



— BUREAU OF —
RECLAMATION

Long-Term Operation – Biological Assessment

Appendix P – Delta Habitat

This page intentionally left blank.

Contents

List of Figures.....	ii
Appendix P Delta Habitat.....	P-1
P.1 Introduction.....	P-1
P.2 Initial Alternative Report.....	P-1
P.2.1 Management Questions.....	P-1
P.2.2 Initial Analyses.....	P-2
P.2.3 Initial Findings.....	P-2
P.2.4 Subsequent Considerations.....	P-2
P.3 Public Draft Environmental Impact Statement Scenarios.....	P-2
P.4 Performance Metrics.....	P-3
P.4.1 Habitat.....	P-3
P.4.2 Zooplankton Abundance, Biomass, and Community Composition.....	P-3
P.4.3 Biological.....	P-3
P.4.4 Water Supply.....	P-4
P.4.5 National Environmental Policy Act Resource Areas.....	P-4
P.5 Method Selection.....	P-4
P.5.1 Datasets.....	P-5
P.5.2 Literature.....	P-5
P.5.3 Models.....	P-15
P.6 Lines of Evidence.....	P-16
P.6.1 Where is a Delta habitat limitation affecting Delta smelt and outmigrating salmonids?.....	P-16
P.6.2 Does habitat restoration increase primary and secondary productivity and improve somatic growth of target species?.....	P-17
P.6.3 What is the energy flow of habitat restoration productivity to different regions of the Delta, fish, and/or clams?.....	P-18
P.6.4 Does habitat restoration provide refuge and improve survival for Delta smelt or salmonids?.....	P-19
P.6.5 How does habitat restoration affect operations for flood conveyance, water supply, and/or water quality?.....	P-19
P.7 Uncertainties.....	P-20
P.8 References.....	P-20

Figures

Figure P-1. Conceptual Model of Attributes Affecting the Transition of Winter-run Chinook Salmon from Rearing Juvenile to Outmigrating Juvenile in the Delta.....	P-6
Figure P-2. Central Valley Juvenile Chinook Salmon Tidal Wetland Conceptual Model	P-7
Figure P-3. Delta Smelt Conceptual Model	P-9
Figure P-4. Juvenile to Subadult Delta Smelt Conceptual Model	P-10
Figure P-5. Subadult to Adult Delta Smelt Conceptual Model.....	P-11
Figure P-6. Foodweb Conceptual Model	P-12
Figure P-7. Invasive Bivalve Conceptual Model	P-13
Figure P-8. Transport Conceptual Model.....	P-14
Figure P-9. Tidal Wetlands Overview Conceptual Model	P-15

Appendix P Delta Habitat

P.1 Introduction

This appendix evaluates lines of evidence assessing Sacramento–San Joaquin Delta (Delta) habitat restoration effectiveness to reduce refuge habitat and food availability and quality stressors on winter-run and spring-run Chinook salmon, steelhead, Delta and longfin smelt.

Operation of the Central Valley Project (CVP) and State Water Project (SWP) includes implementing nonflow habitat-restoration actions to increase rearing habitat, including creation, expansion, and grading of floodplains and side channels, and enhancing foodweb connectivity through increasing tidal habitat. The nonflow habitat actions in the San Francisco Bay/Sacramento–San Joaquin Delta Estuary (Bay-Delta) are focused on foodweb support for Delta smelt and rearing habitat for outmigrating salmonids. These actions may also contribute to levee resilience and increase habitat connectivity to support a broad range of aquatic- and wetland-dependent species. These actions are also expected to restore ecosystem functions associated with tidal marshes, floodplains, and lowland grasslands by establishing unimpeded tidal connectivity, allowing exchange of water, sediment, nutrients, primary productivity, and aquatic organisms.

P.2 Initial Alternative Report

An Initial Alternative Report (*LTO 2021 Consultation Initial Alternatives Appendix P – Delta Habitat Restoration*) developed potential options for the long-term operation of the CVP and SWP to inform alternative formulation by seeking the bounds of potential decisions and a contrast between approaches. Tidal habitat restoration required in the U.S. Fish and Wildlife Service 2008 Biological Opinion was included within the 2020 Record of Decision and its accompanying 2019 Biological Opinions. The *Yolo Bypass Salmonid Habitat and Fish Passage Record of Decision* and the *Suisun Marsh Habitat Management, Preservation, and Restoration Plan Record of Decision* implement additional Delta habitat actions. Contrary to other variable components, initial alternatives for tidal habitat restoration address whether to include or exclude habitat restoration from consideration, and not a range of options.

P.2.1 Management Questions

United States Department of the Interior, Bureau of Reclamation (Reclamation)’s management questions for the formulation of an alternative include:

- Where is a Delta habitat-limitation affecting Delta smelt and outmigrating salmonids?
- Does habitat restoration increase primary and secondary productivity and improve somatic growth of target species?
- What is the energy flow of habitat restoration productivity to different regions of the Delta, fish, and/or clams?

- Does habitat restoration provide refuge and improve survival for Delta smelt or salmonids?
- How does habitat restoration affect operations for flood conveyance, water supply, and/or water quality?

P.2.2 Initial Analyses

Reclamation solicited input for the knowledge base paper, *Delta Habitat Restoration*.

Reclamation completed an exhaustive literature and data review to consider inclusion or exclusion of Delta habitat restoration from consideration in alternatives.

P.2.3 Initial Findings

Most Delta restoration projects have just been completed or are about to break ground, so there is limited information on the direct effect of Delta habitat restoration on growth and survival of fishes or ecosystem function. There is also limited information on the effects of Delta habitat restoration on salmon, steelhead, or smelt. For juvenile salmon and steelhead, current estimates of habitat availability suggest that rearing habitat in some regions may be limiting in some regions of the Delta. The low population of smelt also makes it difficult to directly quantify survival, abundance, and growth of these species.

Tidal marsh restoration successes in other regions of the United States provides a reasonable basis for if Delta habitat-restoration actions may benefit target species and ecosystem processes. For example, projects in Washington estuaries restored wetlands and other intertidal habitats that provided comparable levels of secondary productivity to similar reference sites with suitable habitat for rearing juvenile salmon and steelhead. However, Delta habitat is highly complex, and the success of restoration actions would depend on a variety of factors. For example, restoration effect on total food subsidies is strongly affected by grazers, such as clams, and dependent on the hydrology and design of the site, which effect the transport of these food subsidies.

P.2.4 Subsequent Considerations

Further habitat restoration was excluded from alternatives due to recent completion and uncertainties about the benefits of tidal wetland habitat restoration.

P.3 Public Draft Environmental Impact Statement Scenarios

None of the Public Draft Environmental Impact Statement scenarios include additional Delta wetland habitat restoration.

P.4 Performance Metrics

Performance metrics describe criteria that can be measured, estimated, or calculated relevant to informing trade-offs for alternative management actions.

P.4.1 Habitat

Various field-occupancy and laboratory studies have demonstrated Delta smelt association with a set of physical conditions, such as turbidity, salinity, current speed, and temperature (Feyrer et al. 2011; Bever et al. 2016; Hasenbein et al. 2016; Davis et al. 2019a, Davis et al. 2019b).

Consequently, suitable physical habitat for Delta smelt can be modeled based on appropriate ranges of these variables. Increase of suitable habitat was the basis of the fall X2 action, where the low-salinity zone is moved farther downstream of the Delta. Operation of the Suisun Marsh Salinity Control Gate during summer and fall is expected to increase suitable habitat in Suisun Marsh by lowering salinity (Sommer et al. 2020). However, food-subsidy actions are not expected to have any measurable effect on the physical habitat of Delta smelt.

P.4.2 Zooplankton Abundance, Biomass, and Community Composition

The availability and quality of prey have been identified as important drivers of juvenile and subadult Delta smelt and longfin smelt growth and survival (Figure P-3, Figure P-4, and Figure P-5). An objective of habitat restoration is creating more suitable physical habitat that enhances zooplankton production and biomass. The regional focus of these habitat restoration activities is primarily the Suisun (i.e., Suisun Bay, Grizzly Bay, and Suisun Marsh), Cache Slough, and Yolo Bypass.

A habitat suitability index can include both physical and biological conditions that support Delta smelt. One method is calculating a weighted food-availability score by multiplying the average zooplankton biomass in each region/month for a scenario by the habitat suitability index (California Department of Water Resources 2022). This method has been utilized for summer–fall habitat actions. Including both physical habitat and zooplankton prey in a single index more directly evaluates the potential benefit of habitat restoration projects.

P.4.3 Biological

Biological metrics consider direct observations and environmental surrogates.

- Smelt metrics (Delta and longfin)
 - Survival rate
 - Growth rate
- Juvenile salmonid metrics (winter-run and spring-run Chinook salmon, steelhead)
 - Survival rate
 - Growth rate

P.4.4 Water Supply

Water supply metrics consider the multipurpose beneficial uses of Delta habitat restoration.

- South-of-Delta agricultural deliveries (average and critical/dry years).
- San Joaquin river exchange and settlement contracts and Central Valley Project Improvement Act refuge deliveries.
- Frequency of when Old and Middle River is controlling exports.

Water supply in the Delta can be affected by habitat restoration. CalSim II would support the evaluation of water supply metrics once project-specific design details are available.

P.4.5 National Environmental Policy Act Resource Areas

Considerations under the National Environmental Policy Act would include changes in multiple resource areas. Key resources are anticipated to include surface water supply, water quality, air quality, aquatic resources, terrestrial biological resources, regional economics, land use and agricultural resources, recreation, cultural resources, hazards and hazardous material, and climate change.

P.5 Method Selection

Reclamation and the California Department of Water Resources (DWR) organized the best available information for evaluating the impacts of Delta wetland habitats as described below.

Although there was no knowledge-based paper for Delta habitat restoration, many of the datasets, literature, and models overlapped. These appendices considered the knowledgebase papers and additional literature and determined the most relevant approach for Reclamation in answering management questions and evaluating options for potential alternatives.

Since implementation of the Record of Decision and Incidental Take Permit, Reclamation and DWR have applied a series of non-flow, habitat-restoration actions within the Delta to improve spawning and rearing habitat and foodweb conditions. The *Long-Term Operations Habitat Restoration Seasonal Report*, updated annually or as needed, lists planned, under-construction, and recently completed habitat-restoration actions. Reclamation and California Department of Water Resources have developed multiple documents that are being used to understand and monitor the effects of these actions, identify science and monitoring needs, identify relevant models and data sets, and guide structured decision making. Documents include the following: (1) Science and Monitoring Plan, updated annually; (2) action-specific operations and science plans, updated every 1 to 3 years; (3) structured decision-making process document and performance measure information sheets (California Department of Water Resources 2022, Appendix B); and (4) 2022 Action Plan (California Department of Water Resources 2022).

