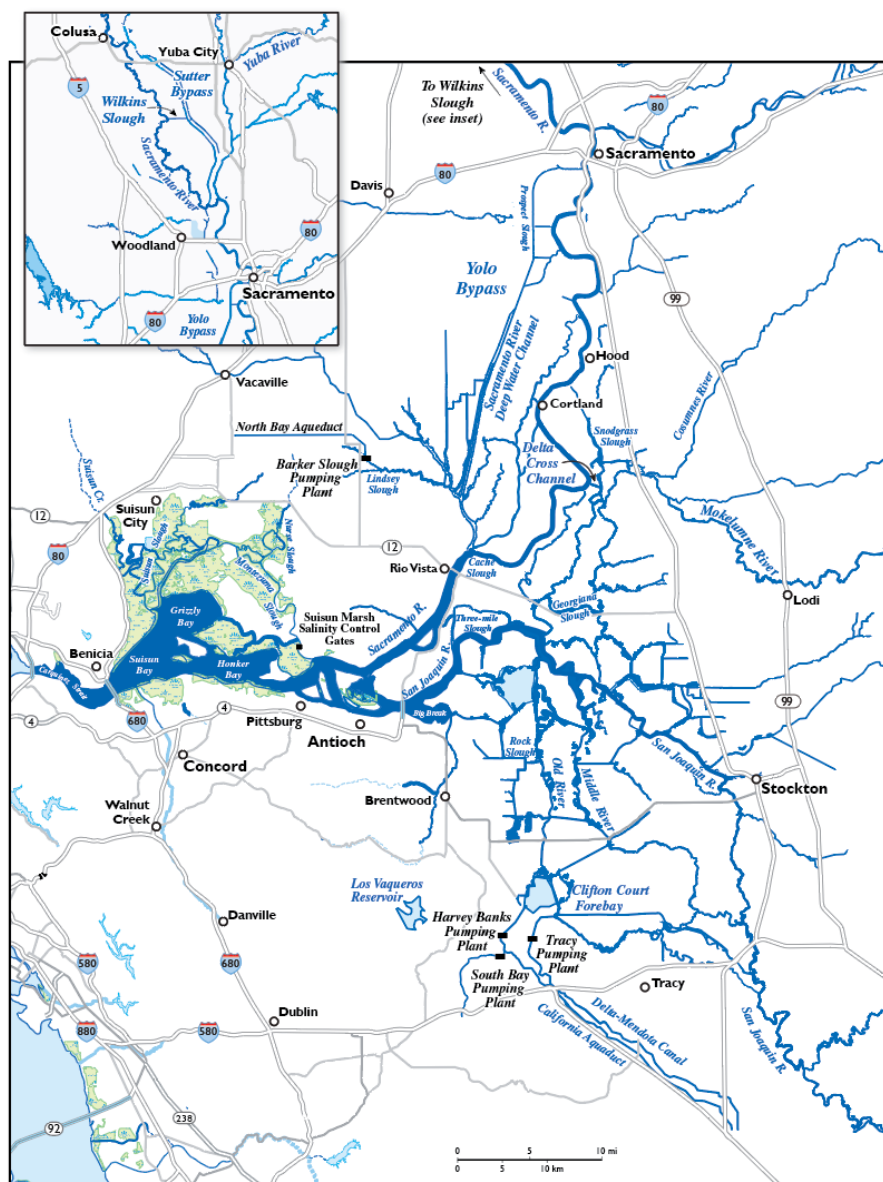


FIGURE A-15 Map of the Delta showing the major water features.

SOURCE: Kevin Lear, International Mapping Associates.

Regional Streamflow Patterns

A general *average* annual water balance of the Delta includes four major inputs: (1) the Sacramento River, 16.1 MAF; (2) the San Joaquin River, 3.1 MAF; (3) the Yolo Bypass, 1.8 MAF; and (4) eastern tributaries, 0.8 MAF (Figure A-16). The major outflows from the Delta are outflows to San Francisco Bay, 15.8 MAF; and exports of water to central and southern California, 5.1 MAF. Estimated inflows exceed the outflows by 0.9 MAF (Sommer, 2024), presumably due to consumptive and evaporative losses within the Delta.

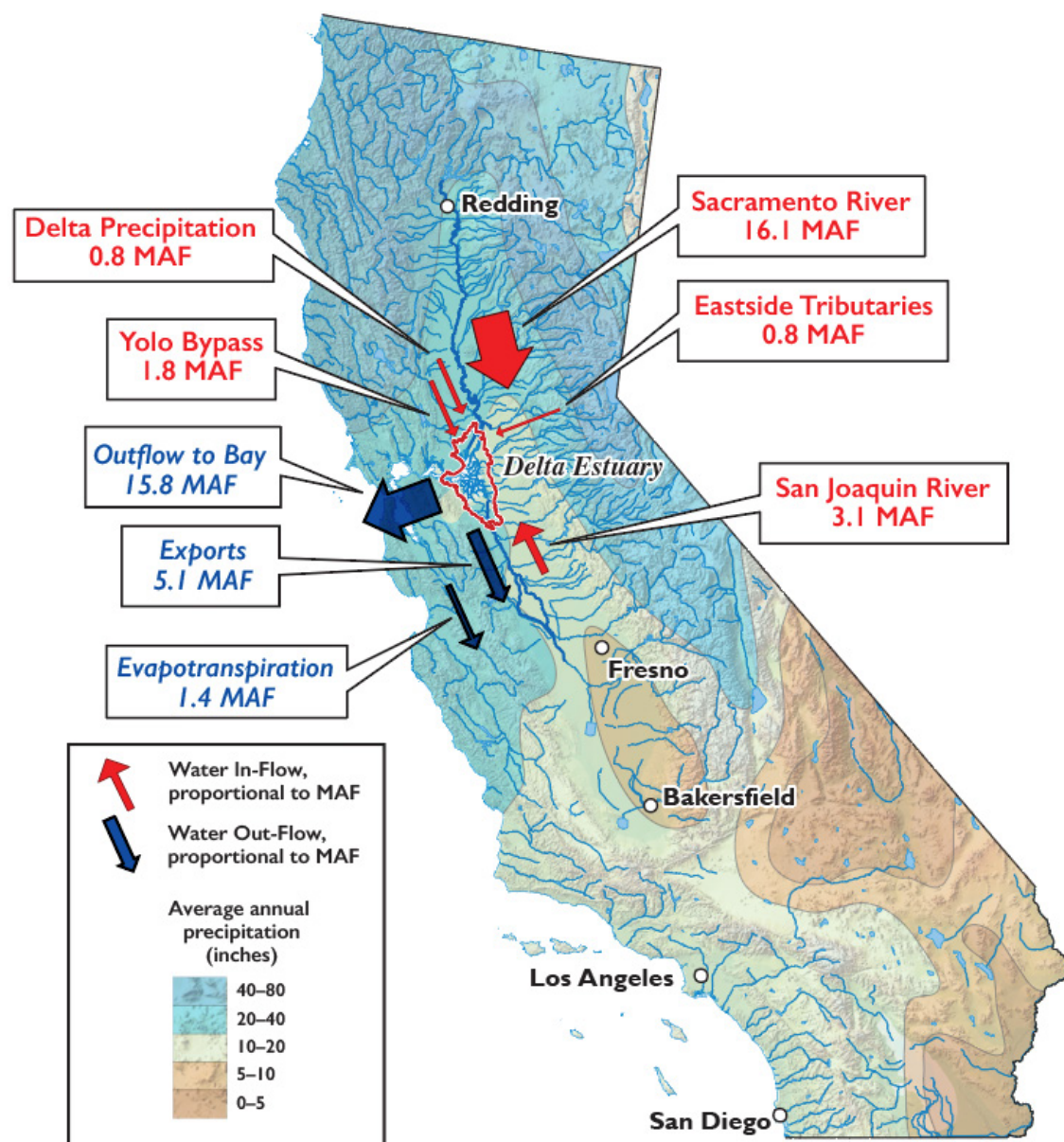


FIGURE A-16 Schematic showing the approximate scale of primary Delta inflows and outflows. SOURCE: Long term modeling from CalSim, shown in Sommer (2024). ET estimates from Medellín-Azuara et al. (2018) and precipitation estimates from Ariyama et al. (2019).

Annual averages, however, do not capture regional, seasonal, and interannual variation in Delta inputs and outputs. One long-term trend in inflows to the Delta, discussed earlier, is the change in the timing and volume of snowmelt runoff of tributaries draining to the Delta, with less streamflow coming in the historical snowmelt period of April to June. This reflects the fact that more of the total precipitation in California is falling as rain (OEHHA, 2022; Figure A-17).

Interannual variability is observed in the mean annual runoff for the entire state of California (Figure A-18). The mean annual runoff is about 80 MAF between 1901 and 2023 (Figure A-18, red line), but this average value occurs rarely. A base flow of about 25 MAF (Figure A-18, green line) occurred in all but one water year (1976–77). This “base flow” is reliable and is exceeded almost every year. The additional flow above this base is highly dependent on the number and magnitude of the atmospheric rivers that impact California in that year (Dettinger et al., 2023). The variation evident in Figure A-18 has significant ramifications for the management of the CVP and SWP.

Flows in California streams have been highly altered by human activities. Of the 540 sites assessed by Zimmerman et al. (2017), greater than 95 percent had at least one month of flow that is depleted or inflated beyond the range of natural variation in the 1996–2015 period. On average, depleted monthly flows were 20 percent of expected natural flows and inflated flows were ten times the magnitude of natural flows. The majority of sites exhibited depleted maximum annual flows and a reduction in flow variability (consistent with Figure A-13). Figure A-19 shows how water supply development has reduced Delta outflow over the last century. It shows both the declining trend in winter/spring outflow and full water year outflow as the water projects were developed, though this decline halted in the 1990s (for winter/spring outflow) and in the 2000s (for full water year outflow).

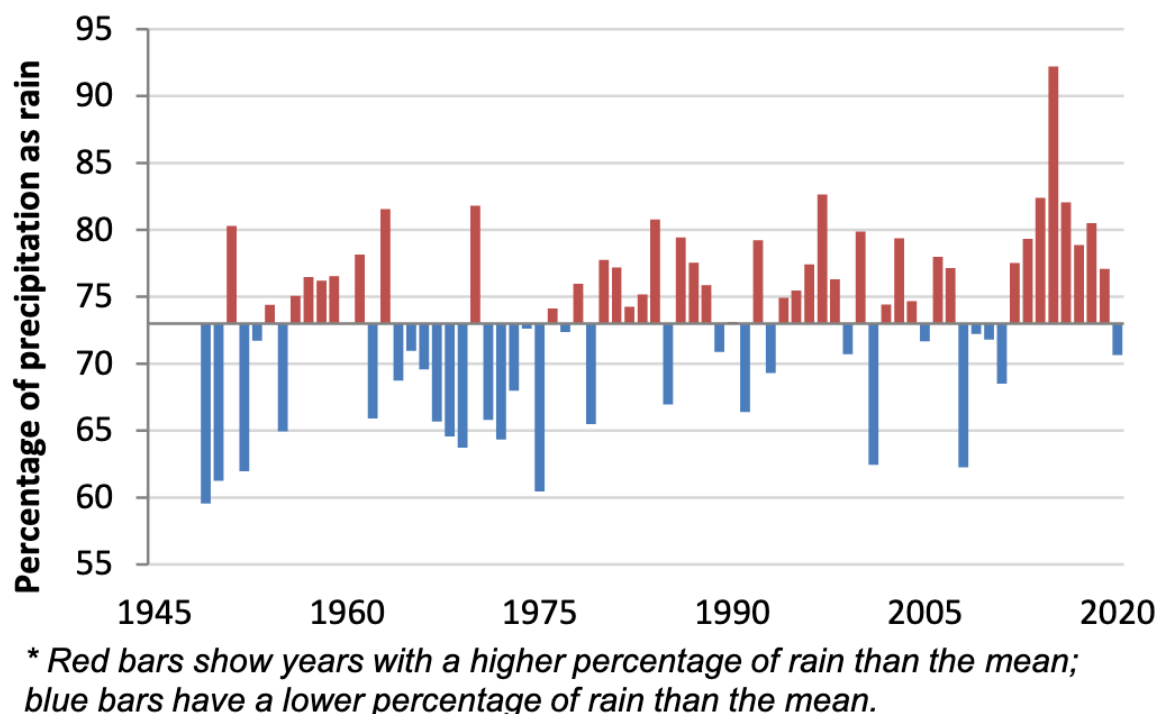


FIGURE A-17 Rain as a percentage of total annual precipitation in California, 1949–2020.
SOURCE: OEHHA (2022), from CDWR (2021).

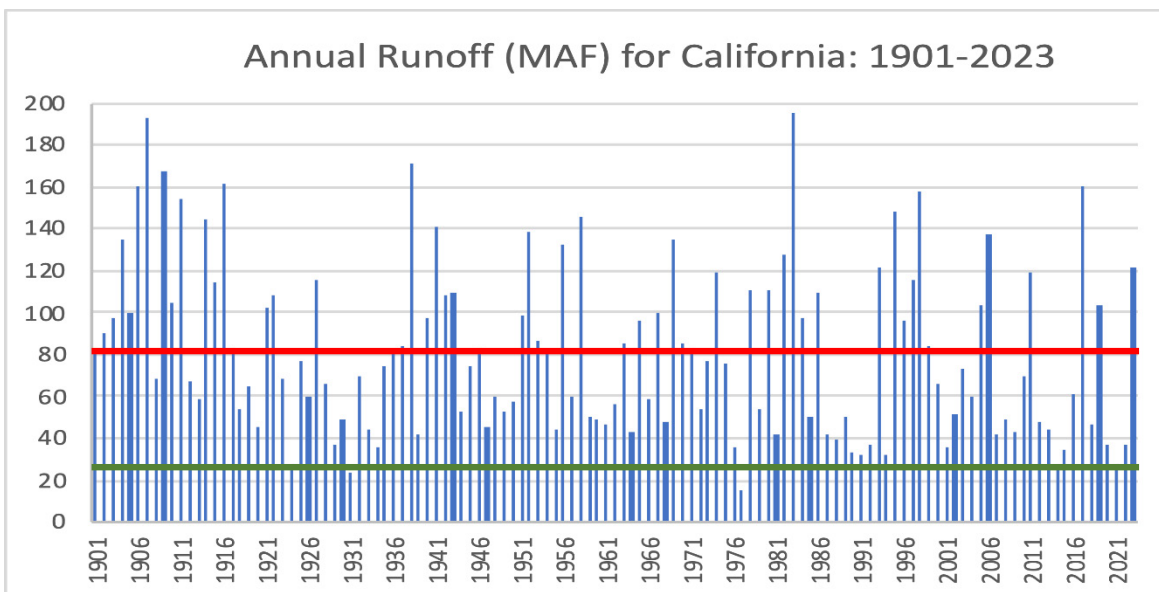


FIGURE A-18 Annual runoff for the State of California.

SOURCE: Data downloaded from *USGS California Water Science web page*.

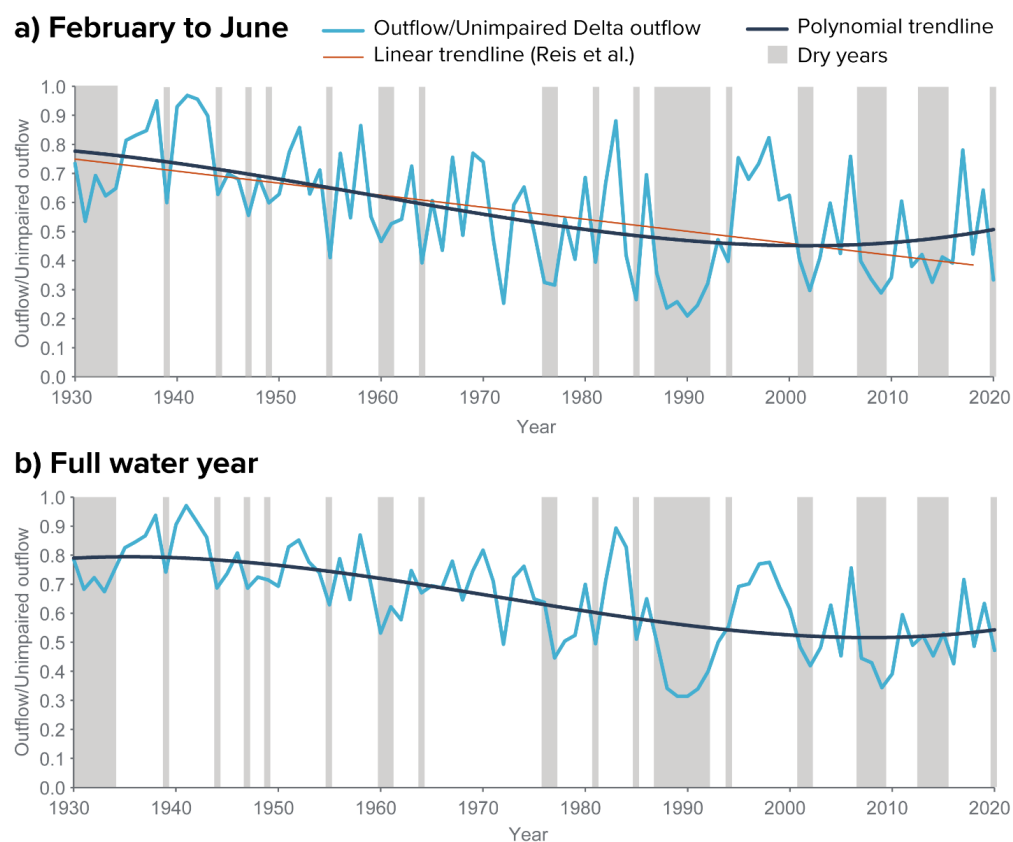


FIGURE A-19 Trends in normalized Delta outflow over time, 1930–2021.

SOURCE: Gartrell and Mount (2022).

Historical Reflection on Delta Inflows

There have been attempts to reconstruct natural flows into San Francisco Bay for the period 1850–1920 (i.e., prior to the time when exports began), but these efforts have not been particularly satisfying. Moftakhari et al. (2015) concluded that there has been an approximately 35 percent decrease in annual flow to San Francisco Bay since the mid-1800s. However, MacVean et al. (2018) concluded that reconstruction of flood frequency and extent was not possible, because a good time-series of levee construction was not available. Reconstructed natural inflows did suggest, however, that annual inflows to the Delta increased due to human activities between 1850 and 1920.

To further explore the changes in the system and their effects within the Delta, Andrews et al. (2017) constructed a 3-D hydrodynamic model to explore the system in its “pre-development” condition, prior to significant modern anthropogenic influence, for comparison to its contemporary condition. The pre-development system model was calibrated by varying marsh plain elevations in order to match sparse observations of tidal characteristics, and it was used to simulate assumed conditions thought to exist prior to the alterations of the past two centuries. The relationship between estuary outflow and the longitudinal distance from the estuary mouth to the 2 psu bottom salinity isohaline (X2⁴) was analyzed. The Andrews et al. (2017) analysis shows much more extensive variation in the position of X2 under predevelopment conditions.

Fox et al. (1990) concluded that there was no decrease in the annual Delta outflow for 1921–1986, despite interbasin exports. There were, however, seasonal changes, including a decreased outflow during April–May, and increased outflow during July–November. Changes in other months were not statistically significant. Changes were attributed to operation of upstream water projects and earlier snowmelt. Hutton et al. (2017) also found no change in annual Delta outflows for 1922–2015, but they did detect statistically significant decreasing outflows in February, April, May, and November, and increasing outflows in July and August. These results generally agree with those of Fox et al. (1990), who had 25 fewer years of data.

Streamflow Changes Caused by Global Warming

Global warming-induced changes in streamflow are affected by changes in other variables such as precipitation, evapotranspiration, and snowpack, to name a few. Furthermore, changes in land surface conditions such as those associated with vegetation cover can significantly alter streamflow characteristics (Zhou et al., 2023). Despite the complexity of processes involved in runoff generation, there is an emerging consensus in the literature that runoff is projected to increase over most global land regions with continued global warming (Zhou et al., 2023) including the western United States (Payton et al., 2023).

Observations-based analysis shows spatial heterogeneity and opposing trends in streamflow magnitude across watersheds. However, changes in streamflow seasonality are arguably the most affected aspect of streamflow due to climate change. Recent studies have documented a reduction in streamflow seasonality in northern high latitudes (above 50 N) that are directly related to anthropogenic global warming (Wang et al., 2024). Furthermore, it has been shown that streamflow seasonality is altered either toward earlier or delayed peaks in streamflow depending on mean snow fraction. More specifically, earlier snowmelt is observed in snow-rich catchments, while less snowy catchments exhibit a delayed streamflow peak (Han et al., 2024).

⁴ X2 is the location kilometers from the Golden Gate Bridge where average daily salinity is 2 parts per thousand at 1 meter from the bottom.

GROUNDWATER

Groundwater is an important freshwater resource for California. USGS reports that roughly 60 percent of statewide water withdrawals is used for the agricultural sector (Brandt, 2018); the California Department of Water Resources (CDWR) indicates roughly 40 percent⁵. The difference among reported amounts arises from different survey methods and assumptions. Groundwater provides about 40 percent of agricultural water, and it provides freshwater for a number of communities, including the Delta communities of Clarksburg, Courtland, Freeport, Hood, Isleton, and Rio (PPIC, 2024).

As a result of groundwater depletion, land subsidence is common in many parts of California, including northwest of Sacramento and portions of the San Joaquin River basin, where subsidence in the western part of the basin has exceeded 25 feet (USGS, 2018a). In the Delta, drainage and oxidation of nutrient-rich peat soils, as well agricultural practices, has caused these lands to subside to 9 to 26 feet below sea level (USGS, 2018b).

TIDES AND SALINITY

Salinity in the Delta substantially determines habitat for fish, and it frequently controls whether the water is fit for municipal uses or agriculture. If saltwater protrudes too far east into the estuary, freshwater in the Delta becomes contaminated and Delta ecosystems are disrupted. For this reason, standards exist on how to operate water exports so that salt does not intrude too far into the Delta.

Surface water flows drive the movement of salts, water quality constituents, and most aquatic organisms and fish in the Delta. These flows are mostly driven by large semi-diurnal tides. In the western Delta average tidal flows vary $\pm 12,000$ cubic meters per second (cms, over 400,000 cfs). The influence of tides within the Delta is shown in Figure A-20, which shows flow rate measured by the USGS Middle River gauge. Tidal elevation and flow changes also drive the existence and functioning of many Delta wetlands and much of its biological productivity.

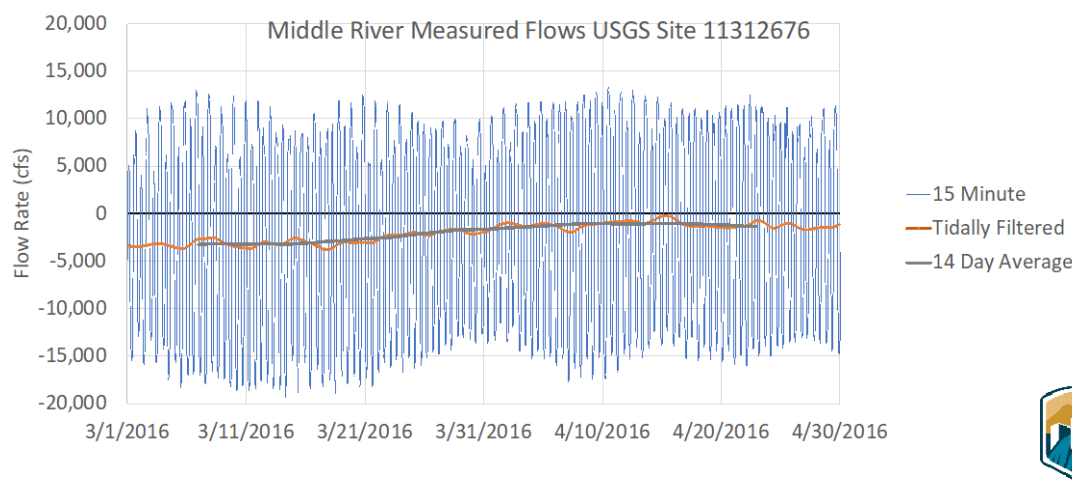


FIGURE A-20 The 15-minute measured flow, low-pass filtered flow, and 14-day moving average of tidally filtered flow in the Middle River at USGS Station 11312676.
SOURCE: Israel (2024).

⁵ See <https://water.ca.gov/Programs/Water-Use-And-Efficiency/Agricultural-Water-Use-Efficiency>.

Interestingly, tides affect river flows beyond the Delta, including as far upstream as Freeport on the Sacramento River and up to Stockton on the San Joaquin River. (Salinity is restricted from traveling this far into the Delta by freshwater river inflows.) As shown in Figure A-21, Freeport has a significant tidal signal, although the tidally averaged or net flows are usually positive—i.e., toward the ocean. Under severe low flow conditions, it is possible for the net flows at Freeport to be negative for periods of time (Figure A-22). Further into the Central Delta, flows usually reverse with the tides, except under flood flow conditions. The influence of tides is diminished throughout the Delta, and salt water is pushed further downstream toward the Bay, during periods of river flooding. Figure A-23 shows that tidal fluctuations are not discernable during the peak days of the flood hydrograph. However, the tidal elevation influences flood elevations within the Delta under these high river flow conditions.

The influence of tides on water elevations and flows has always dominated in the Delta (except for major floods), but it has changed over time. From 1860 to 2018, the average tidal range increased by 2 feet in the San Joaquin River at Stockton and by 0.8 feet in the Sacramento River at Sacramento (Szlemp, 2020). The increase coincided with river deepening, channelization, and floodplain leveeing in the early 20th century. Tidal ranges decreased after the mid-1930s, perhaps from wetland restoration and subsided island failures. Since about 1950, reservoir releases, various gates, and water export pumping have been managed to control seawater intrusion into the Delta while providing local and exported water of acceptable quality. For example, the Suisun Marsh salinity control gates help the marsh remain fresh for Delta smelt and waterfowl. Water levels and flows are also influenced by diversions and operation of temporary barriers within the Delta.

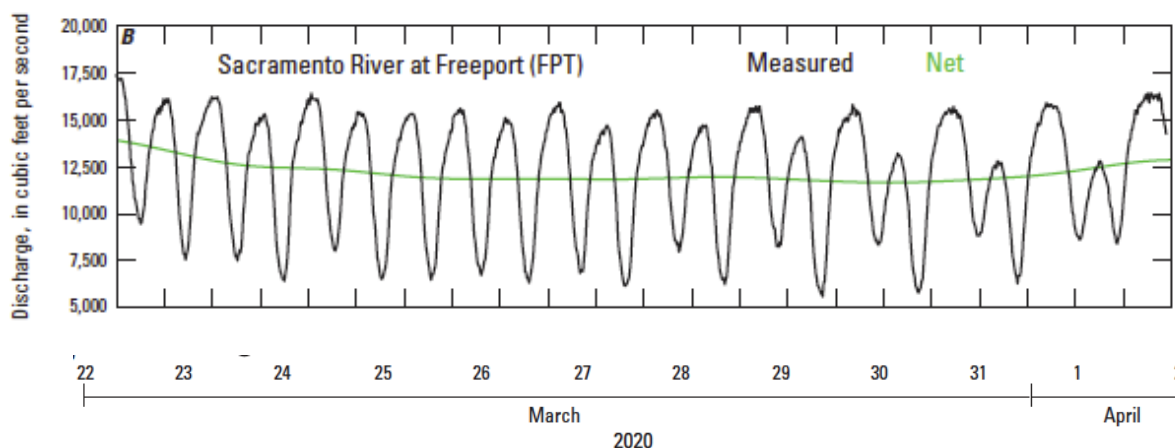


FIGURE A-21 Instantaneous and average flows over a tidal cycle at Freeport on the Sacramento River. SOURCE: Brown et al. (2024).

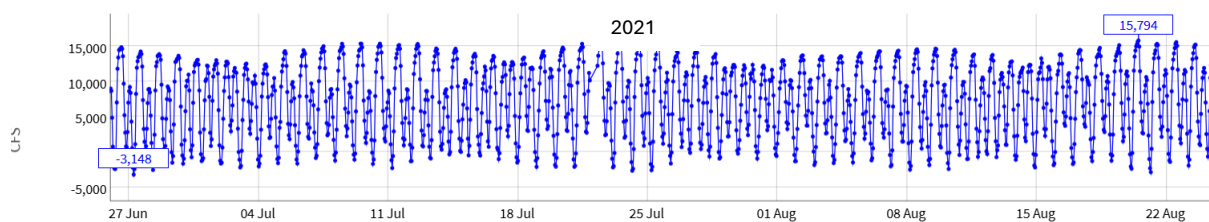


FIGURE A-22 Discharge at the Freeport gage (USGS station 11447650) on the Sacramento River, June 22–August 23, 2021.

SOURCE: data from U.S. Geological Survey.

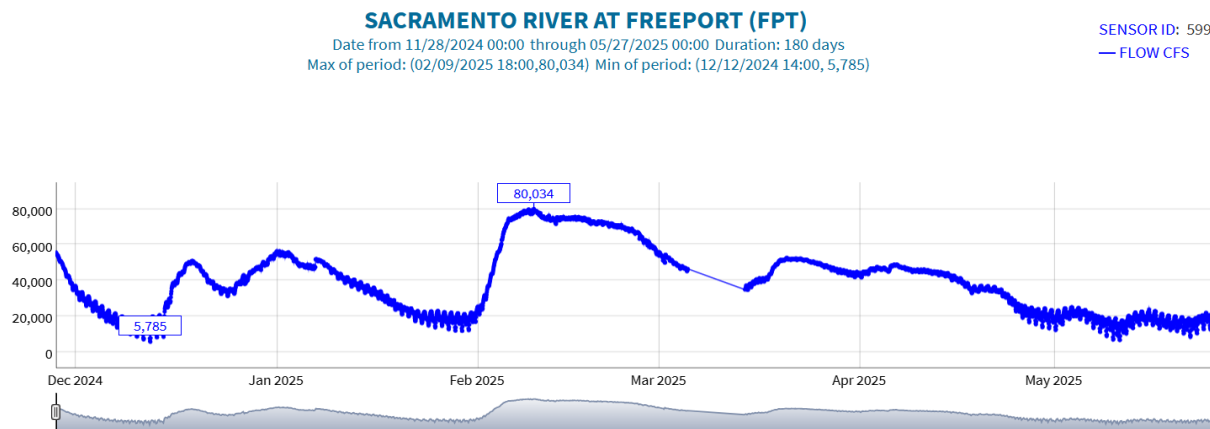


FIGURE A-23 Discharge at Freeport gage (USGS station 11447650), on the Sacramento River, December 2024–May 2025.

SOURCE: Data from U.S. Geological Survey

The primary drivers of subtidal water level variations are barometric pressure variations and lesser effects from wind (Walters, 1982). A residual circulation also can be caused by a longitudinal salinity or temperature density gradient in a tidal system. In most of the Delta, these density gradients are usually too small to cause significant circulation, but when they occur, the results can be biologically and ecologically important (Brown et al., 2024).

Many of the processes discussed above are captured in Figure A-24, which shows the mix of tides, river inflows, and exports that influence flows, salinity, and transport across the California Delta (Brown et al., 2024).

Tidal flows and elevations in the Suisun Marsh area in the western Delta are particularly important. As shown in Figure A-25, tidal flows vary from $\pm 12,000$ cms (400,000 cfs) at Martinez to near zero at Sacramento on the Sacramento River and Stockton on the San Joaquin River. Tidal excursions show the transport of salts, nutrients, and organisms within and across the area over an average tidal cycle. These tidal amplitudes and flows vary considerably across higher and lower daily tidal peaks, spring and neap cycles, and longer seasonal and multi-year cycles. Tidal harmonic studies often cover a 19-year range of cycles, with even longer cycles being important for some purposes (Enright et al., 2013).

Figure A-26 shows how salinity varies across a transect of the Delta relevant to the Summer-Fall Habitat Action, and how this salinity varies with ebb and flood tides. As mentioned previously, if sea salt disperses too far into the estuary, then it contaminates freshwater flowing down the Sacramento River, which is the primary freshwater source for in-Delta uses and water exports. Another source of salinity in the Delta is agricultural drainage from within the Delta and upstream. These salts accumulate in the southern and central Delta unless tidal dispersion moves these salts to other parts of the Delta, higher winter San Joaquin River outflows flush these salts downstream, or these salts are exported from CVP and SWP pumps.

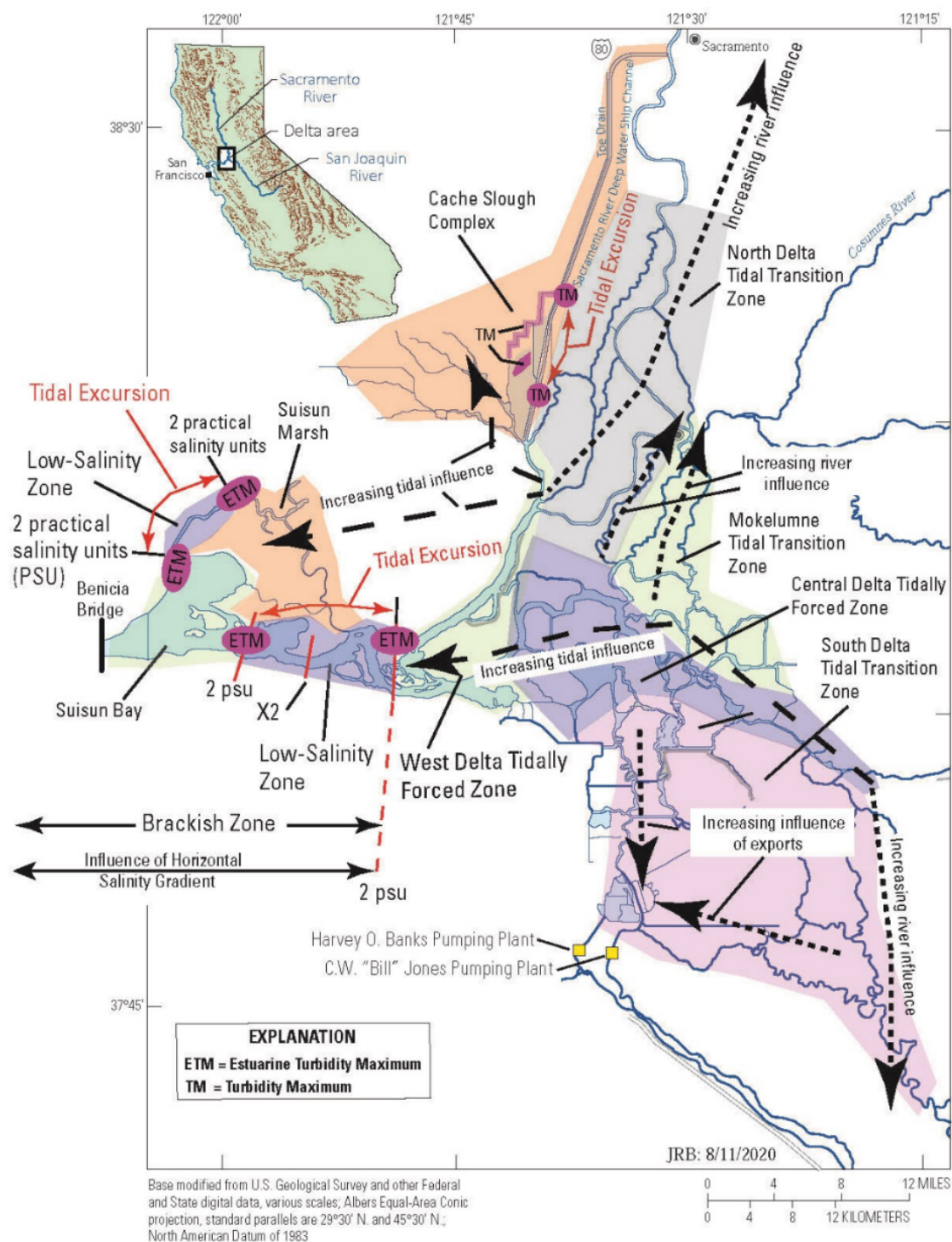


FIGURE A-24 The relative influence of tides, river flows, and exports on flows and salinity across the Delta.

SOURCE: Brown et al. (2024).

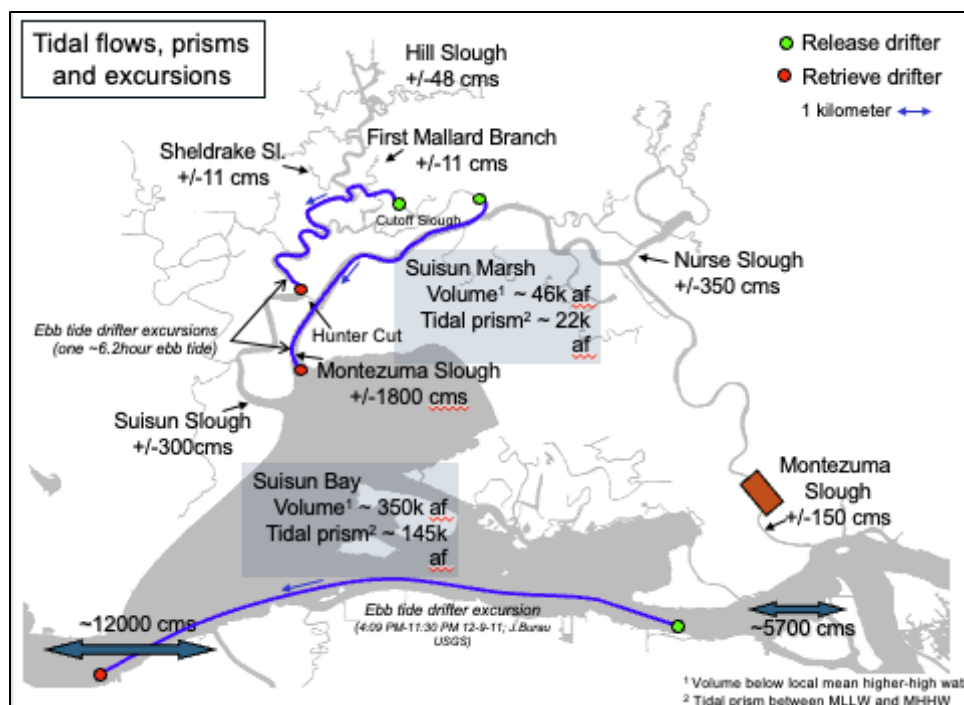


FIGURE A-25 Tidal flows and prisms for the Suisun Bay area. NOTE: Simplistically, the tidal prism is the volume of water between high tide and low tide, measured at a point. Martinez is located near the red dot in the lower left-hand corner. SOURCE: Brown et al. (2024).

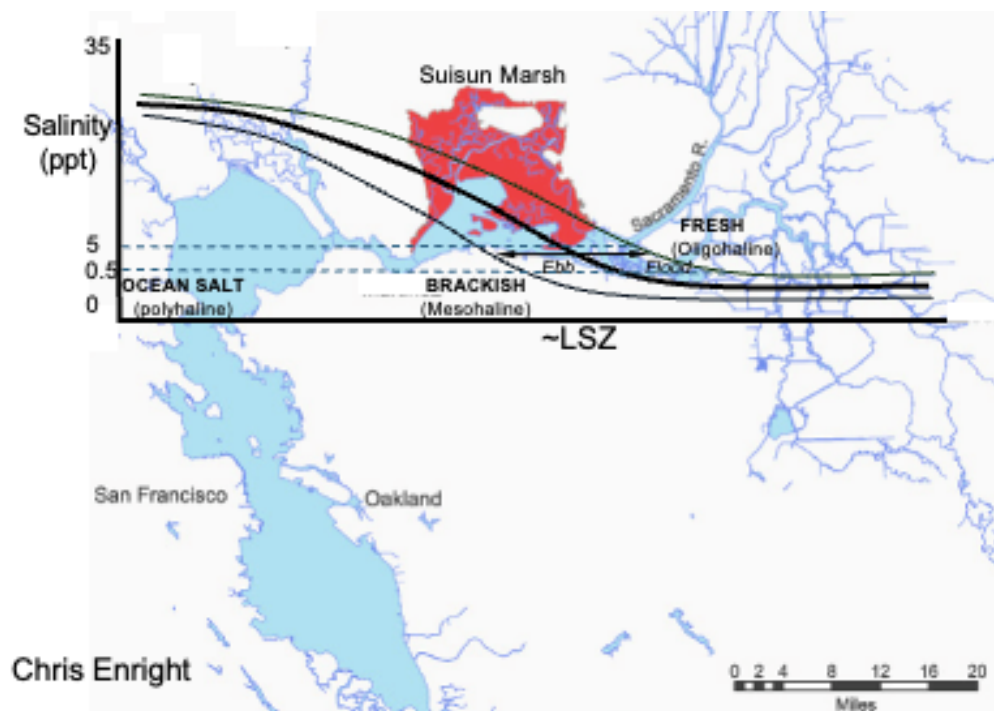


FIGURE A-26 Salinity variations from the ocean and San Francisco Bay, to near zero at Sacramento and Stockton. SOURCE: Sommer (2024).

Sea Level Rise

Climate change-induced sea level rise is reshaping coastlines across the globe, with observable trends indicating a significant increase in sea level over the past few decades. Globally, sea levels have risen by an average of 1.3 inches per decade, but in the contiguous United States, the average increase has been even higher at 1.8 inches per decade (USGCRP, 2023)⁶. However, these rises are not uniform across regions, with varying rates of sea level rise observed in different parts of the country (Figure A-27).

In the United States, sea level rise rates exhibit considerable variation. Over the last 30 years, the most pronounced rise has been observed along the U.S. western Gulf Coast, where sea levels have increased by approximately 3 inches per decade. This substantial increase can be attributed largely to high rates of land subsidence, primarily driven by subsurface groundwater extraction and fossil fuel withdrawal activities. Conversely, the Pacific coastlines of the northwest and southwest regions have experienced relatively lower rates of sea level rise, with increases of around 0.7 and 1 inch per decade, respectively.

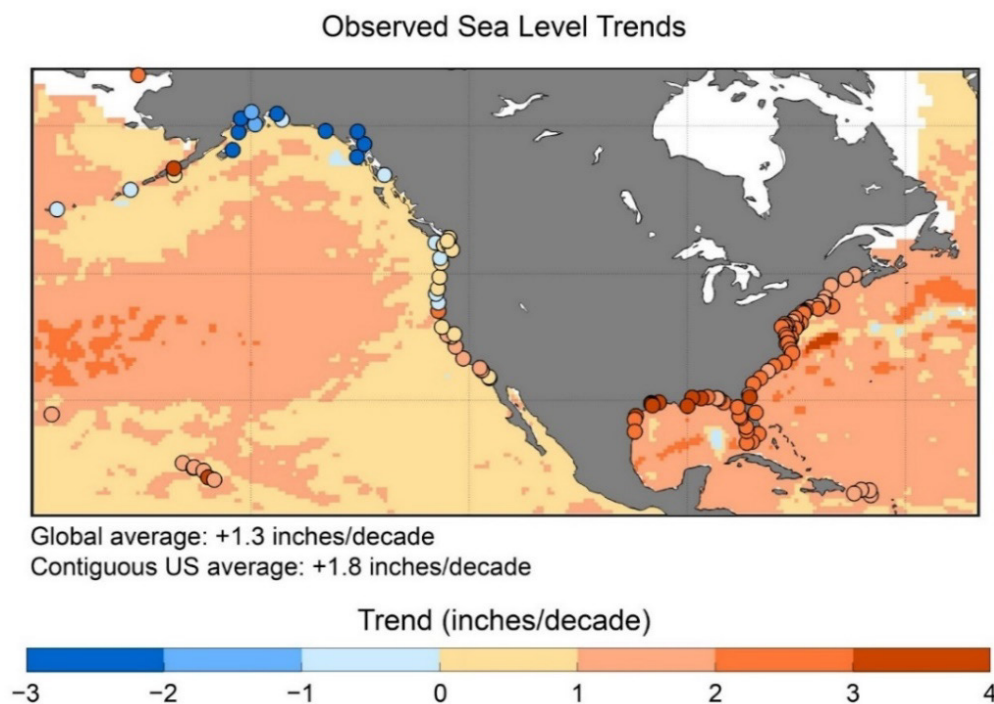


FIGURE A-27 Observed sea level rise trends from satellite and tide gauge data during the period 1993–2020.

SOURCE: USGCRP (2023).

