Chapter 3
Scientific Knowledge to Inform Fish and Wildlife Flow Recommendations

3.1 Introduction

This chapter provides a review and summary of the best available science on flow needs for the protection of fish and wildlife beneficial uses. Specifically, building on the State Water Board's 2010 *Development of Flow Criteria for the Sacramento-San Joaquin Delta Ecosystem* (Delta Flow Criteria Report), this chapter describes the ecosystem functions provided by flow and describes the distribution and abundance of several native Bay-Delta aquatic species and their relationships to flow. This chapter evaluates different methods for developing instream flows and provides a recommended method. In addition, the chapter analyzes the effect of different flow levels on meeting the flow thresholds and on floodplain inundation. This chapter also discusses the expected population abundance responses to different flow levels and evaluates the interaction and need to balance storage and cold water management with inflows.

The chapter focuses on flows to support native aquatic species and habitat and informs the proposed Plan amendments presented in Chapter 5, *Proposed Changes to the Bay-Delta Plan for the Sacramento/Delta*, on changes to the Bay-Delta Plan to protect fish and wildlife, including changes to Sacramento River watershed and Delta eastside tributaries inflows, Delta outflow, interior Delta flow, and cold water habitat requirements. Other important uses, such as municipal, agricultural, and hydropower, also factor into State Water Board decision making regarding updates to the Bay-Delta Plan and are addressed in subsequent chapters.

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

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

The following specific scientific information is relied upon in this Staff Report (or Report).

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

3.2 Flow and the Ecosystem

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

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

The effects of flow modifications on biological resources have been reviewed by several authors who have found that fish abundance and diversity declined in response to reductions in flow across a wide range of biological communities all over the world (Lloyd et al. 2004; Poff and Zimmerman 2010; Rozengurt et al. 1987). Although there is no universal quantitative relationship between flow alteration and ecological response, the risk of ecological change increases with greater magnitudes of flow alteration (Poff and Zimmerman 2010). Richter et al. (2011) concluded that "alterations greater than 20 percent will likely result in moderate to major changes in natural structure and ecosystem functions, with greater risk associated with greater levels of alteration in daily flow." Studies of river-delta-estuary ecosystems in Europe and Asia concluded that water quality and fish resources deteriorate beyond their ability to recover when spring and annual water withdrawals exceed 30 and 40 to 50 percent of unimpaired flow, respectively (Rozengurt et al. 1987). Upstream diversions and water exports in the Delta have reduced median January–June and average annual outflow by 56 and 48 percent, respectively (see Chapter 2, *Hydrology and Water Supply)* (^Fleenor et al. 2010).

3.2.1 Riverine Flows

Altered flow regimes negatively affect native fish communities and their aquatic ecosystem (^Pringle et al. 2000; ^Freeman et al. 2001; ^Bunn and Arthington 2002; ^Moyle and Mount 2007). An assessment of streams across the conterminous United States shows a strong correlation between simplified or diminished streamflows and impaired biological communities that include fish (^Carlisle et al. 2011). In addition, when streams are dammed and flow regimes are simplified by dam releases, stream fish communities tend to become simplified and more predictable, usually dominated by species that thrive in simplified and less variable habitats (^Brown and Bauer 2009; ^Kiernan et al. 2012). This has been found to be the case in the Bay-Delta watershed, where native fish and other aquatic organisms have been increasingly replaced by nonnative species (Feyrer and Healey 2003; ^Brown and May 2006; ^Brown and Michniuk 2007; ^Brown and Bauer 2009; Mahardja et al. 2017). Within the watershed, the regions of greatest flow alteration are the most dominated by nonnative species (^Brown and May 2006; ^Brown and Michniuk 2007) where the altered hydrology likely creates conditions more favorable for spawning and rearing of nonnatives than natives (^Brown and Bauer 2009). Implementation of a more natural flow regime with high spring flows has been shown to favor native over nonnative species in Putah Creek, although nonnatives still dominate in the lowermost reach (^Kiernan et al. 2012).

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

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

The genetic and life-cycle diversity provided by maintaining sub-populations and varied life history timing of Central Valley salmonids through achieving a more natural flow regime with improved temporal and spatial variability would help protect populations against both short-term and long-term environmental disturbances. Fish with differing characteristics among sub-populations (i.e., greater diversity) have different likelihoods of persisting, depending on local environmental conditions. Thus, the more diverse a species is, the greater the probability that some individuals survive and reproduce when presented with environmental variation (McElhany et al. 2000; TBI 2016; Carlson and Satterthwaite 2011; ^Lindley et al. 2007). Genetic diversity also provides the raw material for surviving long-term environmental changes. Salmonids regularly face cyclic or directional change in their freshwater, estuarine, and ocean environments due to natural and human causes. Sustaining genetic and life-cycle diversity allows them to persist through these changes (McElhany et al. 2000; Moore et al. 2010; Carlson and Satterthwaite 2011).

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

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

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

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

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

Increasing turbidity events from more variable flows and the associated geomorphic processes also decrease predation and provide environmental cues needed to stimulate migration (Gregory and Levings 1998; Baxter et al. 2008; ^NMFS 2009). Juvenile salmonids emigrate during periods of increased turbidity that originally arose from the winter storm and spring snowmelt phases of the flow regime. Turbidity reduces predation on young salmon by providing a form of protective cover, enabling them to evade detection or capture (Gregory 1993; Gregory and Levings 1998). Reservoir construction has reduced turbidity by capturing the majority of flow and associated sediment (^Schoellhamer et al. 2016).

Altered flow regimes tend to decrease habitat connectivity in riverine and deltaic systems, which results in a loss of longitudinal and lateral connectivity (^Bunn and Arthington 2002). A more natural flow regime in the Bay-Delta watershed can increase longitudinal connectivity, create more beneficial migration transport, less hostile rearing conditions (protection from predators), greater net downstream flow, and connectivity with the estuary and nearshore ocean during periods that are beneficial for aquatic organisms who have adapted to this system (Kondolf et al. 2006; ^Poff et al. 2007; TBI 2016). A more natural flow regime also can increase the frequency and duration of lateral connectivity to riparian and floodplain habitats, allowing for energy flow between wetland areas and the river, and providing the river and estuary with nutrients and food. Floodplain inundation provides flood peak attenuation and promotes exchange of nutrients, organic matter, organisms, sediment, and energy between the terrestrial and aquatic systems (^Sommer et al. 2001b; ^TBI 1998; ^Whipple et al. 2012). It also improves juvenile fish survival by improving food availability, in addition to providing refuges from predators during the critical spawning, rearing, and migration period of several native Central Valley fish species—especially Sacramento splittail and salmonids (^Sommer et al. 2001b; ^Jeffres et al. 2008; TBI/NRDC 2010a).

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

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

Temperature control devices (TCDs) can control the temperature of water released from dams for the protection of downstream fisheries by varying operations of release gates. Shasta Dam was fitted with shutters to allow water to be drawn from different levels to conserve cold water for spawning of winter-run salmon. Similar outlet shutters, to benefit resident trout and fall-run salmon, are found on Folsom and Oroville Dams. A horizontal thermal curtain is used in Lewiston and Whiskeytown Reservoirs to isolate cold inflowing waters on the Trinity River to maintain cold water outflows (Deas and Lowney 2000). The other rim dams of the Central Valley lack TCDs, so temperature management can be achieved only directly through flow management (^NMFS 2009). See Section 3.4.4, *Dam and Reservoir Effects on Salmonids*, Section 3.14.3, *Cold Water Storage*, and Chapter 5, *Proposed Changes to the Bay-Delta Plan for the Sacramento/Delta,* for more discussion on managing cold water habitat below reservoirs.

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

In addition to changes in temperature due to reservoir storage and releases, reservoirs and diversions also modify the temperature regime of downstream river reaches by altering the volume and thermal mass of water. A smaller quantity of water has less thermal mass and, therefore, a decreased ability to absorb temperatures from the surrounding environment (air and solar radiation) without being affected (USACE 1987). The greatest impact occurs with less flow (less thermal mass) and warmer climate (increased solar radiation), usually in late spring, summer, and early fall periods (Deas and Lowney 2000). The colder summer temperatures may mitigate to some extent the loss of cooler habitat for salmonids upstream of dams and other habitat alterations that affect summer survival of aquatic organisms. At the same time, warmer temperatures (62 degrees Fahrenheit [°F] to 68°F) during salmonid rearing periods also may promote optimal growth, provided that food availability is not a limiting factor (Myrick and Cech 2004). However, temperatures that exceed these levels can raise metabolic rates above the ability of fish to forage and thereby decrease salmonid growth and survival rates and reduce the amount of suitable habitat for rearing (McCullough 1999; ^Myrick and Cech. 2001).

3.2.2 Freshwater Flow and Estuarine Resources

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

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

Natural flows from upstream tributaries create habitat by pushing the salt field down the estuary in spring during snowmelt events as temperatures warm. Historical evidence suggests a dynamic gradient between fresh and saline waters in the estuary; however, these accounts generally indicate that fresh water predominated in the Delta during the early 1800s, with a transition from saline to fresh water in upstream portions of Suisun Bay (^Whipple et al. 2012). While there is high interannual variability in unimpaired flows because of the highly variable climate of California, both Delta outflow and the position of the low salinity zone (LSZ) (X2) (measured in kilometers [km] from the Golden Gate) have been altered as a result of numerous factors.[1] The removal of wetlands and restriction of the rivers to leveed channels removed the absorptive nature of the original landscape and facilitated more rapid runoff in spring and seasonal intrusion of salinity when the river flows declined. The construction of reservoirs and diversions also allowed flows to be removed from the system or changed in time to create a more homogenous flow regime (^Whipple et al. 2012; ^Kelley 1989 pp. 34-33, 252-253, 288-291). Hydrodynamic simulations conducted by ^Fleenor et al. (2010) indicate that the position of the LSZ has skewed eastward in the recent past compared with unimpaired conditions and earlier impaired periods, and that the variability of salinity in the western Delta and Suisun Bay has been significantly reduced (see Chapter 2, *Hydrology and Water Supply*). Analyses show a clear trend in the movement of the LSZ in fall months as well into the deeper channels of the western Delta and a restriction in its area since 1980 (MacWilliams et al. 2016), with a further reduction since 2000 (Cloern and Jassby 2012). As a result of climate change and associated changes in precipitation and sea level rise, outflow and the position of the LSZ may continue to shift dramatically in coming years (Knowles and Cayan ^2002, ^2004).

In the Bay-Delta estuary, the LSZ is an important nursery habitat for several estuarine-dependent fish species (^Kimmerer 2002a; ^Moyle 2002) and is maximized in area and volume in Suisun or San Pablo Bays (Kimmerer et al. 2013) (Figure 3.2-1). The intersection of fresh water and salt water historically created a diversity of habitat due to broad ranges of channels and wetland habitat that flood during spring and fall flow events into the estuary (^TBI 1998; ^Whipple et al. 2012).

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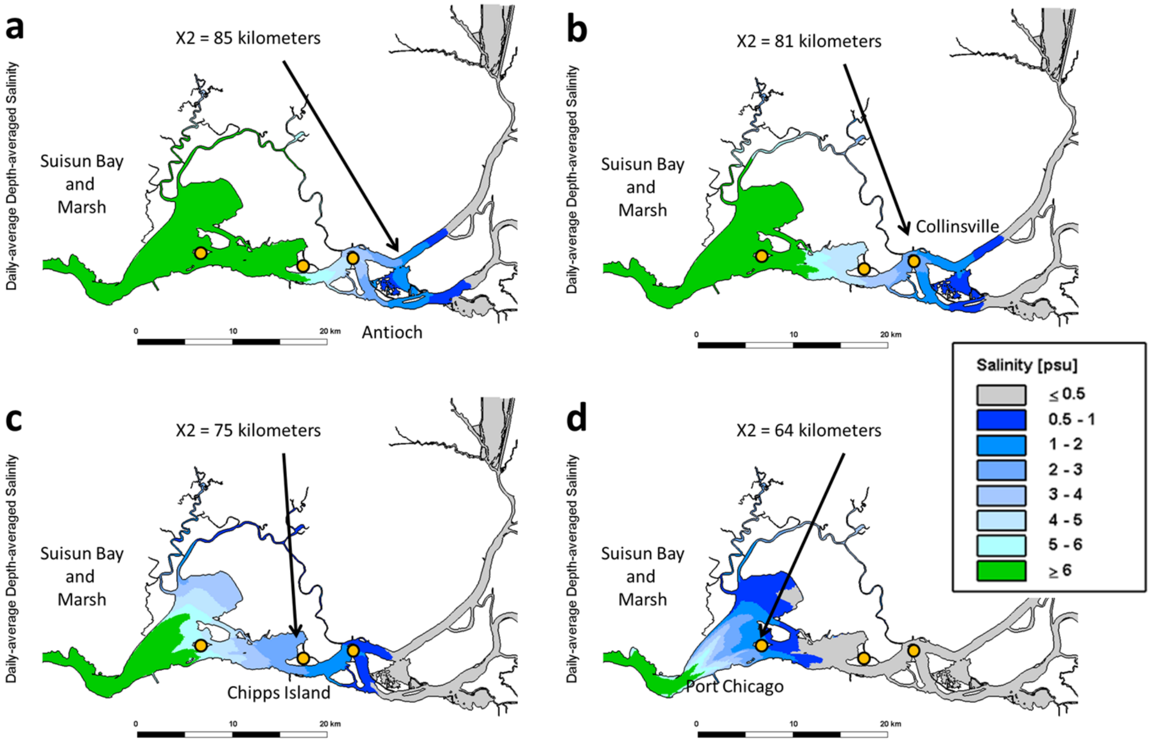
[1] X2 is the location in the Bay-Delta where the tidally averaged bottom salinity is 2 parts per thousand. It is expressed as the distance in kilometers from the Golden Gate Bridge.

Statistically significant inverse relationships have been demonstrated between the landward extent of X2 and the abundance of a diverse array of estuarine species, ranging from phytoplankton-derived particulate organic carbon at the base of the foodweb through primary consumers, benthic fish, pelagic fish, and piscivores (^Jassby et al. 1995; ^Kimmerer 2002b; Mac Nally et al. 2010). The diverse taxonomy, biology, and distribution of these estuarine organisms showing these strong relationships indicates a broad positive response of the estuarine community to increasing outflow (^Jassby et al. 1995). The X2-abundance relationships of many estuarine species have persisted since systematic sampling programs began in 1967. In some cases, the statistical relationships have shown downward step changes in response following the 1987 spread of the invasive clam *Potamocorbula amurensis* (commonly referred to as the *overbite clam*); however, other relationships have not changed through the period (California bay shrimp, Sacramento splittail) (^Kimmerer 2002b; Kimmerer et al. 2009).[2] Most of the flow-abundance relationships persist and continue to explain a large fraction of the variation in the abundances of these species. Updated flow-abundance analyses performed by State Water Board staff are included in the species profiles later in this chapter.



Source: Delta Modeling Associates 2014.
When X2 is near Antioch (a), low salinity habitat is confined to the deep channels of the western Delta. As X2 moves downstream of Collinsville (b), low salinity habitat enters Suisun Bay. With X2 near Chipps Island (c) or Port Chicago (d), low salinity and freshwater habitat occupy the broad shallows of Suisun Bay. Very high outflows can freshen Suisun Bay and push the low salinity zone into San Pablo Bay (not pictured).
psu = practical salinity unit (one gram of salt per 1,000 grams of water)

Figure 3.2-1. Variation in the Position and Extent of Low Salinity Habitat as a Function of X2

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

The specific mechanisms underlying the flow-abundance relationships are generally not resolved (^Kimmerer 2002b). Salinity changes and flow are inseparable, so these relationships are referred to as either flow-abundance relationships or fish-X2 relationships. Further investigations are recommended and ongoing (^Kimmerer 2002a,^2004; ^Reed et al. 2014). However, most of the relationships continue to remain strong since first described, and better understanding of the likely mechanisms is rapidly developing.

Effects of high river flows in freshwater areas are difficult to separate from impacts in the more saline areas of the estuary. For instance, floodplain inundation happens when river flows overtop the weirs into flood bypasses. Floodplain inundation has a variety of beneficial effects, including providing spawning and rearing opportunities for Sacramento splittail (Sommer et al. 2002; Moyle et al. 2004; ^Feyrer et al. 2006b); improved growth for salmon smolts (^Sommer et al. 2001a, ^Sommer et al 2005), including endangered winter-run Chinook salmon (del Rosario et al. 2013); increased turbidity downstream; and mobilization of sediment and food to downstream habitats (Schemel et al. 2004).

Increased turbidity associated with high flows triggers movement of Delta smelt into the Delta (Bennett and Burau 2015) and emigration of young salmon from the Delta. Increased turbidity also enhances feeding of young smelt (^Hasenbein et al. 2013) and reduces predation on young salmon (De Robertis et al. 2003). Turbidity increases in the lower estuary when winds mobilize sediments in the shoals of Grizzly and Honker Bays. Under appropriate salinity and turbidity conditions, Delta smelt are found most frequently in samples from the shoals of these bays rather than in nearby channels (Bever et al. 2016). More broadly, turbidity (or its inverse, water clarity) has been identified as a significant covariate in statistical analyses of abundance and declines of several pelagic species, including Delta smelt and longfin smelt (^Feyrer et al. 2007; ^Nobriga et al. 2008; Mac Nally et al. 2010; Thomson et al. 2010; Latour 2016). Multiple mechanisms may be responsible for these relationships, including effects on habitat suitability, catchability by trawl gear, and correlations with other environmental factors.

Longfin smelt show the strongest statistical relationship with X2. Longfin smelt's relation to X2 has undergone a downward step change in response since the overbite clam invaded, but the relationship before and after the clam's invasion is equally strong (^Kimmerer 2002b). Results of recent investigations show high abundance of longfin smelt in intertidal channels in Suisun and San Pablo Bays when salinity in those areas is low (Grimaldo et al. 2014). This suggests that, like Sacramento splittail spawning in the bypass when it is wet, longfin smelt spawn in greater abundance in springs of high-flow conditions when their wetland spawning habitat is fresh. Such tidal channels are much more common in Suisun and San Pablo Bays than among the riprapped levees lining the Delta; therefore, longfin smelt have much greater spawning habitat when those bays are fresh.

Because the LSZ is an important nursery habitat in many estuaries (e.g., Dance and Rooker 2015; Mapes et al. 2015), much work has been done to attempt to identify a mechanism relating the fish-X2 relationships to changes in the area of the LSZ. Changes in the area of the LSZ at different X2 values are inadequate to explain the fish-X2 relationships (Kimmerer et al. 2009, 2013). The position of the LSZ combines with the bathymetry at each location to provide different depths and areas of the LSZ (^MacWilliams et al. 2015). If the LSZ is defined as the water between 0.5 and 6 practical salinity units, the resultant volume does not change as the area changes; therefore, changes in area are accompanied by concomitant changes in depth (Kimmerer et al. 2009). The area of the LSZ varies between 50 and 100 square kilometers (km), with a significant decline since 1980 in the area of the LSZ from September through November in both areal extent and the percentage of time the zone has occupied more than 75 square km (MacWilliams et al. 2016; ^Baxter et al. 2015). When the LSZ is in Suisun Bay, Delta smelt are much more regularly found in the shoals of Grizzly and Honker Bays than in the deeper channels to the south (Bever et al. 2016). Delta smelt are visual feeders; greater depth of the LSZ decreases the volume of their habitat within the photic zone, where visual feeding generally occurs. Because food limitation in late summer and autumn has been identified as a bottleneck in the growth and survival of Delta smelt (^Baxter et al. 2010; ^Baxter et al. 2015; ^Hammock et al. 2015), the decrease in the extent of suitable feeding area in these months has been a crucial concern in the protection of Delta smelt since first addressed in the U.S. Fish and Wildlife Service (USFWS) 2008 Biological Opinion (USFWS 2008 BiOp) (^USFWS 2008). Protections for Delta smelt summer and fall habitat were included in the USFWS 2019 BiOp (^USFWS 2019) and California Department of Fish and Wildlife (CDFW) 2020 Incidental Take Permit (ITP) (^2020 ITP) and are anticipated to be considered under the ongoing federal Endangered Species Act (ESA) and California Endangered Species Act (CESA) reconsultation processes.

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

3.2.3 San Francisco Bay and Nearshore Coastal Ocean

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

Delta outflow is also important for maintaining physical and chemical processes in San Francisco Bay and the nearshore coast. Freshwater flow through the Bay transforms into a plume of surface brackish water that travels out the Golden Gate in winter and spring. This plume transports nutrients into the Gulf of the Farallones National Marine Sanctuary (^NMFS 2009), promoting phytoplankton growth and contributing to foodweb productivity for invertebrates, fish, birds, and marine mammals (Hurst and Bruland 2008). Cold, nutrient-rich water from the ocean enters the Bay on reverse bottom currents driven by freshwater outflow moving out the Bay into the ocean. Delta outflow influences 86 percent of the variability in salinity at the Golden Gate (Peterson et al. 1995). Freshwater flow also transports sediments to help beach formation along the coastline outside the Golden Gate (Barnard et al. 2013a, 2013b). Lack of sediments causes beach erosion, which removes nesting habitat for birds such as snowy plovers (Tobias 2014). Sediment transport is higher in the San Francisco Bay with greater freshwater flows. This helps improve the stability of wetlands. Higher sediment loads also increase turbidity, which lowers the predation risk for native fish (Gregory 1993; Gregory and Levings 1998; ^Baxter et al. 2015). These examples indicate that the amount of freshwater flow affects multiple trophic levels in San Francisco Bay and the nearshore environment, cascading up the foodweb to top predators like herons, seals, and whales.

3.2.4 Interior Delta Flows and Entrainment

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

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

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

Because it is a tidal environment, water in Delta channels flows both landward and seaward twice each day. The flow volumes of fresh water from the rivers entering the Delta are generally two or three orders of magnitude less than tidal flows. However, the California Department of Water Resources (DWR) can export as much as 10,000 cubic feet per second (cfs), and the U.S. Bureau of Reclamation (Reclamation) can export as much as 5,000 cfs out of the south Delta channels. Because these facilities usually export much more water than the median flow on the San Joaquin River, most of the exported water must move from the Sacramento River and up OMR to Clifton Court Forebay and the Jones Pumping Plant. Movement of Sacramento River water from the central Delta reduces the duration and volume of water flowing down the channels of OMR and results in net negative flows in those channels.

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

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

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

Entrainment occurs when fish and other aquatic life are drawn into a water diversion intake and are unable to escape. In the Delta, entrainment occurs primarily at the CVP facilities (Tracy Fish Facility and the nearby Delta-Mendota Canal [DMC]) and the SWP facilities (including Clifton Court Forebay and the Skinner Fish Facility), as well as other smaller Delta intakes. Some of the entrained fish are *salvaged*, meaning they are caught in facilities at the pumps and then trucked and released to an area beyond the pumps’ influence. The salvage can increase survival of salmon smolts relative to their passage through the Delta when flows are low and temperatures are high. Unfortunately, many fish, including Delta smelt, are not able to survive the collection, handling, transport, and release. Also, high mortality rates in front of the fish screens mean that the number of fish salvaged is a small portion of the fish entrained (Castillo et al. 2012). In addition to high rates of predation that occur at the fish screens, much indirect mortality is thought to occur in the sloughs and channels leading to the export facilities, even before fish enter the facilities. Small fish drawn into this part of the Delta, or that migrate in inappropriate directions in response to changes in channel flows, have a very low chance of survival. Juvenile salmon from the Sacramento River, including listed winter- and spring-run salmon, steelhead, and green sturgeon, enter the central Delta through the DCC or Georgiana Slough and have a lower chance of survival than fish staying in the Sacramento River’s mainstem (^ERP 2014).

3.3 Species-Specific Analyses

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

3.3.1 Updated Quantitative Analysis

In addition to discussion of the life history, population abundance, and flow-abundance relationships of each species published in the existing scientific literature, the species-specific analyses that follow contain updated quantitative analyses performed by State Water Board staff to document abundance trends and flow-abundance relationships, and to estimate ranges of flow predicted to be protective of individual species. Staff obtained abundance index data on predominantly estuarine species from the CDFW fall midwater trawl (FMWT) (CDFW 2016a) and San Francisco Bay Study (Bay Study) otter trawl (Hieb 2017, page ref. n/a) surveys. Staff relied primarily on the published literature for analysis of the effects of flow on salmonid populations, although the flow-abundance relationship for unmarked Chinook salmon (^Brandes and McLain 2001) was updated using Chipps Island trawl data from the Delta Juvenile Fish Monitoring Program (DJFMP 2016a, 2016b, page ref. n/a). In all cases, staff used flow data from Dayflow (^DWR 2017a). Analyses were conducted using the R statistical computing language (R Core Team 2015).

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

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

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

1. **Flow-abundance relationships:** Following the general methodology of ^Jassby et al. (1995) and ^Kimmerer (2002b), staff estimated the relationship between the logarithm of seasonal average Delta outflow and the respective species abundance indices using the most recent data available. Following the methods of ^Kimmerer (2002b), staff incremented abundance indices containing zero values for the purposes of this analysis and included one or more step changes for species that experienced a substantial decline immediately following the introduction of *Potamocorbula* or the pelagic organism decline. The regression was then used to predict the flow associated with the abundance goal. Staff did not use this method if the predicted flow fell outside the range of the observed flow data.

2. **Cumulative frequency distributions of flow:** If staff could identify a period of years during which the abundance goal was attained and the population was not in decline, the median of the seasonal average flows over that period was used as an indicator of the flow that would be protective of the species.
3. **Logistic regression estimates of the probability of population growth:** For species that spawn predominantly at a single age, logistic regression was used to estimate the response of generation-over-generation population growth to seasonal average flow (TBI/NRDC 2010a). For a given population index N, the growth rates were estimated as N(t)/N(t-L), where L is the age of reproduction. These rates were converted to a binary variable (1=growth, 0=decline) and regressed on the logarithm of average seasonal outflow, using a general linear model with a logit link function. Staff interpreted the flow that predicted a 50 percent probability of population growth as a threshold flow that would benefit the species.

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

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

3.4.1 Overview

A combined species evaluation has been prepared for all four runs of Chinook salmon and Central Valley steelhead. Less information is available for steelhead than for salmon. Although distinct differences exist in certain aspects of their life histories and habitat needs (see Section 3.4.2.2, *Central Valley Steelhead*), factors that benefit salmon are also expected to benefit steelhead based on their general ecological requirements. The evaluation provides information on life histories of the species, population abundance trends through time, population restoration goals, and where available, information on the functional flow needed by each run to successfully emigrate from upstream tributaries in the Sacramento/Delta area through the Delta to the Pacific Ocean. Because inflows from the San Joaquin River above the Delta are addressed in the Lower San Joaquin River/South Delta update to the 2006 Bay-Delta Plan, those inflows are not discussed in this chapter. However, issues below the San Joaquin River at Vernalis are discussed as are issues related to the eastside Delta tributaries that flow into the downstream portions of the San Joaquin River in the Delta.

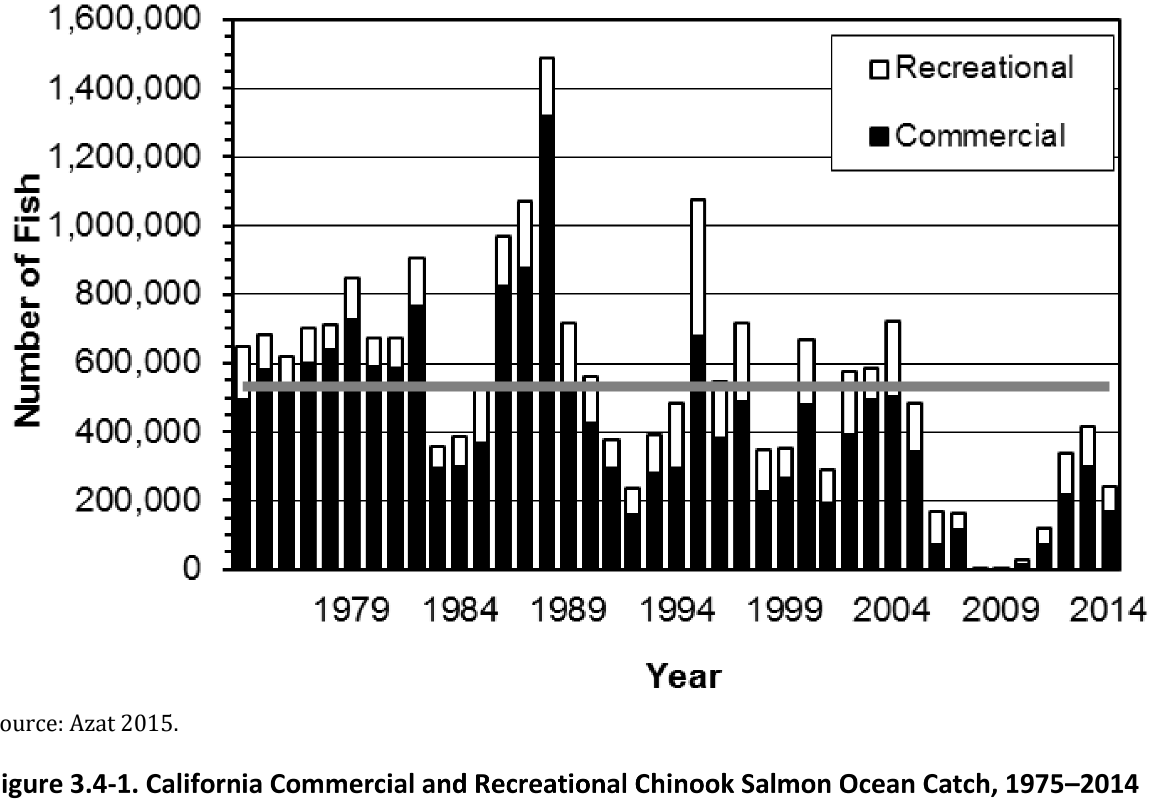
The following evaluation shows that adult and juvenile salmon benefit from an increase in a more natural flow pattern in Central Valley tributaries. Increased tributary flow aids adult upstream spawning migration, juvenile rearing in tributary watersheds, and emigration to the Delta. Juvenile fall- and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

3.4.2 Life History

3.4.2.1 Chinook Salmon

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

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



Source: Azat 2015.

Figure 3.4-1. California Commercial and Recreational Chinook Salmon Ocean Catch, 1975–2014 with 40-Year Mean (gray line)

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

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

	Adult Migration Period	Adult Peak Migration	Adult Spawning Period	Adult Peak Spawning Period	Juvenile Emergence Period	Juvenile Stream Residency (months)
Sacramento River Basin						
Winter-run	Dec–Jul	Mar	Late Apr–mid Aug	May–Jun	July–Oct	5–10
Spring-run	Feb–Sept	May–Jun	Late Aug–Nov	Oct–Nov	Dec–Mar	12–16
Late fall-run	Oct–Apr	Dec–Jan	Early Jan–Apr	Feb–Mar	Apr–Jun	7–13
Fall-run	Jun–Dec	Oct	Late Sep–Jan	Oct	Dec–Apr	1–5
San Joaquin River Basin						
Fall-run	Sept–Dec	Nov	Nov–Jan	Nov–Dec	Dec–Mar	2–5
Steelhead (both basins)	July–Mar	Sep–Oct	Nov–Apr	Dec–Apr	Jan–May	12–36

Source: Modified from ^Yoshiyama et al. 1998 and ^NMFS 2014a.

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

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

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

Adult salmon require suitable flows, water temperatures, and water quality to access their natal streams and reach the spawning grounds at the proper time and with sufficient energy reserves to complete their life cycles (Bjornn and Reiser 1991). Adult Chinook salmon require water depths greater than 0.8 foot and water velocities less than 8 feet per second for successful upstream migration (Thompson 1972). Adult salmon migrating upstream mostly use pool and mid-channel habitat (Stillwater Sciences 2004) and are thought to be primarily active during twilight hours.

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

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

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

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

Upon emergence, fry disperse to the margins of their natal stream, seeking shallow water with slower velocity, and begin feeding on terrestrial invertebrates, zooplankton, and aquatic invertebrates (^Sommer et al. 2001a). Some fry take up residence in their natal stream for up to a year, while others are displaced downstream by the current. Once downstream, migration begins; fry may continue to the estuary and rear there or take up residence in intermediate upstream river reaches for up to a year (Williams 2006, 2012; ^Sturrock et al. 2015).

When juvenile Chinook salmon reach a length of 5 to 6 centimeters (cm), they move into deeper water with greater current velocities but still seek shelter in quiescent areas to conserve energy (Healey 1991). In the Sacramento River near West Sacramento, larger-bodied juveniles were located in the main channel, while smaller fry were found along the river margin (USFWS 1997). When channel depth is greater than 9 to 10 feet, juveniles tend to remain near the surface (Healey 1982). An increase in turbidity from storm runoff, increased flows, or changes in day length trigger emigration of juveniles from the upper Sacramento River basin (Kjelson et al. 1982; ^Brandes and McLain 2001). Juvenile salmon migration rates vary considerably depending on the physiological stage of the individual and ambient hydrologic conditions. Chinook salmon fry can travel as fast as 12 miles per day in the Sacramento River (Kjelson et al. 1982). Sommer et al. (2001a) measured travel rates as low as 0.5 to more than 6.0 miles per day in the Yolo Bypass.

Smolting is the physiological process that increases salinity tolerance and enables salmonids to transition from fresh water to salt water. Smolting usually starts when juveniles are 7 to 10 cm in length (CDFG 2010b); consequently, juveniles may begin this process in their natal streams, in the Delta or estuary, or during transit from their natal streams. Environmental factors, such as increased streamflow and changes in water temperature and photoperiod, also can affect the onset of smolting (Rich and Loudermilk 1991; Quinn 2005). After smolting begins, salmon often rear farther downstream where ambient salinities are higher, such as in Suisun Bay or the coastal ocean (Healey 1980; Levy and Northcote 1981).

The majority of Sacramento River juvenile Chinook salmon enter the Delta between October and May (Table 3.4-2). However, there are run-specific differences and substantial variation in emigration timing from year to year depending on hydrologic conditions (e.g., drought conditions) and the timing of major storm events (Kjelson et al. 1982; Williams 2006; del Rosario et al. 2013). For example, early peak movements of winter-run Chinook salmon juveniles past Knights Landing are triggered by the first major flow events of the season (15,000 cfs at Wilkins Slough), which typically occur from late November through February (del Rosario et al. 2013).

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

Month	Sacramento River Total [a, b] (%)	Fall-Run (%)	Spring-Run (%)	Winter-Run (%)	Sacramento Steelhead [c] (%)
January	12	14	3	17	5
February	9	13	0	19	32
March	26	23	53	37	60

Month	Sacramento River Total [a, b] (%)	Fall-Run (%)	Spring-Run (%)	Winter-Run (%)	Sacramento Steelhead [c] (%)
April	9	6	43	1	0
May	12	26	1	0	0
June	0	0	0	0	0
July	0	0	0	0	0
August	4	1	0	0	0
September	4	0	0	0	1
October	6	9	0	0	0
November	9	8	0	3	1
December	11	0	0	24	1
Total	100	100	100	100	100

Source: NMFS 2009 RPA with 2011 amendments.
RPA = Reasonable and Prudent Alternative
[a] Midwater trawl data.
[b] All runs combined.
[c] Rotary screw trap data from Knights Landing.

Rearing by juvenile Chinook salmon in the Bay-Delta appears to be an important life history component based on otolith microchemistry analysis and broad evidence from other estuaries (Reimers 1973; Healey 1980; Kjelson et al. 1982; Lott 2004; Miller et al. 2010; ^Sturrock et al. 2015). Peak migrations and estuarine abundance of fry in the Bay-Delta correlated with flow magnitude, with peak abundance and downstream extent of fry being highest following major runoff events (Kjelson et al. 1982; ^Brandes and McLain 2001). Rearing juveniles are known to occupy shallow water around the margins of estuaries, utilizing tidal currents to move in and out of wetland and marsh habitats where they benefit from access to shallow water, protective cover, and abundant food resources (McDonald 1960; Dunford 1975; Healey 1980; Levy and Northcote 1981; Healey 1991, Hering et al. 2010). In the Bay-Delta, Kjelson et al. (1982) reported evidence of diel movements of fry from shallow water areas near the shoreline during daylight to offshore areas at night, and a general increase in the size of juvenile salmon with increasing distance from the shore. Cladocerans, copepods, amphipods, and dipterans are common prey items in the Delta and estuary (Kjelson et al. 1982; ^Sommer et al. 2001a; MacFarlane and Norton 2002).

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

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

3.4.2.2 Central Valley Steelhead

Central Valley steelhead (*O. mykiss*) once were widely distributed in the Sacramento and San Joaquin River systems, migrating to spawning and rearing areas primarily in intermediate to upper-elevation Sierra Nevada and Cascade streams (Quinn 2005; ^Yoshiyama et al. 2001).[3] However, most of their historical spawning and rearing habitat is now blocked by dams, restricting anadromous populations to downstream reaches where habitat conditions have been highly modified by regulated flows and other abiotic and biotic stressors (^McEwan 2001; ^NMFS 2014a). Genetic studies have revealed that Central Valley steelhead populations generally lack the strong geographic patterns of genetic differentiation that have been found in other California *O. mykiss* populations (e.g., northern California steelhead distinct population segment [DPS]) (Nielsen et al. 2005; Pearse and Garza 2015). Pearse and Garza (2015) found that Central Valley populations above and below barrier dams are not closely related and that the relationships between below-barrier populations do not fit a pattern of isolation-by-distance. These results likely reflect more than a century of habitat modification and hatchery and stocking practices, including the use of out-of-basin sources to supplement hatchery production (Pearse and Garza 2015).

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

Central Valley migratory steelhead are *winter steelhead*. The naming convention refers to the timing of upstream adult migration. Winter steelhead adults migrate from the ocean as sexually mature

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

individuals and are ready to spawn when they arrive on their breeding grounds (^Moyle 2002; McEwan and Jackson 1996). Adult upstream migration from the ocean occurs throughout the year but peaks in the Sacramento River in September and October (McEwan and Jackson 1996). Migration in the San Joaquin River begins as early as July and continues through April, with a peak in upstream migration between October and February (^USDOI 2008). Adult Central Valley steelhead mostly uses the Sacramento and San Joaquin River channels as a migration corridor to reach upstream natal streams (^Moyle 2002).

Peak spawning generally occurs between January and March in both the Sacramento and San Joaquin River watersheds (Hallock et al. 1961; ^McEwan 2001). Like Chinook salmon, redd site selection is a function of body size; steelhead generally are reported to use water depths ranging from 6 to 36 inches, water velocities ranging from 1 to 3.6 feet per second, and substrates ranging from 0.2 to 4 inches (Bjornn and Reiser 1991; ^McEwan 2001). The time required for egg development is approximately 4 weeks but is temperature dependent (McEwan and Jackson 1996). Optimal egg development occurs at temperatures between 48°F and 52°F. After hatching, the yolk sac alevin remain in the gravel for an additional 4 to 6 weeks before emerging (McEwan and Jackson 1996). Upon emerging, fry move to shallow protected stream margins. Older, larger individuals use riffles and pools. Young steelhead feed on immature aquatic and terrestrial insects (^Moyle 2002; Benigno and Sommer 2008; Weber 2009; ^Kammerer and Heppell 2012).

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

3.4.3 Life History, Distribution, and Abundance Trends over Time

3.4.3.1 Population Abundance Goals and Species Declines

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

Table 3.4-3 indicates significant declines in the natural production of Sacramento River winter-run, spring-run, late fall-run, and San Joaquin fall-run Chinook salmon, notwithstanding the population abundance goals, although uncertainties associated with estimation methods can make estimating natural production challenging (Cummins et al. 2008). Comparable estimates are not available for steelhead because of limited baseline and post-baseline monitoring data (see Section 3.4.3.6, *Central Valley Steelhead*). The best long-term data set are counts of adults passing through the fish ladder at Red Bluff Diversion Dam (RBDD); however, changes in dam operations in 1994 precluded the collection of comparable post-baseline monitoring data (^NMFS 2016a).

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

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

Source: Table 4 in USDOI 2016.

[a] Stanislaus, Tuolumne, and Merced Rivers.

3.4.3.2 Winter-Run Chinook Salmon

Application of genetic stock identification techniques to Chinook salmon sampled in the California recreational ocean salmon fishery between 1998 and 2002 indicate that winter-run Chinook salmon occur largely in central California coastal waters between Point Reyes and Monterey before migrating inland to spawn (Satterthwaite et al. 2015). Adult winter-run Chinook salmon enter the Sacramento River between December and July and spawn between late April and mid-August (Table 3.4-1). Most adults are 3 years old and are sexually immature when re-entering fresh water (^Moyle 2002). Immature adults must hold in fresh water for several months before they are capable of reproducing. Winter-run are unique because they complete sexual development and spawn during summer when air temperature in the Central Valley approaches an annual maximum. Since the construction of Shasta and Keswick Dams, winter-run have been blocked from reaching their native spawning grounds in the upper Sacramento River, including the Pit, McCloud, Fall, and Little Sacramento Rivers (^Yoshiyama et al. 1998). Consequently, spawning is now restricted to between Keswick Dam and RBDD, where releases of cold water from Shasta Dam are used to maintain suitable water temperatures for spawning and incubation (^Good et al. 2005). Temperature control is achieved by managing reservoir storage levels and operating a TCD, which was installed at Shasta Dam in 1998 (^NMFS 2009 BiOp). Maintaining cold water in the Sacramento River below Keswick Reservoir can also benefit spring- and fall-run Chinook salmon and green sturgeon.

Winter-run fry emerge, generally at night, from the gravel between mid-June and mid-October and occupy nearshore shallow habitat with slow water velocity (^NMFS 2014a). Emigration begins as early as mid-July with most emigrants passing RBDD in September and October (Vogel and Marine 1991; ^NMFS 2009 BiOp). Rearing occurs in the Delta and in the Sacramento River below RBDD November through April (Table 3.4-2) (Williams 2006). Timing of migration to nursery locations is variable and is dependent upon flow, dam operations, and water temperature. Rearing generally occurs for 5 to 10 months before smolting and emigration to the ocean. Marine emigration usually begins in fall and continues through spring, with outbound smolts passing inbound spawners (^Moyle 2002).

The Sacramento River winter-run Chinook salmon population includes hatchery production from Livingston Stone National Fish Hatchery (LSNFH) located downstream of Shasta Dam (^NMFS 2014a). Hatchery fish are marked with a coded wire tag (CWT) and a clipped adipose fin to allow fishery managers to differentiate between native and hatchery-produced fish. The LSNFH releases between about 30,000 and 250,000 pre-smolts annually each winter (^NMFS 2014a).[4] In 2014 and 2015, juvenile winter-run production at LSNFH was increased to mitigate for the effects of prolonged drought conditions (elevated water temperatures) on naturally spawning winter-run Chinook salmon in the Sacramento River. Increased hatchery production resulted in the release of 612,000 juveniles in 2014 and 420,000 juveniles in 2015 (NMFS 2016, ^NMFS 2016c). Since the beginning of hatchery production at LSNFH in 1997, the proportion of hatchery-origin winter-run Chinook salmon spawning in the river has increased. Prior to 2005, the proportion of in-river hatchery-origin spawners was between 5 and 10 percent. The average over the last 12 years was approximately 13 percent (with peaks of approximately 20 percent in 2005, 30 percent in 2012, and 23 percent in 2014), raising concerns about potential negative effects on the genetic integrity of the run (NMFS 2016).