P.5.1 Datasets

Habitat restoration can have a positive impact on Federally listed native fish species and its success is influenced by multiple factors, including hydrology, water quality, and fish population abundances and distribution in the Bay-Delta. Monitoring of hydrodynamics, water quality, and fish populations has been ongoing for over forty years, for some datasets, and covers a large spatial extent of the Bay-Delta. None of these have been focused on restoration and baseline sites. However, these data serve as the foundation and to illustrate patterns of interannual variability in historical hydrology and exports and trends in water quality. They also provide data and visualizations of trends in Federally listed native fish population abundances and distribution. These data are presented in Appendix I, *Old and Middle River Flow Management*; Appendix J, *Winter and Spring Pulses and Delta Outflow*; and Appendix K, *Summer and Fall Delta Outflow and Habitat*.

No additional datasets are included for hydrodynamics or water quality, since there are no independent data collected regarding Delta habitat restoration. Additional information regarding biological data being collected around Delta habitat restoration sites is described.

P.5.1.1 Hydrodynamics

No additional data collected at Delta habitat restoration sites.

P.5.1.2 Water Quality Parameters

No additional data collected at Delta habitat restoration sites.

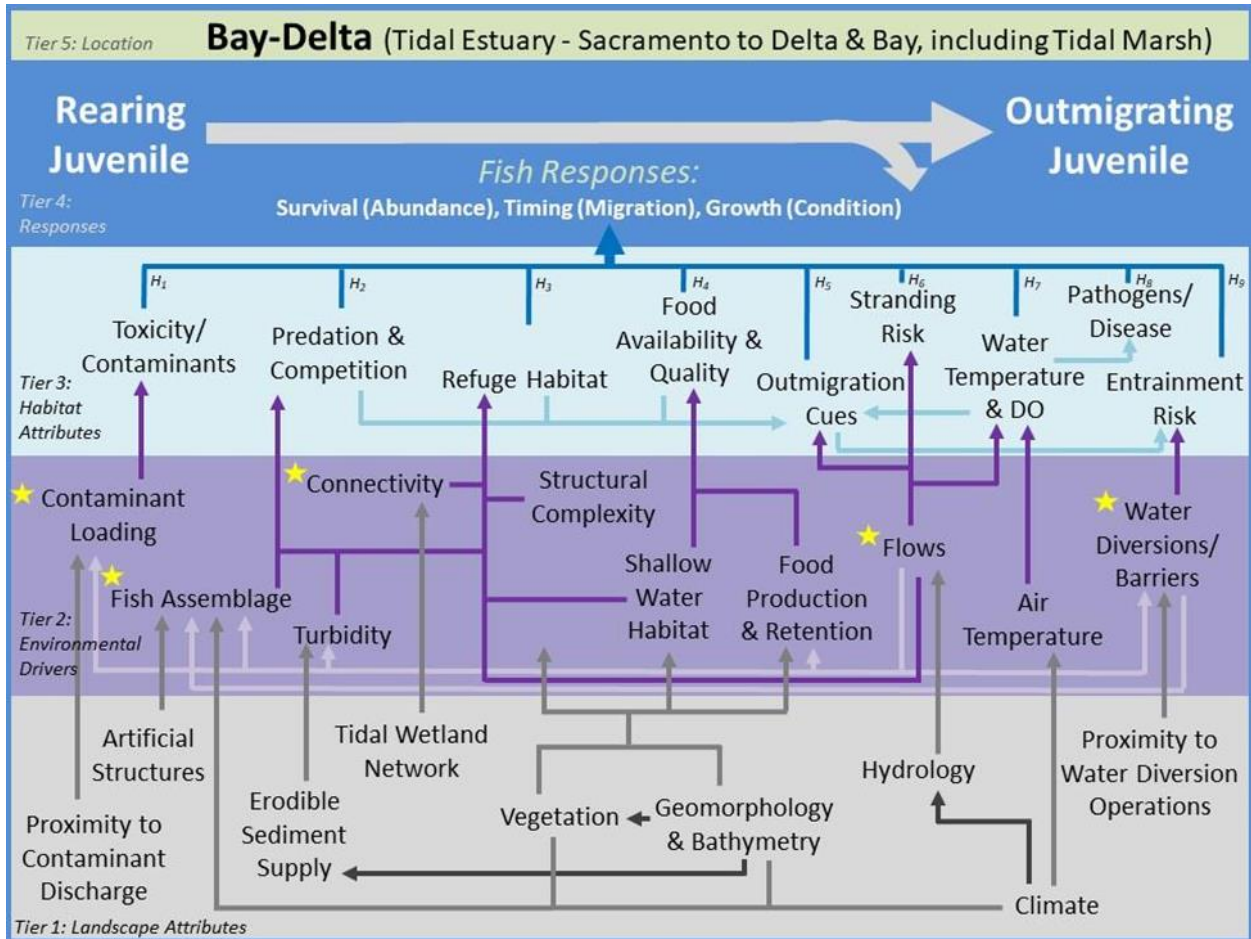
P.5.1.3 Biological Observations

The California Department of Fish and Wildlife (CDFW) Fisheries Restoration Program undertake biological monitoring of restoration and baseline sites in the Bay-Delta. Data collected by CDFW include phytoplankton, zooplankton/mesosoplankton, benthic invertebrates, and fish observations. These data have not been summarized.

P.5.2 Literature

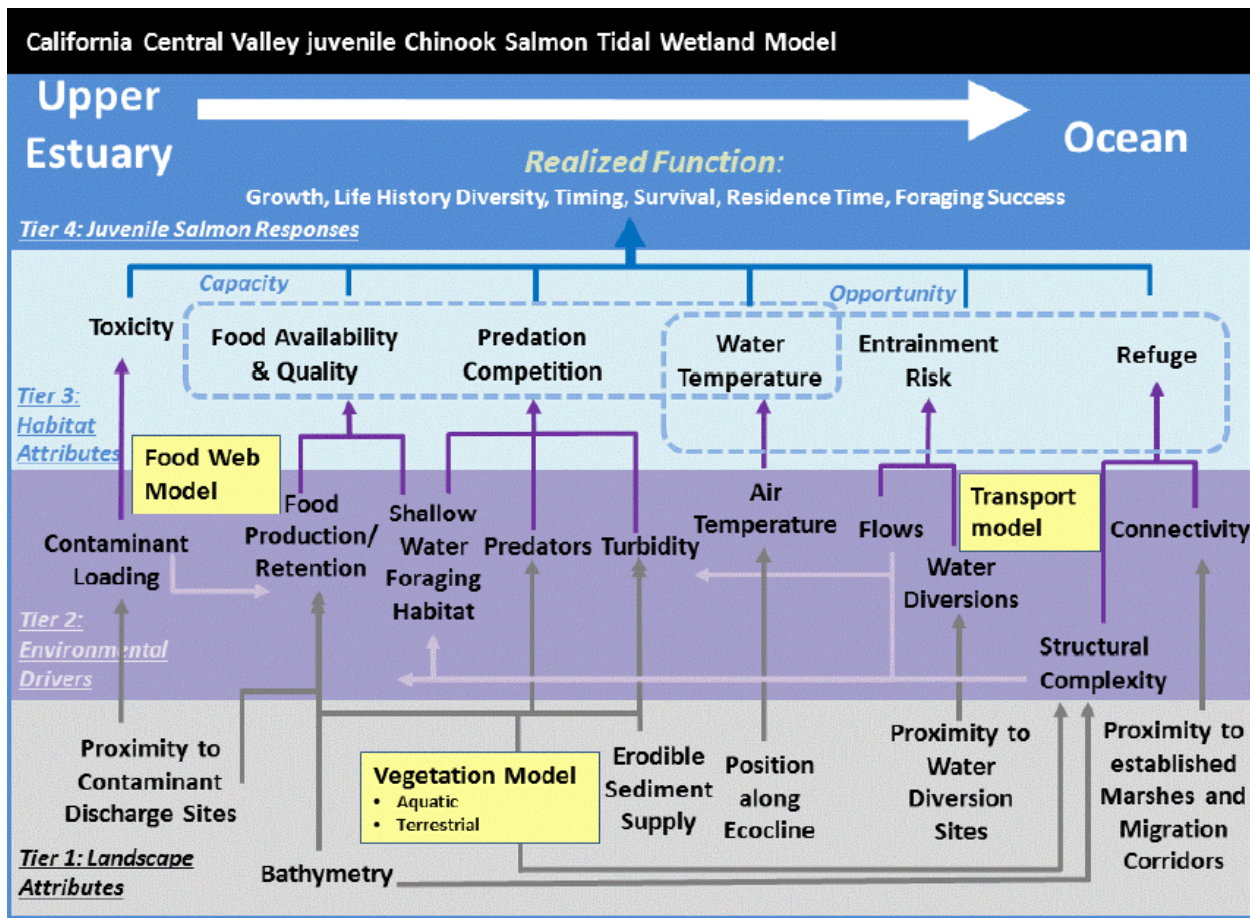
P.5.2.1 Chinook Salmon and Steelhead

Delta habitat restoration can affect the growth, survival, and life-history diversity of juvenile Central Valley Chinook salmon. Chinook salmon and steelhead use side-channel and floodplain habitat along Delta shorelines for feeding and growth, and the Delta can serve as a transition zone between freshwater rearing and saltwater entry. Figure P-1 and Figure P-2 provide conceptual models for effects of habitat conditions on fish responses during the transition from rearing to outmigrating in the Delta. Delta habitat restoration is expected to influence aspects of habitat conditions, including turbidity, structural complexity, connectivity, shallow-water habitat, and food production and retention.



Source: Copied from Windell et al. 2017.

Figure P-1. Conceptual Model of Attributes Affecting the Transition of Winter-run Chinook Salmon from Rearing Juvenile to Outmigrating Juvenile in the Delta



Source: Sherman et al. 2017.

Figure P-2. Central Valley Juvenile Chinook Salmon Tidal Wetland Conceptual Model

Delta habitat restoration can affect the growth of juvenile salmon through modifications to water temperature, food availability, and competition for resources. Shallow Delta habitats, including wetlands and floodplains, typically exhibit greater temperatures, higher residence times, and greater production and retention of macroinvertebrates, with resulting positive effects on growth rates relative to channeled habitat (Schemel et al. 2003; Jeffres et al. 2008).

