

Sacramento-San Joaquin Delta Regional Ecosystem Restoration Implementation Plan

Ecosystem Conceptual Model

Fish Habitat Linkages

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PREFACE

This Conceptual Model is part of a suite of conceptual models which collectively articulate the current scientific understanding of important aspects of the Sacramento-San Joaquin River Delta ecosystem. The conceptual models are designed to aid in the identification and evaluation of ecosystem restoration actions in the Delta. These models are designed to structure scientific information such that it can be used to inform sound public policy.

The Delta Conceptual Models include both ecosystem element models (including process, habitat, and stressor models); and species life history models. The models were prepared by teams of experts using common guidance documents developed to promote consistency in the format and terminology of the models
http://www.delta.dfg.ca.gov/erpdeltaplan/science_process.asp .

The Delta Conceptual Models are qualitative models which describe current understanding of how the system works. They are designed and intended to be used by experts to identify and evaluate potential restoration actions. They are not quantitative, numeric computer models that can be “run” to determine the effects of actions. Rather they are designed to facilitate informed discussions regarding expected outcomes resulting from restoration actions and the scientific basis for those expectations. The structure of many of the Delta Conceptual Models can serve as the basis for future development of quantitative models.

Each of the Delta Conceptual Models has been, or is currently being subject to a rigorous scientific peer review process. The peer review status of each model is indicated on the title page of the model.

The Delta Conceptual models will be updated and refined over time as new information is developed, and/or as the models are used and the need for further refinements or clarifications are identified.

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 FIGURE 1. DELTA AQUATIC HABITAT LINKAGE MODEL25

¹Introduction to the Delta Fish Habitat Linkage Model

^{1,2}The Delta Regional Ecosystem Restoration Implementation Plan ([DRERIP](#)) is one of four regional plans intended to guide the implementation of the CALFED Ecosystem Restoration Program (ERP) element. The DRERIP will refine the planning foundation for the Delta, develop and refine specific restoration actions and provide project implementation guidance, program tracking, performance evaluation and adaptive management feedback specific to the Delta. The *DRERIP Fish Habitat Linkage Model* (FHL model) provides a roadmap for how the various conceptual models designed for the DRERIP process intertwine to define fish habitat and ultimately produce fish. The model identifies the key linkages between hydrology and numerous other components of fish habitat.

The FHL model shows that hydrodynamics and water operations exert influences on fish recruitment by directly influencing transport fates, the water quality components of habitat, and some biotic interactions. The water quality components of habitat interact with structural components of habitat; their interaction affects the strength of biotic interactions (Peterson 2003). Because the FHL model is a generalized model serving as a template or road map, the relative importance of drivers and linkages, and their direction of impact (positive or negative), are not shown in the model diagram because they will depend on which species, contingent (*sensu* Secor 1999), or life stage is being evaluated. Additional general descriptions of the state of knowledge about these linkages are provided in the text boxes for each model component.

Peterson, MS. 2003. A conceptual view of environment-habitat-production linkages in tidal river estuaries. *Reviews in Fisheries Science* 11:291-313.

Secor, DH. 1999. Specifying divergent migrations in the concept of stock: the contingent hypothesis. *Fisheries Research* 43:13-34.

Hydrodynamic Driver Models

³The [Water and Constituent Transport Conceptual Model \(Transport model\)](#) is a comprehensive conceptual model that outputs “Transport of X, where X is water or anything suspended in the water.” The FHL model shows that the *Transport* model has a strong influence on fish and their habitat because it drives both the transport of fish and the transport of water quality constituents that influence habitat suitability and connectivity. Habitat connectivity describes whether nutrients or plankton or fish efficiently move between habitat patches (Fausch et al. 2002; Wiens 2002). Habitat

¹ This model has been prepared in a format for conversion to a web-based model. Future links to other models are highlighted in the text. The ‘footnote’ numbers at the beginning of each section cross reference the sections of the text to the Figure.

connectivity is extremely important for the productivity of aquatic ecosystems. The loss of connectivity among marshes and channels, and floodplains and channels, due to levees and land reclamation, has likely had a large negative effect on the productivity of the San Francisco Estuary and its watershed (Cloern 2007). Thus, increases in and/or restoration of connectivity among these habitats will likely have a positive effect on the productivity of the estuary and its watershed. Habitat connectivity is also influenced by the operation of the State Water Project and Central Valley Project as well as by in-Delta agricultural diversions and returns, as described in the [Aquatic Environment Boundary Conditions](#) element of the [Transport Model](#).

Cloern, JE. 2007. Habitat connectivity and ecosystem productivity: implications from a simple model. *The American Naturalist* 169:E21-E33 (electronic article).