The abundance of winter-run Chinook salmon has declined significantly. Escapement in the 1960s was near 100,000 fish (^Good et al. 2005). Figure 3.4-2 presents escapement for both natural and hatchery production between 1975 and 2014. Escapement was as high as 35,000 fish in 1976 and has since declined to a few thousand individuals (Azat 2015). Natural juvenile production and adult escapement to in-river spawning locations also has declined relative to the 1967 through 1991 baseline CVPIA value (Figure 3.4-3). Natural production was 89 percent less in 1992 through 2015 than in the 1967 through 1991 baseline CVPIA value (Figure 3.4-3).

The Sacramento River winter-run Chinook salmon evolutionarily significant unit (ESU) was originally listed as endangered under ESA in 1994 (59 Fed. Reg. 440).[5] The listing was reaffirmed in 2005 (70 Fed. Reg. 37160) and in 2011 (76 Fed. Reg. 50447). The listing includes both naturally occurring and artificially propagated stock (70 Fed. Reg. 37160). The ESU was listed as endangered under CESA in 1989.

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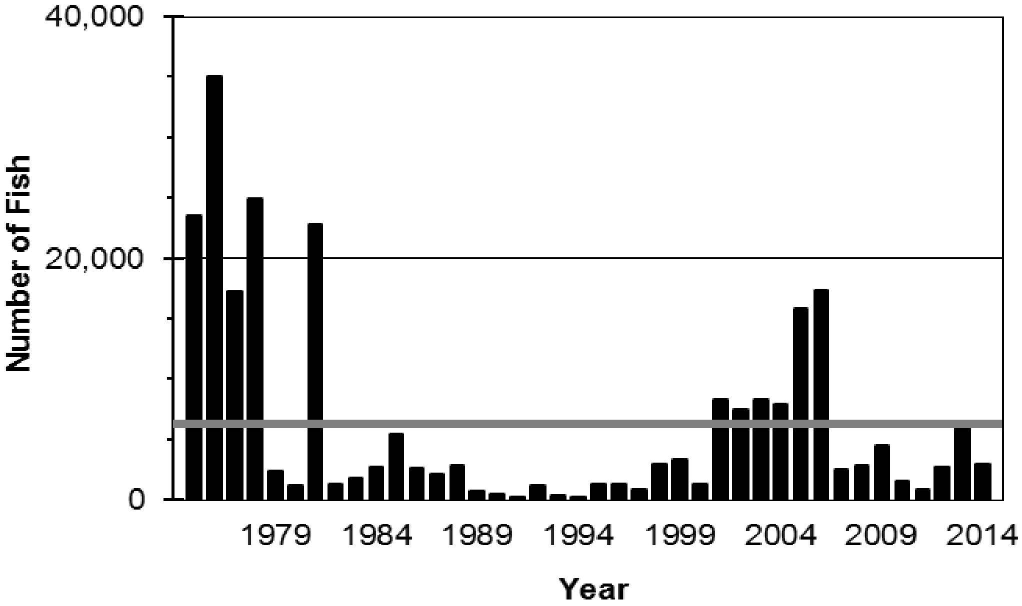
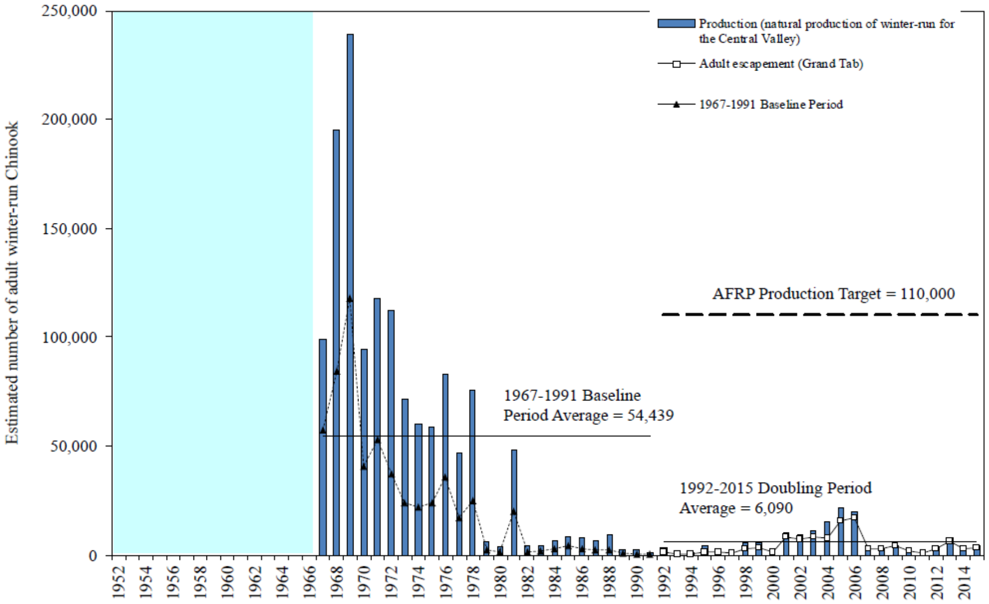
[4] Mean annual release has been about 167,000 fish.

[5] NMFS uses the term *ESU* to identify a DPS as specified in the ESA. The ESA does not define DPS. The DPS and ESU are smaller evolutionary units than a species.



Source: Azat 2015.

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



Sources: Azat 2016, Mills and Fisher 1994, USFWS 2016.
AFRP = Anadromous Fish Restoration Program
No data are available for 1952–1966. 1992–2015 numbers are from Azat (2016). 1967–1991 baseline period numbers are from Mills and Fisher (1994).

Figure 3.4-3. Estimated Yearly Adult Natural Production and In-River Adult Escapement of Winter-Run Chinook Salmon in Central Valley Rivers and Streams

3.4.3.3 Spring-Run Chinook Salmon

Historically, Central Valley spring-run Chinook salmon were likely the most abundant salmon run in the Central Valley. Spring-run used the headwaters of all the major rivers to spawn and rear (^NMFS 2014a). Spring-run enter fresh water as immature adults and ascend to summer holding areas that provide appropriate temperatures and sufficient flow, cover, and pool depths to allow successful maturation (^Yoshiyama et al. 1998). In the Central Valley, ambient summer water temperatures are suitable only above 500 to 1,500 feet elevation, and most of this habitat is now upstream of impassable dams (^NMFS 2014a). As a result, spring-run have suffered the most severe decline of all the four runs of Chinook salmon in the Sacramento River basin (^Fisher 1994).

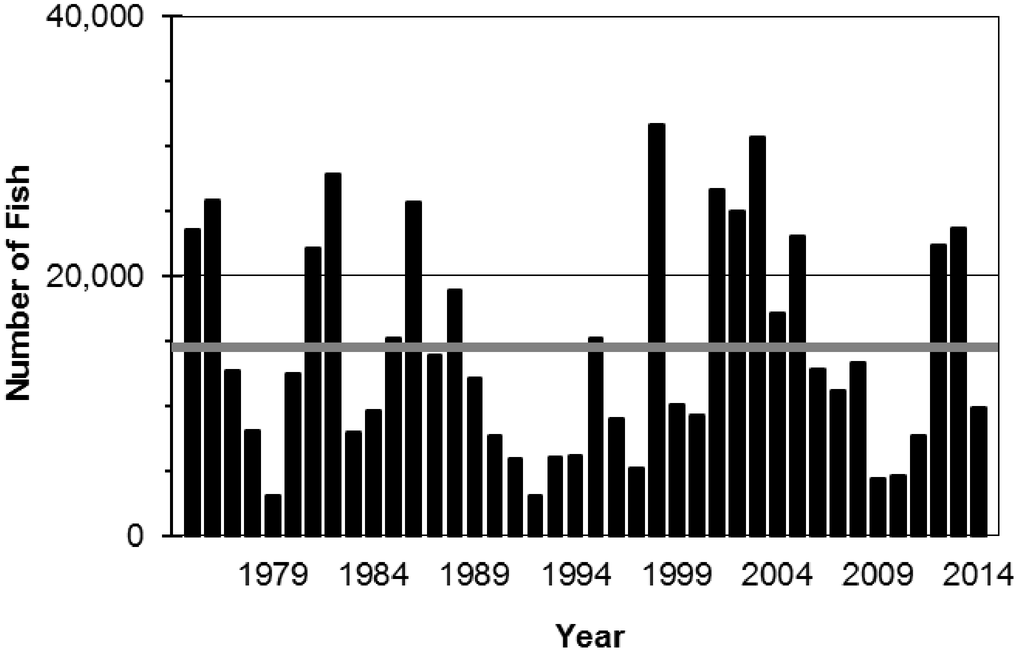
Habitat requirements for spring-run differ from those of winter-run in that suitable habitat is required year-round for successful completion of spring-run freshwater life stages (holding, spawning, and rearing) (Table 3.4-1). Spring-run Chinook salmon migrate to natal streams between February and September, with peak migration in May and June (^Yoshiyama et al. 1998). Following the summer holding period, spawning occurs between late August and November, with a peak in October and November (^Moyle 2002).

The development of embryos and emergence from the gravel is dependent on ambient water temperatures and dissolved oxygen levels. Optimal water temperatures for Chinook salmon egg incubation range from 41°F to 56°F (^NMFS 2009 BiOp). Embryos hatch in 40 to 60 days under these conditions, and the alevin remain in the gravel for an additional 4 to 6 weeks before emerging as fry (^Moyle 2002). Fry leave the gravel between December and March (Table 3.4-1). Juveniles typically may remain in fresh water for 12 to 16 months, but some individuals migrate downstream to the ocean as young-of-the-year in winter or early spring (^NMFS 2014a).

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

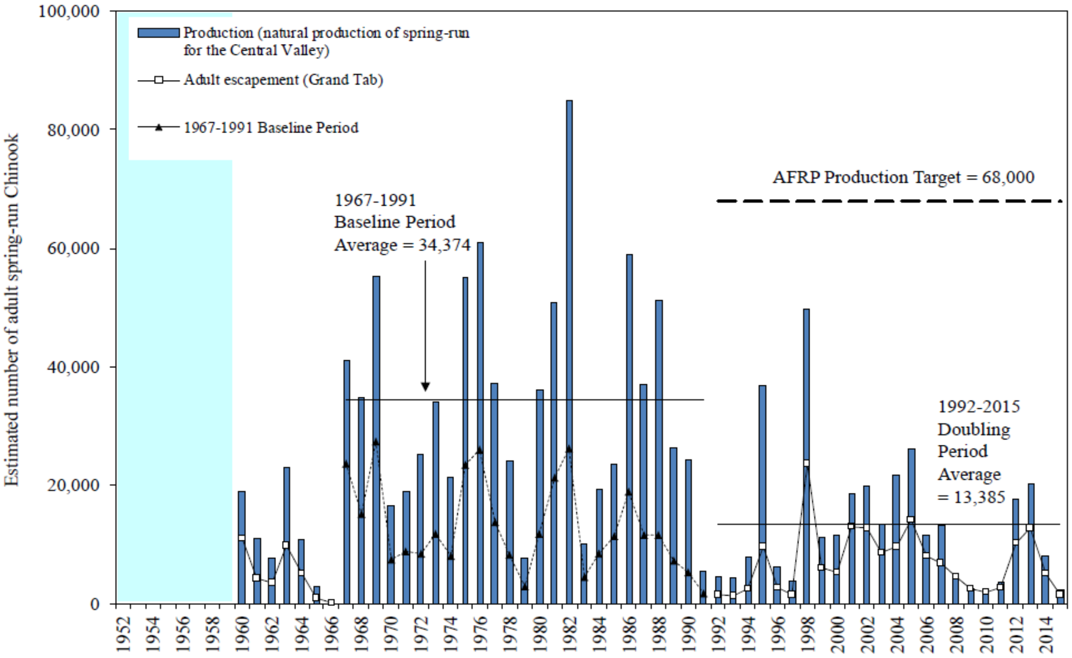
Spawning habitat for Central Valley spring-run Chinook salmon also includes the mainstem Sacramento (between Keswick Dam and RBDD); Feather, and Yuba Rivers; and Cottonwood, Antelope, Thomes, Big Chico, Clear, Battle, Butte, Deer, and Mill Creeks. Self-sustaining populations occur on Mill, Deer, and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

The Central Valley is estimated to have produced spring-run Chinook salmon runs as large as 600,000 fish between 1880 and 1940 (CDFG 1998). More than half a million spring-run salmon are believed to have been caught in the commercial fishery in 1883 (^Yoshiyama et al. 1998). Escapement is now much smaller, with a 40-year average of about 14,500 fish (Figure 3.4-4). Natural production of spring-run Chinook salmon also has declined (Figure 3.4-5). Production in the CVPIA baseline period of 1967 through 1991 was estimated at 34,374 fish. Average production in 1992 through 2015 decreased to 13,385 fish. This represents a 61 percent decline over the baseline period (Table 3.4-3) and is only 20 percent of the CVPIA doubling goal.



Source: Azat 2015.

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



Sources: Azat 2016, Mills and Fisher 1994, USFWS 2016.
No data are available for 1952–1966. 1992–2015 numbers are from Azat (2016).). 1967–1991 baseline period numbers are from Mills and Fisher (1994).
AFRP = Anadromous Fish Restoration Program

Figure 3.4-5. Estimated Yearly Adult Natural Production and In-River Adult Escapement of Spring-Run Chinook Salmon in the Central Valley Rivers and Streams

3.4.3.4 Late-Fall-Run Chinook Salmon

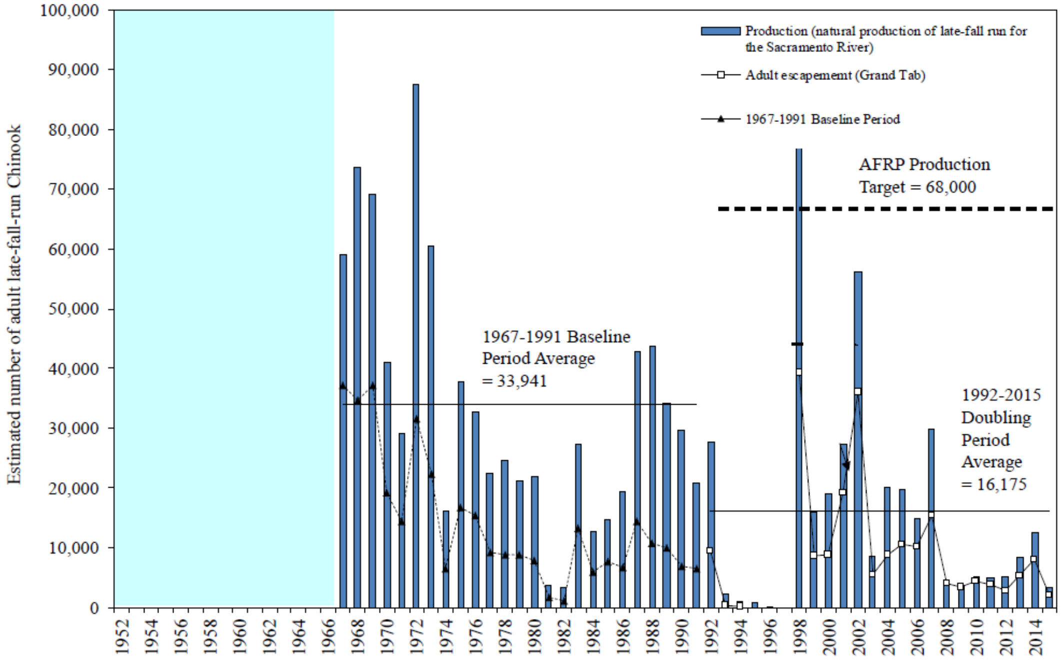
Late fall-run Chinook salmon have the largest body size of the four runs and can weigh 20 pounds or more (^Moyle 2002). Their large size makes them a sought-after recreational trophy sport fish.

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

Late fall-run Chinook salmon migrate upstream in December and January as mature fish, although some upstream migration has been documented as early as October and as late as April (Table 3.4-1) (Williams 2006). Spawning occurs in late December and January as fish arrive on the spawning grounds, although it may extend into April in some years (Williams 2006). Fry begin to emerge from the gravel in April, and emergence is complete by early June. Juveniles may hold in the river for 7 to 13 months before migrating downstream to the ocean (^Moyle 2002). Peak downstream migration is in October, although some individuals may leave at an earlier age and a smaller body size (Williams 2006).

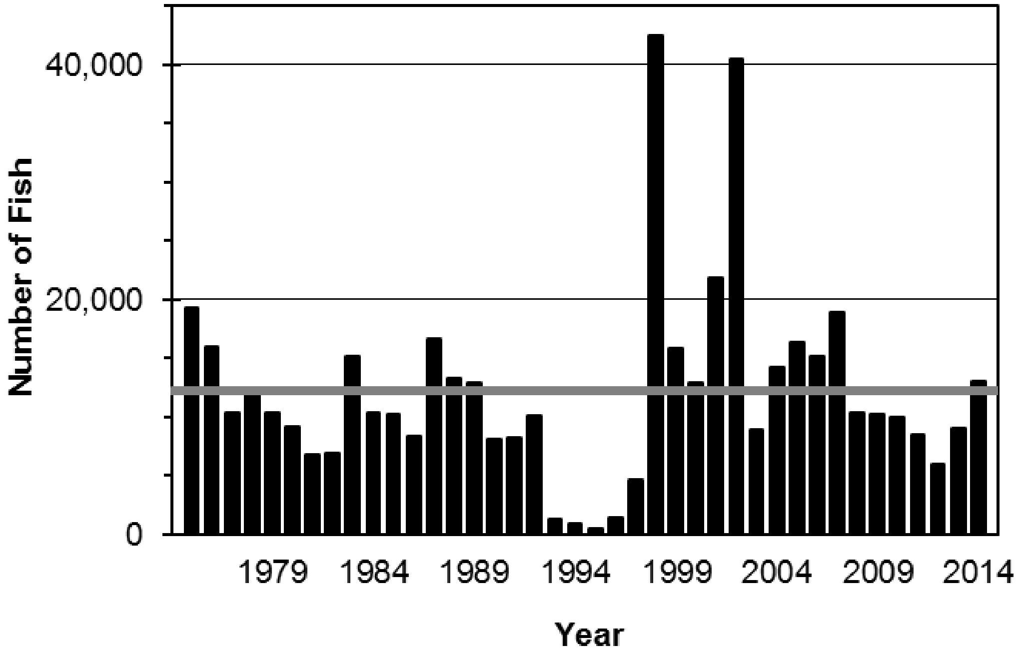
Construction of Shasta and Keswick Dams in the 1940s blocked late fall-run Chinook salmon access to upstream spawning areas where snowmelt and spring water originating from Mount Shasta kept ambient water temperature cool enough for successful spawning, egg incubation, and survival of juvenile salmon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

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



Sources: Azat 2016; Mills and Fisher 2014; USFWS 2016.
No data are available for 1952–1966. 1992–2015 numbers are from Azat (2016). 1967–1991 baseline period numbers are from Mills and Fisher (1994).
AFRP = Anadromous Fish Restoration Program

Figure 3.4-6. Estimated Yearly Adult Natural Production and In-River Adult Escapement of Late-Fall-Run Chinook Salmon in Central Valley Rivers and Streams



Source: Azat 2015.

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

3.4.3.5 Fall-Run Chinook Salmon

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

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

Life history characteristics of the San Joaquin River fall-run Chinook salmon population are similar, but they have small differences compared with that previously described for fall-run Chinook salmon from the Sacramento River basin. Adult San Joaquin River fall-run Chinook salmon migrate through the Delta to their natal streams from late September to early December. Peak migration occurs in November (Table 3.4-1). Spawning can occur at any time between October and January in the Merced, Tuolumne, and Stanislaus Rivers but typically happens in November (McBain and Trush 2002; CDFG 1993). Fry emerge from the gravel between February and March (McBain and Trush 2002). Some individuals immediately migrate downstream to the mainstem San Joaquin River and the Delta, while others linger in their natal stream and emigrate in April and May. Peak emigration past Mossdale occurs between mid-April and the end of May (Figure 3.4-8). Juvenile salmon can rear in the Delta downstream of Mossdale for an additional 1 to 3 months before moving to the San Francisco Bay and Pacific Ocean (Williams 2006).

Fall-run Chinook salmon are the most abundant of all Central Valley salmon runs. The life history strategy of adult Chinook salmon spawning upon entry into the watershed and juveniles leaving shortly after emerging from redds makes them suitable for culture in production hatcheries. Fall-run salmon fry are raised at four Central Valley hatcheries, which together release more than 32 million smolt each year.[6] Hatchery production contributes to a large commercial and recreational ocean fishery and a popular freshwater sport fishery. However, historical levels of genetic and phenotypic diversity of Central Valley stocks have likely been substantially reduced by the cumulative effects of habitat loss and degradation and increasing dominance of hatchery fish in spawning populations (^Williamson and May 2005; ^Barnett-Johnson et al. 2007). These factors are believed to have contributed to the reduced resilience of Sacramento fall-run Chinook salmon and the collapse of the fall-run population in response to poor ocean conditions in 2005 and 2006, (^Lindley et al. 2009)

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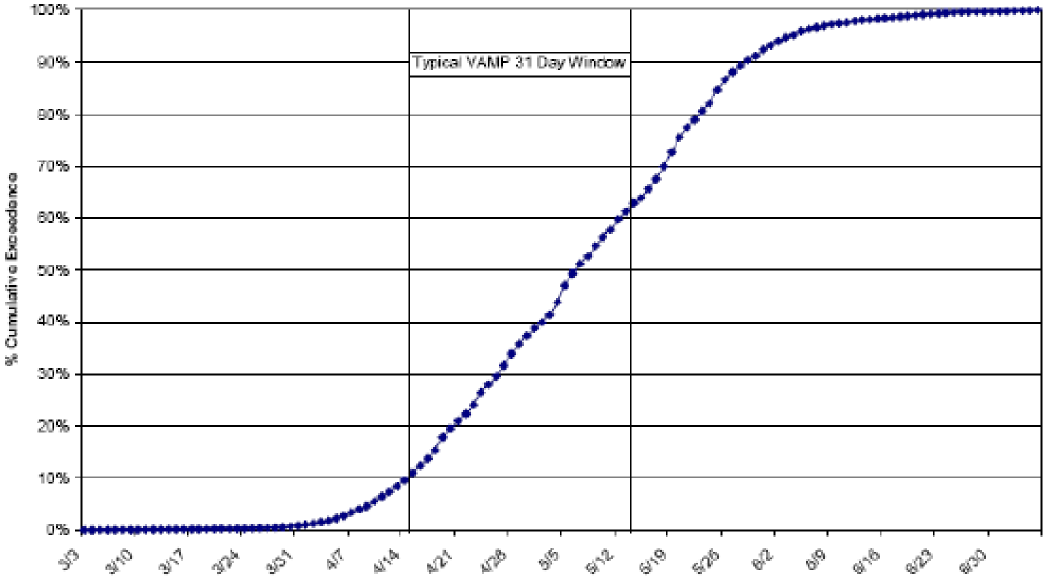
[6] American, Feather, Merced, and Mokelumne River fish hatcheries.

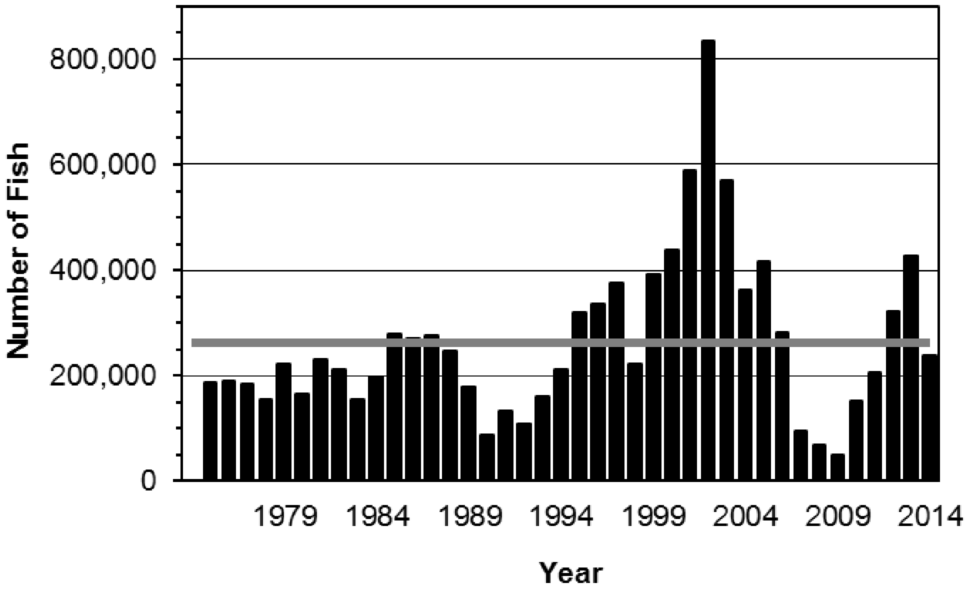
and a large decline in escapement in 2007 and 2008 (Figure 3.4-9). The number of returning adults has since recovered and is now at about the 40-year average (Figure 3.4-9).

Natural production of fall-run Chinook salmon in the mainstem Sacramento River has declined since the CVPIA baseline years of 1967 through 1991; average natural production in the mainstem Sacramento River between 1992 and 2015 was about 57 percent of the baseline period (Figure 3.4-10). Average natural production of fall-run Chinook salmon in the San Joaquin River basin (Stanislaus, Tuolumne, and Merced Rivers) from 1992 through 2015 declined approximately 55 percent since the CVPIA baseline years (Figure 3.4-11).



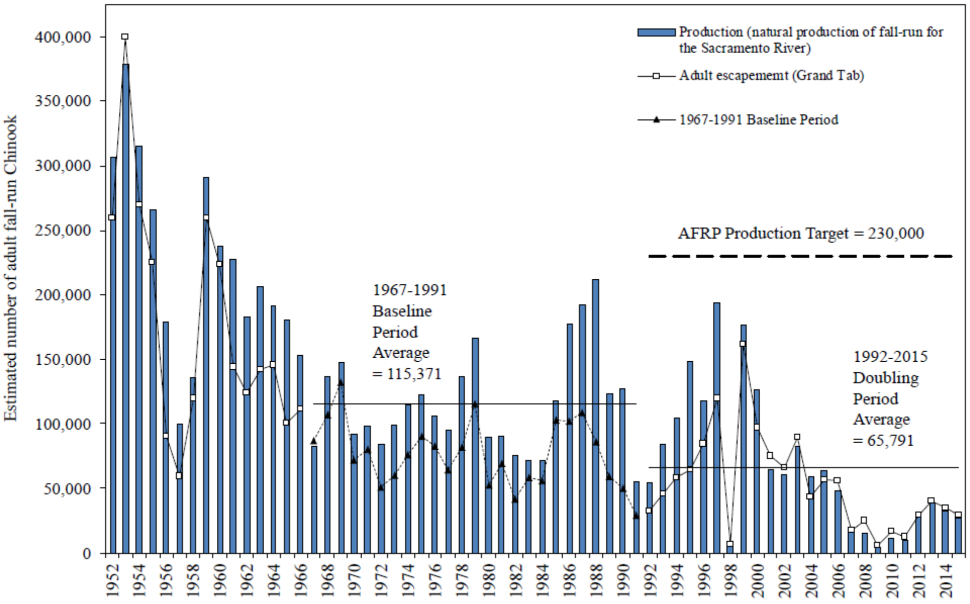
Source: ^CDFG 2005.
VAMP = Vernalis Adaptive Management Plan

Figure 3.4-8. San Joaquin River Basin Smolt Emigration Pattern (1988–2004)



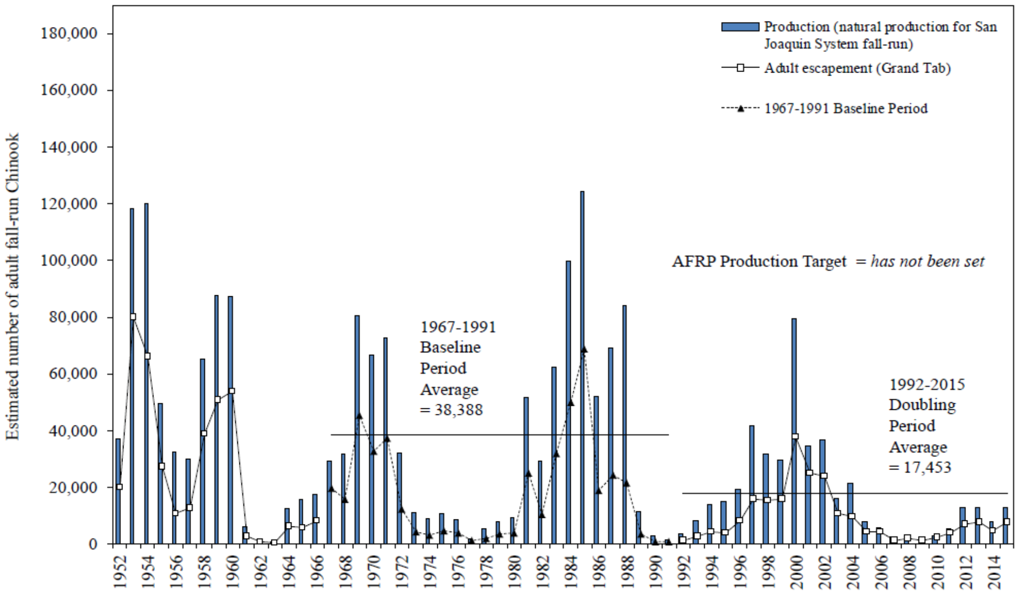
Source: Azat 2015.

Figure 3.4-9. Annual Fall-Run Chinook Salmon Escapement to the Sacramento River Watershed from 1975 to 2014 and 40-Year Mean (gray line)



Sources: Azat 2016; Mills and Fisher 2014; USFWS 2016.
1952–1966 and 1992–2015 numbers are from Azat (2016). 1967–1991 baseline period numbers are from Mills and Fisher (1994).
AFRP = Anadromous Fish Restoration Program

Figure 3.4-10. Estimated Yearly Adult Natural Production and In-River Adult Escapement of Fall-Run Chinook Salmon in the Mainstem Sacramento River



Sources: Azat 2016; Mills and Fisher 1994; USFWS 2016.
The San Joaquin River system is the sum of the Stanislaus, Tuolumne, and Merced Rivers. 1952–1966 and 1992–2015 numbers are from Azat (2016). 1967–1991 baseline period numbers are from Mills and Fisher (1994).
AFRP = Anadromous Fish Restoration Program

Figure 3.4-11. Estimated Yearly Natural Production and Instream Escapement of San Joaquin Adult Fall-Run Chinook Salmon

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

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

3.4.3.6 Central Valley Steelhead

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

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

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

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

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

3.4.4 Dam and Reservoir Effects on Salmonids

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

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

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

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

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

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

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

Reservoirs act as sediment traps and disrupt the natural transport of bedload material, including spawning-size gravel necessary for maintenance of Chinook salmon and steelhead spawning habitat.

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

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

3.4.5 Flow Effects on Salmonids

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

3.4.5.1 Adult Migration, Spawning, and Incubation

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

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

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

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

	Months [a]											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Fall-run Chinook salmon							■	■	■	■	■	■
Spring-run Chinook salmon		■	■	■	■	■	■					
Winter-run Chinook salmon	■	■	■	■	■	■						■
Late fall-run Chinook salmon	■	■								■	■	■
Central Valley steelhead	■	■	■				■	■	■	■	■	■

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

Table 3.4-5. State Water Board Staff Analysis of the Frequency of Common Flow-Related Stressors for Spring-Run Chinook Salmon and Central Valley Steelhead in 22 Salmon-Bearing Tributaries of the Sacramento River

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

Source: ^NMFS 2014b.

Adult salmonids that migrate through the Bay-Delta to return to their natal streams also encounter altered flow pathways resulting from SWP and CVP southern Delta export operations that cause flows to move toward the export facilities rather than toward the ocean. These alterations in flow pathways largely affect fish returning to the San Joaquin River and the Mokelumne River basins. Adult fall-run San Joaquin Chinook salmon migrate upstream through the Delta primarily during October when San Joaquin River flows are typically low (Hallock et al. 1970; Mesick 2001; Marston et al. 2012). As a result, if exports are high, little if any flow from the San Joaquin River basin may make it out to the ocean to help guide San Joaquin River basin salmon back to spawn (Hallock et al. 1970; Mesick 2001; Marston et al. 2012). Analyses indicate that increased straying occurs when exports are greater than 400 percent of the flow of the San Joaquin River at Vernalis, while straying rates decrease when export rates were less than 300 percent of Vernalis flow (Mesick 2001).[7] More recent analyses by Marston et al. (2012) found that straying rates estimated from CWT data from 1979 through 2007 decreased significantly with increasing San Joaquin River flows ($p=0.05$) and increased with increasing exports, although the decrease associated with reductions in exports was not statistically significant ($p=0.1$). Marston et al. (2012) also found that stray rates for San Joaquin fish were greater than those observed in the Sacramento River basin (18 percent versus less than 1 percent, on average). Taken together, this information suggests that pulse flows and exports jointly affect straying rates in the San Joaquin River basin (^Monismith et al. 2014).

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

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

Table 3.4-6. Salmon Returns on the Mokelumne River

Escapement Year	Number of Fall-run Returning	Estimated Stray Rate to American River	Pulse Flow	Delta Cross Channel Closure
2008	412	75%	No	No
2009	2,232	54%	Yes	No
2010	7,196	25%	Yes	Yes (2 day)
201	18,462	7%	Yes	Yes (10 day)

Source: ^CDFG 2012.

3.4.5.2 Juvenile Rearing and Emigration

During their freshwater rearing and emigration periods, juvenile Chinook salmon and steelhead require flows of sufficient magnitude to trigger and facilitate downstream migration to the estuary, provide seasonal access to productive rearing habitats (floodplains), and provide suitable food resources for growth and development (Raymond 1979; Connor et al. 2003; Smith et al. 2003). Central Valley Chinook salmon and steelhead exhibit a broad range of juvenile rearing and migration strategies that likely reflect adaptations to natural hydrologic patterns and the spatial and temporal distribution of habitat extending from their natal tributaries to the estuary. For example, the dominance of an ocean-type life history, in which large numbers of juveniles migrate from natal streams to lower mainstem rivers, Delta, and estuary shortly after emergence, may be linked, in part, to the high productivity of formerly extensive floodplain, wetland, and estuarine habitat that favored rapid growth and survival of juveniles prior to seaward migration (Healey 1991).

A common problem in salmon-bearing tributaries in the Bay-Delta watershed appears to be a lack of juvenile rearing habitat and a lack of connectivity between tributaries and the river due to lack of flow and elevated ambient water temperatures (^NMFS 2014b). The following subsections discuss the need for flow for juvenile salmonids through their migratory corridor from natal tributaries and floodplains, through the mainstem rivers, and then through the Delta to the ocean.

Tributary Habitat

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

Riparian Habitat

Riparian forest vegetation is important to juvenile salmonids for several reasons. Newly hatched larvae move to shallow protected areas associated with stream margins to feed (Royal 1972; Fausch 1984). Terrestrial and aquatic invertebrates are a common food source for juvenile salmon (^Moyle 2002). Juveniles are also reported to select sites with overhead cover (Fausch 1993) and appear to favor stream positions with low ambient light levels (Shirvell 1990). Riparian forests provide shade and reduce ambient water temperature (^NMFS 2014a). Loss of riparian vegetation destabilizes banks and increases erosion, which degrades the quality of spawning gravels. Finally, absence of riparian forests reduces the amount of large woody instream debris that would add spatial complexity and provide refuge from predators (^NMFS 2014a).

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

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

Floodplain Rearing

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

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

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

The NMFS BiOp requires actions to restore floodplain rearing habitat for juvenile winter-run and spring-run Chinook salmon and California Central Valley steelhead in the lower Sacramento River to compensate for unavoidable adverse effects of CVP and SWP operations (^NMFS 2009 BiOp). This may be achieved in the Yolo Bypass or through actions in other suitable areas of the lower Sacramento River. The action recommends an initial size of 17,000 to 20,000 acres with an appropriate frequency and duration of flooding.[8]

3.4.5.3 Juvenile Through-Delta Emigration

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

Winter-run Chinook salmon enter the Delta as early as October with most passing Knights Landing between November and April (del Rosario et al. 2013) (Table 3.4-2). Juvenile spring-run Chinook salmon enter the Delta from the Sacramento Valley approximately between January and April as yearlings and from January through June as young of the year. Juvenile fall-run Chinook salmon from the San Joaquin, Sacramento, and Mokelumne River systems migrate into the Delta between October and May (Table 3.4-2). The emigration of native and hatchery steelhead is spread over an approximate 5-month period between November and March but with peak emigration in February and March. Thus, the emigration of Central Valley salmonids spans the period from October to June, with the largest fraction of each population in the Delta from November to June (see also Vogel and Marine 1991).

Rain-induced pulse-flow events stimulate emigration of juvenile salmon from the upper Sacramento River basin tributaries to the Delta. The first autumn pulse flow exceeding 15,000 to 20,000 cfs on the Sacramento River at Wilkins Slough[9] has been shown to trigger emigration of about half the annual catch of juvenile winter-run Chinook salmon at Knights Landing about 4 days later (del Rosario et al. 2013). The remaining upstream population continues to emigrate to the Delta during subsequent precipitation-induced pulse-flow events. Loss of or decrease in the magnitude of a pulse-flow event because it was captured by diversions or upstream reservoirs may delay emigration of winter-run and other salmonids to the Delta and increase the risk of predation while juvenile fish are in the upper basin.

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[8] The NMFS BiOp required Reclamation and DWR to provide NMFS an Implementation Plan by December 2011. In 2013, Reclamation and DWR submitted their Implementation Plan to NMFS. The initial draft environmental document for the project was completed in the December 2017, with an amended final environmental impact statement/environmental impact report completed in May 2019 (USDOI and DWR 2019).

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

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

^Brandes and McLain (2001) reported a positive relationship between abundance of unmarked emigrating Chinook salmon and April through June flow at Rio Vista (Figure 3.4-12, plot a). Catch appeared independent of flow between about 5,000 and 15,000 cfs, suggesting that there might be a lower threshold effect. Catch increased in a linear fashion between 20,000 and 50,000 cfs. State Water Board staff extended this analysis using Dayflow (^DWR 2017a) and Delta Juvenile Fish Monitoring Program data (DJFMP 2016a, 2016b, page refs. n/a). The results of the updated analysis (Figure 3.4-12, plot b) are substantially similar to the earlier published results.[10]

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

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

No similar flow abundance information is available specifically for spring-run Chinook salmon, which has not been widely studied. However, spring-run Chinook salmon have similar life history characteristics as fall-run Chinook salmon, and it is likely that a similar magnitude of flow would also be beneficial for them. Peak emigration of juvenile spring-run Chinook salmon past Chipps Island is between February and May (^NMFS 2014a). For emigrating steelhead, which peak in abundance at Chipps Island between March and April, higher flows during these spring months are likely to benefit this species as well (^NMFS 2014a). Therefore, spring-run and steelhead are also expected to benefit from flows as high as 20,000 to 30,000 cfs at Rio Vista between February and May.

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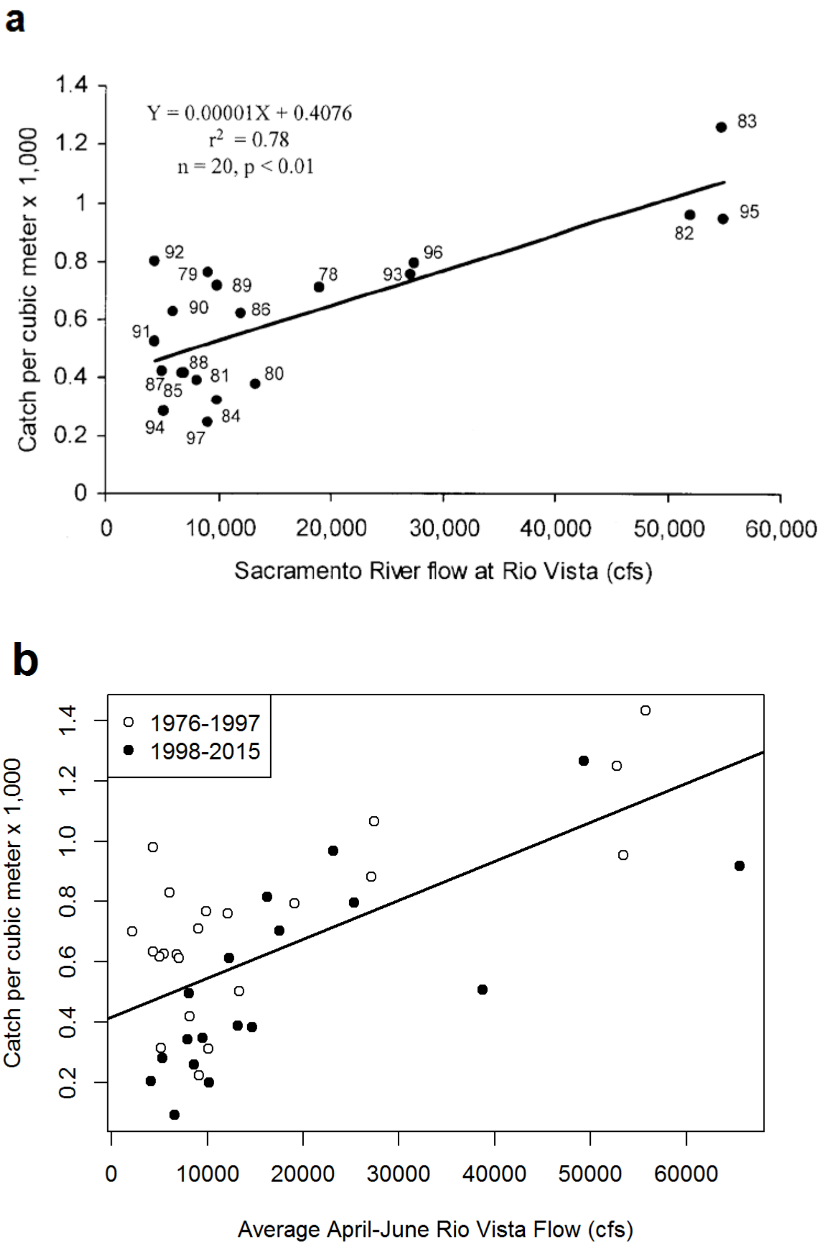
[10] Figures 3.4-12 plot a and plot b differ somewhat in the precise positions of individual data points. Y-axis values in Figure 3.4-12 plot b are based on a calculation of catch-per-unit effort using the catch and sampled water volume data available from DJFMP (2016a, 2016b).