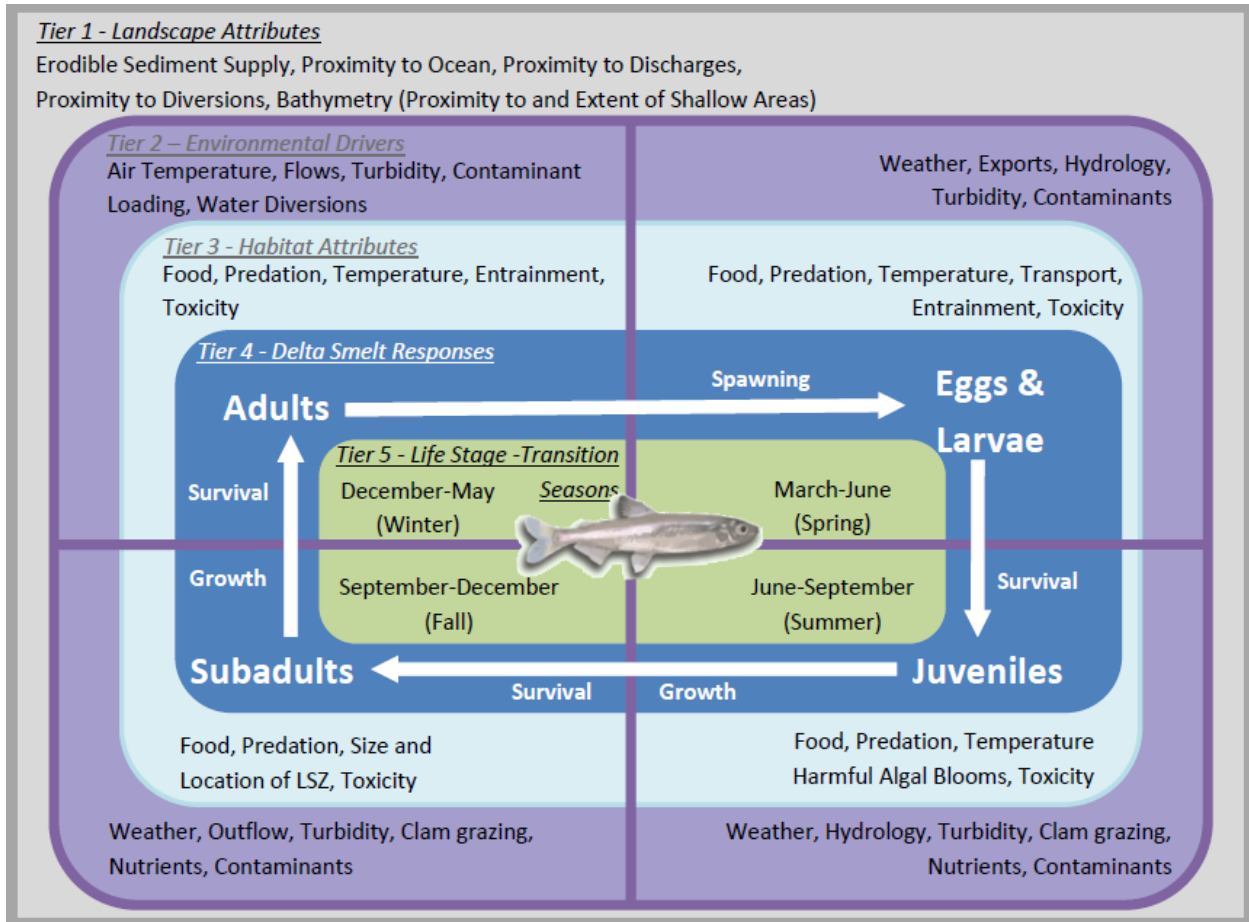
Delta habitat restoration can affect juvenile salmon by providing greater food resources and increasing cover or bathymetric heterogeneity as refugia from predators (Rahel and Stein 1998; Hering et al. 2010). Increased connectivity and habitat heterogeneity also can allow salmon to adapt and move in response to locally stressful conditions (Armstrong et al. 2013).

P.5.2.2 Delta Smelt

The Bay-Delta's Mediterranean climate means that, in a typical year, Delta smelt experience wet conditions (i.e., high precipitation and flows) during the winter and spring months, and dry and low flow conditions in the summer–fall months. Delta smelt occur primarily in the low-salinity and freshwater portions of the Bay-Delta. Historically, the center of distribution of Delta smelt closely followed the location of the low-salinity zone (as approximated by X2; Sommer et al. 2011). However, in more recent years, there is growing recognition that a substantial portion of the Delta smelt population can reside year-round in the perennially freshwater Cache Slough Complex (Mahardja et al. 2019; Hobbs et al. 2019).

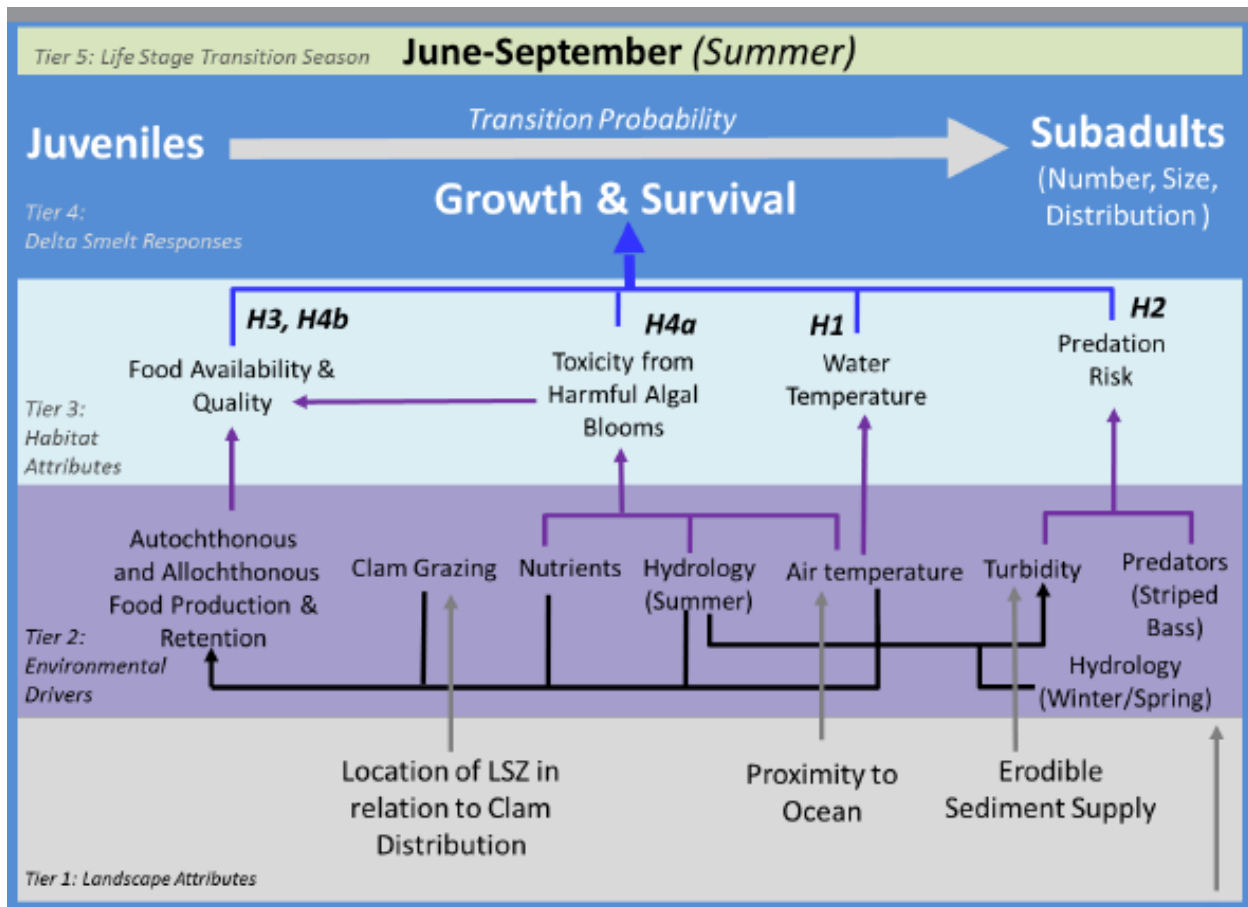
During the summer–fall period, subadult Delta smelt primarily rear in the western Delta, Suisun Bay, and Cache Slough Complex (Merz et al. 2011; Sommer and Mejia 2013; Interagency Ecological Program 2015). Although Delta smelt used to occur in the central and southern Delta during the summer–fall months, this is no longer the case (Nobriga et al. 2008). The degree to which Delta smelt use these areas depends on salinity, temperature, and turbidity (Nobriga et al. 2008; Feyrer et al. 2011); other factors may affect their summer distribution, such as the presence of *Microcystis* blooms and prey density, bathymetric features, or other water-quality constituents. Periods of low outflow are thought to be stressful for Delta smelt because the volume of physically suitable habitat becomes restricted by encroaching salinity (Feyrer et al. 2011). As such, the summer–fall period may represent a seasonal bottleneck for the species as freshwater flows reach their annual nadir, and access to seaward habitat (e.g., Suisun Marsh) is lost, particularly during droughts (Hammock et al. 2021).

Habitat restoration is aimed toward increasing food subsidies for Delta smelt. During the spring and summer, Delta smelt rear in the low-salinity zone. Thus, restoration projects that target areas adjacent to rearing areas (e.g., western Delta, Suisun Bay, Cache Slough Complex) and create suitable conditions for Delta smelt are expected to benefit Delta smelt.



Source: Interagency Ecological Program 2015.