Fausch, KD, Torgersen, CE, Baxter, CV, Li, HW. 2002. Landscapes to riverscapes: bridging the gap between research and conservation of stream fishes. *BioScience* 52(6):1-16.

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Salinity

⁴Salinity refers to the concentration of dissolved minerals in water and is measured in units of parts per thousand (ppt or ‰) or in Practical Salinity Units (PSU). The distribution and transport of salinity are covered in the *Transport Model*. Salinity affects the distribution of estuarine fish because different kinds of fishes (and different life stages of fishes) have different tolerances and preferences for salinity and salinity variation (e.g., Griffin et al. 2004). Bulger et al. (1993) found there were five somewhat overlapping estuarine salinity zones based on east coast fish and invertebrate assemblages: 0-4‰, 2-14‰, 11-18‰, 16-27‰, and 24-33‰. An equivalent model for San Francisco Estuary fish and invertebrates has not been developed, but would probably have similar results.

In the San Francisco Estuary, the vertical distribution of salinity changes at about the 2‰ isohaline (Kimmerer 2004). Landward of this isohaline, the salinity is usually very similar throughout the water column. Seaward of 2‰, the water column is at least partially stratified in the main channel leading to higher bottom salinities compared to the surface. Thus, the 2‰ isohaline (also known as X_2 ; Jassby et al. 1995) X_2 is an estuarine habitat indicator that represents a transition zone between freshwater and estuarine habitat in the San Francisco Estuary. X_2 is defined as the distance in kilometers from the Golden Gate Bridge to the place in the estuary where the average salinity of the bottom water is 2‰. During periods of low freshwater inflow, X_2 may be located in the western part of the Sacramento-San Joaquin Delta, more than 80 km from Golden Gate Bridge. During very wet periods, it may be pushed into San Pablo Bay, less than 50 km from

Golden Gate Bridge.

The location of X₂ within San Francisco Estuary is influenced most strongly by freshwater inflow from the estuary's major tributaries and river flow interactions with saline ocean water that enters the Golden Gate. Note that the exact location of X₂ is always changing due to the effects of river flows, tides and wind on advection and dispersion processes (Walters et al. 1985; *Transport Model*).

This variation in the distribution of estuarine salinity affects the geographical distribution of fish populations (Armor and Herrgesell 1985; Dege and Brown 2004; Kimmerer 2004; Feyrer et al. 2007). The geographic position of fish populations in turn influences the sources of mortality they are exposed to – for instance, fishes are only exposed to entrainment in SWP and CVP diversions when their population distribution includes the San Joaquin River side of the Delta. Similarly, the distribution of fish populations likely also influences the rates of mortality from sources they are always exposed to (e.g., losses to predators).

The influence of salinity variation on San Francisco Estuary fishes has been well-documented by long-term monitoring in Suisun Marsh (Meng et al. 1994; Meng and Matern 2001; Matern et al. 2002) and the upper estuary in general (Stevens and Miller 1983; Armor and Herrgesell 1985; Jassby et al. 1995; Kimmerer 2002; Feyrer et al. 2007). These associations between freshwater flow, estuarine salinity and fish abundance or distribution are a key example of the driver-linkage-outcome concept. For instance, freshwater flow into the estuary during winter and spring (specifically January-June in most instances) is an example driver. An observed outcome is the relative abundance of fish like [longfin smelt](#) and starry flounder, and crustaceans like mysid shrimp (*Neomysis mercedis*) and Bay shrimp (*Crangon franciscorum*) during surveys later in the year. The linkage between the driver and these outcomes is the salinity of the estuary during early life stages of these animals.

Armor, C, Herrgesell, P. 1985. Distribution and abundance of fishes in the San Francisco Bay Estuary between 1980 and 1982. *Hydrobiologia* 129:211-227.

Bulger, AJ, Monaco, ME, Nelson, DM, McCormick-Ray, MG. 1993. Biologically-based estuarine salinity zones derived from a multivariate analysis. *Estuaries* 16:311-322.

Dege, M, Brown, LR. 2004. Effect of outflow on spring and summertime distribution and abundance of larval and juvenile fishes in the upper San Francisco Estuary. *American Fisheries Society Symposium* 39:49-66.

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Symposium 39:37-46.

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Matern, SA, Moyle, PB, Pierce, LC. 2002. Native and alien fishes in a California estuarine marsh: twenty-one years of changing assemblages. *Transactions of the American Fisheries Society* 131:797-816.

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Meng, L, Moyle, PB, Herbold, B. 1994. Changes in abundance and distribution of native and introduced fishes of Suisun Marsh. *Transactions of the American Fisheries Society* 123:498-507.

Stevens, DE, Miller, LW. 1983. Effects of river flow on abundance of young Chinook salmon, American shad, longfin smelt, and delta smelt in the Sacramento-San Joaquin river system. *North American Journal of Fisheries Management* 3:425-437.

