X.1 Status of the Species and Critical Habitat /Environmental Baseline

X.1.1 Legal Status of the Delta Smelt and Environmental Baseline

The Action Area for this consultation encompasses the entire species range including all of the designated critical habitat. For the purposes of this BiOp, the Status of the Species, Status of the Critical Habitat, and Environmental Baseline are combined.

Legal Status of the Delta Smelt

The Service proposed to list the delta smelt (*Hypomesus transpacificus*) as threatened with proposed critical habitat on October 3, 1991 (Service 1991). The Service listed the delta smelt as threatened on March 5, 1993 (Service 1993), and designated critical habitat for the species on December 19, 1994 (Service 1994). The delta smelt was one of eight fish species addressed in the *Recovery Plan for the Sacramento–San Joaquin Delta Native Fishes* (Service 1996). A 5-year status review of the delta smelt was completed on March 31, 2004 (Service 2004). The review concluded that delta smelt remained a threatened species. A subsequent 5-year status review recommended uplisting delta smelt from threatened to endangered (Service 2010a). A 12-month finding on a petition to reclassify the delta smelt as an endangered species was completed on April 7, 2010 (Service 2010b). After reviewing all available scientific and commercial information, the Service determined that re-classifying the delta smelt from a threatened to an endangered species was warranted but precluded by other higher priority listing actions (Service 2010c). The Service reviews the status and uplisting recommendation for delta smelt during its Candidate Notice of Review (CNOR) process. Each year it has been published, the CNOR has recommended the uplisting from threatened to endangered. Electronic copies of these documents are available at https://ecos.fws.gov/ecp0/profile/speciesProfile?sId=321.

X.1.2 Status of the Species and its Critical Habitat

Species Description and Legal Status

Delta smelt: The delta smelt is a small fish of the family Osmeridae. It is endemic to the San Francisco Bay-Delta where it primarily occupies open-water habitats in Suisun Bay and marsh and the Sacramento-San Joaquin Delta (Moyle et al. 1992). The delta smelt is composed of one genetic population (Fisch et al. 2011). The delta smelt is primarily an annual species, meaning that it completes its life cycle in one year which typically occurs from March to the following March plus or minus about one to two months. In captivity delta smelt can survive to spawn at two years of age (Lindberg *et al.* 2013), but this appears to be rare in the wild (Bennett 2005). Delta smelt begin reaching sexual maturity at about 55 mm in length (~ 2 inches) and 50% reach sexual maturity at 60 to 65 mm in length (Rose *et al.* 2013b). In the wild, very few individuals reach lengths over 3.5 inches (90 mm; Damon et al. 2016).

Most delta smelt spawn in fresh-water habitats under tidal influence during late winter and early spring. Most individuals reach the juvenile life stage in June and July. Maturing adults disperse toward spawning habitats in association with early winter storms that bring pulses of freshwater and turbidity into the estuary. Most individuals die after spawning, but as is typical for annual fishes, when conditions allow, some individuals can spawn more than once during their single spawning season.

Environmental Setting (1850-1967)

There are several fish species that use the Bay-Delta that have demonstrable positive population responses to freshwater flows into or out of the Delta. These include the well-described relationships for the survival of emigrating Sacramento basin Chinook Salmon smolts with Sacramento River inflows (Kjelson and Brandes 1989; Perry et al. 2010), the relationship of Sacramento splittail production to Yolo Bypass flow (Moyle et al. 2004; Feyrer et al. 2006), and the 'fish-X2' relationships for striped bass, longfin smelt, and starry flounder (Turner and Chadwick 1972; Jassby et al. 1995; Kimmerer 2002a). The delta smelt with its generally pelagic life-history and affinity for fresh and low-salinity waters of the estuary seems like it should similarly respond to variation in freshwater flows into and out of the estuary. Researchers have searched for some kind of analogous relationship for the delta smelt for several decades, but no persistent relationship has been found (Stevens and Miller 1983; Moyle et al. 1992; Jassby et al. 1995; Kimmerer 2002a; Bennett 2005; Mac Nally et al. 2010; Thomson et al. 2010; Miller et al. 2012). Further, Rose et al. (2013a,b) did not find salinity variation to have much impact on predictions of delta smelt population growth rate. The larger predicted impact in their individual-based model related to flow was due to simulated entrainment in exported water (Rose et al. 2013b; Kimmerer and Rose 2018). Although entrainment was predicted to lower predicted population growth rate, of itself, it could not convert a strongly positive growing population into a declining one without at least one additional factor impacting survival at the same time.

These statistical and individual-based modeling results suggest there are four possible reasons that there has been no demonstrable delta smelt flow relationship despite the availability of monitoring data streams that now exceed 50-60 year time frames. One possibility is that despite what seems logical, the delta smelt's population dynamics were regulated by factors operating independently of freshwater flow variation so that a relationship never existed. A second possibility is that changes to physical habitat conditions in the estuary (e.g., the changes to the landscape and flow regime discussed below) had over-ridden a historical relationship that had been missed by the time monitoring programs began. A third possibility is that changes in biological conditions (species assemblages and food web function) had over-ridden a historical relationship that had been missed by the time monitoring programs began. The fourth possibility is the combination of the second and third ones. The Service is not aware of any available scientific information that can discern among these possibilities.

Over the past few years, the scientific information developed to understand pre- and post-water project changes to the estuary's landscape and flow regime have grown substantially. We review that information below to provide context for the current status of the delta smelt, then follow with reviews of relevant science – both old and new related to the status of delta smelt and the Service's current understanding of the primary constituent elements of its designated critical habitat.

Bay-Delta estuary: The historical Delta ecosystem was a large tidal marsh at the confluence of two floodplain river systems (Andrews et al. 2017; Gross et al. 2018; Figure 1). The Delta itself experienced flooding over spring-neap tidal time scales and seasonal river runoff time scales (winter-spring). Water flowing from the Delta mixed into larger open-water habitats in Suisun and San Pablo bays, which themselves were fringed with marshes and tidal creeks. This pre-development ecosystem was shallower than the modern system. As a result, salinity responded more rapidly to changes in freshwater flow than it does now and less freshwater flow was needed to move salinity isohalines than is presently the case.

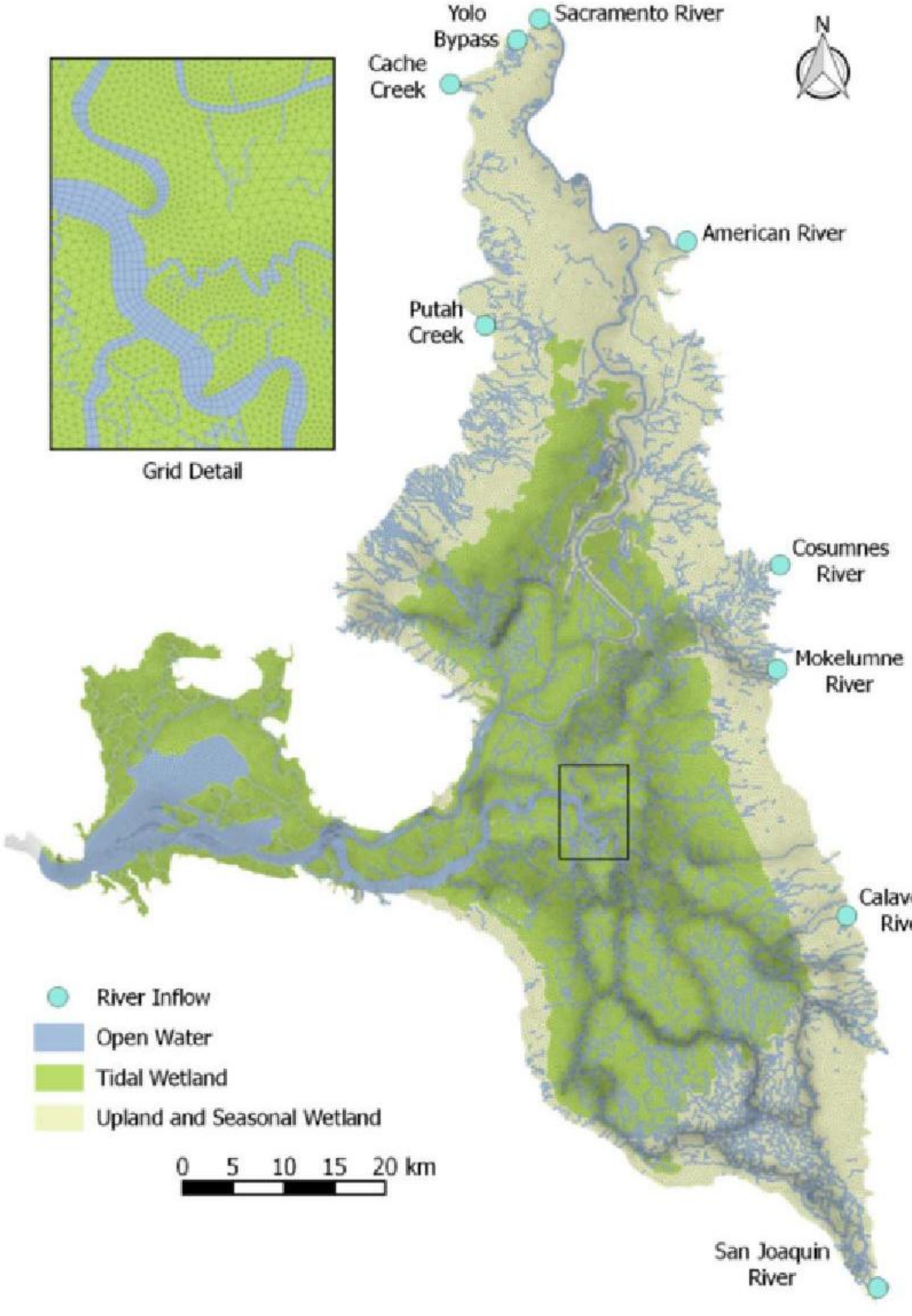


Figure 1. The circa 1850 Delta as depicted in the version of the UnTRIM 3-D hydrodynamic model described by Andrews et al. (2017). Source: Andrews et al. (2017).

Many tidal river estuaries form frontal zones where inflowing fresh water begins mixing with seawater (Peterson 2003). In the Bay-Delta, a frontal zone of historical importance to delta smelt is the low-salinity zone (Moyle et al. 1992). The low-salinity zone is a mobile and variable habitat region; in the Bay-Delta it has historically been indexed using a statistic called X2, which is the geographic location of 2 ppt salinity near the bottom of the water column measured as a distance from the Golden Gate Bridge (Jassby et al. 1995; Figure 2). When Delta outflow is high, saline water is pushed closer to the Golden Gate, resulting in a smaller distance from the Golden Gate Bridge to X2. Conversely, when Delta outflow is low, salinity intrudes further into the estuary resulting in a larger distance from the Golden Gate Bridge to X2. These changes in how salinity is distributed affect numerous physical and biological processes in the estuary (Jassby et al. 1995; Kimmerer 2002a; Kimmerer 2004; MacWilliams et al. 2015).

X2, rather than another salinity isohaline was chosen as the low-salinity zone habitat metric because it is a frontal zone or boundary upstream of which, salinity tends to be the same from the surface of the water to the bottom, and downstream of which, salinity varies from top to bottom. That variability in the vertical distribution of salinity is indicative of currents that help to aggregate passive particles like sediment and phytoplankton near X2.

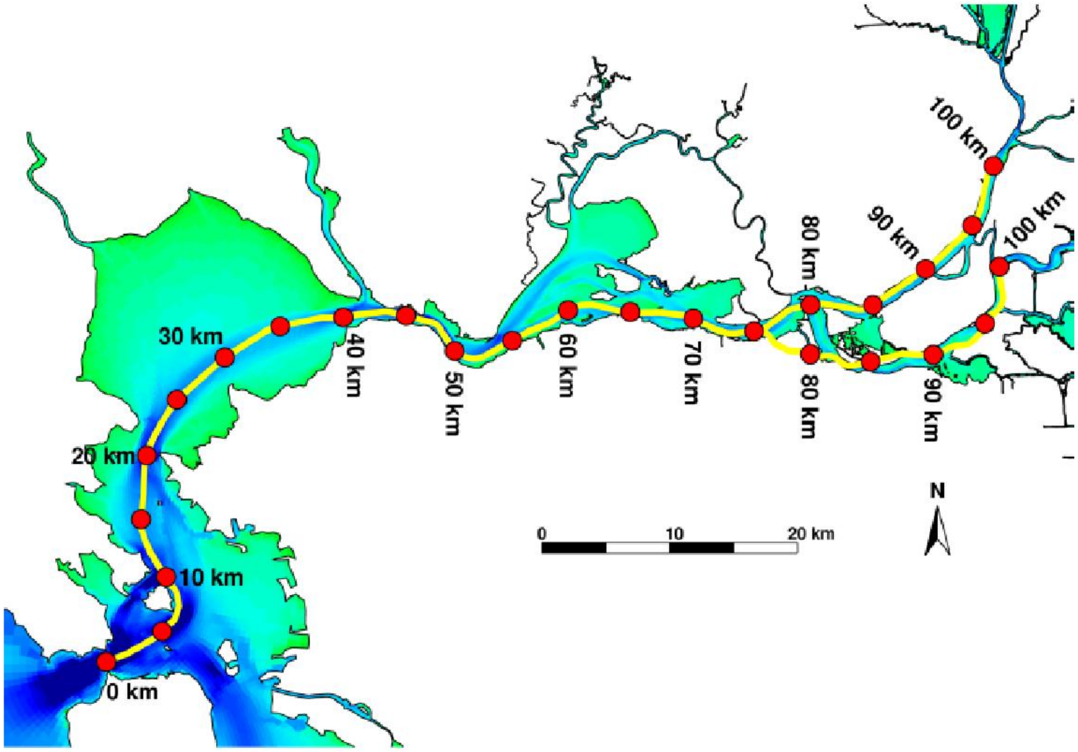


Figure 2. The northern reach of the Bay-Delta as depicted in the UnTRIM 3-D Bay-Delta model. The red circles depict km distances from the Golden Gate Bridge along the axis of the upper estuary into the Sacramento and San Joaquin rivers. Source: MacWilliams et al. (2015).

Pre-development outflows from the Delta were higher in the winter and spring than they are now while summer and fall outflows were lower (Andrews et al. 2017; Gross et al. 2018; Figure 3).

Because Delta outflow is the largest source of freshwater to the estuary, X2 also varied more within and among years than it now does. Presently, X2 typically varies from about 50-100 km depending on season and water year type (Gross et al. 2018, and see Figure 2 for km reference points). It is estimated that pre-development, under the same precipitation regime, it would have varied from about 35-130 km. Given its higher intra-annual variation in Delta outflow and shallower bathymetry, in the pre-development estuary, X2 would remain in San Pablo Bay for months at a time in the winter-spring of below-normal and wetter water year types before rapidly retreating landward (upstream) into the Delta in the late summer-fall. In the contemporary estuary, X2 spends nearly all of its wet season time in Suisun Bay (landward or 'upstream' of historical) and dry season time in the western Delta (seaward or 'downstream' of historical).

By 1920, most of the Delta's tidal wetlands had been reclaimed (Whipple et al. 2012). Further, some sport fishes like striped bass and American shad that were intentionally introduced in the latter 19th century, had successfully established themselves in the estuary-coastal ocean food web (Scofield and Bryant 1926; Moyle 2002). In 1920, the river inflows to the Delta had been reduced all year around, but the shape of the annual hydrograph remained similar to the pre-development condition (Gross et al. 2018; Figure 3). Between 1920 and the onset of SWP exports in 1968, water storage capacity in the Bay-Delta watershed grew from about 4 MAF to more than 40 MAF. Greater reservoir storage and the increasing export of water from the Delta have interacted with non-CVP and SWP water storage and diversions to lessen the inter-annual variablility in Delta outflow and X2 (Andrews et al. 2017; Hutton et al. 2017a,b; Gross et al. 2018; Figure 3). This occurred because the general water management strategy in California is to store water during the wet season and re-distribute it during the dry season to provide a more reliable supply than was available naturally. In addition, the CVP and SWP have had to offset a considerable summertime water deficit to protect the quality of their exported water and to protect water quality for senior water rights holders in the Delta. These uses would be highly impaired without water released from CVP and SWP reservoirs during the summer and fall (Hutton et al. 2017b).

During the 1930s to 1960s, the navigation channels were dredged deeper (~12 m) to accommodate shipping traffic from the Pacific Ocean and San Francisco Bay to ports in Sacramento and Stockton and to increase the capacity of the Delta to convey flood waters. Channel deepening interacted with the simultaneously increasing water storage to change the Bay-Delta ecosystem into one in which Suisun Bay and the Sacramento-San Joaquin River confluence region became the largest and most depth-varying places in the typical range of the low-salinity zone. Even with these changes, the low-salinity zone remained a highly productive fish nursery habitat for many decades (Stevens and Miller 1983; Moyle *et al.* 1992; Jassby *et al.* 1995).

The deeper channels through the estuary improved ship access and flood control, but resulted in more outflow being needed to maintain the low-salinity zone in the Suisun Bay/river confluence region than was once required. The landscape changes that have accumulated since 1850 due to wetland reclamation and channelization were recently estimated to account for an annual average upstream shift in X2 of about 5 km (Andrews et al. 2017). In addition to hydrodynamic changes, the shipping itself has historically been a source of unintentional introductions of non-native organisms. From the 1970s to the 1990s, the propagule pressure from ship ballast water interacted with low outflows during droughts to facilitate numerous species invasions that have changed the ecology of the upper estuary (Moyle 2002; Winder *et al.* 2011; Kratina *et al.* 2014). The lack of new zooplankton or fish species introductions during the most recent droughts between 2007 and 2015 suggests that ballast water regulations are working to limit new species invasions ().