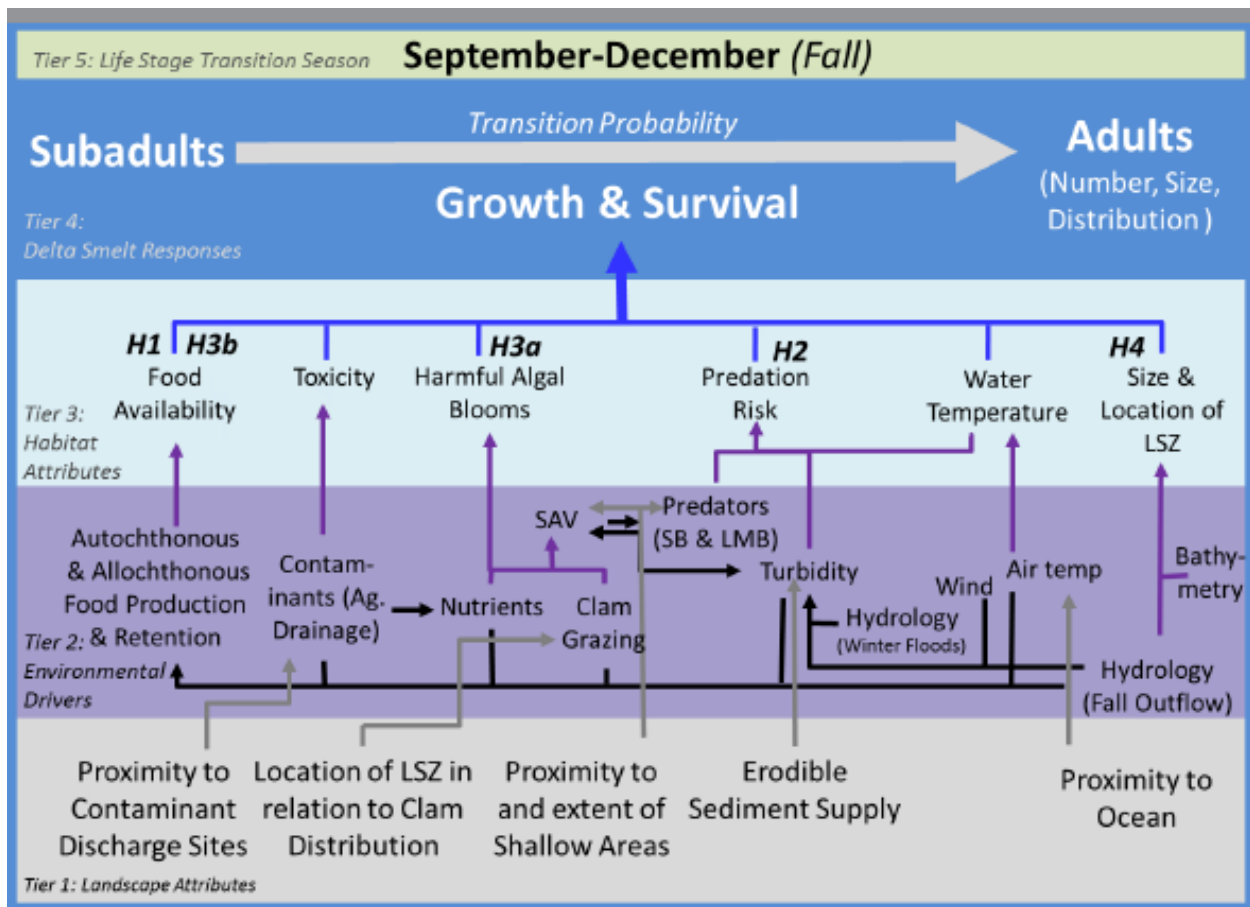
Figure P-3. Delta Smelt Conceptual Model



Source: Interagency Ecological Program 2015.

Figure P-4. Juvenile to Subadult Delta Smelt Conceptual Model

Habitat restoration is designed primarily to increase food availability and quality, leading to increased growth and survival. Site selection and design characteristics are important for determining water temperature, turbidity, and nutrients and can also influence predation risk, clam grazing, and nutrient availability, all of which would affect survival of Delta smelt.

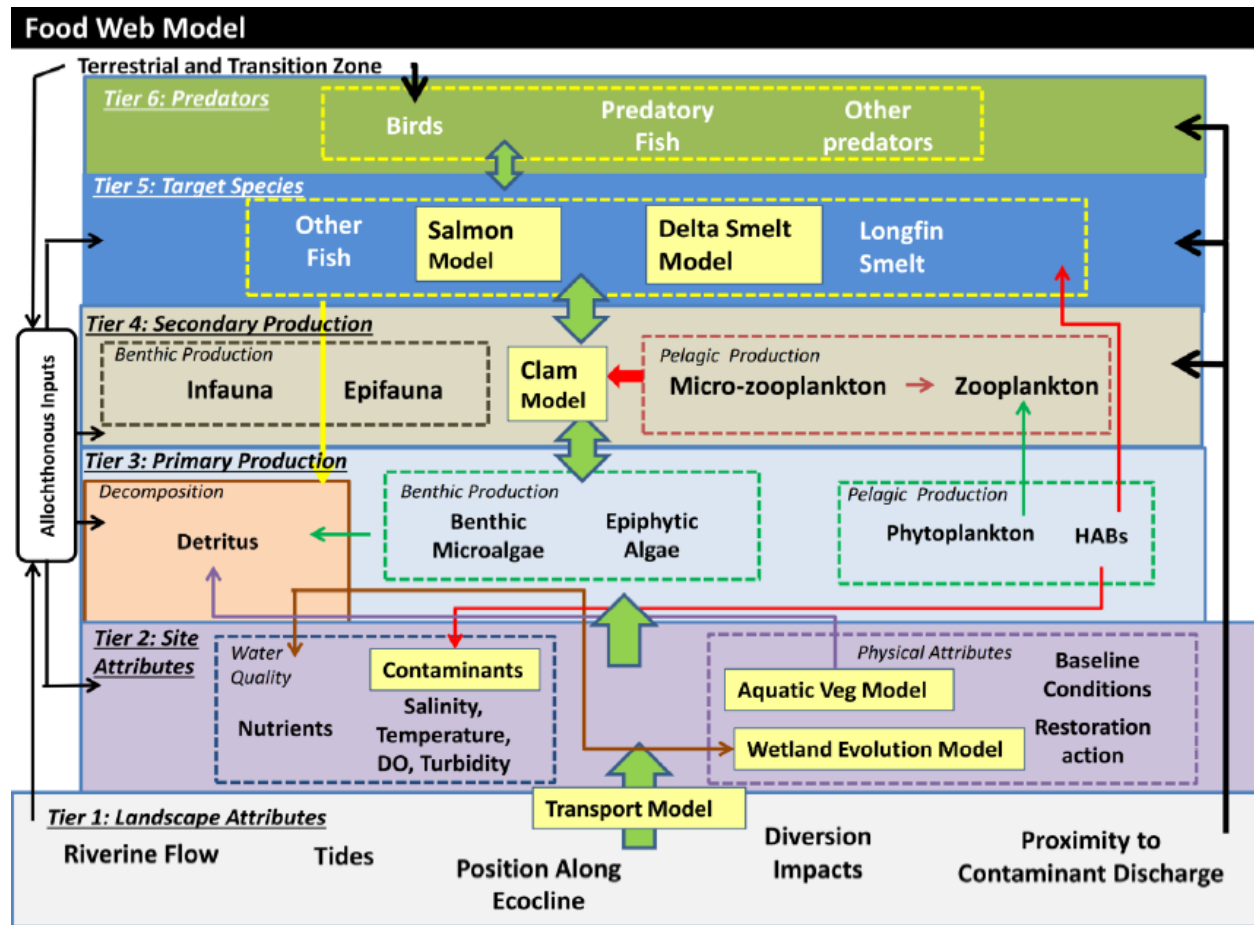


Source: Interagency Ecological Program 2015.

Figure P-5. Subadult to Adult Delta Smelt Conceptual Model

Habitat restoration is designed primarily to increase food availability, leading to greater growth and survival. Site selection and design characteristics are important for determining water temperature, turbidity, and nutrients and can also influence predation risk, submerged aquatic vegetation, clam grazing, and nutrient availability, all of which would affect survival of Delta smelt.

P.5.2.3 Food Web/Transport

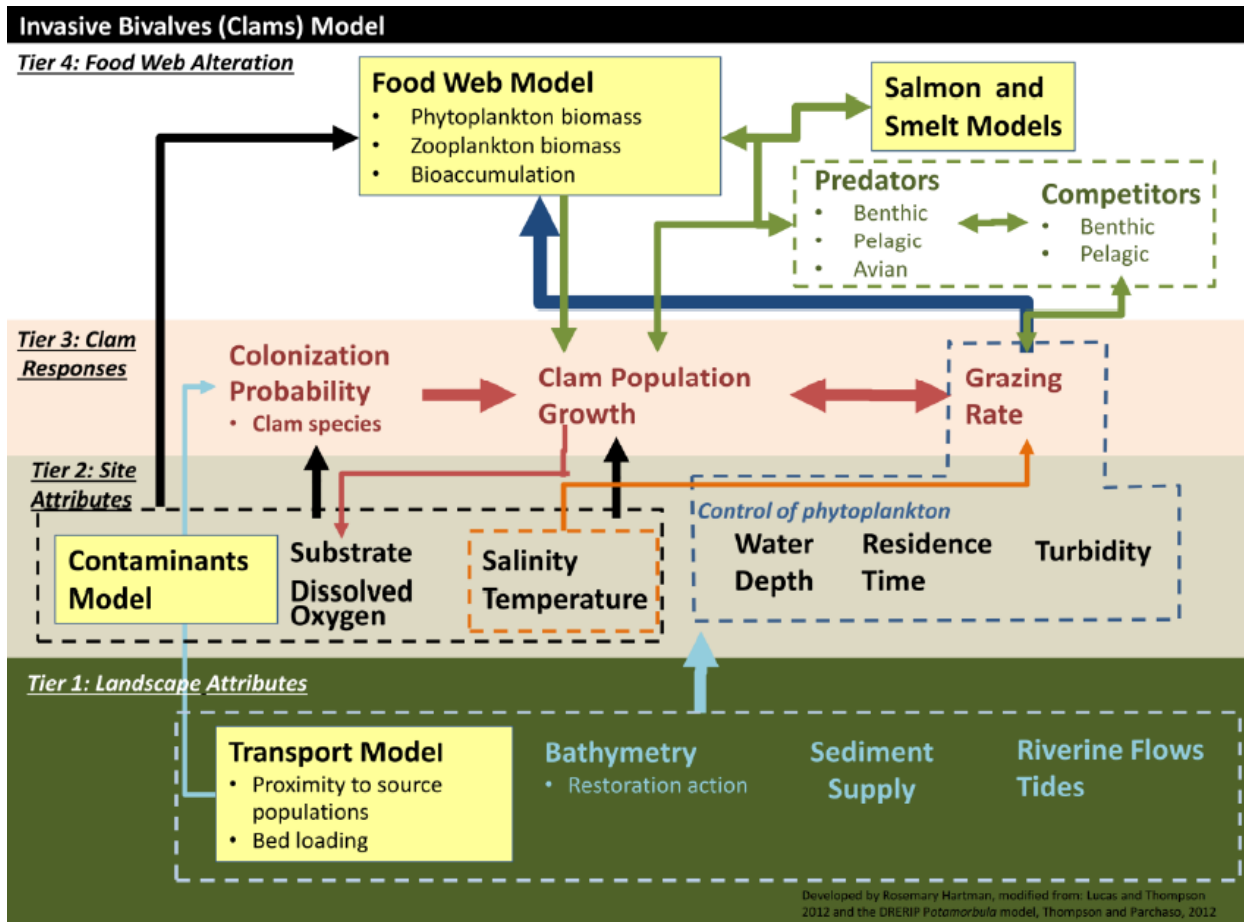


Source: Sherman et al. 2017.