Walters, RA, Cheng, RL, Conomos, TJ. 1985. Time scales of circulation and mixing processes of San Francisco Bay waters. *Hydrobiologia* 129:13-36.

Fish and Zooplankton Transport

^{5,6}Fish and zooplankton are moved around the estuary by both tidal and river currents. Because the Delta is a tidal system, river currents are generally characterized in terms of net flow after the influence of the tides has been mathematically removed. Thus, zooplankton and fish may be dispersed throughout the Delta by the tides, but also have an average net change in geographic position that is influenced by the interaction of river flows, flow rates into water diversions, and organism behavior (Bennett et al. 2002; Kimmerer et al. 2002; Culberson et al. 2004; Dege and Brown 2004; Kimmerer and Nobriga in press). Note that no change in net position equals a change in average net direction of zero. These transport influences can have either positive or negative effects depending on the outcome. Transport of larval fish to a suitable rearing habitat is an

example of a positive transport outcome, while transport to a water diversion is an example of a negative transport outcome.

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Kimmerer, WJ, Nobriga, ML. In press. Investigating particle transport and fate in the Sacramento-San Joaquin Delta using a particle tracking model. *San Francisco Estuary and Watershed Science*.

Water Quality Components of Fish Habitat

⁷Estuarine fish habitat suitability is influenced by the overlap of dynamic water quality habitat attributes and stationary, structural habitat attributes (Peterson 2003). Several water quality parameters such as salinity, turbidity, temperature, dissolved oxygen concentration, and water and sediment-borne contaminants are locally important dynamic attributes of fish habitat. Water quality parameters are considered dynamic because they change rapidly in estuaries as river flows, tidal forcing, and seasons change (Jassby et al. 1995; Manderson et al. 2002). The status, trends, variability, and key drivers of these water quality parameters are described in detail elsewhere: salinity ([Transport Model](#)), turbidity ([Sedimentation Model](#)), [Dissolved Oxygen Model](#), [Contaminants Model](#), but are reviewed briefly here.

Jassby, AD, Kimmerer, WJ, Monismith, SG, Armor, C, Cloern, JE, Powell, TM, Schubel, JR, Vendlinski, TJ. 1995. Isohaline position as a habitat indicator for estuarine populations. *Ecological Applications* 5:272-289.

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Dissolved Oxygen

⁹ Fishes require oxygen just like terrestrial animals. Numerous pathways affect dissolved oxygen variation in coastal ecosystems including estuaries (Cloern 2001). The amount of oxygen dissolved in water can strongly affect the ability of fish to use estuary habitats because many fishes cannot tolerate water when dissolved oxygen is lower than about 2-5 mg/liter (Burton et al. 1980; Howell and Simpson 1994). Low dissolved oxygen also can change estuarine food webs (Breitburg et al. 1997). Fishes generally avoid low oxygen situations, but sensitivity varies by species (Whitmore et al. 1960; Cech et al. 1990). It is common for fishes to show a threshold response to hypoxia; fishes may show no response to decreasing oxygen to a certain point, then show substantial effects when oxygen concentrations are reduced further.

There are a variety of dissolved oxygen-related studies on fishes of the San Francisco Estuary and its watershed. High water temperature often increases fish sensitivity to low oxygen concentrations, but this is not true of all species (Cech et al. 1990). Some fishes like [*splittail*](#) and [*white sturgeon*](#) are tolerant of low dissolved oxygen. Splittail can survive for a while at concentrations < 2 mg/liter (Young and Cech 1996) and white sturgeon reduce their metabolism by reducing their swimming activity to help them tolerate hypoxia (Crocker and Cech 1997). Others fishes are much more sensitive to low DO; in one experiment, the maximum sustained swimming speed of [*chinook salmon*](#) was 38% lower in water with 3 mg/liter of oxygen than in water saturated with oxygen (Davis et al. 1963).

In most of the San Francisco Estuary most of the time, dissolved oxygen is high enough so that it does not impact fish distributions (Kimmerer 2004). However, there are two known problem areas in the estuary for low dissolved oxygen; both in highly altered habitats. There is a decrease in summer-fall dissolved oxygen in 14 km of the San Joaquin Deepwater Ship Channel (Lehman et al. 2004). Several factors contribute to low summer-fall oxygen in the San Joaquin shipping channel, but low flows through this deeply channelized reach are probably the most significant factor (Jassby and Van Nieuwenhuysse 2006). Some channels in Suisun Marsh are also seasonally oxygen depleted because discharge from managed wetlands with limited circulation is released into the adjacent marsh channels (Robert Schroeter, UC Davis unpublished data). Refer to the [*Dissolved Oxygen*](#) conceptual model for more details.