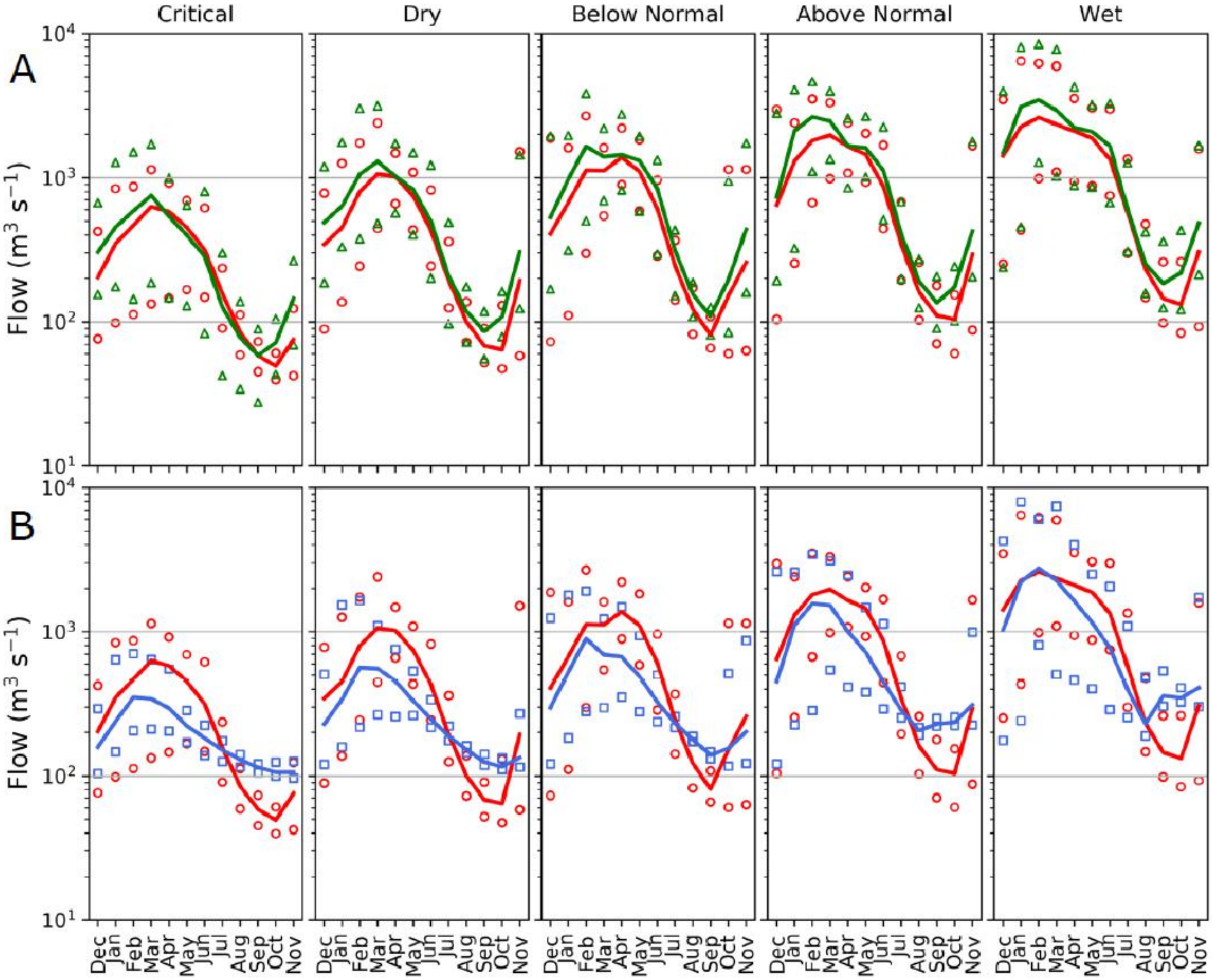


Figure 3. Comparisons of modeled depictions of monthly Delta outflow for five water year types for three historical time periods. Estimates of the circa 1850 flow regime are green symbols and lines in Panel A and red symbols and lines in Panel B. Estimates of the circa 1920 flow regime are red symbols and lines in Panel A and estimates of the contemporary flow regime are blue symbols and lines in Panel B. Source: Gross et al. (2018).

The biomass of delta smelt in the upper estuary was already lower than the other commonly collected pelagic fishes when both projects began exporting water in 1968 (Figure 4). Its biomass had likely always been lower than the native northern anchovy and longfin smelt which had access to marine productivity, but striped bass, American shad, and threadfin shad are non-native species that had all managed to surpass delta smelt in relative importance in the fish community. The delta smelt has been in general decline for much of the past five decades along with other dominant members of the pelagic fish community (see also Feyrer et al. 2015).

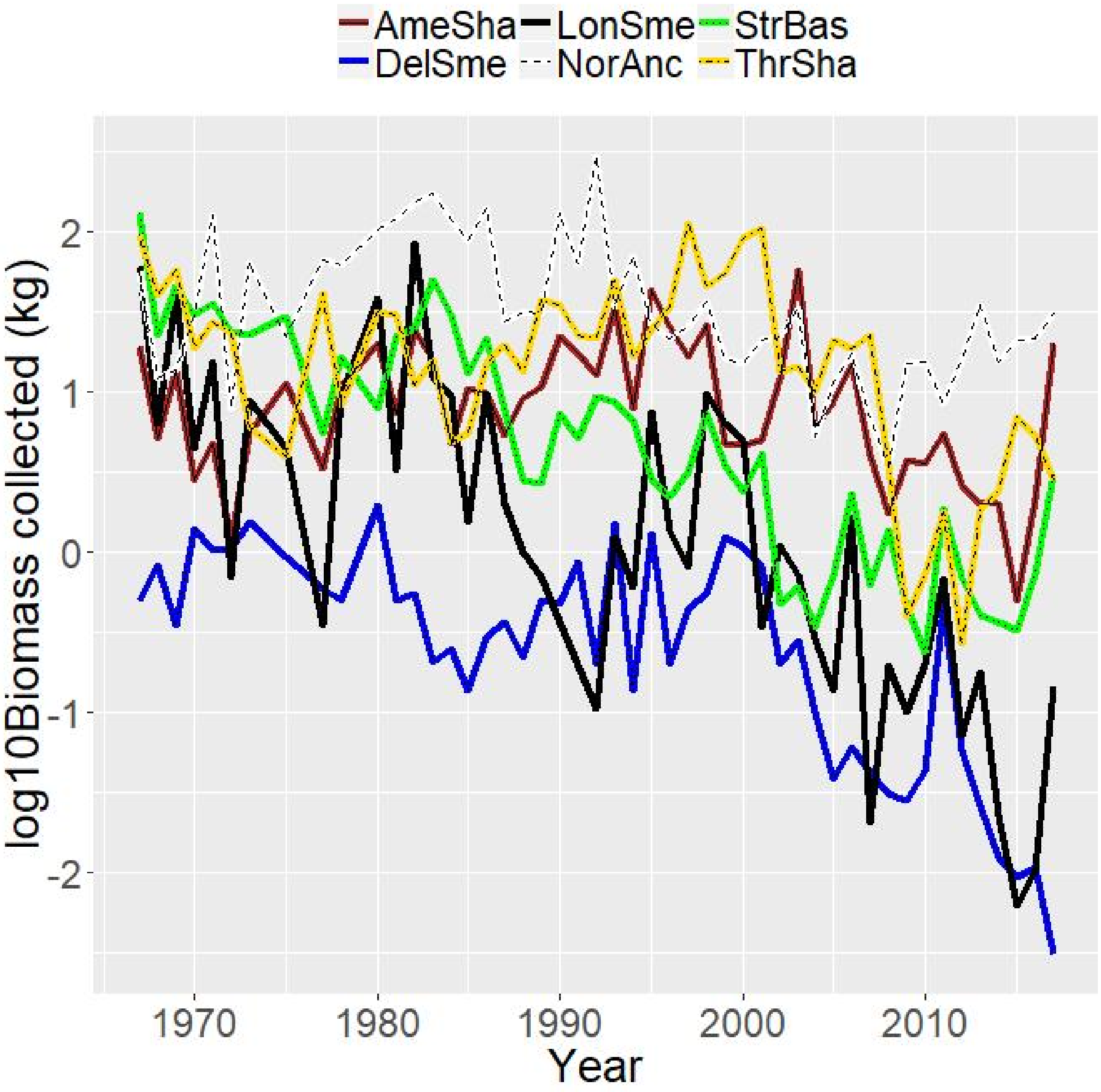


Figure 4. Time series of the collected biomass of six pelagic fishes commonly encountered by the California Department of Fish and Wildlife's Fall Midwater Trawl Survey, 1967-2017. The red line is American shad, the black line is longfin smelt, the green line is age-0 striped bass, the dashed black line with white envelope is northern anchovy, the yellow line

is threadfin shad, and the blue line is delta smelt. Source: USFWS unpublished data analysis.

Trends in Flow and Hydrodynamics (1968-Present)

The development of major new water storage in the Bay-Delta watershed has not increased since the 1980s (Cloern and Jassby 2012; Hutton et al. 2017a). This has combined with increasing human demand for fresh water to result in a zero-sum game between human water demand and environmental water uses – including the maintenance of the hydraulic salinity barrier needed to protect exported water and other in-Delta water users from salinity intrusion (Hutton et al. 2017b; Reis et al. 2019). Exports steadily increased from the 1950s into the 1980s, but average annual exports began to level off in the latter 1980s and early 1990s. As the average annual exports leveled off, the year to year variability in exports increased substantially (Cloern and Jassby 2012), which increases annual uncertainty about how much water will be supplied south of the Delta.

Because of the zero-sum nature of California water, Delta outflow has been trending downward for many decades (Hutton et al. 2017a,b; Reis et al. 2019; Figures 5 and 6), though D-1641 appears to have halted the trend for years in which the eight river index is lower than 20 million acre-feet (MAF; middle panel of Figure 5). In Figure 5, exports were modeled as depletions of water from the system, so the more negative the number on the y-axis of the middle panel, the higher the exports. Thus, Figure 5 shows that in years when the eight river index is more than 20 MAF, exports continue to increase, but in years when the eight river index is lower than 20 MAF, exports have been trending lower, which has helped stem the long-term decline in Delta outflow in these years of lower precipitation. Both of these trends cause the higher year to year variability in water exports.

Delta outflow is a driver or an indicator of many ecological mechanisms in the Bay-Delta (Kimmerer 2002a). Reis et al. (2019) recently described super-critical water years with respect to Delta outflow. The frequency of these super-critical water years has been much higher since 1976 than it was from 1920-1975 (Figure 6). Major changes in the flow regime of an aquatic ecosystem are expected to be accompanied by ecological change, and that is what has been observed over time in the Bay and Delta (Matern et al. 2002; Winder et al. 2011; Feyrer et al. 2015; Conrad et al. 2016). The remainder of this status of the species and its critical habitat section discusses contemporary ecosystem changes and their likely relevance to the delta smelt focusing on both its physical habitat and the food web it is a part of.

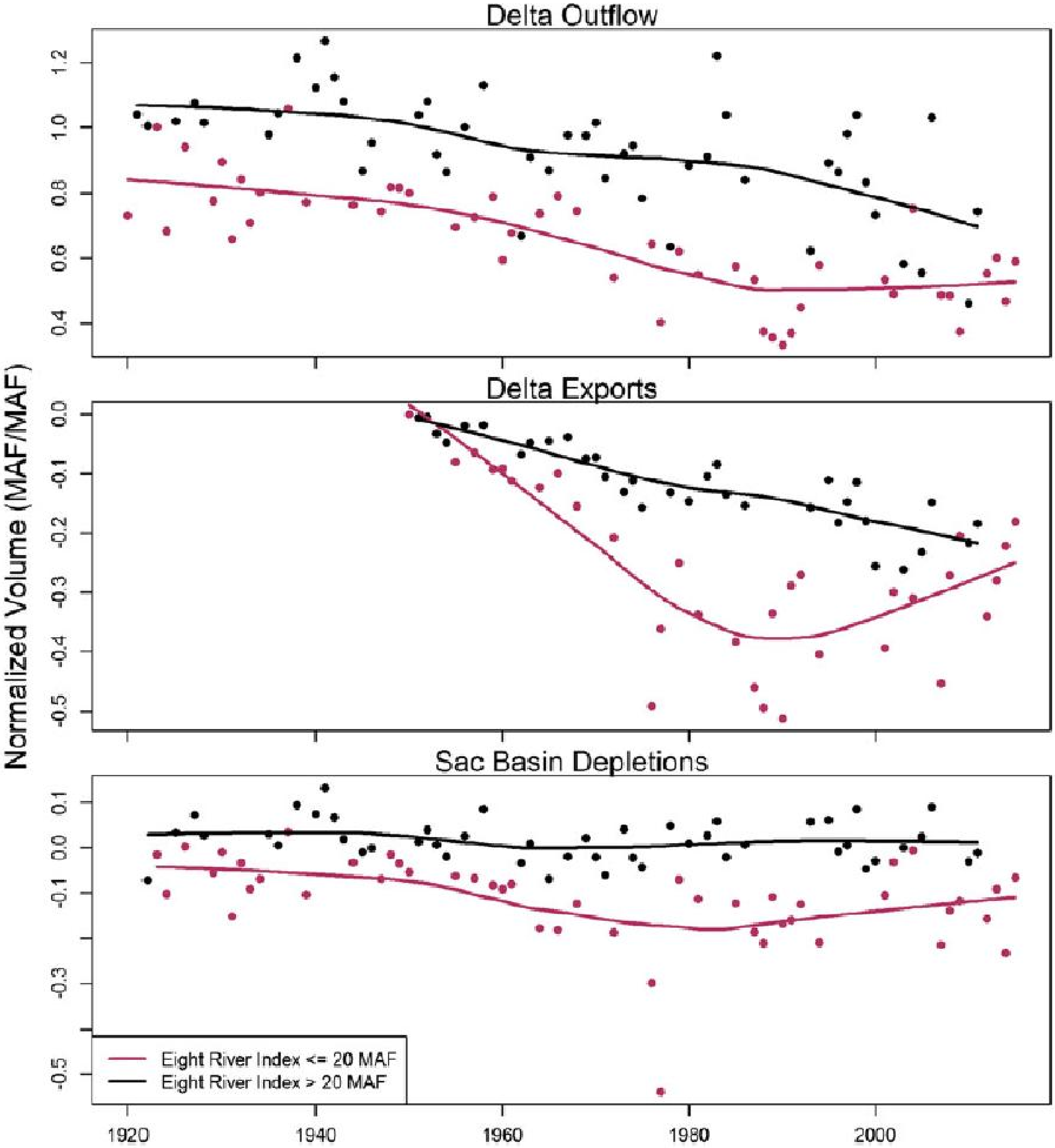


Figure 5. Time series (1922-2015) of statistical trend outputs of annual Delta outflow (top panel), Delta exports treated as depletions so increasing exports are represented by more negative values (middle panel), and water diversions from the Sacramento River basin upstream of the Delta (bottom panel). Black symbols and lines are for years in which the eight river index, a measure of water availability in the Bay-Delta watershed, was greater

than 20 million acre-feet (MAF). Red symbols and lines are for years in which the eight river index was less than or equal to 20 MAF. Source: Hutton et al. (2017b).

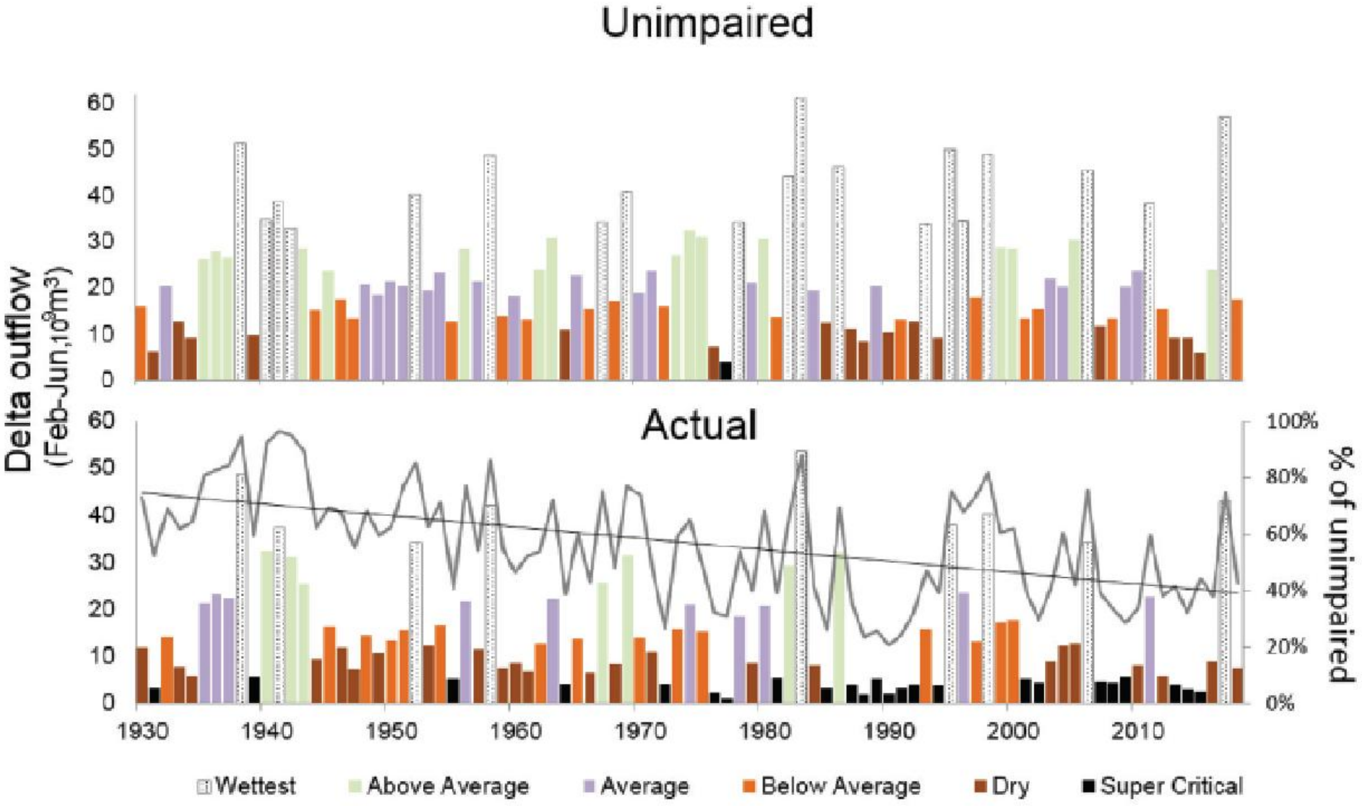


Figure 6. Time series of estimates of unimpaired (upper panel) and actual (lower panel) Delta outflow (February-June) color-coded according to six water year types, 1930-2018. The water year types based on basin precipitation are shown in the upper panel. In the lower panel, the water year types were re-assessed based on their fraction of the estimated unimpaired outflow. The long-term trend in this fraction as "% of unimpaired" is shown on the second y-axis of the bottom panel. Source: Reis et al. (2019).