The foodweb conceptual model describes the foodweb structure in tidal wetlands, with a focus on Species of Concern. Arrows indicate relationships between variables. All variables surrounded by boxes influence each other. The model links to other tidal wetland conceptual models as indicated by yellow boxes.

Figure P-6. Foodweb Conceptual Model

Delta restoration aims to increase food availability for fishes. Site selection and design characteristics can influence the water quality and presence of aquatic vegetation, which would, in turn, influence primary production, secondary production, and, thus, fish growth. Aquatic vegetation and environmental conditions may also influence the presence of predators, which can influence Delta smelt survival.

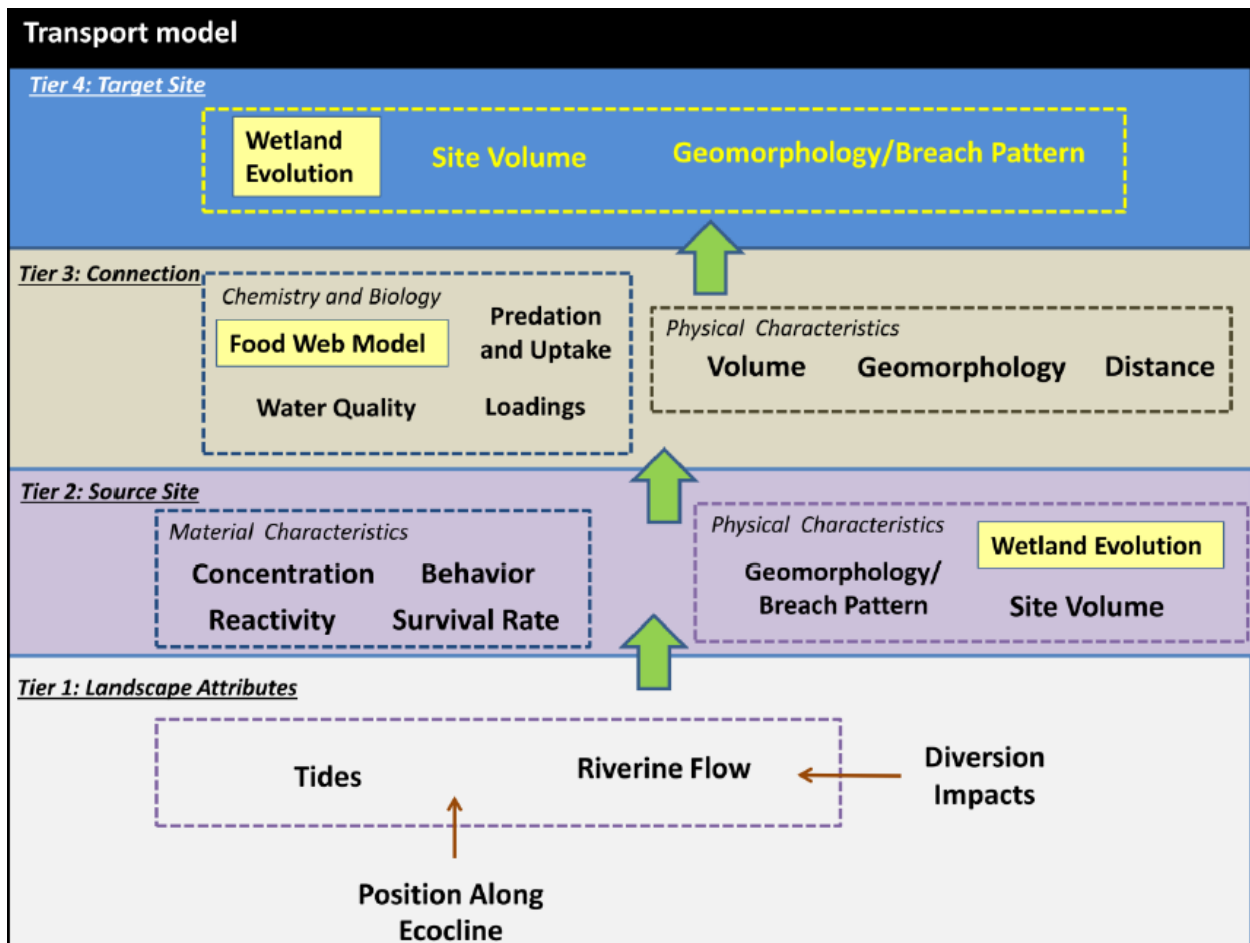


Source: Sherman et al. 2017.

Arrows indicate relationships where variables influence other variables. All variables surrounded by boxes influence each other. The model links to other tidal-wetland conceptual models (i.e., Foodweb Model, Contaminants Model, and Transport Model), as indicated by yellow boxes. (Present model developed by Rosemary Hartman, modified from Lucas and Thompson 2012 and the DRERIP Potamocorbula model, Thompson and Parchaso 2012).

Figure P-7. Invasive Bivalve Conceptual Model

Site selection and restoration design may affect the colonization of a site by invasive clams. Restoration designs that can balance residence time with tidal and riverine flows may influence clam population and growth, which affects the productivity of the food web, and, thus, fish growth and survival.



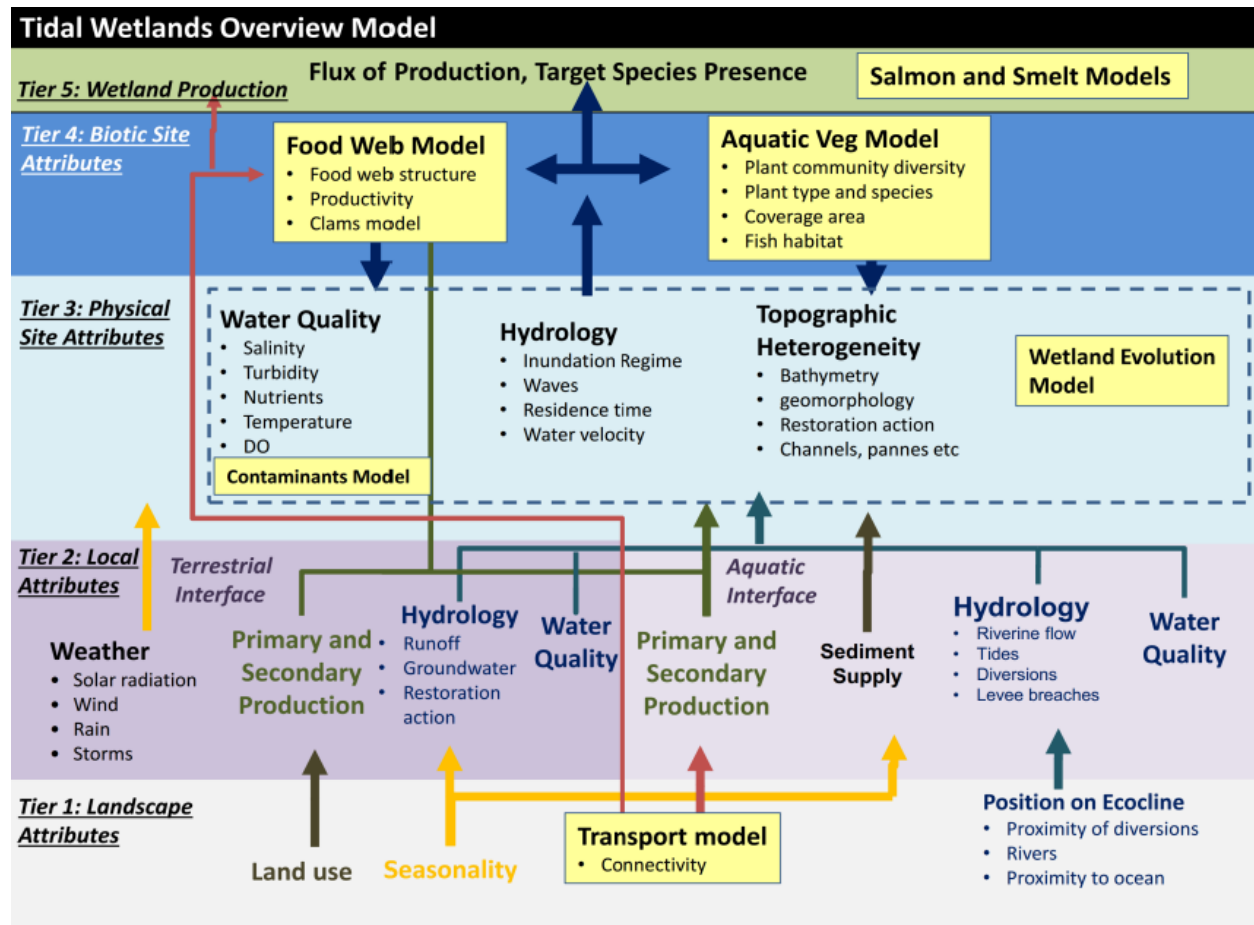
Source: Sherman et al. 2017.

This model depicts a general framework of how materials are exchanged between regions of a tidal estuary. Arrows indicate relationships between variables. All variables surrounded by boxes influence each other. The model links to other tidal wetland conceptual models (Food Web Model and Wetland Evolution Model), as indicated by yellow boxes.

Figure P-8. Transport Conceptual Model

Site selection and design for restoration would determine the effectiveness of food transport. The geomorphology and volume of the entire transport pathway would affect how food is transported into the target site, influencing the habitat conditions, productivity, and ability of fish to access any food created by restoration.

P.5.2.4 Habitat



Source: Sherman et al. 2017.

This conceptual model emphasizes processes that may influence restoration trajectories and affect ecosystem responses. Arrows indicate relationships between variables. All variables surrounded by boxes influence each other. The model links to sub-models, as indicated by yellow boxes.