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Cech, JJ, Jr, Mitchell, SJ, Castleberry, DT, McEnroe, M. 1990. Distribution of California stream fishes: influence of environmental temperature and hypoxia. Environmental Biology of Fishes 29:95-105.

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<http://repositories.cdlib.org/jmie/sfews/vol3/iss2/art2>.

Kimmerer, WJ. 2004. Open-water processes of the San Francisco Estuary: from physical forcing to biological responses. San Francisco Estuary and Watershed Science 2:
<http://repositories.cdlib.org/jmie/sfews/vol2/iss1/art1>.

Lehman, P. W., J. Sevier, J. Giulianotti, and M. Johnson. 2004. Sources of oxygen demand in the lower San Joaquin River, California. Estuaries 27: 405-418.

Whitmore, CM, Warren, CE, Douderoff, P. 1960. Avoidance reactions of salmonid and centrarchid fishes to low oxygen concentrations. Transactions of the American Fisheries Society 89:17-26.

Young, PS, Cech, JJ, Jr. 1996. Environmental tolerances and requirements of splittail. Transactions of the American Fisheries Society 125:664-678.

Suspended Sediments and Turbidity

¹⁰Turbidity refers to the clarity of water and is influenced by factors such as suspended sediment concentration, and particulate and dissolved organic matter; the [Sedimentation Model](#) describes the dynamics of suspended sediment and its effect on water column light penetration. Turbidity affects large river and estuarine fish assemblages because some fishes survive best in turbid (muddy) water, while other species do best in clear water (Blaber and Blaber 1980; Quist et al. 2004). Currently, the main hypothesis to explain the effect of turbidity on fish assemblages is that turbidity strongly influences the success of visual predators; visual predators hunt more successfully in clear water (Rodríguez and Lewis 1994; Gregory and Levings 1998). Note however, that the turbidity-predation mechanism has not been tested for fishes of the Sacramento-San Joaquin Delta. Turbidity also can positively (Baskerville-Bridges et al. 2004), and negatively (Zamor and Grossman 2007), affect the feeding success of small forage fishes.

The turbidity of San Francisco Estuary water is dominated by inorganic particles (i.e., suspended sediments) and is thus affected by river flows; turbidity increases when inflows are high (Kimmerer 2004). Turbidity is also affected by tidal currents, wind events and bathymetry (Ruhl et al. 2001). Turbidity in the Delta has decreased through time (Jassby et al. 2002). The primary hypotheses to explain the turbidity decrease are (1) reduced sediment supply due to dams in the watershed (Wright and Schoellhamer 2004), (2) sediment washout from very high inflows during the 1982-1983 El Nino (Jassby et al. 2005), and (3) trapping by [Submerged Aquatic Vegetation](#) (Brown and Michniuk 2007). Refer to the [Sedimentation Model](#) for more details.

Turbidity is one of several factors that covaries with flow to influence fish assemblages in Suisun Marsh (Matern et al. 2002). The distribution of fish assemblages in the Delta is also influenced by turbidity (Feyrer and Healey 2003; Nobriga et al. 2005; Brown and Michniuk 2007). Turbid habitats have higher proportions of native fishes, while clear-water habitats have higher abundance of submerged aquatic vegetation and nonnative centrarchid fishes like largemouth bass. Largemouth bass are efficient predators on small nearshore fishes, including native fishes like prickly sculpin and tule perch that use the vegetated habitats (Nobriga and Feyrer 2007). [Delta smelt](#) (Feyrer et al. 2007; Nobriga et al. in press) and age-0 striped bass (Feyrer et al. 2007) are distributed mainly in turbid water (i.e., Secchi disk depths < 0.6 m). The feeding success of cultured delta smelt larvae is positively influenced by turbidity (Baskerville-Bridges et al. 2004), apparently because the turbidity provides contrast needed for the larvae to see their prey. High water clarity has also been shown to increase predation risk for young [chinook salmon](#) in a British Columbia river (Gregory and Levings 1998).

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Ruhl, CA, Schoellhamer, DH, Stumpf, RP, Lindsay, CL. 2001. Combined use of remote sensing and continuous monitoring to analyse the variability of suspended-sediment concentrations in San Francisco Bay, California. *Estuarine, Coastal, and Shelf Science* 53:801-812.

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Zamor, RM, Grossman, GD. 2007. Turbidity affects foraging success of drift-feeding rosyside dace. *Transactions of the American Fisheries Society* 136:167-176.