Delta Smelt Population Trend

The California Department of Fish and Wildlife's (CDFW) Summer Townet Survey (http://www.dfg.ca.gov/delta/data/townet/indices.asp?species=3) and Fall Midwater Trawl Survey (http://www.dfg.ca.gov/delta/data/fmwt/indices.asp) are the two longest running indicators of the delta smelt's abundance trend. Indices of delta smelt relative abundance from these surveys date to 1959 and 1967, respectively. The Fall Midwater Trawl (FMWT) index has traditionally been the primary indicator of delta smelt trend because it samples later in the life cycle, providing a better indicator of annual recruitment than the townet survey (Service 1996). It has also sampled more consistently and more intensively than the Summer Townet Survey. The FMWT deploys more than 400 net tows per year over its four-month sampling season. The highest FMWT index for delta smelt (1,673) was recorded in 1970. A comparably high index (1,654) was reported in 1980. The last FMWT index exceeding 1,000 was reported in 1993. The last FMWT indices exceeding 100 were reported in 2003 and 2011. In 2018, the FMWT index was zero for the first time. The Summer Townet index for delta smelt has been zero three times since 2015. Thus, the Summer Townet Survey and FMWT have recorded a 40-50 year decline in which delta smelt went from a minor (but common) pelagic fish species to essentially undetectable by these long-term surveys.

Following the ESA listing of the delta smelt, the CDFW launched a 20-mm Survey (1995) and a Spring Kodiak Trawl Survey (SKT; 2002) to monitor the distribution and relative abundance of late larval stage and adult delta smelt, respectively. The Service recently completed a new delta smelt abundance indexing procedure using data from all four of the CDFW monitoring programs mentioned here (Polansky et al. in revision). The CDFW methods generate abundance indices from each survey but each index is on a different numeric scale. This means the index number generated by a given survey only has meaning relative to other indices generated by the same survey. Further, the CDFW indices lack estimates of uncertainty (variability) which limits interpretation of abundance changes from year to year even within each sampling program. The Service method improves upon the CDFW method because it generates abundance indices in units of numbers of fish along with measures of uncertainty. Service indices of spawner abundance based on combined January and February SKT sampling are listed with their confidence intervals in Table 1. The estimates show the most recent 18 years of the delta smelt's longer-term decline. The 2019 abundance estimate of 5,610 is the lowest on record, though the upper confidence limit for the 2019 estimate overlaps the lower confidence limits from 2016 and 2018. This indicates there is more than a five percent chance that the 2019 abundance index is not different from 2016 and 2018. Regardless of this recent year uncertainty, the 2019 abundance index is much lower than peak abundance estimates in Table 1, which themselves are all based on data streams that started after the species had already declined considerably (Figure 4).

Table 1. Estimates of adult delta smelt population size during January-February of 2002 through 2016 with 95% confidence intervals. If the confidence intervals of any pair of years overlap, then the population may not have differed in size between those years.

			95% Confidence Interval			Number of Delta Smelt Caught in the SKT Survey		
Year	Abundance Estimate	Standard Error	Lower Bound	Upper Bound		January	February	Year-to-Year Ratio
2002	1,093,244	195,329	760,332	1,523,294		262	394	NA
2003	996,055	261,205	581,197	1,597,198		NA	232	0.91
2004	966,981	262,190	553,729	1,573,002		380	300	0.97

2005	715,858	147,190	470,572	1,044,828		220	218	0.74
2006	272,327	42,400	198,681	364,438		44	84	0.38
2007	449,466	128,731	249,216	749,168		109	107	1.65
2008	509,428	188,396	236,859	963,839		132	36	1.13
2009	1,166,145	523,856	459,083	2,464,804		579	61	2.29
2010	251,863	54,580	161,753	374,582		88	57	0.22
2011	461,599	202,547	185,712	962,088		177	128	1.83
2012	1,177,201	328,682	662,728	1,939,836		320	287	2.55
2013	333,682	89,809	191,886	541,064		100	125	0.28
2014	308,972	91,474	167,858	522,884		148	55	0.93
2015	213,345	76,639	101,434	397,439		21	68	0.69
2016	25,445	9,584	11,661	48,622		7	6	0.12
2017	73,331	23,342	38,010	128,459		18	8	2.88
2018	26,649	21,397	5,215	82,805		10	4	0.36
2019	5,610	4,395	1,138	17,135		1	1	0.21

For this opinion, the Service developed three models to explore expected delta smelt population trends between now and the latter 2020s (appendix Polansky). All three models were state-space models that statistically separate uncertainties due to observation errors (sampling error) from variability caused by other sources, often referred to as process noise. State-space models also propagate both sources of uncertainty throughout the time series of their calculations. The first model was a multiple life stage model that predicted delta smelt recruitment between generations as the abundance of age-0 fish in May that were produced by the estimated number of adults alive during the previous February and March. Note that Table 1 presents results for January-February because these months have been the focus of regulatory efforts over the past few years. Thus, the abundance indices used in this model exploration are not the same ones listed in the table, though they are correlated (r^2=0.61). The multiple life stage model also estimated survival of each new generation of recruits at three subsequent points in their life cycle. The model was fit to abundance data for each life stage for the years 1995–2017, and allowed a change in either the expected survival or recruitment beginning in December 2008 to coincide with issuance of the previous delta smelt water operations biological opinion. The latter two models were two variations of an annual time step model, i.e., they are models in which delta smelt abundance was only estimated at the adult life stage each year. One of the annual time-step models used a change-point for years ≥ 2009 and the other did not. This change-point is a statistical term reflecting that this model has a different expected population growth rate and a separate estimate of the process noise for 1995-2008 than it does for 2009-2017. The rationale for the two annual time step model variations was (1) to determine whether there was evidence for a change in population growth rate coincident with the delta smelt and anadromous fish biological opinions, and (2) whether such a change would affect predictions of future abundances. The annual time step models were fit to adult abundance data for 2002-2017. Projections of future abundance were based solely on resampling previously observed population growth rates (λ). When $\lambda > 1$, the population has increased, and when $\lambda < 1$, it has decreased. Because the delta smelt population was declining over the modeled period, the average or median λ was lower than 1. Further details are provided in appendix Polansky.

All three models fit the 2002-2017 adult abundance data well (Figure 7). The stage-structured (multiple life stage) model indicated that winter survival increased during 2009-2017, but that summer and fall survival have likely decreased since 2008 (appendix Polansky). The annual time step models were noisier and therefore, results were less clear. This is somewhat expected since the annual time step models fit to fewer life stages and therefore cannot capture variation that affects recruitment and survival at a time step shorter than the full life span of the delta smelt. Prior to any process noise factors, the mean and median estimated λ were less than one in both annual time step models (and both time steps of the change-point version), reflecting the species' decline. However, confidence intervals showed that these estimates could sometimes be greater than or equal to one.

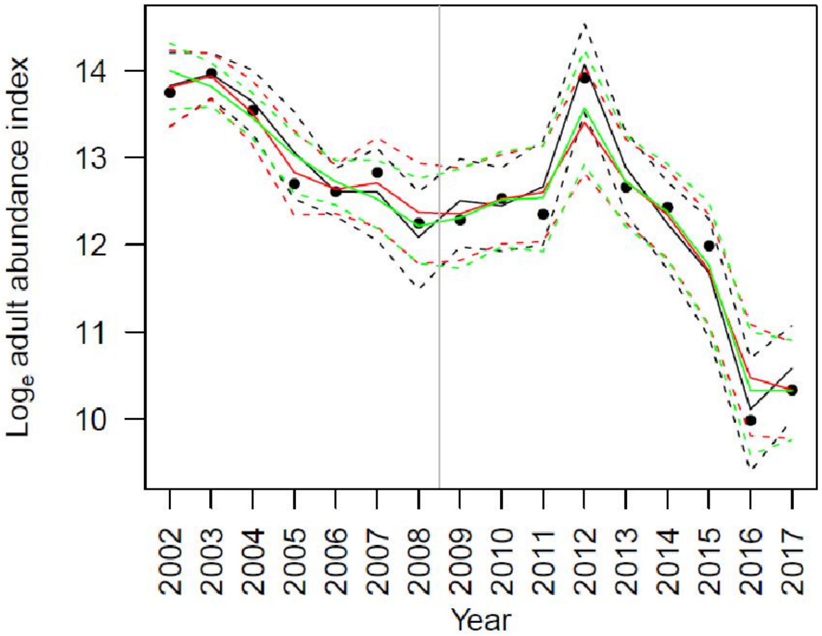


Figure 7. Estimated adult delta smelt abundance indices (on a natural log scale) for 2002-2017 (black circles; Polansky et al. in revision). The solid lines are predictions of the abundance indices from the three models described above (black=stage structured, red=annual model without a change-point, and green=annual model with a 2009 change-point). The solid lines are the mean prediction and the dashed lines represent the limits of the 95% central Bayesian credible intervals. Source: USFWS unpublished data analysis.

Despite the differences in signal to noise ratio in the alternative model constructs, Figure 8 shows that all three models generated similar predictions of the annual population growth rate λ, though the annual model lacking a 2009 change point did not track the stage-structured model predictions as well as the annual model that included the change point. Collectively Figures 7 and 8 confirm that each of the three models would on average be expected to generate similar future projections of λ, and by extension, abundance.

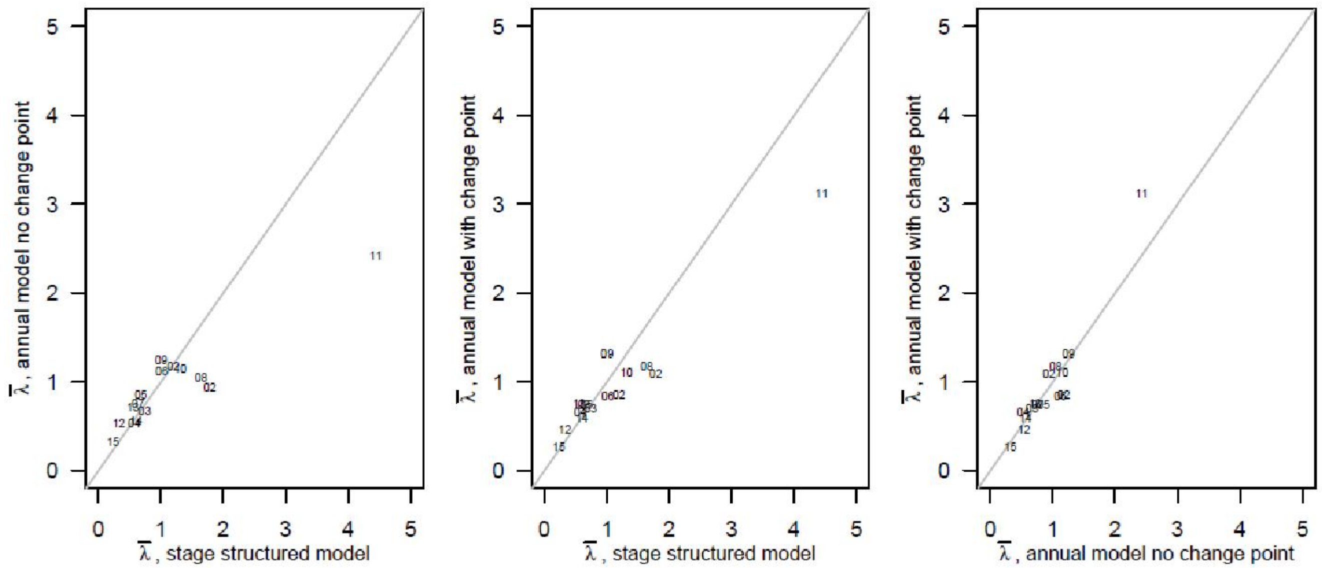


Figure 8. Scatterplots of mean population growth rate (λ) from the three population trend models described above. Data points are labelled by the cohort year. Source: USFWS unpublished data analysis.

Projections of delta smelt abundance indices over a 10-year period were made using the stage-structured (multiple life stage) model and the annual model with a 2009 change point, all of which account for parameter estimate uncertainty and process noise (Figure 9). Both models predict continued decline whether or not pre-2009 or post-2008 vital rates were used to make the projections. This provides strong evidence that the delta smelt population will most likely continue to decline.

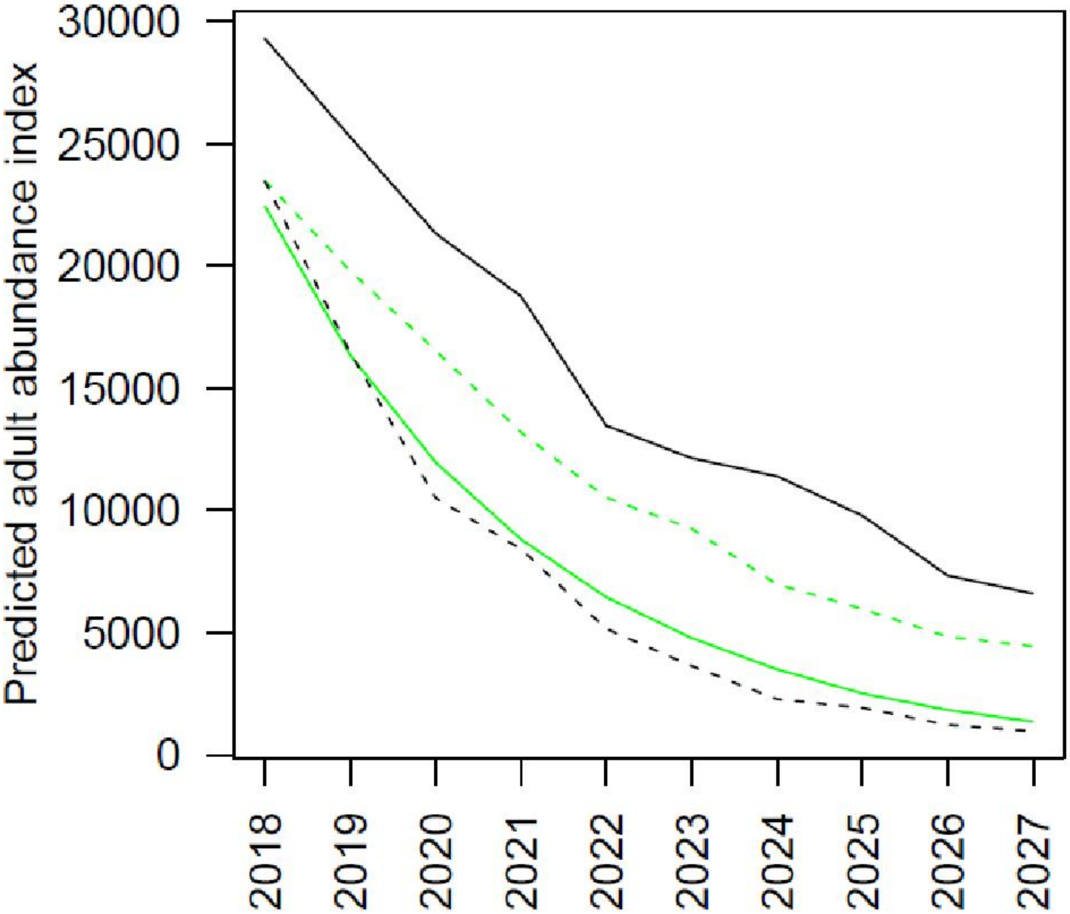


Figure 9. Median future abundance index predictions for delta smelt based on two of the three models described above: black=stage-structured, and green=annual model with a 2009 change-point. Solid lines reflect predictions made using pre-2009 vital rates and dashed lines reflect predictions made using ≥ 2009 vital rates. Source: USFWS unpublished data analysis.

Reproductive Strategy

Delta smelt spawn in the estuary and have one spawning season for each generation, which makes the timing and duration of the spawning season important every year. Delta smelt are believed to spawn in fresh and low-salinity water (Bush 2017). Therefore, freshwater flow affects how much of the estuary is available for delta smelt to spawn (Hobbs *et al.* 2007b).

Delta smelt can start spawning when water temperatures reach about 10°C (50°F) and can continue until temperatures reach about 20°C

(Bennett 2005; Damon et al. 2016). The ideal spawning condition occurs when water temperatures remain 10°C to 20°C throughout February through May. Few delta smelt ≤ 55 mm in length are sexually mature and 50% of delta smelt reach sexual maturity at 60 to 65 mm in length (Rose *et al.* 2013b). Thus, if water temperatures rise much above 10°C in January, the "spawning season" can start before many individuals are mature enough to actually spawn. If temperatures continue to warm rapidly toward 20°C in early spring, that can end the spawning season with only a small fraction of 'adult' fish having had an opportunity to spawn. Delta smelt were initially believed to spawn only once before dying (Moyle *et al.* 1992). It has since been confirmed that delta smelt can spawn about once per month if water temperatures remain suitable for a long enough time, and if the adults find enough food to support the production of another batch of eggs (Lindberg *et al.* 2013; Damon et al. 2016; Kurobe *et al.* 2016). As a result, the longer water temperatures remain cool, the more fish have time to mature and the more times individual fish can spawn. Most adults disappear from monitoring programs by May, suggesting they have passed away (Damon et al. 2016; Polansky et al. 2018).