Sources: (a)^Brandes and McLain 2001; (b) updated analysis by State Water Board staff.
The updated analysis (plot b) shows the same pattern, with somewhat weaker correlation associated with flow ($y = 0.0000129\,x + 0.417$; $R^2 = 0.438$; $p < 0.01$).
cfs = cubic feet per second

Figure 3.4-12. Mean Catch of Unmarked Chinook Salmon Smolt per Cubic Meter (x 1,000) in the Midwater Trawl at Chipps Island between April and June versus Mean Daily Sacramento River Flow (cfs) at Rio Vista between April and June from (a) 1978 through 1997 and (b) 1976 through 2015

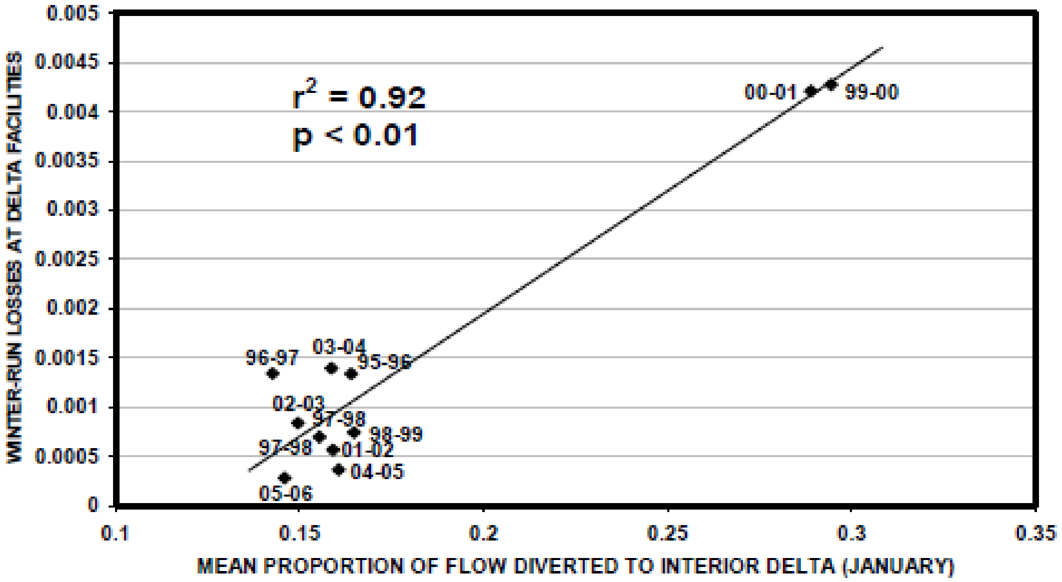
Delta Cross Channel Gate Operations and Georgiana Slough

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

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

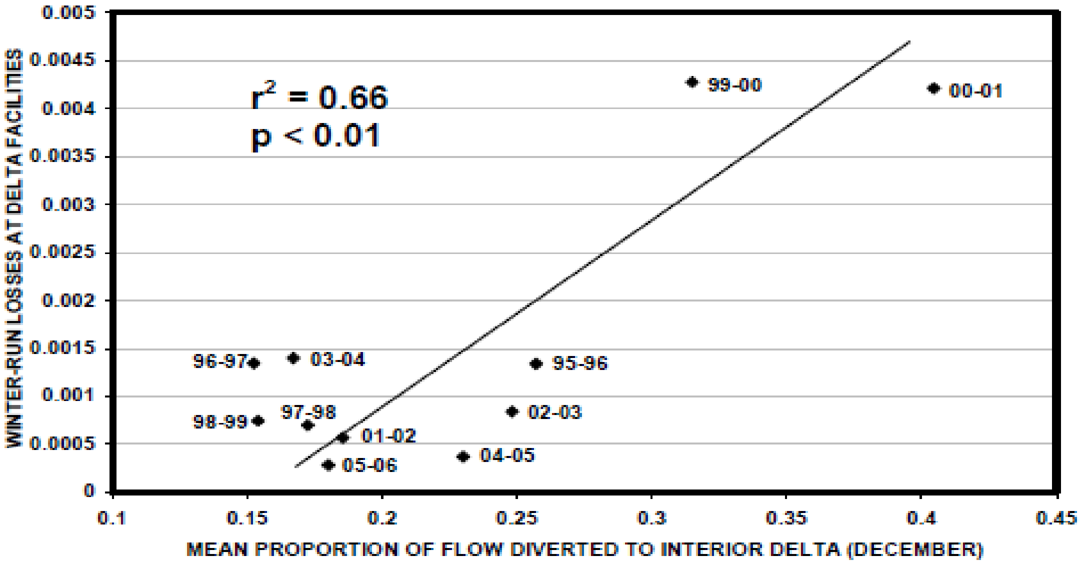
These results are consistent with modeling of the movements of acoustic-tagged fish in response to hydrodynamic conditions at Delta junctions. The modeling indicates that the proportion of flow entering various channels is an important predictor of route selection in the Delta (Cavallo et al. 2015).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

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



Source: ^Low et al. 2006.
Losses divided by the juvenile production index.

Figure 3.4-13. Relationship between the Mean Proportion of Flow Diverted into the Interior Delta in January and the Proportion of Juvenile Winter-Run Lost at the CVP and SWP Pumping Facilities October 1 through May 31, 1996–2006



Source: ^Low et al. 2006.
Losses divided by the juvenile production index.

Figure 3.4-14. Relationship between the Mean Proportion of Flow Diverted into the Interior Delta in December and the Proportion of Juvenile Winter-Run Chinook Salmon Lost at the CVP and SWP Pumping Facilities October 1 through May 31, 1995–2006

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

The U.S. Geological Survey conducted pilot studies to evaluate the effectiveness of non-physical barriers, including a bio-acoustic fish fence that makes use of light, sound, and bubbles and a floating fish guidance structure consisting of a floating boom. Initial results have shown that the bio-acoustic fish fence is marginally effective, reducing entrainment to Georgiana Slough from 22.3 to 7.7 percent in an experiment conducted over a range of flow conditions (Perry et al. 2014). A pilot study using only a floating boom fish guidance structure showed a decrease of entrainment to Georgiana Slough when flows were less than 14,000 cfs and increased entrainment at greater flows (Romine et al. 2017), although similar structures have been effective in the Columbia River system and additional studies are ongoing in the Delta (Perry et al. 2014). Adaptive management of a floating boom fish guidance structure may reduce entrainment to Georgiana Slough under low and moderate flow conditions.

Interior Delta Flows

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

Direct mortality from entrainment at the south Delta export facilities is a risk for Chinook salmon and steelhead from the San Joaquin River basin and Delta eastside tributaries (USDOI 2010). Juvenile salmonids emigrate downstream on the San Joaquin River during winter and spring (Table 3.4-1). San Joaquin River salmonids are at risk of entrainment at the export facilities first at the head of Old River, where a rock barrier (Head of Old River Barrier [HORB]) typically is installed in late spring (see Chapter 2, *Hydrology and Water Supply*). When the HORB is not installed, approximately 50 percent of the San Joaquin River flow is directed into Old River (^NMFS 2009 BiOp) on average; however, a higher proportion of the flow would be routed into Old River under lower flows (SJRGA 2013). When installed, the HORB directs the majority of San Joaquin River flow down the mainstem of the San Joaquin River, reducing the amount of flow that enters Old River and preventing San Joaquin River salmonids from migrating down Old River, a direct route to the Project export facilities. Tagging studies and modeling have generally demonstrated that installation of the HORB improves the survival of emigrating juvenile Chinook salmon from the San Joaquin River basin in spring (SJRGA 2008, 2013; ^Brandes and McLain 2001; ^Newman 2008), attributable to higher survival rates on the San Joaquin River compared with Old River (Buchanan et al. 2021). Survival of emigrating salmonids from the San Joaquin River has been declining since the 1990s (Perry et al. 2016). In the recent low-survival condition, a recent study found that salmon that were salvaged at the CVP and trucked back to release points near Chipps Island had higher survival than fish that stayed in the San Joaquin River channel and migrated naturally through the Delta to Chipps Island (Buchanan et al. 2013, 2018). However, this result was observed with a nonphysical barrier at the head of Old River, and it is possible that the additional flow present in the San Joaquin River when the HORB is in place is needed to increase survival of juveniles emigrating through the San Joaquin River (Perry et al. 2016).

Table 3.4-7. Sacramento River and Interior Delta Flows to Increase the Abundance and Survival of Chinook Salmon Populations

	Months											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Emigration flows for juvenile fall-run [a, b]				>20,000	▨	▨						
Emigration flows for juvenile winter-run [a, c]		>20,000	▨	▨								
Georgiana Slough [c]	17,000–20,000	▨	▨	▨	▨						▨	▨
San Joaquin at Jersey Point [d]	Positive flow	▨	▨	▨	▨	▨				Positive flow	▨	▨
Old and Middle Rivers reverse flow [e]	-2,500 to -5,000	▨	▨	▨	▨	▨						
San Joaquin River export constraint [f]		1:1–4:1	▨	▨	▨	▨				>0.3		

Listed flows (in cubic feet per second) are the monthly average of net daily outflow at Rio Vista unless noted otherwise. The time frame for when each listed flow is relevant is indicated by the gray shading. Though not specifically identified below in the summary of survival and abundance relationships, tributary flows are also needed to provide for connectivity, rearing and passage.

[a] The flow may also aid juvenile spring-run and steelhead. Both species emigrate out of the Delta between February and May.

[b] Flow at Rio Vista.

[c] Flow at Freeport.

[d] 5-day tidally averaged net flow when salmon are present.

[e] 14-day running average of tidally filtered flow at Old and Middle Rivers.

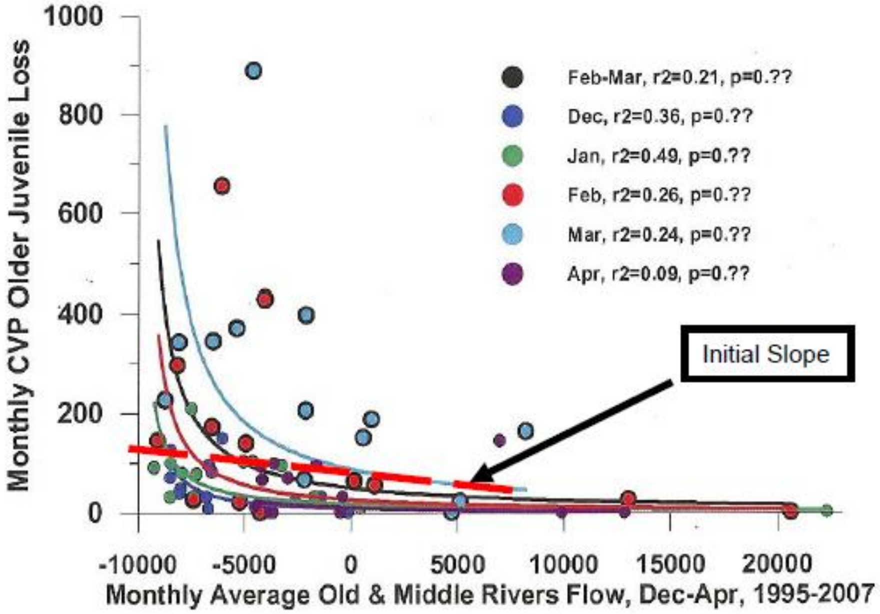
[f] San Joaquin at Vernalis to the sum of CVP and SWP exports when salmon are present.

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

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

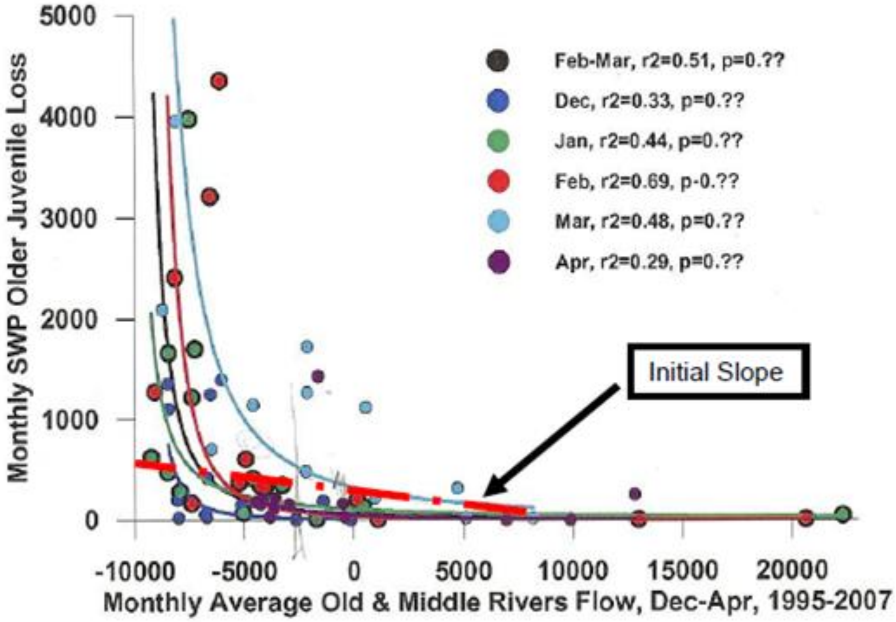
Similarly, salmon that enter the San Joaquin River through the DCC or Georgiana Slough from the Sacramento River may be vulnerable to export effects (^NMFS 2009 BiOp). While fish may eventually find their way out of the Delta, migratory paths through the central Delta channels increase the length and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

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



Source: ^NMFS 2009 BiOp.

Figure 3.4-15. Relationship between Old and Middle Rivers Reverse Flows and Entrainment at the Federal Pumping Facility, 1995–2007

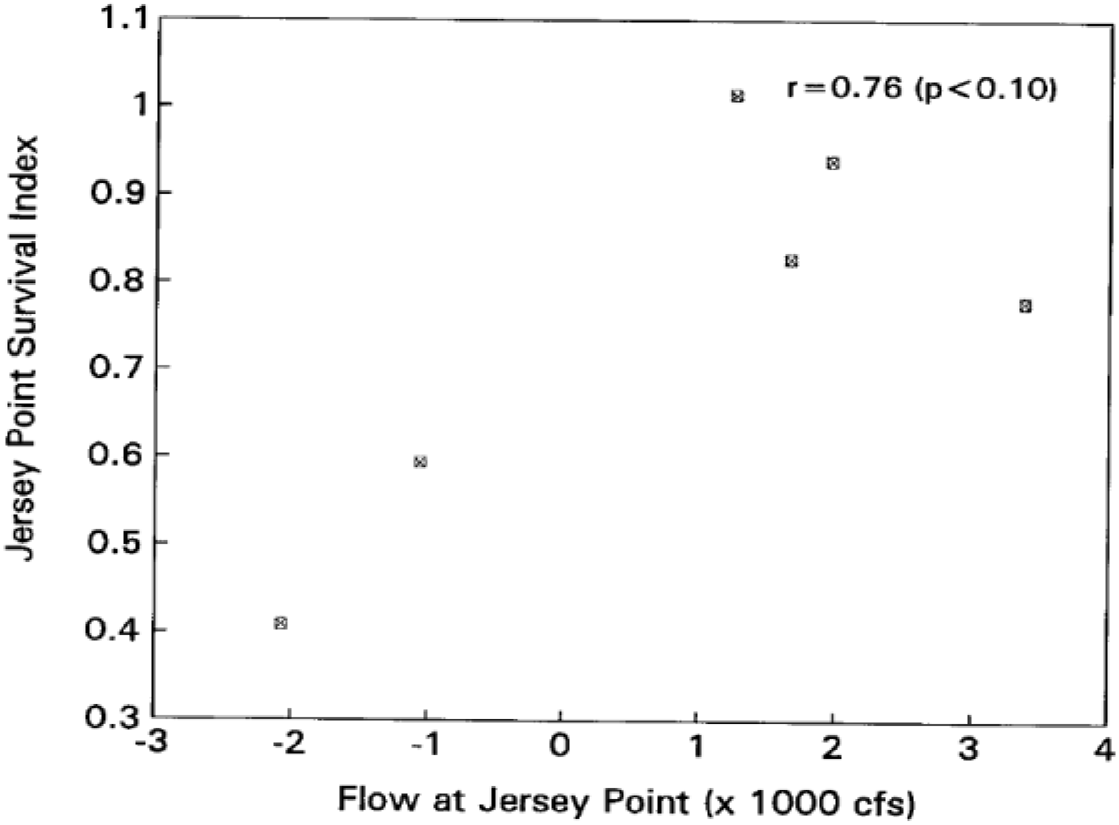


Source: ^NMFS 2009 BiOp.

Figure 3.4-16. Relationship between Old and Middle Rivers Reverse Flows and Entrainment at the State Pumping Facility, 1995–2007

In addition to the effects of OMR net reverse flows, analyses concerning the effects of net reverse flows in the San Joaquin River at Jersey Point were conducted and documented in the USFWS 1995 Working Paper on *Restoration Needs: Habitat Restoration Actions to Double Natural Production of Anadromous Fish in the Central Valley of California* (^USFWS 1995). These analyses show that net reverse flows at

Jersey Point decrease the survival of smolts migrating through the lower San Joaquin River (Figure 3.4-17) (USFWS 1992). Net reverse flows on the lower San Joaquin River and diversions into the central Delta also may result in reduced survival for Sacramento River fall-run Chinook salmon (^USFWS 1995). Based on these factors, net positive flow at Jersey Point between October and June is expected to improve the survival of emigrating juvenile Chinook salmon (Table 3.4-7).



Source: USFWS 1992.
Flow estimates were the 5-day mean value starting on the release date.

Figure 3.4-17. Temperature Corrected (to 61˚F) Survival Indices for Coded Wire-Tagged Salmon Smolt Released at Jersey Point and Recovered at Chipps Island between 1989 and 1991

Flows on the San Joaquin River versus exports also appear to be an important factor in protecting San Joaquin River Chinook salmon. Various studies show that, in general, juvenile salmon released downstream of the effects of the export facilities (Jersey Point) have higher survival out of the Delta than those released closer to the export facilities (^NMFS 2009 BiOp). Studies also indicate that San Joaquin River basin Chinook salmon production increases when the ratio of spring flows at Vernalis to exports increases (^CDFG 2005; ^SJRGA 2007). However, it should be noted that the flow at Vernalis is the more significant of the two factors. Increased flows in the San Joaquin River may also benefit Sacramento River basin salmon by reducing the amount of Sacramento River water that is pulled into the central Delta and increasing the amount of Sacramento River water that flows out to the San Francisco Bay (^NMFS 2009 BiOp). Based on these findings, the NMFS 2009 BiOp calls for export restrictions from April 1 through May 31, with San Joaquin River at Vernalis flows to export ratios ranging from 1.0 to 4.0 based on water year type, and with unrestricted exports above flows of 21,750 cfs at Vernalis, in addition to other provisions for health and safety requirements (^NMFS

2009 BiOp). The NMFS 2009 BiOp also requires a 6-year acoustic tagging study of steelhead survival in the south Delta to inform future management (^NMFS 2009 BiOp).

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

The SST also evaluated the relationship between San Joaquin River inflow to export ratios (I:E) and juvenile salmonid survival through the south Delta. The SST determined that a positive correlation existed between I:E ratios less than 3 in April and May and survival of coded wire-tagged juvenile fall-run Chinook salmon with the HORB in place (^SJRGA 2007). No relationship existed without the barrier. The San Joaquin River Group Authority (^2007) also compared adult escapement against I:E ratios 2.5 years earlier for data from 1951 through 2003 and found a positive association. The SST (2017b) updated the escapement analysis through 2012 and found similar results. These conclusions are consistent with the hypothesis that higher I:E ratios result in higher juvenile survival through the Delta (SST 2017b). Juvenile salmonids migrate out of the San Joaquin River basin from February through June (SWRCB 2012) and may need protection from export-related mortality at any time during this period in order to preserve life history diversity. Although peak emigration occurs in April and May (Figure 3.4-10), recent research has shown that individuals leaving their natal tributaries as fry in February and March can make up a substantial fraction of individuals that ultimately return to spawn (^Sturrock et al. 2015).

In 2019, the NMFS BiOp did not carry over the export restrictions in April and May based on the San Joaquin River inflows or installation of the HORB (^NMFS 2019). In 2020, CDFW did not concur with the 2019 federal BiOps that adequate protections were provided for listed species, electing to issue a separate ITP for the SWP that included the export restriction based on San Joaquin River inflows (CDFW 2020). The court issued a preliminary injunction on May 11, 2020, temporarily requiring Reclamation to operate more in line with the CDFW 2020 ITP and to implement the export restrictions at the CVP export facility. In September 2021, Reclamation and DWR requested reinitiation of consultation, which often takes 2 to 3 years to complete and may amend interior Delta flow requirements in the future.

3.5 Longfin Smelt (*Spirinchus thaleichthys*)

3.5.1 Overview

Longfin smelt was once a common species in the San Francisco estuary, but the population has declined and is now about one-tenth of 1 percent of its abundance when sampling began 50 years ago. The abundance of juvenile longfin smelt in fall is positively correlated with Delta outflow during the previous spawning season. Average daily outflows of 42,800 cfs in January to June are associated with a 50-percent probability of positive population growth. Adult and juvenile longfin smelt are vulnerable to entrainment at the CVP and SWP pumping facilities when the population migrates into the central Delta during the spawning season. However, entrainment is no longer considered a serious population-level effect if the USFWS (^2008) Delta smelt BiOp and CDFW longfin smelt ITP for SWP Delta operations are enforced, which require OMR reverse flows between -1,250 and -5,000 cfs when fish are present in the central Delta.

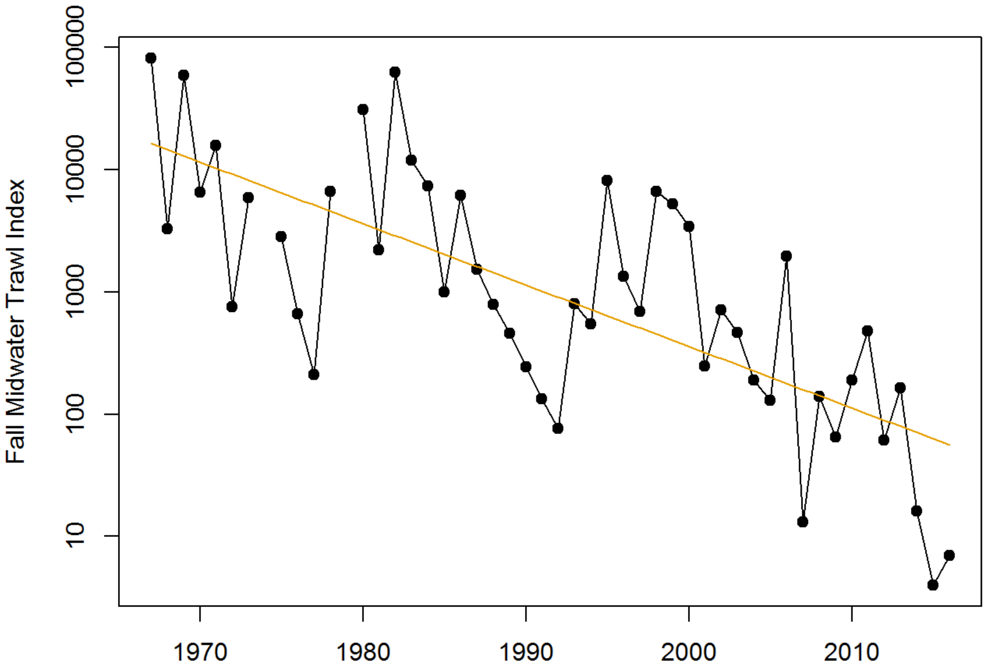
3.5.2 Life History

Longfin smelt are a native semi-anadromous, open water fish that moves between fresh water and salt water (^CDFG 2009; ^Wang 2007). Longfin smelt generally live 2 years, with females reproducing in their second year (^Moyle 2002; ^CDFG 2009). Adults spend time in San Francisco Bay and may go outside the Golden Gate (^Rosenfield and Baxter 2007; ^Wang 2007). Adults aggregate in Suisun Bay and the western Delta in late fall and migrate upstream to spawn as water temperatures drop below 18 degrees Celsius (˚C) (^CDFG 2009; ^Wang 2007; ^Baxter et al. 2009). Spawning habitat in the Delta is between the confluence of the Sacramento and San Joaquin Rivers (around Point Sacramento) to Rio Vista on the Sacramento River side and Medford Island on the San Joaquin River (^Moyle 2002; ^Wang 2007). Reproductive activity appears to decrease with distance from the LSZ, so the location of X2 influences how far spawning migrations extend into the Delta (^Baxter et al. 2009). Larvae spawned in the 2 parts per thousand (ppt) LSZ were most abundant in sub-adult and adult surveys later in the year (Hobbs et al. 2010). Spawning takes place between November and April, with peak reproduction in January to as late as April when water temperature is between 8 and 14.5˚C (^Emmett et al. 1991; ^CDFG 2009; ^Wang 1986, 2007). Eggs are deposited on the river bottom (Martin and Swiderski 2001; CDFG 2010a) and hatch between December and May into buoyant larvae, with a peak hatch in February (CDFG 2010a; Bennett et al. 2002). Net Delta outflow transports the larvae and juvenile fish back downstream to higher salinity habitats. Larvae, juveniles, and adults feed on zooplankton (Slater 2008).

3.5.3 Population Abundance Trends over Time

Longfin smelt population abundance in the Bay-Delta has declined significantly since the 1980s (^Moyle 2002; ^Rosenfield and Baxter 2007; ^Baxter et al. 2010). Thomson et al. (2010) examined trends in abundance using long-term data sets from the FMWT and the San Francisco Bay midwater and otter trawl studies and found a statistically significant decrease in longfin smelt abundance over time. State Water Board staff reexamined the interannual trend in the FMWT index using data collected through 2016 and found a statistically significant decreasing trend (R^2=0.51, P<0.001, two-sided t-test) (Figure 3.5-1). Current indices of population abundance are less than two tenths of 1 percent of the earliest levels observed in the FMWT.[11]

The most recent FMWT indices are about 5 percent of the indices observed in the early 2000s, indicating that the population has continued to decline since revised Delta outflow requirements were implemented in D-1641.[12] The last 3 years of the trend occurred during a drought, which undoubtedly contributed to the decline; however, the time since 2000 also included dry periods. As discussed in Chapter 4, *Other Aquatic Ecosystem Stressors*, multiple stressors in addition to flow may be responsible for the decline (^Sommer et al. 2007).



Source: State Water Board staff analysis.
The solid orange line is the least squares linear regression of the logarithm of the Fall Midwater Trawl index against years. The slope of the regression differs significantly from zero (R^2=0.51; P<0.001, two-sided t-test).

Figure 3.5-1. Interannual Trend in the Fall Midwater Trawl Index for Longfin Smelt, 1967–2016

The Bay-Delta DPS of longfin smelt is currently a candidate for listing under ESA (74 Fed. Reg. 16169). In 2012, USFWS determined that listing the Bay-Delta DPS of longfin smelt was warranted but precluded by higher priority actions at the time of publication (77 Fed. Reg. 19755). In 2009, the Fish and Game Commission listed longfin smelt as threatened under CESA (^CDFG 2009).

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

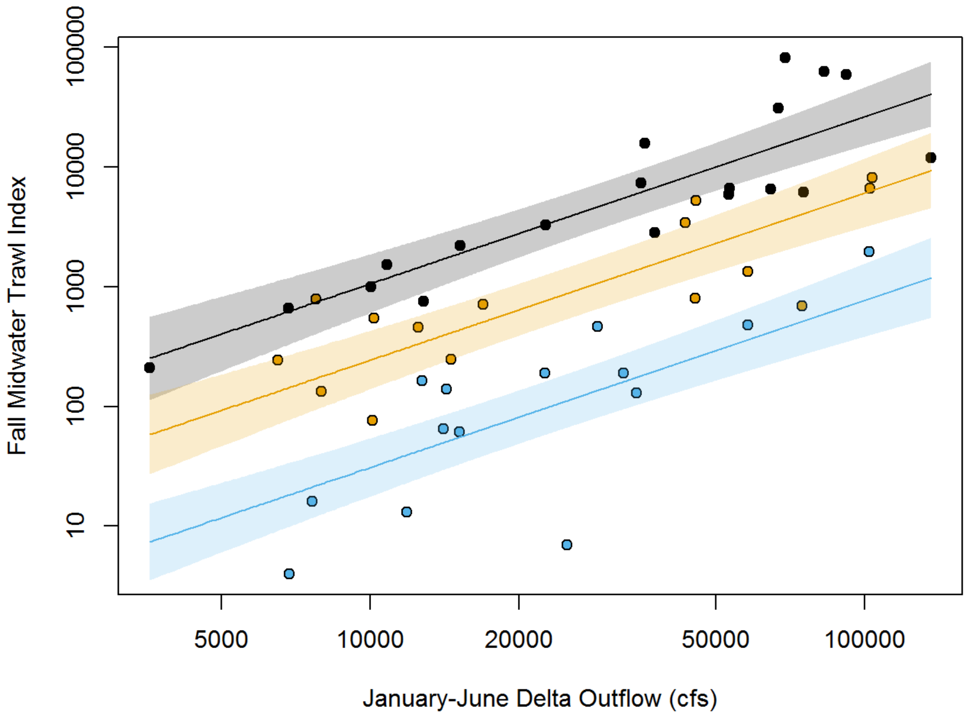
[12] The decrease was also calculated from the average of the first five FMWT index values after implementation of D-1641 (2000–2004) and the most recent 5 years (2012–2016).

3.5.4 Flow Effects on Longfin Smelt

3.5.4.1 Delta Outflow

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

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



Source: State Water Board staff analysis.
Black and orange points and lines are for years before and after the invasion of *Potamocorbula* in 1987, respectively. Blue points and lines represent the post-pelagic organism decline period, beginning 2003. The estimates of flow responses and step changes differ significantly from zero (P<0.001, two sided t-tests; R2=0.83). Colored bands around the lines represent 95-percent confidence limits.

Figure 3.5-2. Fall Midwater Trawl Index Values for Longfin Smelt Regressed against January through June Average Daily Delta Outflow for 1967–2016 with Step Changes following 1987 and 2002

The recent pattern of wet and dry years confirms the importance of Delta outflows on changes in longfin smelt population size (Figure 3.5-1). The 2011 water year was wet, with high Delta outflow in winter and spring. The following 5 years were classified as below normal to critically dry. Longfin smelt abundance increased in 2011 and declined in the following 5 years (Figure 3.5-1). The response indicates that the longfin smelt population is still able to respond positively to favorable environmental flow conditions.

State Water Board staff conducted a logistic regression analysis to estimate the magnitude of flow associated with positive longfin smelt population, using data from 1967 to 2016 (Figure 3.5-3).[13] A similar approach was used by The Bay Institute (TBI) (TBI and NRDC 2010) in analyses submitted for the Delta Flow Criteria Report (^SWRCB 2010), using data from 1988 through 2007. The flows in the State Water Board analyses associated with a 50-percent probability of positive population growth was 42,800 cfs between January and June, respectively (Figure 3.5-3). In comparison, results of the logit analyses were statistically significant, TBI and NRDC (2010) found that positive population growth was predicted for 51,000 cfs between January and March or 35,000 cfs between March and May. The specific flow estimated to correspond to a 50- percent probability of population growth is sensitive to the choice of months and years included in the analysis. However, both sets of results are indicative of the positive response of longfin smelt population growth to an increase in

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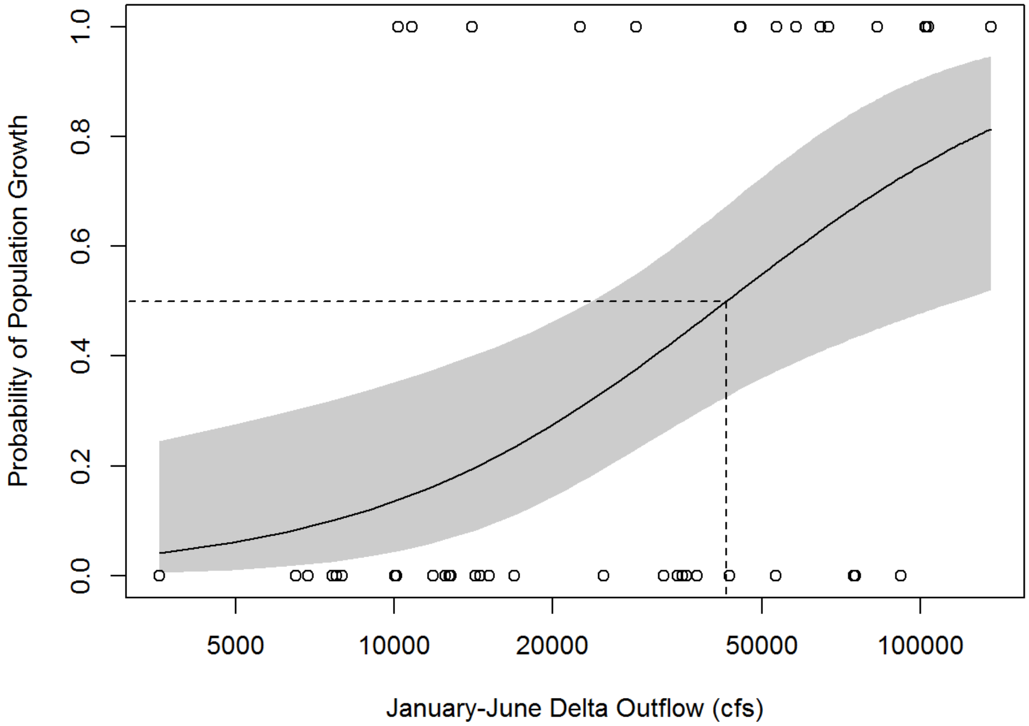
[13] Logistic regression analysis is described in Section 3.3.1, *Updated Quantitative Analysis*.

Delta outflows. Delta outflows predicted to increase the longfin smelt population are summarized in Table 3.5-1.



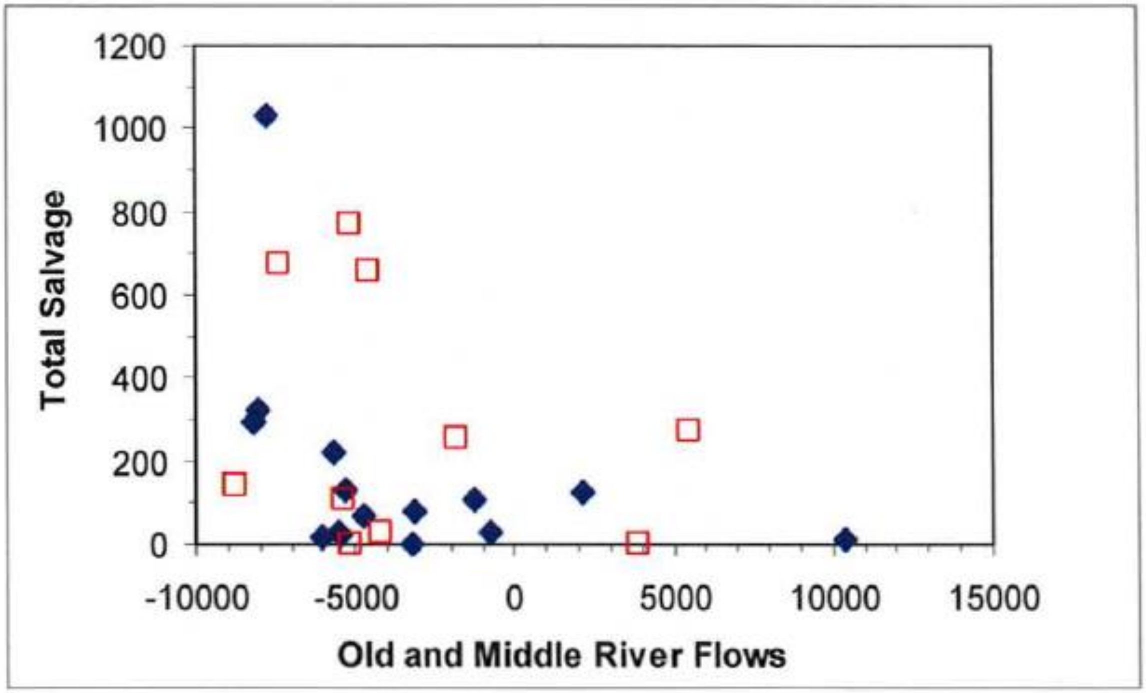
Source: State Water Board staff analysis.
Dashed lines indicate that the flow that is associated with positive population growth in 50 percent of years. The flow effect differs significantly from zero (P<0.01, two-sided Wald test).

Figure 3.5-3. Probability of Positive Longfin Smelt Population Growth and 95-Percent Confidence Limits as a Function of January–June Average Daily Delta Outflow, 1967–2016

3.5.4.2 Interior Delta Flows

Export pumping at the CVP and SWP facilities that causes OMR reverse flow may result in the movement of large numbers of fish, including longfin smelt, into the interior Delta and result in their entrainment (^USFWS 2008; ^NMFS 2009 BiOp). ^Grimaldo et al. (2009) reported that 122,747 longfin smelt were salvaged at the CVP and SWP facilities between 1992 and 2005. However, entrainment loss of fish, including longfin smelt, as a result of OMR reverse flow is difficult to quantify (^Baxter et al. 2009). Estimates of salvage do not account for indirect mortality as individuals move down the rip-rapped channels toward the pumping facilities; counting inefficiencies at the salvage facilities; loss of fish that pass through the screen louvers; and mortalities from handling, transport, and release back into the Delta after salvage (^Baxter et al. 2009). Counts of fish salvaged at the CVP and SWP pumping facilities potentially represent only a small part of the overall loss (^Baxter et al. 2009). Because of the imprecise loss estimates, it is difficult to know whether export pumping has a negative population-level effect on longfin smelt, and no statistical evidence currently exists (Thomson et al. 2010; Maunder et al. 2015; Mac Nally et al. 2010).

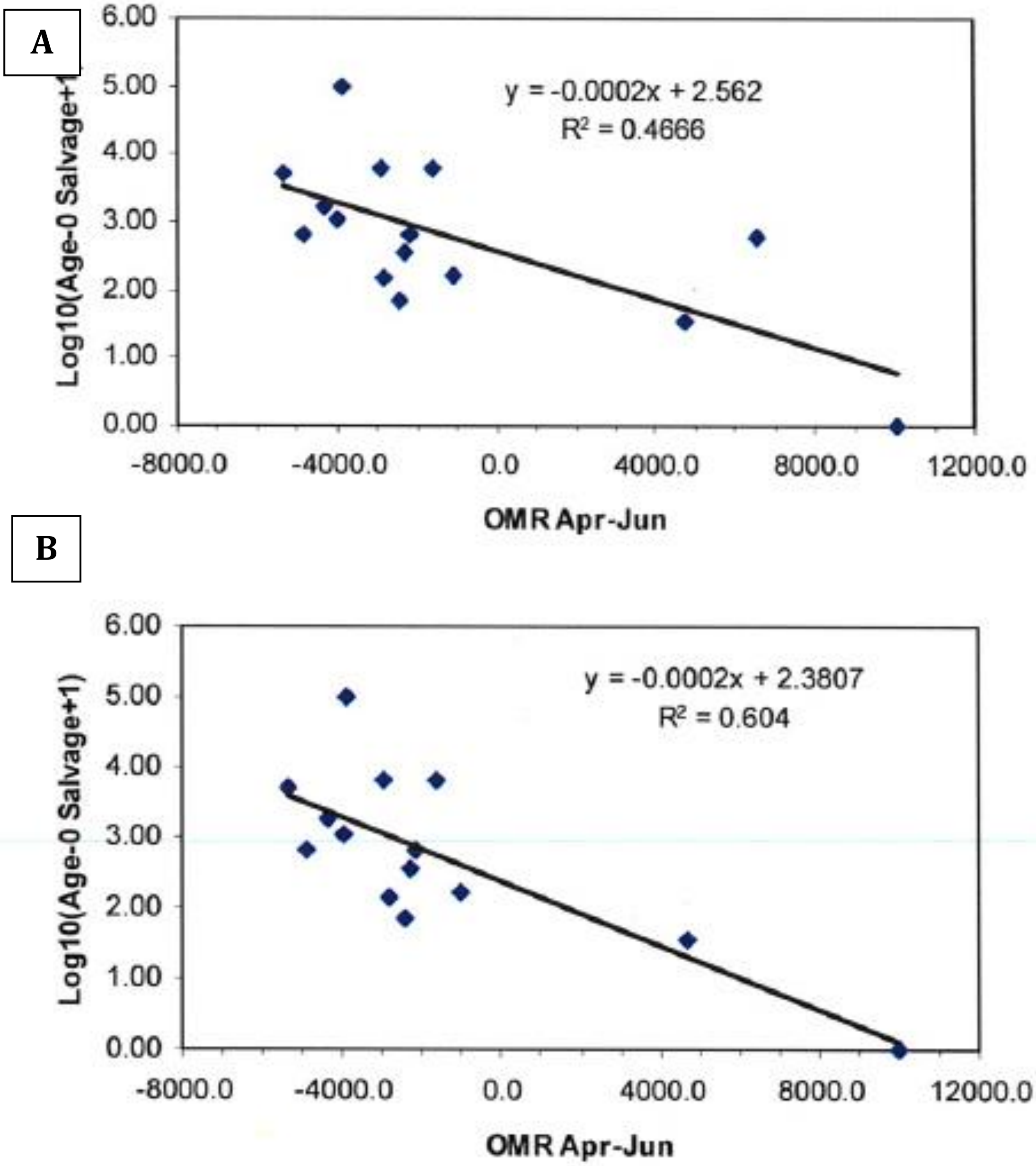
^Baxter et al. (2009) conducted an analysis of CVP and SWP export pumping for the CDFW longfin smelt ITP No. 2081-2009-001-03 and determined that adult longfin smelt became vulnerable to entrainment and salvage between December and March as adults moved onto the spawning grounds. Adult salvage was found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



Source: ^Baxter et al. 2009.
Old and Middle River estimates for 1982–1992 were based upon calculations conducted by Lenny Grimaldo; those for 1993–2007 were from measured flows by the USGS. A single data point with an Old and Middle River reverse flow of -7,744-cfs and a salvage value of 20,962 individuals was not included.