Water Temperature

¹¹Water temperature drives the metabolism of aquatic ecosystems, so it has major effects on fishes and their habitats. For instance, water temperature influences the competitive dominance between brook trout and creek chub providing a potential explanation for why these fishes replace each other along elevation gradients in the Rocky Mountains (Taniguchi et al. 1998). In the Hudson River, seasonal winter water temperatures force young American shad into habitats with higher predation risk because the ‘safer’ upriver environments are too cold (Limburg 1996). Largemouth bass introduced into tropical systems overallocate energy into reproduction during the longer potential spawning season (Neal and Noble 2006). This greatly reduces their longevity and size at age. Currently, there is no DRERIP model specifically for water temperature, though the [*Aquatic Environment Boundary Conditions*](#) model element describes the status, trends, and variability of temperature and the factors known to influence temperature.

In the Delta, water temperature depends mainly on air temperature (Kimmerer 2004). The seasonal variation in water temperature (for example from ~10°C in the winter to over 20°C in the summer at Antioch) is the dominant form of water temperature variation. Lesser variability also arises among different habitat types or regions (Matern et al. 2002; Kimmerer 2004). The seasonal differences in temperature are the primary influence on the timing of spawning for resident fishes. It has recently been shown that the remnant native fish fauna spawns earlier in the season (in cooler water, typically January-May) than most of the nonnative fishes (Meng and Matern 2001; Feyrer 2004; Grimaldo et al. 2004; Sommer et al. 2004). Nonnative fishes typically spawn in the

warmer months of May-August. This might be evidence of a thermal refuge from competition for young native fishes.

There is also a gradient of increasing temperature from northwest to southeast through the Delta (Kimmerer 2004). Long-term monitoring by the Interagency Ecological Program has shown that summer (July) water temperatures have averaged 21°-22°C in Suisun Bay and the lower Sacramento River, but are warmer in the tidal reach of the San Joaquin River and its southern distributaries, averaging 24°C over the same period; water temperature > 22-25°C can limit distribution of *delta smelt* during summer (Nobriga et al. in press). Limited data on the survival of cultured delta smelt larvae suggest their survival is higher at water temperatures near 15°C than at higher or lower temperatures (Bennett 2005). Swanson et al. (2000) showed that nonnative wakasagi, a fish in the same family as delta smelt could survive at higher water temperatures than delta smelt; the critical thermal maximum temperature that delta smelt tolerated in the laboratory was 25.4°C in this study. Marine and Cech (2004) showed that juvenile Sacramento River *chinook salmon* could survive at 17-24°C, but that temperatures this high negatively affected the fishes growth rates, smoltification, and ability to escape from predators.

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Chemical Contaminants

⁸Contaminants refers to toxic chemicals in the water column or sediment that can harm fish or the food webs that support them. There are several contaminants models being developed for DRERIP: an overview model called the [General Toxicity Model](#), and specific models for [Mercury](#), [Selenium](#), and [Pyrethroids](#). The majority of contaminant research has focused on selenium because of its high loadings in agricultural drainwater from the San Joaquin basin, mercury because of its high loadings due to historical mining in the San Francisco Estuary watershed, and pesticides due to high loadings from the large agricultural acreage in the Central Valley. High river flows increase pesticide loading (Kuivila and Foe 1995; Bergamaschi et al. 2001). Recently, *Microcystis aeruginosa* blooms in the upper estuary have also been considered a potential toxic threat (Lehman et al. 2005). There is even newer concern over ammonia originating from urban wastewater treatment plants discharging into the Delta region (Dugdale et al. 2007).

Undiluted agricultural drainwater is often acutely toxic (quickly lethal) to fish (Saiki et al. 1992; Bailey et al. 1994) and invertebrate prey (Bailey et al. 1994; Weston et al. 2004). In fact, the lower San Joaquin River adjacent to the Delta has a very unique, low diversity fish assemblage dominated by short-lived species, particularly red shiner (Brown 2000;

Brown and May 2006). This condition is probably the result of warm water temperatures, degraded habitat associated with human land uses, and very degraded water quality associated with dissolved pesticides and salts from agricultural runoff. Once diluted in the large amount of water in the Delta, acute water toxicity is rare in invertebrates (Kuivila and Foe 1995; Werner unpublished data) and fishes. Rather, the concern for fishes has centered on chronic or sublethal contaminant effects (Bennett et al. 1995; Kuivila and Moon 2004; Stewart et al. 2004; Teh et al. 2004; Bennett 2005) or toxicity to human consumers (Davis et al. 2002). There remains a need to link potential chronic toxic effects to fish population genetics (Whitehead et al. 2003) and population dynamics (Bennett et al. 1995; Bennett 2005). Refer to the [General Toxicity](#) and specific contaminant models linked above for more details.

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Structural Components of Fish Habitat

¹²There are several DRERIP models that describe structural aspects of habitat; all of these are variations of conditions that occur at the aquatic-terrestrial interface. In addition to the general descriptions provided in this model, there are detailed DRERIP models for [Floodplains](#), [Riparian Habitats](#), [Submerged Aquatic Vegetation](#), and [Tidal Marsh](#). There is no DRERIP model specifically for beaches and shorelines.