The reproductive behavior of delta smelt is only known from captive specimens spawned in artificial environments and most of the information has never been published, but is currently being revisited in new research. Spawning likely occurs mainly at night with several males attending a female that broadcasts her eggs onto bottom substrate (Bennett 2005). Although preferred spawning substrate is unknown, spawning habits of delta smelt's closest relative, the Surf smelt (*Hypomesus pretiosus*), are sand or small gravel (Hirose and Kawaguchi 1998; Quinn et al. 2012).

The duration of the egg stage is temperature-dependent and averages about 10 days before the embryos hatch into larvae (Bennett 2005). It takes the fish about 30-70 days to reach 20-mm in length (Bennett 2005; Hobbs et al. 2007a). Similarly, Rose et al. (2013b) estimated that it takes delta smelt an average of slightly over 60 days to reach the juvenile life stage. Metamorphosing "post-larvae" appear in monitoring surveys from April into July of most years. By July, most delta smelt have reached the juvenile life stage. Thus, subtracting 60 days indicates that most spawning occurs from February-May.

Hatching success is highest at temperatures of 15-16°C (59-61°F) and lower at cooler and warmer temperatures. Hatching success nears zero percent as water temperatures exceed 20°C (68°F) (Bennett 2005). Water temperatures suitable for spawning occur most frequently during the months of February-May, but ripe female delta smelt have been observed as early as January and larvae have been collected as late as July, suggesting that spawning itself may sometimes extend into June.

Habitat and Distribution

Because the delta smelt only lives in one part of one comprehensively monitored estuary, its general distribution and habitat use are well understood (Moyle *et al.* 1992; Bennett 2005; Hobbs *et al.* 2006; 2007b; Feyrer *et al.* 2007; Nobriga *et al.* 2008; Kimmerer *et al.* 2009; Merz *et al.* 2011; Murphy and Hamilton 2013; Sommer and Mejia 2013; Mahardja et al. 2019; Simonis and

Merz 2019). There are both location-based (*e.g.*, Sacramento River around Decker Island) and conditions-based (low-salinity zone) habitats that delta smelt permanently occupy. There are habitats that delta smelt occupy seasonally (*e.g.*, for spawning), and there are habitats that delta smelt occupy transiently, which we define here as occasional use. Transient habitats include distribution extremes from which delta smelt have occasionally been collected, but are not collected every year or even in most years.

Delta smelt have been observed as far west as San Francisco Bay near the City of Berkley, as far north as Knight's Landing on the Sacramento River, as far east as Woodbridge on the Mokelumne River and Stockton on the Calaveras River, and as far south as Mossdale on the San Joaquin River (Merz et al. 2011; Figure 10). These extremes of the species' distribution extend beyond the geographic boundaries specified in the critical habitat rule. However, most delta smelt have been collected from locations within the critical habitat boundaries. In other words, observations of delta smelt outside of the critical habitat boundaries reflect transient habitat use rather than permanent or seasonal habitat use. The Napa River is the only location outside of the critical habitat boundaries that may be used often enough to be considered a seasonal habitat rather than a transient one.

The fixed-location habitats that delta smelt permanently occupy span from the Cache Slough 'complex' down into Suisun Bay and Suisun Marsh (Figure 11). The reasons delta smelt are believed to permanently occupy this part of the estuary are the presence of fresh- to low-salinity water year around that is comparatively turbid and of a tolerable water temperature. These appropriate water quality conditions overlap an underwater landscape featuring variation in depth, tidal current velocities, edge habitats, and food production (Nobriga *et al.* 2008; Feyrer *et al.* 2011; Murphy and Hamilton 2013; Sommer and Mejia 2013; Hammock *et al.* 2015; 2017; 2019; Bever *et al.* 2016; Mahardja et al. 2019; Simonis and Merz 2019). With the possible exception of salinity, which is covered in more detail in the status of critical habitat, field observations are increasingly being supported by laboratory research that explains how delta smelt respond physiologically to variation in water quality that can vary with changes in climate, freshwater flow and estuarine bathymetry (e.g., Hasenbein *et al.* 2013; 2016; Komoroske *et al.* 2014; 2016).

The principal variable-location habitat that delta smelt permanently occupy is the low-salinity zone (Moyle et al. 1992; Bennett 2005). The low-salinity zone is a dynamic habitat with size and location that respond to changes in tidal and river flows (Jassby et al. 1995; MacWilliams et al. 2015; 2016; Bever et al. 2016). The low-salinity zone generally expands and moves downstream as river flows into the estuary increase, placing low-salinity water over a larger and more diverse set of nominal habitat types than occurs under lower flow conditions. As river flows decrease, the low-salinity zone contracts and moves upstream.

The low-salinity zone often encompasses many of the permanently occupied fixed locations discussed above. It is treated separately here because delta smelt distribution tracks the movement of the low-salinity zone somewhat (Moyle et al. 1992; Dege and Brown 2004; Feyrer et al. 2007; 2011; Nobriga et al. 2008; Sommer et al. 2011; Bever et al. 2016; Manly et al. 2016; Polansky et al. 2018; Simonis and Merz 2019). Due to its historical importance as a fish nursery habitat, there is a long research history into the physics and biology of the low-salinity zone. The low-salinity zone is frequently defined as waters with a salinity range of about 0.5 to 6 ppt (Kimmerer 2004). This and similar salinity ranges reported by different authors were chosen based on analyses of historical peaks in chlorophyll concentration and zooplankton abundance. Most delta smelt collected in the 20-mm and Summer Townet Surveys have been collected at salinities of near 0 ppt to 2 ppt and most of the (older) delta smelt in the FMWT have been collected from a salinity range of about 1.5 to 4 ppt (Kimmerer et al. 2013). These fish do not tend to be in dramatically different places (Murphy and Hamilton 2013; Figure 11), suggesting that some of the change in occupied salinity with age is due to the seasonal increases in salinity that accompany lower outflow in the summer and fall.

Each year, the distribution of delta smelt seasonally expands when adults disperse in response to winter flow increases that also coincide with seasonal increases in turbidity and decreases in water temperature (Sommer et al. 2011; Figure 11). The annual range expansion of adult delta smelt extends up the Sacramento River to about Garcia Bend in the Pocket neighborhood of Sacramento, up the San Joaquin River from Antioch to areas near Stockton, up the lower Mokelumne River system, and west throughout Suisun Bay and the larger sloughs of Suisun Marsh. Some delta smelt seasonally and transiently occupy Old and Middle rivers in the south Delta each year, but face a high risk of entrainment when they do (Kimmerer 2008; Grimaldo *et al.* 2009). The expanded adult distribution initially affects the distribution of the next generation because delta smelt eggs are adhesive and not believed to be highly mobile once they are spawned (Mager et al. 2004). Thus, the distribution of larvae reflects a combination of where spawning occurred and freshwater flow when the eggs hatch.

In summary, the delta smelt population spreads out in the winter and then retracts by summer into what is presently a bi-modal spatial distribution with a peak in the low-salinity zone and a separate peak in the Cache Slough complex. Most individuals occur in the low-salinity zone at some point in their life cycle (Bush 2017). The use of the Cache Slough complex diminishes in years with warm summers. The part of the population that occupies the low-salinity zone or immediately adjacent waters, varies in concert with variation in the location of X2, though this effect of freshwater flow (or salinity) on distribution weakens as the fish get older.

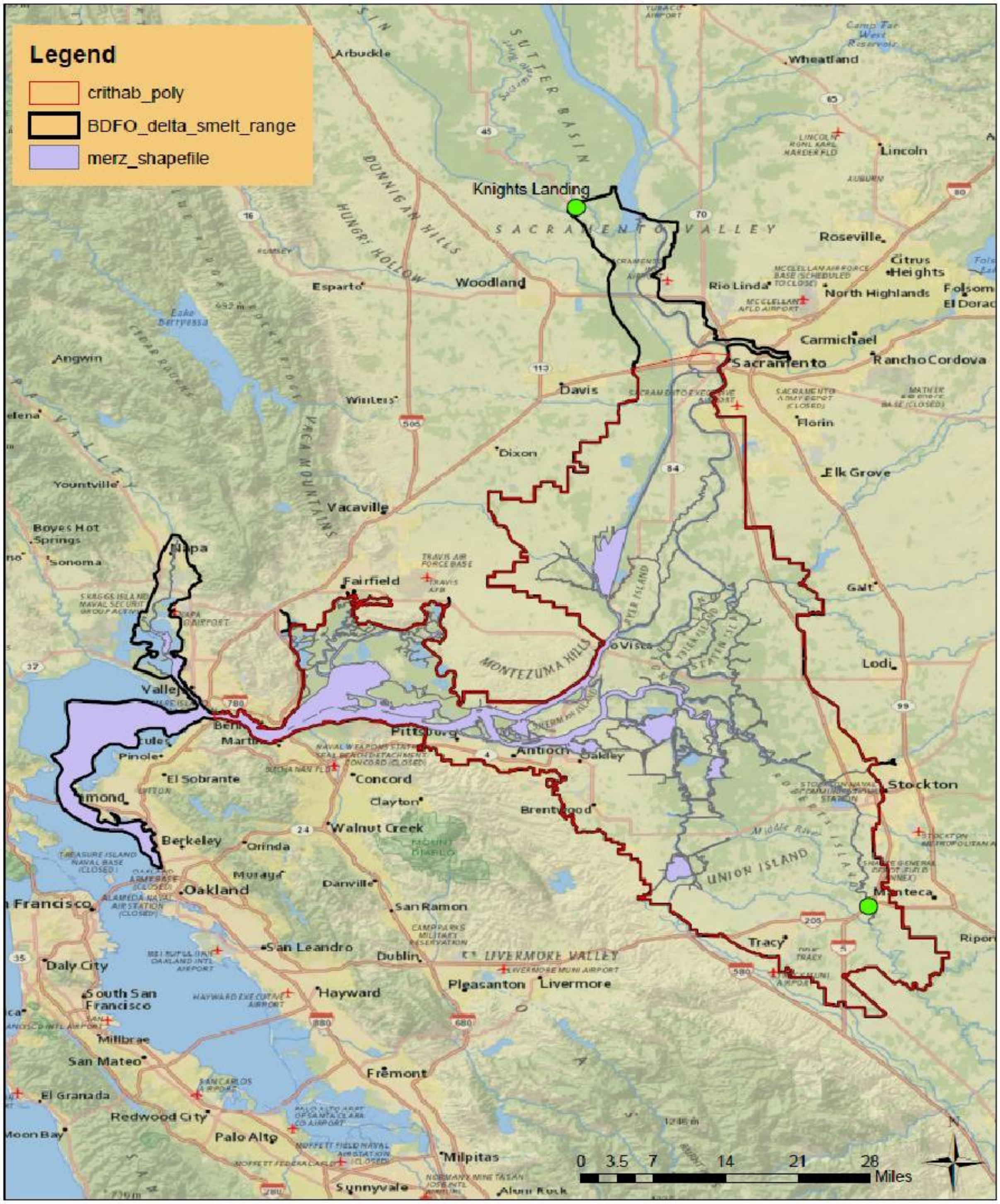
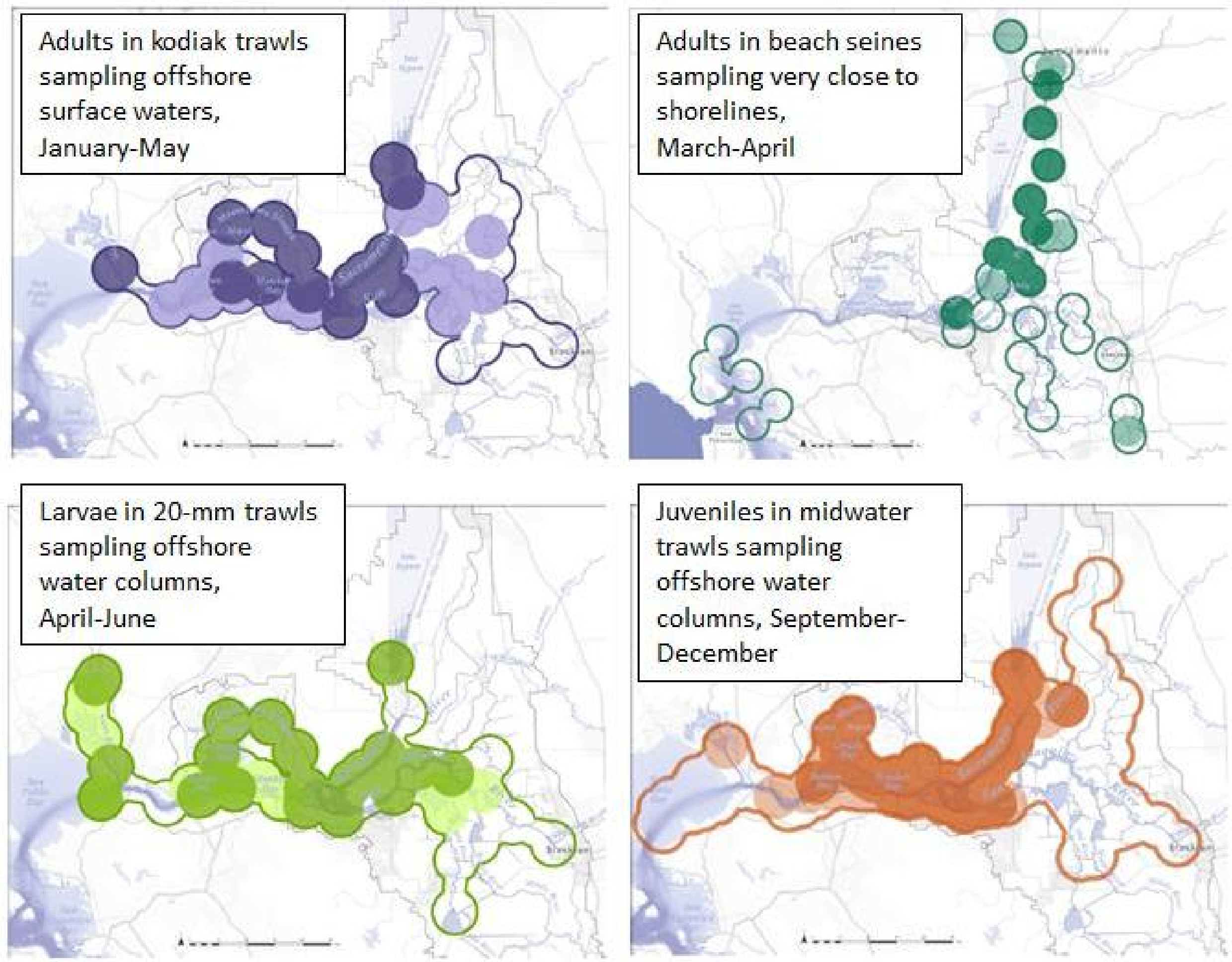


Figure 10. Delta smelt range map. Waterways colored in purple depict the delta smelt distribution described by Merz *et al.* (2011). The Service has used newer information to expand the transient range of delta smelt further up the Napa and Sacramento rivers than indicated by Merz *et al.* (2011). The red polygon depicts the delta smelt's designated critical habitat.



Adults in kodiak trawls sampling offshore surface waters, January-May

Adults in beach seines sampling very close to shorelines, March-April

Larvae in 20-mm trawls sampling offshore water columns, April-June

Juveniles in midwater trawls sampling offshore water columns, September-December

Figure 11. Maps of multi-year average distributions of delta smelt collected in four monitoring programs. The sampling regions covered by each survey are outlined. The areas with dark shading surround sampling stations in which 90 percent of the delta smelt collections occurred, the areas with light shading surround sampling stations in which the next 9 percent of delta smelt collections occurred. Note the lack of sampling sites in Suisun Bay and marsh for the beach seine (upper right panel). Source: Murphy and Hamilton (2013).

Food

At all life stages, numerous small crustaceans, especially calanoid copepods, make up most of the delta smelt diet (Nobriga 2002; Slater and Baxter 2014); however, adult delta smelt also prey on larger crustaceans and larval fishes (Moyle et al. 1992; Hammock et al. 2019). All of the delta smelt's major prey taxa are ubiquitously distributed, but which prey species are present at particular times and locations changes from season to season and has changed dramatically over time (Winder and Jassby 2011; Kratina *et al.* 2014). This has likely affected delta smelt feeding success (Kimmerer and Rose 2018).

An influence of copepod production on the production of delta smelt has been a common finding in quantitative modeling research on delta smelt's population dynamics (Mac Nally et al. 2010; Maunder and Deriso 2011; Miller et al. 2012; Rose et al. 2013a; Hamilton and Murphy 2018; Kimmerer and Rose 2018). In response, the proposed action includes several project elements intended to increase food supplies for the delta smelt. Thus, comprehensive review of historical changes in the Bay-Delta food web is warranted for this biological opinion.