Figure P-9. Tidal Wetlands Overview Conceptual Model

P.5.3 Models

P.5.3.1 Habitat

The habitat suitability index for Delta smelt can be calculated using a methodology derived from Bever et al. (2016), Resources Management Associates (2021), and Bay-Delta SCHISM output (California Department of Water Resources 2022, Appendix B). The index represents spatially and temporally averaged suitability of habitats within the Bay-Delta.

P.5.3.2 Zooplankton

Delta habitat restoration is aimed at creating high-quality, productive habitat for salmon and smelt. To evaluate this action, the Zooper package, with integrated zooplankton data, can be used to calculate zooplankton abundance near different types of habitats.

P.5.3.3 Delta Smelt

Delta Smelt Life Cycle Models

Delta smelt growth and survival historically have relied on monitoring surveys (see Section P.5.1, *Datasets*) for analysis of the population abundance. Fish collected in monitoring surveys have subsequently been processed in laboratory studies of health (Hammock et al. 2021) and growth (Xieu et al. 2022). However, continued decline in the population has made the capture of wild Delta smelt rare and modeling a more resilient management tool for this performance metric. Delta smelt life-cycle models, population models, and growth models are used to model changes in Delta smelt growth and survival under different management actions. Data and model output generated to evaluate habitat suitability and zooplankton prey–performance metrics can be incorporated into some of these models to predict individual (e.g., Delta smelt bioenergetics) and population-level (e.g., Delta Smelt Individual-Based Model) responses to different restoration projects including:

- Kimmerer and Rose (2018): Individual-Based Modeling of Delta Smelt Population Dynamics in the Upper San Francisco Estuary III. Effects of Entrainment Mortality and Changes in Prey
- Bioenergetics-based habitat suitability, from the Individual-Based Model in R (Rose et al. 2013a, 2013b; Smith 2021)
- Delta Smelt Individual Based Model in R (Rose et al. 2013a, 2013b; Smith 2021)
- Bioenergetics-based growth model (Fujiwara et al. 2015)

P.6 Lines of Evidence

Reclamation’s management questions for the formulation of an alternative include the following.

P.6.1 Where is a Delta habitat limitation affecting Delta smelt and outmigrating salmonids?

The San Francisco Estuary Institute characterized expected rearing-habitat availability in the Delta for juvenile Chinook salmon and steelhead using available data and broke down habitat availability by spatial region (San Francisco Estuary Institute 2020). These efforts revealed gaps or limitations in rearing-habitat availability in the Sacramento River Mainstem, San Joaquin Mainstem north of Stockton, Georgiana Slough and North Mokelumne River, and south Delta. The San Francisco Estuary Institute analysis further estimated that an additional 23,475 acres of marsh and other floodplain habitats would be needed for salmon rearing in the Delta, beyond habitat that already exists or is planned for restoration. A separate analysis by Cramer Fish Sciences estimated that 11,200 and 4,600 acres of suitable rearing habitat are necessary in the Lower Sacramento River and Lower San Joaquin River, respectively, to achieve Anadromous Fish Restoration Program doubling goals, based on territory size (California Department of Water Resources 2016).

One of the major stressors implicated in the decline of Delta smelt is the loss of productive wetland habitat (Sherman et al. 2017). Although there is little information available about Delta smelt spawning habitat and the attributes needed for successful spawning (Interagency Ecological Program 2015), wetlands are hypothesized to provide some spawning habitat, and other life stages of Delta smelt appear to benefit from proximity to tidal wetland habitat and other long residence–time habitat (Hammock et al. 2019; Sommer and Mejia 2013). Restoration projects are thus focused on creating areas for rearing and refuge and for increasing and transporting food subsidies to adjacent open-water habitats Delta smelt inhabit (Sherman et al. 2017).

Juvenile Delta smelt are most affected by habitat limitation because their life stage overlaps with warmer temperatures, and Delta smelt are sensitive to high water temperatures. In the field, they are rarely found above 25°C (Nobriga et al. 2008), and they experience sublethal effects above 20°C (Jeffries et al. 2016). During the summer, more food is needed to meet energetic demands. Delta smelt are also particular to specific ranges of salinity and turbidity during each life stage (Dege and Brown 2004; Feyrer et al. 2007; Nobriga et al. 2008; Swanson et al. 2000), and development and climate change are likely to alter these parameters and decrease the amount of suitable habitat in the future (Feyrer et al. 2011). Although less is known about longfin smelt, juvenile and adult longfin smelt are also stressed by temperatures and food availability (Rosenfield 2010).

Delta smelt and longfin smelt migrate throughout the course of the year, so different regions of the Delta may benefit the fishes at different times of the year (Sommer et al. 2011). Juvenile life stages are found in the North Delta Arc, between the Cache Slough Complex and the Suisun Bay and Marsh. Although tidal marsh and shallow, flooded habitat is in the Suisun Marsh, many of these habitats are not connected to the rest of the estuary. Restoration targeting barrier removal and areas adjacent to areas occupied by smelt can increase access to food subsidies for smelt (Hobbs et al. 2017). In the Cache Slough Complex and Yolo Bypass, increasing habitat and tidal wetland restoration could also provide food and habitat for smelt (Hobbs et al. 2017).

P.6.2 Does habitat restoration increase primary and secondary productivity and improve somatic growth of target species?

Primary and secondary productivity depends on restoration design and environmental conditions and can be highly variable, even between similar sites (Lucas et al. 2002, 2009; Sherman et al. 2017). Restoration sites that are shallow and have high residence times are predicted to create higher primary productivity (Sherman et al. 2017; Sommer and Mejia 2013), and when these shallow productive habitats are adjacent to deeper and less-productive channels, they may subsidize food production in pelagic areas (Lucas et al. 2009). Other factors, such as the quality of food (i.e., phytoplankton species), presence of harmful algal blooms, aquatic vegetation densities, nutrient concentrations, and, especially, clam grazing, can interact with and significantly decrease primary productivity and be hard to predict or control in a new restoration site (Cloern and Dufford 2005; Lucas et al. 2002; Sherman et al. 2017; Sommer and Mejia 2013).

Studies of habitat restoration effects in the Delta are rare for salmon and steelhead, but insights may be obtained from monitored restoration efforts in other highly modified estuarine systems. Studies in Washington estuaries observed differing diet composition among restored and reference sites, but similar salmon growth rates (Cordell et al. 2011; David et al. 2014; Woo et al. 2017). Estimated invertebrate productivity from restored mudflat habitat in Washington was comparable to reference sites three years after establishment, and growth rates of juvenile Chinook salmon were similar between restored and reference sites (Davis et al. 2017). These studies suggest that restored sites can result in secondary productivity and fish growth rates similar to similar reference sites (e.g., from a habitat type that did not require restoration). Limited information is available on primary productivity. These findings on restoration and productivity can also inform expected growth of Delta smelt.

Few studies document the effects of habitat restoration on productivity and growth for smelt. In Blacklock Marsh, restored wetland had lower productivity and fish diversity and higher invasive species, as compared with nearby sloughs and managed wetlands (Williamshen et al. 2021). Preliminary studies at the Liberty Island Ecological Reserve indicated that habitat diversity may be beneficial for increasing prey diversity, which may allow smelt to diversify their feeding strategies when pelagic zooplankton are in low abundance (Hartman et al. 2019; Whitley and Bollens 2014). Other studies have also targeted restoration habitat types and areas. In Suisun Marsh, one study found that stomach fullness in Delta smelt increased with increases in tidal wetland areas, attributed mainly to increased predation on larval fish, but also increased predation on zooplankton, and another found that nursery habitat adjacent to shallow, warm water produced larval smelt of higher condition and higher densities of Delta smelt (Hammock et al. 2019; Hobbs et al. 2006). These results indicate that restoration of shallow habitats may benefit feeding opportunities for smelt when adjacent to smelt habitat. Studies in the Yolo Bypass, where restoration is planned, have found greater phytoplankton and insect concentrations in the floodplain, compared with the mainstem river, and greater insect densities during flooding of floodplain habitat (Benigno and Sommer 2008; Sommer et al. 2004).

P.6.3 What is the energy flow of habitat restoration productivity to different regions of the Delta, fish, and/or clams?

Comparisons of phytoplankton biomass, production, and growth rates among depth strata in the Bay-Delta indicate that transport and consumption are meaningful controls on local phytoplankton biomass (Lopez et al. 2006). Transport processes are determined by the nature of the material, the structure of the source and target sites, and the nature of the connecting channels, and can be influenced by tidal cycles and outflow, which influence the water-residence time and flushing rates (Enright et al. 2013; Sherman et al. 2017). Transport of plankton outside of the tidal exchange zone is likely limited. For smelt, productivity transfer is most likely to provide benefits where open waters adjacent to shallow, productive habitats have smaller volumes, so that any productivity created is not diluted (Herbold et al. 2014). Areas colonized by the invasive clam *Corbicula fluminea* functioned as food sinks, due to consumption, whereas uncolonized areas may serve as food sources. Effects of habitat restoration actions may require a regional perspective to capture connectivity among other habitats, and site-specific design understanding transportation is important for supporting phytoplankton reaching targeted species and reducing the effect of nonnative species competing and consuming these food resources (Herbold et al. 2014).

P.6.4 Does habitat restoration provide refuge and improve survival for Delta smelt or salmonids?

Limited information is available about the effects of estuary restoration on juvenile Chinook salmon or steelhead survival in general, let alone in the Delta. Survival of rearing fry is a knowledge gap. One study suggests that survival of wild migrant fry Chinook salmon was higher in pocket-estuary habitat (i.e., areas with less saline water near creek mouths or coastal embayments) in Washington estuaries, which could serve as structural and salinity-based refugia (Beamer et al. 2006). Restoration of similar low-flow habitats in the Delta could provide a similar benefit. The importance of the Delta as a transition zone before saltwater entry suggests that increased habitat availability and capacity via restoration may have indirect, positive effects of survival (del Rosario et al. 2013). Habitat restoration that increases bathymetric heterogeneity may also provide refugia and increase access to preferred depths for rearing fry across tidal cycles (McLain and Castillo 2009; Hering et al. 2010).