The impacts of sea level rise extend beyond coastal infrastructure, leading to increased saltwater intrusion into freshwater habitats and extending the regions of tidal influence. Both ramifications could disrupt Delta ecosystems and threaten the survival of native fish species. Figure A-28 shows the simulated inundation of San Francisco Bay (left) and the larger Bay-Delta (right) resulting from 1 meter of sea level rise.

⁶ If the USGCRP website is not available, similar information can be found at <https://oehha.ca.gov/climate-change/epic-2022/impacts-physical-systems/sea-level-rise> and <https://www.climate.gov/news-features/understanding-climate/climate-change-global-sea-level>.

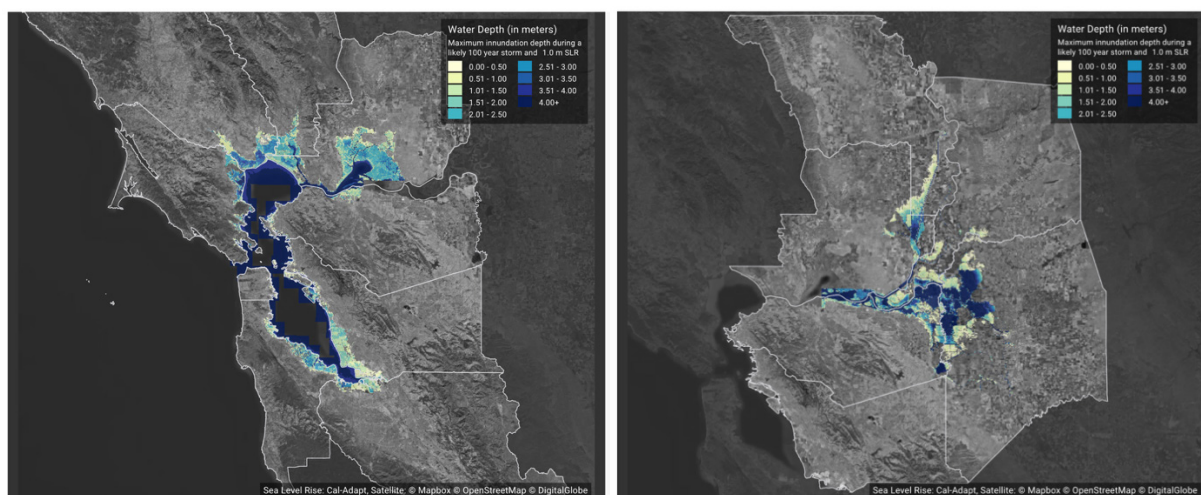


FIGURE A-28 Modeled inundation resulting from 1 meter of sea level rise in San Francisco Bay (left) and the larger Bay-Delta (right).

SOURCE: <https://v2.cal-adapt.org/tools/slr-calflod-3d/>.

DELTA ECOLOGY

Ecological function in the Delta has been shaped by over a century of land use change, along with altered hydrological function and non-native species introductions.

Land use in the Sacramento River and San Joaquin basins and the Delta has been radically transformed since the middle of the 19th century. The most significant change has been the conversion of almost all of the contiguous wetlands to agricultural production (see Figure A-29; Cloern et al., 2021; Whipple et al., 2012) through the drainage of wetlands. Nearly all tidal (98 percent) and nontidal (99 percent) wetlands have been drained and converted for agriculture or open-water habitat, along with a loss of 68 percent of riparian forest habitats (Whipple et al., 2012). Moreover, the current landscape is largely disconnected from its rivers by levees and because of flow regulation from upstream dams.

When the system was dominated by wetlands and a large diversity of plants, vascular marsh plants contributed the majority of net primary productivity, which represents the amount of energy available to support secondary consumers. Phytoplankton and pelagic primary production were a comparatively small component of total system production. Now the Delta region is dominated by agriculture, with the loss of wetland habitat causing an increase in the relative importance of pelagic primary production (phytoplankton and invasive aquatic vegetation) for consumers.

Pelagic ecosystems within the historic Delta are thought to have been dominated by detrital energy flows. Cloern et al. (2021) estimate that with the cumulative loss of 77 percent of Delta wetland habitats, systemwide net primary production was reduced by 94 percent, with sharp declines in energy available to both herbivore (89 percent decline) and detritivore (94 percent decline) components of the food web.

Historically unimpeded flows meant that tidal flushing not only helped to contribute to high rates of primary production but also provided a mechanism to distribute that material to pelagic food webs. Today, tidal hydrodynamics still exert strong controls on the growth of phytoplankton and microalgae and regulate production and the distribution of detrital material.

A historical perspective on the ecology of the Delta and an understanding of how physical and biological conditions have changed are critical for placing the current environmental challenges and management objectives in context. There has been a considerable amount of effort by scientists and natural historians to piece together how Delta ecology has changed over the past century and a half. The description provided below draws from historical reconstructions of Delta morphology and landscape,

empirical studies of species adaptations and habitat use, and analyses of long-term shifts in primary production, trophic pathways, and species abundances. Figure A-30 shows a timeline of key historical and ecological changes in California and the Delta.

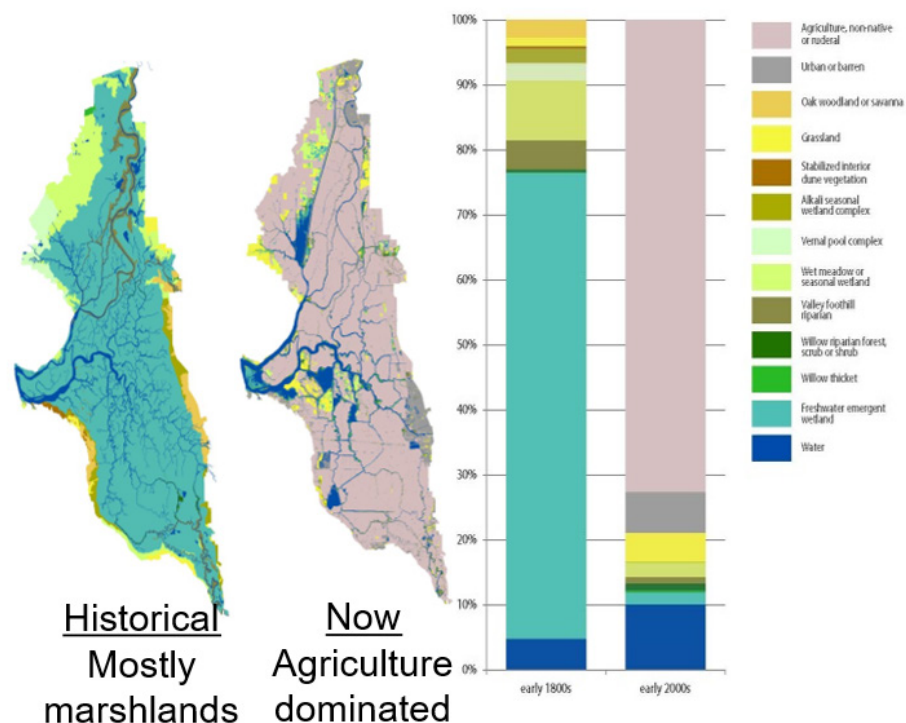


FIGURE A-29 Reconstructed historical San Francisco Bay-Delta land use and current land use. SOURCE: Whipple et al. (2012).

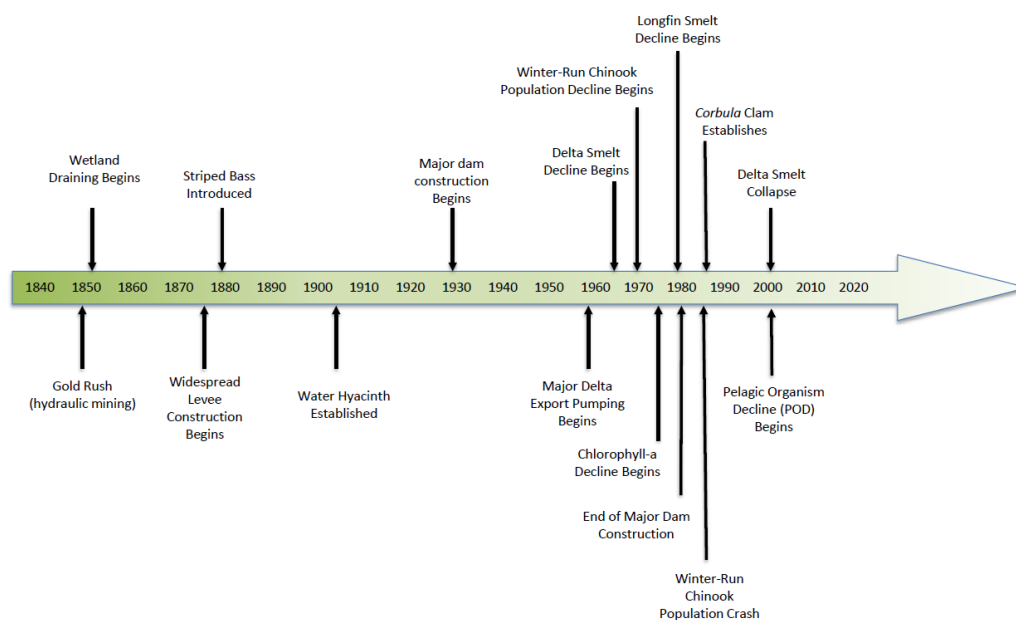


FIGURE A-30 Timeline of key historical and ecological changes in California and the Delta.

Hydrologic Connectivity and Flow Regimes

Historically, the Central Valley and Delta functioned as a hydrologically dynamic system shaped by seasonal flood pulses, variable snowmelt, and tidal mixing. The Sacramento and San Joaquin Rivers regularly overtopped their banks during winter and spring, inundating vast flood basins such as the Butte, Sutter, Yolo, and Colusa Basins. These floodwaters moved slowly across the landscape, recharging wetlands, distributing nutrients, and creating temporally dynamic habitats critical for native fish and bird species (Bay Institute, 1998; SFEI, 2012; Whipple et al., 2012). In the Delta, fluvial and tidal forces interacted to produce a shifting network of distributary channels, backwater sloughs, and tidal wetlands, maintaining salinity gradients and a highly retentive flow regime that supported aquatic productivity (Enright et al., 2013; SFEI, 2012; Whipple et al., 2012).

This regime was radically altered by hydraulic mining, levee construction, large dam projects, and water exports (see Appendix B for a description of these activities). Beginning in the mid-19th century, sediment from hydraulic mining aggraded channels and filled wetlands, reducing their natural flood storage capacity (Gilbert, 1917; Kelley, 1989). By the early 20th century, levees had disconnected more than 90 percent of floodplain wetlands from river channels (Bay Institute, 1998; SFEI, 2012; Whipple et al., 2012). Later, major reservoirs captured spring snowmelt, reducing overbank flooding by greater than 80 percent, and transforming the timing, volume, and thermal characteristics of downstream flows (Bay Institute, 1998; Lund et al., 2007). In the Delta, the CVP and SWP established net southward flow during key ecological periods, reversing natural flow directions in Old and Middle Rivers and increasing the risk of fish entrainment while shortening fish residence times in productive habitats (Cloern and Jassby, 2012; Jassby and Cloern, 2000; Kimmerer, 2008).

Landscape and Habitat Structure

The historical Delta and surrounding Central Valley floodplains were defined by spatial complexity and a high degree of land-water interspersion (Whipple et al., 2012). Natural levees, oxbows, scroll bars, and flood basins created a shifting mosaic of interconnected habitat types — including tidal and non-tidal emergent wetlands, riparian forests, backwater sloughs, and seasonal lakes and ponds (Thompson, 1957; Whipple et al., 2012). In the South Delta, dynamic fluvial-tidal interactions sustained diverse habitats used by splittail, perch, and juvenile Chinook salmon (Sommer et al., 1997, 2001). In the North Delta, warm, shallow lakes supported now-extirpated fish species such as Thicktail chub and Sacramento perch (SFEI, 2012).

This fine-grained landscape structure was steadily dismantled over several decades by wetland reclamation, levee construction, and agricultural development. The Swamp and Overflowed Lands Act of 1850 facilitated large-scale drainage and conversion of wetlands to farmland (Kelley, 1989). By the early 20th century, over 90 percent of Central Valley wetlands had been lost or hydrologically isolated (SFEI, 2012). In the Delta, the construction of a rectilinear network of levees and drainage canals transformed a complex floodplain-tidal system into subsided, disconnected agricultural islands (Lund et al., 2010; Thompson, 1957). Land subsidence driven by peat oxidation pushed some Delta islands more than 5 meters below sea level, further entrenching the need for levee maintenance and eliminating shallow habitat gradients (Bay Institute, 1998).

These changes greatly simplified the physical structure of the landscape and removed the spatial heterogeneity that had supported diverse life histories and ecological functions (Moyle et al., 2010) and a food web structure reliant on wetland inputs (DISB, 2024).

Primary Production, Food-Web Structure, and Energy Flow

Historically, the Delta and its floodplain wetlands were among the most productive wetland ecosystems in North America, supporting spatially complex and seasonally dynamic food webs in which energy moved primarily through detrital and benthic pathways (DISB, 2024). Organic material produced by marsh vegetation and floodplain algae was slowly decomposed and transported through microbial and invertebrate consumers. Blind tidal channels and flood basins retained detritus and organic carbon, allowing energy to be recycled locally and released gradually to the aquatic food web. Flood pulses enhanced lateral connectivity, pulsing nutrients and organic matter across habitat boundaries and fueling bursts of secondary production. Benthic grazers, microbial decomposers, and filter feeders processed this material, supporting a range of consumers from zooplankton to fish (Junk et al., 1989; SFEI, 2012, 2016; Sommer et al., 2001). The Delta's tidal marsh and riparian zone habitats generated an estimated 915 million pounds of organic carbon annually, primarily from emergent vegetation and benthic algae (Bay Institute, 1998). This production was spatially extensive and seasonally mobilized: flood pulses transported detritus and nutrients across land-water boundaries, supporting microbial decomposers, filter feeders, and fish in adjacent aquatic habitats (Junk et al., 1989; Sommer et al., 2001). Organic inputs were predominantly autochthonous and slow-cycling, creating a stable, detritus-based energy system that persisted year-round (Bay Institute, 1998; DISB, 2024).

This regime of highly diffuse marsh and floodplain productivity gave way in the mid-20th century to a system increasingly dominated by pelagic primary production. As tidal wetlands and floodplain habitats were disconnected by draining and levee construction, channel complexity declined, and emergent vegetation and marsh detritus ceased to be the dominant energy sources. The food web instead shifted toward a pelagic-based system supported primarily by phytoplankton and microbial loop dynamics, reliant on phytoplankton produced within the Delta's open water channels—especially diatoms and other fast-growing taxa that flourished in longer, deeper, clearer, and more hydrologically isolated channels (Brown et al., 2016; Cloern, 2007; DISB, 2024; Jassby and Cloern, 2000). In this configuration, phytoplankton served as the primary organic carbon and energy sources, while dissolved organic matter was processed by free-living bacteria and consumed by heterotrophic nanoflagellates, ciliates, and other microbial grazers—a trophic pathway known as the microbial loop (Azam et al., 1983; Hollibaugh et al., 2000). These microbial organisms formed an intermediate step, transferring dissolved organic carbon into particulate forms that, along with phytoplankton biomass, could be consumed by zooplankton (Sobczak et al., 2002; Stepanauskas et al., 2005).

Though simplified relative to the historical system, this mid-20th-century pelagic food web remained sufficiently productive, with chlorophyll *a* concentrations that averaged above 10 µg/L in many regions of the estuary able to support robust populations of copepods, mysid shrimp, and cladocerans that formed the dietary base for native planktivorous fishes such as Delta smelt and longfin smelt (Brown et al., 2016; Jassby et al., 2002; Kimmerer, 2004). However, the physical alterations to the Delta—including levee confinement, reduced residence times, and the elimination of shallow vegetated margins—increasingly constrained the spatial and temporal extent of productive food web zones (Cloern et al., 2012; Monsen et al., 2007).

Over time, additional factors further affected primary production and food availability. The non-native freshwater clam, *Corbicula fluminea*, was introduced to the Delta in 1940s (Brown et al., 2007). While *C. fluminea* entered the system before long-term monitoring was underway, studies suggest, based on its substantial biomass and widespread distribution, that it has substantially influenced the Delta food web (Cohen et al., 1984; Lopez et al., 2006; Lucas and Thompson, 2012). Long-term monitoring data indicate that decreasing trends in phytoplankton biomass and pelagic primary productivity in the Delta and Suisun Bay were already underway during the 1970s (Jassby, 2008), with some evidence suggesting that increasing water exports could explain some of those decreases (Jassby and Powell, 1994).

The “pelagic”-based food-web system experienced a pronounced collapse following the introduction of *Pomatocorbula amurensis* in 1986, which triggered a five-fold decline in phytoplankton

biomass across much of the Delta and Suisun Bay. Chlorophyll *a* concentrations fell to less than 3 $\mu\text{g/L}$, even during periods when biomass had historically accumulated (Cloern and Jassby, 2012).

The collapse of phytoplankton and microbial productivity in the late 1980s triggered a broader unraveling of trophic linkages. The food web became decoupled, meaning that energy no longer moved efficiently from basal producers through zooplankton to native fishes (Greene et al., 2011; Kimmerer et al., 1994; Werner and Hollibaugh, 1993). Native zooplankton populations declined sharply, and the species that replaced them (e.g., invasive cyclopoid copepods) were smaller, less nutritious, and poorly matched to the feeding ecology of native fishes (Bouley and Kimmerer, 2006; Ger et al., 2010). Where benthic filter feeders such as *P. amurensis* and *C. fluminea* occur in high densities, their grazing rates can approach $12 \text{ m}^3 \text{ m}^{-2} \text{ d}^{-1}$ in some seasons (Figure A-31). High grazing rates intercepted phytoplankton and microbial biomass before it could be consumed by zooplankton, severing the direct link between primary producers and higher consumers (Cloern and Jassby, 2012; Greene et al., 2011). The detrital pathways that historically provided a slow and stable source of energy had been largely eliminated because of the loss of marshes and seasonal floodplains (SFEI, 2016; Whipple et al., 2012). The result was a fragmented and inefficient food web in which much of the available carbon was either lost to microbial respiration, sequestered in the benthos, or cycled through pathways that no longer supported zooplankton or fish production (Kimmerer et al., 1994; Sobczak et al., 2002).

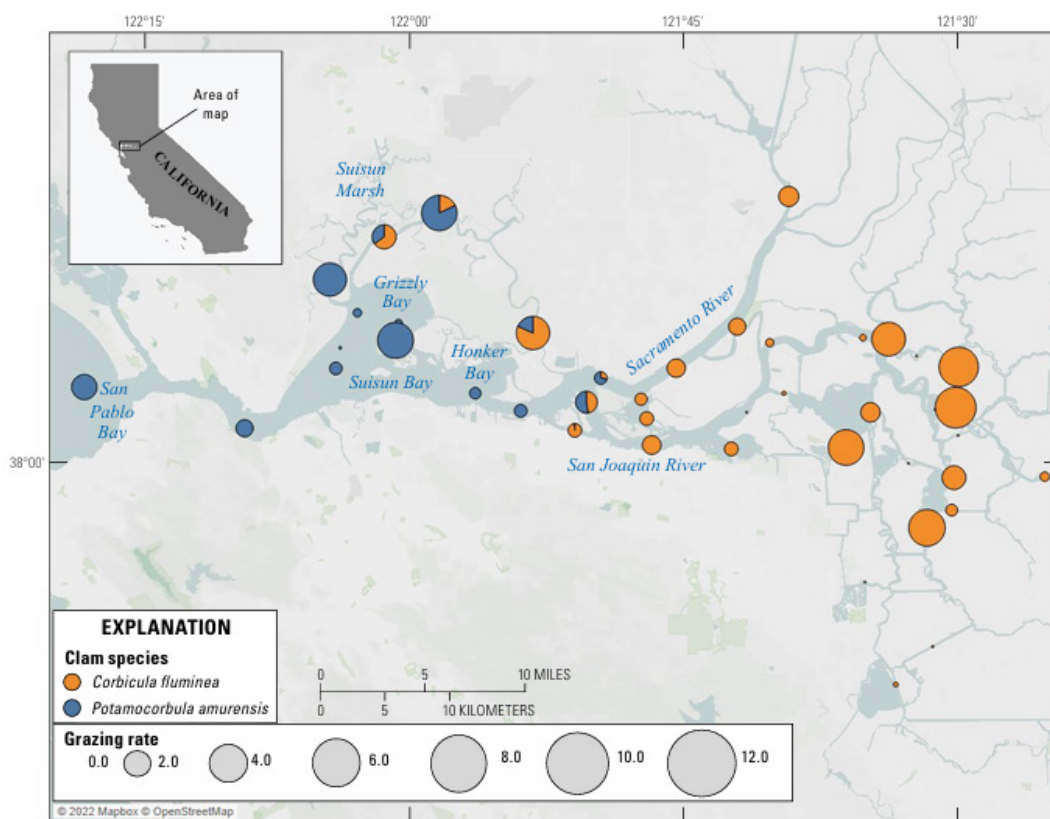


FIGURE A-31 Estimated grazing rates (volume of water filtered per unit area per day [$\text{m}^3/\text{m}^2/\text{d}$]) for *Potamocorbula amurensis* and *Corbicula fluminea* in May 2019. NOTE: In the areas where *P. amurensis* (blue) and *C. fluminea* (orange) overlap, their combined total grazing rate is shown. Grazing rates are based on clam biomass determined through field sampling (g/m^2) converted to grazing (i.e., filtration) rate based on lab-determined conversion factors, with the *P. amurensis* filtering approximately four times faster per unit biomass than *C. fluminea*.

SOURCE: Zierdt-Smith et al. (2023).

Species Composition and Adaptation

Native species in the Delta evolved in response to its historical hydrologic variability, habitat heterogeneity, and seasonal productivity. Fish such as Sacramento splittail, Chinook salmon, steelhead, and Sacramento perch developed life history strategies that depended on predictable access to floodplains, backwater sloughs, and shallow wetlands. Spring inundation cued spawning migrations, provided warm and productive rearing habitats, and sustained invertebrate prey populations. Resident species such as Sacramento perch and Thicktail chub thrived in the Delta's warm, slow-moving, structurally complex backwaters (Moyle, 2002; SFEI, 2012). Waterfowl and other wetland birds also took advantage of this dynamic landscape, using a broad array of habitats during different phases of migration and breeding cycles (Taft and Haig, 2005).

As levees severed floodplain connections, wetlands were drained, and flows became more regulated, the ecological context that had shaped these adaptations disappeared. For migratory fishes, access to critical spawning and rearing habitats was lost or compressed, and the timing and temperature of flows no longer matched evolved life history cues (Jeffres et al., 2008; Williams, 2006). Floodplain specialists such as splittail became increasingly confined to marginal habitat remnants, while salmon populations experienced elevated pre-spawn mortality, juvenile stranding, and reduced outmigration success because of altered flow regimes and degraded rearing conditions (Bay Institute, 1998; SFEI, 2012; Sommer et al., 2001; Appendix E). For resident species, the loss of low-velocity, vegetated margins and shallow warmwater habitats meant both the physical structure and thermal conditions required for persistence were diminished (Moyle et al., 2010).

The biological community of the Delta shifted with the introduction of dozens of non-native species. Predatory fish such as striped bass (*Morone saxatilis*), introduced in the 1870s, became widespread and now consume native juvenile fishes, including Chinook salmon and Delta smelt (Moyle, 1976; Nobriga and Feyrer, 2007). Invasive plankton, such as *Pseudodiaptomus forbesi*, and filter feeders like *Corbula amurensis* restructured lower trophic levels (Greene et al., 2011; Kimmerer and Orsi, 1996). These non-native species often lacked historical controls and were able to exploit simplified or novel conditions, outcompeting native taxa and altering food availability, timing, and spatial distribution in ways that created mismatches between native fish and their prey (Baxter et al., 2008; Brown and Michniuk, 2007).

The resulting biological community is now composed of many species that are either maladapted to current conditions or functionally dependent on relict habitat features and highly managed flow conditions. Population trajectories for native fish and many waterbirds reflect this loss of ecological fit—a pattern that is unlikely to reverse without restoration of key functional processes and habitats (Moyle et al., 2010; SFEI, 2016).

Water Quality, Contaminants, and Novel Stressors

Historically, the Delta's water quality was shaped by natural processes: seasonal runoff, tidal mixing, floodplain inundation, and biogeochemical cycling in marshes and sloughs. These processes maintained relatively high turbidity and buffered nutrient concentrations. Light penetration was limited by suspended sediments mobilized during flood events and tidal currents, which, in turn, constrained algal overgrowth and supported balanced productivity. Nutrients cycled through marsh vegetation and microbial pathways, and shallow, vegetated margins supported denitrification and sediment retention (Cloern, 2001; SFEI, 2012; Tockner et al., 1999).

In the modern Delta, many of these self-regulating processes have been diminished or lost. Levees and flood control infrastructure eliminated lateral exchanges and reduced sediment inputs, contributing to increased water clarity in some regions (Jassby et al., 2002; Wright and Schoellhamer, 2004). This reduction in turbidity has shifted predator-prey dynamics and exposed native fishes to increased visual predation (Ferrari et al., 2014; Nobriga et al., 2005). Flow regulation and channel

simplification reduced residence time and the opportunity for biogeochemical processing (Cloern et al., 2012; Monsen et al., 2007). Meanwhile, nonpoint source pollutants—including agricultural runoff, stormwater, and wastewater effluent—introduced a wide range of contaminants, including pesticides, herbicides, ammonium, and legacy metals (Jassby et al., 2003; Kuivila and Hladik, 2008). These contaminants often exert sublethal effects: impairing olfactory cues critical to migration, reducing reproductive success, and increasing vulnerability to predation (Hasenbein et al., 2014; Scholz et al., 2000). Emerging concerns also include endocrine-disrupting compounds and mixtures of unknown interactions (Anderson et al., 2006; Werner et al., 2010). At the same time, warming temperatures, increased nutrient loading, and longer water residence times have facilitated harmful algal blooms (HABs), particularly during low-flow summers. Cyanobacteria such as *Microcystis* have become recurrent features of the Delta's summer ecology, producing toxins that further degrade habitat quality for fish, zooplankton, and waterfowl (Cloern and Jassby, 2012; Lehman et al., 2005).

Taken together, these novel stressors represent a fundamentally different water quality regime than the one to which native species are adapted. The Delta now hosts a chemically, thermally, and ecologically altered water column—one that interacts with hydrology, habitat loss, and invasive species to intensify ecological stress.

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Appendix B

Background Information Relevant to the Central Valley Project and the State Water Project

This appendix begins with a description of the social history of the Delta region over the past 150 years. It describes how the Central Valley Project (CVP) and the State Water Project (SWP) were developed and the water resources infrastructure that makes up the Projects. It ends with a description of the primary user groups of both projects.

RECENT HUMAN HISTORY IN THE DELTA REGION

It is generally accepted that humans have lived in California fewer than 15,000 years, although recent and hotly disputed findings (Calloway, 2018) suggest humans may have been present more than 100,000 years ago. The human presence prior to the 1800s was unremarkable in terms of its effect on water resources in the region. This situation changed in the middle of the 19th century with the discovery of gold in 1848, intensive European immigration into California after 1849, statehood in 1850, and then the gradual shift to agriculture as the underlying economic force of the state. Indeed, California's economy and population have transformed several times, from a mining economy, to an agricultural economy, to a manufacturing economy, and now a mixed, mostly service-based economy. Since 2017, California has been the fifth largest economy in the world¹. Its population in 2023 was 39.1 million². Throughout the state's recent history, global markets for California's mining, agricultural, and other products have continually reshaped water uses and demands.

Mining

The initial growth in California's population, occurring about 175 years ago, was due to gold mining from 1848 to 1888, beginning with the California Gold Rush. For some time, mining was the base for California's economy, leading to a large influx of immigrants to expand and support the enterprise. The impact of mining on water resources in the region was substantial (Gilbert, 2017; James, 2004; James and Singer, 2008; Kelley, 1998) and due to extensive hydraulic mining from stripping hillsides and mining dredges that produced vast mine tailings. By 1884, hydraulic mining was banned by several court rulings, most accessible gold was depleted, and the accumulated mine tailings were disrupting navigation, flooding lands, and impeding agricultural development.

Providing access and services for the mines relied on water transportation, hence the development of steamship lines and ports up California's major rivers through the Delta up as far north as Red Bluff on the Sacramento River and south beyond Stockton on the San Joaquin River, and sometimes into Tulare Lake and the Kern River with high water. Accessibility improved with railroad and road expansions in the late 1800s along with waterborne commerce to support expansions in agricultural production, which replaced mining as California's the new economic base in the late 1800s.

¹ See <https://www.gov.ca.gov/2024/04/16/california-remains-the-worlds-5th-largest-economy/>.

² See <https://calmatters.org/commentary/2024/05/population-decline-california-grows-again/>.

Agriculture

The variable climate in California has made it challenging to support irrigation in a region that was otherwise almost ideal for profitable agriculture serving continental and global markets. Hence, the decline in mining was followed by extensive irrigated agriculture and associated land development in the Delta region from the 1850s to about 1930. The water navigation routes and railroads developed to support mining were converted to moving agricultural products to regional and international markets.

Early intensive agriculture in California largely began in the Sacramento-San Joaquin Delta. Immigrant farmers from humid regions of the eastern United States knew little of irrigation or institutions and laws needed to support irrigation in such a variable climate as California. Hence, in the Delta and along streams in the region, irrigation was organized by individual landowners or small groups of landowners. These early irrigation systems had little or no seasonal or overyear water storage infrastructure. This lack of water management infrastructure left these regions vulnerable to droughts as well as floods.

Later in the 1800s and the early 1900s, land and water in the Sacramento and San Joaquin valleys was developed extensively for irrigated agriculture via the construction of many local levee systems with irrigation diversions and canals. In the later 1800s, larger irrigation districts were organized to convey water from streams to more distant fields. In the wetter Sacramento Valley, large unirrigated fields of wheat supported a growing agricultural economy. Nonetheless, the overall lack of water and unfamiliarity with irrigation technology and institutions slowed the use of irrigated agriculture in central California (Pisani, 1984).

By the early 1900s, agricultural diversions from streams greatly diminished summer inflows to the Delta, allowing increased salinity intrusion into the Delta. This salinity intrusion harmed Delta towns and agricultural users and became a major motivation for developing large regional and inter-regional water storage and conveyance infrastructure to store water from the wet winters for dry irrigation seasons and move it from wetter to drier regions. The need for inter-regional water infrastructure became the subject of state water plans, beginning in the 1880s and more intensively in the 1920s. These efforts culminated in California's first State Water Plan in 1930. This plan proposed a large reservoir on the Sacramento River and pumping from the south Delta (near Stockton), which would reverse summer flows along the San Joaquin River to better support irrigation in the southern Central Valley. The storage of winter flows from the Sacramento Valley was seen as essential to supply summer irrigation water and Delta outflows without an expensive physical ocean salinity barrier in the western Delta (CDWR, 1930).

Today, agriculture is the largest human water use in California. The U.S. Geological Survey (USGS) indicates that roughly 60 percent of statewide water withdrawals go to the state's agricultural sector³. The availability of water has been the major factor in the development of California's agricultural sector, which made up about 5 percent of California's total economic output in 2012 (Johnson and Cody, 2015). About 9.6 million acres in agricultural production in California are irrigated in 2019, or about 9 percent of the total land in the state (Mount and Hanak, 2019). California accounts for about one-fourth of total applied volume of irrigated water in the United States, growing from 26 million acre-feet in 1960 to 34 million in 2023. Local and regional water sources, water imported from other regions (often using CVP and SWP facilities), and groundwater overdraft have been principal water supplies for agriculture.

Diking and Draining of the Delta

One reason for agriculture's rise in central California was the abundant freshwater available, such that most of the Delta was diked and drained, forming agricultural islands. Hundreds of thousands of acres of wetland were converted to agriculture over the past 150 years, bringing about not only the destruction of wetland habitat (since the early 1800s, 97 percent of wetlands have been lost; Whipple et

³ See <https://www.usgs.gov/centers/california-water-science-center/science/california-water-use>.

al., 2012) but also the oxidation of the Delta's peat soils as they were exposed to the atmosphere. These peat soils were produced from the decay of marsh plants over roughly 6,000 years since sea levels rose to first flood western and central parts of the Delta.

Initially, the agricultural islands formed in the Delta were near sea level and hence were irrigated simply by using tidal gates to irrigate near high tides and drain near low tides (Thompson, 1957). However, as lands subsided below low tide, pumping was needed to keep islands drained for agriculture. They could be watered with siphons. Many islands today have extensive irrigation and drainage networks with pumps and siphons.

The lands in the Sacramento-San Joaquin Delta have been subsiding since they were first drained for agriculture and exposed to oxygen and California's warm temperatures (Deverel and Rojstaczer, 1996; Drexler et al., 2007; Thompson, 1957). These lands continue to oxidize and subside, though usually at a slower rate as the peat layers thin.

From this subsidence, thousands of acres of Delta lands are now 5 to 25 feet below sea level. More than 1,000 miles of levees resist the flooding of Delta lands. However, over time, levee failures have led to the abandonment of some subsided lands to become tidal lakes within the Delta, where the cost of recovery exceeded the productive value of these lands (such as Franks Tract, Liberty Island, and Mildred Island) (Lund et al., 2010). The strengthening of Delta levees has been supported by the state and local landowners, and has greatly improved their reliability, but substantial residual failure risk remains (Suddeth et al., 2010). Failures usually occur because of floods or levee work errors, but some have had unclear causes (such as Jones Tract in 2004⁴), with large earthquakes and larger floods being a particular concern.

Urban Development

Urban development in the Central Valley began with Sacramento in 1848. Mining and agriculture were the economic bases for growing urbanization in the Valley, followed by manufacturing and now services. Growing towns and cities, initially depending on water transportation, faced winter flooding during this period (Kelley, 1998). Their growth and improved understanding of flooding led to the construction of a system of levees and river bypasses in the Sacramento Valley in the early 1900s, followed by the use of new reservoirs for flood control (as well as water supply) in the mid-1900s. Protection from floods has allowed major urban areas in the Delta region (such as Sacramento and Stockton) to grow considerably in terms of population and the economy. The region is inherently flood-prone, and flood vulnerability especially affects small river towns in the Sacramento Valley.

Demographics

The population of California was estimated to be about 92,000 in 1850,⁵ although the indigenous population was not included in the census. The state's population increased to 10.7 million in 1950, with a growth rate of almost 25 percent per year during World War 2, 1940–1945⁶. The population was 20 million in 1971, and 30 million in 1991, and reached its peak of just over 39 million in 2024⁷. The growing population, strong economy, including irrigated agriculture, and climate change are placing increasing demands on water and other natural resources in the state. With this growth came increased demand for reliable water supplies. Figure B-1 shows the trends and projections in California's population from 1850 to 2100 with certain water resources milestones overlaid.

⁴ See <https://damsafety.org/content/2004-failure-jones-tract-levee-potential-causes-and-repair-details>.

⁵ See <https://www2.census.gov/library/publications/decennial/1900/bulletins/demographic/10-population-ca.pdf>.

⁶ See <https://www.macrotrends.net/global-metrics/states/california/population>.

⁷ See <https://www.ppac.org/publication/californias-population/>.

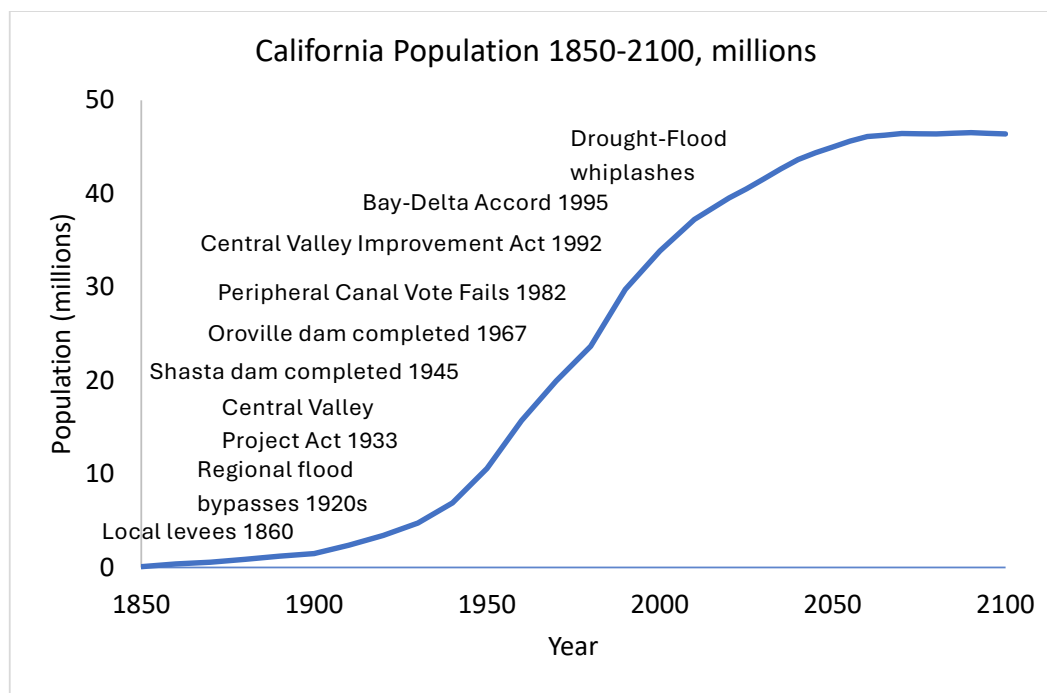


FIGURE B-1 California population, 1850-2100, and some water resources milestones.
 SOURCE: Data from U.S. Census to 2020 and California Department of Finance to 2100;
<https://dof.ca.gov/forecasting/demographics/projections/>.

THE CENTRAL VALLEY PROJECT AND THE STATE WATER PROJECT

The federal CVP and California's SWP are inter-regional water projects that have become foundational water infrastructure for California's metropolitan and agricultural economies since about 1950. Table B-1 provides a timeline of major events that have shaped the development of the CVP and SWP for the past 150 years.

History of Project Development

State-led project planning for large-scale water supply development began with extensive studies and plans in the 1920s and a state project proposal in 1930 (CDWR, 1930). However, in the 1930s, the state was unable to sell bonds to fund project construction, so the project was taken over and re-developed under the U.S. Bureau of Reclamation (USBR) as a Great Depression-subsidized public works project and renamed the Central Valley Project. This project would enable expansion of irrigated land into the San Joaquin and Tulare basins, provide additional water supplies for the San Francisco Bay area, and mitigate salinity intrusion into the Delta. Early water management was not concerned with native species and ecosystems, because these species were considered to be abundant and with little potential for long-term economic development compared to agriculture.

In the 1950s and 60s, growing demands for water from burgeoning metropolitan areas and agriculture (mostly in the Tulare basin) and diminished federal interest in water projects renewed state interest in developing a State Water Project to expand deliveries to these areas (with costs repaid by water users) and to provide ancillary flood, recreation, and hydropower benefits (Hundley, 2001). The California Water Plan of 1957 outlined this plan with an initial large storage reservoir on the Feather River in the Sacramento Valley, a major pumping plant in the south Delta, and the California Aqueduct

TABLE B-1 Timeline of Events Relevant to the Central Valley Project and State Water Project

Year(s)	Events
1849	Gold discovered in California, beginning of great immigrations
1850s	Diking and draining of Delta islands begins, Delta land subsidence begins
1884	Court rulings largely end hydraulic mining
1850s–1920s Local Land, Water, and Irrigation Development	
1864, 1907	Major floods occur
1910–1930s	Upstream irrigation causes summer Delta salination; San Joaquin Valley overdraft and land subsidence begins
1924, 1928–34	Major droughts occur
1920–1982 Inter-Regional and Statewide Water Project Development	
1928–1931 drought	"The Great Crusade for Fresh Water"; Recession shifts 1930 California state water project proposal to federal CVP
1939	Metropolitan Water District of Southern CA Colorado River Aqueduct
1940s–1982	CVP expands supplies to Tulare basin, San Joaquin Valley, and San Francisco Bay Area
1959	Delta Protection Act
1960	Statewide vote to start the SWP
1969–1985?	SWP expands supplies to Tulare basin, Southern California, and San Francisco Bay Area
1976–77	Major post-project drought occurs, causing local and regional innovations
1982	Peripheral Canal rejected by voters
1983–2000 Return to Local and Regional Innovation	
1986	Overbite clam invasion
1987–92 drought	Local and regional expansions in urban water conservation, water markets, groundwater storage, and new surface storage
	Environmental water requirements grow; Agriculture shifts to permanent crops; Major per-capita urban water use reductions
	New roles for old infrastructure
	"Portfolio" solutions
1992	CVPIA
1994	Delta Accord and CalFED
1995–2000	Extremely wet period
1999	D1641 implementing the Delta Accord
2000–future Ecosystem crises in a changing climate	
2007–2009	Drought renews Delta interest
2012–2016	Drought occurs, 2014 California Sustainable Groundwater Management Act Winter-run Chinook salmon becomes hatchery-dependent
2017	Wettest Northern California year, Oroville spillway failures
2021–2022	Drought occurs
202	Delta smelt hatchery releases begin

and San Luis Reservoir (new off-stream storage to be shared with the CVP) to move water to the San Francisco Bay area, the Tulare basin, and Southern California cities. The plan envisioned extensive expansions over time with additional reservoirs, aqueducts, and pumping plants on other streams, including a large peripheral canal to take water gathered from Northern California to intakes for the California Aqueduct. Pre-existing water right holders were integrated into the SWP with priority contracts for SWP deliveries.

Expansions of the SWP and CVP came to a nearly complete halt following a statewide referendum rejecting a peripheral canal around the Delta in 1982. This event greatly reduced federal and state leadership in developing new water projects in California. Subsequent efforts to rejuvenate federal and state CVP and SWP infrastructure expansions have been diminished compared to earlier plans.

OVERVIEW OF INFRASTRUCTURE FOR WATER DELIVERY

The CVP and SWP include a large number of facilities that are operated in coordination to support a number of uses as described above and in adherence to regulations (see Appendix C). Many of these facilities and other features are shown in Figure B-2. Table B-2 documents the capacity of some of the major storage reservoirs within the CVP and SWP.⁸

The CVP facilities include reservoirs on the Trinity, Sacramento, American, Stanislaus, and San Joaquin Rivers. Starting in the north, water from the Trinity River is stored and re-regulated in Trinity Lake, Lewiston Lake, and Whiskeytown Reservoir. Water from the Trinity Division is diverted to the Sacramento River basin via two tunnels and powerplants, where it joins the releases from Shasta Dam in its afterbay Keswick Reservoir to form the main stem of the Sacramento River that flows south to the Delta.

On its way south, Sacramento River water is joined, at Verona, by releases from Lake Oroville and Oroville Dam (a SWP facility) via the Feather River. Lake Oroville stores and re-regulates SWP water. The SWP contractors and SWP water rights settlement contractors divert water from the Feather River and Sacramento River. The next major confluence south of the Feather River is the American River on the east, which delivers releases from USBR's Folsom Dam and its afterbay, Nimbus Dam. On the western side of the Sacramento River, the Yolo Bypass delivers flows from California's Coast Range, its own drainage, and diversions from the Sacramento River.

The Sacramento River carries water to the Sacramento-San Joaquin River Delta. Other river inputs to the Delta are from the Mokelumne and Cosumnes rivers from the east and the San Joaquin River from the south. The Jones Pumping Plant at the southern end of the Delta lifts the water into the Delta-Mendota Canal. This canal delivers water to CVP contractors and exchange contractors on the San Joaquin River and water rights contractors on the Mendota Pool.

The CVP also delivers water from the Friant Dam on the San Joaquin River to CVP contractors located near the Madera and Friant-Kern canals. Water is stored in the New Melones Reservoir for water rights holders in the Stanislaus River watershed and CVP contractors in the northern San Joaquin Valley.

On the state side, the California Department of Water Resources (CDWR) operates 21 dams and more than 700 miles canals, pipelines and tunnels as part of the SWP. SWP water flows are exported from the Delta by the Banks Pumping Plant, which lifts the water into the California Aqueduct, to the South Bay Aqueduct and Bay Area, and conveys water to the San Luis Reservoir. Many of the SWP contractors are in the southern San Joaquin Valley, Central Coastal area, and Southern California. To deliver water to the latter, the water is pumped 2,000 feet over the Tehachapi Mountains. The SWP also delivers water to the Cross-Valley canal between the California Aqueduct and Bakersfield, for CVP water service contractors.

⁸ Additional information is available from <https://www.usbr.gov/mp/cvp/> and <https://water.ca.gov/programs/state-water-project>.