The earliest published paper on a freshwater flow influence on fish production in the Bay-Delta posited that the mechanisms producing striped bass worked primarily through the low-salinity zone food web (Turner and Chadwick 1972). Specifically, these authors posited that higher Delta inflow stimulated the food web that supported striped bass and increased turbidity which hid them from their predators. Because IEP monitoring was originally set up to better understand striped bass recruitment, the IEP has monitored the pelagic food web extensively since the 1970s (Brown et al. 2016). Diatoms are the group of phytoplankton that tend to be the most important in open-water food webs of estuaries and coastal marine systems. Diatoms are aquatic plants so their water supply is taken care of automatically. They need three additional things to grow: sunlight, nutrients, and time. In the Bay-Delta, the primary historical limit on sunlight was the turbidity of the water so diatoms tended to grow best in shallow water, specifically in shoal areas adjacent to the shipping channels (Cloern et al. 1983; Cole and Cloern 1984). From the low salinity zone fish perspective, Suisun Bay and marsh were the most important places for diatom production because the Delta upstream of the Sacramento-San Joaquin river confluence was already leveed and channelized when plankton monitoring programs began in the 1970s. Historically, the estuary was thought to have excess nutrients for diatom growth, so that nutrients were not considered to limit diatom production (Jassby et al. 2002). Newer research into ammonium inhibition of diatom growth (discussed below) has revised this assumption. The third thing diatoms need to grow is time, and the historical limits on this were water residence time and clam grazing rates (Cloern et al. 1983). It was subsequently shown through modeling and data analysis that water exports could affect food web productivity in the low-salinity zone by affecting rates of organic carbon and diatom subsidy from the Delta (Jassby and Cloern 2000). Turbidity, nutrients, hydraulic residence times, exports and clam grazing all continue to influence diatom production (Jassby et al. 2002; Lucas et al. 2009; Kimmerer and Thompson 2014; Dugdale et al. 2016).

There are two clam species that affect phyto- and zooplankton biomass in the low-salinity zone and delta smelt's adjacent freshwater habitats. The freshwater *Corbicula fluminea*, which has been in the Delta and its tributary rivers since the 1940s, and the estuarine overbite clam *Potamocorbula amurensis*, which started invading the estuary in 1986 and was well-established within a year (Alpine and Cloern 1992). The freshwater clam can suppress diatom production in shallow freshwater habitats (Lucas et al. 2002; Lopez et al. 2006). However, the overbite clam appears to have a larger impact on the food web than the freshwater clam (Alpine and Cloern 1992; Jassby et al. 2002; Kimmerer and Thompson 2014), so the focus will be on the overbite clam.

In the 1970s and early 1980s, scientists had learned that year to year variation in Delta inflow (or salinity at Chipps Island) - especially during the spring and summer - drove the year to year variation in the productivity of the low-salinity zone food web (Cloern et al. 1983; Knutson and

Orsi 1983). The main reasons were: (a) in wet years, the flow brought a lot of nutrients and organic carbon into the low-salinity zone (Jassby and Cloern 2000), and in dry years, the elevated salinity allowed a marine clam (*Mya arenaria*) to colonize Suisun Bay and graze the diatoms down to low levels (Cloern et al. 1983). This in turn lowered the production of the opossum shrimp (*Neomysis mercedis*), which was a key food source for several fish species, particularly striped bass (Knutson and Orsi 1983; Orsi and Mecum 1996; Feyrer et al. 2003). This was one of the food web mechanisms that Turner and Chadwick (1972) had hypothesized led to higher striped bass production in higher flow years. Similar 'fish-flow' relationships were later established for longfin smelt (*Spirinchus thaleichthys*) and starry flounder (*Platyichthys stellatus*); both of these fish are also opossum shrimp predators and were shown to have step-declines in their abundance indices associated with the overbite clam invasion (Kimmerer 2002b).

The overbite clam, once established (~ 1987), resulted in a permanent source of loss to diatoms and copepod larvae in the low-salinity zone that resulted in rapid step-declines in the abundance of the most important historical food web components: diatoms, opossum shrimp, and *Eurytemora affinis*; the latter was a major prey for both the opossum shrimp (Knutson and Orsi 1983) and delta smelt (Moyle et al. 1992). However, no change in delta smelt abundance occurred coincident with the establishment of the overbite clam (Stevens and Miller 1983; Jassby et al. 1995; Kimmerer 2002b; Mac Nally et al. 2010; Thomson et al. 2010). However, the average size of delta smelt declined somewhat coincident with the clam invasion (Sweetnam 1999; Bennett 2005).

Some scientists have hypothesized that the diatom decline was caused by ammonium from wastewater treatment plants more than by overbite clams (Glibert et al. 2011; Dugdale et al. 2012; Parker et al. 2012; Wilkerson et al. 2015). One piece of evidence used to support this hypothesis is an observation that ammonium was frequently crossing a critical 4 micro-molar threshold concentration for diatom growth at about the same time the overbite clam became established. These researchers have established that uptake of dissolved ammonium inhibits the growth rate of diatoms in the Bay-Delta. However, diatoms can still grow on ammonium, and actually take it into their cells preferentially over nitrate, they just grow more slowly using ammonium as their cellular nitrogen source (Dugdale et al. 2007). This means that 'but for' the overbite clam, the diatom population in the low-salinity zone would eventually build up enough biomass each year to metabolize ambient ammonium concentrations to levels below the 4 micro-molar threshold and then increase their growth rate using the nitrate that is also in the water. The problem is that the overbite clam, with help from a few other abundant grazers (Kimmerer and Thompson 2014), depletes diatoms faster than they can metabolize the ammonium in the water. Thus clam grazing is the fundamental reason that summer-fall diatom blooms no longer occur (Cloern and Jassby 2012; Kimmerer and Thompson 2014; Cloern 2019). During spring when Delta outflow is higher, outflow can interact with other factors to limit diatom accumulation as well (Dugdale et al. 2012; 2016). Note that Dugdale et al. (2016) suggested that available estimates of the overbite clam grazing rate were over-estimates, but this assertion has been contested (Kimmerer and Thompson 2014; Cloern 2019).

The largest source of dissolved ammonium is the Sacramento Regional Wastewater Treatment Plant. Upgrades to the facility are expected to occur in 2021-2023, which will result in reductions in dissolved ammonia concentrations in the Delta. It is scheduled to virtually cease its input of all forms of nitrogen beginning in 2023. Once that happens, it should become apparent within a few years how important ammonium versus clam grazing has been to diatom production in the low-salinity zone.

Because the overbite clam repressed the production of historically dominant diatoms and zooplankton, there were numerous successful invertebrate species invasions and changes in plant communities that followed for a decade or so thereafter (Kimmerer and Orsi 1996; Bouley and Kimmerer 2006; Winder and Jassby 2011). Note that extreme drought and propagule pressure are also thought to have contributed the zooplankton species changes (Winder et al. 2011). The most important changes for delta smelt have been changes to the copepod community. The copepod invasions of the late 1980s and early 1990s actually helped stem (but not recover from) what had been a major decline in their abundance (Winder and Jassby 2011). Prior to the overbite clam, delta smelt had diets dominated by *E. affinis* from the time the larvae started feeding in the spring until at least the following fall (Moyle et al. 1992). The overbite clam suppressed the production of *E. affinis* (Kimmerer et al. 1994; Kimmerer and Orsi 1996) and that seems to have opened the door for several non-native copepods including *Pseudodiaptomus forbesi*, which became the new main prey of delta smelt (Moyle et al. 1992; Nobriga 2002; Hobbs et al. 2006; Slater and Baxter 2014; Hammock et al. 2017).

The recognition of *P. forbesi*'s importance to delta smelt led to substantial research into this non-native copepod's population dynamics (Kimmerer and Gould 2010; Sullivan et al. 2013; Kimmerer et al. 2014; Kayfetz et al. 2017; Kimmerer et al. 2018a,b). The delta smelt's primary historical prey (*E. affinis*) bloomed from within the low-salinity zone and had peak abundance near X2 (Orsi and Mecum 1986). This copepod still blooms each spring, but disappears by summer due to overbite clam grazing (Kimmerer et al. 1994). The same thing happens to *P. forbesi* in the low-salinity zone (Kayfetz et al. 2017). However, the *P. forbesi* population survives the summer because its center of reproduction is in freshwater habitats landward of the low-salinity zone. It would disappear from the low-salinity zone altogether were it not for a constant replenishment (or subsidy) from upstream where the overbite clam and a predatory non-native copepod are less abundant. It is the combination of tidal mixing and Delta outflow that seems to provide this subsidy (Kimmerer et al. 2018a,b).

The most obvious test of whether the overbite clam affected delta smelt is a before-after comparison. As mentioned above, this has been tested several times and no obvious effect like the ones reported for striped bass, longfin smelt, and starry flounder has been established. Rather, the first big decline in delta smelt abundance occurred prior to the overbite clam invasion and the second one about 15 years after. Thus, if copepod production limits delta smelt production, it is either a part-time limit (e.g., Hamilton and Murphy 2018), or (a) it was a limiting factor prior to the overbite clam, and (b) it did not become a further limit until sometime thereafter. These are not mutually exclusive hypotheses.

Climate Change

Climate projections for the San Francisco Bay-Delta and its watershed indicate that changes will be substantial by mid-century and considerable by the year 2100. Climate models broadly agree that average annual air temperatures will rise by about 2°C at mid-century and about 4°C by 2100 if current atmospheric carbon emissions accelerate as currently forecasted (Dettinger et al. 2016). It remains highly uncertain whether annual precipitation in the Bay-Delta watershed will trend wetter or drier (Dettinger 2005; Dettinger et al. 2016), but the warmer air temperature projections suggest more precipitation will fall as rain rather than snow and that storms may increase in intensity, but have more dry weather in between them (Knowles and Cayan 2002; Dettinger 2005; Dettinger et al. 2016). This will mean less water stored in spring snowpacks, increased flooding and an associated decrease in runoff for the remainder of the year (Hayhoe *et al.* 2004). Changes in storm tracks may lead to increased frequency of flood and drought cycles during the 21st century (Dettinger *et al.* 2015).

As of 2009, sea level rise had not had much effect on X2 (Hutton et al. 2017b). However, additional sea level rise is another anticipated consequence of a warming global climate and if it is not mitigated, sea level rise will likely influence saltwater intrusion into the Bay-Delta (Rath et al. 2017). For instance, the 6 inches of sea level rise modeled for the 2030 condition in the proposed action would be expected to move X2 about 1 km landward without higher outflow to compensate (Rath et al. 2017). Thus, it is likely that CALSIM II had to add more outflow to meet D-1641 standards at times during the 82-year proposed action simulation than it would have had to if an older baseline were being modeled. During the summer of 2015, variation in sea level interacted with very low Delta inflows to cause frequent recurrence of net negative Delta outflow (Monismith 2016).

Central California's warm summers are already a source of energetic stress for delta smelt and warm springs can already severely compress the duration of their spawning season (Rose *et al.* 2013a,b). We expect warmer estuary temperatures to present a significant conservation challenge for delta smelt in the coming decades (Brown et al. 2013; 2016; Figure 12). Feyrer et al. (2011) and Brown et al. (2013; 2016) have evaluated the anticipated effects of projected climate change on several delta smelt habitat metrics. Collectively, these studies indicate the future will bring chronically compressed fall habitat, fewer 'good' turbidity days, a spawning window of similar duration but that is shifted 2-3 weeks earlier in the year, and a substantial increase in the number of days delta smelt will need to endure lethal or near lethal summer water temperatures.

The delta smelt lives at the southern limit of the inland distribution of the family Osmeridae along the Pacific coast of North America. The anticipated effects of a warming climate are expected to create challenging if not inhospitable conditions for delta smelt at some future point. The amount of anticipated change expected between now and 2030 is lower than it is for 2050 or 2100 (Figure 12) and therefore, less certain. For the time being, water temperatures are stressful to delta smelt, but not of themselves lethal in most of the upper estuary (Komoroske et al. 2014).

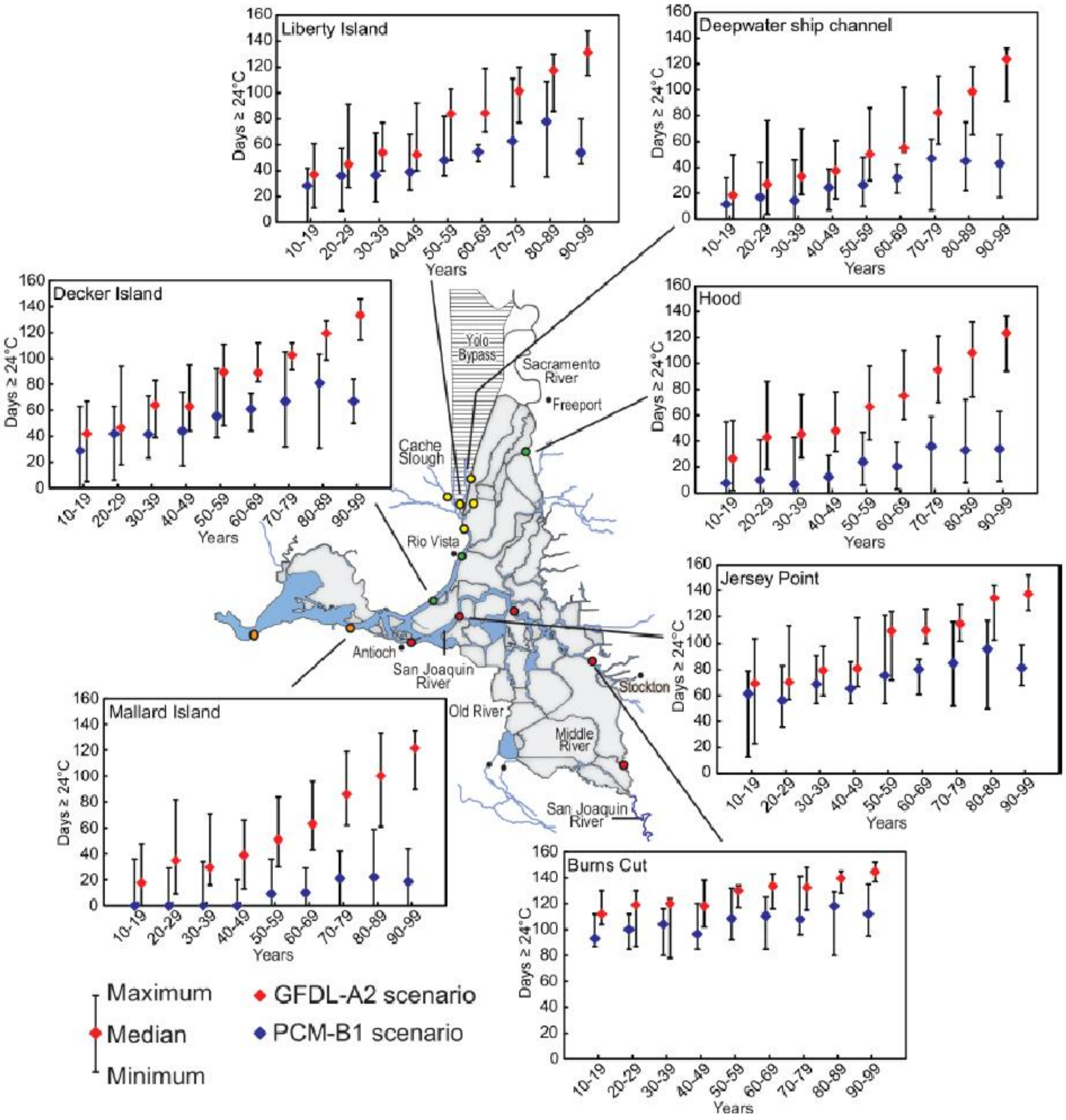


Figure 12. Plots of median, maximum, and minimum number of days each year with an estimated average daily water temperature greater than or equal to 24°C (75°F) at selected sites in the Delta by decade for the 21st century. The water temperature threshold reflects one chosen by the authors to represent near lethal conditions for delta smelt. Source: Brown et al. (2016).

Recovery and Management

Following Moyle *et al.* (1992), the Service (1993) indicated that SWP and CVP exports were the primary factors contributing to the decline of delta smelt due to entrainment of larvae and juveniles and the effects of low flow on the location and function of the estuary mixing zone (now called the low-salinity zone). In addition, prolonged drought during 1987-1992, in-Delta water diversions, reduction in food supplies by nonindigenous aquatic species -specifically overbite clam and nonnative copepods, and toxicity due to agricultural and industrial chemicals were also factors considered to be threatening the delta smelt. In the Service's 2008 biological opinion, the Reasonable and Prudent Alternative required protection of all life stages from entrainment and augmentation of Delta outflow during the fall of Wet or Above-Normal years as classified by the State of California (Service 2008). The expansion of entrainment protection for delta smelt in the 2008 Service BiOp was in response to large increases in juvenile and adult salvage in the early 2000s (Kimmerer 2008; Brown et al. 2009). The fall X2 requirement was in response to increased fall exports that had reduced variability in Delta outflow during the fall months and were anticipated to reduce it further (Feyrer *et al.* 2011).

Consistent with Service (2008), the Service's (2010c) recommendation to uplist delta smelt from threatened to endangered included reservoir operations and water diversions upstream of the estuary as additional water operations mechanisms interacting with exports from the Delta to restrict the low-salinity zone and concentrate delta smelt with competing and predatory fish species. In addition, Brazilian waterweed (*Egeria densa*) and increasing water transparency were considered new detrimental habitat changes. Predation was considered a low-level threat linked to increasing waterweed abundance and increasing water transparency. Additional threats considered potentially significant by the Service in 2010 were entrainment into power plant diversions, contaminants, and reproductive problems that can stem from small population sizes. Conservation recommendations included: establish Delta outflows proportionate to unimpaired flows to set outflow targets as fractions of runoff in the Central Valley watersheds; minimize reverse flows in Old and Middle rivers; and, establish a genetic management plan for captive-reared delta smelt with the goals of minimizing the loss of genetic diversity and limiting risk of extinction caused by unpredictable catastrophic events. The Service (2012b) recently added climate change to the list of threats to the delta smelt.

Continued protection of the delta smelt from excessive entrainment, improving the estuary's flow regime, suppression of nonnative species, increasing zooplankton abundance, and improving water quality are among the actions needed to recover the delta smelt.