Beaches and Shorelines

¹³Narrow intertidal-shallow subtidal beach habitats are common in the Delta and parts of Suisun Bay; extensive (broad) intertidal sandy beach habitats occur mainly around western Chippis Island and Middle Ground in Suisun Bay. In the Delta, most of these sandy, intertidal-shallow subtidal beach habitats occur along leveed channel edges; fewer are along the interior sides of flooded island levees or at the edges of in-channel islands. Most grade abruptly into deeper, dredged channels. The fish assemblages of the Delta beach habitats support a diverse array of fishes; community composition varies regionally based on other habitat attributes. It is unknown whether the size of a shoreline habitat influences fish assemblages in the Delta. Shoreline fish assemblages vary from north to south (Nobriga et al. 2005; Brown and May 2006). Regional variation in hydrodynamic drivers (see the [Transport Model](#)) likely plays a role. For instance, high Sacramento River flows increase the spawning success of *splittail* (Sommer et al. 1997) and bring high numbers of age-1 Sacramento pikeminnow into the Delta (Nobriga et al. 2006). Such reproductive and dispersal responses to high riverine influence ‘seed’ the north Delta with these and other native fish. In the central/southern Delta, more frequent low flow conditions and extensive [Submerged Aquatic Vegetation](#) result in higher water temperature and higher water clarity that seem to have favored centrarchid fishes like largemouth bass, bluegill, and redear sunfish ([link back to turbidity piece](#)). [Delta smelt](#) avoid these conditions during summer-fall (Feyrer et al. 2007; Nobriga et al. in press). Fish assemblages also vary, though less dramatically, in association with local microhabitat conditions within sloughs (Matern et al. 2002; Feyrer and Healey 2003) and flooded islands (Grimaldo et al. 2004).

The characteristics of channel shorelines in the San Francisco Estuary likely influence fish use (Brown and Michniuk 2007). The estuary has a very high proportion of leveed shorelines; particularly in the Delta, where most levees are ‘hardened’ by large rocks known as riprap (Schmetterling et al. 2001). Riprapped stream segments have fewer undercut banks and less overhead cover than natural banks. Thus, riprap reduces habitat diversity along streambanks. In the Columbia River, riprap has been shown to be used less frequently by juvenile [chinook salmon](#) than natural shoreline (Garland et al. 2002). The levees themselves also reduce or eliminate important connectivity between channels and adjacent shallow producer habitats like marshes and floodplains (Bowen et al. 2003; Cloern 2007).

In addition to being simplified habitats, the leveed shorelines of Suisun Marsh and the Delta also have numerous small unscreened water diversion intakes (Herren and Kawasaki 2001). These intakes are a source of fish mortality (Hallock and Van Woert 1959; Nobriga et al. 2004). However, the comparative field studies needed to determine whether they cumulatively contribute to reduced viability of native fish populations are lacking (Moyle and Israel 2005).

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Floodplains as Fish Habitat

¹⁴[Floodplains](#) are generally very dynamic habitats with seasonal or sporadic cycles of flooding and draining (Junk et al. 1989). Thus, floodplain inundation allows fish to temporarily utilize vast areas that are usually dry. The importance of connectivity between channels and their floodplains for ecosystem productivity is analogous to the connectivity between [Tidal Marshes](#) and adjacent channels (Cloern 2007). Floodplain connectivity is also very important to fish habitat variability (Bowen et al. 2003; Feyrer et al. 2006a) and food web structure (Winemiller 1996). Floodplain is considered a [stationary habitat](#) attribute in the FHL model because most of the [DRERIP area of consideration](#) is constrained within levees, including its largest floodplain, the Yolo Bypass. However, the DRERIP [Floodplains Model](#) provides excellent detail regarding the dynamic drivers and outcomes of floodplain habitats.

There has been a lot of research on local floodplain ecology in the past ten years. Moyle et al. (2007) recently categorized fishes occurring on the Cosumnes River floodplain based on their use patterns. They noted that fishes could be floodplain spawners (e.g., splittail and carp), river spawners that inadvertently occur on floodplains (e.g., Sacramento pikeminnow and channel catfish), and floodplain pond fishes, some of which leave ponded areas during flood events to take advantage of foraging opportunities (e.g., largemouth bass and inland silverside). Inundated floodplains provide the primary spawning habitat for [splittail](#) (Sommer et al. 1997; Moyle et al. 2007) and extended periods of springtime floodplain inundation greatly increase splittail production (Sommer et al. 1997; Feyrer et al. 2006b). Local floodplain inundation also stimulates [Food Webs](#) based on aquatic insects and zooplankton (Sommer et al. 2001; Sommer et al. 2004;

Grosholz and Gallo 2006). Thus, inundated floodplain also provides a temporary high quality rearing habitat for splittail, *chinook salmon* (Sommer et al. 2001) and numerous other San Francisco Estuary fishes.