Figure 3.5-4. Total Salvage of Longfin Smelt between December and March as a Function of Average Old and Middle River Flows during the Same Period for Water Years 1982–1992 (squares) and 1993–2007 (diamonds)

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

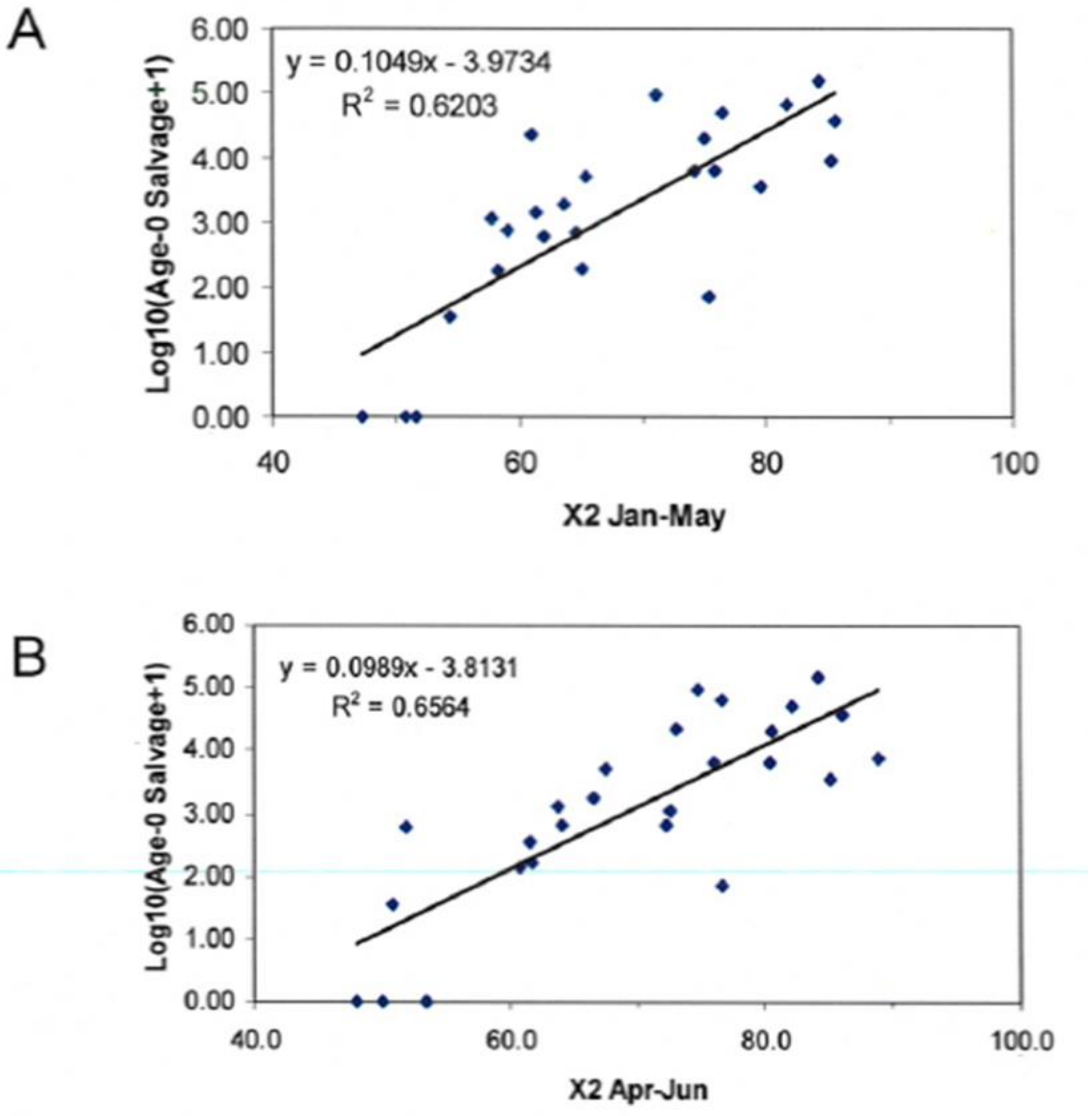


Source: ^Baxter et al. 2009.
In 1998, a protracted SWP export shutdown allowed longfin smelt larvae to grow to salvageable size in Clifton Court Forebay before pumping resumed and fish salvage recommenced. In other years, these fish would have passed through the system as larvae without being counted in the salvage record.
OMR = Old and Middle Rivers

Figure 3.5-5. (A) Relationship between Average OMR Reverse Flows in April to June and the Sum of SWP and CVP Juvenile (age-0) Longfin Smelt Salvage during the Same Time Period, 1993–2007; (B) Same Regression as (A) excluding 1998

Baxter et al. also found that juvenile longfin smelt salvage was positively correlated with X2 and negatively associated with Delta outflow between January and June (Figure 3.5-6) (^Baxter et al. 2009). Salvage increased exponentially with increasing X2 or decreasing Delta outflow. The lowest salvage rate occurred at an X2 of less than 60 km (Figure 3.5-6). The Delta outflow salvage relationship is used to justify suspending the OMR reverse flow requirements when outflow exceeds 55,000 cfs.

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



Source: ^Baxter et al. 2009.
Salvage was incremented by one and log 10 transformed.

Figure 3.5-6. (A) Relationship between the Average Location of X2 between January and May and the Sum of Juvenile (age-0) Longfin Smelt Salvage between March and July at the SWP and CVP; (B) Relationship between the Average Location of X2 in April and June and the Sum of Juvenile (age-0) Longfin Smelt Salvage for April to June at the SWP and CVP

In summary, the salvage export pattern is consistent with what is known about the spawning migration habits of longfin smelt (^Rosenfield and Baxter 2007; ^Baxter et al. 2009). Adults may travel farther into the Delta in some low-flow years to reproduce, and this increases the vulnerability of their offspring to entrainment from OMR reverse flow (Figure 3.5-6). Increased salvage happens at OMR reverse flows more negative than -5,000 cfs (Figure 3.5-4). Juvenile salvage also has an exponential relationship with negative OMR flows (Figure 3.5-5). The lowest salvage rate was measured at positive OMR flow (Figure 3.5-5). Ranges of OMR reverse flows to benefit adult and juvenile longfin smelt by reducing entrainment at the CVP and SWP are summarized in Table 3.5-1 and are consistent with the USFWS Delta smelt BiOp and the CDFW ITP for longfin smelt.

Table 3.5-1. Delta Outflow and Old and Middle Rivers Reverse Flows Indicated to Be Protective of Longfin Smelt Recruitment

<table>
<tr><th></th><th colspan="12">Months</th></tr>
<tr><th></th><th>Jan</th><th>Feb</th><th>Mar</th><th>Apr</th><th>May</th><th>Jun</th><th>Jul</th><th>Aug</th><th>Sep</th><th>Oct</th><th>Nov</th><th>Dec</th></tr>
<tr><td>Delta outflow</td><td colspan="6">42,800</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>OMR reverse flows</td><td colspan="6">-1,250 to -5,000</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

Delta outflows (cubic feet per second) are the monthly averages of net daily outflow as calculated by Dayflow.
OMR – Old and Middle Rivers.

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

3.6.1 Overview

Green and white sturgeon are a long-lived, anadromous, iteroparous, and native species. The southern DPS of North American green sturgeon is federally listed as threatened under the ESA. Recruitment of both species has been episodic in the San Francisco estuary. Years with high precipitation and large Delta outflows in winter and spring are associated with higher white sturgeon recruitment (Klimley et al. 2015; ^Fish 2010), and similar relationships are likely for green sturgeon. Long life and high fecundity make it possible for sturgeon to maintain a stable population with infrequent high-outflow years. The green sturgeon population size has always been much smaller than white sturgeon, making green sturgeon difficult to study. Functional flow requirements for green sturgeon are assumed to be similar to those of white sturgeon. Average Delta outflow of 37,000 cfs or larger between March and July appears to be needed to consistently produce strong white sturgeon recruitment. It is assumed that green sturgeon recruitment has a similar relationship to flow.

3.6.2 Life History

3.6.2.1 Green Sturgeon

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

Spawning is believed to have historically occurred on the Sacramento River above Shasta Dam and possibly on the upper Feather River (^USFWS 1996; ^Lindley et al. 2004). Construction of Shasta and Oroville Dams blocked upstream spawning access above the dams (^USFWS 1996; ^Beamesderfer et al. 2004; ^CDFG 2002). Green sturgeon spawning has been documented in the Feather River and possibly the Yuba River (Seesholtz 2014; ^Bergman et al. 2011). Green sturgeon move upstream from San Francisco Bay, passing the Knights Landing rotary screw trap on the Sacramento River in April (Heublein et al. 2006). Peak spawning activity occurs in May and June (^Emmett et al. 1991; ^CDFG 2002; Poytress et al. 2015). Spawning on the Sacramento River extends from about 36 miles below the RBDD to about 22 miles upstream (Poytress et al. 2015) and is the primary remaining spawning habitat for green sturgeon in the Central Valley (NMFS 2005). Cooler temperatures on the upstream Sacramento River may limit the extent of upstream spawning habitat for green sturgeon as laboratory studies indicate a reduction in hatching rates and smaller embryos at temperatures as low as 11°C (Van Eenennaam et al. 2005). Average river temperature between April and June is less than or equal to 11°C above the confluence of Clear Creek in most years (Poytress et al. 2015).[14]

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

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

3.6.2.2 White Sturgeon

White sturgeon is also a long-lived, late maturing, iteroparous species (^Moyle 2002). Males and females become sexually mature at around 10 and 12 to 16 years of age, respectively (^Moyle 2002). Spawning occurs every 2 to 4 years for females and every 1 to 2 years for males (^Chapman et al. 1996). White sturgeon begin their upstream spawning migration in late fall and early winter, triggered by increased outflow (Miller 1972; ^Kohlhorst et al. 1991; ^Fish 2010; ^Schaffter 1997). Spawning occurs from mid-February through June with peak spawning activity in March and May (^Kohlhorst 1976; ^Schaffter 1997). After hatching, undeveloped larvae disperse downstream. In laboratory studies, the downstream dispersal stage may last for up to 6 days before larvae seek cover for about 10 days to complete absorption of their egg sac (Deng et al. 2002). After the egg sac

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

is absorbed, larvae resume their downstream migration and begin to feed at night (Kynard et al. 2005). Outflow distributes the larvae to rearing habitats throughout the lower Sacramento River and the Delta (McCabe and Tracey 1994; Kynard et al. 2005). High spring outflow is correlated with increased juvenile recruitment (^Fish 2010; ^Kohlhorst et al. 1991).

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

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

3.6.3 Population Abundance Trends over Time

3.6.3.1 Green Sturgeon

Abundance information for the spawning run size of green sturgeon in the Sacramento basin was estimated in a 6-year study with aggregated sample sites expanding a 155 km stretch below Keswick Dam. Mora et al. (2018) tracked populations of the southern DPS of green sturgeon using various monitoring techniques, including dual-frequency identification sonar (DIDSON) sampling, acoustic tagging, and underwater video identification. Results from this study indicate that the size of mating population varied from 336 to 1,236 individuals from 2010 to 2015. This study also suggested that the size of the reproductive portion of the population (adults) was between 1,246 and 2,966 individuals in the Sacramento River. Historically, suitable spawning habitat likely existed in portions of the San Joaquin, Feather, American, and Yuba Rivers but is currently blocked by the presence of impassable barriers (Mora et al. 2009). Successful spawning occasionally occurs in the lower portions of the Feather River and Yuba River, but has not been consistently documented in the last 20 years (NMFS 2021). The USFWS (^1996) Native Fish Recovery Plan recommends a restoration goal of at least 1,000 adult fish in the Sacramento River and Delta during spawning season.

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

3.6.3.2 White Sturgeon

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

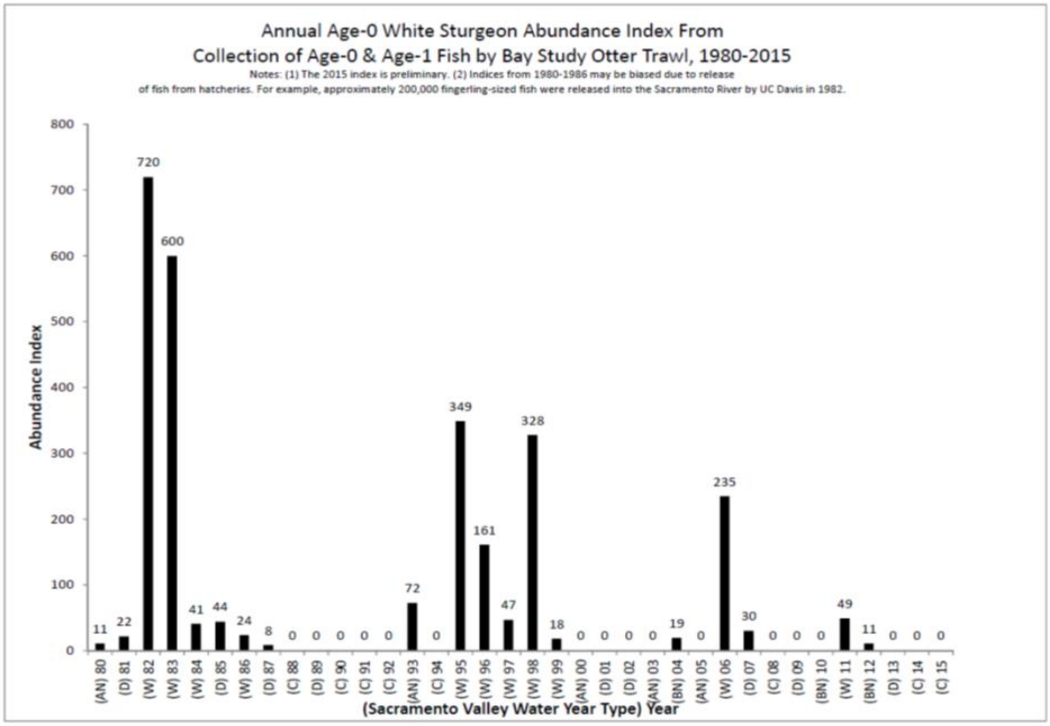
Population trends of legal-sized individuals are based on Commercial Passenger Fishing Vessel CPUE and from the mark-recapture study (Dubois and Gingras 2013). These two measurements generally track one another and indicate that CPUE is highly variable through time. DuBois and Gingras (2013) suggest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

3.6.4 Flow Effects on Green and White Sturgeon

3.6.4.1 Delta Outflow

Less information exists on the flow needs of green sturgeon because of the small size of the population. The assumption is that this species needs flows of a similar magnitude as white sturgeon (^USFWS 1996). Accordingly, the remainder of this discussion focuses on white sturgeon.

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

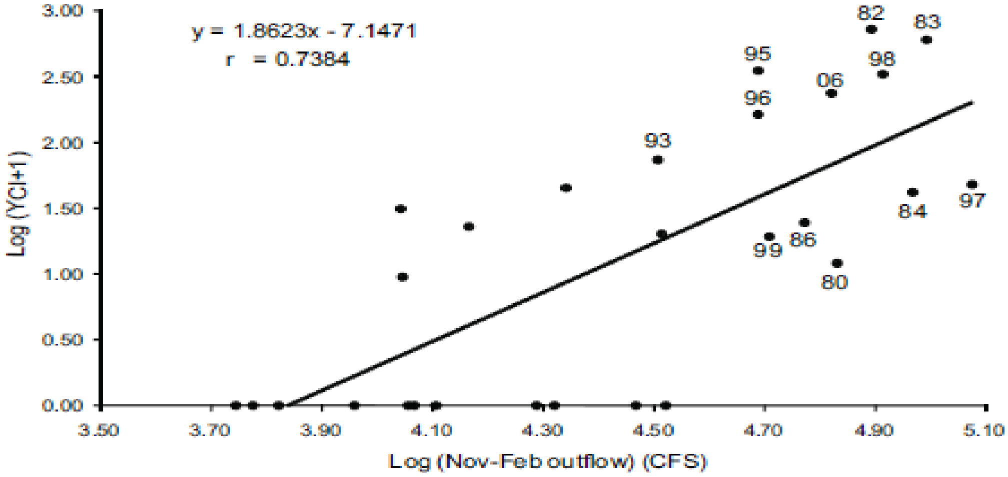


Source: CDFG 1992a.
CDFG (1992a) constructed an index of white sturgeon year class strength using Bay Study survey data for 1975–1990. The strongest relationship was with outflow between April and July. The largest year classes occurred at Delta outflows greater than 60,000 cfs. The CDFG (1992a) study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

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

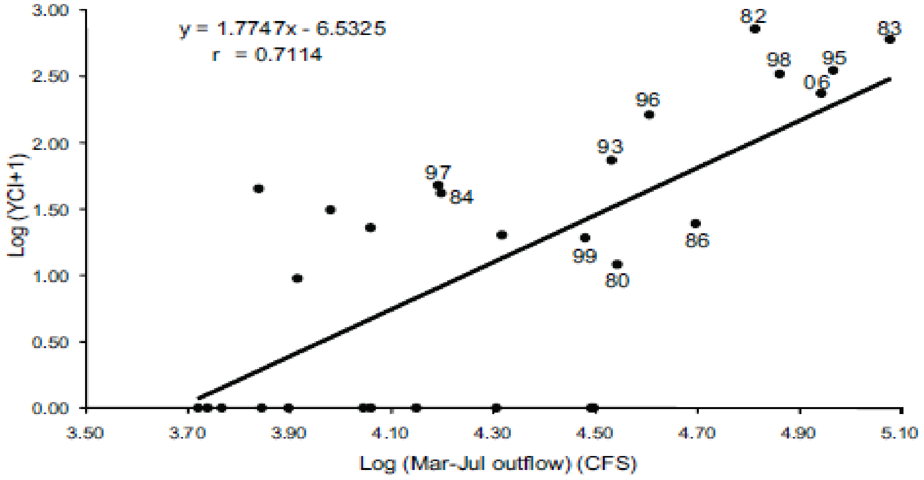
Gingras et al. (2014) reanalyzed the impact of recreational fishing and water operations on white sturgeon population recruitment and confirmed a positive relationship between Delta outflow in winter and spring and recruitment. Average Delta outflows of less than 30,000 cfs had a small probability of producing strong year classes, and outflows of 37,000 cfs or larger between March and July were associated with a 50-percent probability of producing a good year class. The analysis also provided evidence for a stock-recruitment effect. As the number of spawning adults increased, the importance of net Delta outflow declined. Gingras et al. (2014) also implicated recreational fishing as a factor negatively affecting recruitment.

Fish (^2010) analyzed white sturgeon year class data from Bay Study catch data for 1980 through 2006. The study found statistically significant positive correlations between catch and mean daily Delta outflow for November through February and for March through July (Figure 3.6-2 and Figure 3.6-3). Fish (^2010) concluded that white sturgeon year class strength was a function of both attraction flows between November and February that stimulated adult upstream migration and March through July flows that triggered spawning and downstream transport of juvenile fish. Both flow abundance relationships exhibited threshold values around 32,000 cfs (log 4.5). Above the threshold, recruitment was always positive (Figure 3.6-2 and Figure 3.6-3), consistent with conclusions from Gingras et al. (2014). Fish (^2010) observed that the March through July relationship appeared to be the more critical of the two flow events, as all years with high spring outflow produced large sturgeon year classes regardless of the magnitude of the attraction flows that preceded them in November through February (Table 3.6-1). This conclusion is consistent with a recent reassessment of the flow requirements for successful white sturgeon recruitment. The new analysis concluded that strong recruitment occurred in the Sacramento basin only in wet water years when the Sacramento water year index exceeded 10 (DuBois 2017). Robust monitoring and special studies will be needed to determine the causal mechanisms (temperature, habitat, foodweb) to establish priorities for habitat restoration and the best flow regimes to support successful reproduction and survivorship.



Source: ^Fish 2010.
Numbers are adjacent to points to designate year classes (YC).
cfs = cubic feet per second

Figure 3.6-2. White Sturgeon Year Class Index from San Francisco Bay Study Otter Trawl Catch versus Mean Daily Delta Outflow from November through February



Source: ^Fish 2010.
Numbers are adjacent to points to designate year classes (YC).
cfs = cubic feet per second

Figure 3.6-3. White Sturgeon Year Class Index from San Francisco Bay Study Otter Trawl Catches versus Mean Daily Delta Outflow for March through July

Table 3.6-1. Delta Outflow Indicated to Be Protective of White and Green Sturgeon

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

Outflows are monthly averages (cubic feet per second).

3.6.4.2 Interior Delta Flow

Green and white sturgeon have been salvaged at the CVP and SWP pumping facilities during all months of the year (^NMFS 2009 BiOp). The presence of both species in salvage at CVP and SWP pumping facilities indicates that the species are vulnerable to entrainment from exports. However, no statistical evidence exists that exports affect white sturgeon population abundance (CDFG 1992a, ^2002) and there are currently no other OMR restrictions for green sturgeon included in the BiOps or ITPs.

3.7 Sacramento Splittail (*Pogonichthys macrolepidotus*)

3.7.1 Overview

Sacramento splittail is a native species that has decreased in abundance; the age-0 year class is now about 3 percent of its population size when sampling began in 1967. Splittail spawn on flooded vegetation in spring. Large recruitment has been observed only in years when the Yolo Bypass has flooded for more than 30 days. The size of the juvenile splittail population in fall is positively correlated with Delta outflow during the previous spring. Analyses presented below indicate that Delta outflows of 30,000 to 47,000 cfs are needed between February and May to provide strong splittail recruitment. These are among the largest flows needed by any Bay-Delta estuarine fish species for recruitment. The magnitude of these flows might be reduced by installing an operable gate on the Fremont Weir, thereby reducing the river stage required to flood the Yolo Bypass.

3.7.2 Life History

Sacramento splittail is a native cyprinid minnow. Their distribution is mostly in the Central Valley and Bay-Delta estuary, although some fish have been collected in the Napa and Petaluma Rivers (Caywood 1974; ^Moyle 2002; Feyrer et al. 2015). Fish collected in the Napa and Petaluma Rivers have been identified as a genetically distinct population that has limited overlap with the Central Valley population (Baerwald et al. 2008, ^2007). Analysis in this report is for the Central Valley portion of the population. Splittail historically were fished both commercially and by Native Americans and are now part of a small recreational fishery (^Moyle 2002; Moyle et al. 2004).

Adult splittail typically live 5 to 7 years and become sexually mature in their second year (^Moyle 2002; Daniels and Moyle 1983). Adults are mostly observed in Suisun Bay and Marsh and in the western Delta during summer and fall. Mature splittail typically migrate upstream for spawning between November and March (Caywood 1974; Moyle et al. 2004). Seasonally inundated floodplains, vegetated channel margins, and perennial marshes may be used for spawning and rearing (Caywood 1974; Daniels and Moyle 1983; Feyrer et al. 2005; Moyle et al. 2004). Eggs are adhesive; they are laid on submerged vegetation and hatch in 3 to 7 days depending upon temperature (^Wang 1986; ^Moyle 2002; Moyle et al. 2004). Some juveniles remain upstream during their first year, but most migrate downstream in spring and summer, either passively carried by high flows or actively swimming because of warming water temperature (Baxter 1999a; Baxter et al. 1996; Sommer et al. 2002; Moyle et al. 2004). After spawning, adult splittail generally migrate downstream (Moyle et al. 2004).

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

3.7.3 Population Abundance Trends over Time

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

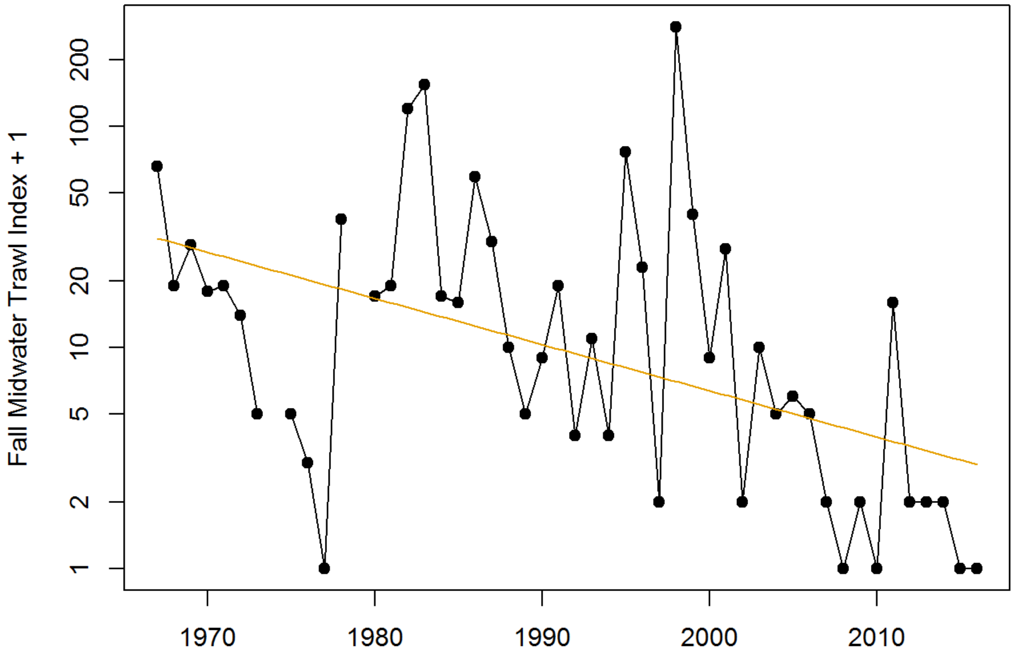
The Delta Flow Criteria Report recommended a goal of stabilizing juvenile Sacramento splittail recruitment and beginning to grow the population (^SWRCB2010). The long-term population index value and recovery goal evaluated for the 2017 Scientific Basis Report was equal to the median FMWT index from 1967 to 2014 as recommended by ^SWRCB (2010) (SWRCB 2017). The median FMWT value between 1967 and 2014 was 10. The average FMWT index from 2012 to 2014 was 1 and has not been above 10 since 2001 (Figure 3.7-1).

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

3.7.4 Flow Effects on Sacramento Splittail

3.7.4.1 Delta Outflow

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

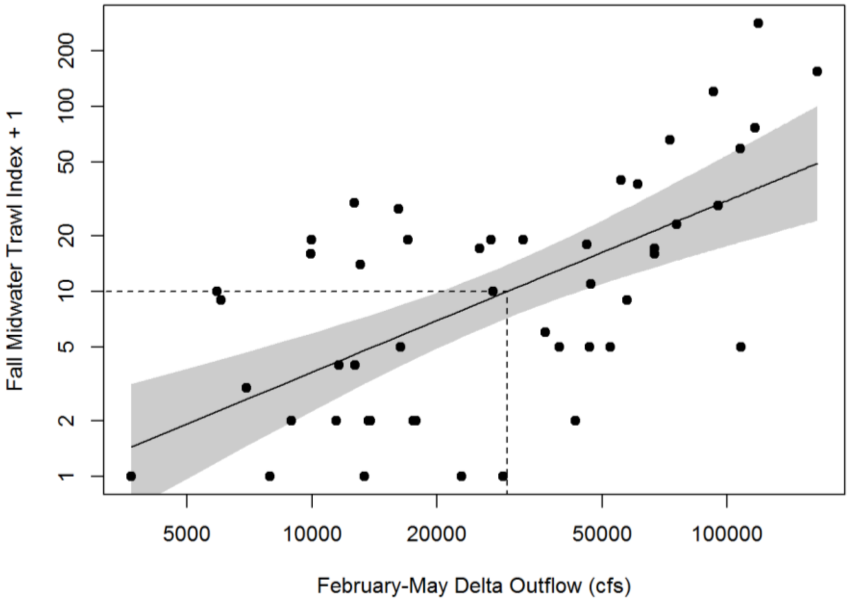


The solid line is the least squares linear regression of the logarithm of the Fall Midwater Trawl index (incremented by 1) against years. The slope of the regression differs significantly from zero ($R^2=0.22$; $P<0.001$, two-sided t-test).

Figure 3.7-1. Sacramento Splittail Population Recruitment as Measured in the Fall Midwater Trawl Survey, 1967–2016

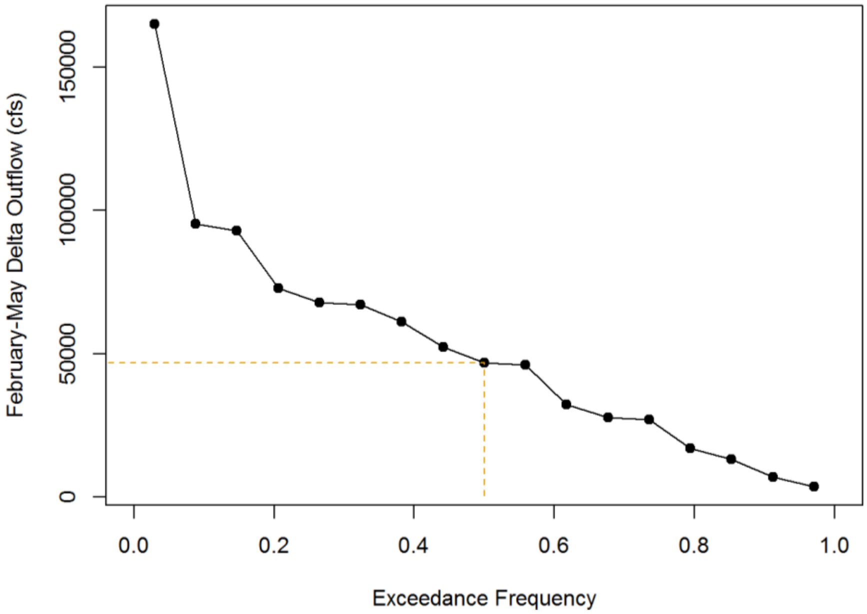
State Water Board staff reassessed the flow recruitment relationship with new data collected through 2016 using the same method employed by ^Kimmerer (2002b) (Figure 3.7-2). The current relationship is still significant (P<0.001). More spring outflow is associated with a higher FMWT index later in the year. This is a long-standing flow recruitment relationship that has existed since sampling began in 1967 (^Kimmerer 2002b). Increased outflow between February and May coincides with the timing of adult spawning and larval rearing in riverine floodplains and terraces and in the Delta (Moyle et al. 2004; Meng and Matern 2001). Increased flow increases both the amount of flooded habitat along vegetated channel margins and the acreage of inundated floodplain in the Central Valley (Moyle et al. 2004).

Two methods were used to determine the flow required to meet the population recruitment goal. First, a regression analysis was conducted with Delta outflow during the February through May time frame and splittail recruitment to determine that 30,000 cfs was correlated with the recruitment goal (Figure 3.7-2). Second, USFWS (^1996) recommended that Sacramento splittail be considered fully recovered if population abundance returned to values measured between 1967 and 1983. The median flow during this 16-year period was 47,000 cfs (Figure 3.7-3). These analyses suggest that an average daily Delta outflow of 30,000 to 47,000 cfs is needed between February and May to meet the recruitment goal (Table 3.7-1). An alternate non-flow-related recruitment goal might be to recommend the magnitude, duration, and frequency of periodic flooding of the Yolo Bypass and other floodplains.



The slope of the flow recruitment relationship differs significantly from zero ($R^2=0.31$, $P<0.001$, two-sided t-test).
The dotted line indicates that a flow rate of 30,000 cfs is correlated with the recommended abundance index of 10.
The shaded band represents the 95-percent confidence limits around the regression line.
cfs = cubic feet per second

Figure 3.7-2. Correlation between the Sacramento Splittail Fall Midwater Trawl Index (1967–2016) and Average Daily Outflow (cfs) between February and May



The dotted line is the daily average outflow (47,000 cubic feet per second [cfs]) that occurred in half of all years.

Figure 3.7-3. Cumulative Frequency Distribution of Average Daily Outflow between February and May, 1967–1983

Table 3.7-1. Delta Outflow Indicated to Be Protective of Sacramento Splittail

	Months											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Delta outflow		30,000–47,000										

Outflows are monthly averages (cubic feet per second).

3.7.4.2 Interior Delta Flow

Sacramento splittail have been salvaged at the CVP and SWP pumping facilities in many years when San Joaquin flows are high and recruitment is good throughout the Bay-Delta system. The risk of splittail entrainment appears greatest during adult upstream spawning migrations and juvenile emigration from the Delta in spring and early summer (^Sommer et al. 1997; Moyle et al. 2004). In 1998, more than 3 million juvenile splittail were taken at the export facilities in early summer, representing a quarter of all the fish salvaged that year (Arnold 1999; Moyle et al. 2004). In 2011, another wet year, almost 9 million splittail were salvaged at the CVP and SWP pumping facilities (Aasen 2012).

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

3.8 Delta Smelt (*Hypomesus transpacificus*)

3.8.1 Overview

Delta smelt were once a common native species in the Bay-Delta estuary. Most individuals live 1 year, with adults moving into areas such as the northern Delta and Suisun Marsh from Suisun Bay and the confluence of the Sacramento and San Joaquin Rivers to spawn and die. Their offspring migrate back to these areas to rear. There is also a resident year-round freshwater population in the Cache Slough complex. Indices of Delta smelt population abundance have declined, and the size of the population is now about 2 percent of what it was 50 years ago. Since 2003, the population abundance of larval Delta smelt in spring has been positively correlated with the magnitude of Delta outflow during the previous winter–spring and fall periods. Delta smelt are entrained and lost at the CVP and SWP pumping facilities when adults migrate into the Delta in winter and early spring to spawn and again when the larvae migrate back downstream in late spring and early summer. The species is listed as threatened by USFWS and as endangered by CDFW. In 2010, USFWS determined that uplisting Delta smelt to endangered status was warranted but was precluded by the need to address higher priority species first.

3.8.2 Life History

Delta smelt are endemic to the Delta and upper Bay-Delta estuary and were once a common pelagic fish species in the estuary (^USFWS 1996). The species has a 1-year life cycle, although some females may live to reproduce in their second year (^Bennett 2005).

Adult Delta smelt undergo an upstream spawning migration from the LSZ to fresh water (^Grimaldo et al. 2009), although there is also evidence of freshwater resident smelt in the Cache Lindsey Slough complex, Sacramento River Deepwater Ship Channel, and lower Sacramento River in the vicinity of Sherman Island (Hobbs et al. 2007; ^Baxter et al. 2015). Spawning migrations occur between late December and February, typically during "first-flush" periods when inflow and turbidity increase on the Sacramento and San Joaquin Rivers because of upstream precipitation (^Grimaldo et al. 2009; Sommer et al. 2011). Catches of adult Delta smelt in the USFWS Chipps Island Survey and in salvage at the CVP and SWP pumping facilities during first-flush events are characterized by sharp unimodal peaks, suggesting that rapid changes in environmental conditions are a factor associated with population-level migrations (^Grimaldo et al. 2009; Sommer et al. 2011). Pre-spawning adults move furthest upstream during low outflow years. If the population migrates into the lower San Joaquin River and the central Delta, the risk of entrainment at the CVP and SWP pumping facilities is high; the risk is less if the migration is into the lower Sacramento River and the Cache Slough complex (Kimmerer and Nobriga 2008).

Adult Delta smelt spawn during late winter and early spring, with most reproduction occurring in April through mid-May (^Moyle 2002). Spawning habitat includes Grizzly Island; the lower Sacramento, San Joaquin, and Mokelumne Rivers; and the northern, western and southern Delta (^Wang 2007; Hobbs et al*.* 2006). Eggs are negatively buoyant and adhesive, with larvae hatching in about 13 days (^Wang 1986, 2007). The initial distribution of Delta smelt larvae is similar to that of their parents and presumably reflects larvae emerging at the locations where the eggs were laid. Upon hatching, the larvae are buoyant for the first several days before becoming semi-buoyant, staying near the bottom (Mager et al. 2004). Within a few weeks, larvae develop swim bladders and become pelagic utilizing vertical tidal migrations to maintain their preferred location in the Delta (Bennett et al. 2002). Dege and Brown (^2004) found that larvae smaller than 20 millimeters (mm) reared several kilometers upstream of X2. As larvae grow and water temperature increases, most larval and juvenile distributions shift downstream toward the LSZ (^Dege and Brown 2004; ^Nobriga et al. 2008).

Delta outflow during late spring and early summer affects the distribution of larval and juvenile smelt by actively transporting them seaward toward the LSZ (^Dege and Brown 2004). Low outflow increases Delta smelt residence time in the Delta, probably leading to increased exposure to higher water temperatures and increased risk of entrainment at the CVP and SWP pumping facilities (^Moyle 2002). Once larvae develop into juveniles, they become capable of exploiting tidal flows to move to new preferred habitat (Bennett et al. 2002). Monitoring in June through August showed that suitable habitat shifted west in the Delta toward the confluence of the Sacramento and San Joaquin Rivers and Suisun Bay (^Nobriga et al*.* 2008). Preferred juvenile habitat in summer was defined by a combination of turbidity, low salinity, and a more optimal water temperature. By fall, the center of the distribution of juvenile and sub-adult Delta smelt is tightly coupled with X2 (Sommer et al. 2011), although this does not mean that all Delta smelt are confined to a narrow salinity range because fish occur from fresh water to relatively high salinity (Sommer and Mejia 2013).

Larval and juvenile Delta smelt primarily consume calanoid copepods, particularly *Eurytemora affinis* and *Pseudodiaptomus forbesi* (Nobriga 2002; ^Slater and Baxter 2014). *E. affinis* is abundant only during winter and spring, whereas *P. forbesi* is common in summer and fall (^Durand 2010; ^Winder and Jassby 2011; Merz et al. 2016). The transition between the high abundance of the two copepods has been hypothesized to create a "food gap" during spring and early summer (^Bennett 2005; Miller et al. 2012). The analyses of ^Kimmerer (2008) and ^Baxter et al. (2015) support the hypothesis that Delta smelt abundance and survival from summer to fall is affected by food availability in the LSZ. The diets of sub-adult Delta smelt are broader and include a higher frequency of amphipods and mysids along with *P. forbesi* (^Baxter et al. 2015).

3.8.3 Population Abundance Trends over Time

The abundance of larval, juvenile, and sub-adult Delta smelt is measured in the 20-mm survey (March–July), Summer Tow Net Survey (STN) (June–August), Spring Kodiak Trawl (SKT) Index (January–May), and FMWT Survey (September–December), respectively (Kimmerer et al. 2009). All four surveys indicate that the Delta smelt population has declined significantly and is at a record low level (La Luz and Baxter 2015).

State Water Board staff reexamined the interannual trend in the FMWT index with data collected through 2016 and found a statistically significant decreasing trend ($R^2=0.53$, $P<0.001$, two-tailed t-test) (Figure 3.8-1). The most recent FMWT index values are about 2 percent of values measured around 1967.[15] Present indices are about 5 percent of values measured around 2000 when D-1641 was implemented. Eleven of the last 12 years had the lowest FMWT index values ever recorded (Figure 3.8-1).

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

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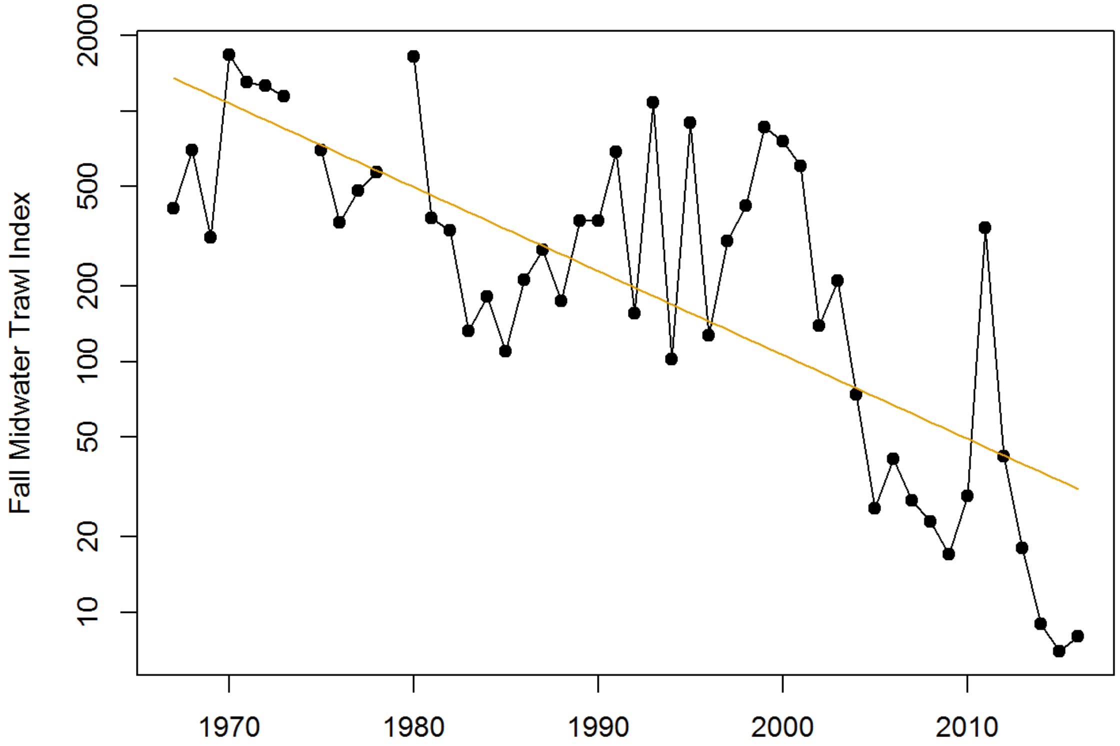
[15] The decrease was estimated from the average of the first five (1967–1971) and the last five (2012–2016) annual FMWT index values to account for interannual variation in population abundance. Similarly, percent change after adoption of D-1641 was calculated from the average of index values for 2000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



The solid line is the least squares linear regression of the logarithm of the Fall Midwater Trawl index against years.

Figure 3.8-1. Interannual Trend in the Fall Midwater Trawl Index for Delta Smelt, 1967–2016

Delta smelt was listed as threatened under the federal ESA in 1993 (58 Fed. Reg. 12863). As previously noted, in 2010, USFWS determined that Delta smelt should be listed as endangered but has not yet reclassified the species because of higher priority listing actions (75 Fed. Reg. 17667). Delta smelt also was listed as threatened under CESA in 1993 (CDFW 2016c) and as endangered in 2009 (CDFW 2016c). Critical habitat was designated in 1994 (59 Fed. Reg. 65256). The critical habitat includes Suisun, Grizzly, and Honker Bays; Mallard and Montezuma Sloughs; and contiguous waters of the legal Delta (59 Fed. Reg. 65256).

3.8.4 Flow Effects on Delta Smelt

Much research has been devoted to investigating the factors responsible for the decline in Delta smelt abundance (^Bennett 2005; ^Kimmerer 2008; Thomson et al. 2010; Maunder and Deriso 2011; Miller et al. 2012). Several factors have been implicated in the decline, including exports (Kimmerer ^2008, 2011; Maunder and Deriso 2011; Rose et al. 2013), food (Maunder and Deriso 2011; ^Hammock et al. 2015; Miller et al. 2012), summer water temperature (Mac Nally et al. 2010; Maunder and Deriso 2011; Miller et al. 2012; Rose et al. 2013), and predators (Maunder and Deriso 2011; Mac Nally et al. 2010). Emerging evidence also suggests that spring outflow may be more critical for production of larvae and maintenance of the adult population than was previously realized (^Baxter et al. 2015). Delta outflow may also be important in summer and fall to provide critical habitat for Delta smelt (^Feyrer et al. 2007; ^Baxter et al. 2015; ^CDFW 2016b).

3.8.4.1 Winter and Spring Delta Outflow

Historically, Delta smelt had highest abundance indices at intermediate outflows between February and June and generally performed more poorly at both extremely high and low outflow (^Baxter et al. 2015). This relationship disappeared after 2001 (^Baxter et al. 2015).

Multivariate statistical modelling was used to explore relationships between spring and fall Delta outflow and juvenile abundance as measured by the 20-mm index.[16] This approach is similar to the method used by ^Jassby et al. (1995) to describe the initial relationship between Delta outflow and the abundance of estuarine-dependent species (^Baxter et al. 2015). The analyses identified a unimodal relationship between X2 or outflow (February–June) and the 20-mm index of larval Delta smelt after 2003. The Delta outflow abundance relationship became statistically stronger when the 20-mm index was standardized by either the number of sub-adult smelt in the previous year's FMWT index[17] or by the number of spawning adults in the SKT survey[18] several months earlier (Figure 3.8-2). The standardization suggests that both the number of available spawners (stock-recruitment effect) and the magnitude of spring outflow are important for determining larval abundance. More spawning adults result in more larvae if outflow is greater during the spawning season. The spring outflow and the stock-recruitment relationships together explained 59 to 65 percent of the variation in the 20-mm index for the 11 years from 2003 to 2013 ($P<0.006$) (^Baxter et al. 2015). The Baxter et al. (^2015) report recommended that conclusions based on the relationship between spring outflow and Delta smelt population abundance be considered preliminary until additional data, analyses, and review were conducted to confirm the robustness of the results.