Summary of the Status of Delta Smelt

The relative abundance of delta smelt has reached very low numbers for a small forage fish in an ecosystem the size of the Bay-Delta and the species is now considered to be on the verge of extinction in the wild (Moyle et al. 2016; 2018; Hobbs et al. 2017). The extremely low 2018-2019 abundance indices reflect decades of habitat change and marginalization by non-native species that prey on and out-compete delta smelt. The anticipated effects of climate change on the Bay-Delta and its watershed such as warmer water temperatures, greater salinity intrusion, lower snowpack contribution to spring outflow, and the potential for frequent extreme drought, indicate challenges to delta smelt survival will increase. Modeling conducted by the Service in support of this biological opinion indicates the population will most likely continue to decline suggesting a very high likelihood the species will not persist until 2030 without supplementation.

9.2.1.3 Status of the Critical Habitat

Legal Status

The Service designated critical habitat for the delta smelt on December 19, 1994 (Service 1994). The geographic area encompassed by the designation includes all water and all submerged lands below ordinary high water and the entire water column bounded by and contained in Suisun Bay (including the contiguous Grizzly and Honker Bays); the length of Goodyear, Suisun, Cutoff, First Mallard (Spring Branch), and Montezuma sloughs; and the existing contiguous waters contained within the legal Delta (as defined in section 12220 of the California Water Code) (Service 1994). The entire designated critical habitat for delta smelt is encompassed by the Action Area for the proposed action. Therefore, we combined the *Status of Critical Habitat* and the *Environmental Baseline/Status of Critical Habitat in the Action Area* into one section.

Conservation Role of Delta Smelt Critical Habitat

The Service's primary objective in designating critical habitat was to identify the key components of delta smelt habitat that support successful completion of the life cycle, including spawning, larval and juvenile transport, rearing, and adult migration back to spawning sites. Delta smelt are endemic to the Bay-Delta and the vast majority only live one year. Thus, regardless of annual hydrology, the Bay-Delta estuary must provide suitable habitat all year, every year. The primary constituent elements considered essential to the conservation of the delta smelt as they were characterized in 1994 are physical habitat, water, river flow, and salinity concentrations required to maintain delta smelt habitat for spawning, larval and juvenile transport, rearing, and adult migration (Service 1994). The Service recommended in its designation of critical habitat for the delta smelt that salinity in Suisun Bay should vary according to WY type, which it does. For the months of February through June, this element was codified by the State Water Resources Control Board's "X2 standard" described in D-1641 and the Board's current Water Quality Control Plan.

Description of the Primary Constituent Elements

The original descriptions of the primary constituent elements are compared and contrasted with current scientific understanding in Table 2.

Table 2. Comparison of delta smelt primary constituent elements of critical habitat between the 1994 publication of the rule and the present.

Primary Constituent Element	1994 critical habitat rule	2016 state of scientific un
Spawning Habitat	Shallow fresh or slightly brackish edge-waters	No change
	Backwater sloughs	Possible, never confirmed. Most have sandy substrates and need n Backwater sloughs in particula substrates that would suffo
	Low concentrations of pollutants	No change
	Submerged tree roots, branches, emergent vegetation (tules)	Not likely. Unpublished observat captive delta smelt suggest spaw oriented horizontally and a prefere that is more consistent with observ in the family Osme
	Key spawning locations: Sacramento River "in the Delta", Barker Slough, Lindsey Slough, Cache Slough, Prospect Slough, Georgiana Slough, Beaver Slough, Hog Slough, Sycamore Slough, Suisun Marsh	All of the locations listed in 1994 spawning, but based on better m Spring Kodiak Trawl Survey, mos been observed to aggregate arou Sherman Island, and in the Cach including the subsequently floo
	Adults could spawn from December-July.	Adults are virtually never fully rip before February and most spawn May.
Larval and juvenile transport	Larvae require adequate river flows to transport them from spawning habitats in backwater sloughs to rearing habitats in the open waters of the low-salinity zone	Not likely. Most delta smelt that s life stage do eventually inhabitat w to 6 ppt range, due to either or b movement or decreasing outflow. larvae can feed in the same habitat and both larval and juvenile fish ca salinity lower than
	Larvae require adequate flow to prevent entrainment	No change
	Larval and juvenile transport needs to be protected from physical disturbances like sand and gravel mining, diking, dredging, rip-rapping	No change, but seems likely to h spawning habitat than larval tra subsequently shown to be related to tidal flows

	2 ppt isohaline (X2) must be west of the Sacramento-San Joaquin River confluence to support sufficient larval and juvenile transport	Subsequent research showed the similarly relative to X2 regardless c is generally west of the river conflu June due to State Water Resource standard; however, the standard do ramp.
	Maturation must not be impaired by pollutant concentrations	No change
	Additional flows might be required in the July-August period to protect delta smelt that were present in the south and central Delta from being entrained in export pumps.	July-August outflow augmentation not to mitigate entrainment becau subsequently shown to no longer o during July-August. Habitat chang south Delta have rendered it seas delta smelt during the summer; en observed past June and the 2008 Se 25 degree Celsius off-ramp that us
Rearing habitat	2 ppt isohaline (X2) should remain between Carquinez Strait in the west, Three-Mile Slough on the Sacramento River and Big Break on the San Joaquin River in the east. This was determined to be a historical range for 2 ppt salinity (including its tidal time scale excursion into the Delta).	Recent research has shown the seasonal X2 movement is much le pre-development. That said, X2 specified region during February-Water Resources Control Board X the standard does have a drought o delta smelt still rear in the low-salin recognized that a few remain in complex as we
Adult migration	Adults require unrestricted access to spawning habitat from December-July	Adults disperse faster than was rec of it is finished by the time Spring January, though local movement longer distance dispersal occurs thr season, which as mentioned above May. The only known ‘barriers’ t water diversion
	Unrestricted access results from adequate flow, suitable water quality, and protection from physical disturbance	No change

Primary Constituent Element 1: “Physical habitat” is defined as the structural components of habitat (Service 1994). As reviewed above, physical habitat in the Bay-Delta has been substantially changed with many of the changes having occurred many decades ago (Andrews et al. 2017; Gross et al. 2018). Physical habitat attributes are important in terms of spawning substrate, rearing habitat (Bever et al. 2016), and foraging habitat (Hammock et al. 2019).

The reproductive behavior of delta smelt is only known from captive specimens spawned in artificial environments and most of the information has never been published, but is currently being revisited in new research. Spawning likely occurs mainly at night with several males attending a female that broadcasts her eggs onto bottom substrate (Bennett 2005). Although preferred spawning substrate is unknown, spawning habits of delta smelt’s closest relative, the Surf smelt (*Hypomesus pretiosus*), are sand or small gravel (Hirose and Kawaguchi 1998; Quinn et al. 2012).

Although the delta smelt is a generally pelagic or open-water fish, depth variation of open-water habitats is an important habitat attribute (Moyle *et al.* 1992; Hobbs *et al.* 2006; Bever et al. 2016). In the wild, delta smelt are most frequently collected in water that is somewhat shallow (4-15 ft deep) where turbidity is often elevated and tidal currents exist, but are not excessive (Moyle *et al.* 1992; Bever *et al.* 2016). For instance, in Suisun Bay, the deep shipping channels are poor quality habitat because tidal velocity is very high (Bever *et al.* 2016), but in the Delta where tidal velocity is slower, the Sacramento Deepwater Shipping Channel is used to a greater extent (Feyrer et al. 2013; CDFW unpublished data). Sub-adult and adult delta smelt also use shoal and edge habitats as tidal current refuges (Bever et al. 2016), migratory corridors to spawning habitats (Bennett and Burau 2015), and foraging habitat (Hammock et al. 2019).

Primary Constituent Element 2: “Water” is defined as water of suitable quality to support various delta smelt life stages that allow for survival and reproduction (Service 1994). Certain conditions of temperature, turbidity, and food availability characterize suitable pelagic habitat for delta smelt and are discussed in detail below. Contaminant exposure can degrade this primary constituent element even when the basic habitat components of water quality are otherwise suitable (Hammock *et al.* 2015).

Turbidity: Turbidity is caused by sediment and to lesser degree phytoplankton in the water. There is substantial spatial variation in turbidity within the critical habitat boundaries (Kimmerer 2004) and on average, turbidity has been trending downward (i.e., a trend toward clearer water; Cloern and Jassby 2012; Figure 13). Sediment supply to the estuary has been declining for a long time due to trapping behind dams, the lack of erosion from rip-rapped levees, and a gradual seaward erosion of sediments washed into the estuary after the era of hydraulic gold mining that had finished washing out by about 1999 (Arthur et al. 1996; Wright and Schoellhamer 2004; Schoellhamer 2011). The spread of Brazilian waterweed (*Egeria densa*), acts like a mechanical water filter that has also contributed to higher water transparency in much of the Delta (Hestir et al. 2016). Water exports from the south Delta may also have contributed to the trend toward clearer estuary water by removing suspended sediment in exported water (Arthur *et al.* 1996), however, the contribution of exports to the total suspended sediment budget in the estuary is small (Schoellhamer 2012).

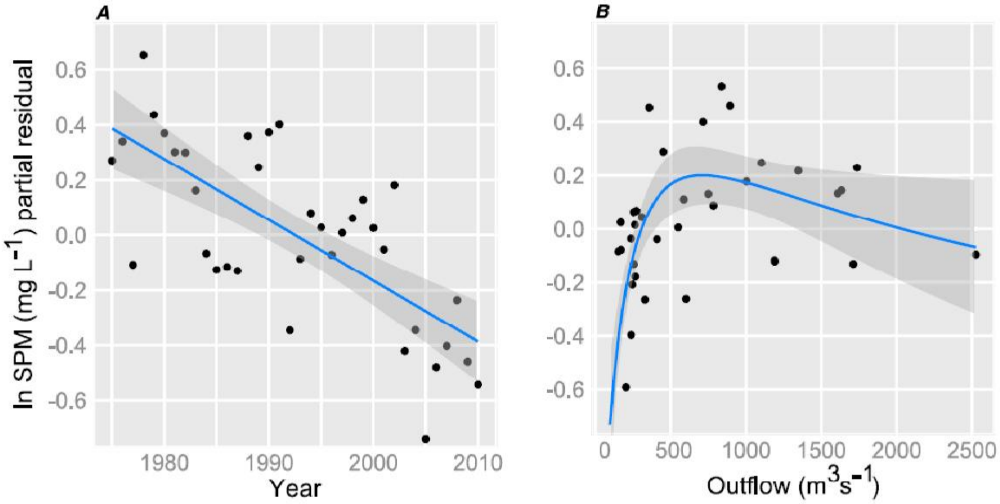


Figure 13. Partial residual plots for a regression model that accounts for variability in annual average concentration of suspended particulate matter at IEP station D8 in Suisun Bay as a result of its long-term trend (left panel) and its relationship to annual average Delta outflow (right panel). The blue lines are loess smoothers and the gray shading is the 95% confidence interval around the line. Source: Cloern and Jassby (2012).

In fish survey data, the longest-term indicator of water turbidity is Secchi disk depth measurements that for several decades have accompanied most individual net tows. Secchi disk depths are basically inverses of turbidity because the less turbid the water is, the deeper into the water column a Secchi disk remains visible. Feyrer et al. (2007) and Nobriga et al. (2008) first established a statistical link between Secchi disk depths and catches of delta smelt in long-term monitoring programs. This initial work was expanded upon by Kimmerer et al. (2009) and Feyrer et al. (2011). Each of the studies cited above, took a very ‘planktonic’ view of delta smelt habitat, meaning the analyses focused on water quality measurements independent of bathymetry or geography. This was later shown to have resulted in models that fit the data better for some parts of the estuary than others (Manly et al. 2016). It is worth noting that once scaled up to the entire FMWT sampling grid, the non-mechanistic model proposed by Manly et al. (2016) generated nearly the same declining habitat suitability trend that was originally reported by Feyrer et al. (2011) (Feyrer et al. 2016). The spatial bias reported by Manly et al. (2016) was also potentially explained at least in part, by a subsequent finding that delta smelt catches tended to be highest in turbid, low-salinity zone water where tidal currents were not excessive, providing a mechanistic explanation to some of the poor spatial fits in the ‘planktonic’ models (Bever et al. 2016).

Recently, two sets of authors have suggested that the link between Secchi disk depths and catches of delta smelt (and other open-water fishes) may be an artifact of fish having more opportunity to see an approaching net in clear water and escape capture than an actual fish-habitat association with turbid water (Latour 2016; Peterson and Barajas 2018). These authors have placed greater emphasis on geographic aspects of the trawl program sampling grids than earlier researchers.

However, there are several reasons the Service believes delta smelt's association with turbid water is a true habitat association rather than a non-mechanistic artifact of fish capture.

First, laboratory research has shown that delta smelt require turbidity to succeed in the Bay-Delta food web. The small plankton that delta smelt larvae eat are nearly invisible in clear water. The sediment (or algal) particles that provide turbidity also provide a dark background that helps delta smelt larvae see these translucent prey and as such turbidity is necessary to initiate a first-feeding response (Baskerville-Bridges *et al.* 2004). The feeding success and survival of older larvae are higher at 12-80 NTU than in water of lower or higher turbidity (Hasenbein et al. 2016). Note that 80 NTU represents very turbid water, indicating that delta smelt have a very high tolerance of turbidity. Juvenile delta smelt are less reliant on turbidity to see their prey or feed successfully (Hasenbein *et al.* 2013), but both larvae (Schreier et al. 2016) and juveniles (Ferrari et al. 2014) seem to need turbid water to help disguise themselves from predators.

Second, other sampling programs that have demonstrated capacity to capture small fishes regardless of water turbidity levels have also tended to catch delta smelt most frequently when the water is turbid. These include the fish salvage facilities in the southern Delta (Grimaldo et al. 2009) and an early-2000s research program deploying 30-m (100 foot long) beach seines (Nobriga et al. 2005).

Third, the increasing Secchi disk depth trends are not uniform across the upper estuary. From a regional perspective, they have been most pronounced in the San Joaquin River half of the Delta (Kimmerer 2004; Feyrer et al. 2007; Nobriga et al. 2008; Hestir et al. 2016), but it is also important to consider the 'planktonic' or hydrodynamic aspect of water turbidity in the estuary. As mentioned above, X2 is a boundary upstream of which, salinity tends to be the same from the surface of the water to the bottom, and downstream of which, salinity varies from top to bottom (Jassby et al. 1995). That variability in salinity from surface to bottom waters is indicative of a front that helps to aggregate turbidity and plankton near X2.

This mobile turbidity front that moves back and forth with variation in tidal and river flows is discernable in Secchi disk depth measurements from the FMWT. The FMWT Secchi disk depth data set dates to 1967 (Figure 14). Boxplots depicting the time series of Secchi disk depth measurements from this survey show the previously reported increasing trend is only pronounced in water with a salinity less than or equal to 1.4 ppt. There has been no trend when and where salinities are highest (≥ 10.1 ppt). At salinities in between 1.4 and 10 ppt, the increasing Secchi disk depth trend has been comparatively slight. Peak delta smelt catches in the FMWT historically occurred very near X2 (at about 1.5 to 4 ppt; Kimmerer et al. 2013). Over this range of salinity, Secchi disk depths increased during the latter 1980s (from a median of 0.3 m to a median of 0.53 m), but have not increased since like they have in fresher water where recent year medians are approaching 1.5 m (Figure 14). In addition, Secchi disk depth measurements deeper than 1 m have been very rare in this mobile frontal zone, whereas Secchi disk depths surpassing 3 m have recently begun to be reported from some freshwater sites. The persistence of turbidity at and very near X2 even as delta smelt catches have continued to decline is inconsistent with the hypothesis that turbidity changes are affecting the ability to catch the fish more than reflecting an actual decline in abundance.

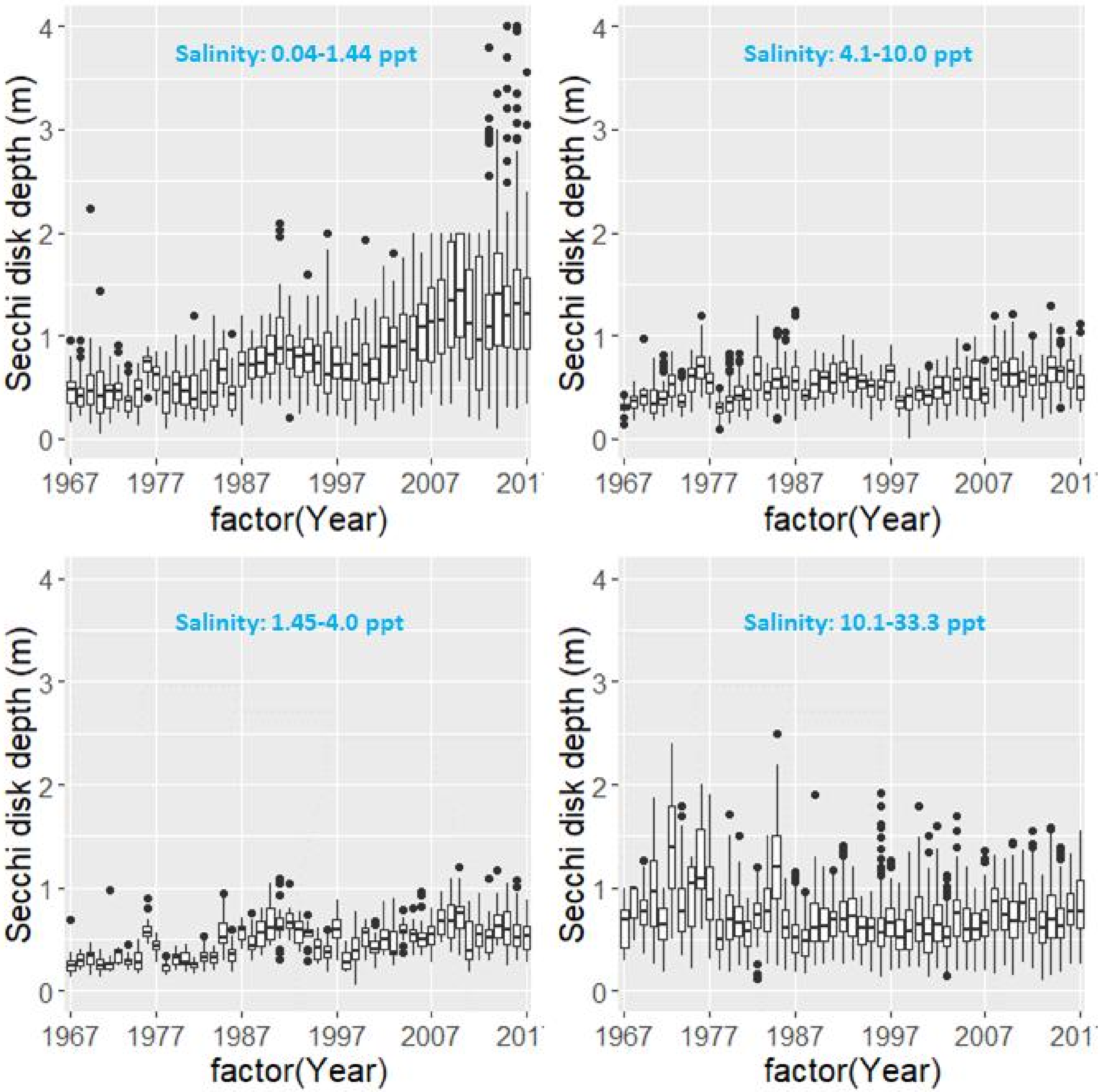


Figure 14. Boxplot time series of Secchi disk depth measurements taken during the California Department of Fish and Wildlife Fall Midwater Trawl Survey, 1967-2017. The boxes depict the central 50% of observations; the line through each box is the median. The black circles are observations outside the central 95% of observations. The data have been grouped into four salinity bins reflecting historical catches of delta smelt as depicted by Kimmerer et al. (2013). The bottom left panel represents the salinity range where peak

catches of delta smelt have typically occurred. The upper left and upper right panels are fresher and more brackish water where catches have been substantially lower. The lower right panel represents a salinity range in which delta smelt have seldom been encountered. Source: USFWS unpublished data analysis.