Riverine fishes that access floodplains may become stranded in ponds and flood control structures as floodwaters recede (Sommer et al. 2005; Moyle et al. 2007); generally however, this risk generally does not appear to outweigh benefits such as expanded spawning habitat, and high food production that stimulates rapid growth. For instance, the survival of chinook salmon emigrating to the Delta through Yolo Bypass is comparable to that of individuals that stay in the main channel of the Sacramento River (Sommer et al. 2005). Both migration routes have risks – stranding in Yolo Bypass versus low food availability and vulnerability to entrainment into the central Delta for fishes remaining in the river.

Native fishes generally do not survive the summer in ponds remaining after floodwaters recede (Feyrer et al. 2004). Historically, there was a warmwater native fish assemblage that routinely used floodplain lakes and ponds and was heavily exploited by Native Americans (Gobalet et al. 2004). However, this portion of the Delta's fish assemblage has been displaced by nonnative fishes like centrarchids and inland silverside that are competitively dominant in very warm water (> 30°C) (Feyrer et al. 2004; Moyle et al. 2007).

The wetting and drying of floodplains catalyzes the transformation of inorganic mercury compounds into methyl mercury, which is highly toxic (*Mercury Model*). A pilot monitoring program using inland silversides as 'biosentinels' shows that silversides collected from some floodplain habitats have elevated body burdens of methyl mercury compared to individuals collected from several other habitat types (D. Slotton, UC Davis, unpublished data). Thus, mercury accumulation in floodplain fishes may be of concern to avian and mammalian predators, and human consumers of floodplain fish. Note however, that this dynamic has probably occurred since the Gold Rush. Thus far, negative effects of mercury contamination on the fishes themselves have not been documented. Native fishes that transiently use the floodplains during high flow events seem unlikely to accumulate levels of methyl mercury that would be harmful to them, but this has not been confirmed.

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Submerged Aquatic Vegetation

¹⁵[Submerged Aquatic Vegetation](#), or SAV, is an important form of cover for the young of some estuarine fishes (Rozas and Odum 1987; Wyda et al. 2002). It has recently been shown that SAV is also a comparatively productive rearing habitat for fishes in the Delta (Grimaldo et al. 2004; Nobriga et al. 2005). Unfortunately, SAV in the Delta is dominated by Brazilian waterweed (*Egeria densa*), an invasive freshwater species that grows in denser stands than native SAV and seems to mainly provide rearing habitat to centrarchid fishes and other nonnative species. The centrarchids are of particular concern because they have increased substantially in abundance since the 1980s (Brown and Michniuk 2007), are aggressively territorial (Moyle 2002), and include the largemouth bass, which is a particularly effective nearshore predator of small fishes (Nobriga and Feyrer 2007). Native fishes are very rare in SAV-dominated habitats within the Delta (Brown 2003; Feyrer and Healey 2003; Grimaldo et al. 2004; Nobriga et al. 2005; Brown and Michniuk 2007). Further, native fish relative abundance has decreased as Brazilian waterweed has spread around the Delta over the past 25 years (Brown and Michniuk 2007).

Why is SAV proliferation in the Delta bad for native fishes? First, Brazilian waterweed grows in dense stands that strongly affect local water quality. For instance, it has contributed to reduced turbidity in the Delta (see the [Sedimentation](#) model). The area with the greatest amount of SAV is the lower-velocity channels and flooded islands of the interior Delta. Examples include Frank's Tract, Mildred Island, Big Break, Sherman Lake, and Old and Middle rivers. These areas generally also have the highest water clarity and are less seldom used by [delta smelt](#) and age-0 striped bass than they were historically (Nobriga et al. 2005; Feyrer et al. 2007). Note that some research in other systems suggests visual predators hunt more successfully in clear water (Gregory and Levings 1998; Gadomski and Parsley 2005). Second, Brown (2003) hypothesized that dense SAV stands could limit the ability of native migratory fishes like [chinook salmon](#), [splittail](#), and delta smelt to access nearshore habitats because their risk of predation would be very high. This hypothesis has supporting evidence. Largemouth bass is a visual predator that often lives in association with SAV and that seems to be a very efficient shallow-water predator. Largemouth bass start eating fish at smaller sizes than other shallow-water predators and they eat more kinds of fish than other shallow-water predators (Nobriga and Feyrer 2007).