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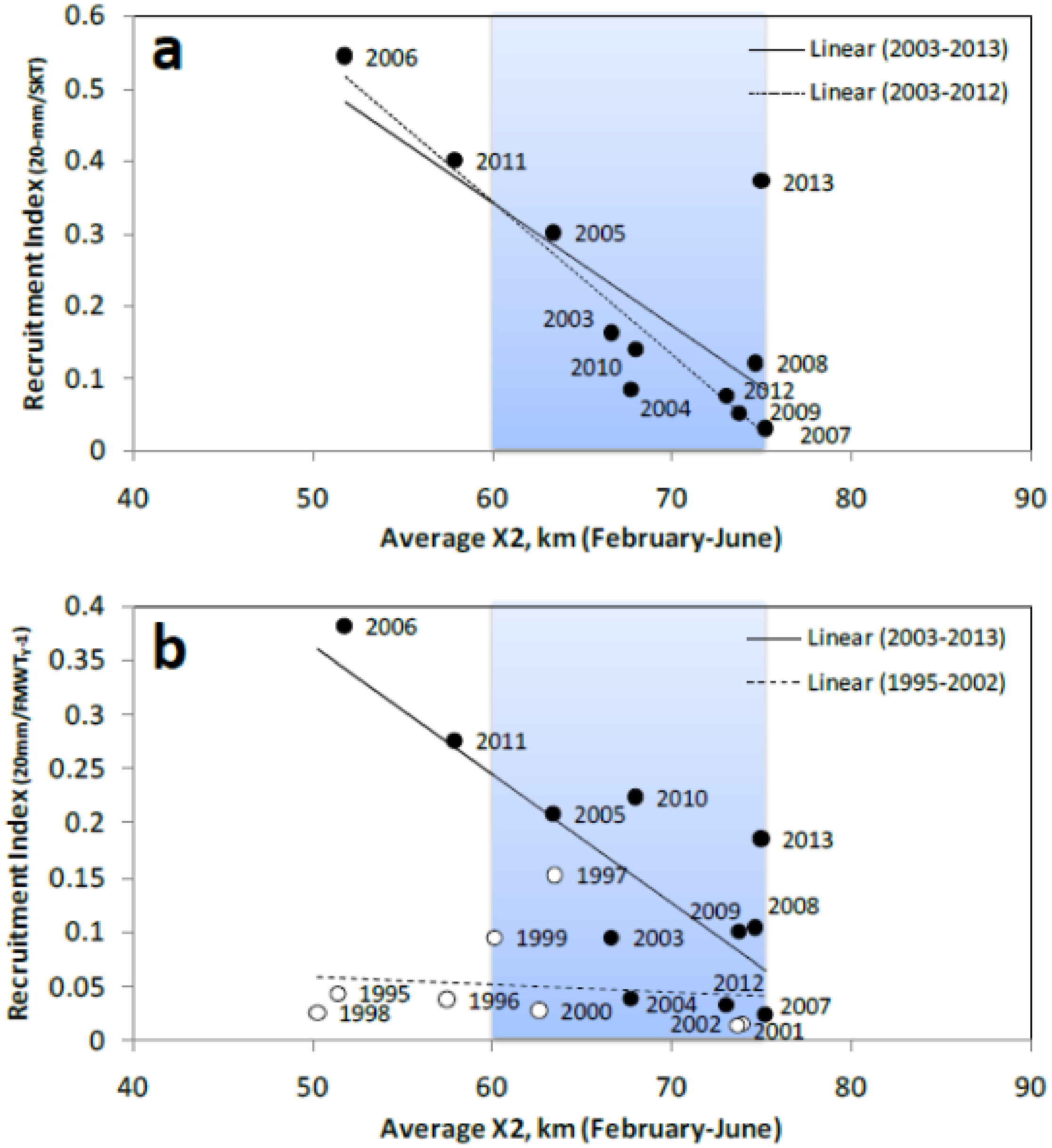
[16] The 20-mm survey is conducted between March and July and indexes the abundance of large larvae and small juvenile smelt with annual indices based on data from two surveys prior and two surveys after mean Delta smelt length reaches 20 mm.

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

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

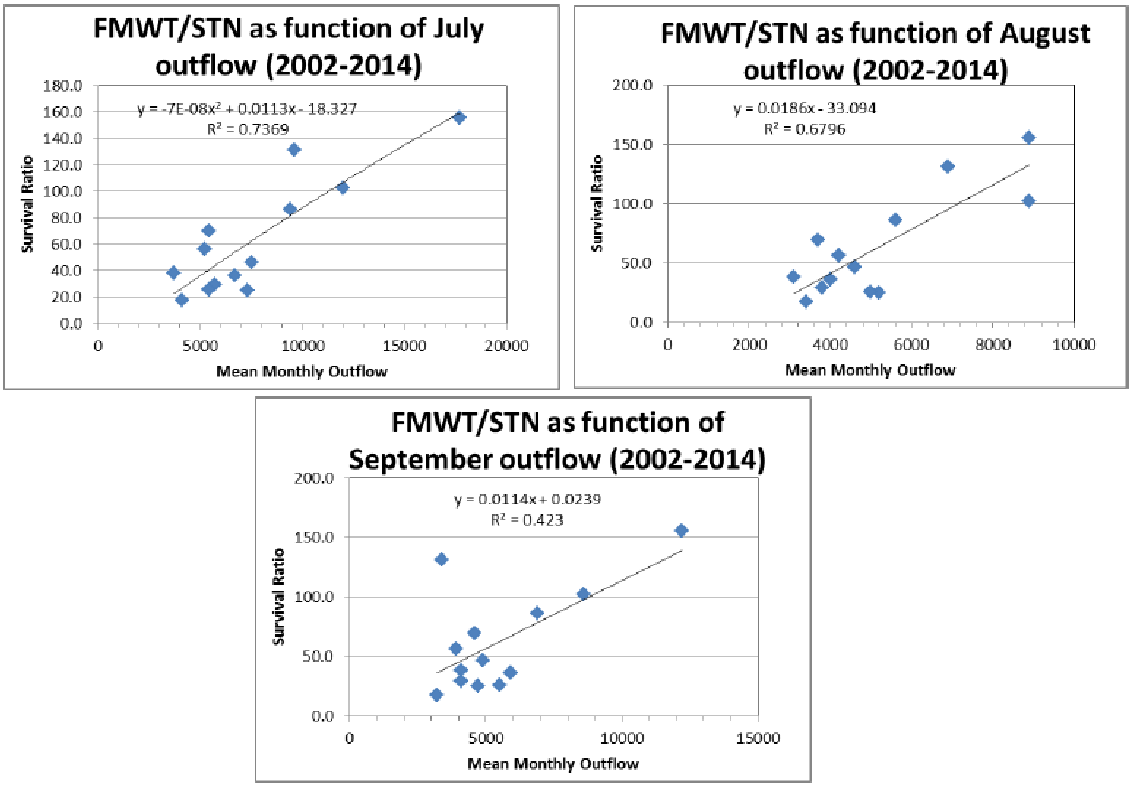


Source: ^Baxter et al. 2015.
km = kilometers
For the 20-mm/Spring Kodiak Trawl (SKT) panel, a linear regression was calculated with and without 2013, which appears to be an outlier. For the 20 mm/Fall Midwater Trawl (FMWT) panel, the period before the pelagic organism decline (1995–2002) and the 2002–2013 period are plotted (figure reproduced from ^Baxter et al. 2015).

Figure 3.8-2. Adult (panel a, SKT) and Sub-Adult (panel b, FMWT from previous year) to Larval (20-mm Survey) Recruitment Indices as a Function of Spring X2 (February–June)

3.8.4.2 Summer Outflow

Recent unpublished scientific evidence suggests that Delta smelt abundance in fall is positively related to Delta outflow during the prior summer. The science indicates that when X2 was greater than 80 km (flows ≤7,500 cfs) between June and August, the population experienced a year-over-year decrease in the FMWT index (^CDFW 2016b). In addition, survival of Delta smelt in summer, as measured by FMWT and STN,[19] was a positive function of Delta outflow (^CDFW 2016b). More flow in July, August, and September resulted in statistically greater survival from the juvenile to sub-adult stages (Figure 3.8-3). Both relationships only appeared after 2002, the start of the pelagic organism decline. Gartrell (2016) in an unpublished report noted that outflow in July, August, and September was positively correlated with flow in earlier months, including spring, when other research has noted a positive relationship between flow and recruitment (Baxter et al. 2015). CDFW (2016b) hypothesizes that increased survival in summer may result from an increase in the quantity and quality of available food, a decrease in the magnitude and frequency of toxic cyanobacterial blooms, a reduction in ambient water temperature, and a reduction in the risk of predation with an increase in summer flow.



FMWT/STN as function of July outflow (2002-2014)

FMWT/STN as function of August outflow (2002-2014)

FMWT/STN as function of September outflow (2002-2014)

Source: ^CDFW 2016b.
Survival is estimated as the quotient of the Fall Midwater Trawl (FMWT) index divided by the Summary Tow Net (STN) index. All three relationships are statistically significant.

Figure 3.8-3. Delta Smelt Survival in Fall as a Function of Monthly Mean Delta Outflow (cubic feet per second), for July (top left), August (top right) and September (bottom)

3.8.4.3 Fall Outflow

Feyrer et al. (^2007, ^2011) used the presence and distribution of Delta smelt from the FMWT survey to determine the environmental characteristics of preferred Delta smelt habitat in fall and used this to develop an abiotic habitat index. The index quantifies the acreage of preferred habitat in terms of salinity and water clarity. The analysis found that if X2 was at 74 km or farther seaward,

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

about 12,000 acres of high-quality habitat was located in Suisun Bay (Feyrer et al. 2011). If X2 was 85 km or more landward, the amount of favorable habitat was about half as large and was located above the confluence of the Sacramento and San Joaquin Rivers (^Feyrer et al. 2011). Intermediate X2 values had intermediate amounts of suitable habitat (^USFWS 2008). Historically, fall X2 was often located in Suisun Bay in wet and above normal water years. Increased CVP and SWP exports combined with declining inflows since 2000 in fall have reduced outflows and decreased the abiotic habitat index for smelt by moving X2 upstream into the Sacramento and San Joaquin Rivers and away from Suisun Bay (^Baxter et al. 2015). The decrease in fall outflow and reduction in preferred habitat is hypothesized to be one factor contributing to the decrease in Delta smelt population abundance. Consistent with this hypothesis is the observation that the abundance of juvenile smelt in summer is a function of the location of X2 during the previous fall (^USFWS 2008). Based on these observations, the USFWS BiOp requires that Delta outflow in September and October be managed so that X2 is no greater than 74 km and 81 km in wet and above normal water year types, respectively (Table 3.8-1) (^USFWS 2008).[20,21] In addition, the USFWS BiOp requires that all flow into CVP and SWP reservoirs in November during wet and above normal water years be released to increase Delta outflow and move X2 farther downstream.

Table 3.8-1. Delta Outflow and Old and Middle River Flows Indicated to Be Protective of Delta Smelt

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

Outflows are monthly averages (cubic feet per second [cfs]).
[a] Release November inflow to Sacramento basin CVP and SWP reservoirs to increase Delta outflow.
[b] 14-day running average in cfs.
[c] Outflow ≥ 7,500 cfs.
AN = above normal; W = wet; OMR = Old and Middle Rivers; km = kilometers

The ^Baxter et al. (2015) report evaluated the effect of fall X2 on larval Delta smelt abundance as measured by the 20-mm index. The analysis found an inverse relationship between X2 during the previous fall and the abundance of larval smelt in the following spring (Figure 3.8-4). The relationship was statistically significant ($P<0.001$) and explained 48 percent of the variation in the 20-mm index. The relationship improved when the index was divided by the FMWT index value for the previous year. For example, the previous fall's X2 value and the FMWT index together explained 62 percent of the variation in the 20-mm index for the 19-year period between 1995 and 2013. More outflow in fall was correlated with a higher 20-mm index for larval Delta smelt the next year. The fall X2 results also support the importance of a stock-recruitment relationship, more breeding adults led to more offspring.

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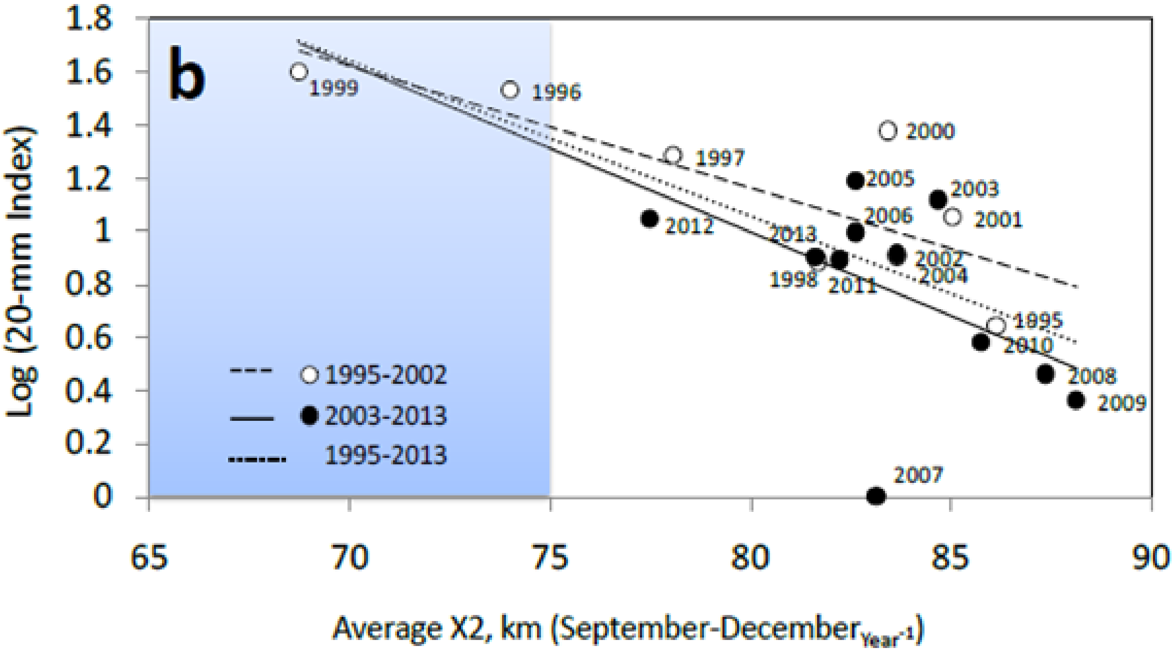
[20] This X2 value is roughly equivalent to a sustained Delta outflow of 11,400 cfs.

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



Source: ^Baxter et al. 2015.
km = kilometers

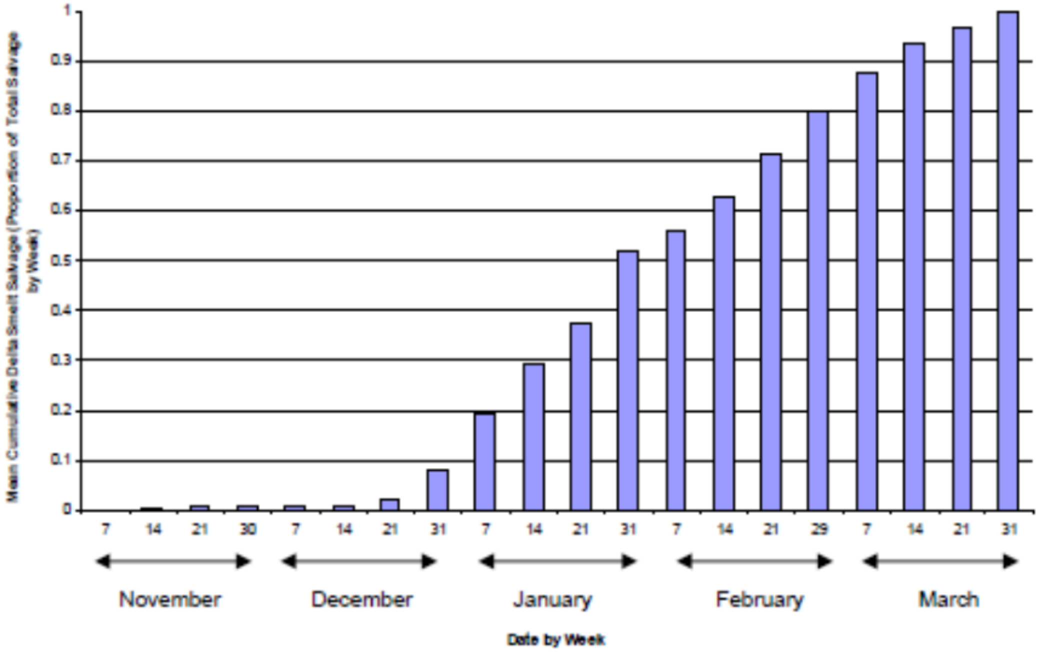
Figure 3.8-4. Plot of the Delta Smelt 20-mm Survey Abundance Index as a Function of the Location of the Previous Year's Fall X2

3.8.4.4 Interior Delta Flow

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

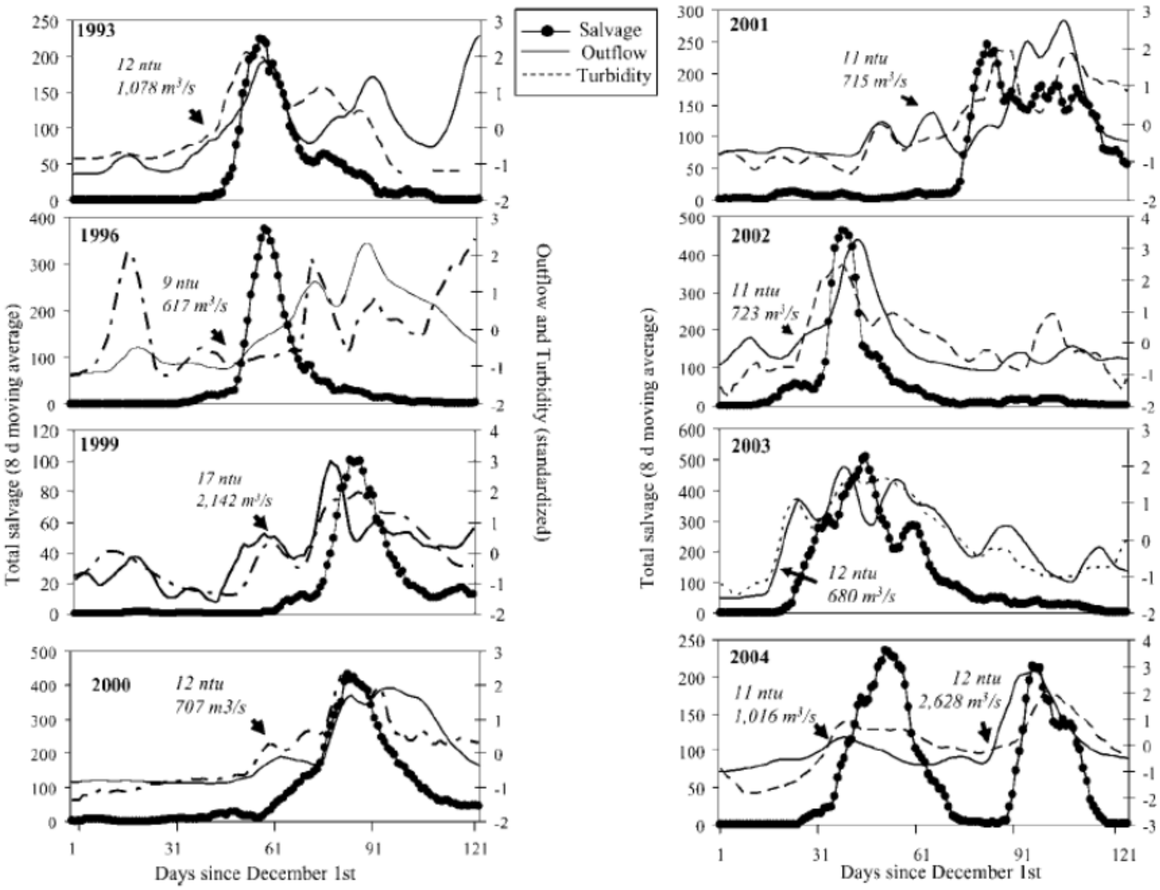
Pre-spawning adults are taken in salvage as they migrate into the Delta between December and March (Figure 3.8-5) (^USFWS 2008). The peak spawning migration is in January and February, although a few adults are salvaged as early as December (Figure 3.8-5). The cue for mass upstream migration appears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

Most of the information about early-stage larval Delta smelt is inferred from the collection of spent adult females in the SKT survey and larval fish in the 20-mm survey. The center of the distribution of early-stage larval smelt is downstream of the location where spent female Delta smelt are caught but upstream of X2 in spring (^Dege and Brown 2004). In addition, a high percentage of Delta smelt is now found year-round in freshwater areas, such as the Cache Slough complex, Sacramento Deepwater Ship Channel, and toe drain of the Yolo Bypass (Merz et al. 2011; Sommer et al. 2011; Sommer and Mejia 2013).



Source: ^USFWS 2008.

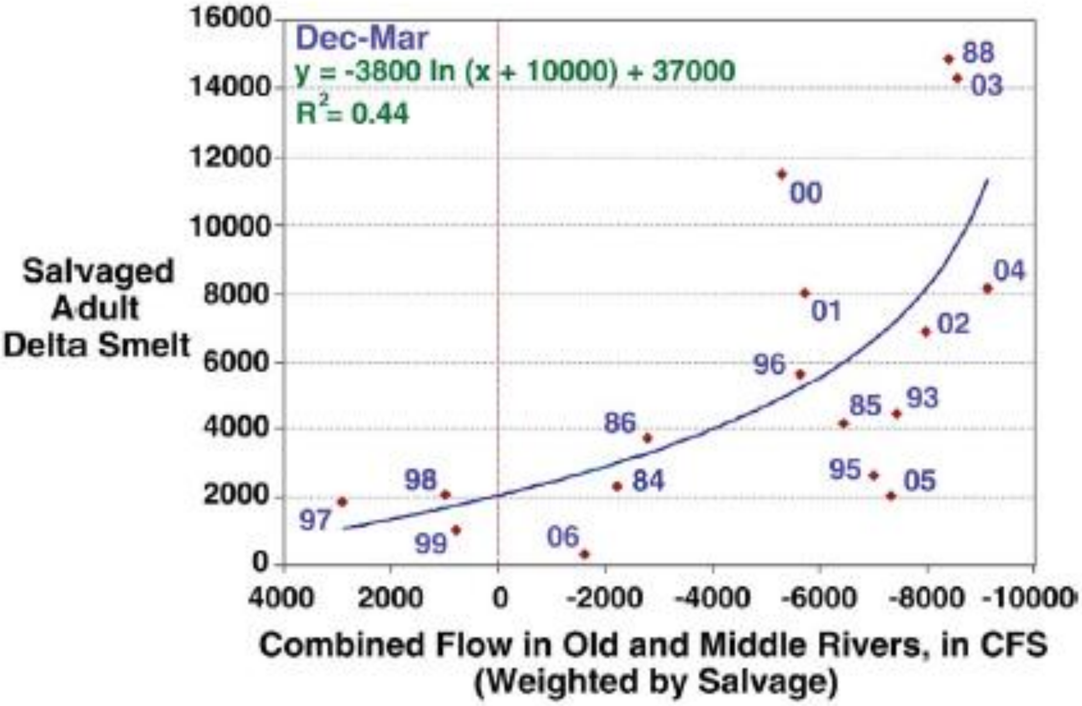
Figure 3.8-5. Cumulative Proportional Adult Delta Smelt Salvage by Week, 1993–2006



Source: ^Grimaldo et al. 2009.
ntu = nephelometric turbidity unit
Total Delta outflow and turbidity were standardized to a mean of zero.

Figure 3.8-6. Eight-Day Running Averages of Adult Delta Smelt Salvage, Total Outflow (m³/s), Turbidity for the Eight Most Abundant Delta Smelt Salvage Years between December 1992 and April 2005 at the SWP and CVP

The risk of entrainment depends on the location of larval and adult Delta smelt relative to the export facilities and the magnitude of OMR reverse flow (^USFWS 2008). USFWS (^2008) evaluated adult salvage by regressing average OMR reverse flow between December and March against adult Delta smelt salvage for 1984 through 2007 (Figure 3.8-7). USFWS found that salvage increased exponentially with increasingly negative OMR reverse flow. An inflection point occurred in the USFWS salvage data, with higher salvage rates at more negative OMR flows than -5,000 cfs. An inflection point at -5,000 cfs is consistent with similar increases in salvage for longfin smelt and salmon (Figure 3.5-4 and Figure 3.4-16). USFWS (^2008) used a piecewise polynomial regression analysis to establish a break point in the data set and determined the reverse flow where smelt salvage first began to increase. The analysis indicated that this occurred at about -1,250 cfs, suggesting a relatively constant amount of entrainment at OMR reverse flows more positive than - 1,250 cfs. USFWS (^2016) determined in their species assessment and listing priority assignment that entrainment at SWP and CVP Delta facilities remains a significant ongoing threat for the Delta smelt population.



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

Source: ^USFWS 2008.
cfs = cubic feet per second
ntu = nephelometric turbidity unit

Figure 3.8-7. Salvage of Adult Delta Smelt as a Function of Old and Middle Rivers Reverse Flows for December through March

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

The conclusions from analyses of the salvage data are consistent with ^Grimaldo et al. (2009) and USFWS PTM results. The PTM analysis confirmed that the probability of entrainment was a function of the location of the Delta smelt population and the magnitude of OMR reverse flow (^USFWS 2008). Together the analyses indicate that OMR flows should be maintained between -1,250 and -5,000 cfs, depending on the presence of Delta smelt and other physical and biological factors, including turbidity, that are known to influence entrainment (Table 3.8-1). These recommendations are consistent with the requirements of Actions 2 and 3 from the 2008 USFWS Delta smelt BiOp reasonable and prudent alternative.

3.9 Starry Flounder (*Platichthys stellatus*)

3.9.1 Overview

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

3.9.2 Life History

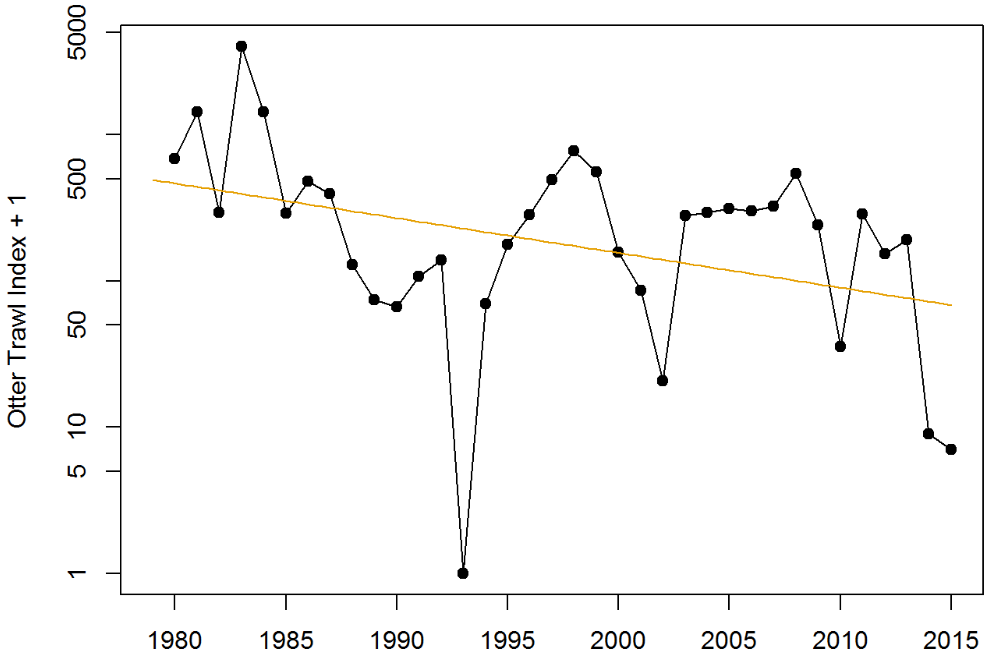
Adults are primarily a marine fish with a geographic distribution from Santa Barbara, California, to the Canadian Arctic (^Moyle 2002; ^Miller and Lea 1972). Starry flounder are taken in the California commercial and recreational fishery (^Wang 1986; Haugen 1992; ^Moyle 2002). The San Francisco estuary serves as rearing habitat for this benthic species (^Moyle 2002).

Starry flounder spawn in shallow coastal marine waters adjacent to sources of fresh water between November and February (Orcutt 1950). The pelagic eggs and larvae are buoyant and are found mostly in the upper water column (Orcutt 1950; ^Wang 1986). After about 2 months, the larvae settle to the bottom and are transported by tidal currents into nearby fresh and brackish water, like San Francisco Bay, between March and June (Baxter 1999a). The juveniles spend the next several years in fresh and estuarine waters (Haertel and Osterberg 1967; Bottom et al. 1984; ^Wang 1986; Baxter 1999a). Starry flounder are common in San Pablo Bay and Suisun Bay and Marsh and can be found upstream of these locations in low-flow years (Haertel and Osterberg 1967; Bottom et al. 1984; ^Wang 1986). The abundance and distribution of starry flounder are not affected by entrainment at the CVP and SWP exports as their distribution is downstream of the influence of the two pumping facilities (Baxter 1999b). The distribution of starry flounder is affected by temperature, with fish most often found at temperatures of 10°C to 20°C (^Wang 1986; ^Moyle 2002).

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

3.9.3 Population Abundance and Trends over Time

The population abundance of young of the year and of 1-year-old starry flounder in the Bay-Delta estuary has been measured by the San Francisco Bay Study since 1980 and is reported as an annual index. Although there has been considerable interannual variability, a statistical trend in abundance of age-1 starry flounder has occurred since sampling began in 1980 ($R^2=0.22$; $P<0.05$) (Figure 3.9-1). There has been little or no additional decline since implementation of D-1641 in 2000. The large drop in population abundance in 2014 coincides with the recent drought. Similar decreases in abundance occurred in earlier droughts and were followed by a rebound in the population in succeeding years.

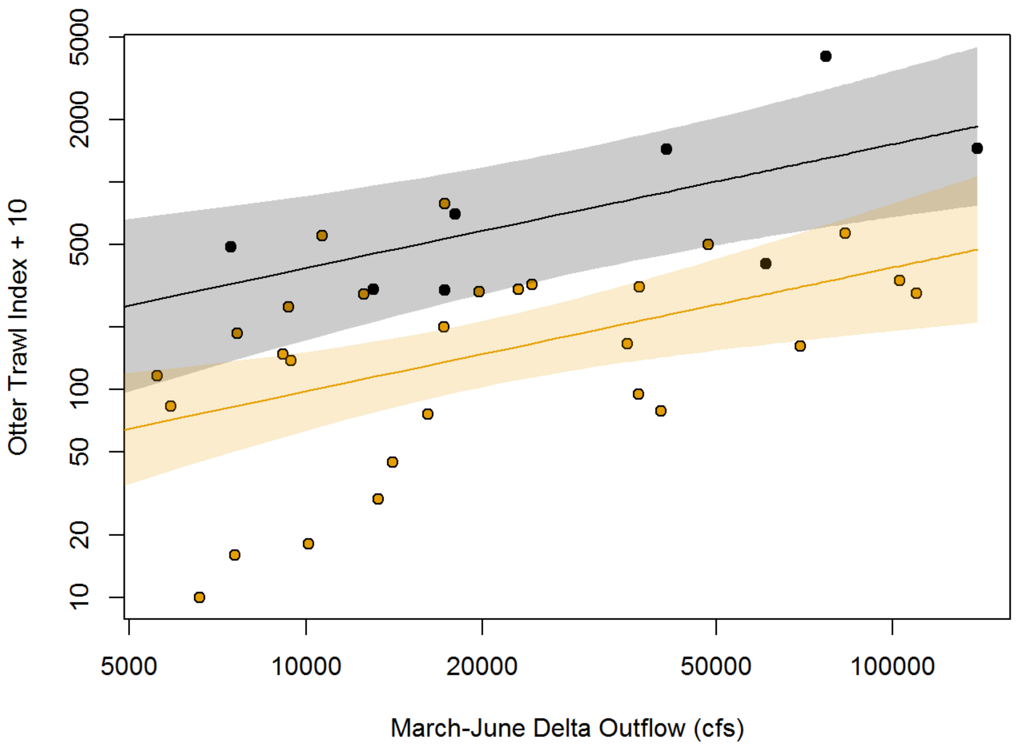


The solid orange line is the least squares linear regression of the logarithm of the Bay Study Otter Trawl index (incremented by 1) against years. The slope of the regression differs significantly from zero ($R^2=0.51$; $P<0.05$, two-sided t-test).

Figure 3.9-1. Population Abundance of Age-1 Starry Flounder as Measured in the San Francisco Bay Study, 1980–2014

3.9.4 Flow Effects on Starry Flounder

Age-1 starry flounder abundance is positively correlated with Delta outflow between March and June of the previous year (CDFG 1992b; ^Jassby et al. 1995; ^Kimmerer 2002b). A statistically significant reduction in the abundance of starry flounder per unit outflow occurred after the invasion of *Potamocorbula* in 1987 (^Kimmerer 2002b). State Water Board staff reassessed the relationship with new data to determine whether starry flounder abundance was still a positive function of Delta outflow (Figure 3.9-2). The flow-abundance relationship was estimated following the methods of ^Kimmerer (2002b), using data collected between 1967 and 2015 (Figure 3.9-2). A single step change was included, following the invasion of *Potamocorbula* (following 1987). More outflow in the previous spring was associated with a higher Bay Study index for age-1 starry flounder the following year (Figure 3.9-2), and no statistical support was found for an interaction between the slope and step change.

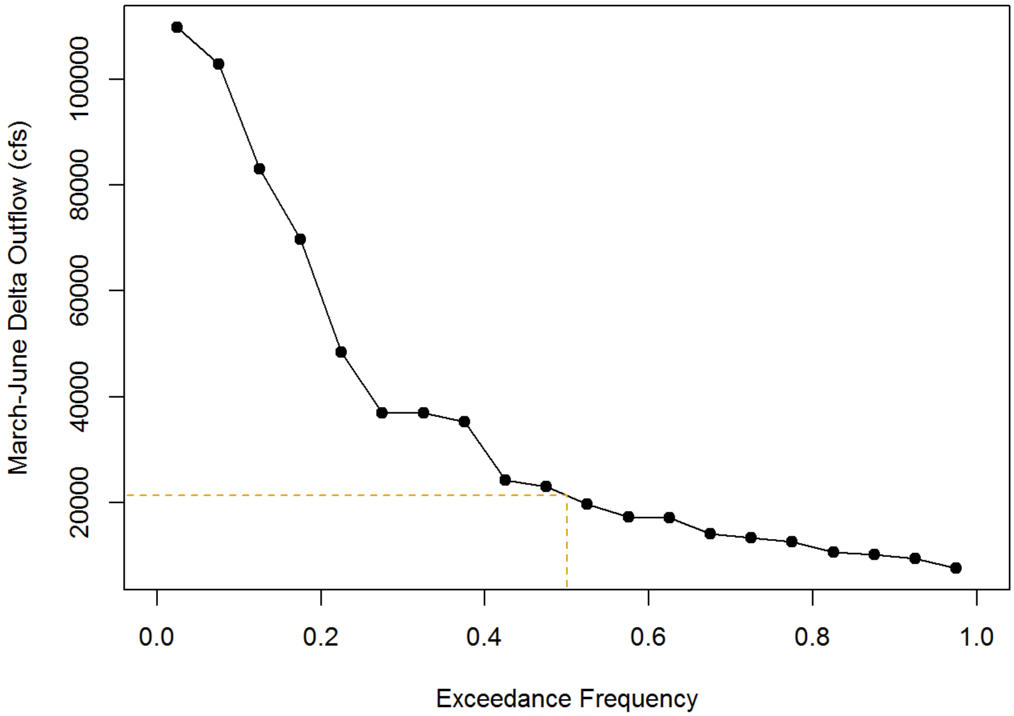


cfs = cubic feet per second
The flow recruitment relationship is statistically significant (two sided t-test, $P<0.01$; $R^2=0.44$). The black line and points are for 1980–1987 while the orange line and points are for 1988–2015. Colored bands around the regression lines represent 95-percent confidence limits.

Figure 3.9-2. Correlation between the Starry Flounder Bay Study Otter Trawl Age-1 Index (1980–2015) and Average Daily Outflow (cfs) between March and June

CDFG (2010a) suggests that there may be at least four possible mechanisms to explain the positive starry flounder flow abundance relationship. First, increasing Delta outflow may provide stronger chemical cues to aid larvae and juvenile flounder locate estuarine nursery habitat. Second, higher Delta outflows generate stronger upstream directed gravitational bottom currents that may assist larval immigration into the San Francisco Bay. Third, higher flow may increase the volume of low-salinity habitat needed for rearing. Finally, Delta outflow is positively correlated with the abundance of California bay shrimp (*Crangon franciscorum*), another benthic species that is an important food resource for young starry flounder (see Section 3.10, *California Bay Shrimp* [*C. franciscorum*]).

A cumulative frequency distribution was calculated for average daily Delta outflow between March and June of 1994 to 2013 to determine the Delta outflow needs of starry flounder (Figure 3.9-3). This 20-year period was selected because the years represent a period when the median annual Bay Study index of age-1 starry flounder (280) was close to the population abundance goal in the Delta Flow Criteria Report of 293. The median outflow during the 20-year period was 21,000 cfs (Table 3.9-1).



The dotted line is the average daily outflow of 21,000 cubic feet per second (cfs) that occurred in half of all years.

Figure 3.9-3. Cumulative Frequency Distribution of Monthly Average Daily Delta Outflow for March through June, 1994–2013

Table 3.9-1. Delta Outflow Indicated to Be Protective of Starry Flounder

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

Outflows are monthly averages (cubic feet per second).

3.10 California Bay Shrimp (*Crangon franciscorum*)

3.10.1 Overview

The California bay shrimp is a native species. Planktonic larvae hatch from eggs released in San Francisco Bay or offshore and are carried into the Delta on bottom gravitational currents. *Crangon* shrimp is important in the diet of several recreationally important fish species in the San Francisco estuary. A positive correlation exists between indices of population abundance of younger than 1-year-old shrimp and Delta outflow in spring. An average Delta outflow between March and May of 19,000 to 26,000 cfs is needed to improve shrimp population abundance.

3.10.2 Life History

There are three common native species of *Crangon* shrimp in the Bay-Delta estuary: *Crangon franciscorum*, *C. nigricauda*, and *C. nigromaculata* (Hieb 1999). This Staff Report refers to *C. franciscorum*. The California bay shrimp is widely distributed along the Pacific Coast of North America from San Diego to Southeastern Alaska (Rathbun 1904; Hieb 1999). The shrimp is primarily an estuarine species, common in bays on mud and sand bottoms and also found in nearshore coastal waters (Schmitt 1921).

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

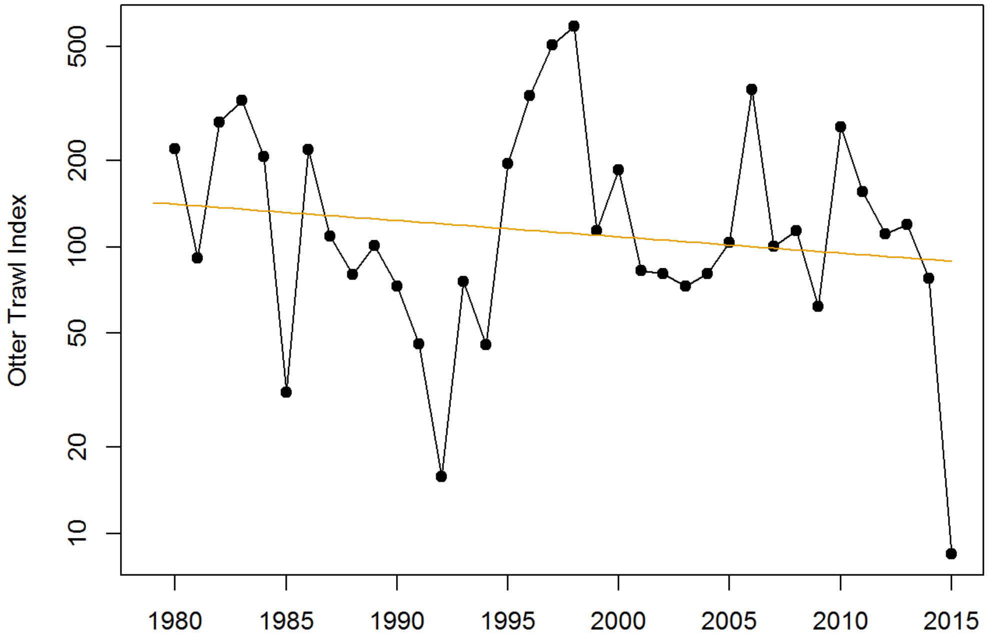
Crangon spp. are a major component in the aquatic foodweb of West Coast estuaries (Siegfried 1989). In the Bay-Delta, the shrimp has been reported in the diet of juvenile and adult striped bass, starry flounder, white and green sturgeon, American shad, white catfish, Pacific tomcod, brown smooth-hound, and staghorn sculpin (Johnson and Calhoun 1952; Heubach et al. 1963; Ganssle 1966; McKechnie and Fenner 1971; Reilly et al. 2001). A change in shrimp abundance could have a significant bottom up effect on population size of important commercial and recreational fish in the estuary.

Female California bay shrimp are reproductively active throughout much of the year (Krygier and Horton 1975). Bay shrimp mature in 1 year and may live for up to 2 years (Hatfield 1985). Females hatch multiple broods during the breeding season (Krygier and Horton 1975), with larval abundance peaking in winter and early spring in California (CDFG 1987a). Larval development is believed to require 30 to 40 days (Hatfield 1985). Early-stage larvae are found in near-surface water while later stages are located closer to the bottom (Siegfried 1989). The bottom orientation of late larval stages may facilitate passive onshore and estuarine migration to the LSZ in bottom gravitational currents (Hatfield 1985). Upstream migration primarily occurs between April and June (CDFG 2010a). Juveniles seek shallow brackish to freshwater nursery habitats, remaining there for up to 6 months before commencing a slow migration back down the estuary (Hatfield 1985). Small juvenile shrimp are common in San Pablo and Suisun Bays during years with high Delta outflow (CDFG 1992b; Hieb 1999), while the population shifts further upstream to Honker Bay and the confluence of the Sacramento and San Joaquin Rivers during low-flow years. In fall, adults migrate back down the estuary to repeat the cycle (Hatfield 1985). The larvae are located too far west in the estuary for significant entrainment to occur at the CVP and SWP pumping facilities.