**FIGURE B-2** Existing federal and state storage and conveyance systems in California.SOURCE: <https://www.usbr.gov/mp/cvp-water/docs/cvp-map-11x17.pdf>.**TABLE B-2** Capacity of Some of the Major Storage Reservoirs within the CVP and SWP

Feature/Facility	Location	Capacity (million acre-feet)
Shasta Dam and Reservoir	Sacramento River	4.6
Trinity Dam and Reservoir	Trinity River	2.4
Whiskeytown Dam and Lake	Trinity River	0.24
Folsom Dam and Reservoir	American River	0.97
Lake Oroville and Oroville Dam	Feather River	3.5
New Melones Dam and Reservoir	Stanislaus River	2.4
Friant Dam forming Millerton Lake	San Joaquin River	0.5
San Luis Reservoir	Off stream storage	2.04

San Luis Reservoir. The San Luis Reservoir is part of the San Luis Unit, a joint venture between USBR and DWR that provides storage, downstream of both pumping plants, during dry seasons. The San Luis Reservoir is the largest off stream storage reservoir in the United States. The William R. Gianelli Pumping-Generating Plant pumps surplus water from both the Delta-Mendota canal (CVP) and the California Aqueduct (SWP) into the San Luis Reservoir. When water flow through the Delta becomes too low, water is released from San Luis into the Delta-Mendota canal and the California Aqueduct to meet demands. In addition, water from the San Luis Reservoir can be conveyed through tunnels to CVP contractors in Santa Clara and San Benito counties.

Many other sizable dams and reservoirs in North and Central California, not shown in Figure B-2, are part of neither the CVP nor the SWP. These include the Pacific Gas and Electric Company's Lake Alamandor in Plumas County, Camanche Dam and Pardee Dam owned by the East Bay Municipal Utility District, City of San Francisco's Hetch Hetchy Reservoir, New Don Pedro Reservoir operated by the Modesto and Turlock Irrigation Districts, and many other local and regional projects, as well as independent federal (USBR and U.S. Army Corps of Engineers) projects.

Because both the CVP and the SWP convey water via the Sacramento River and the Delta, their facility operations are coordinated, based on the Coordinated Operating Agreement (see Chapter 1), the Bay-Delta Plan Accord, and other agreements, to maximize yields and deliver water into the main river channels and canals of the project in an efficient and economical manner.

Water Flows through the Delta

Figure B-3 shows the common pathways for water movement through the Delta, most of which follows the major channels created by the Sacramento and San Joaquin Rivers. Waters entering from the Sacramento River mostly flow directly southwest past the Delta and on to San Francisco Bay (dark blue line). Sacramento River water can flow into the central Delta when the Delta Cross Channel (DCC) is open (light blue lines in Figure B3), initially flowing in the North and South Mokelumne River channel. Upon reaching the deep San Joaquin River channel, water can continue in several directions. The red arrows show the path water takes if it continues south into the Old and Middle River (OMR) channels. When the DCC gates are closed, the entire Sacramento River flows southwest to the San Francisco Bay (small red arrow in Figure B-3). However, depending on inflow and withdrawals from the Delta, some of the Sacramento River flow, averaged over a tidal cycle, travels east and then up the San Joaquin River channel toward the central Delta (small yellow bar in Figure B-3). From the Delta, water is withdrawn and used for agriculture in the Delta, it is withdrawn from the Delta via the state and federal pumps in the South Delta, or it flows out to San Francisco Bay.

Figure B-3 also shows the San Joaquin River (orange) which flows up to the Delta from the South, with the river itself passing through the city of Stockton. (Dredging has deepened the San Joaquin River channel from Stockton to Antioch to provide a shipping channel.) Water from the San Joaquin River can go directly to the pumps or make its way to the central Delta. The specific routes that San Joaquin River water takes through the central Delta are primarily determined by the DCC flow, San Joaquin River inflow from the south, and pumping rates. At times, there is almost no flow out of the San Joaquin River into the Delta.

Although Figure B-3 suggests both certainty and simplicity regarding the direction of Delta flows, the reality is that there is marked variation in the flows through these pathways throughout the year and depending on the water-year type. These variations are explored in Box B-1.

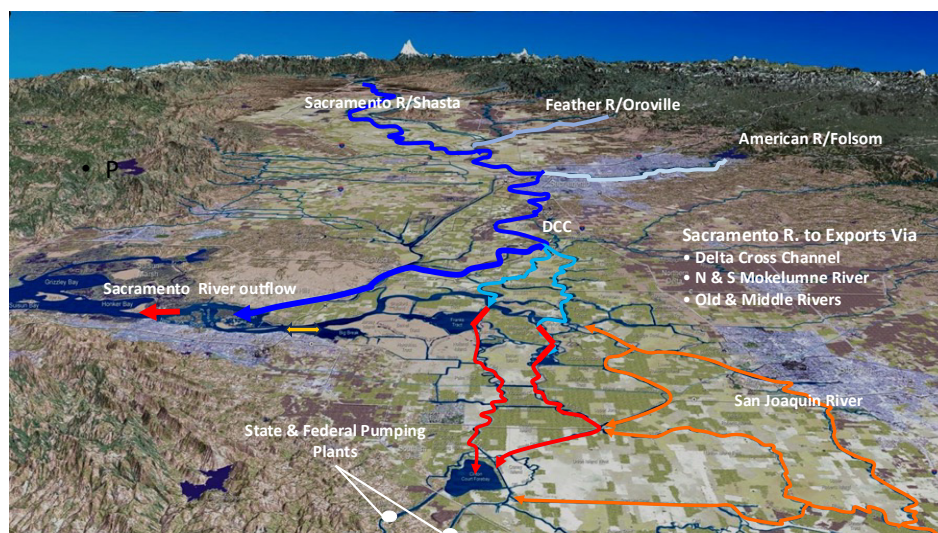


FIGURE B-3 Common paths for water flowing into and through the Delta. NOTES: Dark blue = Sacramento River; medium-blue = Feather River; light-blue = American River; red = flow from Delta south to the state and federal pumping plants via the Old and the Middle rivers; orange = San Joaquin River flows into the Delta. SOURCE: Adapted from Sumer (2024).

BOX B-1

A Comparison of Water Flows Through the Delta for Four Recent Water Years

To understand the challenges of managing flow and water quality parameters (including salinity, turbidity, dissolved oxygen, and temperature) in the Delta, it is necessary to appreciate both annual variability and the interannual variability of daily averaged flow rates, and even flow directions. Using data from the DayFlow website^a, the Committee plotted daily averaged Delta inflows and outflows for four recent years: 2017, 2018, 2020, and 2023. The flows plotted on the inflow graphs are as follows:

- Yolo Bypass at Woodland
- Sacramento River at Freeport
- Consumnes River (inflows to Delta from Sierras to the East)
- Mokelumne River (inflows to Delta from Sierras to the East)
- San Joaquin River at Vernalis
- Delta tributaries

These are recorded inflows and thus are what remains after the large consumptive withdrawals and diversions before the rivers reach the Delta.

The flows plotted on the outflow graphs are as follows:

- DCC and Georgiana Slough
- QWest (San Joaquin River flows out of the Delta at Jersey Point near Antioch)
- Sacramento River at Rio Vista (after the DCC diversion)
- Combined pumping rate for the projects (CVP and SWP)
- OMR flow measured at USGS gauges OBI and MDM (data from CDWR^b)

X2, showing the penetration of salinity into the Delta, is also plotted.

Figure B-4 shows the data from all four years with inflows and outflows plotted separately. Note that the y-axes have the same range as do y-axes for the four outflow graphs.

continued

BOX B-1 continued

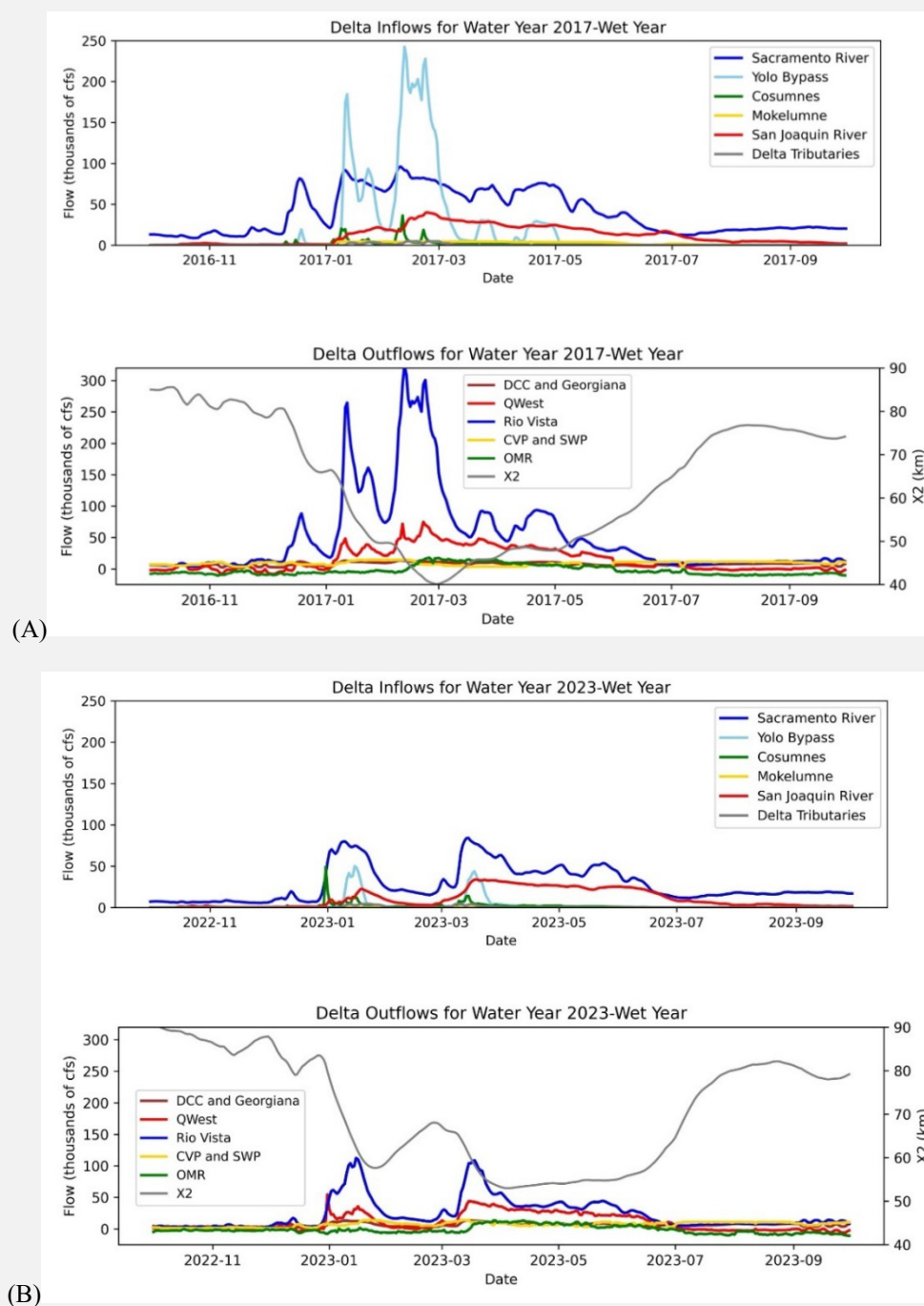


FIGURE B-4 Observed inflows, within-Delta Flows, measured outflows, and X2 for the California Delta in four different years ranging from wet to dry. NOTES: (A) 2017 (“wet year”), (B) 2023 (“wet year”), (C) 2018 (“below normal year”), and (D) 2020 (“dry year”). SOURCE: Data from Dayflow website and CDWR.

continued

BOX B-1 continued

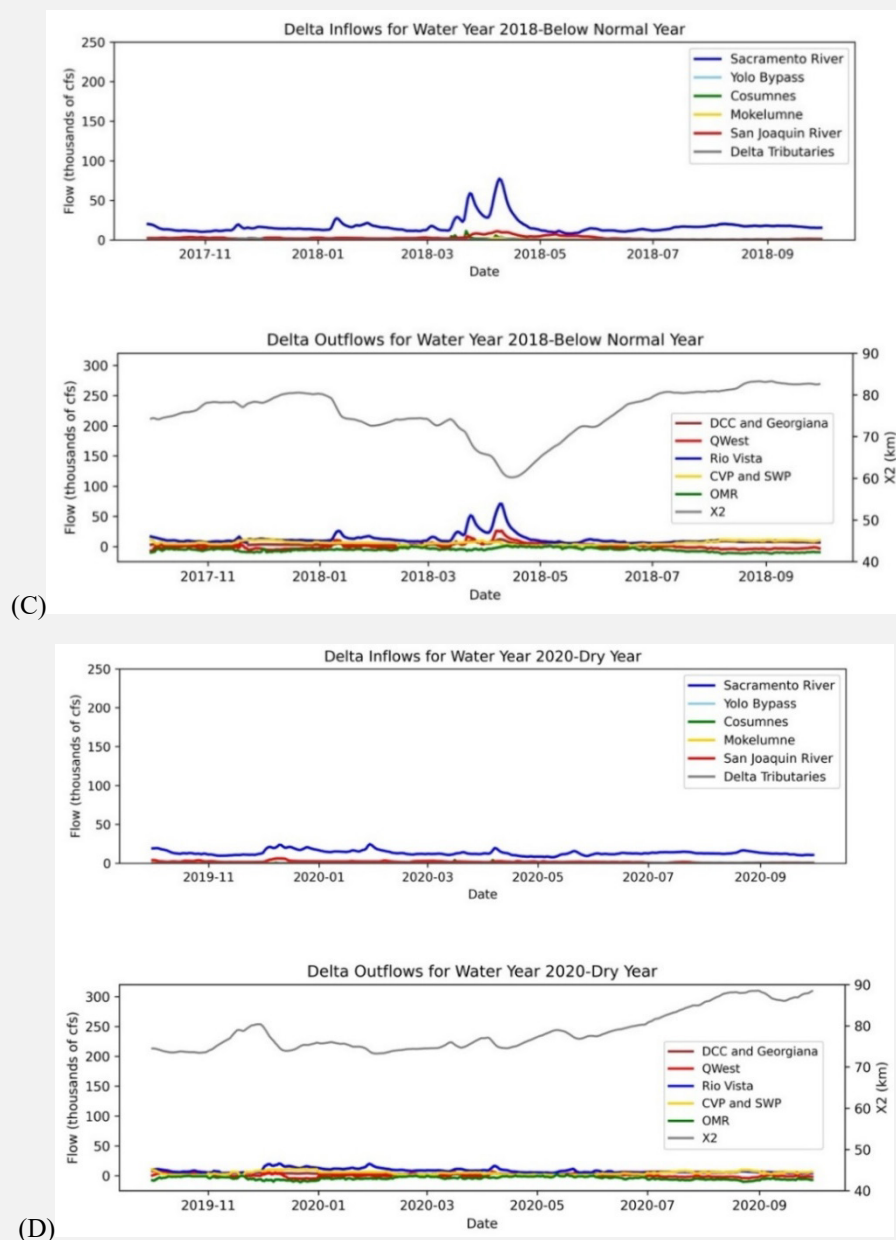


FIGURE B-4 Observed inflows, within-Delta Flows, measured outflows, and X2 for the California Delta in four different years ranging from wet to dry. NOTES: (A) 2017 (“wet year”), (B) 2023 (“wet year”), (D) 2018 (“below normal year”), and (D) 2020 (“dry year”). SOURCE: Data from Dayflow website and CDWR.

Although both 2017 and 2023 were wet years, 2017 was extremely wet, with huge flows from the Yolo Bypass. In 2023, two large storms put water in the Yolo Bypass, but otherwise inflows to the Delta were less than in 2017. In the below normal year of 2018, only Sacramento River and San Joaquin Delta inflows are visible. There appear to be two small storm events, but no flow in the Yolo Bypass. In dry 2020, little Sacramento River water reached the Delta and the San Joaquin River appears dry.

continued

BOX B-1 *continued*

There is large seasonality in flows into the Delta from the Sacramento River, Yolo Bypass and the San Joaquin River, especially in wet years. Water from the Yolo Bypass arrives in large pulses that result from flood waters from the Sacramento River diverted down the Bypass. In below normal and dry years, there can be very little flow from the San Joaquin River at Stockton, requiring that the pumps use water from the Sacramento River either through the DCC or from negative San Joaquin flows at Jersey Point.

There were two very large storms (both with double peaks) in 2017 and a large storm in mid-December of 2016, leading to substantial flows into the Delta from the Yolo Bypass, the Sacramento River, and the San Joaquin River. The peak inflows from the Bypass (242 thousand cubic feet per second [tcf]) and the Sacramento River (96 tcf) combined to yield a Sacramento River outflow peak at Rio Vista of 324 tcf. San Joaquin flows to the Delta generally stayed below 50 tcf. However, peaks from the Consumnes and a little from the Mokelumne pushed San Joaquin outflow at Jersey Point to near 80 tcf. Delta outflow from both rivers persisted with wet conditions extending through June. OMR was negative starting in June reflecting diversions from the Sacramento River to the pumps. Jersey Point flows were often negative after July. The salinity index X2 was less than 80 kilometers (km) from December onward, reaching a value of zero in March 2017. So, the focus for water management in 2017 was flood management.

In 2023, two large storms activated the Delta Yolo Bypass, and Sacramento River flows at Rio Vista peaked around 110 tcf. During July and later, Rio Vista flow is diminished by DCC and Georgiana Slough diversions. Starting in April, San Joaquin River flow into the Delta is similar to the Sacramento River's flow to the Delta until August, when the San Joaquin River flow largely disappears, and OMR and Qwest become negative to compensate for pumping. After February, X2 was generally at or below 80 km.

In 2018, reservoir storage appeared to capture much of the larger flows in the March-to-May period. The Sacramento River supplied water to the Delta as needed through the summer and fall. OMR and Qwest became increasingly negative after August and through September. The DCC and Georgiana diversions plus inward Qwest flows about equal the pumping during that period. X2 stayed around 80 km or less in the late spring.

Significant storms in 2020 were regulated by dams and produced minimal runoff that reached the Delta. Sacramento River inflows after February were generally 10–15 tcf, and San Joaquin inflows remained less than 3 tcf before and less than 1 tcf after February. Because Delta outflow values are so small, Figure B-5 shows those values on an expanded scale. OMR values fluctuated, but were mostly negative, typically near -4 tcf. Pumping rates varied but were generally less than 9 tcf. X2 is generally below 80 km until August, when it begins an increase to almost 90 km.

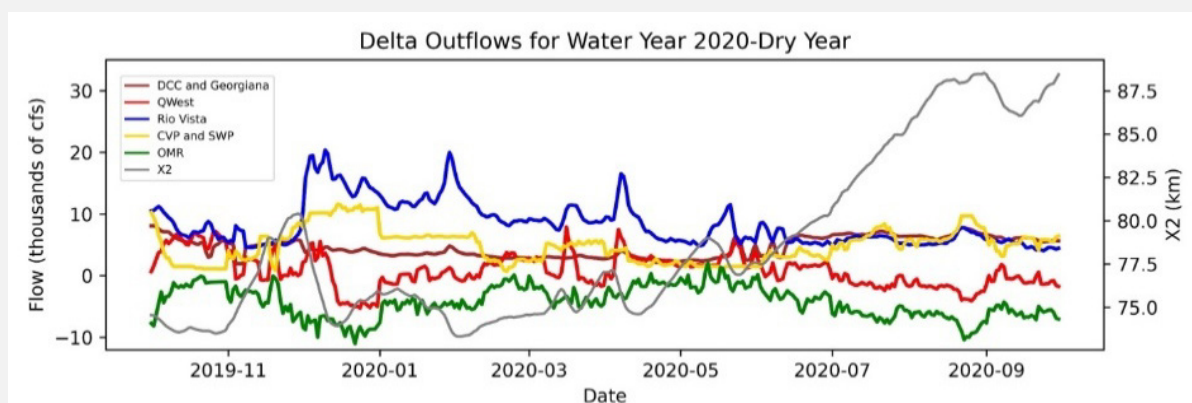


FIGURE B-5 An expanded view of the 2020 dry year Delta outflows and X2.

SOURCE: Data from Dayflow website and CDWR.

continued

BOX B-1 *continued*

One lesson from Figures B-4 and B-5 is that wet years can differ substantially. With the large flows reaching the Delta, 2017 was a flood management year. Although 2023 was also wet, it avoided serious floods. Dry years tend to look more alike, because little water reaches the Delta. On a finer scale, Sacramento River water flowing east around Sherman Island and up the San Joaquin River channel is common in August through September. Indeed, QWEST flows almost mirror the pumping in 2020, suggesting that water for export in June and later is derived primarily from the Sacramento River reversing its natural course to the ocean and flowing up the San Joaquin River. The dynamic nature of the magnitude and direction of flows in various streams and channels makes understanding flows in the Delta difficult. The variation of channel widths and depths (natural and dredged) makes it less than obvious what paths flows will follow. Further, the sloshing of tides creates substantial mixing of waters.

^a See <https://data.cnra.ca.gov/dataset/dayflow>.

^b See <https://cdec.water.ca.gov/dynamicapp/wsSensorData>.

CVP AND SWP AS PARTS OF CALIFORNIA'S LARGER WATER SYSTEM

Even before the peripheral canal referendum in 1982, it was clear that expanding large water projects would not be enough to eliminate water shortages, particularly during droughts. California's driest recorded year to date occurred in 1976–1977, when many water contracts and reliability expectations could not be fulfilled for cities, agriculture, and the environment. Cities, especially, saw seemingly draconian water use reductions, curtailing water use by 25–40 percent in many cases and quickly introduced complex water transfer and exchanges to even out supplies. It became clear that local agencies and users could do more than only seek expansions of statewide water supplies, often with greater local control and reliability, especially because most inexpensive reservoir sites had already been developed. With urban water conservation and declining population growth rates, urban agencies tended to find other water management alternatives more attractive in terms of control, cost, controversy, and reliability.

These many changes in supplies and demands in the late 1970s returned water management focus and initiative to local and regional water agencies and away from state and federal agencies (Hanak et al., 2011; Lund et al., 2018). Local water use efficiencies, water use reductions, conjunctive groundwater use, water interconnections, recharge and reuse of treated wastewater, and inter-regional water market transfers all came to diversify local and imported water supplies starting from the 1976–1977 drought and continuing today. These activities also increased cooperation between water delivery and management agencies regionally and statewide. Diversified supplies could be combined with water use reductions and coordination across local, regional, and statewide scales to foster “portfolio-based” water management with less controversy, greater reliability, and likely lower costs. These strategies were reinforced by the 1987–1992 drought, such that portfolio strategies greatly blunted the impacts of more recent droughts, especially for urban regions (Lund et al., 2018). Portfolio strategies have been less developed for ecosystems and agriculture, perhaps because of less funding and ability to pay and less organized coordination among users. Adoption of the Sustainable Groundwater Management Act of 2014 will likely spur further development of agricultural water management portfolios. With a few exceptions, environmental water management remains underdeveloped in combining science, infrastructure, and operations for ecosystem purposes across scales and is increasingly challenged by non-native species and climate change.

The CVP and SWP were designed for an expected era of indefinite growth in water demands for an economy specializing in agriculture and manufacturing with high per-capita water use. These sectors have developed and prospered, but California's economy and water needs are now very different. Today most urban users and some agriculture water users no longer rely on water project expansions and abundant water deliveries into the future, but rather have diversified their water supplies and manage their

water demands to provide more reliable and affordable water services. The CVP and SWP and their core existing infrastructure will need to accommodate new concerns, technologies, changing environmental concerns (especially with climate change), changing (and often reduced demands) human water demands, and much greater local and regional control, finance, and initiative, requiring broader coordination of water operations across diverse water uses and managers.

Users of CVP and SWP Water

Following the decline of the hydraulic mining era, irrigated agriculture became the largest water user in California, incentivizing local organizations to establish irrigation systems administered by irrigation (or reclamation) districts and small water companies. Limited growth prospects due to insufficient local water availability and funding forced the development of groundwater extraction, particularly in areas lacking access to surface water rights, with accompanying conflict among water users and the detrimental consequences of aquifer overexploitation.

Central Valley Project Water Users

The CVP was authorized in the early 1930s for the purposes of navigation, flood control, water supply and hydropower generation. By the early 1950s water deliveries, hydropower generation, Delta pumping and San Joaquin River diversions were in place, with later systemwide expansions (Hanak et al., 2011). To accommodate pre-existing water users and water rights, many pre-existing users became CVP contractors. Settlement Contractors incorporated pre-existing Sacramento Valley users as high-priority CVP contractors (see Appendix C). Earlier users of San Joaquin River water became Exchange Contractors, receiving higher priority to water pumped from the Delta (which allowed more San Joaquin River water diversion to the Tulare basin). Expansions to the CVP infrastructure were mostly completed by 1960, with a few expansions occurring into the 1980s.

Through roughly 270 contracts or agreements, the CVP delivers water either because of a service contract or a water right. Under water service contracts, USBR delivers water to its contractors, usually for a fee, subject to water availability in storage and forecasts of hydrologic conditions. Service contracts allow for agricultural as well as municipal and industrial water uses. Water rights deliveries, in contrast, often receive higher priority than the water services contracts because of predating of water rights (relative to CVP) or regulation. Those with the highest priority water rights or settlement contracts include the Sacramento and San Joaquin contractors and wildlife refuges (USBR, 2016). A description of the various CVP water rights holders and water service contractors is given in Box B-2.

The CVP has a maximum contract amount of 9.5 million acre-foot per year (MAF/yr) subject to shortage. In addition, the CVP provides 235 thousand acre-feet per year (TAF/yr) from the American and Sacramento rivers to the City of Sacramento not subject to shortage. Historically, CVP supplies around 7 MAF/yr, of which 5 MAF are for irrigation, 600 TAF for municipal and industrial uses, 800 TAF for fish and wildlife, and 410 TAF for refuges (CRS, 2024; Stern et al., 2024). The San Luis Reservoir allows water from the Sacramento Valley to be stored south of the Delta and expansion of irrigated areas in the San Joaquin Valley.

A more detailed table of CVP contractors along with average delivery amounts for the 2013–2024 period is shown in Table B-3. Most of the time, water rights contractors receive their full allocation. The exception is dry years when they receive roughly 75 percent of the maximum contract amount, which is also the case for the Central Valley refuges using Class 2 water, that is the next amount of water available (up to 1.4 MAF) after Class 1 (800 TAF) water.

The Sacramento River Settlement and San Joaquin Valley Exchange Contractors and Level 2 refuges had average allocations above 87 percent for the 2013–2024 time period. Contract water deliveries averaged around 65 percent, excluding Class 2 water in the Friant Division (17 percent). Water service contracts north of Delta and south of Delta have received no allocation in recent droughts.

BOX B-2
CVP Water Users

The highest priority water rights holders and water service contractors are described first.

CVP Sacramento River Settlement Contractors. This user group consists of 146 districts or individuals with water rights that were in place prior to Shasta Dam construction. The CVP Sacramento River Settlement Contractors are entitled to about 2.2 MAF per year except for Shasta Lake *critical* years^a, when allocation is reduced to 75 percent of the full contract amount (1.65 MAF). From the total allocation, 1.76 MAF are considered “base supply” which can be diverted without charge, and 330.2 TAF are “Project water,” which are additional waters that may be diverted subject to pricing and federal requirements (CDWR, 2022). Should their water rights be fully exercised, the ability of the CVP to deliver to water service contractors would be compromised.

San Joaquin River (SJR) Exchange Contractors. The SJR Exchange Contractors represents a group of four entities, namely, Central California, I.D., Columbia Canal Company, San Luis Canal Company, and the Firebaugh Canal Company, that exchanged diversion rights on the SJR and the Kings River for substitute water from the CVP, to facilitate construction and operation of the CVP Friant Division. They receive up to 840,000 AF of water in normal years. However, in Shasta critical years such allocation can be reduced to 650,000 TAF. In the event that USBR cannot fulfill deliveries, the Exchange Contractors can return to SJR diversions largely by reducing Friant Diversion deliveries and other junior water rights holders (CRS, 2024).

CVP Schedule 2 Water Rights, Fresno Slough. In addition to the SJR Exchange Contractors, USBR entered into settlement contracts with water right holders or claimants to the Fresno Slough affected by the construction of the Delta Mendota canal. Such settlements entitled the Fresno Slough water rights contractors to 35,623 AF of Schedule 2 water, which is water delivered at no charge and does not originate from CVP sources, yet it employs CVP infrastructure for storage and conveyance to users. Some users in this group can also receive an additional 55,475 AF per year as contracted water service from the CVP.

CVP Wildlife Refuges. Under the Central Valley Project Improvement Act of 1992, refuges in the Central Valley became co-equal to agriculture, municipal, and industrial uses in the CVP. The Refuge Water Supply Program was established to obtain 555,000 AF per year for 19 refuges, under two categories: Level 2 and Level 4 supplies. Under Level 2, considering average water deliveries prior to the CVP, the refuges get 422,251 AF yearly. During dry years, such allocation is reduced by 25 percent. Level 4 supplies (133,264 AF) are acquired by voluntary measures including purchases through the Central Valley Project Restoration Fund. Level 4 water supply increments above Level 2 supplies are considered optimal for wetland habitat development.

Lower in priority are municipal, industrial and agricultural water service contractors that purchase CVP project water under a long-term (e.g., 40-year) renewable contract. These are discussed below, organized by location: North of Delta, In-Delta, East Side; South of Delta; and the Friant Division.

North of the Delta Water Service Contracts, In-Delta Division, and East Side Division. This user group includes the Sacramento and Trinity River divisions, Corning Canal Unit, Delta Division, the Feather Water District, and the City of West Sacramento, totaling 468,490 AF. By adding the American River Division (313,750 AF), all north of Delta water service contract maximum is 782,640 AF. The “In Delta” Division includes the Contra Costa Water District, which has a maximum contract amount of 195,000 AF. The East Side Division includes storage in the Stanislaus River, Chowchilla River, and Fresno River. Users include the Central San Joaquin Water Conservation District, Stockton-East Water District, Oakdale Irrigation District, and South San Joaquin Irrigation District. The maximum contract amount is 755,000 AF.

South of Delta Water Service Contracts. This area includes various divisions namely the Delta Mendota canal, the Mendota Pool, the Cross Valley canal, the San Felipe Unit, and the San Luis Unit. Altogether these contractor’s maximum contract allocation is 2,112,898 AF.

continued

BOX B-2 *continued*

Friant Division Contracts. This group of 32 water service contractors receive two classes of water: Class 1 (up to 800,000 AF), mostly for municipal and industrial use contractors with no access to groundwater, and Class 2, largely for users with access to groundwater for up to 1.4 MAF per year. During dry years, if USBR cannot provide the SJR Exchange Contractors with their CVP allocation, then these can appropriate Friant Dam-stored water that would otherwise go to the Friant Division contractors. The Chowchilla Water District and the Madera Water District add 24,000 AF each of maximum contract amount for a Friant Division total of 2,249,475 AF.

^a A Lake Shasta critical year is defined as a current year with forecasted inflow of less than 3.2 MAF, or when the total accumulated actual deficiencies below 4 MAF in the immediately prior water year, or series of successive prior water years each of which had flows less than 4 MAF, together with the forecasted deficiency, exceed 800 TAF.

TABLE B-3 Central Valley Project Aggregate of Water Contractors, Maximum Contract Amounts, Municipal and Industrial Historical Use (quantities in AF/yr)

Contractors	Division	Units	Contract Type	Max Contract	M&I Hist.	Agriculture Max	Average of Max %
North of Delta	Sac River	Black Butte, Colusa Drain, Corning, Tehama Colusa, Shasta Trinity	Water Service	468,890	21,628	441,886	63%
North of Delta	American River M&I	Folsom, Folsom South, Upper Am. River	Water Service	313,750	181,047	0	75%
North of Delta	Sacramento River Settlement	Sacramento River W.R. Settlement & Shasta	Water Rights	2,115,620	N/A	N/A	87%
South of Delta	Delta	Delta Mendota Canal, Mendota Pool, Cross Valley, San Felipe, San Luis	Water Service	2,112,898	161,690	1,942,077	37.4%
South of Delta	Delta	Exchange, Settlement	Water Rights	875,623	N/A	N/A	91%
South of Delta	Friant	Friant Dam, Friant-Kern, Miscellaneous	Water Service	800,000 CL1 1,401,475 CL2, and 48,000 Misc	63,880 CL1		62% CL1 17% CL2
In Delta	Delta	Contra Costa	Water Service	195,000	170,000		76%
East Side	East Side	New Melones, Tri-dams	Water Service and Water Rights	755,000	46,214		71%
Refuges	North and South of Delta	North and South of Delta Class 1	Water Rights	422,251	N/A	N/A	89%
CVP total				9,508,507			60%

NOTES: CL1 and CL2 stand for Class 1 and Class 2.

SOURCE: Adapted from USBR (2015), CRS (2024), and CDWR (2018); https://www.waterboards.ca.gov/waterrights/water_issues/programs/hearings/byron_bethany/docs/exhibits/wr/wr225.pdf

Water Allocation and Shortages. CVP water allocation decisions evolve over the water year and are the result of several factors, including surface water storage, forecasted hydrologic conditions, water rights decisions, and regulations protecting habitat for wildlife. Overall, CVP prioritizes water rights contracts and refuge deliveries over water service contracts. Whereas in most years deliveries to water rights contractors and Level 2 water for refuges are met, dry years may reduce their CVP deliveries down to 75 percent. Within the water service contracts, municipal and industrial uses (M&I) are prioritized over irrigation under the current water shortage policy, where the aim is to provide M&I contractors 75 percent reliability with respect to historical use, defined as the average last three years with unconstrained CVP deliveries. Before M&I shortages take effect, irrigation deliveries need to be reduced by at least 75 percent.

In conjunction with hydrologic conditions and water rights, at least three major systemwide legal constraints restrict pumping and hence affect CVP allocation decisions: CA State water quality requirements, Endangered Species Act implementation, and Central Valley Project Improvement Act implementation, along with water conservation requirements. The legal constraints are discussed in Appendix C.

State Water Project Users

The water demands of a growing population and the legal challenges to irrigation water users were instrumental in supporting the building of the SWP. Oroville Dam, the major storage facility of the SWP, was completed in 1967 for water supply, flood control and hydropower. The SWP serves 29 contracts with a total contract amount of 4.17 MAF/yr mostly for M&I (70 percent) and irrigation of roughly 750,000 acres of land. The SWP delivers Table A water, Carryover water, and Article 21 water to contractors. Table A refers to the maximum amount contractors are entitled to request of the SWP, totaling 4.17 MAF/yr based on estimated 1960s delivery capability (Osorio, 2020). Maximum contractual Table A allocations are shown in Table B-4 below. Carryover water is the amount of Table A water that can be saved for next year's delivery to avoid losing undelivered water and hedge in the event of a forthcoming dry year. Carryover requests to the SWP are subject to available storage capacity and the water contractor's specific maximum storage allocation in the San Luis Reservoir, which brings some risks and operational challenges seeking non-SWP storage in the event of a full reservoir. Article 21 water, also known as surplus or unscheduled water, is available mostly in wet years, on top of Table A allocations. Oroville releases water to the Feather River, which is joined downstream by the Yuba and Bear rivers as it travels to the North Delta from the confluence with the mainstem of the Sacramento River. Diversions in the Delta include the North Bay Aqueduct, supplying water mostly to Solano and Napa counties, and the South Bay Aqueduct supplying Santa Clara and Alameda counties. Both aqueducts are owned and operated by CDWR. Water is exported south of the Delta through the Banks pumping plant in the southern Delta.

As with the CVP, allocation decisions in the SWP involve multiple factors including hydrologic conditions, water rights, environmental regulations, water conservation needs, and operational capabilities. Precipitation indexes, snow water content, and storage and water supply indexes can drive water deliveries of water from the SWP. In addition, deliveries are affected by contractor-specific water supply agreement amendments, which include transfers between users, non-SWP water, carryover, and other provisions. Unlike CVP water allocations that privilege senior water rights contractors (e.g., Settlement and Exchange contractors), SWP Table A allocations are more volatile for most contractors. Over the period 2013 to 2024, allocations have been as low as 5 percent, bringing average allocation to 40 percent of the Table A maximum (see Table B-4).

Not included in Table A allocations (and hence not in Table B-4) is Settlement Water in the amount of 31,620 AF for the Solano County Water Agency. Also, CDWR has water rights settlement agreements with the Feather River Service Area districts that include the Western Canal, Joint Water District Board, Plumas Water Conservation District, Garden Highway Mutual Water Company, Oswald

Water District, and Tudor Mutual Water. Such Feather River service area settlement and water rights total 978,455 AF and they are not part of the Table A water in Table B-4. The City of Vallejo has water rights senior to the SWP in the amount of 22,780 AF and not subject to Term 91 curtailments, which restrict diversions from the Delta mostly during dry years (CDWR, 2022).

TABLE B-4 Maximum SWP Contractual Table A Amounts (acre-foot/yr) and 2013–2024 Average Allocation

Area	Contractors	Maximum Table A (Acre-feet/yr)	Average Allocation
Feather River	Yuba City, Butte, Plumas	39,800	52%
North Bay Area	Napa, Solano	76,781	49%
South Bay Area	Alameda (Zone 7), Alameda County, Santa Clara	222,619	40%
Central Coast	San Luis Obispo, Santa Barbara	70,486	40%
San Joaquin	Dudley-Ridge, Empire, Kern (M&I and Agriculture), Kings Oak Flat, Tulare	1,129,556	40%
Southern California	AVEK, Coachella, Crestline, Desert, Littlerock, Mojave, Palmdale, San Bernardino, San Gabriel, San Geronio, Santa Clarita, Metropolitan, Ventura	2,633,544	40%
Total		4,172,786	41%

DATA SOURCES: Maximum Contract Amounts and Deliveries from Bulletin 132-19 (CDWR, 2022) and Bulletin 132 Appendix B for 2024 (CDWR, 2024a). Average allocations were calculated by the Committee based on both Bulletin 132 Appendix B for 2024 Maximum Table A amounts (Table B-4) and final historical SWP Table A Allocations (CDWR, 2025).

Future Challenges and Vulnerabilities for CVP and SWP Water Users

Both Projects operate within a heavily allocated system, where water amounts are often insufficient to meet the competing co-equal goals of water supply and environmental conservation. Future climate conditions, characterized by warmer temperatures and more frequent, intense precipitation and prolonged droughts, are expected to exacerbate these challenges by further reducing water availability.

Some studies estimate that one foot of sea level rise may necessitate approximately 500 TAF of additional Delta outflows to protect water quality (Fleenor et al., 2008). Climate projections also point to decreased runoff in the upper basins feeding the Delta due to higher temperatures and increased evapotranspiration (Null et al., 2010). CDWR (2024b) predicts that by 2043, under climate change, the long-term average percentage of Table A maximum deliveries (see Table B-4) could drop to as low as 41 percent (down from 53 percent under historical climate conditions). Similarly, CDWR's Water Available for Replenishment report (CDWR, 2018) estimates that SWP and CVP annual exports may decline to an average of 4.63 MAF under future conditions without intervention, compared to 4.94 MAF under current conditions.

On the demand side, higher crop evapotranspiration could increase applied water requirements, particularly during multi-year droughts (Moyers et al., 2024). For example, an additional 2–4 inches of crop water demand in a dry year across the Central Valley floor would be sufficient to fill a 1–2 MAF reservoir. Lund et al. (2024) project that future statewide water supply reductions could range from 4 to 7 MAF when accounting for these and other factors. Although some overlap exists among these estimates, the overall projections consistently indicate reduced water availability and heightened demand, complicating efforts to meet demand within current regulatory constraints.

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Appendix C

Laws Governing Project Operations

The U.S. Bureau of Reclamation (USBR) and the California Department of Water Resources (CDWR) operate the Central Valley Project (CVP) and State Water Project (SWP) within a complex legal environment. Both projects are subject to both federal and state law, and the relevant laws include generally applicable laws that cover but are not limited to the reclamation program, laws specific to the reclamation program, and laws specific to the Projects (Benson, 2012). This appendix summarizes the Projects' legal environment, beginning with general and foundational principles and then describing specific applicable laws. It augments the Chapter 1 discussion of the laws and regulations that affect project operation.

On the whole, this legal system is designed to achieve what the Sacramento–San Joaquin Delta Reform Act of 2009, a California statute, describes as the “coequal goals” of water supply and environmental protection. However, it is not a simple balancing system, and in some circumstances, particular goals—often environmental protection requirements—theoretically hold primacy over water-supply commitments.

RECLAMATION LAW

USBR is a federal agency, and like all federal agencies, it was created, and its authority is defined and bounded, by federal statutes (the California Department of Water Resources, CDWR, has the same status under state law). The Reclamation Act of 1902 authorized the creation of what was then called the “Reclamation Service,” and the agency initially was a subagency within the U.S. Geological Survey (USGS). In 1907, it became a separate agency within the Department of the Interior.¹

Because the CVP involves many different units and was constructed over a multi-decade period, it owes its existence to many different pieces of legislation. USBR's website provides a concise summary of this legislation,² part of which is below:

The state legislature passed the Interior Region 10 California-Great Basin California Central Valley Project Act in 1933. The Act authorized the sale of revenue bonds to construct the project, but during the Great Depression, bonds didn't sell.

With the Rivers and Harbors Act of 1935, the federal government assumed control of the project and its initial features were authorized for construction by the U.S. Army Corps of Engineers. Funds for construction of the initial features of the Central Valley Project were provided by the Emergency Relief Appropriation Act of 1935 (49 Stat. 115). The project was authorized by a finding of feasibility by the Secretary of the Interior and approved by the President on December 2, 1935, for construction by Reclamation.

When the Rivers and Harbors Act was reauthorized in 1937 (50 Stat. 844, 850), Reclamation took over CVP construction and operation, and the project became subject to Reclamation law.

¹ For additional information on this history, see The Bureau of Reclamation: A Very Brief History, <https://www.usbr.gov/history/borhist.html>.

² About the Central Valley Project, U.S. Bureau of Reclamation, <https://www.usbr.gov/mp/cvp/about-cvp.html>.

... Additional authorizations were made under the Rivers and Harbors Act of October 17, 1940 (54 Stat. 1198, 1199) and:

- American River features were authorized under the act of October 14, 1949 (63 Stat. 852).
- The Sacramento Valley Canals were authorized under the act of September 26, 1950 (64 Stat. 1036).
- The Trinity River Division was authorized by Public Law 386, 84th Congress, 1st session, and approved August 12, 1955.
- The San Luis Unit, West San Joaquin Division, was authorized as a part of the Central Valley Project on June 3, 1960, Public Law 86-488 (74 Stat. 156).
- The Auburn-Folsom South Unit of the American River Division was authorized by Public Law 89-161 (79 Stat. 615) on September 2, 1965.
- The Tehama-Colusa Canal enlargement, under the Sacramento River Division, was authorized in Public Law 90-65 (81 Stat. 167), August 19, 1967.
- San Felipe Division features were authorized by Public Law 90-72 (81 Stat. 173), signed on August 27, 1967.
- The Allen Camp Unit, Pit River Division, was authorized on September 28, 1976, by Public Law 94-423 (90 Stat. 1324).
- The New Melones Unit, East Side Division, was officially transferred to Reclamation from the Corps by Public Law 87-874 in November 1979.

In addition to the legislation that created the agency and adding units, USBR is governed by many legal provisions affecting its contracting arrangements, rate-setting, and payment policies—as is CDWR. For the most part, those laws are not relevant to the Committee’s work and are not described here. Readers can obtain more information about those laws from USBR’s website for the CVP.³

Project Purposes

USBR projects, including the CVP, generally operate to serve legislatively defined purposes. As USBR explains: “Under the 1937 Act, the CVP’s dams, powerplants, canals, and other facilities had three purposes: (1) regulate rivers and improve flood control and navigation, (2) provide water for irrigation and domestic use; and (3) generate power. Under later reauthorizations and legislation for specific project additions, additional project purposes were added—recreation, fish and wildlife enhancement, and water quality improvements.”⁴ Because these purposes sometimes conflict, much of USBR’s work involves balancing different goals.⁵

CDWR’s management of the SWP is also subject to sometimes-conflicting obligations. The project’s primary purpose is water supply, but governing laws also prioritize hydropower generation, recreation, and environmental protection.

STATE WATER-RIGHTS LAW AND THE PROJECTS

Both projects are governed by California water-rights law and by associated regulatory provisions. State laws clearly apply to the SWP because it is a state project and the CDWR is a state agency. However, those laws also apply to federal project operations. Section 8 of the Reclamation Act of

³ Laws, Regulations, and References, U.S. Bureau of Reclamation, <https://www.usbr.gov/mp/cvp/laws-regs-ref.html>.