Water temperature: Water temperature is the primary driver of the timing and duration of the delta smelt spawning season (Bennett 2005). Water temperature also affects delta smelt's metabolic and growth rates which in turn can affect their susceptibility to contaminants, food limitation, and readiness to spawn (Rose *et al.* 2013a). Water temperature is not strongly affected by variation in Delta inflows except at the margins of the Delta where these inflows enter (Kimmerer 2004). The primary driver of water temperature variation in the delta smelt critical habitat is air temperature (Wagner *et al.* 2011). Very high flows can transiently cool the upper estuary (*e.g.,* flows in the upper 10th percentile, Kimmerer 2004), but the system rapidly re-equilibrates once air temperatures begin to warm.

Research initially suggested an upper water temperature limit for delta smelt of about 25°C, or 77°F (Swanson *et al.* 2000). Newer research suggests delta smelt temperature tolerance decreases as the fish get older, but is a little higher than previously reported, ranging from nearly 30°C or 86°F in the larval life stage down to about 25°C in post-spawn adults (Komoroske *et al.* 2014). It should be kept in mind that these are upper *acute* water temperature limits meaning these temperatures will kill, on average, one of every two fish. Subsequent research into delta smelt's thermal tolerances indicated that molecular stress response begins to occur at temperatures at least 4°C cooler than the acute thermal maxima (Komoroske et al. 2015).

In the laboratory and the wild, delta smelt appear to have a physiological optimum at temperatures of about 16-20°C or 61-68°F (Nobriga *et al.* 2008; Rose *et al.* 2013a; Eder et al. 2014; Jeffries *et al.* 2016). Most of the upper estuary exceeds this water temperature from May or June through September (Komoroske et al. 2014). Thus, during summer, many parts of the estuary are energetically costly and physiologically stressful to delta smelt (Komoroske et al. 2015). Generally speaking, spring and summer water temperatures are cooler to the west and warmer to the east due to the differences in overlying air temperatures between the Bay Area and the warmer Central Valley (Kimmerer 2004). In addition, there is a strong water temperature gradient across the Delta with cooler water in the north and warmer water in the south. The much higher summer inflows from the Sacramento River probably explain this north-south gradient. Note that water temperatures in the north Delta near Liberty Island and the lower Yolo Bypass where summer inflows are low to non-existent, are also typically warmer than they are along the Sacramento River. This may have consequences for the survival of freshwater-resident delta smelt during comparatively warm summers (Bush 2017).

Food: The recent history of Bay-Delta food web alteration was reviewed in the status of the species. Food and water temperature are strongly interacting components of the "Water" element of delta smelt critical habitat because the warmer the water, the more food delta smelt require (Rose *et al.* 2013a). If the water gets too warm, then no amount of food is sufficient. The more food delta smelt eat (or must try to eat) the more they will be exposed to predators and contaminants.

Contaminants: Research conducted over the past 10 years suggests that delta smelt are fairly susceptible to contaminants (e.g., Connon et al. 2009; 2011a,b; Hasenbein et al. 2014; Jeffries et al. 2015; Jin et al. 2018). The effects of ambient Sacramento River water, pyrethroid pesticides, several herbicides, copper, and ammonium have all been examined and all of these compounds have shown at least sub-lethal effects represented by changes in gene expression. In some cases, delta smelt were exposed to higher than observed concentrations of some compounds in order to estimate their LC_{50}, the estimated concentration that kills half of the test fish over the study duration. Exposure durations have varied widely among studies (4 hr to 1 wk), which limits the ability to quantitatively compare toxicity among studies.

Primary Constituent Element 3: "River flow" was originally believed to be critical as transport flow to facilitate spawning migrations and the transport of offspring to low-salinity zone rearing habitats (Service 1994). However, it has subsequently been learned that most transport and retention mechanisms for delta smelt (and their prey) involve the selective use of tidal currents rather than net flows (Kimmerer et al. 1998; 2002; Bennett et al. 2002; Kimmerer et al. 2014; Bennett and Burau 2015). River flow includes both "inflow to" and "outflow from" the Delta, both of which influence the net movements of water through the Delta (Kimmerer and Nobriga 2008) and exert some influence on the distribution of delta smelt (Sweetnam 1999; Dege and Brown 2004; Feyrer et al. 2007; Nobriga et al. 2008; Sommer et al. 2011; Manly et al. 2016; Polansky et al. 2018; Peterson and Barajas 2018; Simonis and Merz 2019).

Net water movements in the Delta have recently been reconstructed and analyzed for long-term trend attribution (Hutton et al. 2018; Figure 15). These analyses demonstrated several net flow variables have experienced strong time trends since the 1920s. In particular, cross-Delta flows have increased during the summer and fall, Rio Vista flows have decreased in the winter and spring and increased in the summer, Jersey Point flow and Old and Middle river flow (OMR) have decreased year-around. The change attribution indicated that CVP and SWP operations were predominantly the source of these net flow changes except for Jersey Point flow in the spring, which is strongly influenced by in-Delta irrigation demand. The net flow changes ultimately influence Delta outflow, which as discussed above, has been trending downward for more than 100 years.

A concise summary of the contemporary Delta outflow hydrograph is shown in Figure 16. A value on the y-axis of 0.5 suggests that since 1968, an outflow on a given day has had an equal chance of being at least as high as one or in some cases all three of the chosen thresholds. Delta outflow at least as high as the Roe Island standard freshens the estuary enough for delta smelt to spawn in typically brackish regions like the Napa River and western Suisun Marsh, and tends to reduce the likelihood of entrainment. Delta outflows at least as high as the Chipps Island standard tend to generate low-salinity zone coverage throughout much or all of Suisun Bay. Outflows near the Collinsville standard are associated with a typical X2 slightly upstream of the confluence of the Sacramento and San Joaquin rivers. Delta outflows equaling or exceeding the Roe Island threshold (27,200 cfs) have had a higher probability of occurring than not from late January through most of March. Delta outflows equaling or exceeding the Chipps Island threshold (11,400 cfs) are much more common and have had a higher probability of occurring than not from early December through the end of May. Delta outflows equaling or exceeding the Collinsville threshold (7,100 cfs) have had a higher probability of occurring than not from about the middle of November through the middle of July. Note that the DAYFLOW calculations used to make Figure 16 can be highly uncertain at values lower than about 10,000 cfs (Monismith 2016).

The tidal and net flow of water toward the south Delta pumping plants is frequently indexed using OMR (Grimaldo et al. 2009; Andrews et al. 2016; Figure 15). The tidal and net flows in Old and Middle rivers influence the vulnerability of delta smelt larvae, juveniles, and adults to entrainment at the Banks and Jones facilities (Kimmerer 2008; 2011; Grimaldo *et al.* 2009; Smith et al. in review). By itself, OMR is not a very good indicator of entrainment risk especially for post-larval life stages of delta smelt (Kimmerer 2008; Smith et al. in review). It has been recognized for some time that high temperatures and high water clarity have created habitat conditions in the south Delta that delta smelt seasonally avoid (Kimmerer 2008; Nobriga et al. 2008), which over time has increasingly kept the fish away from Old and Middle rivers during the summer months. For adult delta smelt, turbidity is an important mediator of entrainment risk even as some fish disperse back into the San Joaquin River and southern Delta (Grimaldo et al. 2009).

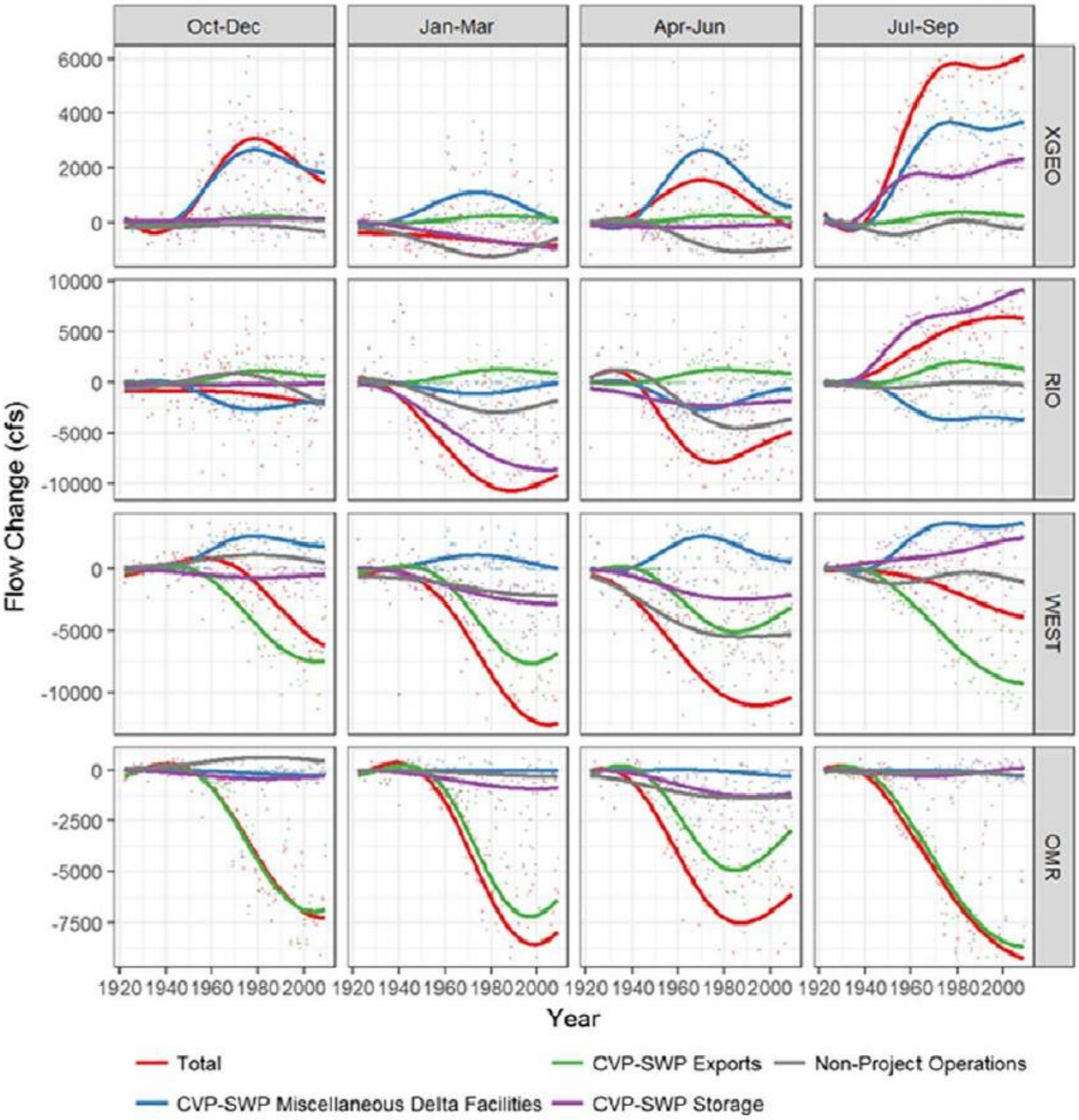


Figure 15. Time series (1922-2009) of statistical trend outputs of annual cross Delta flows (XGEO), net flow at Rio Vista (RIO), net flow at Jersey Point on the San Joaquin River (WEST), and net flow in Old and Middle rivers (OMR). For XGEOnet north to south flows have positive values. For RIO and WEST, net seaward (downstream) flows have positive values. For OMR, which seldom has positive values, net north to south flows are depicted as negative values. The colored lines reflect the statistical trend in the time series with the different colors reflecting the relative contributions of the sources listed in the legend. Source Hutton et al. (2018).

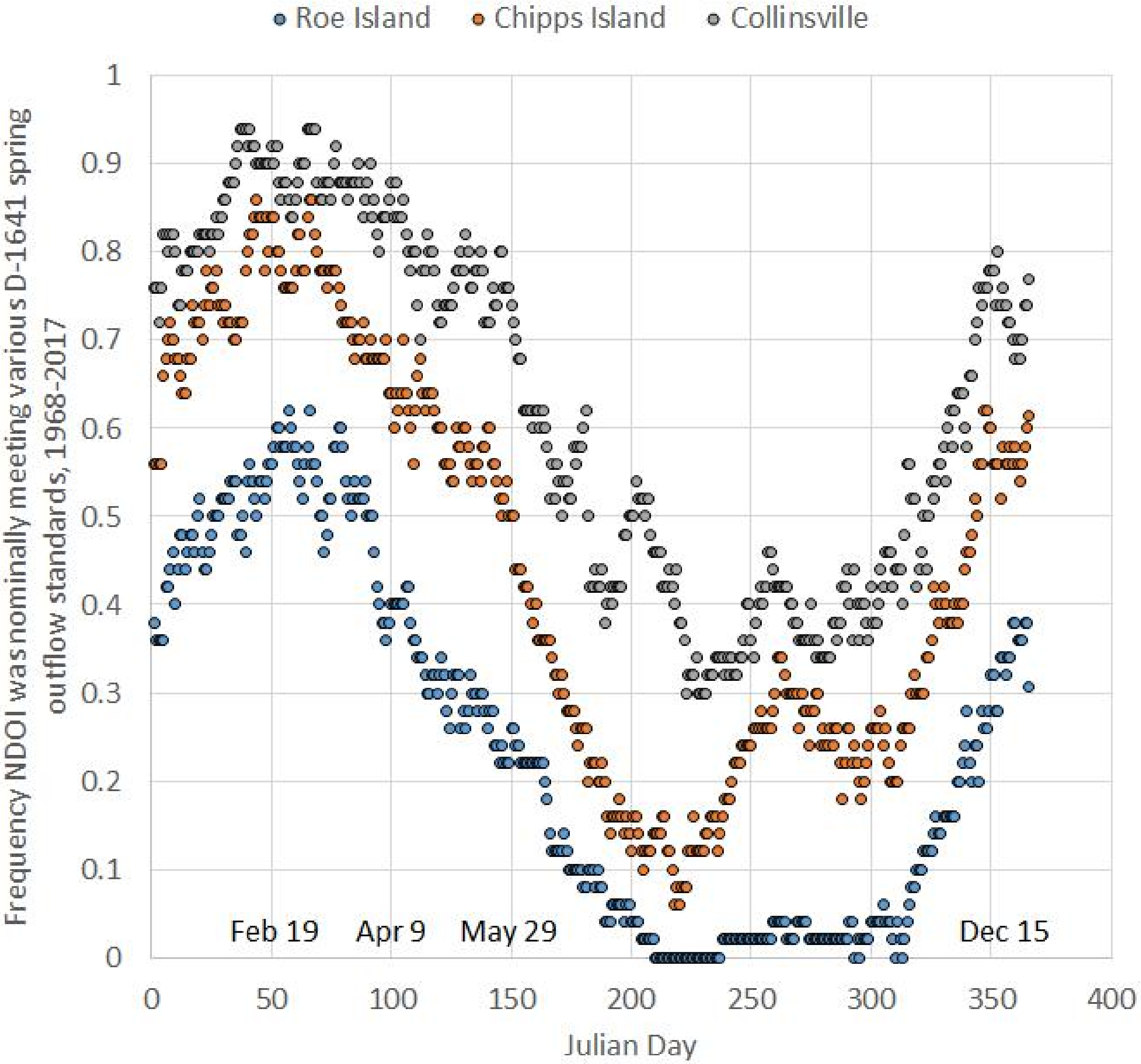


Figure 16. Daily frequency that the Net Delta Outflow Index (NDOI) was at least as high as the steady-state thresholds for the D-1641 'X2 standard' for January 1 (day 0) to December 31 (day 365-366), 1968 through 2017. The steady-state NDOI thresholds used to calculate the frequencies were Roe Island ≥ 27,200 cfs, Chipps Island ≥ 11,400 cfs, and Collinsville ≥ 7,100 cfs. For reference, a frequency of 0.5 means an NDOI at least as high as the threshold occurred half of the time on a given day. Note that this plot is only intended to provide a concise view of the modern seasonality of Delta outflow. It is not intended to

reflect anything about compliance or non-compliance with D-1641. Source: USFWS unpublished analysis of the DAYFLOW database.