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

3.10.3 Population Abundance Trends over Time

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



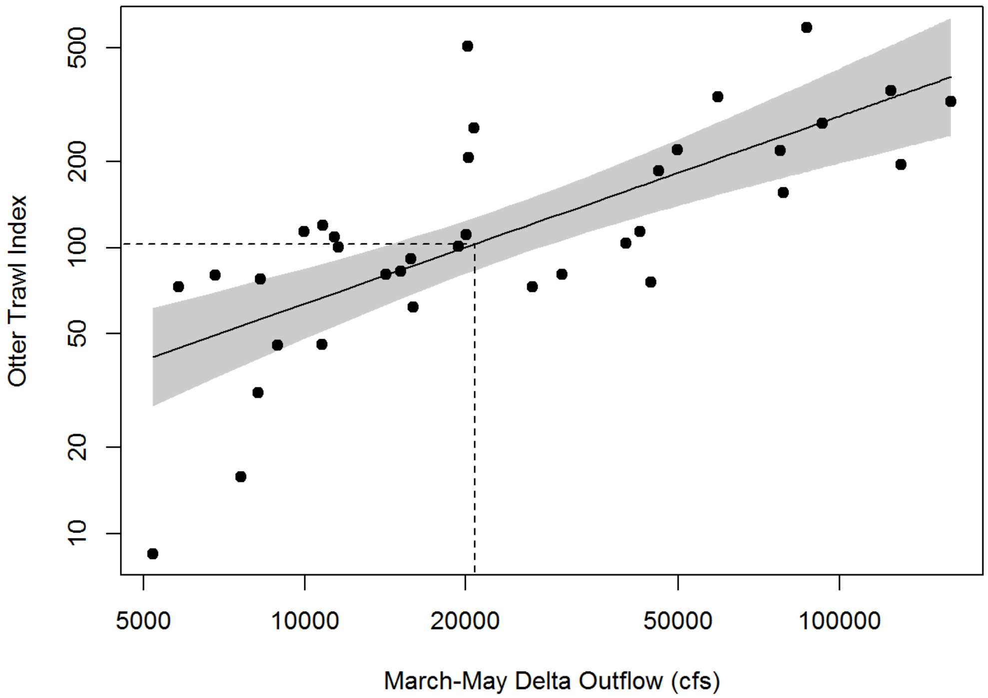
The orange line in Figure 3.10-1 is an estimate of the trend in population abundance over time; the slope of the regression does not differ significantly from zero (two sided t-test, $P>0.05$).

Figure 3.10-1. Index of Juvenile *Crangon franciscorum* Abundance as Measured in the San Francisco Bay Otter Trawl Survey, 1980–2015

3.10.4 Flow Effects on California Bay Shrimp

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

State Water Board staff reassessed the March to May Delta outflow relationship with data collected through 2014 (Figure 3.10-2). The relationship is still significant ($P<0.001$, $R^2=0.49$). More Delta outflow is correlated with higher Bay Study index values for juvenile California bay shrimp.



The flow-abundance relationship is significant ($P<0.001$, $R^2=0.49$). The dotted line indicates that a flow of 21,000 cubic feet per second (cfs) is predicted to produce the recommended population abundance goal. The colored band around the regression line is the 95-percent confidence limits.

Figure 3.10-2. Relationship between Juvenile California Bay Shrimp Abundance, as Measured by the San Francisco Bay Otter Trawl Survey (1980–2013), and Average Daily Outflow (cfs) between March and May of the Same Year

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

3.10.4.1 Delta Outflow

Three methods were used to determine a flow that would benefit California bay shrimp. First, a regression of flow and abundance was used to predict the outflow associated with the recommended 2010 Flow Criteria Report abundance goal. The regression predicted that an average outflow of 21,000 cfs between March and May would achieve the goal (Figure 3.10-2). Second, a cumulative frequency distribution was calculated for the average daily outflow between March and May of 1980 to 2013.[22] The median flow was 20,000 cfs (Figure 3.10-3).

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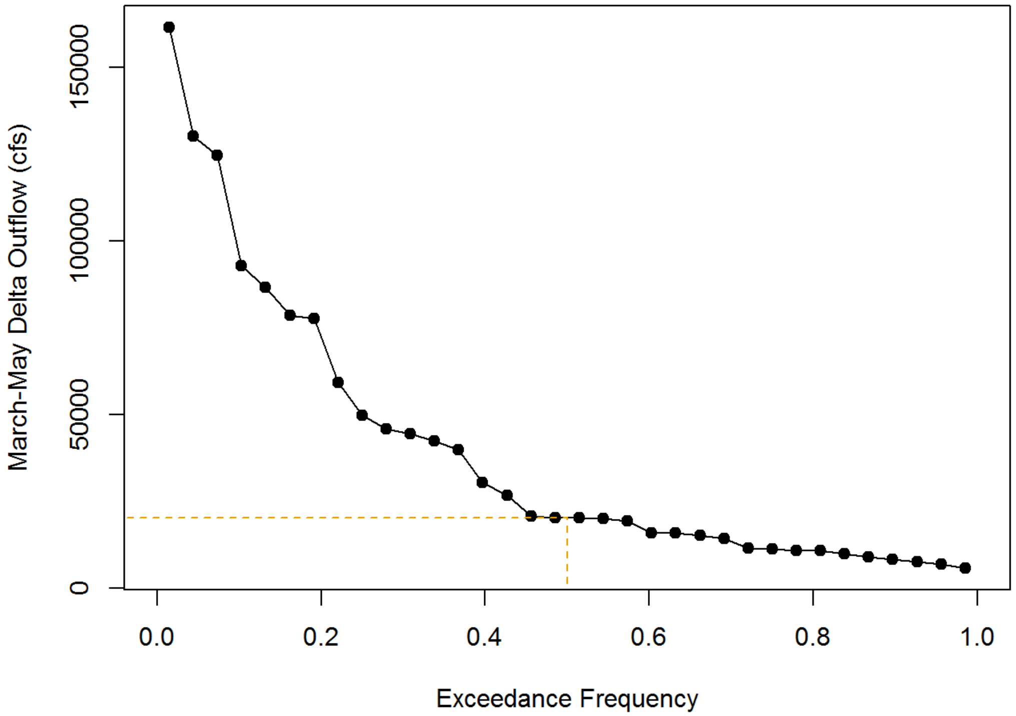
[22] These years were selected for analysis as the median value for the 34-year period (110) is near the 2010 Flow Criteria Report abundance goal of 103.

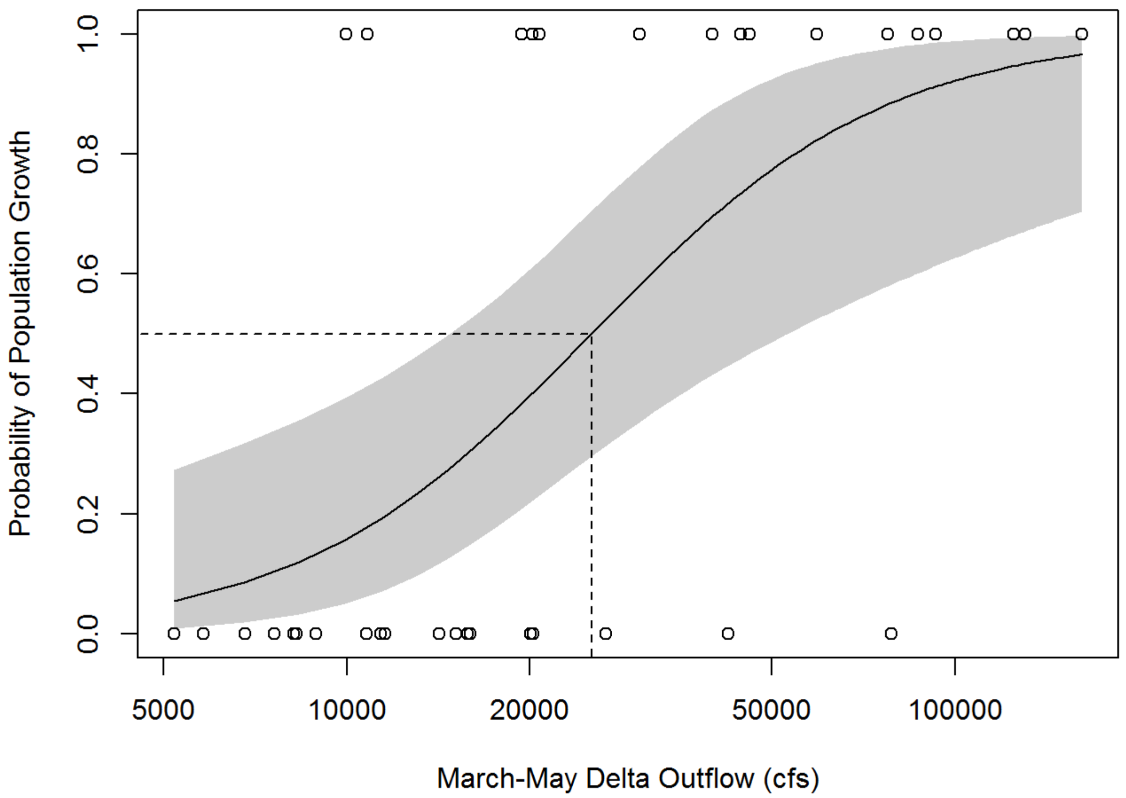


The dotted line is the average daily outflow of 20,000 cubic feet per second (cfs) that occurred in half of the years.

Figure 3.10-3. Cumulative Frequency Distribution of Average Daily Outflow for March–May, 1980–2013

Third, logistic regression analysis predicted that 25,000 cfs is associated with positive population growth in 50 percent of years using Bay Study data for 1980 through 2013 (Figure 3.10-4) The estimate is similar to that of TBI/NRDC (2010a), who employed the same approach for data from 1980 through 2007and estimated positive growth would occur in 50 percent of years at 27,600 cfs (^SWRCB 2010).

In summary, the three analytical methods provide an indication of the magnitude of Delta outflow needed to maintain the present population size of *C. franciscorum* in the Bay-Delta estuary (Table 3.10-1). The methods indicate that a median outflow of 20,000 to 25,000 cfs between March and May should be sufficient to maintain the present population size (Table 3.10-1).



The dotted line indicates that an average daily outflow of 25,000 cubic feet per second (cfs) between March and May is associated with a 50-percent probability of population growth. The band around the line is the 95-percent confidence limit.

Figure 3.10-4. Probability of Juvenile California Bay Shrimp Population Growth as a Function of Delta Outflow from a Logistic Regression Analysis (P<0.01)

Table 3.10-1. Delta Outflows Indicated to Be Protective of California Bay Shrimp

	Months											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
California bay shrimp			20,000 to 25,000									

Outflows are monthly averages (cubic feet per second).

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

3.11.1 Overview

Zooplankton are an important food resource for juvenile fish and for small adult pelagic fish, such as longfin and Delta smelt. Two upper estuary zooplankton species that have exhibited flow-abundance relationships are the mysid *Neomysis mercedis* and the calanoid copepod *Eurytemora affinis*. The population size of both species has declined since the invasion of the overbite clam. Both species have been replaced by a group of alien copepod taxa from East Asia that may not be as available to planktivorous fish*.* CDFW recommends a Delta outflow of 11,400 to 29,200 cfs between February and June for the benefit of the zooplankton community.

3.11.2 Life History

Zooplankton is a general term for small planktonic invertebrates that constitute an essential food resource for fish, especially young fish and all stages of pelagic fishes that mature at a small size, such as longfin and Delta smelt (CDFG 1987b; Kimmerer et al. 1998; Bennett et al. 2002; ^Bennett 2005). Two upper estuary zooplankton species that have exhibited flow-abundance relationships in the past and are important food resources for pelagic fishes are *N. mercedis* and *E. affinis* (^Jassby et al. 1995; ^Kimmerer 2002b)*. Pseudodiaptomus forbesi* is an introduced copepod that has recently become an important food resource for planktivorous fish species.

3.11.2.1 *Neomysis mercedis*

The mysid shrimp, *N. mercedis,* is euryhaline; in California, it has been found in salinities from 0.5 to 32.0 ppt (Orsi and Knutson 1979) but it is most abundant in the LSZ (Orsi and Mecum 1996). The mysid shrimp has an upper thermal limit of 22^{0}C in San Francisco Bay (Orsi and Knutson 1979), with reproduction occurring year-round (Durand 2015). *N. mercedis* is omnivorous and feeds on diatoms, copepods, and rotifers (Siegfried and Kopache 1980).

The range of *N. mercedis* is from Alaska to San Francisco Bay (Orsi and Knutson 1979). The shrimp is found throughout the Delta and San Francisco Bay but is most abundant in the LSZ in Suisun Bay (Orsi and Knutson 1979; Hennessy 2009; Hennessy and Enderlein 2013; Durand 2015). *E. affinis* is a major prey item of *N. mercedis* (Orsi and Mecum 1996).

3.11.2.2 *Eurytemora affinis*

In the San Francisco Bay estuary, the calanoid copepod *E. affinis* has been observed from the LSZ to fresh water in the Sacramento and San Joaquin Rivers (Orsi and Mecum 1996; ^Durand 2010). The copepod is omnivorous and feeds on diatoms, particulate organic matter, detritus, nanophytoplankton, protozoa, microplankton, and ciliates (Siegfried and Kopache 1980; Durand 2015; ^Kimmerer 2002b).

E. affinis can live for up to 73 days, with females producing several clutches of up to 18 eggs during their lifetime (^Durand 2010; Kipp et al.2013). In the Delta, egg production is highest in spring at locations with salinities from 0.5 to 2.0 ppt (^Durand 2010). *E. affinis* is an important food for most small fishes, particularly those with winter and early spring larvae, such as longfin smelt, Delta smelt, and striped bass (Lott 1998; ^Bennett 2005; Nobriga 2002; Moyle et al. 1992; ^Slater and Baxter 2014).

3.11.3 Population Abundance and Trends over Time

3.11.3.1 *Neomysis mercedis*

Mean spring and summer abundance of *N. mercedis* was high prior to 1988 but has since declined to low levels in all seasons, with a 50-fold decline in summer (^Kimmerer 2002b; Orsi and Mecum 1996; Hennessy 2009; CDFG 2010a). Annual abundance now peaks between May and July (Orsi and Mecum 1996). The decline may be due to competition between juvenile mysids and the invasive clam, *Potamocorbula,* for diatom food (Orsi and Mecum 1996; Winder et al. 2011; Hennessy and Enderlein 2013; Durand 2015). The mysid shrimp was an important food resource for many fish in the upper estuary prior to its decline in the late 1980s (Feyrer et al. 2003; Bennet 2005).

3.11.3.2 *Eurytemora affinis*

The calanoid copepod *E. affinis* used to be abundant in the San Francisco Bay year-round but currently is moderately abundant in winter and spring and rare in summer and fall (Durand ^2010, 2015; Merz et al. 2016). The abundance of *E. affinis* began to decline in the 1970s but exhibited a steep decrease in spring and summer after 1987, coincident with the invasion and establishment of *Potamocorbula* and another invasive calanoid copepod, *P. forbesi* (Kimmerer and Orsi 1996; Orsi and Mecum 1996; ^Bennett 2005; ^Winder and Jassby 2011; Hennessy and Enderlein 2013). The decline in copepod abundance after 1987 may have been due to both competition for food with and predation by *Potamocorbula* (^Kimmerer 2006). Zooplankton compete with benthic filter feeders for phytoplankton (^Winder and Jassby 2011), and the naupliar larval stage of *E. affinis* is ingested by *Potamocorbula* (Kimmerer et al. 1994). Grazing rates by *Potamocorbula* are low in winter and spring but increase in summer and fall; this may, in part, explain the seasonal abundance pattern of *E. affinis* (^Durand 2010; Hennessy and Enderlein 2013). The effects of contaminants also may have played a role in the decline (^Kimmerer 2004; Teh et al. 2013).

3.11.4 Flow Effects on Zooplankton

3.11.4.1 *Neomysis mercedis*

Prior to 1987, the abundance of *N. mercedis* in summer increased as X2 moved downstream with higher Delta outflow (^Kimmerer 2002b; ^Jassby et al. 1995; Orsi and Mecum 1996). After 1987, there was an inverse relationship: abundance showed a positive relationship with X2, and low Delta outflows correlated with higher numbers of mysid shrimp (^Kimmerer 2002b).

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

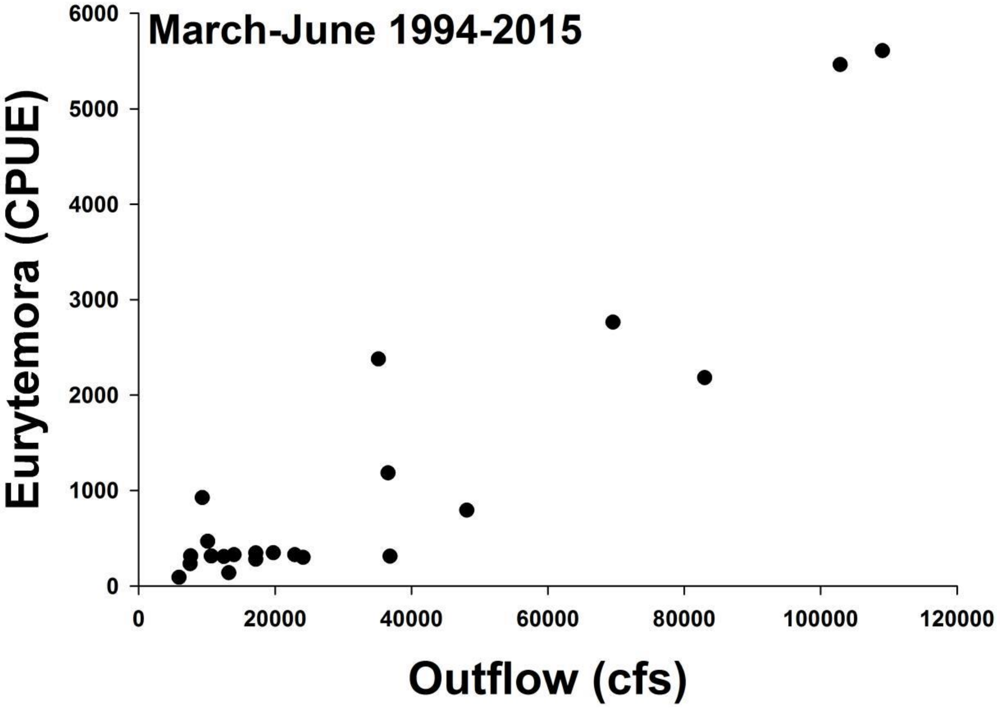
3.11.4.2 *Eurytemora affinis*

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

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

CDFW provided a combined Delta outflow recommendation for *E. affinis* and *N. mercedis* at the 2010 Informational Proceeding (^SWRCB 2010) and recommended maintaining X2 between 75 and

64 km, corresponding to a net Delta outflow of approximately 11,400 and 29,200 cfs, respectively, between February and June (Table 3.11-1).



Source: ^Hennessy and Burris 2017.
cfs = cubic feet per second
CPUE = catch-per-unit effort

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

Table 3.11-1. Delta Outflow Indicated to Be Protective of Zooplankton Species

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

Delta outflows are monthly averages (cubic feet per second).

3.11.4.3 Nonnative Zooplankton

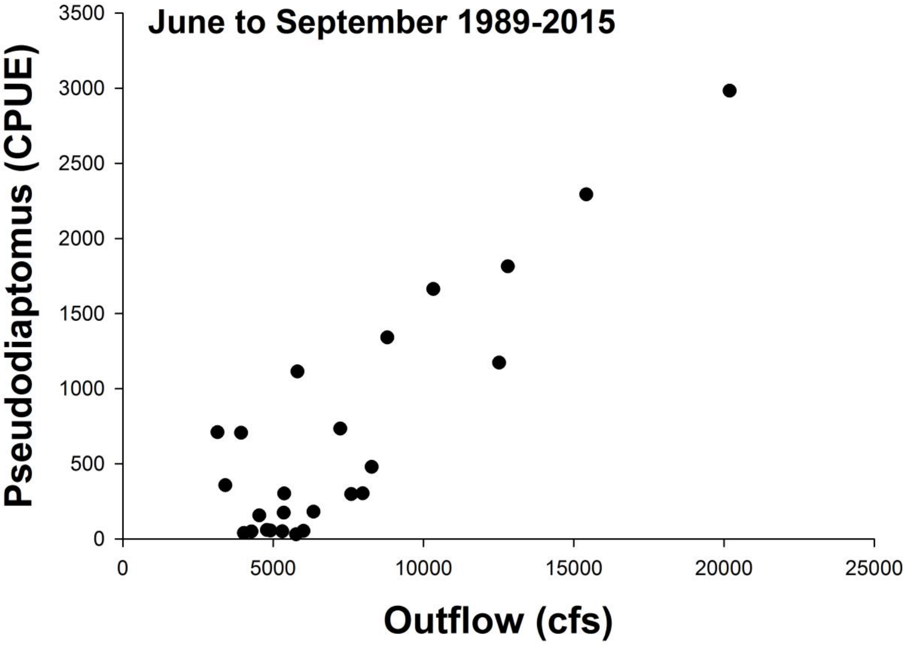
Reduced flows because of the extended drought between 1987and 1994 and changes in benthic and zooplankton community composition have contributed to the decline of common zooplankton species and facilitated the invasion of nonnative copepod and mysid shrimp species (^Orsi and Ohtsuka 1999; ^Winder and Jassby 2011; Kratina et al. 2014). Currently, the Bay-Delta zooplankton community is dominated by invasive copepod species from East Asia, which may be more difficult to catch and, therefore, less available than native copepods to planktivorous fish such as Delta and longfin smelt (^Winder and Jassby 2011). An exception is *Pseudodiaptomus forbesi*, an important component in the diet of longfin smelt, Delta smelt, and other planktivorous fish.

Pseudodiaptomus forbesi

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

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

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



Source: ^Hennessy and Burris 2017
cfs = cubic feet per second; CPUE = catch-per-unit effort

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

3.12 Nonnative Fish Species

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

American shad (*Alosa sapidissima*) was introduced to the Pacific West Coast from the Atlantic seaboard between 1871 and 1881 (MacKenzie et al. 1985; Skinner 1962). American shad historically supported a large commercial gill net fishery in California, but this was banned in 1957 in favor of a rapidly developing recreational fishery (^Moyle 2002; Dill and Cordone 1997). Shad are now a popular sport fish in the Central Valley, especially on the Sacramento, Feather, and American Rivers (Titus et al. 2012).

Three- to 5-year-old American shad return from the ocean and migrate into fresh water between March and May to spawn (Stevens et al. 1987). The peak of the spawning migration occurs in May, with adults reproducing from May through early July in large river channels (Urquhart 1987; Stevens et al. 1987). The FMWT index for American shad is positively correlated with Delta outflow during the previous February to May spawning season (^Kimmerer 2002b; Kimmerer et al. 2009). The slope of the flow abundance relationship has remained positive since FMWT sampling began in 1967, although recruitment of juvenile shad in fall has increased for any given spring Delta outflow value (intercept of the regression line) since the *Potamocorbula* invasion (^Kimmerer 2002b; Kimmerer et al. 2009).

Striped bass (*Morone saxatilis*) was first introduced to the Bay-Delta estuary in 1879 and within 10 years had increased in abundance sufficiently to support a commercial fishery (Herbold et al. 1992). Commercial fishing for striped bass was banned in 1935, but the species has continued to support the most important recreational fishery in the Bay-Delta estuary (Titus et al. 2012; ^Moyle 2002). Adult bass migrate to brackish or marine water in summer and return to fresh water in fall and winter to spawn. Spawning begins on the Sacramento River above the confluence of the Feather River in April, with peak spawning activity in May and early June. Eggs are semi buoyant and require flow to keep them suspended and carry them and newly hatched larvae downstream to low-salinity rearing habitat in the Delta and Suisun Bay (^Moyle 2002).

There is a positive correlation between the survival of striped bass eggs through their first summer and Delta outflow between April and June (^Kimmerer 2002b; Kimmerer et al. 2009). Population abundance indices from the TNS, FMWT, Bay Midwater Trawl and Otter Trawl indices are also positively correlated with Delta outflow in spring (Kimmerer et al. 2009). In each case, higher Delta outflows in spring result in larger index values. The size of the striped bass population has undergone a long-term decline since the 1970s and is one of the four pelagic species that underwent a further decrease in population size around 2000 (Herbold et al. 1992; ^Sommer et al. 2007).

An increase in Delta outflow in spring is predicted to increase the population abundance of striped bass and American shad, two important sport fish in the Bay-Delta estuary.

3.13 Method for Developing Environmental Flows

The recognition of the adverse effects of flow alteration on aquatic ecosystems has led to the development of a large number of methods for determining flows needed to preserve the physical and biological integrity of these systems, often referred to as *environmental flows* (Tharme 2003;

Annear et al. 2004; Linnansaari et al. 2013). Although an exhaustive review of environmental flow methods is beyond the scope of this Staff Report, a brief summary of different methods is provided in the following sections, including a description of the method with which the proposed approach aligns.

3.13.1 Environmental Flow Methods

Environmental flow methods can be classified into four mostly distinct categories: (1) hydrological methods; (2) hydraulic rating methods; (3) habitat simulation methods; and (4) holistic methods (Tharme 2003; Linnansaari et al. 2013). Most of the research to date has focused on formulating methods for rivers, while estuaries have received much less attention (Adams 2014).

3.13.1.1 Hydrological Methods

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

3.13.2 Hydraulic Rating Methods

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

3.13.3 Habitat Simulation Methods

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

3.13.4 Holistic Methods for Determining Environmental Flows

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

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

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

3.13.5 Justification for Environmental Flows

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

Together, the proposed Plan amendments described in Chapter 5, *Proposed Changes to the Bay-Delta Plan for the Sacramento/Delta*, including the flow and complementary ecosystem measures, are proposed to work together to provide comprehensive protection to the ecosystem and native aquatic species from natal streams through the Delta and Bay in a manner consistent with the holistic approach. The use of unimpaired flows is proposed to create a water supply budget for the protection of the ecosystem and native fish and wildlife in the Sacramento River, its tributaries, and the Delta eastside tributaries. Those inflows, and inflows from the San Joaquin River, would provide outflow to protect fish and wildlife throughout their migratory range. Unimpaired flow represents the total amount of water available at a specific location and time, a percentage of which can be allocated to beneficial uses and the environmental functions supporting those uses. As discussed previously, while unimpaired flow is not the same as natural flow, it is generally reflective of the frequency, timing, magnitude, and duration of the natural flows to which fish and wildlife have adapted, particularly in tributaries. Where unimpaired flows may not provide for all the attributes of natural flow functions that would be protective of the ecosystem, adaptive management provisions are proposed. A flow requirement based on a percent of unimpaired flow is intended to ensure that a minimum amount of available supply from a watershed is allocated for the reasonable protection of native fish and wildlife beneficial uses. Adaptive management provisions, including any necessary sculpting of that flow, would provide specific functional flows to improve fish and wildlife protection. Biological goals would be used to help inform adaptive management decisions by informing proposed adaptive management measures and assessing how well they worked.

The flow regime has widespread effects on physical and biological processes in both the riverine and tidal portions of the Bay-Delta watershed. The long-term physical characteristics of flow variability have strong ecological consequences at local to regional scales, and at time intervals ranging from days (ecological effects) to millennia (evolutionary effects) (^Lytle and Poff 2004). Nearly every other habitat factor that affects community structure, from temperature to water chemistry to physical habitat complexity, is influenced by flow (Moyle et al. 2011). Consequently, using a river's unaltered hydrographic condition as a foundation for determining ecosystem flow requirements is well supported by the current scientific literature (^Poff et al. 1997; Tennant 1976; Orth and Maughan 1981; ^Marchetti and Moyle 2001; Mazvimavi et al. 2007; Moyle et al. 2011; ^Kiernan et al. 2012). For these reasons, regulatory programs in Texas, Florida, Australia, and South Africa have developed flow prescriptions based on unimpaired hydrographic conditions in order to enhance or protect aquatic ecosystems (Arthington et al. 1992, 2004; NRC 2005; Florida Administrative Code 2010). The World Bank also now uses a framework for ecosystem flows based on the unaltered quality, quantity, and timing of water flows (Hirji and Davis 2009). Researchers involved in developing ecologically protective flow prescriptions concur that mimicking the unimpaired hydrographic conditions of a river is essential for protecting populations of native aquatic species and promoting natural ecological functions (^Sparks 1995; Walker et al. 1995; Richter et al. 1996; ^Poff et al. 1997; Tharme and King 1998; ^Bunn and Arthington 2002; Richter et al. 2003; Tharme 2003; Poff et al. 2006; ^Poff et al. 2007; ^Brown and Bauer 2009). In their report describing methods for deriving flows needed to protect the Bay-Delta and watershed, ^Fleenor et al. (2010) suggest that, while using unimpaired flows may not indicate precise, or optimal, flow requirements for fish under current conditions, it would provide the general seasonality, magnitude, and duration of flows important for native species (see also Lund et al. 2010).

Unimpaired flow is not a fixed quantity, but varies with local and seasonal hydrology, so it is more reflective of the conditions to which the species being protected are adapted (^SWRCB 2010) and to the availability of water for all purposes. The percent of unimpaired flow approach encourages the diversity of flow needed for ecosystem functions described in this chapter. Specifically, information indicates that salmonids respond to variations in flow and need continuity of flow between natal streams and the Delta for transport and homing fidelity. Healthy salmonid populations also require healthy subpopulations in different streams with different life history strategies to maintain genetic diversity and distribute risk to the population that may occur from ecological disturbances. The historical practice of developing fixed monthly flow criteria to be met from a few sources is not optimal, while unimpaired flow requirements from different tributaries are optimal for providing these functions. At the same time, however, given the impediments to fish passage into historical spawning and rearing areas, there are also needs within some tributaries to diverge from the natural hydrograph at certain times of the year to provide more flow than might have naturally occurred or less flow to ensure that sufficient water is available at other times of year to mitigate the loss of access to appropriate habitat, particularly during summer and fall.

In addition to the scientific basis for the unimpaired flow approach, the approach affords public transparency as to the allocation of water between fish and wildlife and other beneficial uses. The percent of unimpaired flow approach identifies the allocation of a seasonally and annually variable quantity of water for the reasonable protection of fish and wildlife and other beneficial uses. In contrast, a table of different flow requirements to protect fish and wildlife in different seasons and under different hydrologic conditions provides no indication of the allocation that has occurred between beneficial uses of the water. The use of a percent of unimpaired flow approach assigns a percent of the available water to fish and wildlife and leaves the remainder for other uses.

3.13.6 Summary for Evaluating Environmental Flows

For the reasons discussed, the State Water Board is proposing an unimpaired flow approach for inflows and outflows that includes adaptive management provisions that allow for the percent of unimpaired flow budget to be sculpted to provide for specific functional flows and adaptive management experiments, and to respond to new information and changing circumstances. In addition, other flow and water project operational measures and recommendations for non-flow measures meant to ensure comprehensive protection of fish and wildlife from natal streams through the Delta and San Francisco Bay are proposed consistent with the holistic approach. To assist the State Water Board in determining the amount of water that should be provided to reasonably protect fish and wildlife beneficial uses, a range of flow scenarios from 35 to 75 percent unimpaired flow from the Sacramento/Delta tributaries is analyzed in Section 3.14, *Evaluation of Bay-Delta Environmental Flow Effects*, in 10 percent increments, along with an analysis of the existing Bay-Delta Plan flow levels. Specifically, the following parameters are analyzed: the frequency of meeting the flow targets for the protection of different indicator species, changes in floodplain inundation, and changes in reservoir carryover storage and associated cold water supplies in reservoirs.

3.14 Evaluation of Bay-Delta Environmental Flow Effects

Additional modeling and technical analyses are presented in the following sections to evaluate the protectiveness of different flow levels to help determine the inflow and outflow levels that represent reasonable protection of fish and wildlife. The analyses include an evaluation of how often different flow levels achieve flow thresholds for the protection of different species, an evaluation of the floodplain inundation benefits of different flow levels, and an evaluation of the ability to preserve cold water under different flow levels. Flow scenarios between 35 and 75 were evaluated in 10 percent increments, along with an evaluation of existing flow requirements and existing flow levels. Modeling assumptions and results are described in Appendix A1, *Sacramento Water Allocation Model Methods and Results*, and Chapter 6, *Changes in Hydrology and Water Supply*. These evaluations are used along with the information included in Chapter 7, *Environmental Analysis*, which evaluates the environmental impacts of potential changes; and Chapter 8, *Economic Analysis and Other Considerations*, which evaluates the economic effects of potential changes that informed the development of the proposed changes to the Bay-Delta Plan and that will inform the State Water Board's decision on those changes.

3.14.1 Summary of Flow Thresholds for Species Protection

The species-specific analyses in Sections 3.3, *Species-Specific Analyses*, through 3.12, *Nonnative Fish Species*, demonstrate positive relationships between several seasonal flow summaries and the population abundances, reproductive success, and migration success of aquatic species residing in and migrating through the Delta. Population abundance increases for all the native estuarine species and nonnative American shad and striped bass with increasing Delta outflow in winter and spring. The slope of the flow-abundance relationship has changed for some species during the last half century of monitoring but has always remained positive. More Delta outflow in winter and spring consistently has been associated with a higher abundance of fish in fall. The relationship demonstrates that one option for increasing population abundance of these species is to increase Delta outflow in winter and spring.

Population abundance goals were previously identified in the Delta Flow Criteria Report for restoring some estuarine species. The species evaluations contain an analysis of the Delta outflow needed to achieve these restoration goals and/or a 50-percent probability of positive population growth. These flows are summarized in Table 3.14-1. When possible, multiple methods were used to estimate flows predicted to increase the population size of each species, and this has resulted in a range of Delta outflows for some taxa. The range emphasizes that there is no single correct outflow for any species. Likewise, other restoration goals may be proposed in the future, and similar analytical methods may be used to estimate the new flows predicted to achieve these goals. Nonetheless, the present analyses provide an estimate of the range of flows that are expected to benefit each species. Together, the flows in Table 3.14-1 provide an indication of the magnitude, duration, and seasonality of flow that may be required to support a healthy aquatic estuarine community.

Table 3.14-1. Magnitude and Timing of Delta Outflows Indicated to Be Protective of Estuarine-Dependent Species

	Months											
Species or Purpose	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Estuarine habitat	7,100–29,200	▨	▨	▨	▨	▨						
Longfin smelt	42,800	▨	▨	▨	▨	▨						
Starry flounder			>21,000	▨	▨	▨						
California bay shrimp			20,000–25,000	▨	▨							
Sacramento splittail		30,000–47,000	▨	▨	▨							
White sturgeon			>37,000	▨	▨	▨	▨					
Delta smelt							X2≤80 km[a]	▨	Fall X2[a, b]	▨		
Zooplankton		11,400–29,200	▨	▨	▨	▨						

Cubic feet per second (cfs) are monthly averages.
km = kilometer

[a] July, August, and September of all years; flow ≥ 7,500 cfs.

[b] Wet water year >11,400 cfs; above normal water year >7,100 cfs.

The analyses indicate that multiple species would benefit from a similar magnitude and timing of Delta outflow (Table 3.14-1). For example, flow from January through June for longfin smelt would also meet the flows predicted to support the populations of starry flounder, California bay shrimp, Sacramento splittail, and zooplankton during the same months. Sturgeon need higher flows after June than longfin smelt. The long life and high fecundity rate of sturgeon make this species less dependent on frequent high Delta outflow than other species, although the population does not appear stable and exhibits progressively diminished recruitment in recent wet years. The flows predicted to benefit Sacramento splittail might be reduced if the Yolo Bypass was able to be flooded at a lower Sacramento River flow. The USFWS (^2008) BiOp required that the location of X2 in September and October of wet and above normal water years be further west than 74 and 81 km, respectively (Table 3.14-1).[23] In addition, recent scientific findings suggest that the abundance of Delta smelt in fall is positively related to Delta outflow in summer (i.e., more flow in July, August, and September typically results in greater survival through the summer) (Table 3.14-1). Adoption of the USFWS 2019 BiOp and CDFW 2020 ITP have modified summer and fall habitat actions to protect Delta smelt.

The timing of the biological mechanisms that may account for the statistically significant relationships between Delta outflow and the population abundance of estuarine-dependent species is listed in Table 3.14-2. Most of the functional flows provide mechanisms to increase reproductive output and survival of young. The mechanisms include adult attraction flows, transport flows to carry weakly swimming larvae to rearing habitats, higher flows to create spawning and rearing floodplain habitat in the Central Valley, and low-salinity rearing habitat in Suisun Bay and Marsh.

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

Table 3.14-2. Functional Flow Needs for Estuarine-Dependent Species

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

Adapted from ^SWRCB (2010) and CDFG (2010a, 2010b).

[a] • = Flow timing important during this month, ••=Flow timing very important during this month.

Historically, the Delta received higher outflow in winter and spring than in recent years, placing X2 farther downstream under these conditions (see Chapter 2, *Hydrology and Water Supply*). The highest protective outflows identified for estuarine-dependent species were 42,800 cfs in January through June for longfin smelt, 30,000 to 47,000 cfs between February and May for Sacramento splittail, and greater than 37,000 cfs for white sturgeon in June and July (Table 3.14-1). The median unimpaired Delta outflow between February and May is greater than 50,000 cfs, but flows of this magnitude rarely occur under current conditions in the watershed (see Figure 2.4-8 in Chapter 2, *Changes in Hydrology and Water Supply*). Median unimpaired flows in June are less than 50,000 cfs but near the 37,000 cfs needed by sturgeon, demonstrating that native fish evolved under a regime of higher Delta outflows than occurs now. Loss of functional flows in winter and spring reduce potential recruitment opportunities and the viability of the estuarine-dependent community.

Another indication of the importance of flow comes from a comparison of the response of the estuarine community to wet and dry water years. 2011 was wet, with high Delta outflow in winter and spring. The following 3 years were classified as dry or critically dry. FMWT indices of population abundance of longfin smelt, Delta smelt, and Sacramento splittail all increased in 2011 and declined in the following 3 years (cfs = cubic feet per second

FMWT = Fall Midwater Trawl

Figure 3.14-1). The increased population size of these estuarine-dependent species indicates that their populations are still able to respond positively to favorable environmental flow conditions.

Adult and juvenile salmonids benefit from an increased, more natural flow pattern in Central Valley tributaries. At least one salmonid run is migrating through the Delta or holding in the upper Sacramento basin each month of the year, necessitating near year-round tributary inflows (Table 3.4-4). Adult salmonids require tributary flows of sufficient magnitude, duration, and longitudinal extent to provide the olfactory cues and passage conditions needed to find, enter, and successfully reach holding and spawning areas in their natal streams. NMFS (2014b, Appendix A) determined that warm water and low flow resulted in a reduction in adult attraction and migration cues and a delay in immigration and spawning, which appear to have negatively affected adult salmon in the majority of tributaries evaluated (Table 3.4-5). The seasonal decrease in flow that now occurs for tributaries is illustrated in Chapter 2, *Hydrology and Water Supply*, for Antelope, Mill, and Deer Creeks. The combined flow for the three creeks is lower between April and October than under unimpaired conditions, with the greatest impairment occurring in May through September of drier years when the creeks sometimes go dry.

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

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

The abundance and survival of juvenile fall and winter run Chinook salmon emigrating past Chipps Island increase when Sacramento River flow is greater than 20,000 cfs between February and June (Table 3.4-7). Flows of this magnitude may also aid emigration of juvenile spring-run Chinook salmon and steelhead. The Sacramento River is the main source of water for Delta outflow. Current Sacramento River flow is less than the unimpaired flow at Freeport between February and June (see Figure 2.2-5 in Chapter 2, *Hydrology and Water Supply*). The median flow is now 64 percent of unimpaired flow between January and June, with median April and May flows below 50 percent of the unimpaired flow rate. If higher outflow for longfin smelt and other estuarine-dependent species is provided in winter and spring (Table 3.14-3), this flow would also assist salmon to emigrate past Chipps Island (Table 3.4-7). The survival of emigrating juvenile salmonids from the San Joaquin River basin increases when flow at Jersey Point is positive (Figure 3.4-17). USFWS (^1995) recommends positive flows for Jersey Point from October 1 through June 30 to improve survival of salmonids migrating through and rearing in the Delta and to provide attraction flow for returning adults (Table 3.4-7).

Export pumping at the CVP and SWP facilities causes OMR reverse flows and draw large numbers of fish into the interior Delta, resulting in their entrainment and salvage. The risk of entrainment depends on the location of the fish relative to the export facilities and the magnitude of OMR reverse flows. Juvenile salmonids emigrating from the San Joaquin River basin and Delta eastside tributaries are at risk of entrainment when migrating through the central Delta. Sacramento River salmon are vulnerable if they migrate into the central Delta through the DCC gates or Georgiana Slough. Delta smelt and longfin smelt are vulnerable if adults migrate into the central Delta to spawn. Salvage data and PTM results for all these species demonstrate that salvage increases exponentially with increasingly negative OMR reverse flows (Figure 3.4-15, Figure 3.4-16, Figure 3.5-4, and Figure 3.8-7). An inflection point occurs for all species at about -5,000 cfs with much higher salvage rates at more negative OMR reverse flows. The lowest salvage rates are measured at positive flow rates. Fishery agencies recommend that CVP and SWP exports be managed to maintain OMR reverse flows between -1,250 and -5,000 cfs from January to June, with flows adaptively managed based upon the abundance and distribution of salmonids and smelt and other physical and biological factors known to affect entrainment (Table 3.14-3).

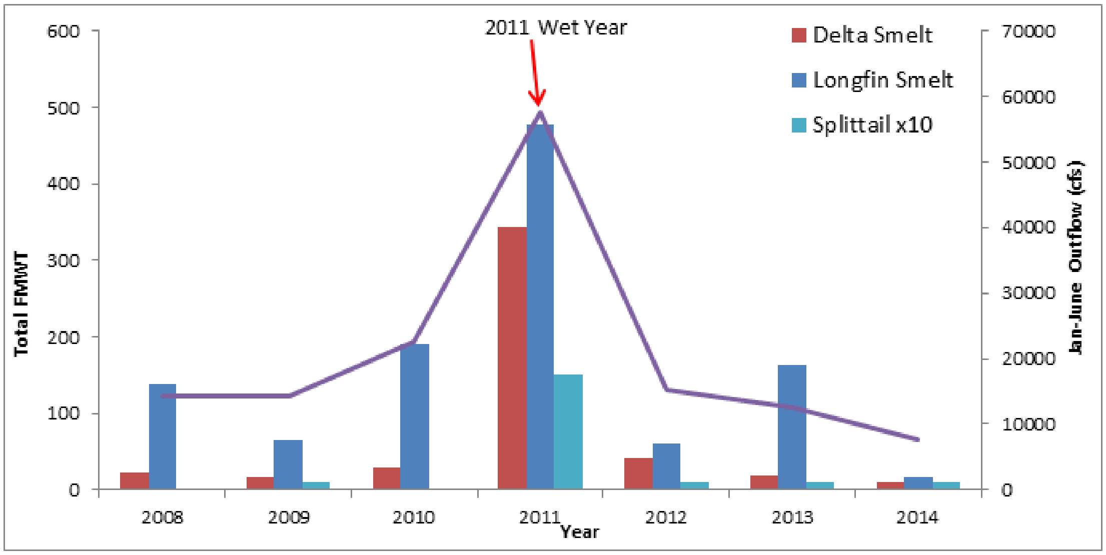
Table 3.14-3. Summary of Interior Delta Flows Indicated to Be Protective of Salmonids and Estuarine-Dependent Fish Species (cubic feet per second)

	Months											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
NMFS Biological Opinion for OMR flow [a, b]	-2,500 to -5,000	▨	▨	▨	▨	▨						
USFWS Biological Opinion for OMR flow [b, c]	-1,250 to -5,000	▨	▨	▨	▨	▨						▨
CDFW Incidental Take Permit for OMR flow [b, d]	-1,250 to -5,000	▨	▨	▨	▨	▨						▨
Georgiana Slough [e]	17,000–20,000	▨	▨	▨	▨	▨					▨	▨
San Joaquin River @ Jersey Point [f]	Positive flow	▨	▨	▨	▨	▨				▨	▨	▨
San Joaquin River Export Constraint [g]		1:1–4:1	▨	▨	▨	▨				>0.3 [h]		

Cubic feet per second are monthly averages.
OMR = Old and Middle Rivers

[a] When Chinook salmon or steelhead are present.
[b] 14-day running average of tidally filtered flow at Old and Middle Rivers.
[c] When adult and juvenile Delta smelt are present.
[d] When longfin smelt are present.
[e] To minimize reverse tidal flow when salmonids are present.
[f] When salmonids are present.
[g] San Joaquin River at Vernalis to sum of CVP and SWP exports.
[h] Minimize adult straying.