⁴ About the Central Valley Project, U.S. Bureau of Reclamation, <https://www.usbr.gov/mp/cvp/about-cvp.html>.

⁵ See Benson, *supra* note ___, at 1054.

1902 directs USBR to obtain and exercise its water rights “in conformity” with state law.⁶ In multiple cases, courts have held that this provision requires the USBR to comply not only with state law defining water rights, but also with state laws regulating the exercise of water rights.⁷ Somewhat similarly, section 101(b) of Public Law 99-546 requires that CVP operations be consistent with California water-quality standards unless such operational constraints are “not consistent with the congressional directives applicable to the project.”⁸

Because both agencies obtain their water rights under state law, they participate in California’s system of appropriative water rights. In a prior appropriation system, water users generally obtain rights by diverting water from a waterway and putting that water to beneficial and continual use. Prior appropriation prioritizes more senior water rights, meaning those rights must be satisfied before more junior users can obtain water.⁹ Since 1914—well before construction of the CVP and SWP—an applicant for a water right needed that right to be approved by the California State Water Resources Control Board (SWRCB), which exercises continuing supervisory authority over rights.¹⁰

This seniority system has important implications for the Projects. By the time CVP and SWP construction began, other water users already had obtained water rights in the Central Valley. Many of these rights predate 1914. California also recognizes riparian rights, which entitle riparian landowners to divert directly from waterways.¹¹ California law prioritizes riparian rights over appropriative rights, except when the water that riparian-right holders would like to divert would not be present at all unless an appropriator had stored it in an upstream reservoir.¹² This means that the Projects share the Central Valley with many water users whose rights take priority over those of USBR and CDWR. Many of those pre-1914 and riparian users’ rights are only minimally documented, and California’s system of water-use reporting is a work in progress, which means that state regulators, USBR, and CDWR cannot always know how much water should be available to the projects.¹³

California statutory law bolsters these protections for other water users. California has enacted a series of “area of origin” laws, which prioritize in-basin uses over exports. While these laws have rarely been litigated, they do establish additional boundaries on the projects’ ability to export water.¹⁴ Similarly, a series of federal and state laws—in addition to the Clean Water Act and the Porter-Cologne Water Quality Control Act, both of which we discuss below—seeks to protect other in-Delta water users from the salinity impacts water exports could create.¹⁵

⁶ See 43 U.S.C. § 383. Section 383 states:

Nothing in this Act shall be construed as affecting or intended to affect or to in any way interfere with the laws of any State or Territory relating to the control, appropriation, use, or distribution of water used in irrigation, or any vested right acquired thereunder, and the Secretary of the Interior, in carrying out the provisions of this Act, shall proceed in conformity with such laws, and nothing herein shall in any way affect any right of any State or of the Federal Government or of any landowner, appropriator, or user of water in, to, or from any interstate stream or the waters thereof.

Id.

⁷ See, e.g., *California v. United States*, 438 U.S. 645, 650, 678 (1978); *Natural Resource Defense Council v. Patterson*, 333 F.Supp.2d 906, 913-14 (E.D. Cal. 2004).

⁸ Pub. L. 99-546, 100 Stat. 3050 (1986).

⁹ In practice, gaps in monitoring and enforcement sometimes mean that junior appropriators can take water to which their entitlement is questionable.

¹⁰ See *California Farm Bureau Federation v. State Water Resources Control Bd.*, 274 P.3d 112, 117-18 (Cal. 2011).

¹¹ See *Water Rights: Frequently Asked Questions*, California State Water Resources Control Board, https://www.waterboards.ca.gov/waterrights/board_info/faqs.html#toc178761088.

¹² See *In re Waters of Long Valley Creek Stream System*, 559 P.2d 656, 660 (1979) (holding that even “a dormant riparian right is paramount to active appropriate rights.”).

¹³ See Michael Kiparsky et al., *Piloting a Water Rights Information System for California* (2021) (describing inadequacies in existing water rights information).

¹⁴ See Craig M. Wilson, *California’s Area of Origin Laws* (2013), https://www.waterboards.ca.gov/board_info/agendas/2013/oct/100813_7origin.pdf.

¹⁵ E.g. Delta Protection Act of 1959, Stats. 1959, Ch. 1766 (codified at Cal. Water Code §§ 12200 – 12204).

Contracts

USBR distributes water to end users through contracts. Those contracts generally specify quantities of water that the USBR will try to deliver and prices that recipients will pay. They also typically contain shortage provisions, which allow USBR to deliver less than the full contractual amount if conditions—including environmental restrictions—prevent the USBR from doing so.¹⁶ Some of the contractors, those known as “Settlement” and “Exchange” Contractors, are entities that gave up their senior water rights in return for promises of service by the CVP.¹⁷ When USBR allocates water, the Settlement and Exchange Contractors hold seniority over the USBR’s other contracts, which means their needs must be satisfied first.¹⁸

USBR’s water rights describe fixed quantities of diversions, and its contracts with the entities it supplies specify delivery amounts. However, neither of these amounts is a guarantee. USBR cannot divert water unless that water is available after more senior users and riparians have taken their shares. In addition, USBR’s rights and contractual obligations are limited by state and federal environmental laws and by California’s requirements that water use be reasonable and consistent with the state’s public trust doctrine.¹⁹

Similar constraints apply to SWP projects. The contracts specify maximum entitlements, but they do not obligate CDWR to deliver the full contract amount, and, as discussed above, CDWR rarely does so. Beyond limitations on the physical availability of water, CDWR’s deliveries also can be limited by environmental laws, the public trust doctrine, and reasonable use requirements.²⁰

ENVIRONMENTAL LAWS

Project operations are constrained by a variety of environmental laws, the most important of which address water quality and endangered species protection.

Water Quality Laws

The most important constraints on project operations come from federal and state water-quality laws. The federal Clean Water Act establishes a national regime for water quality protection, and it allows states to take the lead in implementing many elements of the regulatory scheme.²¹ Through the Porter-Cologne Water Quality Control Act²² and associated administrative programs, California has taken on

¹⁶ See *O’Neill v. United States*, 50 F.3d 677, 684 (9th Cir. 1995) (“We conclude that the contract’s liability limitation is unambiguous and that an unavailability of water resulting from the mandates of valid legislation constitutes a shortage by reason of ‘any other causes.’”).

¹⁷ See History of SJRECWA, San Joaquin River Exchange Contractors Water Authority, <https://www.sjrecwa.net/about/history/>; Sacramento River Settlement Contractors, <https://sacriverse.org/>.

¹⁸ See, e.g., Reclamation Increases 2024 Central Valley Project Water Supply Allocations, Bureau of Reclamation, <https://www.usbr.gov/newsroom/news-release/4782>.

¹⁹ See *Northern Cal. Water Ass’n v. State Water Resources Control Bd.*, 230 Cal. Rptr. 3d 142, 166 (Cal. Ct. App. 2018). As the court explained, “the USBR operates the CVP and allocates CVP water *subject to* a comprehensive scheme of environmental statutes and regulations, and various state and federal regulations. . . . Moreover, the CVP contractors take their interest in the USBR’s water rights subject to these legal obligations. . . . and the USBR cannot give away more than it has.” *Id.* (internal citations omitted).

²⁰ See *State Water Resource Control Bd. Cases*, 39 Cal. Rptr. 3d 189, 294 (2006) (“because the rights of an appropriator are always subject to the public trust doctrine . . . the same is true of the rights of a person who contracts with an appropriator for the use of the water appropriated.”).

²¹ See 33 U.S.C. §§ 1251 – 1389.

²² Cal. Water Code §§ 13000 – 16104.

Clean Water Act primacy, and in some ways, Porter-Cologne establishes more extensive requirements than federal law.²³ Because of this substantial overlap and intertwinement, the discussion below addresses both laws simultaneously.

For the CVP and SWP, the most important water-quality requirements come from water quality standards. Both the Clean Water Act and Porter-Cologne direct the state to establish water quality standards.²⁴ Those standards identify desired beneficial uses of waterways and set protective criteria, some qualitative and some quantitative, designed to ensure the protection of those beneficial uses, all with the overarching goal of sustaining or improving water quality. The state then implements those protections through water-quality permitting. Importantly for the projects, California also uses its oversight of water rights to implement water quality standards.²⁵ That is, water quality is regulated via a water rights decision called D-1641 (California State Water Resources Control Board, 1999), which is intended to protect in-Delta water uses and fish and wildlife habitat. Some water quality objectives are accomplished via pumping restrictions for both the CVP and SWP (OMR Flow Management Action—see Chapter 3). Other water quality regulations stemming from water right D-1641 include requirements for the location of X2 from for fall months with the intent to ensure suitable habitat for native fish (Summer-Fall Habitat Action—see Chapter 4).

Key beneficial uses of the Delta include supplying water for in-Delta farms and drinking water to urban areas with intakes in the western Delta, and both of those uses require water with low salinity.²⁶ The location of the freshwater-saltwater interface also is important for many Delta species, and the Clean Water Act treats “biological integrity” as an element of water quality, as does California law.²⁷ The State has long used restrictions on diversions, including diversion by USBR, to protect these beneficial uses, and courts have upheld the state’s ability to do so.²⁸

Endangered Species Acts

The federal and state Endangered Species Acts (ESAs) also have important implications for project operations. Those implications arise partly because many state- and federally listed species are present in, or are affected by conditions in, the Bay-Delta watershed. And they extend to the SWP—even under provisions that do not typically apply to state activities—because state and federal project operations are so intertwined.

Both acts prohibit “take” of listed species.²⁹ A “take”, under federal or state law, is an action that, among other possibilities, kills, wounds, harms, or captures a protected species.³⁰ The statutes also contain exemptions to these prohibitions, but obtaining coverage under the exemptions requires the USBR to comply with the procedural and substantive requirements of Section 7 of the federal ESA.³¹

Section 7 establishes two main prohibitions, a set of procedural requirements, and one key exception. Section 7 prohibits federal agencies from taking actions that are likely to put a species’

²³ The most notable differences pertain to regulation of nonpoint source pollution, which is not a central focus of this committee. See Cal. Water Code § 13369.

²⁴ 33 U.S.C. § 1313; Cal. Water Code 13241.

²⁵ See *United States v. State Water Resources Control Bd.*, 227 Cal. Rptr. 161, 166 (Cal. Ct. App. 1986).

²⁶ State Water Resources Control Board, Water Quality Control Plan for the San Francisco Bay/Sacramento-San Joaquin Delta Estuary 9-21 (2018).

²⁷ 33 U.S.C. § 1362(19); Cal. Water Code § 13050(g); see *PUD No. 1 of Jefferson County v. Wash. Dept. of Ecology*, 511 U.S. 700, 719-20 (1994) (rejecting a distinction between water quantity and water quality as “artificial”).

²⁸ See *United States v. State Water Resources Control Board*, 227 Cal. Rptr. at 166.

²⁹ 16 U.S.C. § 1538; Cal. Fish & Game Code § 2080.

³⁰ 16 U.S.C. § 1532(19); Cal. Fish & Game Code § 86.

³¹ See 16 U.S.C. § 1536(b)(4); Cal. Fish & Game Code § 2080.1 (making federal-law incidental take statement or incidental take permit a shield against state-law take liability).

survival in “jeopardy” or to adversely modify its “critical habitat.”³² It also requires agencies taking actions that might adversely affect listed species to undergo a process called “consultation,” through which the agency obtains, from the U.S. Fish and Wildlife Service (USFWS) or the National Oceanic and Atmospheric Administration (NOAA) National Marine Fisheries Service (NMFS), a “biological opinion” explaining whether the proposed action will cause jeopardy or adverse modification.³³ If the wildlife agency reaches a jeopardy or adverse modification determination, then it can propose a “reasonable and prudent alternative,” which is an alternative way to proceed with the project without causing jeopardy or adverse modification.³⁴ Completion of a consultation process also allows the USBR to obtain “incidental take authorization,” which provides legal protections for takes.³⁵ However, that protection is conditioned on compliance with “reasonable and prudent measures,” which are specific measures defined in the biological opinion and designed to minimize the extent of take.³⁶

All of these requirements affect day-to-day project operations. The Projects take species, most visibly through entrainment at the pumps, and therefore cannot operate without incidental take authorization. For that reason, and also because CVP operations are federal actions that affect listed species, USBR and CDWR must consult on project operations. Across the nation, consultations very rarely lead to jeopardy and adverse modification findings, largely because the agencies usually negotiate over project changes that will avoid the need for such a finding.³⁷ However, for several years, the Projects were a rare exception to those norms. In 2004, USFWS issued biological opinions that did not find jeopardy or adverse modification, but those opinions were challenged in court and set aside.³⁸ In 2009, USFWS and NMFS issued biological opinions finding jeopardy and adverse modification, and from then until 2019, the CVP and SWP operated under reasonable and prudent alternatives.³⁹ From 2019 until 2024, USBR operated the CVP under new biological opinions that do not find jeopardy but that contained a range of constraining rules for project operations.⁴⁰ In 2024, USBR finalized another reconsultation leading to new biological opinions for the listed species (NMFS, 2024; USFWS, 2024) and modifications to the long-term operations of the CVP (USBR, 2024) and SWP (CDFW, 2024).

National Environmental Policy Act

USBR also must comply with the National Environmental Policy Act (NEPA), although NEPA is less important than water-quality and endangered-species laws to ongoing operations. NEPA requires a federal agency taking a “major... action that may significantly affect the quality of the human environment” to prepare an environmental impact statement (EIS) for that action.⁴¹ An EIS is a detailed

³² 16 U.S.C. § 1536(a)(2).

³³ 16 U.S.C. § 1536(a)-(d).

³⁴ 16 U.S.C. § 1536(b)(3)(A).

³⁵ 16 U.S.C. § 1536(b)(4).

³⁶ *Id.*

³⁷ See Jacob W. Malcolm & Ya-Wei Li, Data Contradict Common Perceptions about a Controversial Provision of the US Endangered Species Act, 112 PNAS 15,844, 15846 (2015) (providing statistics on the rarity of jeopardy and adverse modification findings); Dave Owen, The Negotiable Implementation of Environmental Law, 75 Stan. L. Rev. 137, 163-66 (2023) (describing the typical course of section 7 consultations).

³⁸ Natural Resources Defense Council v. Kempthorne, 506 F. Supp. 2d 322 (E.D. Cal. 2007); Pacific Coast Fed. of Fishermen’s Assoc. v. Gutierrez, 606 F.Supp.2d 1122 (E.D. Cal. 2008).

³⁹ NMFS Biological Opinion on Long Term Operation of the Central Valley Project and the State Water Project 10 (2019) (table summarizing the history of NMFS consultations addressing the CVP); USFWS, Central Valley Project and California State Water Project Consultation, <https://www.fws.gov/project/central-valley-project-and-california-state-water-project-consultation>.

⁴⁰ NMFS Biological Opinion on Long Term Operation of the Central Valley Project and the State Water Project (2019).

⁴¹ 42 U.S.C. § 4332(C).

review of the environmental setting for the project, the project's likely environmental impacts, and alternatives to the proposed project. The agency must allow public comment on a draft statement. Once the process is complete, NEPA does not impose any substantive constraints.⁴²

NEPA applies to USBR if it makes major changes to CVP infrastructure or agrees to new contracts. It does not apply, however, to ongoing operations, so long as those operations are generally consistent with historic operations.⁴³ In other words, NEPA's requirements apply when an agency initially decides to take some new action, but the agency has no obligation to continually update its NEPA studies as it carries out the action.

The California Environmental Quality Act (CEQA) does not govern USBR's operations, but it does govern actions taken by CDWR and by the CVP and SWP contractors (all of which are government entities). Broadly speaking, CEQA establishes requirements similar to NEPA, but there are important differences. Most significantly, CEQA does impose substantive constraints; it requires action agencies to avoid or mitigate significant environmental impacts if it is feasible to do so. In addition, the judicial culture surrounding CEQA is quite different from the federal judiciary's approach to NEPA. The United States Supreme Court has never ruled in favor of a NEPA plaintiff and writes somewhat dismissively about the statute.⁴⁴ The California Supreme Court, in contrast, has often ruled in favor of CEQA plaintiffs. That culture means that agencies often prepare full-length CEQA documents for which federal agencies would be highly unlikely to prepare EISs.

California Fish and Game Code Section 5937

California Fish and Game Code section 5937 requires operators of dams to maintain below-dam fish populations "in good condition." In a series of cases, some involving the CVP, California and federal courts have interpreted that requirement to mean that fisheries must be maintained at historic levels.⁴⁵ Federal courts also have determined that this requirement applies to USBR's operation of the CVP.⁴⁶

To date, Fish and Game Code section 5937 has only been directly applied to CVP flows in the San Joaquin River, where lengthy litigation and subsequent settlement led to a restoration program that included requirements for increased instream flows, and to other streams outside the Central Valley. By its terms, however, it applies to all below-dam fisheries, which means it could affect USBR or CDWR operations anywhere in California where either agency operates a dam.

Central Valley Project Improvement Act

Congress enacted the Central Valley Project Improvement Act (CVPIA) in 1992. The Act's primary goal was to rebalance water delivery and environmental protection, and it sought to do this by providing more secure water supplies for wildlife refuges, establishing restoration goals for salmon populations, and dedicating more water to environmental flows.⁴⁷ The statute also seeks to promote increased operational flexibility and to facilitate voluntary water transfers. Much of the legal controversy

⁴² See *Robertson v. Methow Valley Citizen's Council*, 490 U.S. 332, 350 (1989) (emphasizing NEPA's lack of a substantive mandate).

⁴³ See Benson, *supra* note __, at 1055.

⁴⁴ See, e.g., *Seven County Infrastructure Coalition v. Eagle County, Co.*, __ S. Ct. __ (2025).

⁴⁵ See *Natural Resources Defense Council v. Patterson*, 333 F. Supp. 2d 906, 916, 924 (E.D. Cal. 2004); *California Trout, Inc. v. Superior Ct.*, 266 Cal. Rptr. 788, 802 (Cal. Ct. App. 1990).

⁴⁶ *Patterson*, 333 F. Supp. 2d at 913-14.

⁴⁷ See *San Luis & Delta Mendota Water Auth. v. U.S.*, 672 F.3d 676, 684-85 (9th Cir. 2012) (summarizing the act's requirements).

about implementing the Act has pertained to its environmental flow requirements, with consumptive water users arguing that flow releases should count against the CVPIA's environmental-flow budget.⁴⁸

Voluntary Agreements

The preceding discussion might convey the impression that management of the Bay-Delta is constrained by laws that, while complicated, provide clear marching orders once they are clearly understood. The reality, however, is different. Determining out how laws apply to specific circumstances can be quite difficult and is often contested, particularly if the effects of management actions on species are not fully understood. In addition, different stakeholders have different views about the appropriate roles of regulatory controls and enforcement mechanisms, and those disagreements often become intertwined with debates about the legal requirements. Those disagreements have been ongoing for decades, and sometimes stakeholders resolve them through some sort of negotiated arrangement rather than through regulatory enforcement or litigation.

A good example of these debates, and of the potential for different ways to resolve challenges, is the long-running debate over “voluntary agreements” or, more recently, “Agreements to Support Healthy Rivers and Landscapes.” The proposed voluntary agreements are somewhat like detailed settlement agreements reached in the shadow of regulatory constraints. They would specify sets of actions and regulatory requirements that would serve as an alternative to the regulatory constraints that the SWRCB would otherwise impose on water-right holders. Without a voluntary agreement, the SWRCB typically would impose these constraints by updating water quality standards and then using those standards to change water-right permits and licenses, most likely by limiting diversions and thus preserving higher levels of flow. A voluntary agreement, if done well, could substitute other protective mechanisms, such as habitat restoration, that the SWRCB might not be able to order directly but that might provide greater benefits for fish at a lower cost to diverters.

For several reasons, voluntary agreements are controversial. Many environmental advocates disagree that the currently proposed voluntary agreements are protective enough and worry that while voluntary agreement development has been underway—a process that has been ongoing for over a decade—water quality standards were not being updated. Environmental advocates also have been frustrated with the voluntary agreement process, arguing that they were insufficiently involved or that their views were being ignored. Meanwhile, many water users are frustrated with the slow pace of voluntary agreement development, and they have argued that the proposed voluntary agreements would be more protective than the status quo and provide a better compromise than would likely emerge from regulatory action or litigation.

This report expresses no opinion on how those controversies should be resolved. This discussion is used just to illustrate a key, and lasting, point about the law governing the Delta. The process of turning statutes and court decisions into actual implementation is often filled with controversy and heavily determined by discretionary judgments, both scientific and political, and negotiations.

Although this summary may seem complex, it actually understates both the complexity and the dynamism of the legal regimes governing CVP and SWP operations. For reasons of space, not every relevant law is described. Each law also contains layers of intricacies, and implementing regulations and court decisions add additional layers (while also clarifying some questions that otherwise would be ambiguous). New legislation, regulations, and court decisions also can and probably will change elements of these laws. Nevertheless, the core point of this discussion—that governing laws both engage in and require multifaceted balancing acts—will likely remain a constant.

⁴⁸ See, e.g., *id.*

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Appendix D

Descriptions of Monitoring and Modeling Relevant to the Projects

This appendix is a background reference document to the three action chapters. It discusses the monitoring enterprise in the Delta region, including a catalogue of the major monitoring networks relevant to the listed fish species and other physical and chemicals parameters and hence broadly applicable to the Central Valley Project (CVP) and the State Water Project (SWP). It is valuable to know where long-standing physical, chemical, and biological monitoring data come from and what agencies or organizations are maintaining the networks. Previous reviews of the Delta monitoring enterprise are compiled. More thorough descriptions of the biological monitoring tools used for Shasta coldwater pool management are found herein.

The second half of this appendix itemizes and summarizes some major numerical models of physical processes common to all the actions reviewed by the Committee, particularly the core models used to simulate water quantity and quality for project operations. It also catalogues the life cycle models for the listed fish species. Finally, it describes the biological tools and models used for Shasta coldwater pool management.

MONITORING TO SUPPORT THE CVP AND SWP

Monitoring is fundamental to understanding ecosystem status and responses to environmental and management drivers and hence is a key component of the long-term operations of the CVP and the SWP. Monitoring that supports the operation of CVP and SWP can serve one or more of three main purposes:

1. **Real-time Operations.** These daily and weekly data inform the day-to-day project operations such as scheduling of releases and diversion. Examples of these types of data include water quality measurements to ensure compliance with salinity and flow standards in the state's D-1641 regulation (see Appendix C), or fish data to ensure compliance with the 2024 Biological Opinions and Incidental Take Permit (ITP) (such as salvage data for Old and Middle River [OMR] management).
2. **Status and Trends.** These are surveys on the long-term status of ecosystems. Examples include data on primary production, abundance of fish, and the enhanced Delta smelt monitoring survey that provides population estimates. Some of these monitoring networks have been in place for a very long time (decades). They provide baseline knowledge of the system and are used for many purposes, such as to understand generally how actions may impact long-term metrics.
3. **Special Studies.** Monitoring data collected during targeted studies is used to address a hypothesis. How are certain management actions working? Some of this work could be considered performance monitoring.

Various components of ongoing Delta monitoring support CVP and SWP management objectives for protecting water quality, fish, and fish habitat. These components include measurements of water flow, water quality, primary production, secondary production, and fish surveys. Surveys with particular relevance to the three actions reviewed in this report are listed in greater detail in Table D-1.

TABLE D-1 Major Monitoring Networks in the Delta with Possible Relevance to the 3 Actions Reviewed in the Report

Program/ Project	Agency	Purpose/ Study Type	Project Description Notes	Variables Monitored	Website
20 mm Survey	CDFW	Short term/ operations & Long Term	Larval fish survey to determine timing, distribution, and abundance of Delta smelt larvae and their food supply.	WQ, Fish, Zooplankton	https://wildlife.ca.gov/Conservation/Delta/20mm-Survey
Fall Mid-water Trawl (FMWT)	CDFW	Short term/ operations & Long Term	Fish survey targeting adult fish abundance throughout the upper estuary during the fall.	WQ, Fish, Zooplankton	https://wildlife.ca.gov/Conservation/Delta/Fall-Midwater-Trawl
Spring Kodiak Trawl (SKT)	CDFW	Short term/ operations & Long Term	The SKT determines the relative abundance and distribution of spawning Delta smelt. The SKT samples 40 stations.	Fish	https://wildlife.ca.gov/Conservation/Delta/Spring-Kodiak-Trawl
Summer Towntet (STN)	IEP, CDFW	Short term/ operations & Long Term	Fish survey targeting Delta smelt and age-0 striped bass June through August.	WQ, Fish, Zooplankton	https://iep.ca.gov/Science-Synthesis-Service/Monitoring-Programs/Summer-Towntet
USGS Continuous WQ	USGS	Short term/ operations & Long Term	Continuous water quality (WQ, i.e., temperature and salinity) and water level monitoring	WQ	
Smelt Larva Survey (SLS)	CDFW	Short term/ operations & Long Term	Near real-time distribution data for longfin smelt in the upper estuary.	WQ, Fish	https://wildlife.ca.gov/Conservation/Delta/Smelt-Larva-Survey
EMP: Discrete WQ	CDWR	Long Term	WQ and nutrient monitoring in the Delta, Suisun Bay, and San Pablo Bay.	WQ	https://iep.ca.gov/Science-Synthesis-Service/Monitoring-Programs/EMP
EMP: Phytoplankton	CDWR	Long Term	Phytoplankton monitoring in the Delta, Suisun Bay, and San Pablo Bay.	Phyto	https://iep.ca.gov/Science-Synthesis-Service/Monitoring-Programs/EMP
EMP: Zooplankton	CDFW	Long Term	Microzooplankton (63–150 mm), mesozooplankton (150–500 mm), and mysid (>500 mm) samples collected throughout the estuary	WQ Zooplankton	https://iep.ca.gov/Science-Synthesis-Service/Monitoring-Programs/EMP
EMP: Benthic Invertebrates	CDWR	Long Term	Benthic invertebrate monitoring in the Delta, Suisun Bay, and San Pablo Bay.	Phytoplankton, Benthic invertebrates	https://iep.ca.gov/Science-Synthesis-Service/Monitoring-Programs/EMP
Fish Restoration Program	CDFW	Long Term	Monitors fish and invertebrate abundance in or near restored tidal wetlands	WQ, Fish, Phytoplankton, Zooplankton, Benthic invertebrates	https://iep.ca.gov/Science-Synthesis-Service/Monitoring-Programs/Tidal-Wetland

Program/ Project	Agency	Purpose/ Study Type	Project Description Notes	Variables Monitored	Website
Yolo Bypass Fish Monitoring Program	CDWR	Long Term	Monitors lower trophic levels, fish, hydrology, and WQ in the Yolo Bypass	WQ, Fish, Phytoplankton, Zooplankton, Other invertebrates	https://iep.ca.gov/Science-Synthesis-Service/Monitoring-Programs/Yolo-Bypass
San Francisco Bay Study	CDFW	Long Term	Survey targeting both pelagic and demersal fish, shrimp, and crabs using otter trawls and midwater trawls throughout the Bay and upper estuary.	WQ, Other invertebrates, Fish	https://wildlife.ca.gov/Conservation/Delta/Bay-Study
Fish Salvage Monitoring	CDFW/ DWR	Short term/ operations & Long Term	Data collected on fish entrained and salvaged at the Skinner Delta Fish Protection Facility.	Fish; regular counts and larval sampling	https://wildlife.ca.gov/Conservation/Delta/Salvage-Monitoring
Fish Salvage Monitoring	USFWS/ USBR	Short term/ operations & Long Term	Data collected on fish entrained and salvaged at the Tracy Fish Facility	Fish; regular counts and larval sampling	https://data.usbr.gov/catalog/4494
Suisun Marsh Survey	UC Davis	Long Term	Year-round fish surveys in Suisun Marsh	WQ, Fish	https://iep.ca.gov/Science-Synthesis-Service/Monitoring-Programs/Suisun-Marsh
Delta Juvenile Fish Monitoring Program	USFWS	Long Term	Established in the 1970s to monitor juvenile salmon abundance in the Bay-Delta using trawling and beach seine nets.	Fish	https://www.fws.gov/project/delta-juvenile-fish-monitoring-program
Enhanced Delta Smelt Monitoring	USFWS	Long Term	Weekly surveys of fish communities, gear types rotate seasonally to target Delta smelt.	WQ, Fish	https://www.fws.gov/project/enhanced-delta-smelt-monitoring-program
USGS Polaris-Peterson Cruises	USGS	Long Term	Long-term boat-based monthly WQ samples	WQ, Phytoplankton, Other	https://www.usgs.gov/centers/california-water-science-center/science/water-quality-san-francisco-bay-research-and
USGS Hydro-dynamics Group Flow Network	USGS	Short term/ operations & Long Term	15-minute flow and WQ data collected at fixed stations	WQ, Other	https://iep.ca.gov/Science-Synthesis-Service/Monitoring-Programs/Delta-Flows
USGS Biogeo-chemistry Group	USGS	Short term/ operations & Long Term	15-minute WQ data collected at fixed stations	WQ, Phytoplankton, Other	https://sciencetracker.deltacouncil.ca.gov/activities/continuous-flow-and-water-quality-monitoring-network-sacramento-san-joaquin-delta
Red Bluff Diversion Dam RST	USFWS	Short term/ operations & Long Term	Currently provides bi-weekly, real-time, summarized daily passage estimates of all four runs of Chinook salmon and steelhead	Fish	https://www.fws.gov/project/red-bluff-diversion-dam-juvenile-fish-monitoring

Program/ Project	Agency	Purpose/ Study Type	Project Description Notes	Variables Monitored	Website
Upper Sacramento River Basin Salmonid Monitoring	CDFW	Long Term	High-priority stranding locations along the Upper Sacramento River Basin between RM 300–246.	Fish	https://www.calfish.org/Programs/ConservationandManagement/CDFWUpperSacRiverBasinSalmonidMonitoring/tabid/357/Agg1606_SelectTab/4/Default.aspx
Sacramento Valley Tributary Monitoring	CDFW	Long Term	Mainstem Sacramento R and its tributaries including Butte Creek, Big Chico Creek, Feather R, Yuba R, Bear R, Colusa Basin Drain, Natomas Cross Canal, American R, Cache Creek, Auburn Ravine, Cosumnes R, Mokelumne R, and the Calaveras R.	Fish	https://www.calfish.org/ProgramsData/ConservationandManagement/CentralValleyMonitoring/SacramentoValleyTributaryMonitoring.aspx
Middle Sacramento River Salmon and Steelhead Monitoring	CDFW	Long Term	Monitoring program at Knights Landing and Tisdale Weir. Rotary screw traps in the Sacramento River from Oct-June targeting juvenile Chinook salmon.	Fish	https://www.calfish.org/ProgramsData/ConservationandManagement/CentralValleyMonitoring/SacramentoValleyTributaryMonitoring/MiddleSacramentoRiverSalmonandSteelheadMonitoring.aspx
Feather River Fish Monitoring Station RST	DWR	Long Term	The purpose of the FMS is to obtain accurate counts, determine temporal trends, and identify the origin of spring-run Chinook salmon, fall-run Chinook salmon, and steelhead that enter the Low Flow Channel of the Feather River	Fish	https://www.calfish.org/ProgramsData/ConservationandManagement/CentralValleyMonitoring/SacramentoValleyTributaryMonitoring/DWR-FeatherRiverFishMonitoringStation.aspx
Lower Feather River RST Monitoring	CDFW	Long Term	Estimate the number of juvenile spring-run emigrating from the Feather River to the Sacramento River and thence the Delta for use in the development of a JPE for spring-run chinook salmon in the Sacramento River watershed.	Fish	https://www.calfish.org/ProgramsData/ConservationandManagement/CentralValleyMonitoring/SacramentoValleyTributaryMonitoring/LowerFeatherRiver-RSTMonitoring.aspx
Stanislaus River (Caswell) - RST Monitoring	USFWS	Long Term	The primary objectives of the study are to collect data that can be used to estimate the passage of juvenile fall-run Chinook salmon and to quantify the raw catch of steelhead.	Fish	https://www.calfish.org/ProgramsData/ConservationandManagement/CentralValleyMonitoring/StanislausRiver-RSTMonitoring.aspx

Program/ Project	Agency	Purpose/ Study Type	Project Description Notes	Variables Monitored	Website
Directed Outflow Project - Delta Smelt and lower trophic	USBR	Special Study	USBR and CDWR, along with collaborators, are continuing efforts to evaluate the hypothesized benefits of outflow and outflow alteration for Delta smelt. The collective aim of these efforts is to better inform management actions that will bolster and stabilize the Delta smelt population.	Fish, WQ, Phytoplankton, Zooplankton	https://sciencetracker.deltacouncil.ca.gov/activities/directed-outflow-project
Fish Diet and Condition Study	CDFW	Special Study	This study has provided information on the foraging habits of pelagic fishes in the San Francisco Estuary (SFE) since 2005. This study was created to address food limitation in young fish by understanding the types and amount of prey eaten among seasons and regions of the SFE.	Fish stomach contents	https://wildlife.ca.gov/Conservation/Delta/Special-Studies
North Delta Flow Action	DWR	Special Study	This project monitors and evaluates the effects of augmented summer and fall flows in the Yolo Bypass and North Delta on lower trophic food web dynamics and the benefits to listed fish species	WQ, Phytoplankton, Zooplankton	https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=225604&inline
Suisun Marsh Salinity Control Gate Study	DWR	Special Study	WQ, fish, phytoplankton, clams and zooplankton monitoring to support the Summer-Fall Suisun Marsh Salinity Control Gates Action, summer and fall 2018–2021.	WQ, Phytoplankton, Zooplankton, Benthic invertebrates, Fish	
Larval Entrainment Pilot Study	CDFW/ DWR	Special Study	Project seeks to better understand larval osmerid entrainment into Clifton Court Forebay.	WQ, Fish	https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=225646&inline

As illustrated and summarized in Table D-1, many state and federal agencies have been collecting large amounts of a wide range of data, for some time. Because it focuses on the three actions, Table D-1 is not exhaustive of all Delta monitoring efforts. For additional information, the reader is referred to the Nelitz (2020a) monitoring inventory report, which presents a table with more than 150 surveys, including invasive species surveys.

Past Reviews of Delta Monitoring Programs

Several reviews on monitoring programs in the Delta have been undertaken in the past 10 years. The breadth of these reviews has ranged from comprehensive (all agencies and types of monitoring) to specific topics (e.g., invasive species or trawling), species, or programs.

The Delta Independent Science Board (DISB, 2022) completed the most comprehensive recent review of the monitoring enterprise in the Delta. This four-year effort was based on three contracted reports (Nelitz et al., 2019, 2020a,b) which included a detailed inventory and an analyses of monitoring integration across agencies, a workshop, surveys, interviews, a comprehensive literature review, and a series of scientific panels and seminars. The comprehensive inventory of the monitoring enterprise of the Delta was particularly noteworthy (Nelitz et al., 2020a). It included discussions of the size and geographic scope of monitoring programs across federal, statewide, regional, local, agency, and private entities. Monitoring activities were categorized by management themes: water supply, flood management, habitat management, native species management, invasive/non-native species management, water quality, and land-use management. The inventory includes 120 unique monitoring activities spanning more than 1,500 sampling locations within the Delta and Suisun Marsh. Detailed tables show which entities are doing the monitoring as well as the years sampled, and specific parameters measured. For example, sampling of Chinook salmon, steelhead, and green sturgeon were found to be part of 31, 26, and 18 monitoring activities, respectively (Nelitz et al., 2020b). There is also an analysis of interactions among agencies doing the monitoring.

The review identified five best practices that should be formally adopted into individual monitoring programs to help address the challenges and issues identified in the review:

1. Monitoring should be tied to the goals, objectives, and specific questions of interest to managers, decision makers, scientists, and stakeholders.
2. Monitoring should also be informed by stakeholder engagement and participation, and, when appropriate, include alternative forms of data and knowledge such as Traditional Knowledge, experiential information, and qualitative observations.
3. Monitoring plans should have enough flexibility to take advantage of new information and opportunities to adapt to issues, to scientific opportunities such as unusually low or high flows, and as new techniques and technologies become available.
4. Monitoring programs must include adequate data management, quality control, analysis, and synthesis, and should strive to improve statistical validity.
5. Monitoring programs should ensure that the data produced are accessible and shared with the public and other agencies.

The Interagency Ecological Program review (IEP Long-term Survey Review Team, 2021) considered three long-term bottom and midwater trawl fish surveys (San Francisco Bay Study, Fall Midwater Trawl, and Suisun Marsh—see Table D-1) that collect data on abundance and distributions of multiple fish species in the San Francisco Bay and Estuary ecosystem. The review notes that the three fish surveys have had a range of objectives that have shifted over their 50-year history. It adds that the fish surveys are useful primarily for looking at changes in relative abundance, because absolute abundance cannot be directly calculated given gear selectivity and environmental factors that affect catchability across different fish sizes and environmental sampling conditions. The review also notes that

unavailability of measures of uncertainty compromises the reliability of long-term trends in abundance and that evaluations of year-to-year trends need to assume that all catchability factors (e.g., turbidity, temperatures) do not vary among years.

In October 2021, CSAMP (a voluntary collaboration of 17 entities representing state, federal, public water agencies, and non-governmental organizations) held a workshop that focused on six monitoring reviews (described in Conrad and Moffett, 2022):

1. The Delta Independent Science Board monitoring enterprise review 2018–2022
2. Historical Interagency Ecological Program (IEP) Monitoring Program Reviews 2004–2019
3. IEP Long-term Monitoring Element Review: Pilot Approach and Methods Development
4. Six-agency monitoring redesign 2020–2022
5. Winter-run Chinook Salmon and Sturgeon Assessment of Indicators by Life Stage (SAIL) 2015–2016
6. U.S. Fish and Wildlife Service (USFWS) Monitoring Review to support Delta smelt Life-Cycle Modeling (since 2008)

According to Conrad and Moffett (2022), CSAMP members “indicated that they rely on the existing monitoring programs for status and trends; real-time information, including regulatory compliance; and assessing the effectiveness of management actions.” CSAMP members also used monitoring data to support modeling and targeted research. The CSAMP report also discussed resource allocation and balance among objectives and agencies, the value of monitoring programs, gaps in information, and the time and space scales of monitoring relative to operations and management. It recognized the need for flexibility in monitoring given the potential for rapid changing conditions (e.g., climate change, sea level rise, invasive species).

Biological Monitoring in Support of Shasta Coldwater Pool Management

Redd Monitoring

Redd surveys are conducted weekly between Keswick Dam and Balls Ferry from May to August to document location, timing, and success of Chinook spawning activity. Surveys by CDFW and USFWS involve walking or boating along critical reaches of the Sacramento River to document the location, depth, and surrounding flow conditions of each redd, noting any signs of dewatering or sediment exposure, and whether the eggs or fry remain viable. To complement ground surveys, drones and aerial surveys are used once or twice a season in large and difficult-to-access areas to identify trends in redd distribution across a broader region.

During the spawning season (May–September), data collected from weekly redd surveys are combined with water temperature data and flow modeling to estimate the survival of incubating eggs. The information is fed into temperature-dependent mortality models (e.g., the Martin or Anderson models—see Chapter 2), to simulate the proportion of eggs that survive to the fry stage under specific environmental conditions. The findings directly inform flow release schedules from Shasta Reservoir, ensuring that water levels remain adequate to protect redds during critical incubation periods. Survival estimates also contribute to long-term management strategies by identifying trends in habitat quality, spawning success, and areas requiring restoration, such as gravel augmentation or sediment removal.

Carcass Surveys

Carcass surveys, which provide data on adult salmon escapement, spawning success, and population resilience, are conducted weekly from May to September by the California Department of Fish

and Wildlife (CDFW) in collaboration with USFWS, with more frequent surveys during peak spawning periods. Surveys involve systematically identifying and collecting salmon carcasses from spawning reaches downstream of Keswick Dam. Carcasses are located using methods such as boat and snorkeling surveys, and they are tagged and returned to the river for mark-recapture estimates, which form the basis for escapement estimates. Fin clips, otoliths, and scales are also collected from carcasses to analyze genetic diversity, hatchery contributions, age structure, and life history traits.

Although they do not directly inform operational decision-making, carcass surveys contribute to validation of long-term flow management actions and planning. Escapement data and spawning success rates help to evaluate the effectiveness of flow and temperature strategies implemented earlier in the season. Insights from carcass surveys help to determine flow schedules or coldwater allocation strategies for subsequent years based on population trends and spawning success. Moreover, genetic and biological data collected during carcass surveys are used to assess the relative contribution of hatchery-origin fish to the total population.

Juvenile Salmon Monitoring

Juvenile outmigration monitoring is a critical component of assessing the survival, migration success, and population dynamics of winter-run Chinook salmon. This monitoring involves rotary screw traps, acoustic tagging, and environmental data collection to track juvenile salmon as they migrate downstream. CDFW, USFWS, and the National Marine Fisheries Service (NMFS) collect these data to inform short-term operational decisions such as flow adjustments and long-term strategies for species recovery.

Rotary screw traps installed in key migration corridors on the Sacramento River are the most widely used method for estimating abundance, survival, and timing of juvenile outmigration. Traps at the Red Bluff Diversion Dam provide data shortly after the fish leave spawning areas downstream of Keswick Dam while traps at Knights Landing enumerate juveniles as they move further downstream toward the Delta. Traps are operated daily during the outmigration season, typically from June through March. Captured fish are measured, counted, and assessed for condition before being released back into the river. Data on size and growth patterns provide insights into how rearing conditions, such as water temperature and habitat quality, affect juvenile development. Water temperature, turbidity, and flow are also measured to assess how these factors influence migration success. Importantly, population size estimates rely on mark-recapture of juveniles. Best practices would involve performing mark-recapture at daily time scales under variable flow conditions to capture the breadth of potential variability affecting recapture. Apparently, however, recapture at Red Bluff is performed only a few times a season, with important implications for the accuracy of out-migrating population estimates.

Acoustic tagging is used to complement rotary screw trapping by providing detailed data on migration routes, survival, and habitat use. Wild fish are captured, tagged, and released at various points along the Sacramento River; hatchery fish are also tagged and released. Outmigration dynamics of tagged fish are tracked using a network of stationary acoustic receivers deployed throughout the river, which enables researchers to identify migration bottlenecks, such as predation hotspots or areas with poor habitat connectivity. The data are processed and analyzed weekly or biweekly during the migration season. In the short term, the data inform operational managers about the timing and magnitude of juvenile outmigration, enabling flow adjustments to enhance migration conditions. In the long term, these data are used to assess the effectiveness of coldwater pool management strategies on juvenile survival, evaluate population trends, and guide habitat restoration efforts aimed at improving rearing and migration conditions. Insights from outmigration monitoring are also critical for refining predictive models and setting conservation goals for winter-run Chinook salmon recovery.

Current rotary screw trap and acoustic tagging methods have limited spatial and temporal resolution. Expanding spatial coverage to include under-monitored areas, such as downstream reaches and alternative migration pathways through the Sacramento Valley, would provide a more comprehensive

understanding of juvenile survival throughout the river system. Adding more monitoring stations in restored floodplains and side channels could help evaluate the effectiveness of these habitats in supporting juvenile growth and survival. Increasing the frequency of monitoring during peak outmigration periods or high-risk environmental conditions would enable managers to detect rapid changes in juvenile abundance and migration timing, improving the responsiveness of flow and temperature management.

Alternative methods of tagging fish, such as micro-PIT (Passive Integrated Transponder) tags, could enable researchers to include earlier life stages and smaller fish in monitoring efforts. Pairing tagging data with real-time environmental monitoring of water temperature, turbidity, and predator presence would provide managers with a clearer picture of the factors affecting survival and migration success. Real-time data on juvenile survival and migration timing could enable flow adjustments to improve passage conditions and reduce risks, such as predation or unfavorable hydrodynamics.

Habitat Surveys

Rearing habitat surveys evaluate the quality and availability of habitats critical for juvenile growth and survival by assessing off-channel habitats, floodplains, and mainstem river areas to determine their suitability for rearing during key life stages. CDFW, USFWS, and NMFS lead these efforts in collaboration with local watershed groups and conservation organizations. Surveys are conducted seasonally, peaking during juvenile rearing and outmigration periods (December through March). The data are used to guide operational flow decisions, restoration planning, and long-term recovery strategies for winter-run Chinook salmon.