Limited information is also available about the effects of estuary restoration on Delta smelt and longfin smelt. There is some evidence of higher abundances of longfin smelt in restored tidal wetlands in the San Francisco Bay (Lewis et al. 2020); however, smelt, especially Delta smelt, are rarely caught in surveys. Thus, many evaluations of restoration success are more focused on increasing productivity. Habitat restoration may improve survival where sites meet the habitat requirements of species (e.g. water quality), where there are few predators, contaminants, clams, and invasive species, where sites are far from export facilities, and where there is potential to accommodate sea-level rise (Herbold et al. 2014; Sherman et al. 2017; Sommer and Mejia 2013). Restoration outcomes can be very different, though, depending on the physical configuration of projects (U.S. Geological Survey et al. 2020). Restoration is most likely to provide benefits where open waters adjacent to shallow, productive habitats have smaller volume, so any productivity created is not diluted (Herbold et al. 2014).

P.6.5 How does habitat restoration affect operations for flood conveyance, water supply, and/or water quality?

Habitat restoration is constrained by flood conveyance, water supply, and water quality and can contribute to increasing flexibility in each factor. For example, the flood conveyance baseline continually changes as riverbeds downgrade from sediment movement without replacement. The downgraded condition becomes the new baseline for subsequent habitat projects, which limits the scope of the project. When habitat projects can expand flood conveyance laterally, they can increase habitat, while maintaining and potentially increasing conveyance capacity. These same projects can increase the amount of time that water remains on streamside areas, thus increasing groundwater storage for the future.

Habitat projects can be designed to provide suitable habitats at flow regimes with less variability than the historic habitats experienced. Downcutting of river mainstems has disconnected off-channel habitat, such as side channels and floodplains. Restored habitats can be developed to inundate in lower-flow conditions and result in less water needed to maintain suitable habitats.

Habitat restoration can improve water quality by providing backwater areas for suspended sediment to settle out, resulting in cleaner water and fertile soils for riparian or marsh vegetation establishment.

P.7 Uncertainties

Hydrodynamic and water quality effects of tidal wetland restoration on refuge habitat and food quantity and quality stressors are not well documented. The Bay-Delta lacks mechanistic models to explain individual effects to fish from these restoration actions. Uncertainty remains around how individual effects, from Delta habitat restoration, may affect Endangered Species Act (ESA) listed species populations.

Special studies of high value that may reduce uncertainty about the effectiveness of wetland restoration for ESA listed salmonids and smelt include:

- Summer-Fall Habitat Action for Delta Smelt
- Tidal Habitat Restoration Effectiveness for smelt and salmonid fishes
- Spring outflow

P.8 References

Armstrong et al. 2013

Beamer, E., A. McBride, R. Henderson, J. Griffith, K. Fresh, T. Zackey, R. Barsh, T. Wyllie-Echverria, and K. Wolf. 2006. Habitat and fish use of pocket estuaries in the Whidbey Basin and North Skagit County bays 2004–2005. Skagit System Cooperative. Available: <http://skagitcoop.org/documents/>.

Benigno, G. M., and T. R. Sommer. 2008. Just add water: Sources of chironomid drift in a large river floodplain. *Hydrobiologia* 600(1):297–305. doi: <https://doi.org/10.1007/s10750-007-9239-2>.

Bever, A. J., M. L. MacWilliams, B. Herbold, L. R. Brown, and F. V. Feyrer. 2016. Linking hydrodynamic complexity to delta smelt (*Hypomesus transpacificus*) distribution in the San Francisco Estuary, USA. *San Francisco Estuary and Watershed Science* 14(1). doi: <http://dx.doi.org/10.15447/sfews.2016v14iss1art3>.

California Department of Water Resources. 2016. *Central Valley Flood Protection Plan Conservation Strategy. Appendix H – Central Valley Chinook Salmon Rearing Habitat Required to Satisfy the Anadromous Fish Restoration Program Doubling Goal*.

California Department of Water Resources. 2022. Delta Smelt Summer-Fall Habitat Action 2022 Action Plan. Division of Integrated Science and Engineering. 32 pp + appendices. Available on request.

Cloern, J. E., and R. Dufford. 2005. Phytoplankton community ecology: Principles applied in San Francisco Bay. *Marine Ecology Progress Series* 285:11–28. doi: <https://doi.org/10.3354/meps285011>.

- Cordell, J. R., J. D. Toft, A. Gray, G. T. Ruggerone, and M. Cooksey. 2011. Functions of restored wetlands for juvenile salmon in an industrialized estuary. *Ecological Engineering* 37:343–353.
- David, A. T., C. S. Ellings, I. Woo, C. A. Simenstad, J. Y. Takekawa, K. L. Turner, A. L. Smith, and J. E. Takekawa. 2014. Foraging and growth potential of juvenile Chinook salmon after tidal restoration of a large river Delta. *Transactions of the American Fisheries Society* 143:1515–1529.
- Davis, M. J., C. S. Ellings, I. Woo, S. Hodgson, K. Larsen, and G. Nakai. 2017. Gauging resource exploitation by juvenile Chinook salmon (*Oncorhynchus tshawytscha*) in restoring estuarine habitat. *Restoration Ecology* 26(5):976–986.
- Davis, B. E., D. E. Cocherell, T. Sommer, R. D. Baxter, T.-C. Hung, A. E. Todgham, and N. A. Fangué. 2019a. Sensitivities of an Endemic, Endangered California Smelt and Two Non-Native Fishes to Serial Increases in Temperature and Salinity: Implications for Shifting Community Structure with Climate Change. S. Cooke (ed.). *Conservation Physiology* 7(1). doi: <https://doi.org/10.1093/conphys/coy076>.
- Davis, B. E., M. J. Hansen, D. E. Cocherell, T. X. Nguyen, T. Sommer, R. D. Baxter, N. A. Fangué, and A. E. Todgham. 2019b. Consequences of temperature and temperature variability on swimming activity, group structure, and predation of endangered Delta smelt. *Freshwater Biology* 64(12):2156–2175. doi:10.1111/fwb.13403.
- Dege, M., and L. R. Brown. 2004. Effect of Outflow on Spring and Summertime Distribution and Abundance of Larval and Juvenile Fishes in the Upper San Francisco Estuary. 18.
- del Rosario, R. B., Y. J. Redler, K. Newman, P. L. Brandes, T. Sommer, K. Reece, and R. Vincik. 2013. Migration patterns of juvenile winter-run-sized Chinook salmon (*Oncorhynchus tshawytscha*) through the Sacramento-San Joaquin Delta. *San Francisco Estuary and Watershed Science* 11(1). doi: <https://doi.org/10.15447/sfews.2013v11iss1art3>.
- Enright, C., S. D. Culberson, and J. R. Burau. 2013. Broad Timescale Forcing and Geomorphic Mediation of Tidal Marsh Flow and Temperature Dynamics. *Estuaries and Coasts* 36(6):1319–1339. doi: <https://doi.org/10.1007/s12237-013-9639-7>.
- Feyrer, F., M. L. Nobriga, and T. R. Sommer. 2007. Multidecadal trends for three declining fish species: Habitat patterns and mechanisms in the San Francisco Estuary, California, USA. *Canadian Journal of Fisheries and Aquatic Sciences* 64(4):723–734. doi: <https://doi.org/10.1139/f07-048>.
- Feyrer, F., K. Newman, M. Nobriga, and T. Sommer, T. 2011. Modeling the Effects of Future Outflow on the Abiotic Habitat of an Imperiled Estuarine Fish. *Estuaries and Coasts* 34(1):120–128. doi: <https://doi.org/10.1007/s12237-010-9343-9>.

- Fujiwara, M., and J. E. Cohen. 2015 Mean and variance of population density and temporal Taylor's law in stochastic stage-structured density-dependent models of exploited fish populations. *Theoretical Ecology* 8:175–186. doi: <https://doi.org/10.1007/s12080-014-0242-8>.
- Hammock, B. G., R. Hartman, S. B. Slater, A. Hennessy, and S. J. Teh. 2019. Tidal Wetlands Associated with Foraging Success of Delta Smelt. *Estuaries and Coasts* 42(3):857–867. doi: <https://doi.org/10.1007/s12237-019-00521-5>.
- Hammock, B. G., R. Hartman, R. A. Dahlgren, C. Johnston, T. Kurobe, P. W. Lehman, and L. S. Lewis. 2021. Patterns and predictors of condition indices in a critically endangered fish. *Hydrobiologia* 849(3):675+. Available: <https://link.gale.com/apps/doc/A689823152/AONE>.
- Hartman, R., S. Sherman, D. Contreras, A. Furler, and R. Kok. 2019. Characterizing macroinvertebrate community composition and abundance in freshwater tidal wetlands of the Sacramento-San Joaquin Delta. *PLOS ONE* 14(11):e0215421. doi: <https://doi.org/10.1371/journal.pone.0215421>.
- Hasenbein, M., N. A. Fangué, J. P. Geist, L. M. Komoroske, and R. E. Connon. 2016. Physiological stress biomarkers reveal stocking density effects in late larval Delta smelt (*Hypomesus transpacificus*). *Aquaculture* 450:108–115. doi: <http://dx.doi.org/10.1016/j.aquaculture.2015.07.005>.
- Herbold, B., D. M. Baltz, L. Brown, R. Grossinger, W. Kimmerer, P. Lehman, C. (Si) Simenstad, C. Wilcox, and M. Nobriga. 2014. The Role of Tidal Marsh Restoration in Fish Management in the San Francisco Estuary. *San Francisco Estuary and Watershed Science* 12(1). doi: <https://doi.org/10.15447/sfews.2014v12iss1art1>.
- Hering, D. K., D. L. Bottom, E. F. Prentice, K. K. Jones, and L. A. Fleming. 2010. Tidal movements and residency of subyearling Chinook salmon (*Oncorhynchus tshawytscha*) in an Oregon salt marsh channel. *Canadian Journal of Fisheries and Aquatic Sciences* 67(3):524–533.
- Hobbs, J. A., W. A. Bennett, and J. E. Burton. 2006. Assessing nursery habitat quality for native smelts (*Osmeridae*) in the low-salinity zone of the San Francisco estuary. *Journal of Fish Biology* 69(3):907–922. doi: <https://doi.org/10.1111/j.1095-8649.2006.01176.x>.
- Hobbs, J. A., P. B. Moyle, N. Fangué, and R. E. Connon. 2017. Is Extinction Inevitable for Delta Smelt and Longfin Smelt? An Opinion and Recommendations for Recovery. *San Francisco Estuary and Watershed Science* 15(2). doi: <https://doi.org/10.15447/sfews.2017v15iss2art2>.
- Hobbs, J. A., L. S. Lewis, M. Willmes, C. Denney, and E. Bush. 2019. Complex life histories discovered in a critically endangered fish. *Scientific Reports* 9:16772. doi: <https://doi.org/10.1038/s41598-019-52273-8>.
- Interagency Ecological Program. 2015. An updated conceptual model of Delta Smelt biology: our evolving understanding of an estuarine fish. IEP Technical Report No. 90.