The production of San Joaquin River basin Chinook salmon increases when the ratio of spring flow on the San Joaquin River at Vernalis to combined CVP and SWP exports increases. The NMFS (^2009) BiOp requires export restrictions from April 1 through May 31.[24] However, juvenile salmonids migrate out of the San Joaquin River basin from February to June and may need protection from export-related mortality during this entire period (Table 3.14-3).



cfs = cubic feet per second
FMWT = Fall Midwater Trawl

Figure 3.14-1. Comparison of the Change in Magnitude of Fall Midwater Trawl Indices for Delta Smelt, Longfin Smelt, and Sacramento Splittail in Wet and Dry Water Years

3.14.1.1 Achievement of Flow Thresholds

Analyses were conducted to determine the frequency with which the flow scenarios achieve flows protective of the specific species identified in this chapter and the potential for increasing native fish abundance under the flow scenarios. However, benefits to species also are expected at flows lower than these thresholds. Generally, the higher the flows up to 100 percent of unimpaired flow (and higher in summer and fall) and the lower the X2 value, the greater the expected benefits are for native species and the ecosystem, provided that adequate supplies are maintained for cold water and flows at other times. The flows found in the scientific literature or estimated using the methods described above should not be taken to represent absolute flow needs that must be met at all times or in all years to support species. Rather, they serve as indicators of conditions that favor native species and constitute a set of quantifiable metrics that can be used to assess the relative protection afforded by a range of flow regimes. The scientific information supporting modifications to existing flow requirements is broader than these quantitative relationships and includes knowledge of life history, ecology, and the conditions under which native species evolved. The analysis in this section shows how frequently the flows that are expected to achieve specified species population levels or population growth rates (species flow) would be realized under a range of flow requirements (35 to 75 scenarios).

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

These analyses include a comparison of the modeled baseline condition under SacWAM with modeled flows that would be expected using SacWAM, including other expected uncaptured flows (other regulatory flow requirements, flood control releases, and other flows that occur in the system because the water is not needed for diversion or not able to be diverted due to physical or other limitations; see Appendix A1, *Sacramento Water Allocation Model Methods and Results*, and Chapter 6, *Changes in Hydrology and Water Supply*, for further discussion of modeling methods and results). Analyses also were presented in the Scientific Basis Report of Delta inflow and Delta outflow levels that do not include other uncaptured flows. The analyses of expected flows show greater benefits than the results for the flow levels presented in the Scientific Basis Report due to these other flow contributions from flood control releases, other regulatory requirements, and other purposes. However, because there may be additional water diversions in the future that reduce the amount of other uncaptured flows, the range of expected benefits of the different flow levels is also informative to development of the proposed Plan amendments (see Sections 5.2.3, *Discussion*, and 5.3.3.2, *Benefits of Increased Delta Outflow*, of the Scientific Basis Report), though those results are not repeated here.

For the analysis of Delta outflow, the scenarios reflect inflows from the three major regions tributary to the Delta: the Sacramento River basin, the Delta eastside tributaries, and the San Joaquin River basin, as well as other expected accretions and depletions. The three regions differ in the timing of peak contributions to Delta inflow (see Chapter 2, *Hydrology and Water Supply*). Flow contributions from the San Joaquin River upstream of Vernalis are being addressed through a separate process. The three regions differ in the timing of peak contributions to Delta inflow (see Chapter 2). While the State Water Board is considering updated San Joaquin River flow requirement in the Bay-Delta Plan, those amendments have not yet been approved. Accordingly, the analyses in this report (except for the cumulative impacts assessment) assume San Joaquin River flow contributions to Delta outflows consistent with the 2006 Bay-Delta Plan requirements. The updated flow requirements would produce somewhat higher outflows than those identified in the flow scenarios evaluated in this report. As necessary, the State Water Board may conduct additional sensitivity analyses of these outflow levels following approval of the updates to the San Joaquin River flow requirements by the State Water Board and Office of Administrative Law.[25]

For Delta outflows, an analysis is first provided of existing flow requirements and existing flows compared with several significant historical time periods, followed by the evaluation of flow thresholds for the protection of different native species.[26] In these analyses, modeled values of existing minimum required Delta outflow (MRDO) pursuant to the requirements of the 2006 Bay-Delta Plan (as implemented by D-1641), and the USFWS BiOp are provided for comparison. The MRDO lines in the figures do not include other uncaptured flows beyond the Bay-Delta Plan or USFWS BiOp flow requirements that would occur as a result of flood control releases, other regulatory flow requirements, or other reasons. Additional flows expected to occur in reality as a

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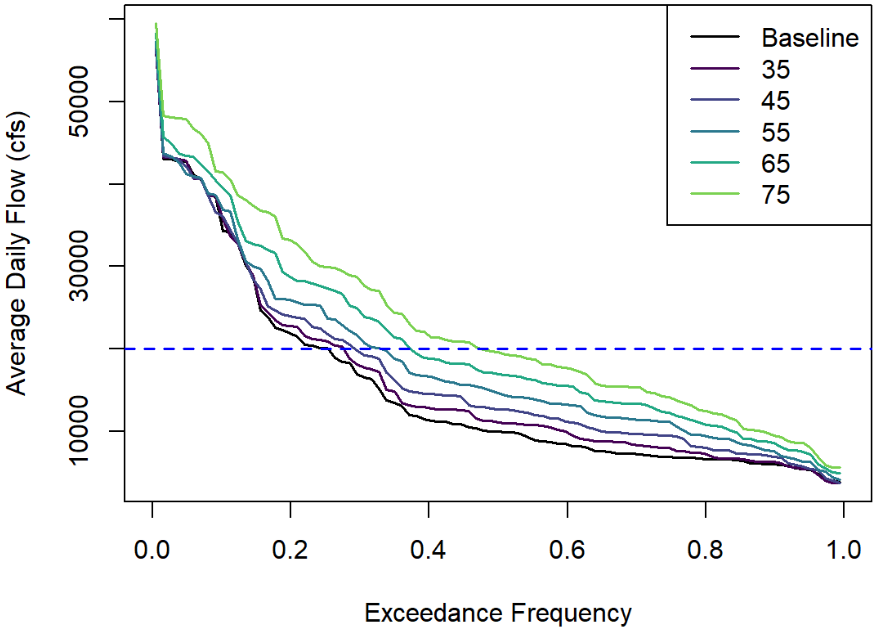
[25] The inflow-based Delta outflow requirements in the modeled scenarios were derived by (1) estimating unimpaired Delta outflow using SacWAM, as described in Chapter 2, *Hydrology and Water Supply,* and Appendix A1, *Sacramento Water Allocation Model Methods and Results*; (2) subtracting the modeled unimpaired San Joaquin River inflow at Vernalis to provide an estimate of the Delta outflow contributed by the Sacramento River basin and Delta eastside tributaries; (3) scaling the values obtained in (2) by the percent of unimpaired inflow being provided from the Sacramento River basin tributaries and Delta eastside tributaries; and (4) adding the required inflow at Vernalis pursuant to the current regulatory requirements of D-1641 and the Bay-Delta Plan.

[26] Similar analyses were presented in the Scientific Basis Report, which have been updated in this Staff Report, though the results are very similar.

result of flood control releases, other regulatory flow requirements, or other reasons are reflected in the existing flows shown in the figures. The difference between the MRDO "line" in the figures and the existing flow level in the figures represents flows that are not required under the Bay-Delta Plan and the USFWS BiOp that could be diminished in the future as the result of additional diversions in the absence of additional regulatory flow requirements. The significant difference between these flow levels indicates that existing Bay-Delta Plan and BiOp flow requirements are not adequate to ensure Delta outflow conditions necessary for the reasonable protection of fish and wildlife beneficial uses. Because there are very limited existing flow requirements for inflows in the Bay-Delta Plan and BiOps, a similar comparison for inflows would be with zero flow instead of the MRDO lines, meaning that on many streams there are limited or no requirements that prevent flows from being completely removed from streams. Again, this circumstance indicates that existing inflow requirements included in the Bay-Delta Plan and BiOps are inadequate to reasonably protect fish and wildlife beneficial uses.

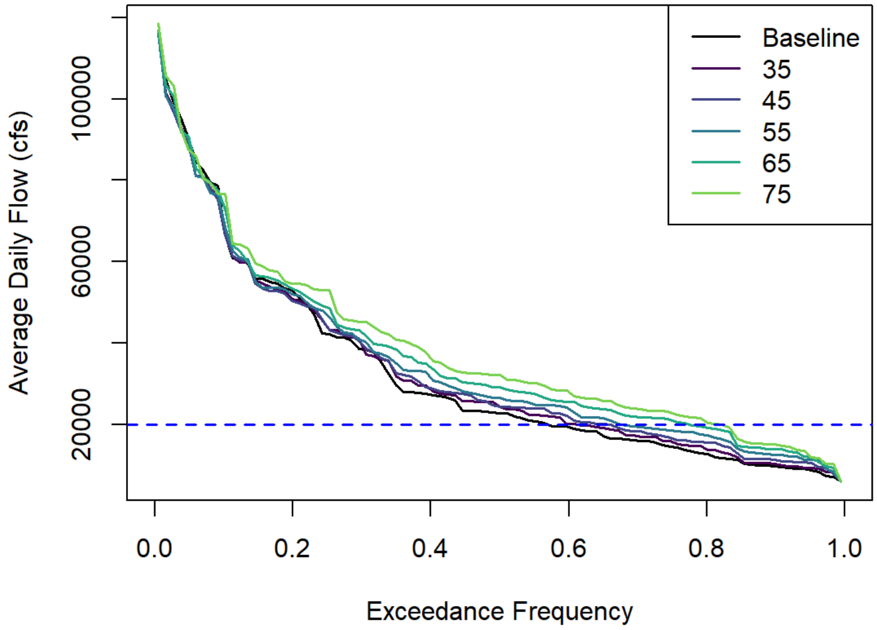
Achievement of Inflow Thresholds

There are only very minimal inflow objectives in the Bay-Delta Plan for the Sacramento/Delta tributaries during fall, and these inflow levels are largely incidentally met due to other constraints. The exceedance plots in Figure 3.14-2 and Figure 3.14-3 show the distributions of average lower Sacramento River flows at Rio Vista under the SacWAM modeled existing (baseline) condition and the modeled expected flows under 35 to 75 scenarios of April through June and February through April levels. The existing flows do not represent required flows, particularly because many tributaries do not have flow requirements. The dashed horizontal lines indicate flows of 20,000 cfs to support outmigration of juvenile Chinook salmon, and their intersections with the exceedance curves provides an estimate of how frequently these flows would be observed under this range of conditions. Even without accounting for controlled and uncontrolled flows (see Figures 5.2-1 and 5.2-2 of the Scientific Basis Report), flows greater than the 55 scenario increase the frequency of average April through June and February through June flows exceeding 20,000 cfs relative to current conditions. When accounting for these other flows in the range of flow scenarios (Figure 3.14-2 and Figure 3.14-3), these flows are achieved substantially more often as indicated below.



cfs = cubic feet per second
Modeled by SacWAM, and 35–75 scenarios at Rio Vista when accounting for other expected flows.

Figure 3.14-2. Frequency of Meeting April–June Sacramento River at Rio Vista Flows of 20,000 cfs for Current Conditions



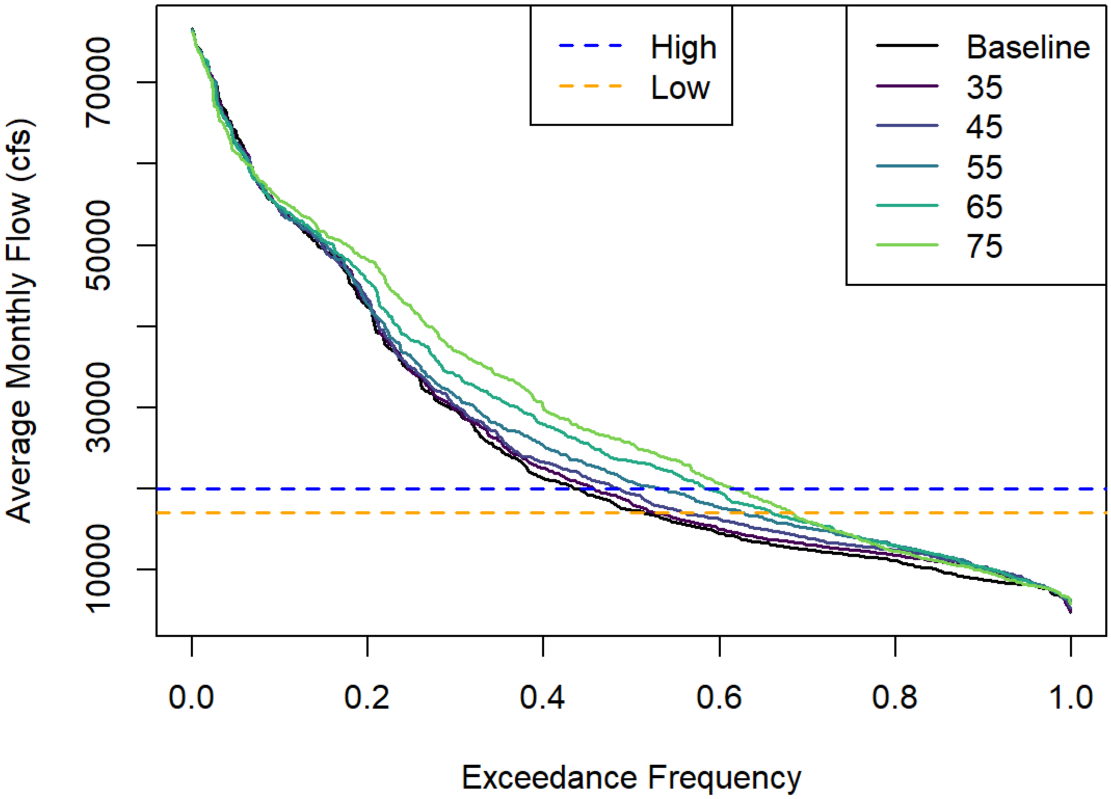
cfs = cubic feet per second
Modeled by SacWAM, and 35–75 scenarios at Rio Vista when accounting for other uncaptured flows.

Figure 3.14-3. Frequency of Meeting February–April Sacramento River at Rio Vista Flows of 20,000 cfs for Current Conditions

In addition to the Rio Vista flow levels evaluated in Figure 3.14-2 and Figure 3.14-3 and Table 3.14-4, flows exceeding 17,000 to 20,000 cfs at Freeport on the Sacramento River (Table 3.14-5) prevent reverse flows at Georgiana Slough, thus decreasing the likelihood of entrainment of Sacramento River basin salmonids to the interior Delta, where survival is lower. Figure 3.14-4 shows the exceedance frequency distributions of monthly Freeport flows from November through May for current conditions and the modeled expected flows under the range of flow scenarios. Similar to the pattern seen for Rio Vista flows, higher flows provide conditions more often that prevent flow reversals in late fall and winter, and higher benefits are expected when accounting for other uncaptured flows as demonstrated in Figure 3.14-4 than without (as presented in the Scientific Basis Report in Figure 5.2-3).

Table 3.14-4. Frequency of Meeting Rio Vista Targets for Chinook Salmon Species

Species	Baseline	35	45	55	65	75
Fall-run	26	28	29	33	38	47
Winter-run	57	61	67	68	77	83



Modeled by SacWAM and 35–75 scenarios accounting for other expected flows. Flows greater than 17,000 (orange line) to 20,000 cubic feet per second (cfs) (blue line) prevent tidal reversal at Georgiana Slough.

Figure 3.14-4. Exceedance Frequency of Monthly Flow at Freeport on the Sacramento River for November–May under Current Conditions

Table 3.14-5. Frequency of Meeting Freeport Targets for November–May

Flow Level	Baseline	35	45	55	65	75
17,000 cfs	51	53	56	63	66	68
20,000 cfs	44	46	49	54	58	62

cfs = cubic feet per second

Evaluation of Existing Bay-Delta Plan Outflows

To assist with determining the adequacy of the existing Delta outflow objectives in protecting fish and wildlife beneficial uses, an analysis was conducted (Figure 3.14-5) to compare the existing objectives and fall BiOp flows (MRDO) with estimated current outflow levels (^DWR 2017a) and observed historical flows during four historical time periods based on significant events in the development of Bay-Delta water resources and regulations: prior to completion of Shasta Reservoir (1930–1945), prior to completion of Oroville Reservoir (1946–1967), prior to adoption of D-1641 (1968–1999), and following adoption of D-1641 (2000–2016).

The difference between the MRDO “line” in the figures and the existing flow level in the figures represents flows that are not required under the Bay-Delta Plan and the USFWS BiOp that could be diminished in the future as the result of additional diversions in the absence of additional regulatory flow requirements. The significant difference between these flow levels indicates that existing Bay-Delta Plan and BiOp flow requirements are not adequate to ensure Delta outflow conditions necessary for the reasonable protection of fish and wildlife beneficial uses. Because MRDO represents existing regulatory minimum flows, it is often substantially lower than flows observed under current conditions.[27] Over time with increasing water development and climate change, it is expected that flows under future conditions would be reduced below current conditions without additional regulatory requirements, perhaps to a substantial degree to a level approaching MRDO flows, which are not protective of fish and wildlife.

Modeled flows are most similar to regulatory minimums during the dry season of July through October but deviate substantially during wetter months. Differences between observed and modeled flows reflect differences in intensity of water development, the regulatory environment, and underlying hydrology. For example, the lower outflow observed in fall from 2000 through 2016 reflects increased water development relative to earlier periods, dry hydrology relative to both earlier periods and the 1922 through 2015 SacWAM record, and the absence of a fall X2 requirement in the first half of the period. Higher winter-spring outflows and lower summer-fall outflows from 1930 through 1945 reflect the lack of major storage regulation in the watershed and the inability to maintain outflows during dry months of dry years. Although a portion of the wet season difference between MRDO and modeled outflows is due to other regulatory constraints, such as the export to inflow ratio and limitations on OMR reverse flows, much of the surplus Delta outflow modeled above MRDO and observed under current conditions results from the inability to capture valley floor runoff. The most striking difference between required and observed flows is seen during winter and spring of wetter years, when both modeled and observed flows greatly

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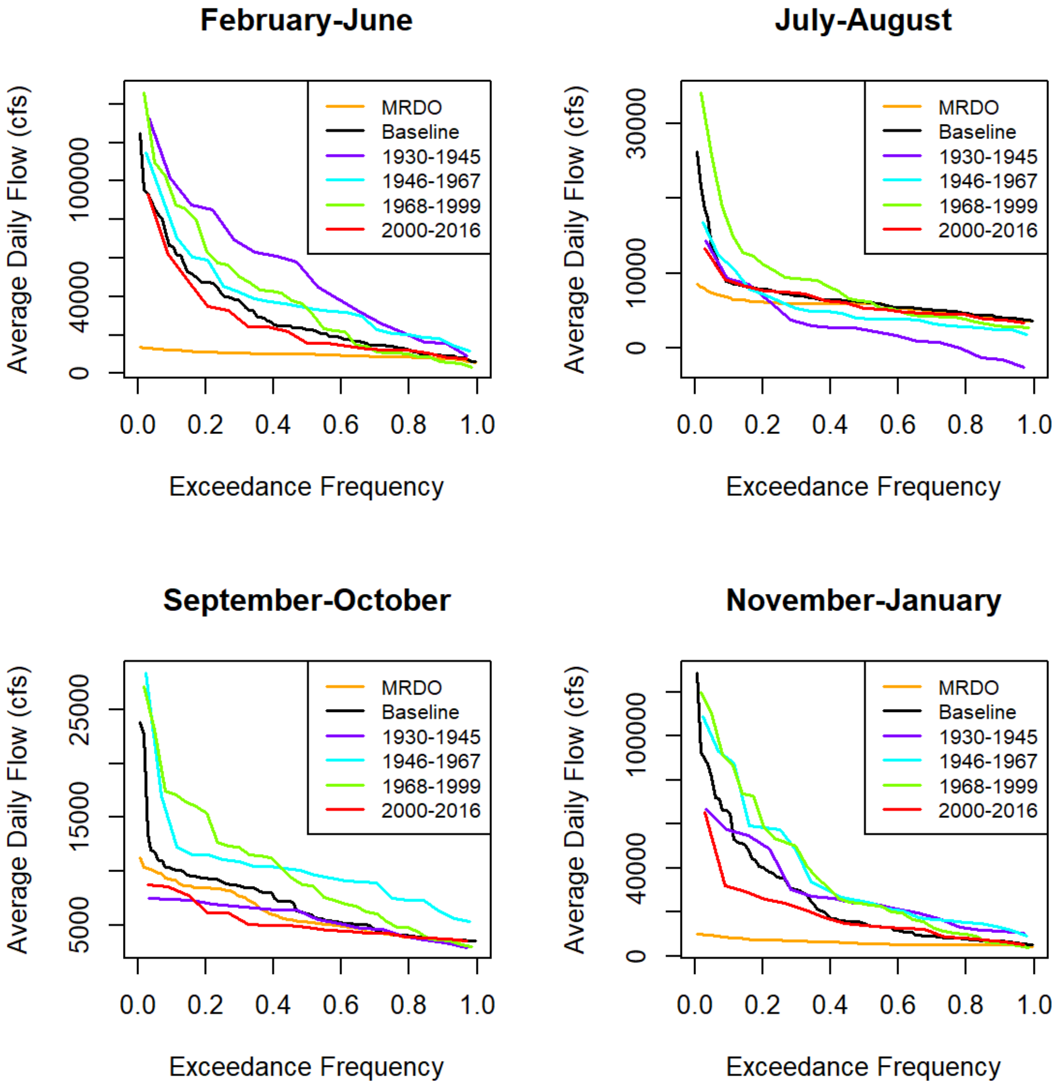
[27] *MRDO* is defined as the minimum Delta outflow needed to meet the Delta outflow and X2 requirements in Bay-Delta Plan Tables 3 and 4, salinity control for the protection of agricultural and municipal beneficial uses in Bay-Delta Plan Tables 1 and 2, and fall X2 requirement in the USFWS BiOp. The values used in this chapter are those modeled by SacWAM (^SacWAM 2023) and are obtained by taking the maximum of the flow requirements REG_X2, REG_MRDO, and Delta outflow needed for salinity control. This procedure is equivalent to summing the arcs D407 and C407_ANN in CalSim II (DWR 2015).

exceed regulatory minimums. Because these flows may be reduced by future water development, additional flow requirements would be needed to ensure the existing level of protection of estuarine-dependent fish and wildlife that these higher flows provide.



cfs = cubic feet per second
MRDO = minimum required Delta outflow

Figure 3.14-5. Seasonal Comparisons of Minimum Required Delta Outflow (orange line), SacWAM Modeled Delta Outflow (black line), and Observed Delta Outflow. Observed Delta outflow is divided into four historical periods: prior to the completion of Shasta Reservoir (1930-1945, purple line), prior to the completion of Oroville Reservoir (1946-1967, cyan line), prior to the adoption of D-1641 (1968-1999, green line), and following the adoption of D-1641 (2000-2016, red line) (Dayflow data, DWR 2017a).

Achievement of Delta Outflow Thresholds

Table 3.14-1 summarizes the flow relationships of several estuarine species that serve as indicators of ecosystem health. A comparison of these flows with MRDO shows that the existing Delta outflow objectives for winter and spring do not generally achieve the species-specific flow levels. Existing flows generally exceed minimum D-1641 Delta outflow objectives for February through June, which means that over time, with increasing water development, existing outflows would likely diminish with additional diversions without additional regulatory requirements. This also indicates that the 2006 Bay-Delta Plan and D-1641 do not provide sufficient flow during dry water years for any of the species in Table 3.14-1. Likewise, the flows shown in Table 3.14-1 to support longfin smelt, Sacramento splittail, and white sturgeon are larger than the maximum flow requirement in D-1641 of 29,200 cfs. Thus, minimum D-1641 outflows are not at the flow levels indicated to be protective of these three species under any hydrologic condition. It is important to note, however, that while Sacramento splittail and sturgeon may need higher flows after March than most other species, the flows needed for Sacramento splittail might be reduced if the Yolo Bypass was able to be flooded at a lower Sacramento River flow. Also, the long life and high fecundity rate of sturgeon make this species less dependent on frequent high Delta outflow events. Nonetheless, the science indicates that increased flows would help to protect all the species discussed in this chapter.

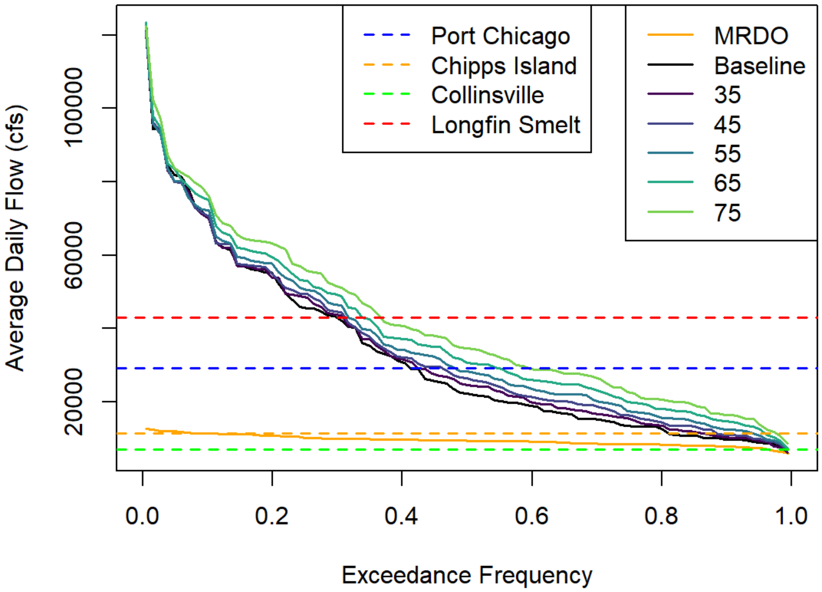
The exceedance plots in Figure 3.14-6 through Figure 3.14-10 show the distributions of average Delta outflows over each of the multi-month periods in Table 3.14-1, with dashed horizontal lines indicating each of the flows over that period identified to achieve species population levels. The intersections of the horizontal lines with the exceedance curves provide an estimate of how frequently each species flow would occur in each flow scenario. The more frequently a species flow is met, the more favorable conditions are to support the beneficial use. The results of this analysis are summarized in Table 3.14-6. As with the inflow analysis, the analyses presented below account for other uncaptured flows (flood flows and uncapturable flows). Additional analyses that do not include these additional flows are included in the Scientific Basis Report in Figures 5.3-2 to 5.3-6 and Table 5.3-3.

The frequency of meeting the flows to support estuarine beneficial uses increases with each increase in the range of flow scenarios (Table 3.14-6) and is greater when accounting for other expected flows. For example, flows that correspond to an average X2 position downstream of Port Chicago occur 41 percent of the time under current conditions but are estimated to occur 59 percent of the time at the 75 scenario (Table 3.14-6). Also, the probability of achieving a species flow target varies among species. Targets requiring lower flow are met more frequently than those needing high flow. For example, the low flow target of 19,000 cfs for California bay shrimp is met 51 percent of the time under current conditions and increased to 87 percent of the time at the 75 scenario (Figure 3.14-7). In contrast, the high flow target of 47,000 cfs for Sacramento splittail is met 25 percent of the time under current conditions and only increases to 38 percent of the time at the 75 scenario (Figure 3.14-9). None of the species-specific flows is met 100 percent of the time, even at the 75 scenario.

Table 3.14-6. Summary of Frequency of Meeting Winter–Spring Delta Outflows to Benefit Estuarine Habitat and Species

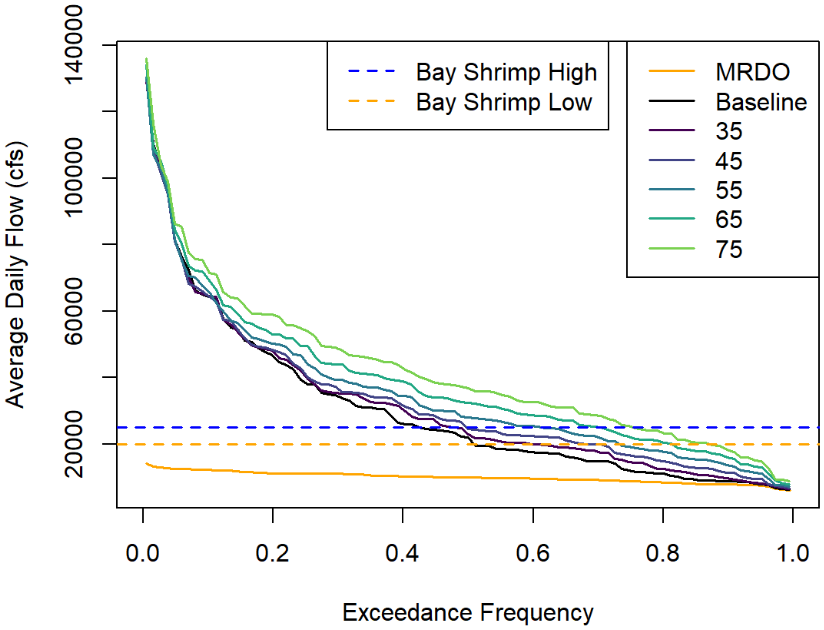
Species or X2 Location	MRDO	Baseline	35	45	55	65	75
Collinsville	96	99	99	99	100	100	100
Chipps Island	10	81	87	88	95	96	98
Port Chicago	0	41	43	46	48	55	59
California bay shrimp, high	0	43	48	49	61	71	75
California bay shrimp, low	0	51	59	70	73	82	87
Green and white sturgeon	0	15	15	15	19	24	28
Longfin smelt	0	30	31	31	32	34	37
Sacramento splittail, high	0	25	26	27	29	31	38
Sacramento splittail, low	0	40	45	49	54	62	70
Starry flounder	0	44	49	52	63	72	80

MRDO = minimum required Delta outflow



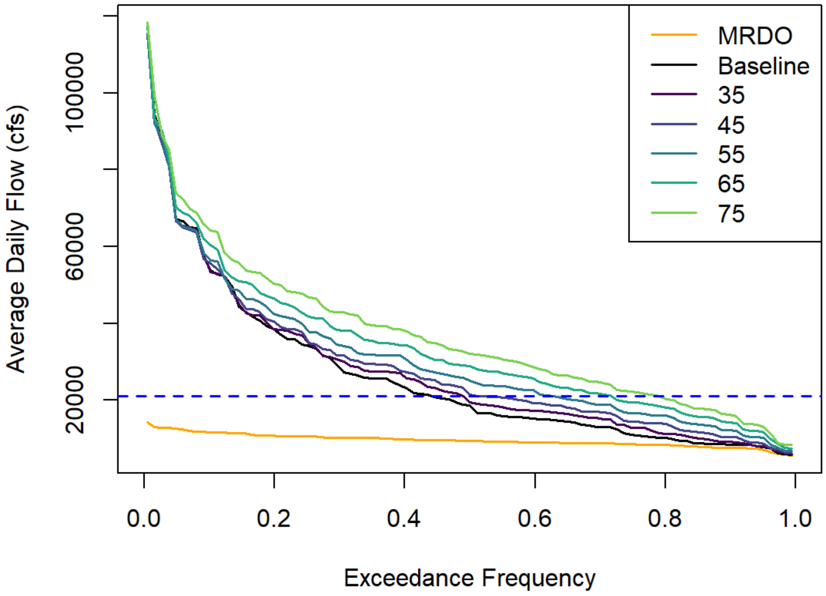
Current conditions as modeled by SacWAM, and Delta outflows resulting under range of flow scenarios when accounting for other expected flows.
cfs = cubic feet per second; MRDO = minimum required Delta outflow

Figure 3.14-6. Frequency of Meeting January–June Delta Outflows to Benefit Estuarine Low Salinity Zone Habitat and Longfin Smelt for Minimum Required Delta Outflow



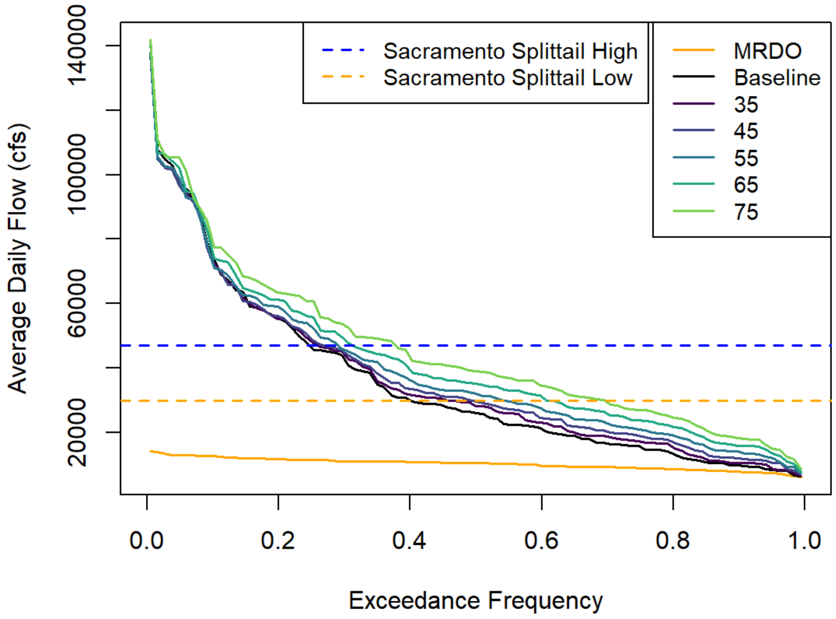
Current conditions as modeled by SacWAM, and Delta outflows resulting under range of flow scenarios when accounting for other expected flows.
cfs = cubic feet per second
MRDO = minimum required Delta outflow

Figure 3.14-7. Frequency of Meeting March–May Delta Outflows to Benefit California Bay Shrimp for Minimum Required Delta Outflow



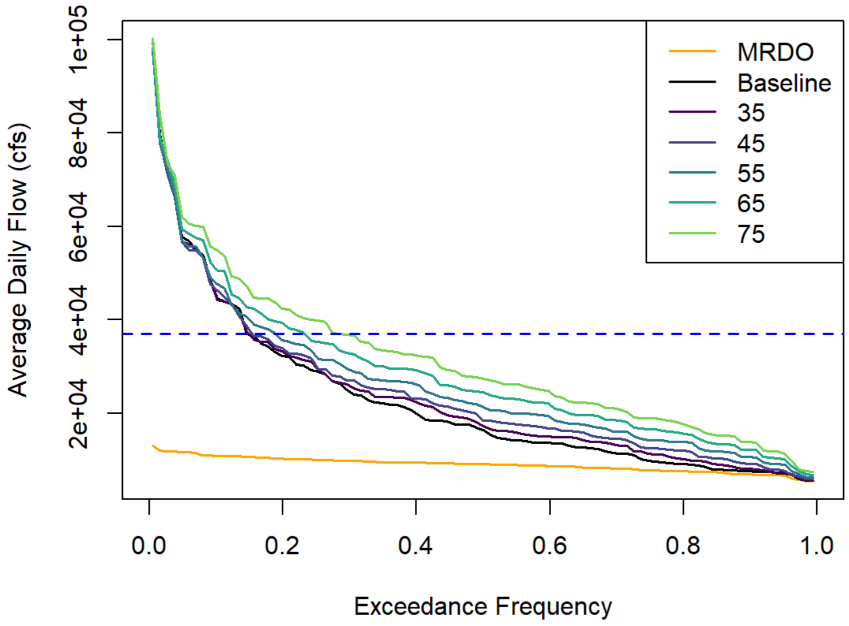
Current conditions as modeled by SacWAM, and Delta outflows resulting under range of flow scenarios when accounting for other expected flows.
cfs = cubic feet per second; MRDO = minimum required Delta outflow

Figure 3.14-8. Frequency of Meeting March–June Delta Outflows to Benefit Starry Flounder for Minimum Required Delta Outflow



Current conditions as modeled by SacWAM, and Delta outflows resulting under range of flow scenarios when accounting for other expected flows.
cfs = cubic feet per second; MRDO = minimum required Delta outflow

Figure 3.14-9. Frequency of Meeting February–May Delta Outflows to Benefit Sacramento Splittail for Minimum Required Delta Outflow



Current conditions as modeled by SacWAM, and Delta outflows resulting under range of flow scenarios when accounting for other expected flows.
cfs = cubic feet per second; MRDO = minimum required Delta outflow

Figure 3.14-10. Frequency of Meeting March–July Delta Outflows to Benefit White and Green Sturgeon for Minimum Required Delta Outflow

The flow frequency distributions suggest that population abundance of native species would increase with increasing Delta outflows. However, the population recovery rate may vary among species because the flow needs of the different species vary substantially, and this changes the frequency with which the species-specific flows are likely to be met. The potential increase in population abundance was estimated for several species using the flow-abundance relationships above. For each flow scenario, expected abundance indices were generated for the average seasonal flows for each water year type and scenario by applying the flow-abundance regression formula. To estimate the uncertainty in expected abundance index increases, 1,000 bootstrapped samples were created of each abundance index, and the percent increase was calculated for each bootstrapped sample. The 1,000 bootstrapped samples of percent change were then aggregated to the 2.5 percent, 50 percent (median), and 97.5 percent quantiles to quantify the uncertainty and central tendency of the predictions (Table 3.14-7). This calculation is meant to give a general sense of the relative benefit each species may realize for a given flow scenario and should not be interpreted as a prediction of future population abundances. Actual outcomes would depend on future flows, management of other stressors, and factors such as stock rebuilding that cannot be accounted for without life cycle models and appropriate data to parameterize them. According to this analysis, estuarine species would be expected to derive more limited benefits from the 35 or 45 scenarios. Modest benefits would be expected from the 55 scenario, and more substantial benefits from 65 and 75 scenarios when compared with current conditions. More information on the methods for this analysis can be found in the Final Draft Scientific Basis Report Supplement, Section 5.2 (Appendix G2).