Rearing habitat surveys typically involve field assessments of water depth, temperature, turbidity, flow velocity, and cover availability, including vegetation, woody debris, and overhanging banks—factors that influence juvenile survival by providing refuge from predators, maintaining optimal temperatures, and supporting prey availability. Riparian and floodplain habitats, which provide optimal foraging and refuge from predation, are monitored for connectivity during high-flow periods. Although much of the monitoring data are collected manually by wading or through boat surveys, drone imagery is used to map habitat extent, and high-frequency sensors are used to monitor environmental co-variables such as temperature and dissolved oxygen continuously. Biological sampling is often conducted in conjunction with habitat surveys to evaluate prey abundance and the presence of predators.

In the short term, data from rearing habitat surveys are integrated into flow management tools, such as hydrological models (e.g., CalSim), to adjust reservoir releases and ensure adequate connectivity between the mainstem river and off-channel habitats during critical rearing periods. Over the long term, rearing habitat data are used to identify areas for targeted restoration, such as floodplain reconnection, channel reconfiguration, or invasive species removal. These data inform the Winter-Run Chinook Salmon Lifecycle Model (Hendrix et al., 2019), which evaluates population viability and recovery progress under various habitat and operational scenarios.

MODELING

Since the 1970s, computer models have supported discussions, management, and policymaking for the CVP and the SWP in terms of water supply, flood, and hydropower operations. These modeling capabilities began with earlier organized hand calculations and the automation of these hand calculations. Over more than 50 years of computer modeling for these systems, modeling for water supply, floods, and hydropower has advanced greatly. Although these models have limitations (like all models), their accuracy and precision have improved, and they are usually useful, but still sometimes fallible, guides for managers and policymakers. These models, if run well, are usually much more accurate than our unaided intuitions or even the unaided intuitions of experienced experts. Perhaps more importantly, modeling provides a framework for assembling more detailed and integrated knowledge and

understanding of physical and policy aspects of these systems, which can enhance and test proposals for improving operation, infrastructure, and policies.

In contrast, modeling for ecosystem and environmental purposes is more difficult, because this requires the coupling of models of various physical processes with models of additional water quality, biological, and ecological processes. Such complex couplings require routine, tested, and long-term data development and quality control. It requires that more than a few modelers are experienced and comfortable with model architecture, construction, use, and shortcomings. Therefore, it is not surprising that modeling for ecological and environmental purposes is less advanced and less mature than that for physical processes in the Delta. Furthermore, when life-cycle models rely on underlying models of water flow and quality, such ecosystem models accumulate uncertainties, errors, and simplifications from underlying hydrodynamic and water quality models along with the errors already present from an imperfect understanding of biological and ecological processes.

Improving and interpreting both types of models are often hindered by the lack of field and laboratory data. Field data are especially expensive and time-consuming to gather, so most fish and ecosystem models have coarser spatial and temporal resolutions and tend to be less accurate than their underlying hydrodynamic and water quality models. Collecting sufficient field data is particularly hindered when the target is an endangered species; for example, Delta smelt modeling is challenged by the lack of wild Delta smelt populations for calibrating and testing mechanistic life-cycle models. This situation reduces the value and future of mechanistic modeling for guiding Delta smelt management actions, unless wild Delta smelt populations recover at least somewhat. It seems important to aggressively develop life-cycle and ecological models for other desired Delta fishes, so these models can become insightful enough to guide management and policy actions before fish populations decline so far that the models can no longer be tested and updated for changing conditions with new field population data.

Few species life-cycle and ecological models for the Delta are likely to be accurate enough to firmly guide Delta ecosystem management for several years, but they are important today for firming up, exploring, and tentatively testing ideas and trade-offs for Delta management. They are also an essential platform for coordinating and bringing together scientific activities and results. Without an integrative framework and empowered leadership for bringing science together with evolving management and policy contexts, most of the Delta monitoring work will offer only meager insights.

The Central Valley's ecosystems and water management system face unprecedented changes in climate (higher temperatures, sea level, and storm frequency and intensity), invasive species (e.g., the Golden mussel), and economic and demographic pressures (see Appendix A). Other regions, such as the Great Lakes, are struggling with similar ecological disruptions (Egan, 2017). Tools for both strategic and tactical decisions for the Central Valley (and California) are highly fragmented and mostly ad hoc in their development and testing. Particularly for ecological aspects of these systems, the collection of data and development and use of models are rarely organized for longer-term decisions that have only been (and can mostly only be) vaguely defined.

A suite of numerical models is available for long-term operations of the CVP and SWP, generally using a sequence of hydrologic, operations, hydrodynamics, water quality and fisheries analyses. These linked modeling analyses provide an integrated assessment of how CVP and SWP operations affect Delta resources such as water supply, surface water, groundwater, and aquatic ecosystems. Figure D-1 below is a linkage schematic of models used for this purpose, with the model in each box providing input information to the subsequent models for the Shasta Coldwater Pool Management Action, the OMR Flow Management Action, and the Summer-Fall Habitat Action. The figure clearly highlights the central role of CalSim3 currently in simulating the long-term operation of CVP and SWP facilities. Water agencies have freedom to select models at their discretion for assessments. However, for Biological Opinion-related work, models require USFWS and NMFS approval.

Only some of the models shown in Figure D-1 are described in detail in this appendix. First, previous chapters describe several of the numerical models of physical processes that are the subject of conclusions and recommendations, including CalSim, Delta Simulation Model II (DSM2), Semi-implicit Cross-scale Hydroscience Integrated System Model (SCHISM), and UnTRIM. Second, a table of the fish

life-cycle models relevant to the three actions reviewed in this report is provided here. Finally, more detailed descriptions of the biological models and tools relevant to Shasta coldwater pool management are provided than were found in Chapter 2.

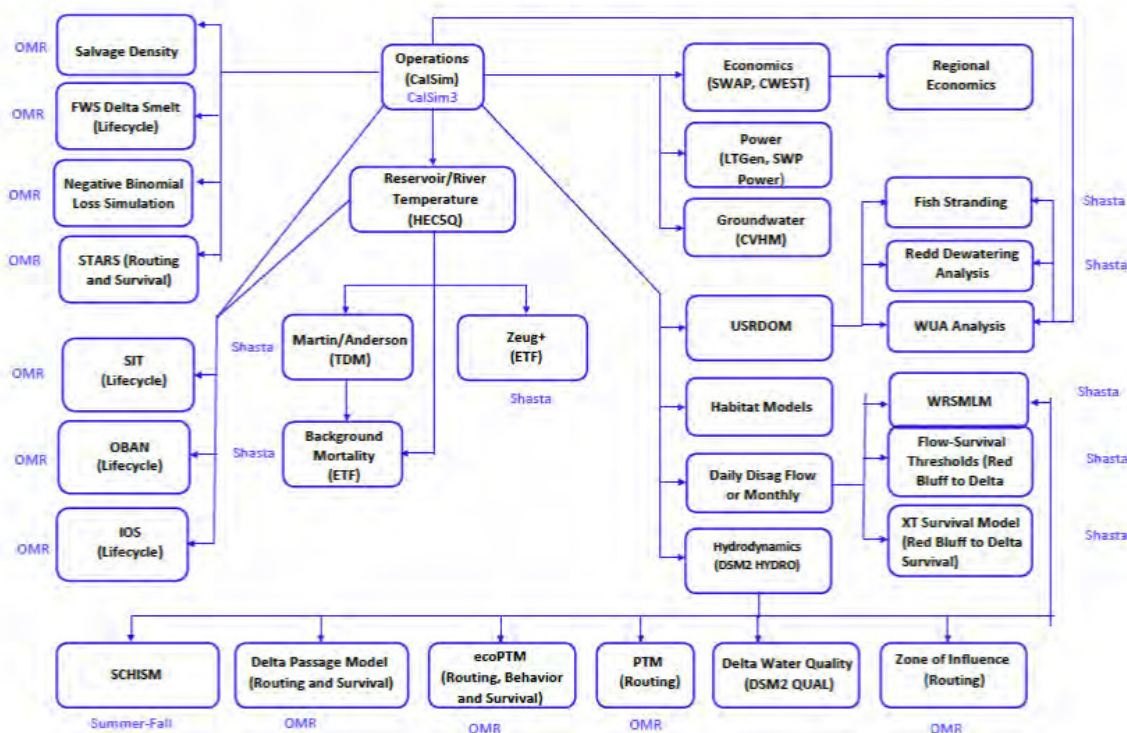


FIGURE D-1 A schematic of model linkages identified in long-term operations. NOTE: In 2025, HEC-5Q has been replaced by the more comprehensive Water Temperature Modeling Platform (WTMP) which utilizes a combination of CE-QUAL-W2 and HEC ResSim. SOURCE: USBR (2024a).

Numerical Models of Physical Processes

Because it is the underpinning of all flow actions in the CVP and SWP, including those being reviewed by this committee, the following section first describes the CalSim3 model to acquaint the reader with its general uses, strengths, and weaknesses. The section below also describes DSM2, SCHISM and UnTRIM because of their frequent use in Delta management.

CalSim3

The backbone of current long-term operations modeling is CalSim3, jointly developed by DWR and USBR as a planning tool (Draper et al., 2004; CalSim3, 2022; see Figure D-2). It has become the key tool for water operations for the Central Valley because it generates estimates of river flows, exports, storage, deliveries, power generation, fish salvage, routing, and many other parameters. All CVP and SWP long-term operational/planning models receive input from CalSim3. It can also be used for short-term operations; for example, Delta boundary flow inflows/exports from CalSim3 are used to drive the hydrodynamic model DSM2-HYDRO, the output of which is used for execution of DSM2-QUAL (water

quality) and DSM2-PTM (particle tracking) models. CalSim3 was the subject of a recent extensive modeling review by the Delta Science Program (Rose et al., 2024).

CalSim3 represents operational decisions using a sequence of single-time-step linear optimizations with constraints and weighted priorities, within the general-purpose simulation environment “Water Resources Integrated Modeling System (WRIMS)” developed by DWR in 2000. CalSim3 simulates long-term operations for multi-year periods, using a monthly time step, over a 100-year time period (e.g., 1921–2021). It assumes constant facilities, land use, water contracts and regulations for a fixed present or future development period. The highest spatial resolution is Demand Units (DUs), identified as areas with uniform water rights, contracts and sources, land use (e.g., agricultural, urban, wetland) and delivery and irrigation efficiencies. These areas usually represent large irrigation districts or groups of local water districts or a metropolitan area. Groups of DUs form a Water Budget Area (WBA), for computations.

Hydrologic inputs to CalSim3 include rim watershed hydrology and valley surface hydrology. The rim hydrology is mainly estimated by snowfall, snowmelt, and precipitation runoff from peripheral mountains (rim inflows), and is preprocessed as a time series of unimpaired runoff entering the rim boundary at the foothills. The valley floor hydrology is simulated using an array of models representing various valley floor hydrologic processes, with input files in the form of a Hydrologic Engineering Center-Data Support System (HEC-HMS) model (Anderson et al., 2002). Input hydrologic models are run external to CalSim3 without dynamic linkages. These models encapsulate the surface runoff from precipitation, applied water demand for rice (AWr), applied water demand for other agricultural crops (AWo), applied water demand for permanent, semi-permanent, and seasonal wetlands (AWw), urban demand, combining indoor and outdoor components, tailwater from irrigated agricultural land, wastewater return flows from wastewater treatment plants, and deep percolation from all land-use classes. The groundwater system and its interaction with surface water is also included (Brush et al., 2013).

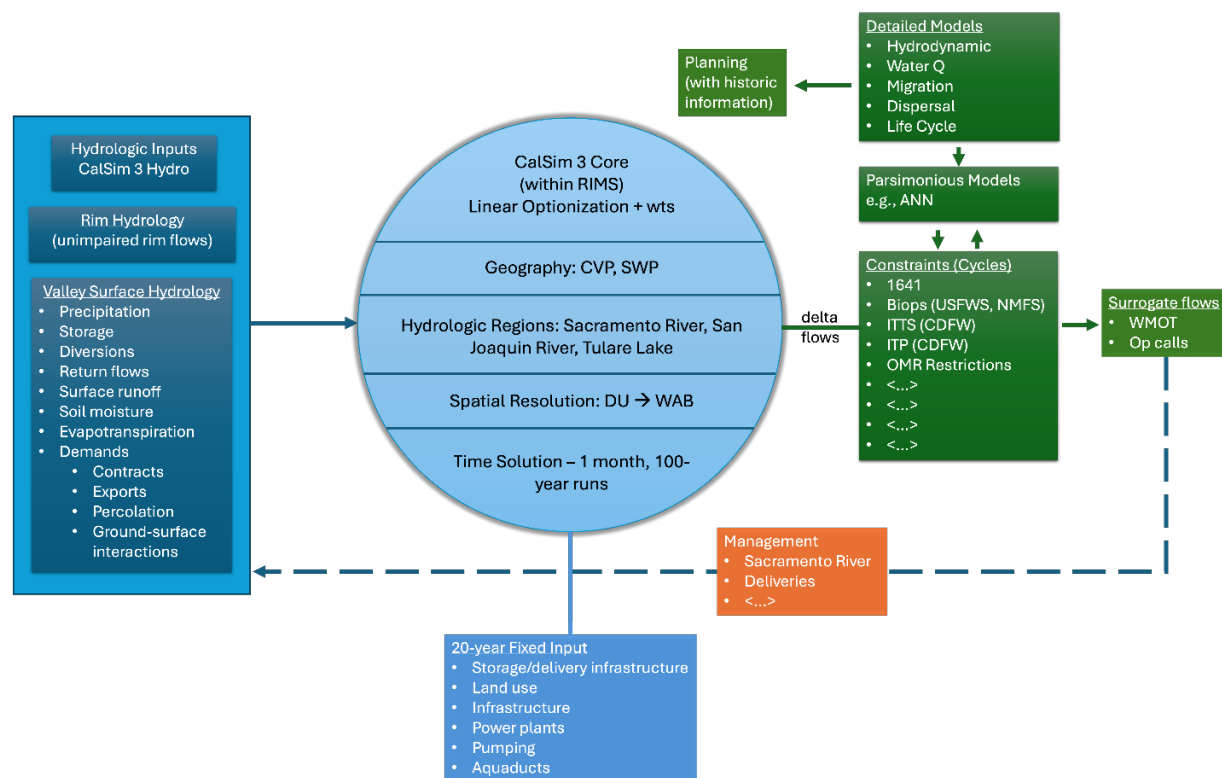


FIGURE D-2 A schematic of CalSim3 based water resources modeling for long-term operations.

CalSim3 is run on demand for Delta flow management, and its coarse monthly time resolution enables model execution in about three to four hours for 100 years. CalSim3 output is flow at DU spatial scales, so higher resolution information for finer time and geographic scales needs suitable downscaling for many water quality, fish and ecological purposes. To meet salinity and X2 standards for the Delta, CalSim3 relies on DSM2 model simulations of water quality and water quality standards. However, DSM2 is too computationally expensive for long-term planning runs (a run takes 6-8 hours). Therefore, CalSim3 uses simplified flow-salinity relationships (based on more parsimonious models, described below) to calculate flows needed to meet a particular water quality standard.

Artificial neural networks (ANN) (Anderson, 2004; Sandhu et al., 1999; Wilbur and Munevar, 2001) are routinely employed within CalSim3, trained using data from offline DSM2 simulations, that translate salinity into flow equivalents (Jayasundara et al., 2020). These ANNs, are surrogate models for DSM2 to represent the impact of operations on salinity standards and X2. They simulate salinity based on seven input variables in the Delta, including water control gate operations, water exports, tidal stage and flow, and salinity boundaries, and has been trained a priori for bulk flow-salinity relationships using an ensemble of DSM2 simulations. The 12 regulatory salinity control stations are Emmaton, Jersey Point, Collinsville, Rock Slough, Antioch, Mallard Island, Old River at Highway 4, Martinez, Middle River Intake, Victoria Intake, CVP Intake, and Clifton Court Forebay Intake, and currently the first four are calculated/used for decision making, for which the required CalSim3 runtimes are practicable. Variants of ANNs (not yet implemented in CalSim3) are available, such as those of Qi et al. (2021, 2022) that simultaneously predict salinity at all 12 regulatory water quality monitoring stations as well as the model developed by Namadi et al. (2023) for estimating ion constituents based on salinity.

For a given (monthly) time step, submodels are run to ensure that regulatory constraints are met (e.g., Water Rights Decisions D-1422, D-1616, D-1641, biological opinions, OMR flow surrogates). These submodels are discussed in greater detail in Chapter 3 under Modeling for the OMR Flow Management Action.

DSM2

DSM2 (CDWR-DSM2, 2019) is a relatively coarse shallow-water one-dimensional (1-D) model of Delta hydrodynamics (DSM2-HYDRO) with extensions for water quality (DSM2-QUAL) and particle tracking (DSM2-PTM). The basic model is typically run with a 15-minute time step. The use of DSM2 in OMR flow management is described in greater detail in Chapter 3. Figure D-3 shows the DSM model grid.

Sridharan et al. (2018) describe and evaluate the accuracy of DSM2. Not surprisingly, modeling of junction flow splits, tidal phasing, and particle tracking tend to be faster but less accurate with DSM2 compared with the more detailed SCHISM modeling.

SCHISM

SCHISM is a three-dimensional hydrodynamic and water quality model developed by DWR to represent detailed water level, flow, and water quality responses to tides, inflows, wind, and atmospheric pressure in the Delta. SCHISM is the predominant model used by CDWR. It runs at fine spatial and temporal scales (over more than 300,000 spatial elements¹ with 90-second time steps) to estimate local water elevation, velocity, and water quality effects in a tidal environment with numerous water and constituent inputs and outputs. Its long run times preclude its use for long-term simulations, but it is commonly used for policy and planning evaluations, as well as for providing physics-based water

¹ See <https://resources.ca.gov/-/media/DWR-Website/Web-Pages/Programs/State-Water-Project/Operations-And-Maintenance/Files/Bay-Delta/Monitoring-Special-Study/MSS-Plan/Attachment-3---SCHISM-3D-Hydrodynamic-and-Water-Quality-Modeling-Work-Plan.pdf>.

elevation, velocity, and salinity results that can then be used to calibrate simpler models (such as DSM2) for highly altered conditions such as sea-level rise or major infrastructure changes. The SCHISM model of the Delta that can be supplemented with additional water quality, biological, and ecosystem models to provide additional results for short representative time periods (e.g., Wang et al., 2020), particularly using particle tracking methods. Indeed, it is one of a variety of other two and three-dimensional models of the Delta have been developed and used by consultants and researchers (MacWilliams et al., 2016). In general, these models have greatly enhanced our ability to understand tidal effects on the physics, water quality, and ecological processes of the Delta.

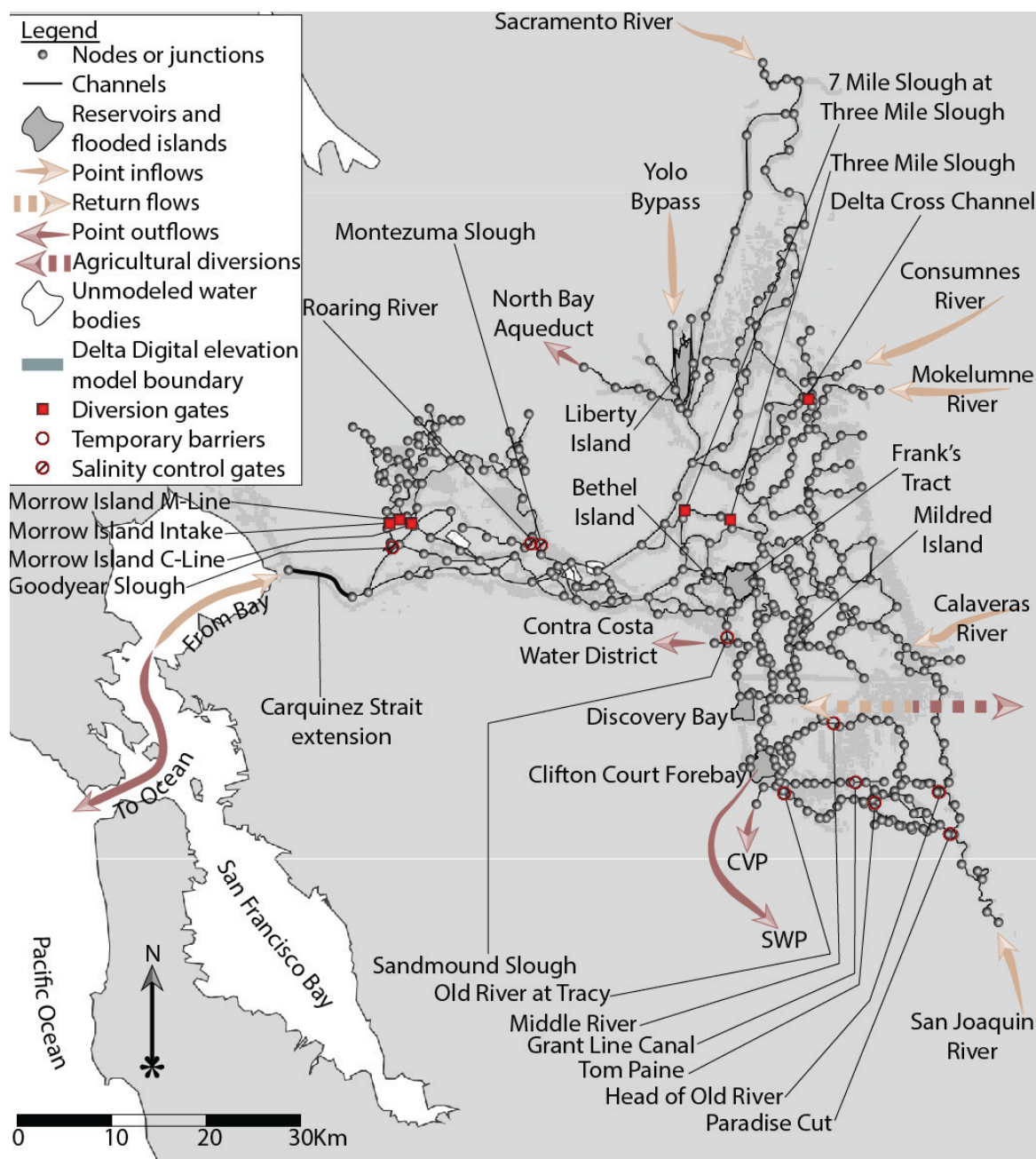


FIGURE D-3 DSM2 model grid.

SOURCE: SOURCE: Sridharan et al. (2018).

UnTRIM

UnTRIM is a hydrodynamic model based on three-dimensional shallow water equations as well as transport equations, adapted for Bay-Delta boundary conditions. It is used to test hypotheses and evaluate impacts of varying management actions, climate scenarios, and hydrology. The model provides predictions of water level, tidal flows, current speed, and salinity. Use of an unstructured mesh grid at varying resolutions allows for individual cells to be wetted and dried in both horizontal and vertical directions by solving Navier-Stokes equations in the horizontal plane. Varying grid size allows for flexibility in a single model: localized model predictions can be made while still incorporating estuary-wide hydrodynamics. The model incorporates high-resolution bathymetric data varying from 10-meter to 90-meter resolution within different Bay regions (e.g., San Pablo Bay derived from 30-meter, Suisun Bay derived from 10-meter). Calibration includes water level, flow, and salinity observations from the San Francisco Bay and Delta (Casulli and Zanolli, 2002; MacWilliams et al., 2015). Model calibration and validation show that UnTRIM provides accurate predictions of flow, stage, and salinity (USBR, 2024c).

Water Temperature Modeling Platform (WTMP)

The WTMP² is a major initiative by USBR to establish a community model that informs water temperature management through cascades of reservoirs and the intervening river reaches. In 2025, WTMP will replace HEC-5Q and comprises a new data management system, the CE-QUAL-W2 and HEC-ResSim models. The Shasta coldwater pool management action will use the WTMP. This suite of models will be available through the USBR and the intent is to enable a community of interested modelers to be established that can access and use the tool. USBR plans training opportunities with future developments being guided by USBR and this modeling community. The model platform has been designed to be accessible and transparent but the code is not open-source. HEC-ResSim was under development at the time of writing this report with constructive preliminary independent peer reviews of both the WTMP and HEC-ResSim being completed by the Delta Science Program in 2023 and 2025. The WTMP is expected to go live in late 2025.

Fish Life-Cycle Models

A life cycle is the series of stages in form and functional activity through which an organism passes between successive recurrences of a specified primary stage. It represents various developmental stages that occur during an organism's lifetime including reproduction, thus creating the cycle. Different stages can include survivorship and growth and potentially evolutionary aspects.

A life cycle model is an attempt to conceptualize subjectively or quantitatively the life cycle of an organism. Illustrated figures, such as Figure D-4, are often used to provide conceptual visual frameworks for discussion, but quantitative models can also be built, and these can come in various forms and different degrees of complexity. Hendrix et al. (2014) indicates that such quantitative life cycle models for fish can often be referred to age-, size- or stage-structured models. Such a definition includes the quantitative population dynamics models used for estimating fish abundance for commercial fisheries using catch landings and catch per unit effort indices. Examples include assessments for species such as pollock, cod, herring and various flatfish. However, for anadromous fish such as salmon, sturgeon, and some smelt species, the riparian or estuarine elements are often highlighted separately from the oceanic life stages to appropriately characterize differences in how survivorship occurs and how strongly various anthropogenic influences transpire. These anthropogenic influences include changes to the landscape, climate change, and harvest and, more recently for the species in consideration here, influences occurring

² See <https://www.usbr.gov/mp/bdo/cvp-wtmp.html>.

through population supplementation efforts. The breakout between rearing stages in riparian and estuarine habitats and the adult oceanic stages also represent differences in temporal and spatial scales as well as life-history stage.

The life-cycle models listed in Table D-2 for some of the listed species are simulation models as opposed to estimation models such as those described above for stock assessment. This means that input parameters for processes such as survivorship, growth, movement, and reproductive rates as well as abiotic environmental factors such as temperature and habitat preferences are needed to run the model. Although several of the papers cited in Table D-2 indicate gaps in this information, additional information has been collected over time and the life-cycle models have grown in sophistication.

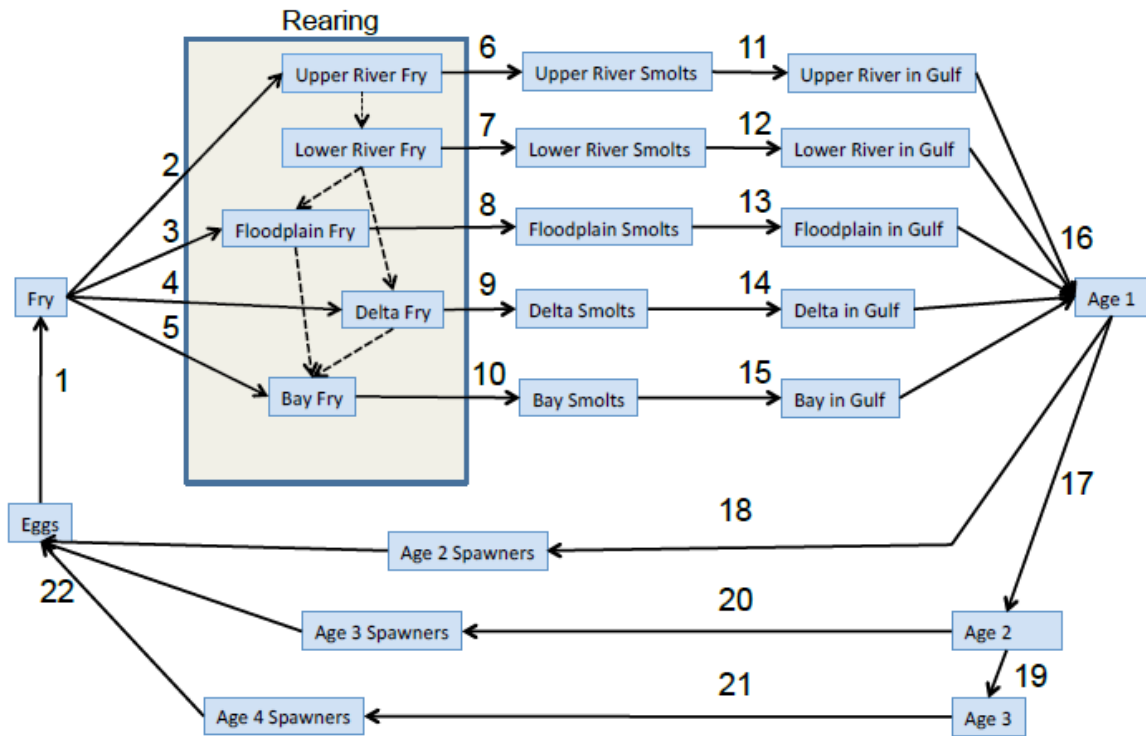


Figure 4. Central Valley Chinook transition stages. Each number represents a transition equation through which we can compute the survival probability of Chinook salmon moving from one life stage in a particular geographic area to another life stage in another geographic area.

FIGURE D-4 Winter-run life-cycle model.
SOURCE: Hendrix et al. (2019).

Other Models and Tools in Support of Coldwater Pool Management

Redd Dewatering Tools

Redd dewatering tools simulate the interaction between river stage and the spatial distribution of salmon redds to assess the risk that developing eggs become exposed during flow recession (USBR, 2024b). These tools help evaluate trade-offs between early-season flow stability and coldwater pool conservation for later use. Although conceptually straightforward, they are sensitive to the resolution of topographic data, accuracy of stage-discharge relationships, and the timing and location of spawning. The primary approach uses stage-discharge relationships developed by the U.S. Fish and Wildlife Service for

key spawning reaches in the upper Sacramento River. Redds mapped through ground and aerial surveys are assigned to elevation bands based on high-resolution topographic and bathymetric data. Projected river stages under different flow scenarios—modeled with HEC-RAS—identify redds at risk of dewatering during drawdown. This knowledge informs operational decisions on ramping rates, fall flow targets, and stabilization periods in the early spawning season (USBR, 2024b).

While operationally useful, these tools have several limitations. They assume that redd elevation is fixed and accurately mapped, yet ground surveys may be incomplete, and aerial surveys can miss or misclassify redds in complex habitats. Elevation data often lack the vertical precision needed to capture biologically meaningful inundation thresholds. Dewatering is typically treated categorically (CDFW, 2014; USFWS, 2006) or modeled as a binary outcome (either inundated or not, USBR 2024b), ignoring sublethal risks such as thermal exposure, partial drying, or behavioral avoidance by spawners associated with hydrological gradients (Dudley et al., 2022). Most tools also assume static stage-discharge relationships, which may shift due to sedimentation, bed mobility, or vegetation growth. These simplifications limit predictive accuracy in dynamic channels, especially in low-flow years when small discharge changes cause large shifts in wetted area (Gosselin and Beer, 2024). Despite these constraints, redd dewatering models remain a valuable component of Shasta operations planning. Their outputs are regularly used alongside temperature forecasts and spawning surveys to assess risks to early-incubating eggs, especially when considering flow reductions after spawning onset (USBR, 2024b).

TABLE D-2 Select Quantitative Biological Models Used in the Long-term Operations of the CVP and SWP

Citation	Model Type	Fish Species
Newman, 2003	Bayesian nonlinear hierarchical model	Winter-run Chinook
Lindley et al., 2007	Quantitative extinction model	Spring-run and Winter-run Chinook, Steelhead
Crozier et al., 2008	Stochastic, density-dependent life-cycle model	Spring-run Chinook
Maunder and Deriso, 2011	State-space multistage life cycle model	Delta smelt
Zeug et al., 2012	Stochastic life-cycle simulation model	Winter-run Chinook
Rose et al., 2013a,b	Individual-based population model	Delta smelt
Hendrix et al., 2014, 2019	Winter-Run Life-Cycle Model, a stage structured, stochastic model	Winter-run Chinook
Johnson et al., 2017	Uses same life-stage-dependent conceptual models as Windell	Winter-run Chinook
Windell et al., 2017	SAIL effort that looked at conceptual models	Winter-run Chinook, green and white sturgeon
Castillo, 2019	Community matrix model	Delta smelt
Cordoleani et al., 2020	Spatially explicit stage-structured model (similar to Windell and Hendrix)	Spring-run Chinook
Polansky et al., 2021	Nonlinear state-space model	Delta smelt
Chen et al., 2023	Stage-structured model	Winter-run Chinook

Juvenile Stranding Tools

Juvenile stranding tools estimate the likelihood that outmigrating Chinook salmon become trapped in disconnected pools or side channels following rapid declines in river flow. Risk curves developed by the USFWS (2006) are used to evaluate the risk of stranding to the rate and magnitude of stage decline associated with operational changes such as pulse flow recession or hydrograph drawdown (USBR, 2024b). In most cases, these tools are implemented as categorical or threshold-based tools to

guide operational decision-making. These tools are most applicable during periods of high flow variability—such as storm events or managed pulses—when the margin between accessible and isolated habitat changes rapidly.

Because the tools are based on empirical observations, they are effective in identifying high-risk discharge scenarios. However, the tools have several constraints. They do not simulate fish behavior or spatial habitat dynamics mechanistically. For example, they cannot account for localized variations in channel complexity, substrate permeability, or hydraulic roughness that influence whether stranding occurs. Nor do they differentiate between the risks faced by fry versus smolts, which differ in mobility and habitat selection. Another limitation is the static nature of the risk curves. Stranding risk is not necessarily fixed across years, because it can be influenced by antecedent flow patterns, sediment deposition, riparian vegetation encroachment, and changing fish distributions.

Floodplain Inundation and Habitat Models

Floodplain inundation and rearing habitat models estimate how variations in river discharge regulate access to off-channel habitats that support juvenile salmon growth and survival. These habitats offer increased foraging opportunities, thermal buffering, and predator refuge, and are particularly important for early life stages. Inundation models are used as a tool to identify the timing, duration, and spatial extent of floodplain access under different flow scenarios. Modeling typically relies on HEC-RAS in combination with digital elevation models and hydrologic time series from CalSim 2 or CalSim 3 (USBR, 2024a). These models simulate the timing and extent of overbank flow and water surface elevations across various floodplain areas (e.g., Yolo and Sutter bypasses).

These models support scenario comparisons across water year types, helping quantify the biological benefits of proposed spring flow pulses or increased baseflows. For example, model outputs are used to estimate the number of acres inundated during juvenile outmigration windows and the duration of access to productive habitats (Yarnell et al., 2012). This knowledge enables managers to evaluate the trade-offs between flow magnitude and rearing opportunity, and to design pulse events that align with peak rearing periods or life stage transitions. Empirical validation is supported by remote sensing, aerial imagery, and field-deployed temperature and velocity loggers. Validation data are often limited in spatial and temporal coverage, however, and may not fully capture intra-annual variation in habitat accessibility or quality.

These models have substantive limitations. Most assume static topography and land cover, even though sediment deposition, vegetation encroachment, and infrastructure changes can alter floodplain hydrodynamics over time (Jeffres et al., 2008). Most models treat floodplain habitat as a binary (inundated or not), with limited ability to account for variation in food availability, predator pressure, or connectivity to mainstem channels. Moreover, most simulations do not dynamically model juvenile fish behavior, movement, or bioenergetics. Empirical evidence that floodplain benefits to juvenile salmon growth diminish when inundation is shorter or less extensive (Sommer et al., 2001) suggest that models may overestimate habitat value when access is intermittent or when thermal or predation conditions are suboptimal.

Despite their limitations, these models are a core component of seasonal flow planning and are especially important in wet and above-normal years when larger volumes of water are available for managed inundation. They are also used to support justification for spring pulse flows under habitat-based objectives in Endangered Species Act (ESA) consultations and flow standard evaluations. Continued refinement of floodplain modeling is focused on coupling hydrodynamics with ecological response models that include growth, survival, or condition factors. There is also growing interest in integrating these models with temperature-dependent mortality or life cycle models to improve cumulative impact assessment under different operational regimes.

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Appendix E

Listed Fish Species

This appendix discusses the seven fish species in the California Bay-Delta that are listed under the Endangered Species Act (ESA) or the California Endangered Species Act (CESA; see Appendix C), along with one nonlisted but economically valuable fish. These species include Delta smelt, longfin smelt, Sacramento River winter-run Chinook salmon, Central Valley spring-run Chinook salmon, Central Valley fall run Chinook (currently unlisted), California Central Valley steelhead, the Southern distinct population segment of North American green sturgeon, and white sturgeon (a candidate for listing as of July 2024). For each fish, this chapter briefly describes its life history, monitoring of species and abundance data, conceptual models and quantitative life cycle models for the species, the effect of the Central Valley Project (CVP) and State Water Project (SWP) operations on the species, the role of hatcheries in maintaining the population, and key uncertainties that lead to science needs for the species.

In 2023, the U.S. Bureau of Reclamation (USBR) and the California Department of Water Resources (CDWR) reinitiated ESA Section 7 consultation for the Long-term Operations of the CVP and SWP. As part of that process, USBR prepared an environmental impact statement (including a Biological Assessment for each fish species) to assess how alternative management actions related to the long-term operations of the CVP and SWP would affect a suite of life stage-specific stressors of the ESA-listed species and their critical habitats. Information in this chapter draws largely on the Biological Assessments for six of the listed species (USBR, 2024a,b,c,d,e,f), and the reader is referred to those documents¹ for more detailed information.

DELTA SMELT

The Delta smelt (*Hypomesus transpacificus*) is a small (60–70 millimeter [mm]), silvery-blue fish in the family Osmeridae (distantly related to salmonids). Delta smelt are endemic to the Sacramento-San Joaquin Delta, where they were historically found from the San Pablo Bay upstream into the Central Valley. They are adapted to a broad range of environmental conditions and use a wide variety of Delta habitats to complete their different life stages (reviewed in USBR, 2024a).

The Delta smelt was once considered one of the most abundant fishes in the Delta and as such was considered an indicator of ecosystem health (Bennett, 2005; Skinner, 1962; Sweetnam et al., 2001). However, the conditions of the Delta ecosystem have been altered to such a degree that recruitment (the transitioning of a fish from the juvenile life stage to the mature life stage) of Delta smelt is nearly absent, and Delta smelt are now extremely rare, with zero having been caught in many catch indices in recent years (USBR, 2024a). They may be locally, functionally extinct, meaning that there may be a few individuals still living, but the species is no longer able to produce healthy offspring due to low numbers and is no longer playing a significant role in the ecosystem (e.g., Jørgensen, 2002).

In 1991, the U.S. Fish and Wildlife Service (US FWS) proposed to list the Delta smelt under the ESA as threatened with proposed critical habitat; the threatened listing occurred in 1993 (USFWS, 1993) and the designated critical habitat listing for the species occurred in 1994 (USFWS, 1994). The species was listed as endangered under the California ESA in 2009, although it is still only listed as threatened under the federal ESA.

¹ See https://www.usbr.gov/mp/nepa/nepa_project_details.php?Project_ID=54661.

Life History and Stages

The Delta smelt is primarily an annual species that completes its life cycle in one year, beginning in approximately March to the following March, a window that varies by one to two months (Moyle et al., 2016). Delta smelt has been described as a semi-anadromous species, migrating from brackish low-salinity (1–6 PSU) habitats downstream of the confluence of the Sacramento and San Joaquin Rivers to tidal freshwater habitats in the Delta (see conceptual model in Figure E-1). However, recent analyses have demonstrated substantial variation in life history expression (phenotypes) including a freshwater resident, brackish-water resident, and semi-anadromous fish; of the most recent viable cohorts, the greatest proportion were semi-anadromous (Hobbs et al., 2019). The low-salinity zone, which migrates up- and downstream depending upon Delta water outflow (e.g., Dege and Brown, 2004), has been changing in areal magnitude and physical characteristics such as turbidity, salinity, and temperature, in ways that appear to be to the detriment of Delta smelt (USBR, 2024a).

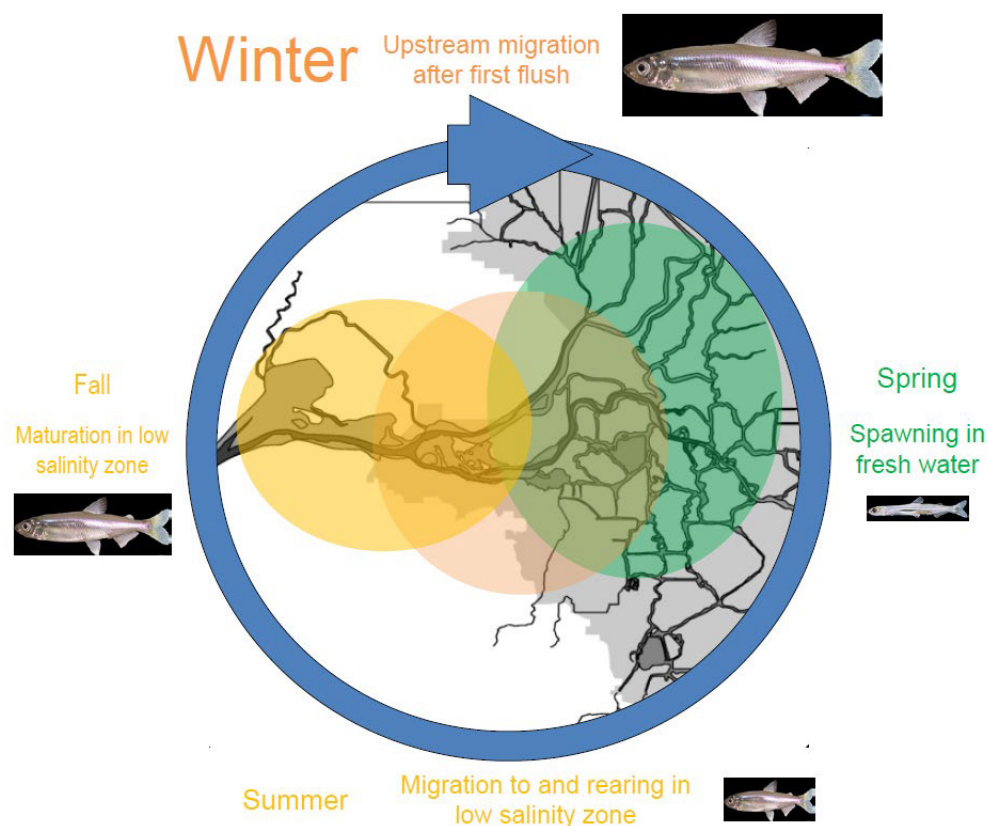


FIGURE E-1 Life history of the Delta smelt and where life stages reside in the Delta.
SOURCE: IEP MAST (2015).

Historically, most Delta smelt spawning was thought to occur in upstream freshwater areas that are tidally influenced backwater sloughs and low-velocity channel edgewater. The eggs are adhesive and are believed to be batch-released over firm substrates or sand.² The adult fish generally migrate upstream in the winter, following the first flush of turbid freshwater from precipitation, to then spawn in the spring.

² See <https://wildlife.ca.gov/Conservation/Fishes/Delta-Smelt>.

The first-flush period preceding the winter migration coincides with increased freshwater availability and elevated pumping rates to fill storage reservoirs for the dry season; thus, migration is a critical life stage during which adult Delta smelt can be entrained into the South Delta and possibly be salvaged at the export facilities.

Delta smelt are primarily planktivores, feeding on small, free-floating (pelagic) crustaceans and also sporadically on insect larvae and even larval fish. Traditionally, the main prey of Delta smelt was a copepod (*Eurytemora affinis*), but also cladocerans and mysid shrimp (*Neomysis mercedis*; reviewed in USBR, 2024a).

Monitoring for Delta Smelt and Abundance Data

Figure E-2 shows the four Delta-wide monitoring networks of the California Department of Fish and Wildlife (CDFW) that measure for Delta smelt (20mm Survey, Summer Trawl, Fall Midwater Trawl, Spring Kodiak Trawl—see Appendix D and Table D-1). Together these survey a wide variety of habitats and regions of the estuary at all times of year, providing a reasonable picture of smelt distribution and abundance. However, the capture efficiencies of the sampling gear involved in the four networks are poorly known and difficult to compare among surveys. With the exception of the Spring Kodiak trawl surveys, none of the sampling programs was specifically designed to capture Delta smelt and they all have limitations. For example, the Fall Midwater Trawl is not ideal because Delta smelt will school and avoid the net. Furthermore, to optimize monitoring of Delta smelt, sampling should be done at night.

In late 2016, the Enhanced Delta Smelt Monitoring (EDSM) program was created by US FWS in response to the low numbers of smelt being observed in the other monitoring networks. Its goals are “to (1) estimate the total abundance of Delta smelt on a weekly basis, (2) estimate their spatial distribution at spatial and temporal scales relevant to management, and (3) provide data that support management decisions and address scientific questions to further understanding of sampling efficiency, drivers of Delta smelt population patterns, and other conservation and management-relevant topics.”³ EDSM is a high-effort, year-round monitoring program that samples randomly selected locations throughout the San Francisco Estuary. This sampling technique provides well-distributed site locations to produce better spatial information. Throughout the year, the program targets three Delta smelt life stages (larvae, juvenile, and adult) using multiple gear types. EDSM reports data in near-real time.