The clearer water likely also increases the foraging success of large striped bass inhabiting the open-water areas. The combination of a reef-foraging predator and an open-water predator has been shown to intensify the predation loss of small fishes in a coral reef environment because it restricted behavioral responses of the young fish, which could not escape predation either by hiding in the reefs or by temporarily moving into open water (Hixon and Carr 1997). The combination of increased water clarity and 'new' structural complexity offered by the proliferation of SAV may have created a situation in the Delta that is analogous to the coral reef example by increasing the abundance and foraging success of largemouth bass in the nearshore environment and increasing the foraging success of striped bass in the open water environment.

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Tidal Marshes

¹⁶[Tidal marshes](#) are a common habitat feature of temperate zone estuaries (Mitsch and Gosselink 2000) and often are a significant rearing habitat for estuarine fishes (Beck et al. 2001). A large majority of the original tidal marshes of the San Francisco Estuary have been converted to other land uses (Brown 2003 and unpublished references therein). There is interest in tidal marsh restoration because the lost connectivity to this productive habitat type has probably had a profound negative influence on the ability of the estuary to produce fish (Cloern 2007). However, there is concern about how restorable San Francisco Estuary tidal marshes are, especially in the Delta, because of land subsidence (Mount and Twiss 2005), low sediment supply (Williams and Orr 2002), and the intractability of reintroducing natural disturbance regimes (Simenstad et al. 2006).

Tidal marshes can provide spawning and rearing habitat and foraging opportunities to fishes that enter marsh channels. They may also export food to adjacent habitats through a “trophic relay” whereby small fish and invertebrates that access marsh plains are consumed by larger fishes that transiently visit marsh channels (Kneib 1997). Perhaps the best example of a San Francisco Estuary fish that benefits from trophic relay is striped bass, which is the most common and ubiquitously distributed fish in Suisun Marsh (Matern et al. 2002). Ebbing tides also may export food organisms produced in marsh habitats to fishes occupying adjacent waterways. However, the limited extent of marsh habitats in the Delta suggests marshes are not currently a significant source of prey to open-water habitats.

Many fishes use San Francisco Estuary’s remnant tidal marshes to varying degrees; long-term fish monitoring in the brackish Suisun Marsh provides the bulk of the knowledge base about local tidal marsh fishes (Moyle et al. 1986; Meng et al. 1994; Meng and Matern 2001; Matern et al. 2002). The fishes of Suisun Marsh seem to have been impacted similarly to fishes outside the marsh; total fish catch has declined since routine monitoring began in 1979, and the proportion of native fishes has declined (Matern et al. 2002). Fish diets also changed considerably after the overbite clam became established in Suisun Bay (Feyrer et al. 2003). Note however, that research at a relatively undisturbed site in Suisun Marsh, Rush Ranch Reserve, found high abundance of phytoplankton, mysid shrimp, and native fishes (Robert Schroeter, UC Davis, unpublished presentation at the 2006 CALFED Science Conference).

Fish use of freshwater tidal marsh in the Delta is poorly understood, mainly because very little such habitat remains. Currently, the largest area of tidal marsh in the Delta is restoring itself in Liberty Island. There has been some limited monitoring of this marsh, but nothing is currently summarized or published. Most other remnant marsh habitats in

the Delta are small and their channels and margins are dominated by [*Submerged Aquatic Vegetation*](#). Thus, they tend to be dominated by the nonnative fish assemblage that associates closely with SAV (Brown 2003; Grimaldo et al. 2004). These remnant central Delta marshes also seem to have a fairly self-contained food web that has limited interchange with adjacent open water areas (Grimaldo 2004).

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Biotic Interactions: Interactions Among Living Organisms

¹⁷Biotic interactions refer to the effects that plants and animals have on each other. The primary example is the trophic interactions detailed in the *Delta Aquatic [Food Webs Model](#)*. A second example is competition among fishes. There are no published studies that document competition among fishes in the Delta, but competitive interactions are hypothesized to have played a role in the extirpation of Sacramento perch and the decline of *delta smelt* (Moyle 2002). Peterson (2003) included five processes in his estuarine fish habitat conceptual model: survival, foraging, growth, density, and predation. All five processes are influenced by biotic interactions among fishes and other organisms sharing their environment. The first four increase fish biomass and are thought to be maximized where a fish's optimal [dynamic habitat](#) and [stationary habitat](#) attributes overlap. In contrast, predation, which removes fish biomass, is thought to be maximized where a fish's optimal dynamic habitat and stationary habitat attributes are out of synch. Note that a fish's ability to compete can be strongly affected by abiotic conditions. Thus, a reasonable conceptual starting point would be to also assume that a fish's competitive ability is maximized when its optimal stationary and dynamic habitat attributes overlap and impaired when they do not.

The San Francisco Estuary food webs have been greatly changed from their native condition (Moyle 2002), but they also have been changing rapidly and dramatically since the mid-1980s. These changes are outlined in detail in the *Delta Aquatic [Food Webs Model](#)*.

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Figure 1. Delta Aquatic Habitat Linkage Model¹