- Jeffres, C. A., J. J. Opperman, and P. B. Moyle. 2008. Ephemeral Floodplain Habitats Provide Best Growth Conditions for Juvenile Chinook Salmon in a California River. *Environmental Biology of Fishes* 83:449–458.
- Jeffries, K. M., R. E. Connon, B. E. Davis, L. M. Komoroske, M. T. Britton, T. Sommer, A. E. Todgham, and N. A. Fangué. 2016. Effects of high temperatures on threatened estuarine fishes during periods of extreme drought. *Journal of Experimental Biology* 219(11): 1705–1716. doi: <https://doi.org/10.1242/jeb.134528>.
- Kimmerer, W. J., and K. A. Rose. 2018. Individual-Based Modeling of Delta Smelt Population Dynamics in the Upper San Francisco Estuary III. Effects of Entrainment Mortality and Changes in Prey. *Transactions of the American Fisheries Society* 147(1):223–243.
- Lewis, L. S., M. Willmes, A. Barros, P. K. Crain, and J. A. Hobbs. 2020. Newly discovered spawning and recruitment of threatened Longfin Smelt in restored and underexplored tidal wetlands. *Ecology* 101(1):e02868. doi: <https://doi.org/10.1002/ecy.2868>.
- Lopez, C. B., J. E. Cloern, T. S. Schraga, A. J. Little, L. V. Lucas, J. K. Thompson, and J. R. Burau. 2006. Ecological values of shallow-water habitats: implications for the restoration of disturbed ecosystems. *Ecosystems* 9:422–440.
- Lucas, L. V., J. E. Cloern, J. K. Thompson, and N. E. Mosen. 2002. Functional Variability of Habitats Within the Sacramento–San Joaquin Delta: Restoration Implications. *Ecological Applications* 12(5):1528–1547. doi: [https://doi.org/10.1890/1051-0761\(2002\)012\[1528:FVOHWT\]2.0.CO;2](https://doi.org/10.1890/1051-0761(2002)012[1528:FVOHWT]2.0.CO;2).
- Lucas, L. V., J. R. Koseff, S. G. Monismith, and J. K. Thompson. 2009. Shallow water processes govern system-wide phytoplankton bloom dynamics: A modeling study. *Journal of Marine Systems* 75(1):70–86. doi: <https://doi.org/10.1016/j.jmarsys.2008.07.011>.
- Mahardja, B., J. A. Hobbs, N. Ikemiyagi, A. Benjamin, and A. J. Finger. 2019. Role of freshwater floodplain-tidal slough complex in the persistence of the endangered Delta smelt. *PLoS One* 14(1). doi:10.1371/journal.pone.0208084.
- McLain, J. S., and G. C. Castillo. 2009. Nearshore areas used by fry Chinook salmon, *Oncorhynchus tshawytscha*, in the Northwestern Sacramento-San Joaquin Delta, California. *San Francisco Estuary and Watershed Science* 7(2):1–13.
- Nobriga, M. L., T. R. Sommer, F. Feyrer, and K. Fleming. 2008. Long-Term Trends in Summertime Habitat Suitability for Delta Smelt, *Hypomesus transpacificus*. *San Francisco Estuary and Watershed Science* 6(1). doi:10.15447/sfews.2008v6iss1art1. Available: <https://escholarship.org/uc/item/5xd3q8tx>.
- Rahel, F. J., and R. A. Stein. 1998. Complex predator-prey interactions and predator intimidation among crayfish, piscivorous fish, and small benthic fish. *Oecologia* 75(1):94–98.
- Resources Management Associates. 2021. Numerical Modeling in Support of Reclamation Delta Smelt Summer/Fall Habitat Analysis. Report for the Bureau of Reclamation.

- Rose K. A., W. J. Kimmerer, K. P. Edwards, and W. A. Bennett. 2013a. Individual-based modeling of Delta Smelt population dynamics in the upper San Francisco Estuary: I. Model description and baseline results. *Transactions of the American Fisheries Society* 142(5):1238–1259. doi: <http://dx.doi.org/10.1080/00028487.2013.799518>.
- Rose, K. A., W. J. Kimmerer, K. P. Edwards, and W. A. Bennett. 2013b. Individual-Based Modeling of Delta Smelt Population Dynamics in the Upper San Francisco Estuary: II. Alternative Baselines and Good versus Bad Years. *Transactions of the American Fisheries Society* 142(5):1260–1272.
- Rosenfield, J. A. 2010. Life History Conceptual Model and Sub-Models for Longfin Smelt, San Francisco Estuary Population. Final Report submitted for the Delta Regional Ecosystem Restoration Implementation Plan. 45 pp.
- San Francisco Estuary Institute. 2020. Identifying Suitable Rearing Habitat for Chinook Salmon in the Sacramento–San Joaquin Delta. Publication No. 972. San Francisco Estuary Institute, Richmond, CA.
- Schemel, L. E., R. L. Brown, and N. W. Bell. 2003. Salinity and temperature in South San Francisco Bay, California, at Dumbarton Bridge: results from the 1999–2002 water years and an overview of previous data. U.S. Department of the Interior, U.S. Geological Survey.
- Sherman, S., R. Hartman, and D. Contreras. 2017. Effects of Tidal Wetland Restoration on Fish: A Suite of Conceptual Models. IEP Technical Report No. 91. p. 365. Department of Water Resources. Available: https://www.researchgate.net/profile/Pascale_Goertler/publication/321686857_Central_Valley_juvenile_Chinook_salmon_Pages_307-358_in_S_Sherman_R_Hartman_and_D_Contreras_editors_Effects_of_tidal_wetland_restoration_on_fish_a_suite_of_conceptual_models_IEP_Technical_Report_91/links/5a2b1231a6fdccfbbf8523b5/Central-Valley-juvenile-Chinook-salmon-Pages-307-358-in-S-Sherman-R-Hartman-and-D-Contreras-editors-Effects-of-tidal-wetland-restoration-on-fish-a-suite-of-conceptual-models-IEP-Technical-Report-91.pdf.
- Smith, W. E., L. Policansky, and M. L. Nobriga. 2021. Disentangling risks to an endangered fish: using a state-space life cycle model to separate natural mortality from anthropogenic losses. *Canadian Journal of Fisheries and Aquatic Sciences*. doi: <https://doi.org/10.1139/cjfas-2020-0251>.
- Sommer, T., F. H. Mejia, M. L. Nobriga, F. Feyrer, and L. Grimaldo. 2011. The Spawning Migration of Delta Smelt in the Upper San Francisco Estuary. *San Francisco Estuary and Watershed Science* 9(2). doi:10.15447/sfew.2014v9iss2art2. Available: <http://escholarship.org/uc/item/86m0g5sz>.
- Sommer, T., and F. Mejia. 2013. A Place to Call Home: A Synthesis of Delta Smelt Habitat in the Upper San Francisco Estuary. *San Francisco Estuary and Watershed Science* 11(2). doi:10.15447/sfew.2013v11iss2art4. Available: <https://escholarship.org/uc/item/32c8t244>.

- Sommer, T., R. Hartman, M. Koller, M. Koochafkan, J. L. Conrad, M. MacWilliams, A. Bever, C. Burdi, A. Hennessy, and M. Beakes. 2020. Evaluation of a large-scale flow manipulation to the upper San Francisco Estuary: Response of habitat conditions for an endangered native fish. *PLoS One* 15(10):e0234673. doi: <http://dx.doi.org/10.1371/journal.pone.0234673>.
- Sommer, T. R., W. C. Harrell, A. M. Solger, B. Tom, and W. Kimmerer. 2004. Effects of flow variation on channel and floodplain biota and habitats of the Sacramento River, California, USA. *Aquatic Conservation: Marine and Freshwater Ecosystems* 14(3), 247–261. doi: <https://doi.org/10.1002/aqc.620>.
- Swanson, C., T. Reid, P. S. Young, and J. J. Cech Jr. 2000. Comparative Environmental Tolerances of Threatened Delta Smelt (*Hypomesus Transpacificus*) and Introduced Wakasagi (*H. Nipponensis*) in an Altered California Estuary. *Oecologia* 123(3):384–90. doi: <https://doi.org/10.1007/s004420051025>.
- U.S. Geological Survey, L. R. Brown, B. Bergamaschi, J. R. Burau, E. T. Dailey, B. Downing, M. Downing-Kunz, F. V. Feyrer, B. Huntsman, T. Kraus, T. Morgan, J. R. Lacy, F. Parchaso, C. A. Ruhl, E. Stumpner, P. Stumpner, J. Thompson, and M. J. Young. 2020. Physics to Fish: Understanding the Factors that Create and Sustain Native Fish Habitat in the San Francisco Estuary. Final Draft. p. 210.
- Whitley, S. N., and S. M. Bollens. 2014. Fish assemblages across a vegetation gradient in a restoring tidal freshwater wetland: Diets and potential for resource competition. *Environmental Biology of Fishes* 97(6):659–674. doi: <https://doi.org/10.1007/s10641-013-0168-9>.
- Williamshen, B. O., T. A. O’Rear, M. K. Riley, P. B. Moyle, and J. R. Durand. 2021. Tidal restoration of a managed wetland in California favors non-native fishes. *Restoration Ecology* 29(5):e13392. doi: <https://doi.org/10.1111/rec.13392>.
- Windell, S., P. L. Brandes, J. L. Conrad, and more. 2017. Scientific Framework for Assessing Factors Influencing Endangered Sacramento River Winter-Run Chinook Salmon (*Oncorhynchus tshawytscha*) Across the Life Cycle. NOAA Technical Memorandum NMFS NOAA-TM-NMFS-SWFSC-586.
- Woo, I., M. Davis, and S. De La Cruz. 2017. Nisqually River Delta Summary: Early phase restoration performance and prey contributions to juvenile Chinook salmon within a habitat mosaic. U.S. Geological Survey Administrative Report to WA Department of Fish and Wildlife, Estuary and Salmon Restoration Program. 37 pp.
- Xieu, W., L. S. Lewis, F. Zhao, R. A. Fichman, M. Willmes, T. Hung, L. Ellison, T. Stevenson, G. Tigan, A. A. Schultz, and J. A. Hobbs. 2022. Experimental validation of otolith-based age and growth reconstructions across multiple life stages of a critically endangered estuarine fish. *PeerJ* 9:e12280. doi: <https://doi.org/10.7717/peerj.12280>.

This page intentionally left blank.