Because Delta smelt are now rare, the effectiveness of the monitoring is limited, to the extent that indices of abundance, rather than abundance estimates or absolute numbers, are used. This approach is necessary because their distribution is patchy and mobile, and Delta smelt may at times occupy regions that are difficult to sample.

Abundance

Until the 1980s, the Delta smelt was an abundant fish in the upper estuary, moving with tides and river flows between the freshwater Delta and brackish Suisun Bay. Because Delta smelt is primarily an annual species, it exhibits highly variable year-to-year abundance, although in general Delta smelt appear to demonstrate higher population viability in very wet and cool conditions, such as those present in 2011 (USBR, 2024a). Delta smelt experienced a major decline in the early 1980s, followed by a substantial but brief increase in the late 1990s. This increase, in turn, was followed by an abrupt decline in the early 2000s, part of the pelagic organism decline (see Box E-1 and Baxter et al., 2008) that has continued to the present.

³ See <https://www.fws.gov/project/enhanced-delta-smelt-monitoring-program>.

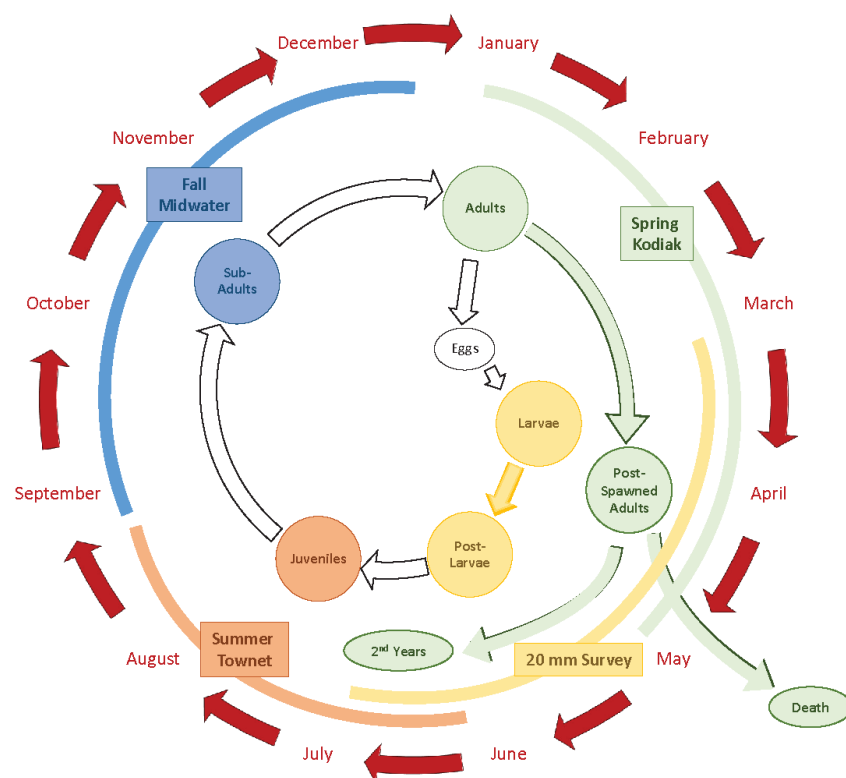


FIGURE E-2 Simplified Delta smelt life stages across the year superimposed on the four large monitoring networks in the Delta.
SOURCE: Moyle et al. (2016).

BOX E-1 Pelagic Organism Decline

The “pelagic organism decline” refers to the pattern in Fall Midwater Trawl abundance indices observed around year 2000 for four major pelagic fishes of the upper estuary (Delta smelt, longfin smelt, striped bass, and threadfin shad). This sharp decline was surprising because these four species vary widely in life histories and estuary use. In 2005, an Interagency Ecology Program team investigated possible causes of the decline (Sommer et al., 2007), including bottom-up controls (food limitation), top-down pressure (predators), trends (previous abundance), and habitat (including water quality variables). The introduction and spread of non-native grazers (*Corbula* and *Potamocorbula*) in the mid-1980s that sequester the pelagic energy, resulting in the loss of rotifers, calanoid copepods, and mysids, seems to have been one major driver of the decline, along with the lack of recovery of pelagic fishes in wet years. According to Sommer et al. (2007): “The grazing effects from *Corbula* are thought to have resulted in a substantial decline in phytoplankton and calanoid copepods, the primary prey of early life stages of pelagic fishes. As a consequence, comparable levels of flow did not generate the expected levels of fish biomass (as indexed by abundance) after 1986. [...] Hence, it appears that the response of these pelagic fishes to environmental conditions has fundamentally changed.”

Potamocorbula clams (*P. amurensis*), a brackish/saltwater clam species, were introduced to Suisun Bay around 1987 and quickly became established throughout Suisun Bay. (They are rarely observed or are at low abundances east of the Sacramento River/San Joaquin River confluence). As a dominant grazer, *P. amurensis* has substantially reduced phytoplankton biomass and copepod nauplii. Corbicula clams (*C. fluminea* and *C. largillierti*) were probably introduced to the San Francisco Estuary in the early 20th century and quickly spread

continued

BOX E-1 continued

throughout the estuary and into the Delta. They are found in both sandy and muddy sediment types. They are simultaneous hermaphrodites, eggs develop into larvae (glochidia) within the brood chambers of females, and after release the glochidia are parasitic on fish gills for weeks to months. Juveniles then detach from fish and develop in the sediments. Because of their rapid reproduction, their effective dispersal, and their efficient filtering of overlying water, the clams have become an aggressive invasive species responsible for a profound shift in biomass within parts of the Delta. Their high filtering rate of particulate organic matter means that they can regulate water clarity, nutrient concentrations, and dynamics within the sediments. Figure E-3 shows the correlation between *Corbula* increases and decreases in zooplankton and chla.

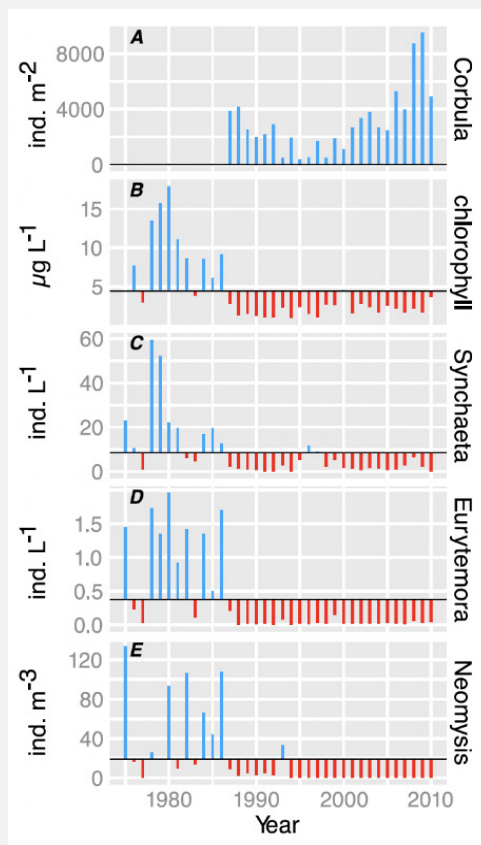


FIGURE E-3 Response of the planktonic food web in Suisan Bay to an introduced clam, *Corbula amurensis*. NOTES: (A) *Corbula* abundance. (B) Phytoplankton biomass as chl-*a* concentration. (C) Density of the rotifer *Synchaeta bicornisa*. (D) Density of the copepod *Eurytemora affinis*. (E) Density of the mysid shrimp *Neomysis mercedis*. The horizontal line in (B)–(E) is the long-term mean. SOURCE: Cloern and Jassby (2012).

In 2022, the Spring Kodiak Trawl abundance index was 1.7, which is the fourth lowest on record (reviewed in USBR, 2024a). The 2023 actual abundance was estimated to be 4,656 adults (95 percent CI: 1178–12730); this is the lowest abundance since that survey began in 2002 (see Figure E-4). Furthermore, all CDFW relative abundance indices show a declining trend since the early 2000s. The extremely low spawning stock of Delta smelt relative to historical numbers suggests that the population is vulnerable to stochastic events and Allee effects (e.g., not finding mates, toxic spills) as well as continued anthropogenic alteration of the Delta including the direct (e.g., entrainment) and indirect (e.g., predation) impacts of CVP and SWP operation (USBR, 2024a).

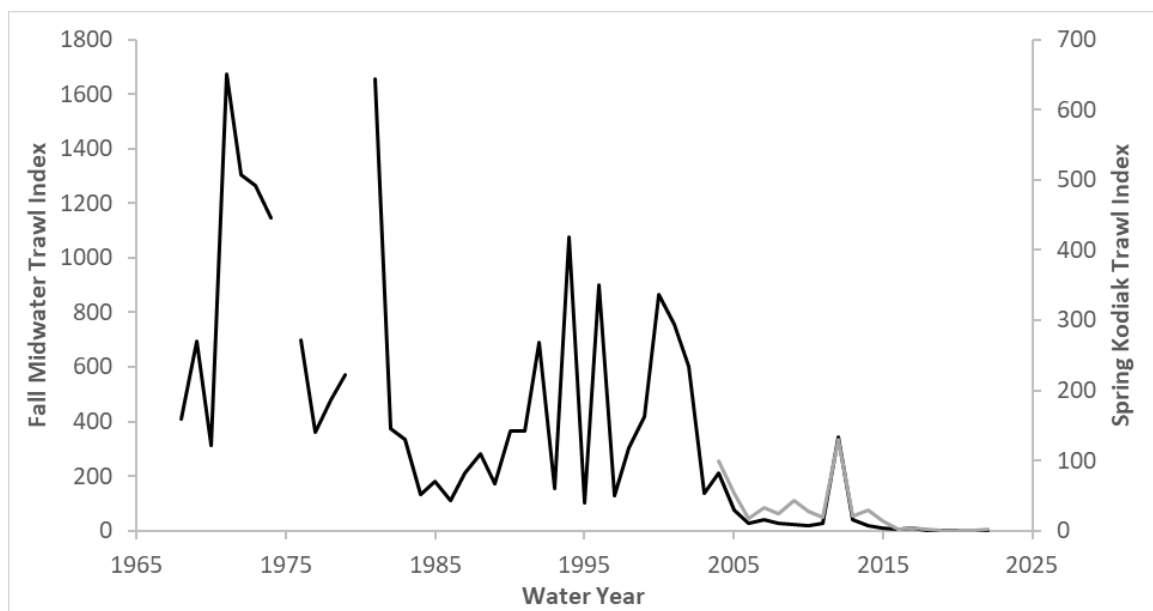


FIGURE E-4 Time series of Delta smelt data from the Fall Midwater Trawl (black line; primary y-axis; water years 1968–2023) and Spring Kodiak Trawl (gray line; secondary y-axis; water years 2004–2022) Abundance Indices for Delta smelt.

SOURCE: USBR (2024a).

Conceptual Models and Quantitative Life-Cycle Models for Delta Smelt

The many conceptual models of the Delta smelt life cycle, and several quantitative life cycle or population dynamics type models, generally tend to agree about the status and limiting factors for Delta smelt. Baxter et al. (2015) updated previous conceptual models with new information to (1) provide decision makers with a practical tool for evaluating difficult trade-offs associated with management and policy decisions; (2) provide scientists with a framework from which they can formulate and evaluate hypotheses using qualitative or quantitative models; and (3) provide the general public with a new way of learning about Delta smelt and their habitat. Baxter et al. (2015) show that while good larval recruitment is essential for setting the stage for a strong year class, increased growth and survival through subsequent life stages are also necessary to achieve and sustain more viable higher population abundances.

Rose et al. (2013a,b) developed a spatially explicit, individual-based population model of Delta smelt constructed for the upper estuary. Predicted and observed spatial distributions in the fall showed moderately good agreement for extremely low- and high-outflow years. A high outflow year (1998) was predicted to have a high population growth rate, and a low outflow year (2001) was predicted to have a lower population growth rate due to entrainment and stage-specific survival rates. Smith et al. (2021) developed a state-space life cycle model that predicts that as outflow declines in the summer, the estimated mortality of juveniles increases, natural mortality in the fall season is negatively associated with turbidity, and natural mortality of late sub-adult and adult stages is negatively associated with food. Similarly, Maunder and Deriso (2011) developed a state-space life cycle model fitted to Delta smelt abundance indices at four life stages and environmental covariate data from the 1995–2015 period. They predicted that the most important factors affecting population dynamics were food abundance, water temperature, predator abundance, and density dependence. Polansky et al. (2021) used nonlinear state-space modeling to predict the probability of survival of different life stages. They predicted that larval survival is influenced by covariates related to abiotic habitat conditions (e.g., temperature, X2 position, outflow, turbidity) and biological factors (e.g., prey availability, competitors, predators); post-larval survival was influenced by outflow and turbidity; juvenile survival was influenced by turbidity and

temperature; and sub-adult survival was influenced by turbidity in the South Delta, Old and Middle River (OMR) flow, and adult striped bass (*Morone saxatilis*).

How Project Operations and Climate Change Affect Delta Smelt

Operation of the CVP and the SWP impact Delta smelt via several often interconnected pathways. There are two types of possible entrainment. First, fish encountering CVP and SWP facilities may be pulled into diversions or the export facilities as they follow net flows (Grimaldo et al., 2009). Second, fish can be routed through specific migratory pathways in the Delta where tidal surfing behaviors (Sommer et al., 2011) draw Delta smelt into areas with increased entrainment risk. Entrainment of adult Delta smelt into the South Delta and the pumping facilities is most likely during the movement of fish from brackish waters to freshwater regions (Grimaldo et al., 2009, 2021; Kimmerer, 2008; Smith et al., 2021). Entrainment into the facilities tends to be highest when OMR flows are negative (i.e., toward the pumps) and when turbidity is high (Smith et al., 2021).

The projects indirectly affect Delta smelt by reducing the size of the low salinity zone due to reductions in freshwater flow through the lower Sacramento River system in summer and fall. In addition, the projects have altered the hydrology of the Sacramento River in ways that negatively affect Delta smelt, such as trapping sediment behind upstream dams, which increases water clarity. Introduced species, such as the overbite clam and the invasive aquatic weed *Egeria densa* that traps sediment, have also increased water quality to the detriment of Delta smelt. In particular, increases in dense submerged aquatic vegetation in terminal sloughs (Moyle et al. 2016; Christman et al., 2023; Smits et al., 2024) pose the dual threat of increasing water clarity and blocking access to Delta smelt spawning habitats.

A third major stressor on Delta smelt attributable to the projects are changes in food quality and quantity, potentially due to spatial and temporal mismatches between low velocity pelagic habitat, nutrients and carbon, primary and secondary production, and the timing and distribution of larval smelt. The Summer-Fall Habitat Action (SFHA) aims to address this mismatch (see Chapter 4). Finally, the Delta smelt is now subject to greater predation, particularly by non-native predators, in slow water habitat created by the CVP and SWP, where Delta smelt may artificially congregate or be concentrated by flow patterns (Brown et al., 2024; Moyle et al., 2016; USBR, 2024a).

These threats and others are summarized in detail by life stage in USBR (2024a) and at an ecosystem level in Brown et al. (2024). One major conclusion is that **all life stages are at risk nearly year-round**.

Based on 30-year averages, temperatures in the Bay-Delta region are getting warmer and drier; however, extremes are also increasing in both directions, in part increasing the duration of dry spells (Appendix A; Anderson, 2024). Because Delta smelt appear to survive best in wet and cool years, an increase in warmer, drier conditions could be expected to further decrease population viability. Komoroske et al. (2014) demonstrated that juvenile tolerance limits are close to what occurs currently such that this life stage may be the most susceptible to future climate warming. Furthermore, they predicted that otherwise suitable habitat for all life stages could be lost if high maximum temperatures, which are currently rare, increase in occurrence. Brown et al. (2013) evaluated potential changes in the position of the low salinity zone, using a habitat suitability index, turbidity, and water temperature based on four 100-year scenarios of climate change. Overall, they found that the availability of suitable habitat would be similar to the worst droughts observed on record. Brown et al. (2016) then demonstrated, using global climate change model output downscaled to the watershed scale and then coupled with ecophysiological metrics, the effects of warming on Delta smelt by integrating localized projected water temperatures with thermal sensitivity metrics (for such things as tolerance, spawning and maturation windows, and sublethal stress thresholds) across life stages. Lethal temperatures occurred under several scenarios, but sublethal effects resulting from chronic stressful temperatures were more common across the estuary. Behavioral avoidance of such stressful temperatures would make a large portion of the potential range of Delta smelt unavailable during the summer and fall. In addition, the Delta smelt

maturation window was shortened by 18–85 days, revealing cumulative effects of stressful summer and fall temperatures with early initiation of spring spawning that may negatively impact fitness. Collectively, it appears that climate change will exacerbate the stress of Project operations on Delta smelt.

Hatchery Potential

Multiple generations of Delta smelt have been successfully reared in captivity in recent years. Beginning in 2021, cultured Delta smelt from the University of California (UC) Davis Fish Culture and Conservation Laboratory have been released into the north Delta. These releases are expected to continue and even increase as production capacity increases (USBR, 2024a). Although these captive fish offer opportunities for supplementation, there are few examples available where supplementing natural populations of fish in the wild from hatchery fish has led to recovery, in the absence of eliminating the limiting factors (e.g., McMillan et al., 2023). If limiting factors can be minimized or eliminated, then the hatchery fish could be critical for restarting the natural population. In addition, the hatchery fish offer an excellent opportunity to treat actions, or components of actions, as natural experiments. As discussed in Chapter 4, tagged hatchery fish could be released in areas targeted for the SFHA. It is unknown how well released hatchery fish thrive and whether or not they reproduce in the wild. Reducing these uncertainties will require many more fish than the hatchery currently produces.

Uncertainties That Complicate Management of Delta Smelt

After updating the Delta smelt conceptual model, Baxter et al. (2015) developed a series of hypotheses for evaluating why Delta smelt abundance increased in 2011. Ongoing research addresses some of these issues, but there have been few definitive conclusions to date. The hypotheses are broken up by life stage and include the following:

1. Adults

- How do hydrology and exports interact to influence adults?
- How does hydrology interact with turbidity to affect predation risk?
- How does predator distribution affect predation risk?
- How does variability in prey availability during winter and spring affect growth and fecundity (eggs per clutch and number of clutches)?

2. Larvae

- Are larvae numbers positively affected by increased duration of the temperature spawning window?
- Will increased food availability result in increased larval abundance and survival?
- Does high abundance of Mississippi Silverside increase predation risk/rate on larval Delta smelt and can this be counteracted by increased turbidity?
- How do hydrology and water exports interact with one another to influence direction of transport and risk of entrainment?

3. Juveniles

- How does high water temperature reduce juvenile growth and survival (bioenergetic stress; reduced distribution)?
- Does the distribution and abundance of striped bass, temperature, and turbidity influence predation risk/rate?
- How are growth and survival affected by food availability?
- Are survival and growth reduced by harmful algal blooms, and if so, how (direct effects such as habitat quality and toxicity or indirect effects such as food quality and quantity)?

LONGFIN SMELT

The longfin smelt (*Spirinchus thaleichthys*) is a small (<150 mm) pelagic fish native to the Bay-Delta but with a widespread distribution in coastal estuaries stretching from San Francisco to Alaska. Within California, it is also found in Humboldt Bay, Russian River, Eel River, and Klamath River and has been caught as far south as Monterey Bay. The San Francisco Bay-Delta population is the southernmost reproductive population and is considered a genetically distinct population.

Longfin smelt have been historically very abundant and were even considered one of the most abundant species in the San Francisco Bay Estuary. There was even a baitfish commercial fishery in the 1970s. Over the past few decades, abundance of this species has progressively declined, with, in particular, a more precipitous decline after the invasion of the overbite clam in 1980. Longfin smelt are part of the pelagic organism decline in the California Delta (see Box E-1); abundances have collapsed to an estimated 1 percent of former levels. This decline resulted in longfin smelt being listed as threatened under the CESA in 2009 (CDFG, 2009a,b). This listing “prohibits unpermitted possession, purchase, sale or take.” USFWS listed the Bay-Delta distinct population segment of longfin smelt as endangered in August 2024,⁴ and habitat protection was afforded in January 2025.⁵

Life History and Stages

A recent detailed literature review of the life history, reproduction, distribution, diet, and habitat requirements (i.e., temperature, salinity, turbidity, diet) of the longfin smelt can be found in the Species Status Assessment for the Bay-Delta published by USFWS (2022, pp. 9-27). The longfin smelt has a widespread distribution throughout the San Francisco Bay and much of the Delta (see Figure E-5). It lives in freshwater, estuarine, and marine habitats at different stages of its life history. It is considered to be an anadromous species that reproduces in fresh or low-salinity water but spends its late juvenile and adult life in estuarine (Bay) or nearshore marine coastal waters. Longfin smelt generally have a two-year lifespan in the Bay-Delta. Adults migrate to fresher waters in the fall and spawn from about November through April with a peak in February (Figure E-6). Adults generally die after spawning.

The exact spawning regions for the longfin smelt are unknown, but smelt are believed to spawn in freshwater or in very low salinity waters in the Delta or San Francisco Bay tributaries. Females produce up to 12,000 eggs. Eggs are adhesive and are believed to be deposited on hard substrate, possibly sand, gravel, or other structures as the species does in other areas. Low salinity regions may be a critical habitat for early life stages of this species. There are ongoing otolith studies to better understand habitat needs for young-of-the-year and to reconstruct growth and salinity history in relation to climate and outflow history at the UC Davis Otolith Geochemistry and Fish Ecology Laboratory (e.g., Hobbs et al., 2010).

When the larvae reach 10-12 mm, they can move up and down in the water column and maintain position relative to the estuarine/freshwater (i.e., X2) interface where zooplankton food production is high. The juvenile stage is reached in about 90 days when the fish are about 20 mm in size. The smelt then spend the late juvenile and adult stage in estuarine or marine coastal waters as far out as the Farallon Islands.

Longfin smelt is generally considered to be a cooler-water species with preferences of 16–18°C (60.8–64.4°F) and spawning temperatures of 7–14.5°C (44.6–58.1°F). They are sensitive to temperatures above 20°C (68°F). The longfin smelt is a pelagic species and feeds largely on zooplankton. Larvae and young juveniles feed mainly on calanoid copepods whereas older juveniles and adults feed mainly on mysids. Longfin smelt are likely prey for Mississippi silversides and striped bass.

⁴ See <https://www.govinfo.gov/content/pkg/FR-2024-07-30/pdf/2024-16380.pdf>.

⁵ See <https://www.govinfo.gov/content/pkg/FR-2025-01-15/pdf/2024-29641.pdf>.

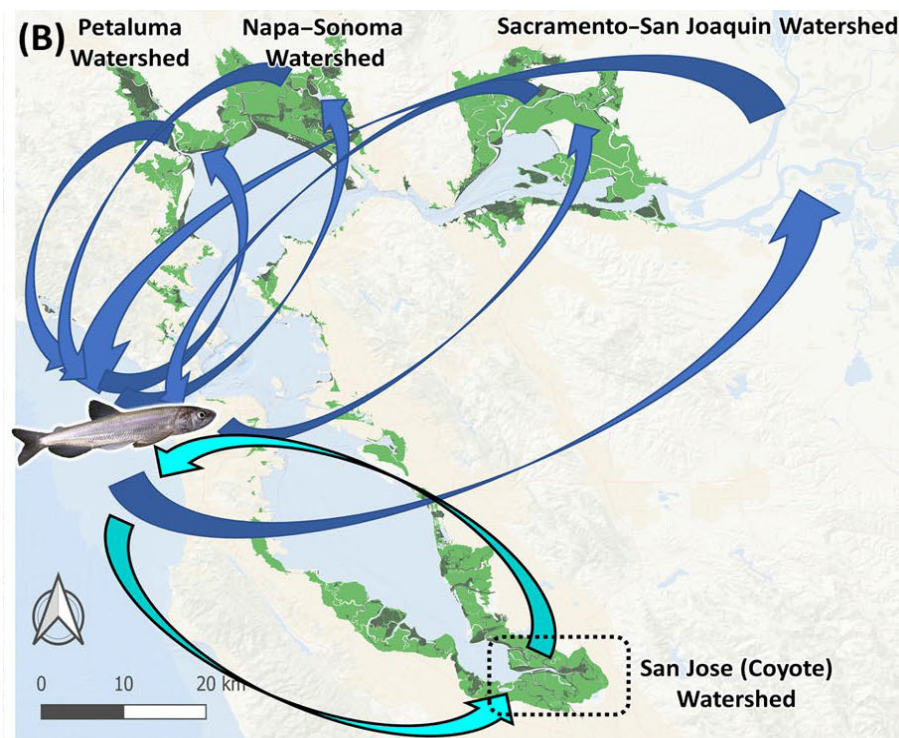


FIGURE E-5 Distribution of longfin smelt.

SOURCE: Lewis et al. (2020).

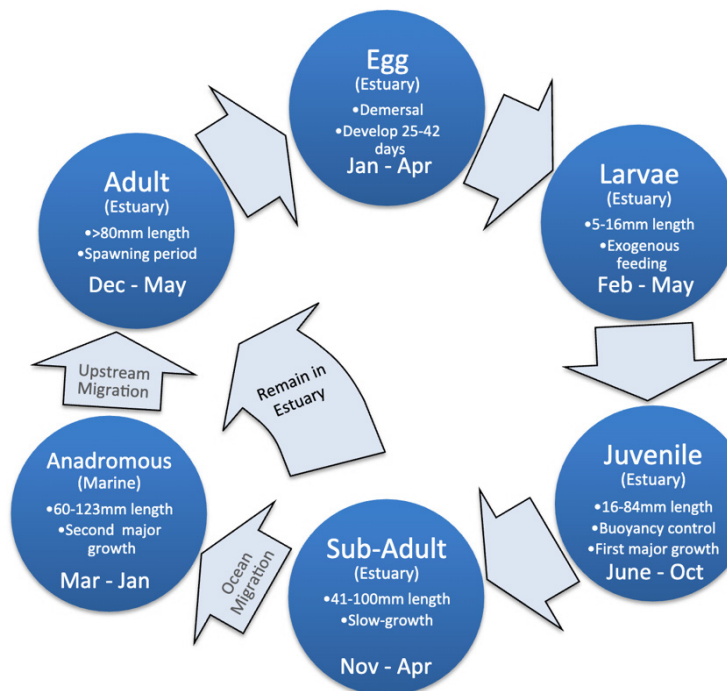


FIGURE E-6 Life cycle of longfin smelt.

SOURCE: Merz et al. (2013) cited as being adapted from the Delta Regional Ecosystem Restoration Implementation Plan Conceptual Models.

Monitoring for Longfin Smelt and Abundance Data

Like Delta smelt, longfin smelt are assessed and caught in most monitoring trawl surveys. New methods to assess larval smelt abundances are being developed to better assess the potential for larval fish entrainment (Mora et al., 2024). Although the abundance of longfin smelt has declined precipitously in recent decades, it is not considered almost functionally extinct like the Delta smelt. Figure E-7 shows longfin smelt data from the Fall Midwater Trawl and the San Francisco Bay Study Midwater Trawl over the past 50 years.

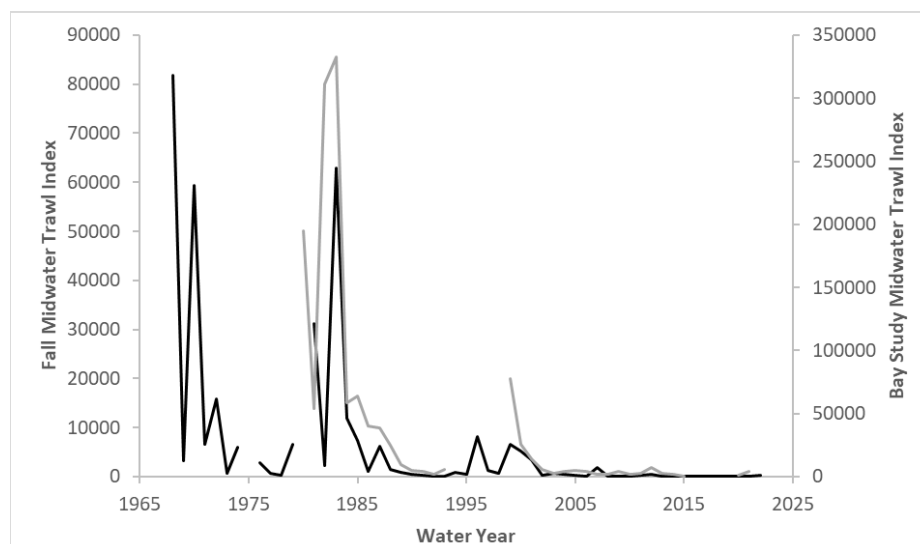


FIGURE E-7 Time series of longfin smelt data from the Fall Midwater Trawl (FMWT; black line; primary y-axis; water years 1959–2022) and Bay Study Midwater Trawl (gray line; secondary y-axis; water years 1995–2021). Data are abundance indices for longfin smelt (all ages). SOURCE: USBR (2024b).

Conceptual Models and Quantitative Life Cycle Models

Given the complex life-history of the longfin smelt, the seasonal changes in distributions and stressors, and the vulnerability of the species to high salinity levels as well as to co-occurring stressors (e.g. higher water temperatures), a mechanistic life cycle model for this species may be warranted (see Maunder et al., 2015 and Nobriga and Rosenfield, 2016 for examples of statistical life cycle models). Developing such a mechanistic model could help to assess population-level impacts of entrainment, better understand the winter/spring flow impacts, and predict impacts of interannual or climatic effects of changing temperatures on survival. A life cycle model is currently under development by the USFWS and partners (Tobias et al., 2024), with completion expected by 2027.

How Project Operations and Climate Change Affect Longfin Smelt

The recent longfin smelt Species Status Assessment (USFWS, 2022, pp 28–42) discusses the following stressors in detail: food limitation, temperature, loss of suitable spawning habitat, predation, contaminants, and entrainment. In general, the widespread distribution of longfin smelt means that different life stages are vulnerable to different drivers during different seasons. Recent declines in abundance are believed to have been caused by reduced freshwater flow during incubation and larval

rearing, because increases in salinity are known to decrease fertilization success (Rahman et al., 2023). Indeed, the relationship between freshwater outflows and longfin smelt juvenile production (and thus total abundance) is well documented (Kimmerer, 2002; Nobriga and Rosenfield, 2016). However, there is also debate about whether the flow-ecology relationship for this species may have weakened over time (Nobriga and Rosenfield, 2016; Rosenfield and Baxter, 2007; Thomson et al., 2010), coinciding with step-changes in the species population size. Active research is underway focusing on this consequential issue, to parse out the effects of the small population on limited recruitment from the effects of freshwater outflow on recruitment,⁶ which may both explain the decrease in longfin smelt production per unit of flow. The unique effects of low-flow conditions on longfin smelt rearing and persistence have also been challenging to quantify, because low-flow years are also typically warmer, and longfin smelt in the Delta are living near their upper limit of 20°C (68°F). Upriver shifts in salinity (e.g., as measured by X2) seem to be the strongest proximal driver of changes in freshwater outflow on longfin smelt recruitment, as suggested by the fact that persistent low-salinity spawning and rearing habitat in high precipitation and outflow years coincide with strong recruitment (Lewis et al., 2020). The Species Status Assessment discusses the potential of climate change and suprasedseasonal droughts to continue to change flow rates and increase salinity, cause sea level rise, and cause warm water temperatures in the fall—stressors that if not counteracted, will likely compound and accelerate the decline of the species.

Hatchery Potential

The longfin smelt has been successfully bred and raised in the laboratory and so has the potential for the creation of hatcheries (e.g., Hung et al., 2024).

Uncertainties That Complicate Management of Longfin Smelt

A detailed science plan for the longfin smelt has been proposed for 2020–2030 (CDWR et al., 2020). This plan includes a critical discussion of the literature with knowns and unknowns including the nuances about the species' lifestyle and ecological role in the Delta. Seven priority science areas were identified in the science plan. For each of these topics, the discussion includes past research on the topic, current needs, management applications, and scientific approaches. The seven priority areas were:

1. Life-cycle modeling
2. Factors affecting abundance, growth, and survival
3. Improved distribution monitoring
4. Improved larval entrainment monitoring
5. Longfin smelt culture
6. Fish migration and movements
7. Spawning and rearing habitats for longfin smelt

Additional science topics were also identified to stimulate research. These topics were as follows:

- Invasive species effects
- Contaminant effects
- Possible role of diseases in longfin smelt population dynamics
- Identification of the food web for longfin smelt
- Development of new tools (e.g., monitoring, health)
- Measurement of vital rates (e.g., growth, survival, reproduction)
- Climate change effects (e.g., hydrology, temperature)

⁶ See <https://caseagrant.ucsd.edu/our-work/research-projects/examining-relationship-between-longfin-smelt-zooplankton-and-flow-san>.

CENTRAL VALLEY CHINOOK SALMON

Chinook salmon (*Oncorhynchus tshawytscha*) are anadromous fish native to the North Pacific Ocean. North American populations of Chinook salmon range from central California to Kotzebue Sound, Alaska, and migrate to spawning areas in streams from near tidewater to 3,200 kilometers (km) upstream (Major et al., 1978, Roni and Quinn, 1995). Adult fish typically range in size from 60 to 90 centimeters (cm) (24 to 36 inches) but may be up to 150 cm (58 inches) in length; they average 4.5 to 22.7 kilograms (kg) (10 to 50 pounds) but may reach 59 kg (130 pounds) (Roni and Quinn, 1995). Central Valley Chinook salmon are anadromous and semelparous (with the exception of cases where introduced or isolated populations are prevented from ocean migration by dams or other human constructed barriers). They are generally considered to be the largest Pacific salmon but exhibit great variation in size and life history traits across individuals and populations including the duration of juvenile residence in freshwater, size at age, age at maturity, ocean distribution, migration time, and spawning time (Healey, 1991; Ricker, 1972; Roni and Quinn, 1995).

Chinook can have extended lifespans, in which some fish spend one to five years in the ocean, reaching age eight. More northerly populations tend to have longer lives. Salmon need suitable freshwater spawning habitat including clean, cool, oxygenated, and sediment-free fresh water for egg development. Chinook use larger sediment (gravel) sizes for spawning compared to other Pacific salmon. Riparian vegetation and woody debris help juvenile salmon by providing cover and maintaining low water temperatures in streams.

California's Central Valley drainages formerly produced immense numbers of Chinook salmon. Four seasonal runs occur in this system—fall, late-fall, winter, and spring runs. Differences in life history timing and spatial distribution enabled the four runs to maximally use the drainages and diverse mosaic of available habitats. Table E-1 provides a summary of the timing ranges for late fall-, fall-, winter-, and spring-run life history stages in the Sacramento and San Joaquin basins, respectively, and Figure E-8 shows the typical stages of the Chinook life cycle.

TABLE E-1 Generalized Life History Timing of Central Valley Chinook Salmon

Run	Migration	Peak migration	Spawning period		Juvenile emergence	Juvenile stream residency (months)	Smolt out-migration
			Total	Peak			
Sacramento River basin							
Late-fall	Oct–Apr	Dec	Early Jan–Apr	Feb–Mar	Apr–Jun	7–13	Nov–May
Winter	Dec–Jul	Mar	Late Apr–early Aug	May–Jun	Jul–Oct	5–10	Nov–May
Spring	Mar–Sep	May–Jun	Late Aug–Oct	mid-Sep	Nov–Mar	3–15	Mar–Jun and Nov–Apr
Fall	Jun–Dec	Sep–Oct	Late Sep–Dec	Oct–Nov	Dec–Mar	1–7 ^a	Mar–Jul
San Joaquin River basin (Tuolumne River)							
Fall ^b	Oct–early Jan	Nov	Late Oct–Jan	Nov	Dec–Apr	1–5 ^a	Mar–Jun

^a At high streamflows, an unknown proportion of fry may emigrate downstream within a few weeks of emergence to rear in the Sacramento–San Joaquin Delta (Rutter 1904a; Kjelson et al. 1982; USFWS 1995; FERC 1996). A small fraction of fall-run juveniles (roughly, <5% of the total number) remain in freshwater for over one summer and emigrate as yearling smolts in the following Nov–Apr period (USFWS 1995).

^b In the San Joaquin River basin, spawning migration and spawning in the tributaries may occur later than in the Sacramento River basin, depending on streamflow conditions (T. J. Ford, Turlock and Modesto Irrigation districts, personal communication). The Tuolumne River fall-run exemplifies a naturally sustained population in the San Joaquin River basin (based on FERC 1996; Ford, unpublished data).

SOURCE: Yoshiyama et al. (2001) based on Fisher (1994), USFWS (1995).

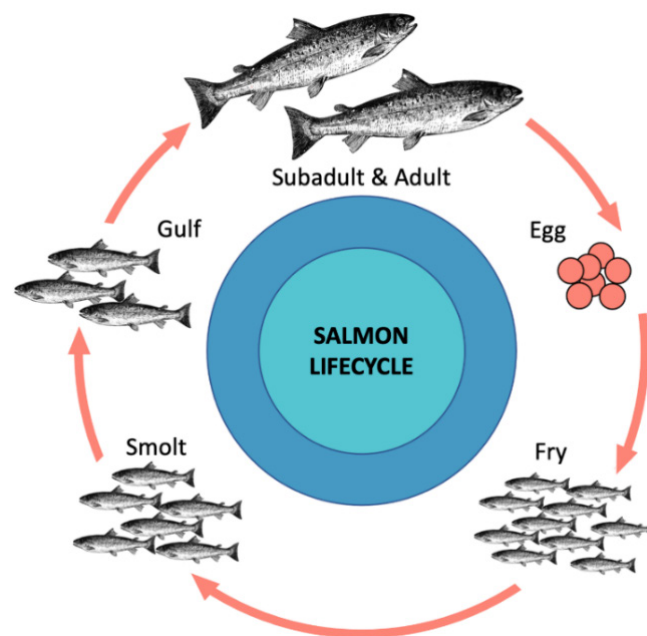


FIGURE E-8 Chinook salmon life cycle.

SOURCE: Winter-run Chinook Salmon Lifecycle model, see <https://oceanview.pfeg.noaa.gov/wrlcm/src/lifestage-plots.html>.

The spatial distribution and diversity in run timings of Central Valley (CV) Chinook salmon historically contributed to the region being one of the richest in the world for Chinook salmon production, conservatively estimated to have reached approximately one to two million spawners annually (Yoshiyama et al., 1998). Sacramento River winter-run Chinook salmon, also known as king salmon, is one of five Evolutionarily Significant Units (ESUs) of Chinook salmon found in California (Moyle, 2002). As of May 16, 1989, the California Fish and Game Commission listed the Sacramento River winter-run Chinook salmon as endangered under the CESA. Subsequently, the Sacramento River winter-run Chinook Salmon ESU was listed as threatened under the federal ESA on August 4, 1989, and then updated to endangered on January 4, 1994⁷.

The historical range of the CV spring-run Chinook salmon ESU encompassed most of the Central Valley and its rivers; from the upper Sacramento River south through the San Joaquin River, down to the Kings River (Lindley et al., 2004). The San Joaquin River and its tributaries historically supported the largest run of spring-run Chinook (Yoshiyama et al., 1998), with an estimated 200,000 to 500,000 adults returning to the San Joaquin River annually before the completion of Friant Dam in 1942 (Yoshiyama et al., 2001). Friant Dam and other dams blocked access to nearly all CV spring-run Chinook salmon spawning habitat in the San Joaquin basin, causing severe population declines. At the time of the 1999 listing, CV spring-run Chinook salmon in the San Joaquin basin were considered extirpated; therefore, only CV spring-run Chinook salmon in the Sacramento River and its tributaries were formally listed as threatened under the ESA (Gutierrez et al., 2024).

Although not a state or federally listed species, fall-run Chinook salmon populations across the Central Valley are severely impacted and vulnerable to extinction (Katz et al., 2012). Over the past two decades, production of fall-run Chinook salmon in the San Joaquin River basin has fallen to very low levels (SEP, 2016) and Sacramento River basin production has exhibited some of the lowest returns in recorded history, resulting in multiple closures of both commercial and recreational fisheries.

⁷ See <https://wildlife.ca.gov/Conservation/Fishes/Chinook-Salmon/Winter-run>.

Life History and Stages

The following provides a generalized overview of CV Chinook salmon life stage needs and associated vulnerabilities with an emphasis on those factors directly or indirectly affected by CVP and SWP operations.

Adult Migration and Spawning

Chinook salmon return from the ocean to spawn in freshwater, notably the rivers of the Central Valley. Adults cease to eat during their spawning migrations and die after spawning. Somatic energy reserves and nutrients are used to complete the upstream journey, attain and defend nest sites, mate, and spawn. Nutrients and energy are also allocated to the production of gametes. Adult migration and gametogenesis are energy-intensive and time sensitive activities. Therefore, delays to migration and spawning caused by barriers, false pathways, or disorientation can result in death, lost opportunities to spawn, or other forms of reduced reproductive success (SEP, 2016).

Chinook salmon typically return to their natal streams to reproduce, a process called homing. A limited percentage of locally adapted wild populations and a larger percentage of hatchery populations also exhibit the opposite behavior (i.e., returning to a non-natal stream to spawn), which is known as straying. Several modes of orientation play a role in successful homing. However, once adult fish enter freshwater, olfactory identification of water emanating from the natal stream is the dominant cue driving salmonid orientation (Healy, 1991; Quinn, 2005). In highly managed watersheds such as those of the Central Valley where large fractions of a river's flow may be diverted at one or more locations along the migration path, homing success can be influenced by the amount of flow from a particular spawning stream that reaches a migrating adult salmon and the ratio of flow from various source streams in a watershed (Marston et al., 2012; SEP, 2016).

Egg Incubation and Emergence

Suitable water temperature is necessary and perhaps most essential for viability of the Chinook salmon egg incubation stage. Indeed, the egg stage has stringent requirements for cold water as an inherent consequence of their large size (for fish eggs). Water temperature and developmental rate are tightly and positively correlated in salmonids (Healey, 1991; Quinn, 2005), such that above certain temperatures, enzymatic function is compromised, resulting in inefficient use of food resources (SEP, 2016). Eggs and alevins incubated at temperatures that are too warm produce smaller fry than they would at optimal temperatures (EPA, 2001, 2003). Hatching and emergence success decrease as temperatures rise above the threshold for optimum development. Direct egg mortality due to elevated temperatures is known to occur in the Central Valley (Williams, 2006) and temperature-related mortality and habitat limitation will likely become an increasingly serious challenge for CV salmonids as climate changes (Lindley et al., 2007).

Juvenile Rearing and Migration

The juvenile rearing and migration life stage encompasses all those developmental stages, life history strategies, behaviors and phenotypic expressions that occur subsequent to emergence and prior to either ocean entry and/or sexual maturation, including fry, parr, smolt, and yearling developmental stages. Generally, optimal conditions for juvenile CV Chinook salmon rearing involve a balance of (a) water quality conditions (e.g., temperature, dissolved oxygen, contaminant concentrations); (b) physical attributes of habitat (water depth, suitable cover, and substrate); (c) extent of available habitat relative to

fish territory size (as a function of fish size, fish density, prey density, and habitat structure); (d) ecosystem and food web conditions (e.g., prey availability and density, predator density, and competition); and (e) activity levels (as a function of the interaction of a, b, c, and d with water velocity)—such that juvenile salmonids can sustain metabolic needs while maximizing growth (Quinn, 2005). However, these conditions vary across a range of sub-habitat types within the riverine landscape used by juvenile salmonids. Various subhabitats may also be used differently by specific life history stages of a given salmonid species (Bradford et al., 2001; Merz et al., 2015; Roper et al., 1994), and by individuals within a life history stage that are developing at different rates (e.g., “young”/small parr may utilize habitats differently than older/larger smolts).

Research from both the Sacramento and San Joaquin basins suggest that fall-run juvenile Chinook salmon experience superior foraging conditions in and prefer off-channel and floodplain rearing habitat to adjacent in-channel habitat, and they exhibit improved growth and survival when rearing on seasonally inundated floodplains (Merz et al., 2015; Sommer et al., 2001a,b, 2005). The interaction of different life-stages and histories with different sub-habitats can additionally reinforce cohort and population-level life history diversity and associated resilience (McClure et al., 2008; Zimmerman et al., 2015). For example, juvenile Chinook salmon rearing on floodplains can experience greater maximum size, diversity in growth, and exposure to environmental pollutants than juvenile salmon reared in the associated river channel (Henery et al., 2010; Jeffres et al., 2008; Sommer et al., 2001a,b, 2005).