Table 3.14-7. Potential Percent Increase in Median Abundance Indices Relative to Baseline Condition, with 95 Percent Confidence Intervals and by Water Year Type

Species	Water Year Type	35 (%)	45 (%)	55 (%)	65 (%)	75 (%)
California bay shrimp	Critical	5.4 (3.8 to 7.3)	13.6 (9.4 to 18.7)	23.5 (16.1 to 32.9)	34.1 (23.0 to 48.4)	44.1 (29.4 to 63.6)
California bay shrimp	Dry	10.1 (7.0 to 13.8)	17.6 (12.2 to 24.5)	27.2 (18.5 to 38.3)	37.8 (25.4 to 54.0)	48.2 (32.0 to 69.8)
California bay shrimp	Below Normal	6.8 (4.7 to 9.2)	12.2 (8.5 to 16.8)	19.5 (13.4 to 27.1)	28.6 (19.4 to 40.3)	38.0 (25.6 to 54.3)
California bay shrimp	Above Normal	2.5 (1.8 to 3.4)	4.2 (2.9 to 5.7)	8.3 (5.8 to 11.4)	13.4 (9.3 to 18.4)	19.8 (13.6 to 27.5)
California bay shrimp	Wet	0.2 (0.1 to 0.2)	0.6 (0.4 to 0.8)	2.1 (1.5 to 2.8)	5.3 (3.7 to 7.2)	8.9 (6.2 to 12.2)
Longfin smelt	Critical	7.2 (5.7 to 8.6)	20.1 (15.9 to 24.5)	36.1 (28.1 to 44.5)	62.4 (47.6 to 78.4)	89.6 (67.2 to 114.7)
Longfin smelt	Dry	16.6 (13.1 to 20.1)	29.7 (23.2 to 36.4)	50.8 (39.1 to 63.3)	79.6 (60.0 to 101.2)	113.2 (83.6 to 147.0)
Longfin smelt	Below Normal	12.2 (9.7 to 14.7)	21.4 (16.9 to 26.1)	35.4 (27.5 to 43.6)	54.6 (41.9 to 68.3)	79.1 (59.7 to 100.6)
Longfin smelt	Above Normal	4.9 (3.9 to 5.9)	8.7 (6.9 to 10.4)	16.4 (13.0 to 19.9)	25.8 (20.3 to 31.6)	39.9 (31.0 to 49.4)
Longfin smelt	Wet	0.0 (0.0 to 0.0)	0.9 (0.7 to 1.1)	3.3 (2.6 to 3.9)	8.7 (6.9 to 10.5)	14.7 (11.7 to 17.8)
Sacramento splittail	Critical	6.4 (4.1 to 9.0)	19.0 (11.9 to 27.2)	31.9 (19.7 to 46.7)	49.2 (29.6 to 73.9)	67.4 (39.7 to 103.8)
Sacramento splittail	Dry	13.2 (8.3 to 18.6)	23.1 (14.4 to 33.3)	37.1 (22.7 to 54.7)	55.1 (32.9 to 83.4)	73.9 (43.2 to 114.9)
Sacramento splittail	Below Normal	8.5 (5.4 to 11.9)	14.5 (9.1 to 20.5)	23.2 (14.5 to 33.5)	35.0 (21.5 to 51.5)	49.1 (29.6 to 73.7)
Sacramento splittail	Above Normal	3.0 (1.9 to 4.1)	4.7 (3.0 to 6.6)	9.5 (6.1 to 13.4)	15.4 (9.7 to 21.9)	24.0 (15.0 to 34.7)
Sacramento splittail	Wet	-0.4 (-0.5 to -0.2)	-0.1 (-0.1 to-0.1)	1.7 (1.1 to 2.3)	5.6 (3.6 to 7.8)	9.8 (6.2 to 13.7)
Starry flounder	Critical	4.3 (2.1 to 7.0)	10.8 (5.2 to 18.1)	19.4 (9.2 to 33.3)	28.7 (13.3 to 50.4)	37.5 (17.0 to 67.5)
Starry flounder	Dry	8.2 (4.0 to 13.6)	15.0 (7.1 to 25.3)	23.7 (11.1 to 41.1)	33.2 (15.2 to 59.1)	42.6 (19.2 to 77.6)

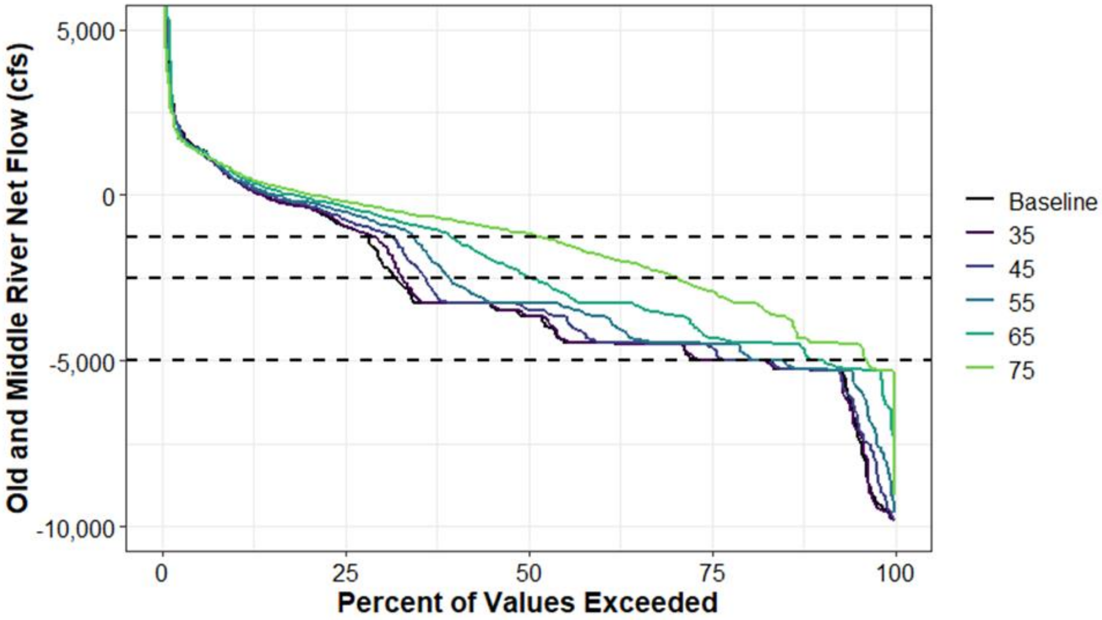
Species	Water Year Type	35 (%)	45 (%)	55 (%)	65 (%)	75 (%)
Starry flounder	Below Normal	6.7 (3.2 to 11.0)	12.4 (6.0 to 20.9)	19.8 (9.3 to 33.9)	28.5 (13.2 to 50.1)	37.4 (17.0 to 67.2)
Starry flounder	Above Normal	2.5 (1.2 to 4.1)	4.8 (2.3 to 7.9)	9.3 (4.5 to 15.5)	14.6 (6.9 to 24.6)	20.9 (9.8 to 36.0)
Starry flounder	Wet	0.3 (0.2 to 0.5)	1.0 (0.5 to 1.6)	2.6 (1.3 to 4.3)	5.9 (2.9 to 9.7)	9.5 (4.6 to 15.9)

Achievement of Interior Delta Flow Thresholds

Table 3.14-3 summarizes interior Delta flow thresholds that are found to be protective of salmonids and other estuarine-dependent species residing in or migrating through the Bay-Delta watershed. Sacramento River flows that prevent tidal reversal at Georgiana Slough are analyzed with other inflow thresholds (see Figure 3.14-4). Flow thresholds for OMR reverse flows (cfs = cubic feet per second

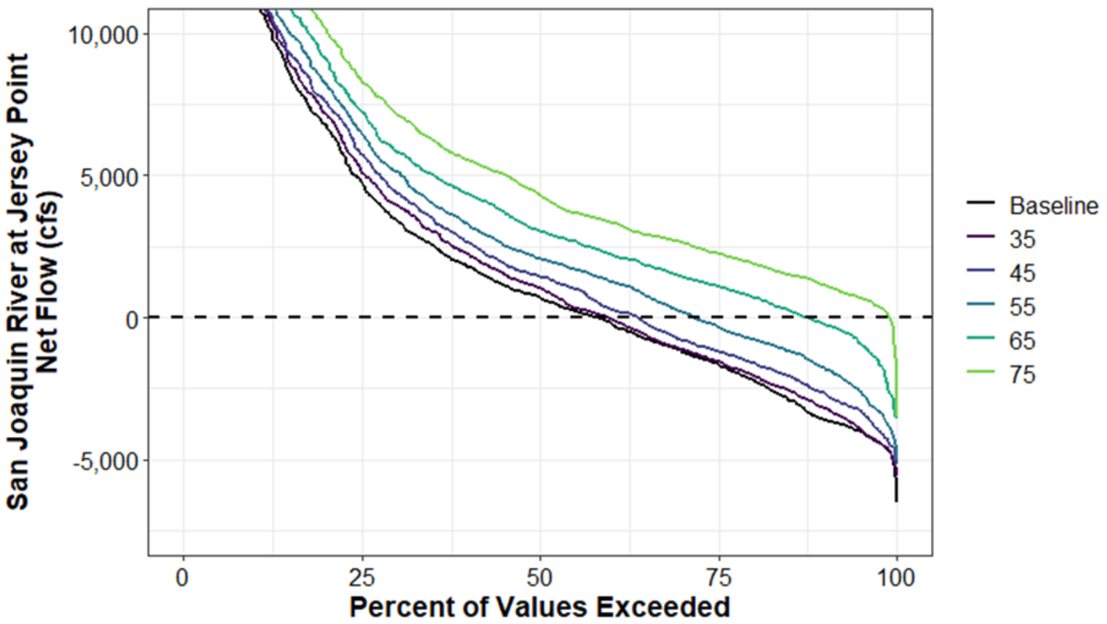
Figure 3.14-11) and positive flow on the San Joaquin River at Jersey Point (also known as QWest; cfs = cubic feet per second

Figure 3.14-12) are generally met more frequently under the flow scenarios relative to the baseline condition. Interior Delta flow requirements do not differ between the baseline condition and flow scenarios, but reductions in reverse flows and increases in positive flows result from decreases in exports associated with meeting inflow, outflow, and cold water objectives. In particular, OMR reverse flows are substantially reduced for 65 and 75 scenarios, and positive flows on the San Joaquin River at Jersey point are substantially increased for the 55, 65, and 75 scenarios. More natural interior Delta flows such as those seen under the higher flow scenarios would improve conditions for native fish residing in or migrating through the Delta. Interior Delta flow results and benefits are discussed further in Section 7.6.2, *Aquatic Biological Resources*.



cfs = cubic feet per second

Figure 3.14-11. Frequency of Meeting Old and Middle River Reverse Flow Thresholds to Protect Salmonids and Estuarine-Dependent Fish Species during December through June under Range of Flow Scenarios



cfs = cubic feet per second

Figure 3.14-12. Frequency of Meeting Positive Flows on the San Joaquin River at Jersey Point during November through June under Range of Flow Scenarios

3.14.2 Salmonid Tributary Habitat Analyses

As described in Appendix A8, *Salmonid Tributary Habitat Analysis*, and in Section 3.4, *Chinook Salmon (*Oncorhynchus tshawytscha*) and Central Valley Steelhead (*Oncorhynchus mykiss*)*, salmonid populations benefit from access to suitable habitat conditions for spawning and rearing, and the dynamic connectivity between river flows and their floodplains (^Jeffres et al. 2008). Suitable spawning and rearing habitat have been characterized by sufficient surface water depth and velocity (Benjankar et al. 2016; Bowen et al. 2012). For spawning, optimal water temperatures for egg incubation are necessary for eggs to remain viable until hatching (^NMFS 2009 BiOp). Additionally, increasing the extent, duration, and frequency of floodplain inundation in the watershed of the Sacramento River and its tributaries improves ecosystem processes, foodweb dynamics, and native fish abundance. For juvenile salmonids in the Central Valley, floodplain habitats have been found to have a positive effect on growth (^Sommer et al. 2001a; ^Sommer et al. 2005; Jeffres et al. 2020). For example, record growth rates were found in juvenile Chinook salmon reared on floodplain wetland (^Jeffres et al. 2008).

As described in the Central Valley Flood Protection Plan's Conservation Strategy (Conservation Strategy) (DWR 2016), floodplain inundation that contributes to successful juvenile salmonid rearing consists of a flow event that occurs over the landscape during winter or spring for a duration of several days or multiple weeks, at an average frequency of every other year. This ecologically meaningful inundation regime has been substantially altered relative to historical conditions. In the Sacramento/Delta and Central Valley, floodplain rearing habitat for Chinook salmon has been reduced by more than 95 percent relative to historical conditions, primarily through levee construction that has disconnected rivers from their floodplains and prevented peak flows from interacting with the landscape. Increased flows, along with restoration of floodplain habitat, would help to restore the important functions provided by floodplain inundation.

All these benefits would be enhanced even further with physical habitat restoration actions that maximize the effectiveness of additional flow, such as removing or setting back levees. For example, on the Cosumnes River, levee breaches (^Booth et al. 2006) and floodplain restoration have provided important dynamic connectivity between the channel and floodplain, which has greatly improved conditions for native fishes (^Moyle et al. 2007). Multi-benefit levee modification projects that also address flood risk and/or groundwater recharge, such as those proposed in the Central Valley Flood Protection Plan (DWR 2017b), would be further enhanced by flows associated with the Plan amendments. Also, the benefits described above, which were limited to rivers with major storage, demonstrate the need to protect the functions of floodplain inundation that are already occurring along other rivers without major storage. Implementation of the proposed Plan amendments would protect these rivers from flow diversions associated with future projects that may affect ecologically meaningful floodplain flows.

3.14.2.1 Spawning and Rearing Habitat

To evaluate the potential changes in salmonid habitat area under each flow scenario, the tributary habitat analysis methods for existing habitat from the Final Draft Scientific Basis Report Supplement were applied to the flow scenarios (See Section 5.1 of the Final Draft Scientific Basis Report Supplement [Appendix G2] for a full description of the methods, and Appendix A8, *Salmonid Tributary Habitat Analysis,* for a description of additional steps taken for the application of the methodology to the flow scenarios). Briefly, habitat suitability criteria for velocity and depth were empirically derived for each tributary by associating fish presence with depth and velocity values. These criteria were paired with hydraulic model outputs of depth and velocity to weight habitat areas for each flow level, resulting in relationships between flow and suitable habitat area. These flow-suitable habitat area relationships were mostly compiled within the DSMHabitat R package[28] and are documented in Appendix A8. Flow-suitable habitat area relationships for tributaries included in the proposed VAs initially were developed using data from DSMHabitat and were then iteratively updated with input from watershed representatives to reflect the most up-to-date habitat. SacWAM-modeled flows for each flow scenario then were applied to these flow-suitable habitat area relationships to estimate the area of suitable habitat for spawning, instream rearing, and floodplain rearing. Temperature criteria then were applied to filter out habitat area where temperatures would be unsuitable as defined by temperatures above 13 °C for spawning and 18 °C for rearing. These analyses were applied within appropriate seasons for each salmon run and habitat type: fall-run rearing = February through June, fall-run spawning = October through December, spring-run rearing = November through May, and spring-run spawning = March through October.

Most analyses were focused on fall-run Chinook salmon, but some were focused on spring run. Results differentiate fall-run and spring-run results only for tributaries for which spring run were evaluated; results for all other tributaries represent only fall-run results.

Spawning Habitat Results

Many of the Sacramento River tributaries show no change in suitable spawning habitat area across the flow scenarios analyzed (FR = fall-run

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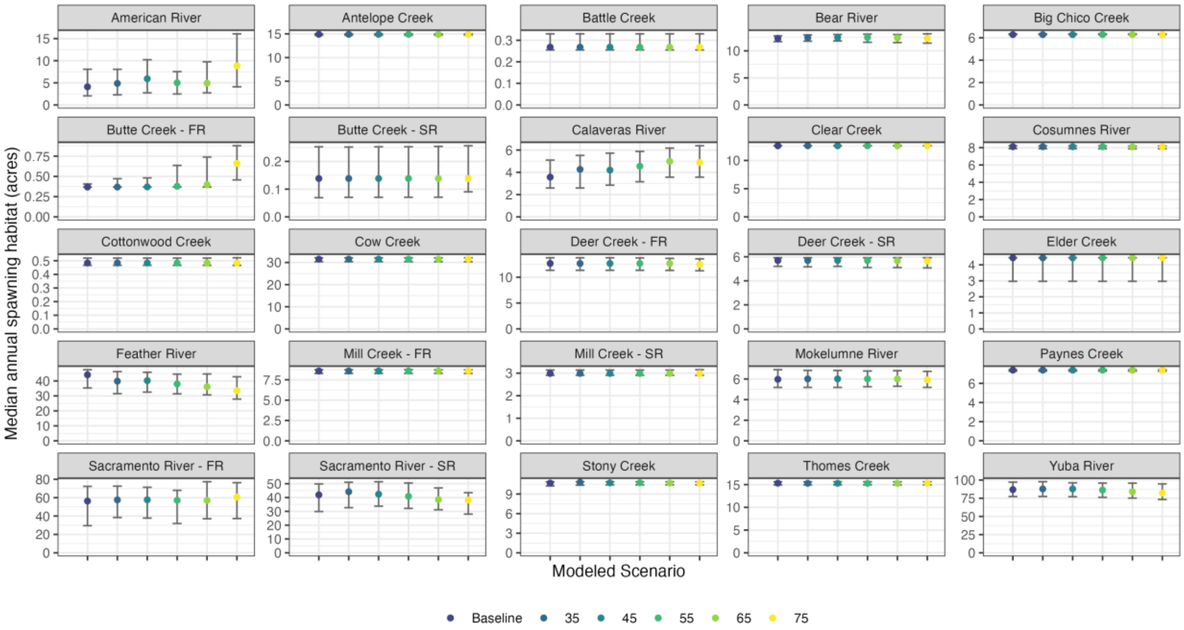
[28] https://cvpia-osc.github.io/DSMhabitat/

SR = spring-run, Table 3.14-8). There are some fluctuations in spawning habitat for the following tributaries: American River, Butte Creek (fall-run), Calaveras River, Feather River, and Sacramento River (spring-run). Spawning habitat is lowest under the baseline scenario and highest under the 75 scenario for the American River, Butte Creek, and Calaveras River. On the Feather River and Sacramento River, there is an inverse relationship where suitable spawning habitat is highest under the baseline conditions and lowest under the 75 scenario due to an inverse relationship in the flow-to-spawning habitat area curves in the flow ranges analyzed for these watersheds.



Error bars represent the upper and lower quartiles. Medians and quantiles were calculated across all years; therefore, the quantiles represent year-to-year variability, not the full uncertainty in expected outcomes. Unless noted otherwise, results are for fall-run.
FR = fall-run
SR = spring-run

Figure 3.14-13. Median (across All Years Modeled) Spawning Habitat (acres)

Table 3.14-8. Change in Median (across All Years Modeled) Spawning Habitat from Baseline for Each Flow Scenario

Watershed	35	45	55	65	75
American River	0% (0)	8% (0)	0% (0)	4% (0)	84% (3)
Antelope Creek	0% (0)	0% (0)	0% (0)	0% (0)	0% (0)
Battle Creek	0% (0)	0% (0)	0% (0)	0% (0)	0% (0)
Bear River	1% (0)	1% (0)	1% (0)	1% (0)	2% (0)
Big Chico Creek	0% (0)	0% (0)	0% (0)	0% (0)	0% (0)
Butte Creek - FR	0% (0)	0% (0)	0% (0)	1% (0)	54% (0)
Butte Creek - SR	0% (0)	0% (0)	0% (0)	0% (0)	0% (0)
Calaveras River	6% (0)	10% (0)	16% (1)	22% (1)	28% (1)
Clear Creek	0% (0)	0% (0)	0% (0)	0% (0)	0% (0)

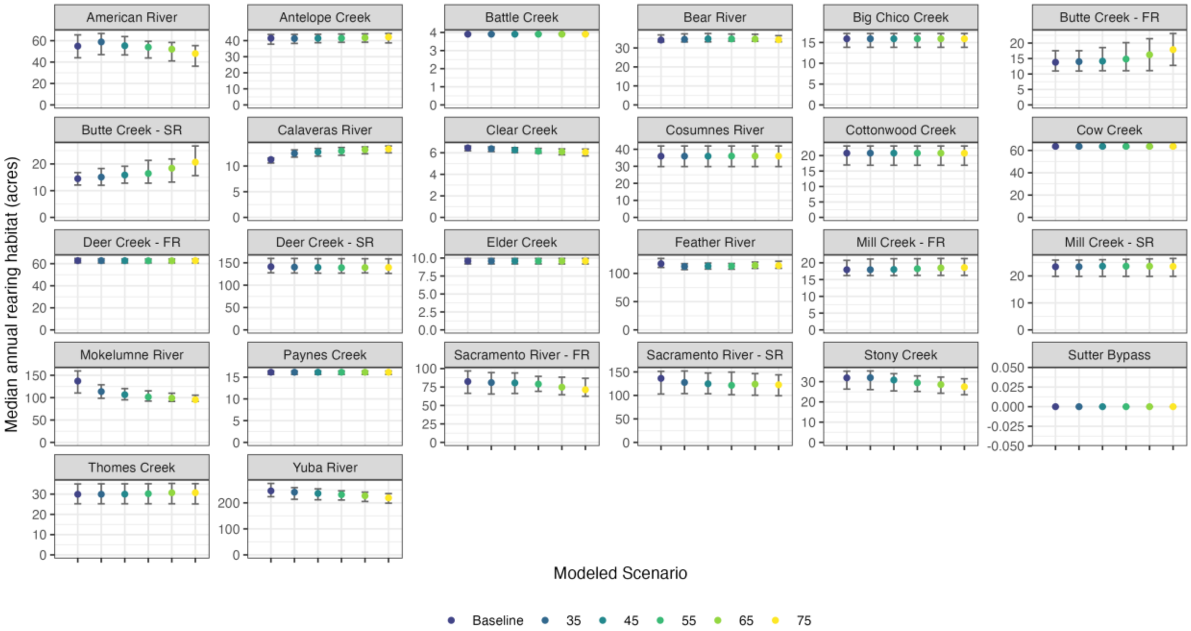
Watershed	35	45	55	65	75
Cosumnes River	0% (0)	0% (0)	0% (0)	0% (0)	0% (0)
Cottonwood Creek	0% (0)	0% (0)	0% (0)	0% (0)	0% (0)
Cow Creek	0% (0)	0% (0)	0% (0)	0% (0)	0% (0)
Deer Creek - FR	0% (0)	0% (0)	0% (0)	0% (0)	0% (0)
Deer Creek - SR	0% (0)	0% (0)	0% (0)	0% (0)	0% (0)
Elder Creek	0% (0)	0% (0)	0% (0)	0% (0)	0% (0)
Feather River	-1% (-1)	-5% (-2)	-9% (-4)	-8% (-3)	-15% (-6)
Mill Creek - FR	0% (0)	0% (0)	0% (0)	0% (0)	0% (0)
Mill Creek - SR	0% (0)	0% (0)	0% (0)	0% (0)	0% (0)
Mokelumne River	0% (0)	0% (0)	0% (0)	0% (0)	0% (0)
Paynes Creek	0% (0)	0% (0)	0% (0)	0% (0)	0% (0)
Sacramento River - FR	0% (0)	0% (0)	0% (0)	4% (1)	4% (3)
Sacramento River - SR	0% (0)	0% (0)	-1% (-1)	-9% (-4)	-9% (-4)
Stony Creek	0% (0)	1% (0)	1% (0)	1% (0)	1% (0)
Sutter Bypass	0% (0)	0% (0)	0% (0)	0% (0)	0% (0)
Thomes Creek	0% (0)	0% (0)	0% (0)	0% (0)	-2% (-2)
Yuba River	0% (0)	8% (0)	0% (0)	4% (0)	84% (3)

Results are presented as percent change with the difference in acres in parentheses, both rounded to the nearest whole number. Unless noted otherwise, results are for fall-run.
FR = fall-run
SR = spring-run

Rearing Habitat Results

Many of the Sacramento River tributaries show no change in suitable instream and floodplain rearing habitat area across the flow scenarios analyzed (Error bars represent the upper and lower quartiles. Medians and quantiles were calculated across all years; therefore, the quantiles represent year-to-year variability, not the full uncertainty in expected outcomes. Unless noted otherwise, results are for fall-run.
FR = fall-run
SR = spring-run

Figure 3.14-14, Table 3.14-9). There are some fluctuations in rearing habitat for the following tributaries: American River, Butte Creek (fall-run, spring-run), Calaveras River, Mokelumne River, Sacramento River (fall-run, spring-run), and Stony Creek. Instream rearing habitat is lowest under the baseline scenario and highest under the 75 scenario for Butte Creek and the Calaveras River. On the American River, Mokelumne River, Sacramento River, and Stony Creek there is an inverse relationship where habitat is greatest under the baseline scenario and lowest under the 75 scenario due to an inverse relationship in the flow-to-instream rearing habitat area curves in the flow ranges analyzed for these watersheds. Results for instream habitat alone can be found in Appendix A8, *Salmonid Tributary Habitat Analysis*.



Error bars represent the upper and lower quartiles. Medians and quantiles were calculated across all years; therefore, the quantiles represent year-to-year variability, not the full uncertainty in expected outcomes. Unless noted otherwise, results are for fall-run.

FR = fall-run

SR = spring-run

Figure 3.14-14. Median (across All Years Modeled) Rearing Habitat (acres) for Each Watershed, Including Both Floodplain and Instream Rearing Habitat

Table 3.14-9. Change in Median (across All Years Modeled) Rearing (Instream and Floodplain) Habitat from Baseline for Each Flow Scenario

Watershed	35	45	55	65	75
American River	1% (1)	1% (1)	3% (2)	2% (2)	4% (4)
Antelope Creek	0% (0)	0% (0)	1% (0)	1% (1)	1% (1)
Battle Creek	0% (0)	0% (0)	0% (0)	0% (0)	0% (0)
Bear River	0% (0)	-1% (-1)	-3% (-2)	-5% (-4)	-7% (-5)
Big Chico Creek	0% (0)	0% (0)	0% (0)	0% (0)	0% (0)
Butte Creek - FR	0% (0)	0% (0)	0% (0)	0% (0)	1% (0)
Butte Creek - SR	0% (0)	0% (0)	0% (0)	0% (0)	-1% (-1)
Calaveras River	12% (1)	14% (2)	16% (2)	18% (2)	19% (2)
Clear Creek	2% (0)	2% (0)	4% (0)	5% (0)	6% (0)
Cosumnes River	0% (0)	0% (0)	0% (0)	0% (0)	0% (0)
Cottonwood Creek	0% (0)	0% (0)	0% (0)	0% (0)	0% (0)
Cow Creek	0% (0)	0% (0)	0% (0)	0% (0)	0% (0)
Deer Creek - FR	0% (0)	0% (0)	0% (0)	0% (0)	0% (0)
Deer Creek - SR	0% (0)	0% (0)	0% (0)	-1% (-1)	-1% (-1)
Elder Creek	0% (0)	0% (0)	0% (0)	0% (0)	0% (0)
Feather River	10% (21)	22% (45)	33% (78)	44% (102)	54% (125)

Watershed	35	45	55	65	75
Mill Creek - FR	0% (0)	0% (0)	0% (0)	1% (0)	2% (0)
Mill Creek - SR	0% (0)	0% (0)	0% (0)	0% (0)	1% (0)
Mokelumne River	8% (17)	16% (32)	25% (47)	31% (60)	38% (70)
Paynes Creek	0% (0)	0% (0)	0% (0)	0% (0)	0% (0)
Sacramento River - FR	0% (0)	0% (-1)	-1% (-2)	-1% (-3)	-1% (-2)
Sacramento River - SR	0% (-1)	-1% (-2)	-1% (-3)	-2% (-5)	-1% (-2)
Stony Creek	3% (1)	2% (1)	2% (1)	3% (1)	4% (2)
Sutter Bypass	-1% (-22)	0% (9)	1% (31)	1% (51)	-6% (-242)
Thomes Creek	0% (0)	0% (0)	0% (0)	0% (0)	0% (0)
Yuba River	-1% (-2)	-2% (-6)	-4% (-10)	-4% (-12)	-5% (-12)

Results are presented as percent change with the difference in acres in parentheses, both rounded to the nearest whole number. Unless noted otherwise, results are for fall-run.
FR = fall-run
SR = spring-run

3.14.2.2 Floodplain Inundation Results

To help inform development of the proposed Plan amendments, an additional analysis was conducted to evaluate the quality of floodplain habitat under each flow scenario in terms of the duration, frequency, and timing of floodplain inundation at different magnitudes of suitable floodplain area inundation. This Meaningful Floodplain Event (MFE) approach evaluates the proportion of years in which floodplain inundation events of a given magnitude (suitable habitat area) occur for at least 2 months during the rearing period and for 2 out of every 3 years (i.e., did inundation events occur in at least 2 years out of the current year and the year before and after). The MFE frequency was estimated for a range of magnitudes, representing 25, 50, 75, and 100 percent of the area estimated to support offspring of the doubling goal population at the fry stage. If a doubling goal population was not available, the percentages were applied to the maximum habitat area. Table 3.14-10 presents the percent of years in which MFE events are attained in each Sacramento River watershed tributary. Methods are described in Appendix A8, *Salmonid Tributary Habitat Analysis*.

Table 3.14-10. Percent of Years in Which Meaningful Floodplain Events Are Attained in Each Tributary

Tributary	Baseline	35	45	55	65	75
American River	0%	0%	0%	0%	0%	0%
Antelope Creek	27%	27%	27%	27%	27%	27%
Battle Creek	0%	0%	0%	0%	0%	0%
Bear River	94%	96%	96%	96%	96%	96%
Big Chico Creek	1%	1%	1%	1%	1%	1%
Butte Creek - FR	98%	98%	98%	98%	98%	98%
Butte Creek - SR	98%	98%	98%	98%	98%	98%
Calaveras River	0%	0%	0%	0%	0%	0%
Clear Creek	0%	0%	0%	0%	0%	0%
Cosumnes River	76%	74%	74%	74%	74%	74%
Cottonwood Creek	39%	39%	39%	39%	39%	39%
Cow Creek	25%	25%	25%	25%	25%	25%

Tributary	Baseline	35	45	55	65	75
Deer Creek - FR	20%	20%	20%	20%	20%	20%
Deer Creek - SR	15%	15%	15%	15%	15%	15%
Elder Creek	57%	57%	57%	57%	57%	57%
Feather River	47%	51%	67%	76%	83%	88%
Mill Creek - FR	0%	0%	0%	0%	0%	0%
Mill Creek - SR	4%	4%	4%	4%	4%	4%
Mokelumne River	69%	95%	98%	98%	98%	98%
Paynes Creek	34%	34%	34%	34%	34%	34%
Sacramento River - FR	19%	20%	19%	19%	19%	20%
Sacramento River - SR	49%	48%	48%	46%	53%	59%
Stony Creek	15%	12%	15%	12%	12%	12%
Sutter Bypass	95%	95%	95%	94%	94%	87%
Thomes Creek	22%	22%	22%	22%	22%	22%
Yuba River	11%	14%	13%	11%	19%	22%

Results are presented for 25% of the doubling goal habitat area (or 25% of the maximum habitat area if no doubling goal was available). Full results are available in Appendix A8, *Salmonid Tributary Habitat Analysis*. Unless noted otherwise, results are for fall-run.
FR = fall-run
SR = spring-run

In most tributaries, there were no differences among scenarios (Table 3.14-10). In some cases, the lack of a difference between MFE occurrence under different flow scenarios is due to the assumption that flows greater than a certain magnitude do not create additional suitable floodplain rearing habitat area. This assumption is reflected in the flow-to-floodplain area curves used to conduct the MFE analyses. Results are described in more detail below only for tributaries with notable results; the full results can be found in Appendix A8, *Salmonid Tributary Habitat Analysis*.

The American River, Battle Creek, and Clear Creek MFE analysis indicates that there are no MFEs (at any magnitude of floodplain area) for any of the flow scenarios. MFEs may be met at magnitudes lower than 25 percent of the habitat area needed to support the doubling goal but are not included in this analysis.

The Bear River MFE analysis indicates a higher proportion of MFEs (at all magnitudes) for the unimpaired flow scenarios compared with the baseline scenario. However, there is little difference in proportion of MFEs between the different percent of unimpaired flow scenarios. One reason for these minimal differences is that the maximum flow for the flow-to-floodplain area relationship for Bear River is about 5,500 cfs. Therefore, suitable floodplain area does not increase for flows greater than 5,500 cfs.

The Feather River MFE analysis indicates an increasingly higher proportion of a 288-acre magnitude MFE (25 percent of the habitat needed to support the doubling goal) with higher magnitude flow scenarios, such that MFEs occurred 47 percent of years in the baseline, 76 percent of years under the 55 scenario, and 88 percent of years under the 75 scenario. For MFEs of a greater area magnitude, there is little difference between flow scenarios; likely due to insufficient flow, even at the 75 scenario, to substantially increase floodplain habitat area above 288 acres.

The Mokelumne River MFE analysis indicates a higher proportion of MFEs (at all magnitudes) for the flow scenarios compared with the baseline condition, with the highest MFEs at the greatest magnitudes under the 65 and 75 flow scenarios. Differences among the flow scenarios were generally small but increased with increasing habitat area. At 25 percent of the doubling goal habitat area, MFEs occur in 69 percent of years in the baseline, and 98 percent of years under the 45 through 75flow scenarios.

The Stony Creek MFE analysis indicates a slightly higher proportion of a 43-acre magnitude MFE for the baseline and 45 flow scenarios (15 percent of years for each) compared with all other scenarios (12 percent of years). For MFEs of a greater magnitude, there is little difference between the scenarios. This is likely related to fluctuations in the flow scenarios rather than the flow-to-floodplain habitat area relationship for Stony Creek.

The Sutter Bypass MFE analysis indicates a higher proportion of a 5,000-acre magnitude MFE for the baseline, 35 scenario, and 45 scenario compared with all other scenarios. The 75flow scenario results in a lower proportion of MFE occurrence (87 percent) compared with baseline (95 percent), likely due to an inverse relationship between flow and area for flows greater than approximately 10,000 cfs. For MFEs of a greater magnitude, there is little difference between the scenarios; likely due to insufficient flow, even at the 75flow scenario, to substantially increase floodplain habitat area.

The Yuba River MFE analysis indicates a higher proportion of a 77-acre magnitude MFE (25 percent of the habitat needed to support the doubling goal) under the 65and 75flow scenarios compared with all other scenarios. MFEs occurred in 11 percent of years in baseline and the 55scenario, and 19 percent and 22 percent of years under the 65and 75flow scenarios, respectively. For MFEs of a greater magnitude, there is little difference between the flow scenarios, likely due to insufficient flow—even under the 75flow scenario, to substantially increase floodplain habitat area.

3.14.3 Cold Water Storage

In addition to evaluating the frequency with which the flow scenarios achieve the flow thresholds associated with improved protection of fish and wildlife and floodplain inundation, the ability to maintain reservoir carryover storage on the Sacramento/Delta tributaries was evaluated to determine the effectiveness of the scenarios in protecting fish and wildlife. As discussed in the preceding subsections, as a result of construction of dams that block access to upstream natal cold water habitat and the operations of those dams, nearly all of the tributaries with reservoirs in the plan area have significant problems with maintaining suitable temperatures for native fish and other species downstream of those reservoirs. Salmon, steelhead, and other species that require cold water habitat now depend on cold water releases from reservoirs in summer and fall for their protection. The proposed Plan amendments are intended to improve protection of these native species through implementation of the inflow and cold water habitat objectives. However, there are tradeoffs between providing instream flows and carryover storage that are considerations in determining the required flow and cold water habitat measures, including the flow levels, carryover storage requirements, and flexibility and adaptive management provisions.

The amount of water retained in storage is a product of the amount of water that comes into the reservoir from precipitation and upstream releases from storage and losses from the reservoir from diversions, instream flow releases, and evaporation and seepage. Implementation of the flow requirements can result in reduced abilities to store water coming into the reservoir because that water is required to be bypassed through the reservoir and released for inflow purposes downstream of the reservoir. Generally, the ability to store water under the flow scenarios decreases as the flow levels increase. However, there is still the ability to store flows above the instream flow level (e.g., under the 55 scenario, 45 percent of the inflow could still be stored). Implementation of the flow scenarios could also result in changes in diversions that diminish storage. With higher instream flow requirements water suppliers may rely more on water from storage (rather than natural flows that are required to be bypassed) to meet their demands.

Chapter 6, *Changes in Hydrology and Water Supply*, includes an analysis from SacWAM of the potential changes in reservoir storage under the various flow scenarios. All the scenarios include assumptions that attempt to reduce diversions to some extent to maintain reservoir carryover storage for cold water protection. However, determining exactly what measures are needed for cold water habitat management is a complex evaluation of the physical characteristics of the reservoir, the hydrological and physical characteristics of the watershed, the water diversion and hydropower production infrastructure and operations, the biological resources that are intended to be protected, the unique circumstances of each temperature control season and the connection of seasons throughout the year and from year to year, and other local and regional factors. These are all factors that warrant specific targeted evaluation and planning, as described in the cold water habitat objective discussion in Chapter 5, *Proposed Changes to the Bay-Delta Plan for the Sacramento/Delta*.

General assumptions were developed for determining the approximate amount of water that may need to be maintained in storage for the reasonable protection of cold water habitat. Although general, these assumptions are appropriate for this process to understand the costs and tradeoffs of providing for carryover storage and inflows. Those assumptions are described in Chapter 6, *Changes in Hydrology and Water Supply*, and Appendix A1, *Sacramento Water Allocation Model Methods and Results*, and are based on existing general information regarding reservoir cold water pool needs.

The sensitivity analyses also evaluate somewhat higher instream flows on some of the tributaries during summer and fall in the event that higher flows may be needed for cold water habitat protection. As described in Chapter 2, *Hydrology and Water Supply*, the Sacramento/Delta tributaries and their flow regimes have been dramatically modified for water supply, flood control, and hydropower production purposes. Flows on tributaries with major storage reservoirs are generally significantly diminished during winter and spring when water is being stored. Flows are then significantly higher in summer and fall when flows are being released for water supply and hydropower production purposes. Providing more natural flows that increase releases in winter and spring would affect the amount of storage going into the summer to some extent. As a result, the modeling constrains the amount of water released for water supply purposes during summer and fall to ensure that carryover storage levels are maintained into the fall. However, it is possible that in some cases, flows would need to be higher in summer and fall than that originally evaluated for temperature control purposes. These are general assumptions meant to provide a general understanding of the tradeoffs and potential impacts of different flow levels for policy-level considerations. More detailed specific evaluations, studies, and other work are needed when implementing cold water habitat actions to plan and implement actual operations and other temperature control measures.

In recognition that cold water pool management and temperature control are most problematic when reservoir storage is lower and less problematic at higher storage levels, the reservoir carryover modeling assumptions generally allow carryover storage to be somewhat lower in wetter conditions and provide for higher storage in drier conditions to represent measures that could be implemented to protect cold water supplies (including those discussed in the cold water habitat discussion that follows). Generally, this pattern is intended to improve conditions when temperature control is most problematic, while allowing the reservoir to be drawn below baseline conditions at other times when cold water management is less problematic to reduce the water supply impacts of providing inflows. The modeling is not intended to be prescriptive but instead to provide for a general realistic assessment of constraints that exist in the system with (1) providing for increased instream flows while preserving water in storage for cold water and other purposes; and (2) maintaining water diversions to some extent, though at reduced levels as the flow levels increase. However, the general trends identified in the modeling are still representative of the constraints that exist between carryover storage and instream flow levels.

Chapter 6, *Changes in Hydrology and Water Supply*, evaluates changes in end-of-September carryover storage for the 35 to 75 scenarios in 10-percent increments compared with baseline conditions for rim reservoirs, upstream reservoirs, and total storage in each tributary. These analyses generally indicate that carryover storage can be maintained (with less than a 10-percent change) in the tributaries under the 35, 45, and 55 scenarios, except for Stony and Putah Creeks (Black Butte Reservoir and Lake Berryessa, respectively) and the Calaveras and Mokelumne Rivers (Comanche and Pardee Reservoirs, respectively) (see Tables 6.3-8 and 6.3-9 in Chapter 6, *Changes in Hydrology and Water Supply*). These tributaries are highly impaired, creating challenges for carryover storage and temperature control. In the 65 scenario, carryover storage becomes more challenging for these tributaries as well as for the Yuba River. In the 75 scenario, it is not possible to maintain carryover storage as modeled. Although modeling assumptions could be modified to further reduce diversions in an attempt to better achieve carryover storage levels, it would not be possible to significantly improve carryover storage levels without dramatic water supply reductions.

3.15 Conclusion

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

Indices of population abundance for all the estuarine species are at all-time low levels, except for California bay shrimp (Table 3.15-1, Figure 3.15-1). The population abundances of Sacramento splittail, Delta smelt, and longfin smelt have declined by 98, 98, and 99 percent, respectively, since sampling began in 1967. The three native species have continued to decline since implementation of D-1641 in 2000 (Table 3.15-1). Several of these species are protected under the federal ESA and CESA (Table 3.15-1). The population abundance of the California bay shrimp is an exception and has remained near its long-term median abundance since monitoring began in 1980.

The natural production of all four runs of Chinook salmon and Central Valley steelhead is also in decline. Natural production of winter-, spring-, late-fall-, and fall-run Chinook salmon has decreased from the annual average baseline conditions from 1967 through 1991 by 89, 61, 52, and 43 percent, respectively (Table 3.4-3). As discussed above, natural production of steelhead has also declined substantially in recent decades. Hatcheries now provide most of the salmon and steelhead caught in the commercial and recreational fisheries.

The analysis of modeled flow results in Section 3.14, *Evaluation of Bay-Delta Environmental Flow Effects*, show biological benefits associated with the adoption of new flow requirements that favor more flow of a more natural pattern from major Sacramento/Delta tributaries. These benefits include improved estuarine habitat, greater expected population abundances of estuarine fish, increased outmigration success of salmonids, increased floodplain inundation, and improved flow conditions for native fishes in the interior Delta.

Table 3.15-1. Estuarine-Dependent Species Listed under the California and Federal Endangered Species Acts and Changes in Indices of Their Population Abundance in the San Francisco Estuary

	Listing				
Species	CESA	ESA	Statistically Significant Long-Term Decline Since Sampling Began?	Continued Decline Since Adoption of D-1641 in 2000?	Present Abundance [a]
Starry flounder			Yes [b]	No	Lowest on record
Sacramento splittail	Species of special concern		Yes [c] (-97%) [d]	No (-91%)	Lowest on record
Longfin smelt	Threatened	Proposed Endangered	Yes [c] (-99%)	Yes (-95%)	Lowest on record
Delta smelt	Endangered	Threatened	Yes [c] (-98%)	Yes (-95%)	Lowest on record
California bay shrimp			No [b]	No	Near median value

CESA = California Endangered Species Act
ESA = federal Endangered Species Act
D-1641 = State Water Resources Control Board Water Right Decision 1641

[a] 2014/2015.

[b] San Francisco Bay study (1980–present).

[c] Fall Midwater Trawl Index (1967–present).

[d] The percent decrease was estimated from the average of the first 3 and last 3 years of index values to account for interannual variability.

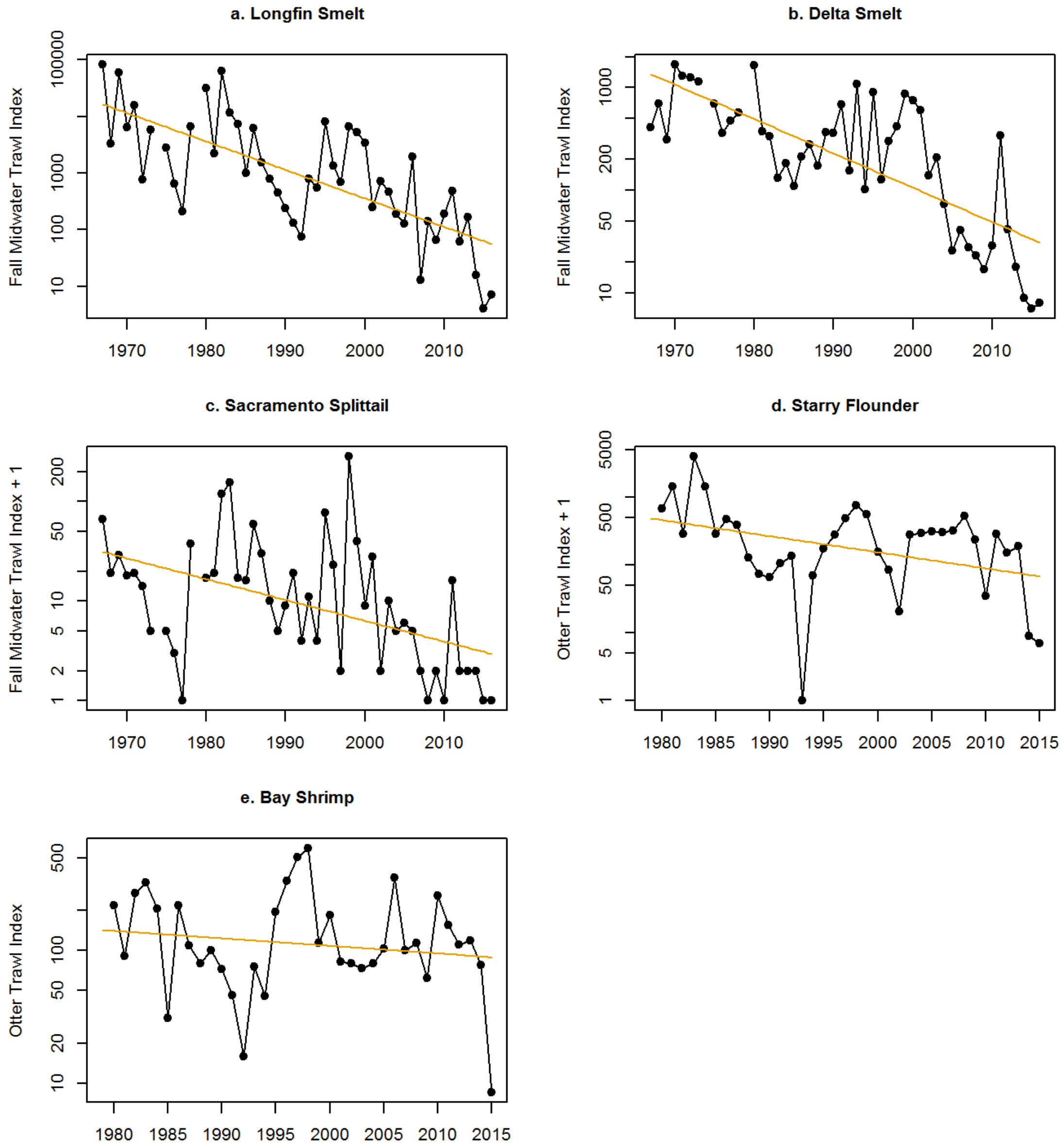


Figure 3.15-1. Trends over Time in Indices of Abundance for Native Fish and Invertebrate Species from the San Francisco Estuary

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3.16.1 Common References

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