CV fall- and spring-run Chinook salmon have also been observed rearing in non-natal tributaries as well as in the Delta (Cordoleani, et al., 2021a; Limm and Marchetti, 2009; Sturrock et al., 2015). However, the extent to which these expressions are a response to limited off-channel rearing habitat in their natal streams and/or were strategies exhibited by a significant portion of the population historically is unknown.

Key Differences in Life Histories of the Runs

Winter-Run Chinook Salmon. Adult winter-run Chinook salmon return from the ocean in the winter and migrate through the Bay-Delta and up the mainstem Sacramento River to reach the upper Sacramento River. Prior to the building of Shasta Dam, winter-run Chinook reached the Pit, McCloud, and upper Sacramento rivers, and Battle Creek, where summer water temperatures were typically 10–15°C (50–59°F), and it was under these conditions that they held and spawned, their eggs incubated, and their young reared. Since the construction of the dams, winter-run migration has ended in the stretch of the Sacramento River below Keswick Dam where adults hold until spawning, followed by egg incubation and fry emergence in the summer. Given their evolution in cold-water spawning grounds, the winter-run Chinook have stringent temperature and dissolved oxygen requirements as shown in Table E-2.

In addition to these temperature and dissolved oxygen requirements, winter-run Chinook salmon require certain water velocities during holding, spawning, and egg incubation (summarized in USBR 2024e), as well as clean loose gravel 0.75–4.0 inches in diameter for successful spawning (NMFS, 2014). The outmigration requirements for fry include streamside habitats containing riparian vegetation and associated substrates that provide aquatic and terrestrial invertebrates for food, predator avoidance cover, and slower water velocities for resting (NMFS, 2014).

Spring-run Chinook Salmon. Spring-run Chinook salmon evolved to take advantage of the geography and hydrology of the California Central Valley and surrounding mountain ranges where melting snow from high elevations provides cold water for adult and juvenile salmon to survive and thrive during the hot Central Valley summers (Fry, 1961). Adult spring-run Chinook salmon leave the Pacific Ocean to begin their upstream migration to natal streams in late January and early February (Yoshiyama et al., 2001) and enter the Sacramento and San Joaquin rivers from March to September, with peak migration during the spring months (Moyle, 2002; Yoshiyama et al., 1998). They enter rivers in a sexually immature state, they then hold in deep, cold freshwater pools for several months to mature, and

then adults spawn from mid-August to early October, with peak spawning occurring in September (Moyle, 2002). Hence, access to cold water habitats during the summer and early fall months is a critical component of spring-run adult holding, spawning, egg incubation, and juvenile rearing life stages (Gutierrez et al., 2024).

TABLE E-2 Temperature Requirements of Winter-run Chinook Salmon by Life Stage

Life Stage	Temperature	Dissolved Oxygen (mg/L)
Adult Migration	37.9°F–68°F (3.3°C–20°C)9, 10, 11	5.0
Spawning Initiation	42.1°F–55°F (5.6°C–12.8°C)10	5.0
Egg/Alevin	42.8°F–56°F (6°C–13.3°C)1, 2, 3,4, 5	5.5
Juvenile Migration	62.6°F–68°F (17°C–20°C)3, 6, 7	5.0
Smolt Migration	55.4°F–60.8°F (13°C–16°C)7, 8	5.0

Sources: Slater 1963; U.S. Fish and Wildlife Service 1999; Myrick and Cech 2004; Bratovich et al. 2012; Martin et al. 2017; Myrick and Cech 2001; Marine and Cech 2004; Clark and Shelbourn 1985; Reiser and Bjornn 1979; McCullough 1999; Goniea et al. 2006.

*Exact endpoints fall somewhere between 53.6°F and 56°F (12°C and 13.6°C), with recommended upper thermal optimum of 53.6°F to 55.9°F (12.0°C–13.3°C)3,4

°C = degrees Celsius; °F = degrees Fahrenheit

SOURCE: USBR (2024e).

Spring-run Chinook salmon have two distinct juvenile life-history strategies that enable them to take advantage of California’s variable climate: (1) the “sub-yearling” life-history strategy in which juveniles rear and then migrate downstream to the ocean within three to eight months of hatching and (2) the “yearling” life-history strategy in which juveniles rear in the river for a more extended 8- to 12-month period prior to migrating to the ocean. The yearling life-history strategy helps to ensure species’ survival across a range of hydrological conditions and water year types (Cordoleani et al., 2021b). Yearling juveniles are typically larger in size than sub-yearling juveniles at the time of outmigration. Cordoleani et al. (2021b) found that spring-run Chinook salmon yearlings comprised roughly 10 percent of juveniles, but approximately 60 percent of returning adults when averaged across years in Mill and Deer Creeks in the Sacramento River basin. The number of returning adults with the yearling juvenile life-history strategy was even higher (77–100 percent) in drought years. Hence, ensuring that habitat conditions are suitable for the expression of the yearling life-history strategy in all water year types is critical for CV spring-run Chinook salmon survival and recovery, particularly in challenging conditions created by climate change and the varying water year types of the California Central Valley (Gutierrez et al., 2024).

Fall-run Chinook Salmon. Fall-run Chinook salmon were historically the most widely distributed of the Central Valley runs, with more than 30 independent populations (Yoshiyama et al., 2001) across the Sacramento and San Joaquin basins, and that continues to be true under current conditions. Indeed, because of the decline in spring-run Chinook salmon, fall-run is now the dominant population supporting the California and Southern Oregon commercial salmon fisheries (Huber and Carlson, 2015).

Like the spring-run Chinook, the fall-run Chinook may include a small fraction of juveniles that over-summer and emigrate as yearlings (Yoshiyama et al., 2001; SEP, 2016). Run timing for fall-run relative to hydrologic conditions and other run timings likely resulted in their occupying and spawning in lower reaches of the CV rivers closer to the valley floor. For this reason, their spawning habitat was less

(although still significantly) impacted by the construction of the rim dams, relative to winter- and spring-run populations.

Monitoring of Chinook and Data on Abundance

A range of monitoring surveys for CV Chinook salmon is targeted at each of the life stages, for each of the run-types, across a broad range of the geographies they occupy. In the Sacramento River system, a significant portion of the monitoring for all run timings is an outgrowth of monitoring to support the conservation of winter-run and is conducted by diverse agencies and entities. A summary of these monitoring efforts is provided in Table E-3. In addition to adult and juvenile monitoring in the Sacramento River, additional monitoring for Chinook salmon occurs via salvage data from the Tracy and Skinner fish collection facilities (discussed in Chapter 3), via seasonal fish assemblage trawls and the Delta Juvenile Fish Monitoring Program (DJFMP) (including the Sacramento, Mossdale, and Chipps Island trawls and beach seines), and in commercial and recreational ocean fisheries via coded wire tag.

In terms of abundance, winter-run Chinook salmon population estimates were as high as 120,000 fish in the 1960s but declined to less than 200 fish by the 1990s (NMFS, 2014). As shown in Figure E-9, during 1970–2021, the highest escapement values were seen in the early 1970s, followed by low values in the early 1990s, increases in the early 2000s, and varying between ~1,000 and ~10,000 individuals since 2007. For context, the “doubling goal” under the Central Valley Project Improvement Act targets 110,000 winter-run Chinook salmon. Since 2001, the majority of winter-run Chinook salmon redds have occurred in the first ten miles downstream of Keswick Dam (USBR, 2024e).

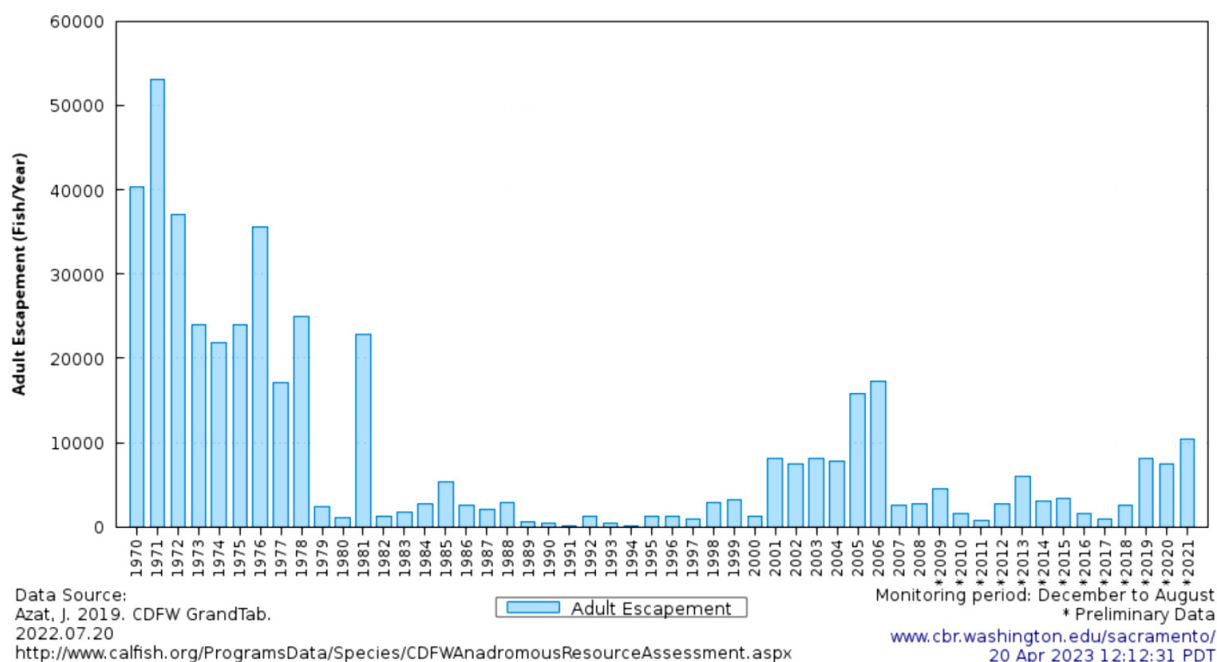


FIGURE E-9 Winter-run Chinook salmon adult annual escapement in the Central Valley, 1970–2021.
SOURCE: USBR (2024e).

TABLE E-3 Summary of Annual Chinook Salmon Monitoring Efforts on the Sacramento River and Tributaries

Run and Life Stage	Action	Location	Frequency	Agency	Notes
WR/FR/LFR – Juveniles	Rotary screw trap	Red Bluff Diversion Dam		USFWS	Used to determine Juvenile Production Estimate (JPE) for all runs except for SR
WR – Juveniles (fry)	Rotary screw trap	McCloud River, Head of reservoir (McCloud River Bridge)	March–December (or as flows permit)	CDFW, Pacific States Marine Fisheries Commission (PSMFC), Winnemem Wintu Tribe	
WR – Juveniles	WR jumpstart monitoring	Battle Creek		USFWS	Coleman National Fish Hatchery
WR – Juveniles	Rotary screw trap	Glenn Colusa Irrigation District (GCID) bypass channel within the Sacramento River near RM 205		CDFW, GCID	GCID recently stopped operating the trap
WR – Juveniles	Livingston Stone fish hatchery (LSFH)	Sacramento River near Redding	December–March	USFWS	200,000–600,000 WR are raised annually at LSFH and released into the river at Caldwell Park in December/January during high flow/turbidity events
WR – Juveniles	Juvenile Salmonid Collection System	McCloud River, Head of reservoir (downstream of Screw Trap)	Mid-August–January	CDWR	
WR – Egg-Fry	Survival monitoring	McCloud River, Ah Di Na campground		UC Davis, Winnemem Wintu Tribe, CDFW	
WR – Adults, Juveniles	Monitoring and relocation (seine)	Sutter and Yolo bypasses and related facilities including Tisdale, Fremont, and Sacramento weirs	Multiple times per year (depending on flow and environmental conditions)	CDFW	Juveniles are identified using length-at-date criteria (sometimes larger juveniles are confirmed with genetic analyses). Adults are identified via genetic analyses.
WR – Adults	Monitoring and relocation (trap)	Wallace Weir Fish Collection Facility located in the Knights Landing Ridge Cut within the Yolo Bypass		CDFW	Adults are identified via genetic analyses.
WR - Adults	Shallow Redd monitoring	Red Bluff Diversion Dam to Keswick	June–November	CDFW	Shallow = less than 2' water depth when first encountered; informs USBR Keswick Dam operations during incubation

Run and Life Stage	Action	Location	Frequency	Agency	Notes
WR - Adults	Livingston Stone fish trap			CDFW and PSMFC	WR are captured, and either spawned or released based on a spawning matrix
WR - Adults	Carcass Survey	Mainstem Sacramento River, Balls Ferry Bridge to Keswick	7 days a week, May–September	CDFW, PSMFC, and USFWS	Population estimates are determined using a Cormack Jolly Seber model.
WR - Adults	Aerial (helicopter) redd survey	Red Bluff Diversion Dam to Keswick Dam	Weekly May–September		Redd surveys provide expansion factor for redds that fall outside of the carcass survey reach
SR/ Steelhead - Adults	Livingston Stone fish trap			CDFW and PSMFC	Adult SR and steelhead captured; spring-run released either into other SR tributaries or back into the river; more recently, some captured unmarked SR held and spawned at LSFH; the eggs from these SR were raised in hatch partner boxes in Clear Creek below Whiskeytown Dam. Adult steelhead are PIT-tagged and released back into the river at Caldwell Park.
FR/LFR/SR - Adults	Shallow Redd monitoring	Mainstem Sacramento	Respective spawning seasons	CDFW	Monitored for potential dewatering; only early SR redds (September) are monitored due to overlap with FR spawning in October
FR/LFR - Adults	Redd survey	Woodson Bridge to Keswick Dam	Bi-weekly October–May		Historically began at Princeton and extended up to Keswick Dam. More recently the starting point moved to Woodson Bridge (Corning) as fewer and fewer redds have been observed in the section below Corning.
FR - Adult	Carcass survey	Mainstem Sacramento River, Balls Ferry Bridge to Keswick	3–5 days a week (FR spawning season)	CDFW and PSMFC	Population estimates are determined using a Cormack Jolly Seber model.
All runs & Steelhead - Juveniles	Rotary screw trap	Three locations upstream of the Tisdale Weir near RM 120	late August/early September to May/June	CDFW	Fish are identified using length-at-date criteria

Run and Life Stage	Action	Location	Frequency	Agency	Notes
All runs & Steelhead - Juveniles	Rotary screw trap	Three locations Knights Landing near RM 88	late August/ early September to May/June	CDFW	Fish are identified using length-at-date criteria
All runs & Steelhead - Juveniles	Rotary screw trap	Three locations near town of Verona and RM 75	October to May/June	CDFW	Fish are identified using length-at-date criteria
All runs & Steelhead - Juveniles	Rotary screw trap	Lower Feather River near RM 17		CDFW	Juvenile WR are consistently captured at this location, assumed to be non-natal rearing. E.g., during January–February 2024, 35 juvenile WR (32 unmarked; 3 marked, based on length-at-date criteria) were captured. WR assumed to have originated from LSFH.
All Runs - Juveniles	Pre- and post-restoration habitat monitoring – Snorkel Surveys	Red Bluff Diversion Dam to Keswick Dam	Year-round, (or when conditions allow)	CDFW, PSMFC, Chico State and Tussing Enterprises	Juveniles are identified using length at date and enumerated as part of snorkel surveys on proposed and completed habitat restoration projects
All Runs - Juveniles	Stranding and rescue surveys	Los Molinos to Keswick Dam (documented stranding sites)	Following flow reductions from Keswick or flood releases	CDFW and PSMFC	Conducted as a component of operations for Keswick; all salmonid species are identified to species and/or run using the length-at-date criteria.

RM = river mile

SOURCE: Table information drawn primarily from Michael Memeo, CDFW Region 1, personal communication, 2025.

Conceptual Models and Quantitative Life Cycle Models

There are two primary life-cycle models for Chinook salmon that are used in the Delta, the Winter-Run Life Cycle Model (WRLCM) (Hendrix et al., 2014, 2019) and the Central Valley Project Improvement Act (CVPIA) decision support model (DSM) (Peterson and Duarte, 2020). Although other models exist, the WRLCM and CVPIA models are perhaps the most widely leveraged for landscape scale population management and planning, for many reasons. Their development was led by the federal agencies overseeing fish management (National Oceanic and Atmospheric Administration's National Marine Fisheries Service [NOAA/NMFS] for the WRLCM and USFWS and USBR for the CVPIA) and offered many engagement opportunities for a diverse suite of stakeholders. Their scope is broad, including the complete species lifecycle and range of habitats and capturing effects from the individual to the population level. And finally, they were designed to provide decision support in critical management areas related to flow allocations (WRLCM) and habitat investments (both the CVPIA DSM and WRLCM).

The WRLCM was briefly discussed in Chapter 2, with a focus on its potential application for the Shasta Coldwater Pool Management Action. Figure D-4 shows the processes included in the model.

USBR and USFWS established the Science Integration Team (SIT) to use structured decision making to identify priorities for Chinook salmon, steelhead, and green and white sturgeon. The SIT is a self-selected technical group of agency staff and stakeholders that employ a collaborative and transparent process to identify, compile, and provide access to appropriate data; develop decision support models consistent with CVPIA fish doubling goals (see Appendix C); and provide input into the development of CVPIA priorities for restoration actions and information needs.

The SIT developed and continues to maintain models to support the development of restoration strategies as a basis for guiding CVPIA investments in CV salmon recovery. The stochastic stage-based CVPIA Chinook model tracks the number of Chinook salmon in four juvenile size classes: small, <42 mm total length; medium, 42–72 mm; large, 72–110 mm; and very large, >110 mm, for both natural and hatchery origin fish (Figure E-10). The model operates on a monthly time step over a simulated 20-year period. Transitions between stages are estimated using sub-models that predict survival, growth, and movement as functions of input parameters that represent conditions in the Bay, Delta, migratory corridors, and natal tributaries. The decision support models are parameterized and updated using empirical data, existing models, analyses of existing data, and a minimal amount of expert opinion. The decision support models for the three Chinook salmon runs have the same general structure but differ with respect to timing and inputs (Peterson and Duarte, 2020).

Beginning in 2021, Reorienting to Recovery (R2R), a non-regulatory, voluntary, collaborative process lead by nongovernmental organizations and water agencies and focused on the application of lifecycle models and structured transparent processes to develop a widely supported pathway to salmon recovery in the Central Valley, started to apply the CVPIA decision support model. In order to explore approaches to achieving salmon recovery that integrated the range of management action categories applicable to salmon (hydrology, habitat, hatcheries and harvest and commonly termed “the 4Hs”), the R2R process assembled a diverse group of CV salmon experts and built out the decision support models, which were used by the CVPIA primarily to contemplate habitat actions and to be able to evaluate combinations of actions integrating all 4Hs. The resulting R2R decision support model is also publicly available.

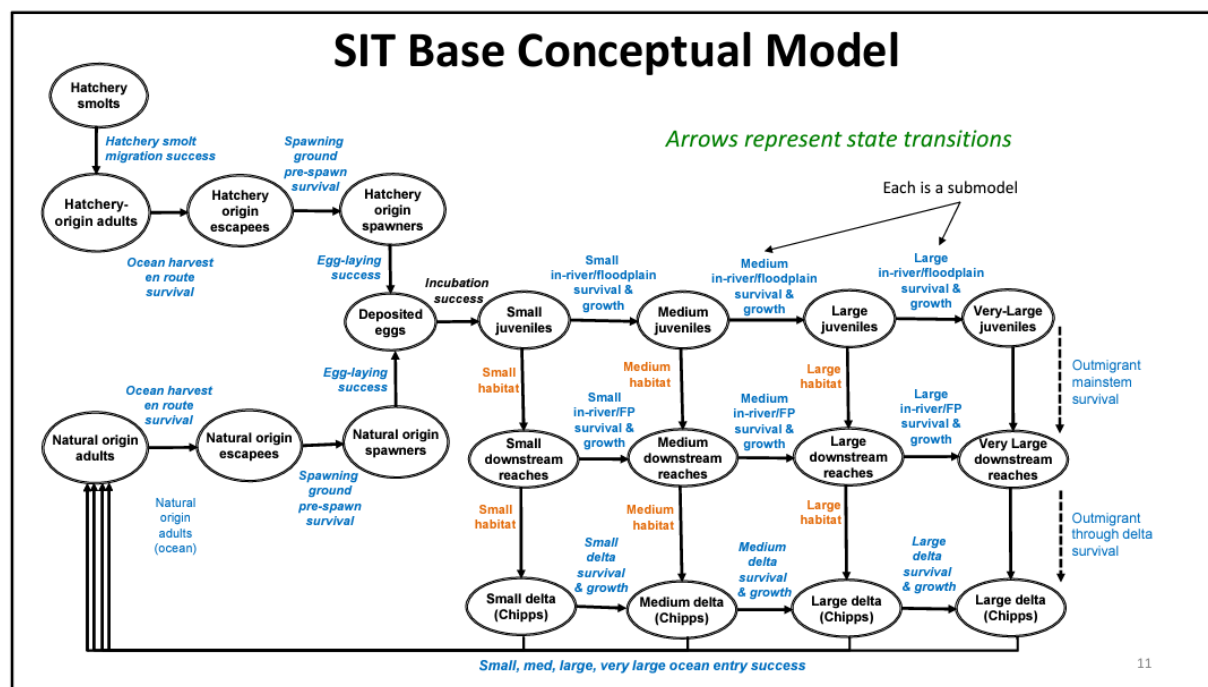


FIGURE E-10 Base conceptual model of CV Chinook transition stages applied in the CVPIA SIT Decision Support Model. NOTE: Each arrow represents a state transition (i.e., a function such as survival or growth). Parameter estimates and sources are in Peterson and Duarte (2020). SOURCE: <https://cvpia.scienceintegrationteam.com/cvpia-sit/resources/documents>.

The existence of three landscape-scale decision support models for winter-run Chinook salmon in part emanates from a collective evolution in management from a more-narrow focus to a more integrative one. Shortly after its development, the WRLCM was viewed primarily as a tool to assess the impact of flow management on winter-run Chinook salmon as it pertained to regulatory compliance and was primarily applied to the evaluation of a range of proposed flow management scenarios. The WRLCM also lacked some of the key parameters (e.g., growth) and relationships (e.g., habitat specific growth and survival and survival to adulthood) that rearing habitat projects were often designed to affect. The CVPIA model, by contrast, was initially designed to provide guidance for CVPIA investments in habitat restoration and enhancement projects with a focus on fall-run Chinook salmon which, though not listed, make up the majority of California's commercial and recreational harvest and are the focus of the CVPIA Salmon Doubling Goal⁸.

Since their initial development, both the CVPIA decision support model and the WRLCM have been expanded and refined, resulting in diversification (and convergence) in the range of decision support applications that they are positioned to inform. For example, the WRLCM has been expanded to include effects of habitat on fish growth and size, and CVPIA decision support models have been developed for winter-run and spring-run Chinook. The R2R decision support model expanded the CVPIA decision support model to include parameters and relationships enabling the integrated evaluation not only of hydraulic and habitat related actions, but also of hatchery and harvest management actions as well (i.e., "the 4Hs"). The R2R process also applies both the WRLCM and the R2R decision support models in order to compare and contrast performance of the same suite of actions in the two different models.

⁸ See <https://www.fws.gov/project/CVPIA>.

How Project Operations and Climate Change Affect CV Chinook Salmon

The geographic and temporal diversity and extent of its freshwater habitat use has resulted in CV Chinook salmon being susceptible to impacts from a commensurately diverse range of landscape and ecosystem changes through time including (but not limited to): loss of access to historic spawning and rearing habitat; reduction and degradation of salmon habitat and alterations to stream flows by dams, levees, and water diversions; decreased ecosystem productivity and altered food-web dynamics; increased predation as a result of introduced species and altered hydraulic and habitat conditions; overfishing; hatchery practices (both introgressions⁹ and competition with natural origin fish); blockage and degradation of streams by mining activities; and climate change (Katz et al., 2012; SEP, 2016; Yoshiyama et al., 1998)¹⁰. While survival at ocean entry (which itself is strongly related to dynamics during the freshwater portion of the lifecycle) and ocean conditions may also play a significant role in survival to adulthood and resulting population dynamics, environmental drivers for freshwater life stages have been shown to have a higher correlation with smolt-to-adult ratios than two marine productivity indices (Michel, 2019).

The four Chinook salmon runs experience different degrees of impact from different stressors generally and from those stressors most closely related (directly or indirectly) to CVP and SWP operations specifically. Of particular interest are stressors that (1) have a significant impact on the species/run timing, (2) are proximate to CVP and SWP operations (e.g., linked either directly or indirectly via a well-established driver-linkage-outcome relationship), and (3) could be significantly reduced or eliminated by changes to CVP and SWP operations alone or in combination with other actions. Stressors meeting these three criteria for winter-, spring- and/ or fall-run Chinook salmon in the Central Valley are described below.

Loss of Habitat (Due to Physical Alterations and Infrastructure)

Historically, Chinook salmon adult spawning was widespread throughout the mid and upper river reaches of the Sacramento and San Joaquin Basins (Yoshiyama et al., 1996). At least 1,057 miles (mi) of the stream lengths historically available to salmon (or 48 percent of the total habitat, >72 percent of the spawning habitat) have been lost as a function of dams from the original total of 2,183 mi in the Central Valley drainages (Yoshiyama et al., 2001). This impact is especially pronounced for winter- and spring-run Chinook salmon that primarily occupied the higher elevation portions of the spawning habitat that is more likely to provide the cold spring and snowmelt-fed summer conditions they require for over-summering and the yearling life-history strategy (Cordoleani et al., 2021b; Gutierrez et al., 2024).

The extent of upper elevation habitat blocked from access by dams is mirrored on the valley floor. As much as 80 percent of the floodplain habitat historically accessible to fall-run Chinook salmon has been lost as a function of levees and reduced flows during critical portions of the outmigration window (Katz, 2012). Of the remaining portion, the vast majority for the Sacramento drainage is located within the Yolo and Sutter bypasses and activated primarily during flood events. Lack of access to floodplain rearing habitat along channel margins and floodplain habitat being concentrated in the Yolo and Sutter bypasses results in those highly productive habitat types being available to juveniles only during normal and above normal water years, and specifically when the bypasses are inundated, magnifying the difference in rearing habitat quantity and quality experienced by juvenile Chinook salmon in those years.

⁹ Introgression is a technical term that refers (in this case) to hatchery fish mating with natural origin fish. It can also be used in other cases where presumed “natural” reproductive behavior has been interrupted, for example between different run timings as a function of habitat loss. Since their habitat was restricted to below dam reaches, spring-run populations experience significantly higher levels of introgression than fall-run populations.

¹⁰ See <https://wildlife.ca.gov/Conservation/Fishes/Chinook-Salmon/Winter-run>.

Degradation in Habitat Quality/Suitability

The disruption of longitudinal connectivity in the river continuum from dams, of latitudinal connectivity with floodplains from levees, and of seasonal hydrodynamics caused by physical structures, diversions, and managed flows has resulted in the disruption of ecosystem and food-web processes in the habitats that remain accessible to CV Chinook salmon. In rivers, the abundance and accessibility of food and the energetic consequences of foraging vary among habitats and through time, providing a shifting mosaic of growth opportunities for fish (Rossi et al., 2024). The flood pulse and seasonal inundation of floodplains drive key hydrologic and geomorphic processes that provide habitat and trophic benefits to river ecosystems and fish species (Junk, 1989; Junk and Wantzen, 2004; Poff et al., 2010). Floodplain inundation and the extension of the photic zone it creates have been shown to enhance phytoplankton biomass (Ahearn et al., 2006; Schemel et al., 2004; Sommer et al., 2005), zooplankton growth (Grosholz and Gallo, 2006; Müller-Solger et al., 2002), and drift invertebrate biomass (Benigno and Sommer, 2008; Sommer et al., 2001a,b). Greater frequency of inundation has also been linked to higher levels of invertebrate productivity (Grosholz and Gallo, 2006). It is therefore not surprising that juvenile Chinook salmon rearing in the Yolo Bypass and other CV floodplains and off-channel habitats tend to be larger and in better physical condition than those that rear in the river main channels (Henery et al., 2010; Jeffres et al., 2008; Limm and Marchetti, 2009; SEP, 2016; Sommer et al., 2001a).

For outmigrating Chinook salmon in the Yolo Bypass specifically, survival can be similar to that of fish outmigrating through the Sacramento River in dry years (Johnston et al., 2018) despite greater diversity in travel time and growth experienced by fish using the Yolo Bypass (Johnston et al., 2018; Takata et al., 2017), suggesting that it is not only access to the bypass as rearing habitat and migratory pathway but also the extent and duration of Yolo Bypass habitat inundation that supports the bioenergetic differences and consequent superior growth observed in Yolo Bypass fish during wetter years (Sommer et al., 2001a; Takata et al., 2017).

For juvenile Chinook salmon rearing and outmigrating in the Sacramento River channel, their survival may be correlated with flow during key periods. In an analysis of flow–survival relationships for Chinook salmon in the Sacramento River across a range of water years, Michel et al. (2021) found a relationship best described by a step function, with three distinct flow thresholds that they defined as minimum (4,259 cubic feet per second [cfs]), historic mean (10,712 cfs), and high (22,872 cfs), where survival varied by threshold: 3.0 percent below minimum, 18.9 percent between minimum and historic mean, 50.8 percent between historic mean and high, and 35.3 percent above high.

Stranding/False Pathways Including Delta Routing

Chinook salmon in the Central Valley evolved to take advantage of the heterogeneity of the habitat both in terms of landform and hydrology. Therefore, impacts to these species resulting from stranding (due to hydraulic variation), false pathways, or detrimental routing are generally attributable to human alteration of the landscape, migration corridors, and hydrograph.

As a function of the cumulative impacts on survival for juvenile Chinook salmon during rearing and outmigration in the river, poor through-Delta survival, which is the final stage of outmigration, can have a disproportionately large influence on survival to adulthood. That is, losing 10 percent of newly emerged fry matters less to adult returns than losing 10 percent of the smolts in the Delta. In recent years, through-Delta survival has been consistently low for San Joaquin River Chinook salmon and more variable for Sacramento River Chinook salmon (SST, 2017). For San Joaquin River Chinook salmon, since 2002 through-Delta survival has been extremely low (less than 0.2) even in higher flow years (e.g., 2006, 2011), which is not consistent with results of earlier survival studies showing evidence of increased juvenile survival as Delta inflows increased during the migration period (SST, 2017). Perry et al. (2018) found that travel time was inversely related to river inflow in all reaches and that survival was positively related to inflow in reaches that transitioned from bidirectional tidal flows to unidirectional flow with

increasing inflows, suggesting that factors affecting through-Delta survival are flow-mediated in the non-tidal reaches at a minimum. In addition, Perry et al. (2018) found that the probability of fish entering the low-survival interior Delta declined as inflow increased.

Interspecies Competition (including Chinook runs)

It has long been hypothesized that fall-run redds may be dewatered by the constraining of flow releases for meeting winter-run temperature requirements, and that this could be a primary driver of impacts to fall-run production in the Sacramento River in years where winter-run temperature standards are met and upheld. Stranding of juveniles can also occur during ramp-down periods after large flow releases. Although these phenomena have been observed, the extent of their impact (if any) on cohorts in any given year varies, and information on potential population level effects is sparse at best.

Entrainment in Diversions

Water export operations contribute to salmonid mortality in the Delta via direct mortality at the pumping facilities. However, direct mortality does not account for the majority of the mortality that juvenile Chinook salmon experience in the Delta (see Chapter 3). The mechanism and magnitude of indirect effects of water project operations on Delta mortality outside the facilities is uncertain. Direct mortality (at the facilities) is a combination of pre-screen and within-facility mortality (including mortality during salvage and transport), and entrainment into the pumps and water conveyance canals (SST, 2017).

Hatchery Potential

Hatchery supplementation remains a key conservation strategy for winter-run Chinook salmon, with two USFSW locations at the Livingston Stone Fish Hatchery just downstream of Shasta Dam and the Colman National Fish Hatchery along Battle Creek. Colman also supports populations of fall-run and late fall-run Chinook salmon. At the time of the 2024 Five-Year Review (NMFS, 2024) the biological status of the winter-run Chinook salmon population had declined since 2016, with the single spawning population on the mainstem Sacramento River at a high risk of extinction. Evidence suggested that the population, experiencing a declining trend in abundance through 2017, had begun to rebuild to a point where the population decline viability criteria might indicate a low risk of extinction for winter-run Chinook salmon, were it not for the influence of the hatchery broodstock remaining at a level above that indicative of a low or moderate extinction risk.

The fall-run stock from both the Sacramento and San Joaquin basin populations is largely dominated by hatchery production and has shown high variability in adult returns, suggesting that hatchery practices are now critical to the sustainability of the fishery (Huber and Carlson, 2015). Nevertheless, spawning of hatchery fish in the wild poses a potentially serious threat to the viability of natural populations (Lindley et al., 2007).

STEELHEAD

Steelhead (*Oncorhynchus mykiss*) are an anadromous salmon native to tributaries of the Pacific basin in Northeast Asia and North America. They are adapted to cold, nutrient-poor water with seasonally variable food sources (Budy et al., 2019). California Central Valley Steelhead (CCV steelhead) (and resident rainbow trout) were historically present in nearly every Central Valley tributary (NMFS, 2014).

The distinct population segment of steelhead found in the California Central Valley is federally listed as threatened. Like the smelt and Chinook previously discussed, designated critical habitat occurs in the areas affected by the seasonal operations of the SWP and the CVP.

There is no commercial fishery for CCV steelhead, but CCV steelhead support a popular and lucrative recreational fishery in Northern California.

Life History and Stages

Like other anadromous trout and salmon, steelhead spawn in freshwater, smolts migrate to the ocean to forage for several years, and adults return to their natal streams to spawn. Many populations of CCV steelhead were historically iteroparous (can spawn repeatedly), but iteroparity is now considered to be rare (USBR, 2024c; Moyle, 2002). Adults migrate into freshwater primarily between September and January, adults spawn primarily from March, adults emigrate between March and June, eggs emerge between March and May, and juveniles migrate to the ocean between January and June. However juvenile steelhead can be found in the Sacramento River year-round (McEwan, 2001; NMFS, 2014; USBR, 2024c). The geographic location of the different life stages is summarized in Figure E-11. Spawning and rearing habitat is typically characterized as perennial streams with clear, cold, fast-flowing water, high dissolved oxygen content, and abundant riffles and gravel (Kershner et al., 2019; USBR, 2024c). Steelhead are different from many other imperiled CV fish in that spawning peaks during lower flows, and wet years are predicted to have lower spawning success.

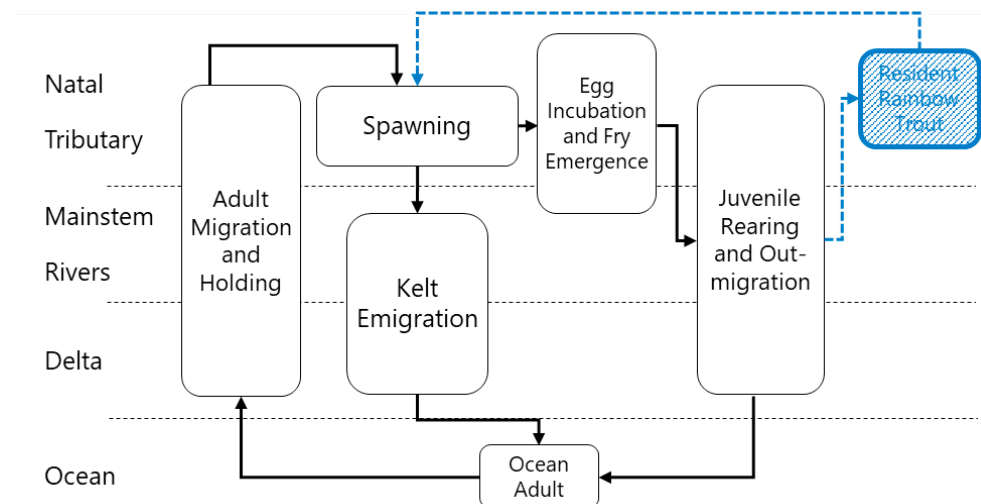


FIGURE E-11 Simplified geographic life stage domains for steelhead.

SOURCE: USBR (2024c) and adapted from Windell et al. (2017).

When steelhead do not migrate to the ocean, they are considered resident, non-listed (ESA) rainbow trout, which complicates conservation and management. There is some indication that the expression of anadromy is decreasing in CCV steelhead, and there are many biological reasons why that pattern is of concern (e.g., CBEC, Inc., 2022). The factors that influence the expression of anadromy versus residency includes genetics, individual condition, and water temperature (reviewed in Kendall et al., 2015). Overall, the decision of whether or not to migrate appears to be related to juvenile growth rates and factors that determine those growth rates (Budy et al., 2019).

Steelhead are opportunistic carnivores, and as such, their diet varies by time and space (Budy et al., 2019).

Monitoring of Steelhead and Data on Abundance

CCV steelhead were historically distributed from the upper Sacramento and Pit River systems (upper Sacramento, McCloud, Pit and Fall rivers) far south to the Kings River (and possibly Kern River systems in wet years) and in both east- and west-side tributaries of the Sacramento River and east-side tributaries of the San Joaquin River (McEwan, 2001). Currently, CCV steelhead are found in the Sacramento River downstream of Keswick Dam and in the major tributary rivers and creeks in the Sacramento River watershed. Steelhead are present in three tributaries to the San Joaquin River (Stanislaus, Tuolumne, and Merced rivers) as well as in the Calaveras River.

The different life stages of CCV steelhead are monitored in the major rivers and the Delta and using salvage data from the fish collection facilities in the South Delta. Juvenile passage monitoring at Red Bluff Diversion Dam, a primary population metric, is affected by flow and turbidity, which affects trap efficiency. Therefore, comparisons across years can be confounded by monitoring conditions for a given year. Estimates of juvenile passage monitored at the Red Bluff Diversion Dam consistently exceeded 80,000 fish/year from 2002 to 2013, but since 2014, estimates have averaged around 28,000/year (USBR, 2024c). Catch and passage indices exist for Knights Landing, the Sacramento River, Battle Creek, Clear Creek, the American River, and several locations in the Delta. Although variable, most of these indices demonstrate much higher numbers in the early 2000s and much lower numbers more recently (see Figure E-12). The observation that CCV steelhead are becoming rare where they were once abundant indicates that an important component of their life history diversity is being lost (Lindley et al., 2007). In addition, a potential shift to greater rates of residency and lower rates of anadromy is a conservation concern and is a focus of current monitoring (USBR, 2024c).

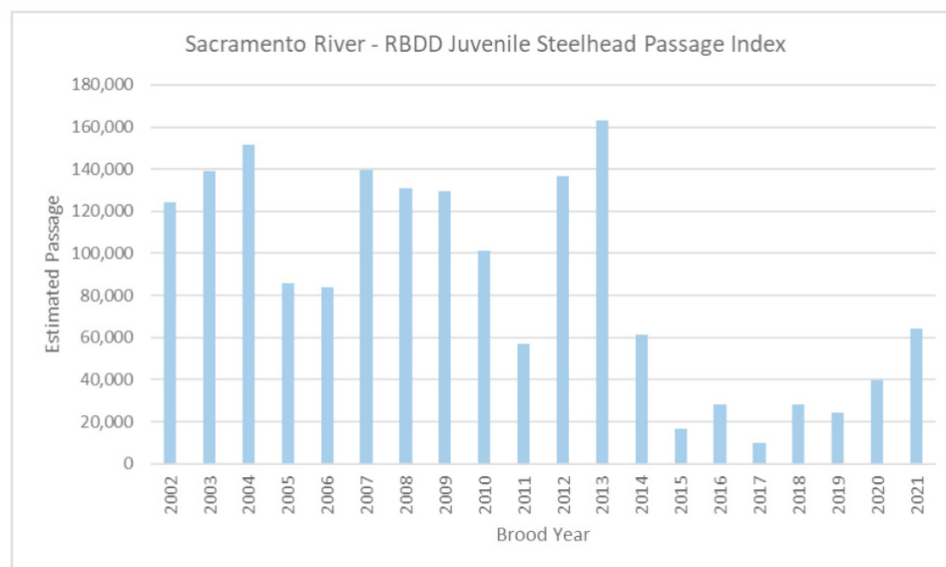


FIGURE E-12 Steelhead juvenile passage index, Sacramento River at Red Bluff Diversion Dam rotary screw trap, 2002–2021.

SOURCE: USBR (2024c).

Conceptual Models and Quantitative Life Cycle Models

There is currently no quantitative CCV steelhead-specific life-cycle model. For the chapter on steelhead in the Biological Assessment, a habitat suitability modeling approach was used to determine the

amount of suitable spawning habitat available at different river flows, and the results are presented as standard Wetted Usable Area (WUA) metrics for different flow scenarios (USBR, 2024c). Based on results from that modeling effort, under all scenarios considered, WUA increases from wetter to drier years.

Trout Unlimited and USFWS have developed a modeling framework to investigate the effects of altered flow and temperature regimes on the expression of steelhead anadromy (promoted or suppressed) in the Lower Yuba River (CBEC Inc., 2022). The approach is empirical and relates variability in flow and temperature to the level of anadromy. They observed that streams dominated by a resident life history expression tended to have more stable flows and/or higher flows in the summer. In contrast streams dominated by a migratory life history expression tended to have more variable flows and/or lower flows in the summer. Temperatures have also become less variable and more stable and warmer in the winter, a pattern thought to be contributing to the increased rates of residency.

How Project Operations and Climate Change Affect Steelhead

The long-term operation of the CVP and SWP impact steelhead via a suite of limiting factors (Perry et al., 2016; USBR, 2024c). First, as with other salmonids, the Projects have blocked steelhead access to 80 percent of its historical habitat and have contributed to the degradation of the remaining accessible habitat. Pumping has led to direct (e.g., mortality due to entrainment) and indirect (e.g., predation, delayed mortality due to collection and transport) impacts (Perry et al., 2016). In water year 2023, a total of 1,015 natural steelhead were “taken” from December 1 to March 31, which exceeded the 50 percent single year loss threshold for that period. A two-year tagging study of the Salmon Technical Working Group found that 31 percent of steelhead arriving at the export facility ended up in CVP salvage, with the likelihood of that happening increasing with reverse net OMR flow (STWG, 2024).

Other important stressors that derive from project existence and operation include the blocking of coarse sediment from reaching rivers and tributaries, which affects spawning success and can reduce egg-to-fry survival; operation of outdated fish screens resulting in fish entrainment and likely mortality; diversion dams, which can lead to fish stranding and high mortality; fish ladders, which have variable effectiveness at providing passage upstream over dams; simplified habitat due to levee construction and maintenance and disconnection of off-channel habitat; and confounded migratory cues caused by reverse flow in the Central and South Delta. The relative importance of these stressors varies by life stage, with some stressors (such as confounded migration) being highly synergistic with other stressors (e.g., entrainment).

Despite evidence that pumping entrains steelhead, it is not clear that exports are the most important factor affecting steelhead mortality. The Salmon Technical Working Group reviewed recent science including up-to-date analyses of survival through the Delta via acoustic tag networks and concluded that San Joaquin River inflow was the primary environmental driver of through-Delta survival for steelhead and not exports (STWG, 2024). Yet, survival remains low, which is an obvious incongruence.

Many steelhead recovery plan activities are described in USBR (2024c), primarily for the tributaries and headwaters, including but not limited to water temperature management plans, experimental pulse flows to benefit juvenile emigration, temperature induced anadromy, gravel and large wood supplementation, floodplain and riparian restoration, mitigating predation, and increasing in-stream flows.

Climate change that leads to increasing water temperatures and altered precipitation patterns is likely to become a substantial stressor for steelhead in the near future. Because water temperature constrains all aspects of trout physiology, cues for migration, and the potential production of the food base, the current and potential future trajectory of climate change is a critical uncertainty for steelhead and will likely include direct (e.g., incipient temperature regime) and indirect effects (i.e., growth potential, oxygen concentrations).

Hatchery Potential

There are many steelhead stocking programs in lakes and tributaries above rim dams, such as the Feather River Hatchery, the Mokelumne River Hatchery, and the Nimbus Fish Hatchery—all run by the CDFW (USBR, 2024c). Many populations are largely supported by hatcheries (IEP, 2022). Presumably, the combination of hatchery production of steelhead has impacted population genetics, which is a component of viability necessary for delisting. Unlike for the listed Chinook salmon, there are remnant populations of steelhead above all of the major rim dams that in some or all cases may contain ancestral genetics (USBR, 2024c); evidence from other populations suggests these fish could revert to anadromy if/once passage is restored (e.g., Fraik et al., 2021). However, as managed currently, there are no protections for those populations because of their not having an opportunity to express that anadromy.

Uncertainties That Complicate Management of Steelhead

As mentioned previously, there is currently no operational, quantitative life-cycle model for steelhead, which limits the ability to assess the relative impacts of different stressors across the life cycle, determine the most limiting factors, and effectively manage long-term operations to reduce impacts on steelhead. NOAA indicates that a life cycle model maybe under development.

The degree to which through-Delta survival of steelhead is directly affected by long-term operations of the projects remains uncertain. What is known is that through-Delta survival is low (< 25 percent), variable annually, and appears to be strongly affected by San Joaquin River inflow (see above). Salvage efficiency goals at the CVP and SWP export facilities are not being met, and predation in the forebays may be a key limiting factor (STWG, 2024).

Although many habitat restoration (e.g., gravel addition) activities have occurred largely in the tributaries and headwaters, the only indication is that the habitat has been enhanced, not that the sub-populations of steelhead have responded to the habitat restoration (USBR, 2024c).

It has been suggested that pulse flows are needed to support different life stages of steelhead, but this recommendation does not appear to be linked to available data or modeling (e.g., WUA) (Rose et al., 2024).

Impacts of Chinook Salmon Decline on Steelhead

During their spawning periods, Chinook salmon eggs have historically been (and continue to be) a major food-source for *O. mykiss*, especially in the more nutrient-poor, higher-elevation habitat where steelhead historically over-summered. There is reason to believe that the decline in steelhead is closely coupled with the decline in Chinook salmon (especially spring-run Chinook with whom they historically shared habitat), even if buffered by greater life history plasticity and iteroparity in steelhead.

San Joaquin Steelhead Declines

San Joaquin steelhead populations have declined precipitously to the point where generally only a handful are detected. This decline is likely a function of (1) the San Joaquin basin geography/topography and the Valley portion of rivers (below the dams) being more inhospitable during the warmer times of year than those areas in the Sacramento River for species that over-summer; (2) lower through-Delta survival for species emigrating from the San Joaquin River, and (3) collapse of San Joaquin salmon populations, especially spring-run (see above).

STURGEON

Two species of anadromous sturgeon are the focus of concern in the Bay-Delta because of declining populations. One is *Acipenser medirostris*, the southern distinct population segment (sDPS) of the North American green sturgeon that spawns in the Sacramento River yet spends much of its life in the nearshore marine environment and coastal bays and estuaries along the west coast of North America. In waters inland from the Golden Gate Bridge in California, sDPS green sturgeon are known to range through the estuary and Delta and up the Sacramento, Feather, Stanislaus, San Joaquin, and Yuba rivers (Anderson et al., 2018; Beamesderfer et al., 2004; Israel et al., 2009; Root et al., 2020; Seesholtz et al., 2014). NMFS listed green sturgeon as threatened under the federal ESA on April 7, 2006 (71 Federal Register [FR] 17757), and its critical habitat was designated on October 9, 2009 (74 FR 52300).

The second sturgeon of concern, white sturgeon (*Acipenser transmontanus*), ranges in the Eastern Pacific from the Gulf of Alaska to Monterey, California, although some are landlocked in the Columbia River drainage, in Montana, and in Shasta Reservoir in California. In addition to residing in the ocean, they also inhabit large rivers and their associated estuaries, including the Sacramento-San Joaquin Delta, where they represent the southernmost spawning population of white sturgeon. Some spawning has recently been documented in the San Joaquin River, and may also occur in tributaries including the Feather, Yuba, and Bear rivers.¹¹ White sturgeon are the largest freshwater fish species in North America and can reach 1.6 meters (m) (5.2 feet [ft]) in length, while the maximum length recorded of any age class is 6.1 m (20 ft), with common lengths around 2.1 m (6.9 ft). In one 1995 study, a sample of adults weighed from 34 to 75 kg (75 to 165 lb) (Watson et al., 1995).

Because green sturgeon has been listed as threatened under the ESA for almost two decades, it was the subject of one of the Biological Assessments written during the 2021–2024 reconsultation for the NFMS Biological Opinions (USBR, 2024d). No such assessment exists for white sturgeon, although on June 19, 2024, the California Fish and Game Commission approved white sturgeon as a candidate species for listing under the CESA.¹²

Life History and Stages

Green sturgeon in the Sacramento-San Joaquin Delta have been well documented since the late 1800s. The life stages of sDPS green sturgeon are schematically shown in Figure E-13 and described in detail in Heublein et al. (2017b). Green sturgeon reach maturity around age 15 and can live to be 60–70 years old and grow to a size of 6.5 feet (USBR, 2024d). Around age 15, adults migrate into the San Francisco estuary from late winter to early spring, with elevated Delta outflow a likely spawning cue for mature adults to enter the river system (Heublein et al., 2009; Moyle et al., 1995). Adult green sturgeon have been found to arrive upstream of the Glen-Colusa Irrigation District's water diversion on the upper Sacramento River in April and May to spawn (Moyle, 2002). Generally, adults spawn every three to four years, with a range two to six years. Following spawning, adults may remain in the Sacramento River basin for up to a year (Miller et al., 2020; Moser et al., 2016), although the upstream extent of historical spawning by green sturgeon in the Sacramento River is unknown (Beamesderfer et al., 2007).

The majority of post-spawn adult green sturgeon will move down river to the Delta during the fall through winter, although some adult green sturgeon move back downstream as early as April and May through the Delta region, either as early post-spawners or as unsuccessful spawners. Fish that over-summer in the upper Sacramento River will move downstream when the river water cools and rain events increase the river's flow and either hold in the Delta or migrate directly to the ocean (USBR, 2024d).

For juvenile green sturgeon, the mainstem Sacramento River and Delta serve as rearing habitat and a migratory corridor. Some rearing also may occur in the lowest reaches of the lower American River

¹¹ See <https://wildlife.ca.gov/Conservation/Fishes/Sturgeon/White-Sturgeon>.

¹² See <https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=218091>.

where deep pools occur for rearing of older life stages (Thomas et al., 2013). Juvenile green sturgeon can rear up to four years in the Delta and San Francisco Estuary before entering the ocean as sub-adults (Moyle et al., 1995).

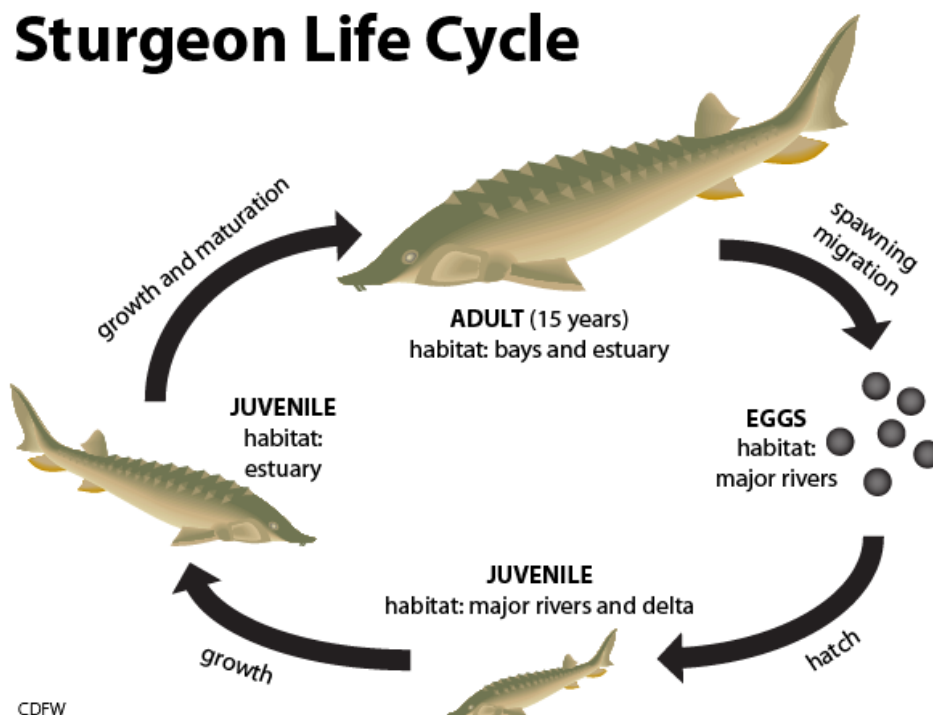


FIGURE E-13 Life cycle of green sturgeon.

SOURCE: <https://wildlife.ca.gov/Conservation/Fishes/Sturgeon>.

Hildebrand et al. (2016) provide an overview of white sturgeon life history stages. Although white sturgeon potentially have access to the ocean, use of marine environments is not obligatory to the completion of their life cycle, and most populations show no evidence of consistent or recurring movements to marine environments.

The spawning periodicity of white sturgeon is thought to be two to four years for females and one to two years for males. Kohlhorst (1976) found that (presumably) white sturgeon have a spawning period in the Sacramento and San Joaquin rivers between mid-February to late May, with peak activity during March and April. Behavior during spawning is not well known, but it is known that they are communal broadcast spawners, where a female's eggs are fertilized by many males. When ready to spawn, white sturgeon choose a variety of substrates dependent on the river system, spawning on gravel or rocky substrate in moderate to fast currents, with observed depths of 3–23 m (9.8–75.5 ft), and water velocities at the bottom on a range of 0.6–2.4 m/sec (Marineau et al., 2017). Optimal temperature is 14–16 C (57–61 F), with mortality observed below 8 C (46 F) and above 2 C (36 F) (Coutant, 2004).

Temporally, spawning adult green and white sturgeon can overlap in the general timing of migrations but differ in the median timing of their entry and exit of each reach and the duration spent within each reach (Miller et al., 2020). Spatially, they differ in the location of their spawning reach and route selection in the Delta. Juveniles and subadults also differ in their spatial and temporal distributions within the San Francisco Estuary.

Monitoring of Sturgeon and Data on Abundance

Data on green sturgeon abundance come from three primary sources. The first are salvage data from the CVP and SWP pumps. In general, a decrease in sDPS green sturgeon abundance has been inferred from the amount of take observed at the South Delta pumping facilities, although salvage data cannot be used to rigorously quantify abundance. Second, green sturgeon juvenile abundance has been monitored in rotary screw traps at Red Bluff Diversion Dam since 2002 by USFWS. Abundance, measured as catch per unit volume (CPUV), was consistently < 3 fish/acre-feet before 2011, but near or greater than 3 fish/acre-feet in most years since 2011, including four years during which CPUV exceeded 20 fish/acre-feet (Figure 8-2 in USBR, 2024d). Third, since 2010 acoustic telemetry as well as dual-frequency identification sonar (DIDSON) have been used to locate green sturgeon in the Sacramento River and derive an adult spawner abundance estimate (Mora et al., 2018). These surveys have recently been used to generate an adult sDPS green sturgeon abundance estimate of 2,106 (95 percent confidence interval = 1,246–2,966; Mora et al., 2018). These estimates do not include the number of spawning adults in the lower Feather or Yuba rivers, where green sturgeon spawning has been confirmed (Seesholtz et al., 2014).

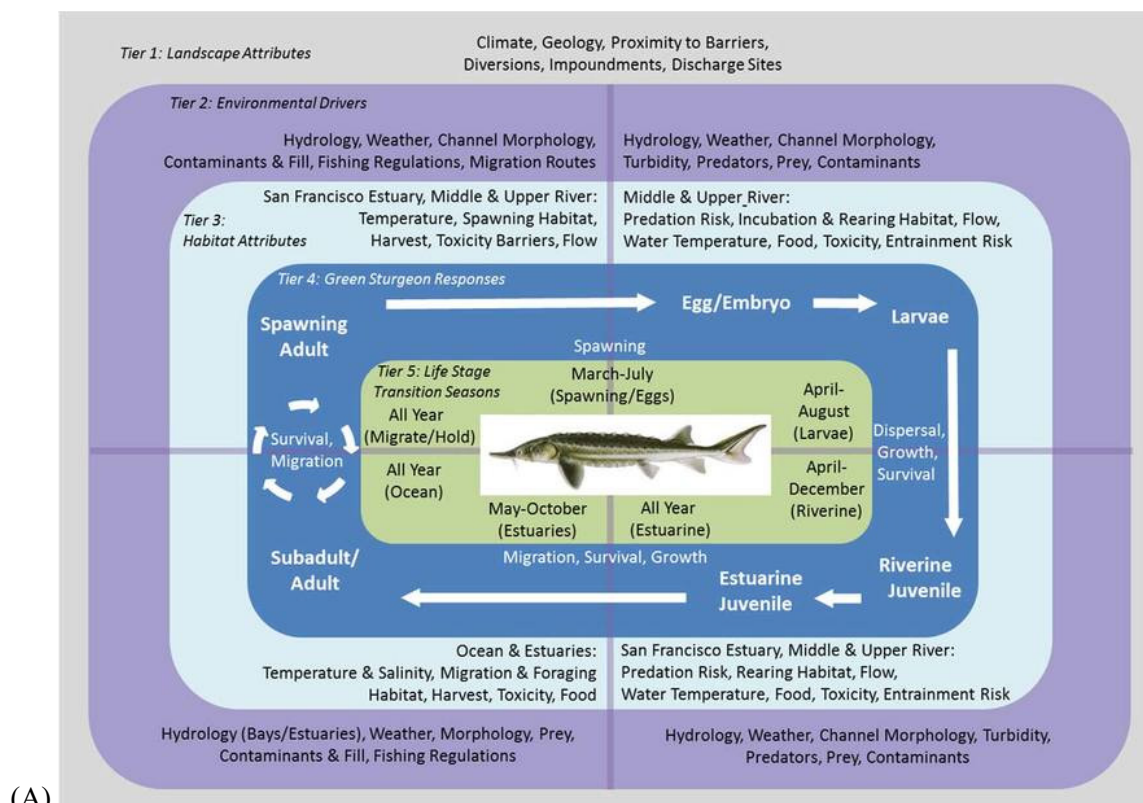
A recent YouTube video from the CDFW states that white sturgeon in the Bay-Delta area has declined by 85 percent over the past 25 years.¹³ Kohlhorst (1980) used commercial passenger fishing boat and tagging records to evaluate white sturgeon population trends in the Sacramento-San Joaquin Estuary. Population estimates suggested that a decrease in abundance occurred between 1967 and 1974 with an increase between 1974 and 1979. The mean size of sturgeon caught increased from 1964 to 1974 and then decreased through 1978. Annual survival rate changed little over this period (84–88 percent with harvest rates of 6–7 percent). Population decline was likely due to poor recruitment from year classes produced after the mid-1950s. Suggested influences on recruitment include degradation of juvenile habitat, environmental contaminants (such as polychlorinated biphenyls), and spawning stock size.

As is common with many sturgeon life histories, low recruitment, delayed age at maturity and multi-year intervals between spawning events make white sturgeon vulnerable to population interventions (Blackburn et al., 2019). Blackburn et al. (2019) further note that white sturgeon were historically abundant in the Delta, but altered habitat and hydrological conditions coupled with overexploitation are considered to have caused the declines in population abundance and distribution (Hildebrand et al., 2016; Moyle et al., 2011; Nichols et al., 1986). CDFW's most recent estimate of the five-year average of the harvestable population is about 33,000 fish (CDFW, 2023). Recruitment is influenced by survival at early life stages (Hildebrand et al., 1999; Jackson et al., 2016 at p. 172 citing Kohlhorst et al., 1991; Secor et al., 2002), and as such is dependent on the frequency of high magnitude spring-summer river flows.

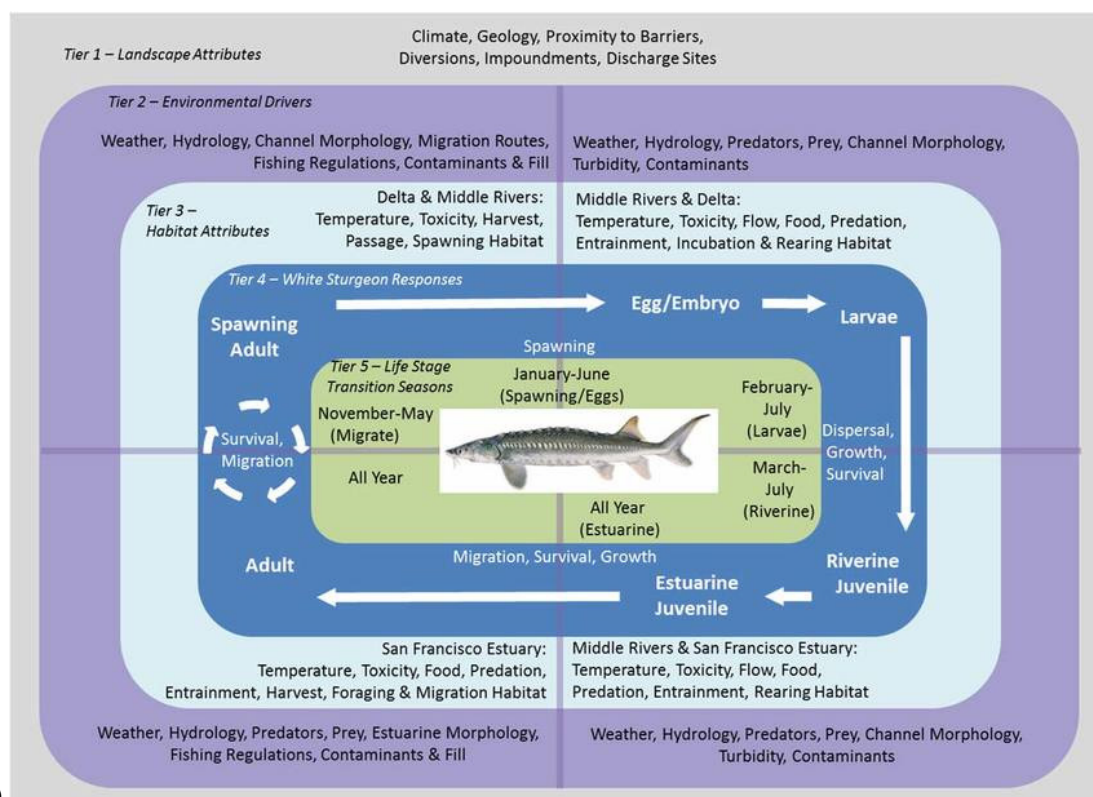
Conceptual Models and Quantitative Life-Cycle Models for Sturgeon

Life cycle models for both sturgeon species have been developed (Figure E-14), and they are remarkably similar, with the exception of the locations of various life stages. Modeling of green sturgeon is inherently more complex because of their multi-state movements compared to the mostly local estuarine white sturgeon.

¹³ See <https://www.youtube.com/watch?v=rbBDZBgTRsI&t=118s>.



(A)



(B)

FIGURE E-14 (A) Green sturgeon and (B) white sturgeon life cycle models.

SOURCE: Heublein et al. (2017a).

Israel et al. (2009) developed a conceptual life-history model of white sturgeon (Figure E-15) and the factors that affect reproduction, growth, and survival in the Sacramento-San Joaquin Rivers and the Delta. This model can be used to organize, visualize, and evaluate how the complex life history of white sturgeon relates to the spatial and temporal variability of riverine and estuarine ecosystems and potential consequences of ecosystem restoration and water management alternatives. The model has a geographic emphasis on the Sacramento River and Delta regions, although the entire distribution of white sturgeon should be considered when population level responses are of concern, because of the migratory life history of this species.

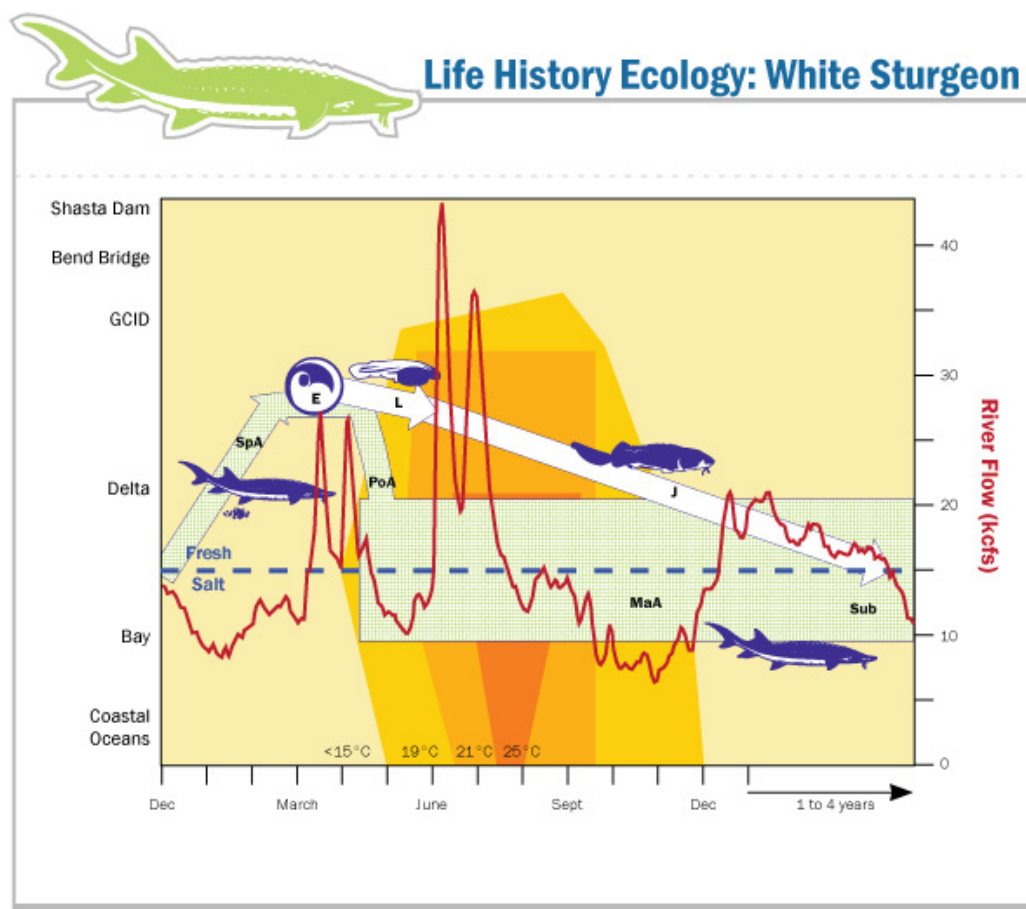


FIGURE E-15 Conceptual life history ecological interaction model for white sturgeon in the Sacramento and San Joaquin rivers and Bay-Delta. NOTE: Spawning white sturgeon adults (SpA) enter the river in the winter to spawn and outmigrate quickly as post-spawners (PoA). Eggs (E) are broadcast spawned and mature into larvae (L), then enter and remain in the estuary at juveniles (J). Black line represents 2006 daily average flow at Vernalis (waterdata.usgs.gov). Temperature data are 2006 data from Bend Bridge, GCID, Bethel Island, Port Chicago, and Martinez (cdec.water.gov). SOURCE: Figure 4 from Israel et al. (2009).

How Project Operations and Climate Change Affect Sturgeon

The sturgeon conceptual models in Figure E-14 suggest that Project operations negatively affect all life stages of green and white sturgeon in much the same manner as they do Chinook salmon, with an emphasis on blockage from traditional spawning locations, altered flow regimes that misroute fish and prevent access to floodplain habitat, and temperature-dependent mortality that decreases spawning success and eggs survival. Finally, larval, juvenile, and adult sturgeon risk entrainment in the South Delta if exports are high enough.

Like the other salmonids, the viability of sDPS green sturgeon is constrained by many factors including a small population size and restriction of spawning sites to a few locations (USBR, 2024d)—the latter of which is a direct result of the CVP and SWP. However, according to USBR (2024d), “there is much uncertainty regarding the scope of threats and the viability of the population based on abundance indices.” The most recent five-year status review for sDPS green sturgeon found that some threats to the species have been eliminated, such as take from commercial fisheries and removal of some passage barriers, but many other threats still exist (NMFS, 2021). According to McElhany et al. (2000), the sDPS does not meet the definition of viable as an independent population having a negligible risk of extinction due to threats from demographic variation, local environmental variation, and genetic diversity changes over a 100-year timeframe.

Hatchery Potential

The UC Davis Green Sturgeon Broodstock program is the only captive breeding population of green sturgeon.¹⁴ A variety of hatcheries for white sturgeon exist in the region, because of the harvesting of caviar.

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Appendix F

Biographies and Disclosures for the Committee

Peter Goodwin (*Chair*) is recently retired as the President of the University of Maryland Center for Environmental Science and Vice-Chancellor of Environmental Sustainability for the University of Maryland system, where he served from September 2017 to September 2023. He played an integral role on the Governor’s Chesapeake Bay Cabinet, as well as being the lead science advisor on the Maryland Commission on Climate Change. Before joining the University of Maryland, Dr. Goodwin was the founding Director of the Center for Ecohydraulics Research at the University of Idaho. From 2015 to 2019, he was the President of the International Association for Hydro-Environment Engineering and Research (IAHR)—a worldwide independent organization of engineers and water specialists working in fields related to the hydro-environmental sciences and their practical application. His research has focused on hydrodynamic and geomorphic modeling, tidal wetland restoration, and river and ecosystem management. Dr. Goodwin was the lead scientist for the Delta Science Program in California from 2012 to 2015 and has also served on the Delta Independent Science Board. He is a Fellow of both the Institution of Civil Engineers, United Kingdom, and the American Society of Civil Engineers. Dr. Goodwin holds a Ph.D. and M.S. in hydraulic and coastal engineering from University of California, Berkeley, and a B.S. in civil engineering from University of Southampton, United Kingdom. He served on the National Academies of Sciences, Engineering, and Medicine Committee on the Restoration and Protection of Coastal Louisiana.

Jerad D. Bales is recently retired as Executive Director of the Consortium of Universities for the Advancement of Hydrologic Science, a non-profit research organization representing more than 130 U.S. universities and international water science-related organizations. Previously, Dr. Bales was Chief Scientist for Water at the U. S. Geological Survey (USGS) from 2009 to 2016, where he was responsible for, among other things, the USGS Bay-Delta program through the National Research Program. In this position, he was the Senior Executive responsible for \$100 million of activities related to the planning and development of national hydrologic research and technology transfer. Dr. Bales is a hydrologist with expertise in water resources management, hazards, water quality issues, and climate science and has published more than 120 articles and technical reports on this work. He also has served on many interagency committees, including serving as Co-Chair of the Office of Science and Technology’s Subcommittee on Water Availability and Quality, as Chair of the U.S. National Committee for the UNESCO International Hydrological Programme, and as a member of the Board of Scientific Counselors for the U.S. Environmental Protection Agency’s Safe and Sustainable Water Resources program. Dr. Bales holds a Ph.D. in civil engineering and environmental engineering from the University of Texas at Austin, and both a M.S. and B.S. in civil engineering from the University of Tennessee.

Stephen B. Brandt is a Professor Emeritus in the Department of Fisheries, Wildlife, and Conservation Sciences at Oregon State University where he specializes in fish ecology and management in marine and freshwater ecosystems. Previously, he held faculty positions at the University of Maryland’s Chesapeake Biological Laboratory, SUNY College at Buffalo, and SUNY ESF Syracuse. Dr. Brandt directed the National Oceanic and Atmospheric Association (NOAA) Great Lakes Environmental Research Laboratory for 12 years and earned the President’s Rank Award. There, he created and led the NOAA Center of Excellence for Great Lakes and Human Health. He has written more than 150 publications and given 300 scientific presentations on food webs, fish bioenergetics and habitat quality, physical/biological interactions, hypoxia, and ecosystem forecasting spanning the Great Lakes, Chesapeake Bay, Gulf of Mexico, Adriatic Sea, South Pacific, Western Atlantic and small lakes. Dr.

Brandt received his Ph.D. and M.S. in oceanography and limnology from the University of Wisconsin, Madison. He has served on the National Academies of Sciences, Engineering, and Medicine Committee on the St. Lawrence Seaway and the Panel on Niagara River Ice Boom Investigations. He spent ten years on the Independent Science Board of the Delta Stewardship Council, during which time he was twice elected as Chair.

Dr. Brandt served as a compensated panelist for the Delta Science Program during May and June 2025 on peer review of the Healthy Rivers and Landscapes Science Plan.

Erin N. Bray is an Associate Professor in the School of the Environment and leads the Rivers Lab at San Francisco State University. Previously, she was an Assistant Professor at California State University Northridge where she served as the Co-Lead for the Water Science Program. Dr. Bray's research focuses on hydrology and fluvial geomorphology, with an emphasis on river processes, river restoration, and water resources management. She has developed a model that, together with field measurements and climate data, can be used to study impacts of flow releases from dams and climate on the energy balance and water temperature of rivers. She also conducts in-situ field measurements of saturated hydraulic conductivity to better understand the impacts of sediment transport, sediment permeability, and flow on patterns of hyporheic exchange, and how those patterns generate and sustain physical processes that support salmon spawning habitat. Dr. Bray was a Postdoctoral Fellow at the University of California, Berkeley, and the University of California, Santa Barbara, supported under a fellowship from the Delta Stewardship Council. She received her Ph.D. from the University of California, Santa Barbara, her M.A. from Brown University, and her B.S. from Cornell University.

Dr. Bray's research is partially funded by the U.S. Geological Survey and the State Water Contractors.

Phaedra E. Budy is a Professor of fisheries management and aquatic ecology in the Department of Watershed Sciences at Utah State University and the Unit Leader of the U.S. Geological Survey Utah Cooperative Fish and Wildlife Unit. She has worked broadly in conservation biology, invasion ecology, and food web dynamics of aquatic systems, covering a wide geographical range including Utah (from the south of the state up to high elevation points in the Bear River drainage), the Columbia River basin, the Colorado River basin, the Rio Grande basin, Nevada, and Alaska. She has studied many species of salmonids, imperiled native desert fishes, and numerous warm water lentic fishes—particularly those that have been imperiled due to hydrological alteration of aquatic habitats through river regulation, human water use, and introduction of nonnative competitors and predators. She has taken part in conservation actions such as nonnative fish suppression, flow experiments designed to benefit nearshore habitats, adaptive stream restoration, and large river management. Her current research also considers the effects of climate change on mountain stream hydrology and the resulting effects on downstream aquatic communities and their management. Dr. Budy completed her B.S. in limnology from the University of California, Davis, and her Ph.D. in aquatic ecology from Utah State University.

Harindra J. Fernando is the Wayne and Diana Murdy Endowed Professor of Engineering and Geosciences at University of Notre Dame. Prior to Notre Dame, he spent more than 20 years at Arizona State University. His research has spanned the topics of basic fluid dynamics, experimental methods, oceanography, atmospheric sciences, environmental sciences and engineering, air pollution, climate, alternative energy sources, acoustics, heat transfer and hydraulics and fluids engineering. He has served on numerous domestic and international committees, including the Louisiana Coastal Area Science Board, the Delta Independent Science Board (for 10 years), and National Science Foundation Directors' Advisory Committee for Environmental Research and Education. Dr. Fernando is a Fellow of the American Society of Mechanical Engineers, American Physical Society, American Meteorological Society, American Association for the Advancement of Science, American Geophysical Union, and International Association of Hydro-Environmental Research and Engineering. He was elected to the European Academy in 2009. He has a docteur honoris causa from University of Grenoble, France, and a

Doctor of Laws Honoris Causa from University of Dundee, Scotland. He received his B.S. in mechanical engineering at the University of Sri Lanka, and his M.A. and Ph.D. in geophysical fluid mechanics from the Johns Hopkins University.

Rene E. Henery is an ecologist and ecogeographer who serves as California Science Director for Trout Unlimited, the country's oldest and largest salmon conservation organization. His work over the past decade has focused on cultivating spaces for collaborative engagement around freshwater systems and the diverse communities that they connect, with a particular focus on the science and policy of river and floodplain restoration in California's Central Valley and mountain meadow restoration in the Sierras and Cascades. His work outside of the United States includes United for Lake Atitlán (Unidos por Lago Atitlán), a multi-national effort to build capacity for the long-term health and resilience of Guatemala's Lake Atitlan Watershed, and participation in the conservation of Mongolia's Eg River and its population of Hucho Taimen, the world's largest salmon. He is a member of the Water Solutions Network and co-founder of the Central Valley Salmon Habitat Partnership and the Sierra Meadows Partnership. Dr. Henery received his B.A. in English literature from Reed College and his Ph.D. in environmental geography from the University of California, Davis.

Dr. Henery's research is partially funded by the State Water Contractors and the Delta Science Program.

Jay R. Lund is a Distinguished Professor Emeritus at the University of California (UC), Davis, and Vice Director of the UC Davis Center for Watershed Sciences. His research interests are water and environmental systems engineering, management, and policy, approached by combining traditional engineering with operations research and economics. He has worked on a wide range of water resources issues including water supply, flood control, ecological sustainability, reservoir operations, and demand management, primarily in California. From 2012 to 2022 he served on the Delta Stewardship Council's Independent Science Board, including a rotation as chair. He has co-authored three books on the Sacramento San Joaquin Delta: *Managing California's Water: From Conflict to Reconciliation* (2011), *Comparing Futures for the Sacramento-San Joaquin Delta* (2010), and *Envisioning Futures for the Sacramento-San Joaquin Delta* (2007) and has authored more than 170 journal articles. Dr. Lund has won a variety of professional awards and is a member of the National Academy of Engineering. He has a B.A. in international relations and regional planning from the University of Delaware, a M.S. in geography from the University of Washington, and a B.S.C.E. and Ph.D. in civil engineering from the University of Washington. Dr. Lund has served on earlier National Academies of Sciences, Engineering, and Medicine committees including those on the Review of the New York City Watershed Protection Program and Further Studies of Endangered and Threatened Fishes in the Klamath River.

Josué Medellín-Azuara is a Professor at the University of California, Merced. His research interests include large scale hydro-economic modeling for water management and policy analysis; water management for agricultural, environmental, and urban uses; agricultural production adaptation to drought and climate change; sustainable agroecosystems for water and food security; water informatics; consumptive water use in agriculture using remote sensing; and impact analysis using partial and general equilibrium models. His work spans across California and both Central and South America. In addition to more technical issues, he has published on the socioeconomic inequities experienced by disadvantaged communities in terms of representation in scientific papers, California newspaper articles, and legislative bills. Dr. Medellín-Azuara holds a B.S. in mechanical and electrical engineering and an M.B.A., both from Instituto Tecnológico y de Estudios Superiores de Monterrey, Mexico. He received an M.S. in agricultural and resource economics and a Ph.D. in ecology and environmental policy analysis, both from the University of California, Davis.

Michelle E. Miro is a Senior Information Scientist at the RAND Corporation and Professor at the Pardee RAND Graduate School. She has a broad portfolio of work across climate resilience and

adaptation and disaster recovery for critical infrastructure, with a focus on the water sector. Her research supports international, federal, and local emergency, infrastructure, and resource management agencies with climate adaptation, disaster resilience and recovery, and water resources planning. She has worked on projects related to climate adaptation across California's Central Valley and Southern California, including carrying out climate stress tests of imported water supplies. She holds an M.S. in civil engineering from the University of Illinois Urbana-Champaign and a Ph.D. in civil engineering from the University of California, Los Angeles. Dr. Miro also serves as a co-investigator for the National Oceanic and Atmospheric Administration Mid-Atlantic Regional Integrated Sciences and Assessments (MARISA) Climate Adaptation Partnership program, and she has recently served as a co-investigator on a National Academy of Sciences coastal resilience grant focused on future flood risk for communities in the Gulf of Mexico.

Dr. Miro's research is partially funded by the San Bernardino Valley Municipal Water District and has been partially funded during the past five years by Westlands Water District.

Mohammed Ombadi is an Assistant Professor in the department of Climate and Space Sciences and Engineering at the University of Michigan. Prior to his appointment at the University of Michigan, Ombadi was a Post-doctoral Fellow at Lawrence Berkeley National Laboratory. He has a keen interest in understanding and quantifying climate change impacts on hydroclimatic extremes. From heavy storms and floods to extreme heatwaves and droughts, Dr. Ombadi's research focuses on the changing characteristics of these events and their impacts on our daily lives. In addition, his recent work has focused on developing new techniques to measure resilience of environmental systems to extreme events, with the ultimate goal of informing mitigation and adaptation strategies to climate change. His work has been acknowledged with awards from the American Geophysical Union, Orange County Engineering Council, UC Irvine School of Engineering and U.S.-China Clean Energy Research Center for Water-Energy Technologies. He holds a Ph.D. and M.S. in civil and environmental engineering from University of California, Irvine, and a B.S. in civil engineering from University of Khartoum.

David R. Owen is the Harry D. Sunderland Professor of Law and Associate Dean for Research at University of California (UC) Law, San Francisco. He previously was a professor at the University of Maine School of Law and the University of San Diego School of Law, a practicing water lawyer, a clerk to Judge Samuel Conti (United States District Court, Northern District of California), and, before law school, a geologist for an environmental consulting firm. He teaches environmental, water, energy, and administrative law. His research focuses primarily on water resource management, including groundwater-surface water interactions and groundwater-use regulation, the roles of negotiation in environmental decision-making, implementation of the Clean Water Act, Endangered Species Act, and public trust doctrine, and dam removal. His peers have recognized many of his articles as among the top environmental-law articles of their year, and he also has won UC Law's highest teaching award. Mr. Owen has co-authored two books: *Practicing Environmental Law* (2021) and *Natural Resources Law: A Place-Based Book of Problems and Cases* (2022). He earned his J.D. from the UC Berkeley and his B.A. in geology from Amherst College.

Dr. Owen's research was partially funded by the State Water Resources Control Board.

Denise J. Reed is a Research Professor at the University of New Orleans. She served as a Distinguished Research Professor at the University of New Orleans and spent five years as Chief Scientist at The Water Institute of the Gulf. Dr. Reed's research has focused on coastal marsh sustainability and the role of human activities in modifying coastal and deltaic systems, and she has more than 35 years of experience studying coastal management issues in the United States and abroad. She has been involved in restoration and resilience planning in coastal Louisiana for more than three decades, as well as in the California Bay-Delta, San Francisco Bay, and Puget Sound. She has served on numerous boards and panels addressing the effects of human alterations on natural environments and the role of science in guiding restoration including the National Oceanic and Atmospheric Administration Science Advisory

Board and the U.S. Army Corps of Engineers Environmental Advisory Board. Dr. Reed received her B.S., M.A., and Ph.D. degrees in geography from the University of Cambridge, UK. She has served on several National Academies' committees including Sea Level Rise in California, Oregon, and Washington (2010-2013), Everglades restoration (2015–2023), and sustainable management of the California Bay-Delta (2009–2012).

Dr. Reed's work has been partially funded in the past five years by the State Water Contractors and the USBR.

Albert Ruhi is a freshwater ecologist and Associate Professor at the University of California, Berkeley. His research involves combining field experiments and large-scale data analysis to advance understanding of the ecology and conservation of rivers and wetlands, focusing on aquatic food-web responses to hydrologic regimes. He has conducted most of his research in water-scarce regions of the world—namely, the Mediterranean basin and the American Southwest—and has been the principal investigator on six research grants focused on modeling Bay-Delta fisheries and food webs. Previously, he was a postdoctoral researcher at Arizona State University, and a Fellow at the National Socio-Environmental Synthesis Center in Maryland, where he studied impacts of flow alteration by U.S. dams. Dr. Ruhi has published more than 60 papers, is an Associate Editor for the journal *Conservation Letters*, and has received numerous awards, such as a National Science Foundation CAREER award, a California Sea Grant New Faculty Award, a Hellman Fellow Award, and University of Girona's Extraordinary Doctoral Degree Award in Environmental Sciences for his Ph.D. work on wetland ecosystem restoration. Dr. Ruhi received a B.S. in biology and a Ph.D. in ecology from the University of Girona (Catalonia, Spain).

Dr. Ruhi's research is partially funded by the Delta Stewardship Council, the State Water Contractors, and the California State Water Resources Control Board.

Steven Sadro is an Associate Professor of limnology and aquatic ecosystems ecology in the Department of Environmental Science and Policy at the University of California, Davis. His research broadly examines how abiotic and biotic factors interact to control the structure and function of lakes, ponds, estuaries, and wetlands. Much of his work focuses on ecosystem energetics and metabolic rates, the biogeochemical cycling of carbon and nutrients within ecosystems and through food webs, and how aquatic ecosystems respond to global change. His research is carried out in the mountains of California and portions of the Sacramento-San Joaquin Delta. His research group maintains one of the longest running lake-watershed studies in California, and it developed the California Mountain Lake Network, a network of more than 25 lakes located throughout the state instrumented with environmental sensors that seeks to understand how local scale factors mediate regional scale processes associated with climate change. He worked for nearly a decade studying intertidal and estuarine ecology in the Pacific Northwest as a researcher for the University of Oregon, South Slough National Estuary Research Reserve and the U.S. Environmental Protection Agency. Since 2016 he has served on the Tahoe Science Advisory Council, working to advise policy makers to promote, enhance, and maintain the ecological integrity of Lake Tahoe and its watershed. He holds a B.A. from the University of California, Santa Cruz, where he studied the biology of intertidal invertebrates, and a Ph.D. from the University of California, Santa Barbara, in limnology and aquatic ecosystems ecology.

Dr. Sadro's research is partially funded by the U.S. Bureau of Reclamation.

David B. Senn is a Senior Scientist at the San Francisco Estuary Institute (SFEI), with research interests in the biogeochemistry and fate and transport of nutrients and trace metals/metalloids in lakes, rivers, wetlands, and estuarine/marine systems. He is the lead scientist for San Francisco Bay Nutrient Management Strategy, which seeks to understand how high nutrient concentrations (mainly from discharged wastewater) can cause increased phytoplankton biomass, low dissolved oxygen, and increased harmful algal blooms and toxins, with detrimental effects on species and ecosystems. Before joining SFEI, Dr. Senn's research focused on nitrogen pollution and iron and arsenic cycling in contaminated

urban lakes; mercury cycling, bioaccumulation, and human exposure in the Gulf of Mexico; and the ecological impacts of large dams in the Zambezi River Basin in southern Africa. Dr. Senn holds a B.S. in civil and environmental engineering from Rutgers University and a Ph.D. in civil and environmental engineering from the Massachusetts Institute of Technology.

Jery R. Stedinger is the Dwight C. Baum Professor of Engineering Emeritus in Civil and Environmental Engineering at Cornell University. His research has focused on statistical issues in hydrology and optimal operation of water resource systems. His projects have addressed the value of historical and paleoflood data in flood frequency analysis, regional hydrologic regression and network analyses, risk and uncertainty analysis of flood-risk reduction projects, calibration and uncertainty analysis for rainfall-runoff-quality models, stochastic simulation of water resource systems, and efficient multiple-reservoir and hydropower system operation considering dynamic energy markets and stochastic inflows and forecasts. He is a member of the National Academy of Engineering and has won numerous awards, including the ASCE Julian Hinds and Ven Te Chow awards for contributions to water resources and to hydrology and the ASCE-EWRI Lifetime Achievement Award. He holds a Ph.D. in environmental system engineering from Harvard University and a B.A. in applied mathematics from the University of California, Berkeley. Dr. Stedinger has served on several committees of the National Academies, including the committees on Risk Based Analyses for Flood Damage Reduction Studies, on American River Flood Frequencies, and on Flood Control Alternatives in the American River Basin.

Patrick J. Sullivan is Professor Emeritus in the Department of Natural Resources and the Environment at Cornell University. His research interests include developing and applying advanced statistical methods to estimate and analyze the spatial and temporal dynamics of fish in freshwater, estuarine and marine environments. In addition, he has statistically characterized the dynamics of marine mammals, birds, bats, insects, invertebrates, forests, soils, wetlands, microplastics and aquatic toxins. Dr. Sullivan holds a B.S. in biology from the University of California, Davis, an M.S. in fisheries biology from the University of Washington, and a Ph.D. in biomathematics and biostatistics from the University of Washington. He has chaired National Academies' committees on Improving the Collection, Management and Use of Marine Fisheries Data (2000) and the Review of Recreational Fisheries Survey Methods (2006) and has co-chaired the committee on Evaluating the Effectiveness of Stock Rebuilding Plans of the 2006 Fishery Conservation and Management Reauthorization Act (2013). He was a committee member on Science and Its Role in the National Marine Fisheries Service (2002) and gave testimony to and reviewed the product from the committee on Improving the Use of the "Best Scientific Information Available" Standard in Fisheries Management.