The Service has begun to further evaluate this interacting relationship between turbidity and OMR. Some of this work has been done under the auspices of CSAMP. The Service has coupled its adult delta smelt abundance estimates with estimates of entrainment to develop estimates of the proportion of the adult population entrained from 1993-2015 (appendix#Smith). These estimates range from near zero to almost 20%. We used these proportional entrainment estimates as a response variable in a linear regression model involving December-February averages of OMR and system-wide averages of Secchi disk depth to demonstrate the strongly interacting influence of these variables. The model was constructed to test for the possibility that the OMR and Secchi disk depth factors influenced proportional entrainment of adult delta smelt differently during three periods of very different management strategies for winter exports. These were a “pre-CALFED” era (1993-1998), which was generally a very wet period with highly variable OMR, a “CALFED” era (1999-2006), which had consistently high winter exports and very negative OMR, and a “BiOp years” era (2007-2015), which had less negative OMR flows due to Court decisions and biological opinions for delta smelt and anadromous fishes. This era also had less turbid water as indexed by Secchi disk depth data. Further details of the regression approach are provided in appendix#Smith.

The best-supported model was the one that included all predictor variables (OMR, Secchi disk depth, their interaction, and the categorical era variable (Figure 17; appendix#Smith). Figure 17 contrasts the regression predictions for a Secchi disk depth of 42 cm versus 53 cm to show how sensitive the results were to what may seem like relatively small changes in system wide water transparency. At a Secch disk depth of 42 cm, proportional entrainment was predicted to increase as OMR flow became increasingly negative. However, at a Secchi disk depth of 53 cm, there was no relationship predicted between OMR flow and proportional entrainment of adult delta smelt. For reference, the annual mean Secchi disk depths ranged from less than 40 cm to more than 70 cm.

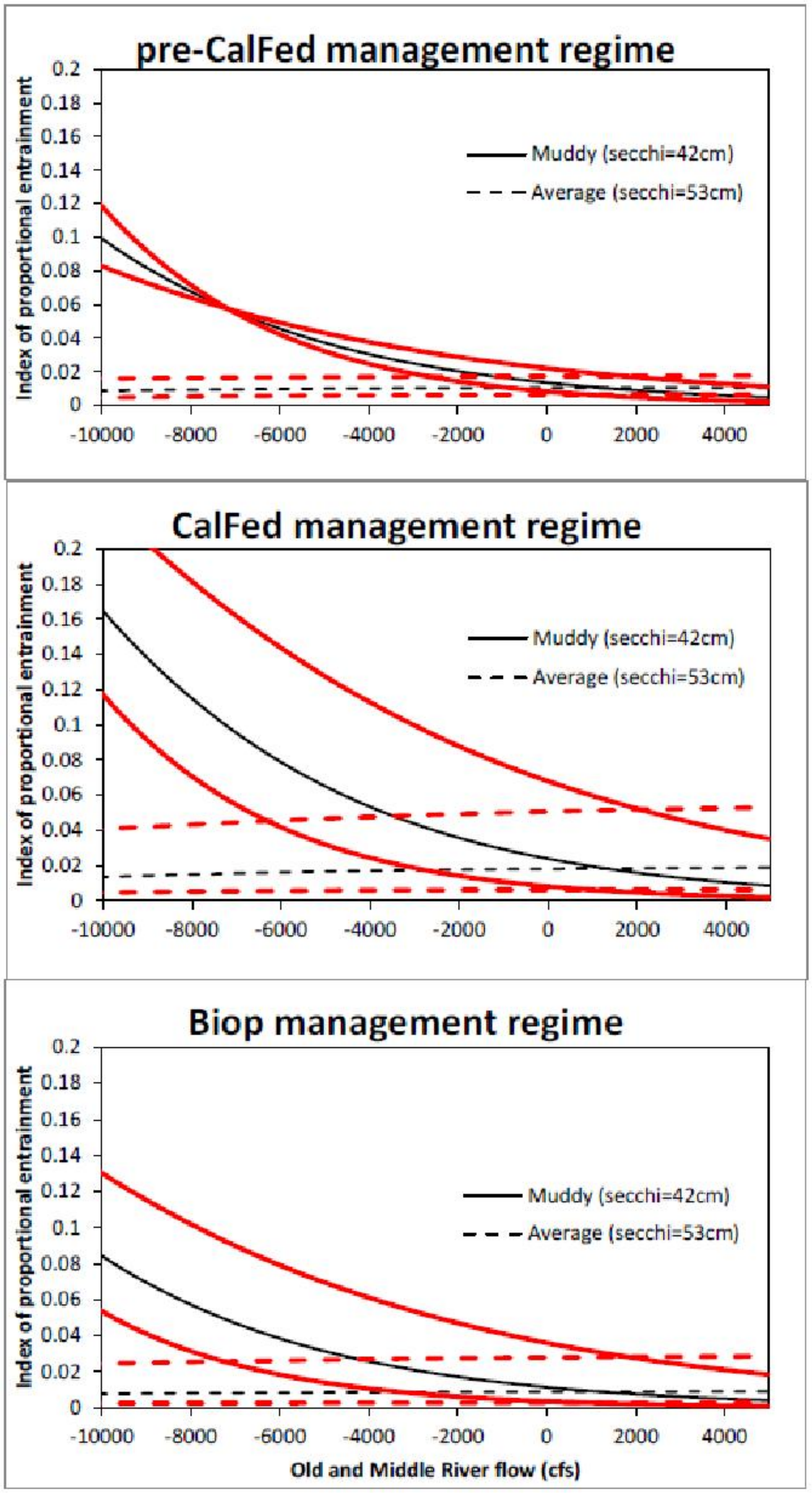


Figure 17. Predictions from a beta regression model of the variability in an index of proportion of the adult delta smelt population entrained into the south Delta fish facilities

and pumping plants that can be explained by an interaction between OMR flow and average Secchi disk depth measured in concurrent fish surveys (December-March). See appendix#Smith for further details. Source: USFWS unpublished data analysis.

Primary Constituent Element 4 "Salinity": Fish assemblages are able to lessen competition among species and life stages by partitioning habitats. For instance some fish species and life stages are more shoreline oriented whereas others are more offshore oriented. Some species are better adapted to midwater or surface waters, while others are more adapted to stay close to the substrate. Some fish are tolerant of turbidity, while others are not. In estuaries, salinity is often a dominant factor separating different groups of fishes. In the Bay-Delta, dominant fishes replace one another at several places along the salinity gradient (Feyrer et al. 2015).

Delta smelt is part of the fish assemblage that uses the low salinity waters of the estuary (Kimmerer et al. 2009; 2013). Thus, the Primary Constituent Element "Salinity" helps define its nursery habitat (Service 1994). Initial research indicated that delta smelt have an upper acute salinity tolerance of about 20 ppt (Swanson *et al.* 2000) which is about 60% of seawater's salt concentration of 32-34 ppt. Newer research suggests that some individual delta smelt can acclimate to seawater, but that about one in three juveniles and one in four adults die within a few days if they are rapidly transitioned from low-salinity water to marine salinity water (Komoroske *et al.* 2014). The survivors can live for at least several weeks in seawater, but lose weight (Komoroske et al. 2014; 2016). This clear evidence of physiological stress for delta smelt exposed to seawater has not been observed at lower salinity challenges – including salinities as high as 18-19 ppt. Different molecular responses have been observed, particularly at salinities higher than 6 ppt (Komoroske et al. 2016). These different molecular responses may reflect physiological stress, but this is not certain. There are currently several published studies that have examined aspects of delta smelt physiology at salinities in the 12-19 psu range; none have found obvious evidence of an inability of the delta smelt to adjust its physiology to handle salinity in this range (Komoroske et al. 2014; 2016; Kammerer et al. 2016; Davis et al. 2019).

These findings are interesting because wild delta smelt have seldom been collected at a salinity higher than 5 ppt and only very seldomly collected at a salinity higher than 10 ppt (Kimmerer 2004; Bennett 2005; Kimmerer et al. 2009; 2013). This contrast between where most wild delta smelt are found and what laboratory research indicates they can easily tolerate suggests one of two things. Either there is a persistent laboratory artifact, or it may be evidence that delta smelt's distribution along the estuary salinity gradient is due to a factor or factors other than salinity *per se*. Historically, delta smelt's prey were most abundant in the low-salinity zone, but that has not been the case for more than 30 years. One parsimonious explanation that may better align with recent laboratory research is that turbidity is the more important physical habitat attribute. Relatively turbid waters occur as a mobile front near X2 and occur regularly in Grizzly and Honker bays and the Cache Slough complex, all of which are places delta smelt have frequently been collected from. For the time being, this is speculative, but if correct, it may suggest that hiding from predators or minimizing competition are the more relevant drivers of delta smelt distribution. The Service will advocate for the use of cultured fish enclosures placed along the estuary salinity gradient to explore this possibility.

Summary of Status of Delta Smelt Critical Habitat

The Service's primary objective in designating critical habitat was to identify the key components of delta smelt habitat that support successful completion of the life cycle, including spawning, larval and juvenile transport, rearing, and adult migration back to spawning sites. Since the implementation of the RPA in the Service's 2008 BiOp, there has been much lower likelihood of water operations that are highly detrimental to the spawning migration of adult delta smelt, the spawners themselves, or larval transport.

The delta smelt's critical habitat, which is synonymous with the downstream waters of the Action Area, is currently doing a poor job of serving its intended conservation role and function because there are very few locations that consistently provide all the needed habitat attributes for larval and juvenile rearing at the same times and in the same places (Table 3). The Service's review indicates it is rearing habitat that remains most impacted by ecological changes in the estuary, both before and since the delta smelt's listing under the Act. As described above, those changes have stemmed from chronic low outflow, species invasions and associated changes in how the upper estuary food web functions, declining prey availability, high water temperatures, declining water turbidity, and localized contaminant accumulation by delta smelt.

Table 3. Summary of habitat attribute conditions for delta smelt in six regions of the estuary that are permanently or seasonally occupied in most years.

	Landscape	**Turbidity**	**Salinity**	**Temperature**	**Food**
Montezuma Slough	Appropriate	Appropriate	Appropriate *when outflow is sufficient*	Usually appropriate	Appropriate
Suisun Bay	Appropriate except in shipping channel	Appropriate, but declining	Appropriate *when outflow is sufficient*	Usually appropriate	Depleted
West Delta	Limited area 4 to 15 feet deep	marginal, declining	Appropriate	Can be too high during summer	Depleted
North Delta (Cache Slough region)	Appropriate	Appropriate	Appropriate	Can be too high during summer	Appropriate, but associated with elevated contaminant impacts
Sacramento River near proposed California WaterFix Diversion(s)	Limited area 4 to 15 feet deep; swift currents	Marginal except during high flows, declining	Appropriate, but possibly lower than optimal	Usually appropriate	Likely low due to swift currents and wastewater inputs

South Delta	Appropriate except too much coverage by submerged plants	Too low	Appropriate	Too high in the summer	Appropriate

Environmental Baseline

The Environmental Baseline describes the past and present impacts of all Federal, State, or private actions and other human activities in the Action Area, the anticipated impacts of all proposed Federal projects in the Action Area that have already undergone formal or early section 7 consultation, and the impact of State or private actions, which are contemporaneous with the consultation in process (50 CFR 402.02). The key purpose of the Environmental Baseline is to describe the condition of the listed species/critical habitat that exist in the Action Area in the absence of the action subject to this consultation.

The Environmental Baseline does not include the effects of the action under review in the consultation. In this case, the effects of the action are those resulting from the Coordinated Long-term Operation of the CVP and SWP from now until 2030, and are therefore, not included in the Environmental Baseline for this consultation. The effects of past CVP/SWP operations are incorporated in the Environmental Baseline because those effects have undergone consultation and contributed to the current condition of the species and critical habitat in the action area. Other past, present, and ongoing impacts of human and natural factors (including proposed Federal projects that have already undergone section 7 consultation) contributing to the current condition of the species and critical habitat in the action area are included in the Environmental Baseline and Status of the Species, Status of the Critical Habitat for section 7 consultation purposes. A description of previous actions that have contributed to these current conditions are described below in Factors Affecting Delta Smelt and Critical Habitat Within the Action Area.

It is important to note that for ESA section 7, each time the operations of the CVP and SWP are consulted on (e.g., 2004, 2008/2009, and current) a new federal action is proposed, and the previous consultation and the impacts of past and present operations of the CVP and SWP become part of the environmental baseline. The operation of the CVP and SWP since the water projects' inception is not one continuous federal action in the context of ESA compliance. The CVP and SWP proposed action covered in the 2004 biological opinion was different from the proposed action consulted on in 2008/2009, which is different from the proposed action analyzed in this biological opinion – they each had proposed action-specific components and operating criteria, so they are separate federal actions requiring separate ESA section 7 consultations and analyses.

A "without action" scenario was provided by Reclamation in the BA. Like the hydrodynamic modeling studies reviewed above, this without action scenario provides context for how the existence of the CVP and SWP facilities have shaped the habitat conditions for species and critical habitat in the action area. Unlike the hydrodynamic modeling studies reviewed above, which recreated historical conditions as best as can be done with currently available information, this “without action” scenario includes the existence of the dams and south Delta facilities, but removes operations of these facilities, since the action under this consultation is operations. The Bureau provided quantitative modeling and data and qualitative conceptual models of this scenario in their BA, which help support this context.

The ”without action” scenario does not address how past operations of the CVP and SWP have contributed to the current condition of the species and critical habitat in the action area or the overall status of delta smelt and critical habitat. As described in our Analytical Framework for the Jeopardy Determination and Analytical Framework for the Adverse Modification Determination for this consultation, our analysis includes factors responsible for both the range-wide condition and condition within the action area of delta smelt and critical habitat. Operations of the CVP and SWP are among the factors responsible for these current conditions and are, therefore, necessary to include in this consultation. The “without action” scenario is layered on a qualitative look at current operations and how those operations inform the current condition of the species and critical habitat in the action area, in addition to all of the other factors contributing to the current condition. A Current Operations scenario was incorporated in the BA to represent a trend to consider when addressing effects of the action in the aggregate. This layered Environmental Baseline is added to the range-wide status of the species and critical habitat to provide a complete picture for delta smelt and critical habitat at the time of this consultation. The effects of the proposed action and cumulative effects are then added to this status and baseline to inform whether or not the proposed action is likely to jeopardize delta smelt and/or destroy of adversely modify delta smelt critical habitat.

Factors Affecting Delta Smelt and Critical Habitat Within the Action Area

There have been hundreds of consultations on effects to delta smelt completed since the species was listed under the ESA in 1993. The previous partial and completed consultations related to CVP/SWP water operations are reviewed in the *Consultation History* section of this biological opinion. The consultations that are most relevant to understanding the factors that have led to the current condition of the species and critical habitat in the action area are summarized in Table X.1.

Table X.1. Summary of select ESA consultations for the delta smelt that are highly relevant to the Environmental Baseline for this consultation.

Consultation	Description
2008 OCAP Biological Opinion	In December 2008, the Service issued a biological opinion that concluded the co operation of the CVP and SWP was likely to jeopardize the continued existence destroy or adversely modify its critical habitat. Key elements of the Service's 20 RPA Component 1: The objective of Component 1 (comprised of Actions 1 and entrainment of pre-spawning adults by controlling OMR flows during periods o entrainment risk. Action 1 is designed to protect migrating delta smelt. Action 2 protect adult delta smelt that are residing in the Delta prior to spawning. Overall increases the suitability of spawning habitat for delta smelt by decreasing the am affected by the CVP and SWP export pumping plants' operations prior to, and d spawning period; RPA Component 2: The objective of Component 2 is to limit entrainment of lar smelt by reducing net negative flow conditions in the central and south Delta, so juvenile delta smelt can successfully rear in the Delta and move downstream wh RPA Component 3: The objective of Component 3 is to improve fall habitat co smelt by increasing Delta outflow during fall of Wet and Above-normal years to variability in habitat conditions during this time of year; RPA Component 4: The objective of Component 4 is to restore a minimum of 8 intertidal and associated subtidal habitat in the Delta and Suisun Marsh to increa for delta smelt; and RPA Component 5: Component 5 provides for monitoring and reporting. Recla shall ensure that information is gathered and reported to ensure: (1) proper impl restoration actions, (2) that the physical results of the restoration actions are ach

	information is gathered to evaluate the effectiveness of these actions on the targe delta smelt so that the actions can be refined, if needed. For more information, the 2008 Service BiOp can be found at: https://www.fws.gov/sfbaydelta/documents/SWP-CVP_OPs_BO_12-15_final_s
California EcoRestore	This State of California-led initiative proposes to restore at least 30,000 acres of floodplain, upland, riparian, and fish passage improvements in the Delta by 202 8,000 acres of tidal habitat required under the 2008 Service biological opinion. T following tidal marsh restoration projects have begun construction: Tule Red, Y and Decker Island Tidal Marsh Restoration Projects. These projects have been d food web benefits to delta smelt. Although projects have been chosen to receive have been completed (fully constructed) to date. The ROC PA includes a commi Reclamation and DWR to complete the remainder of the 8,000 acres of tidal hab 2030.
California WaterFix	On June 23, 2017, the Service issued the biological opinion for California Wate Service's opinion addressed effects of CWF operations programmatically, and a these effects would begin after the term of the ROC on LTO consultation (i.e., 2 operational scenario proposed in 2017 is likely to change based on factors descr opinion. Operations of CWF cannot occur absent a subsequent consultation to a operating the CWF facilities. Other CWF activities addressed programmatically the North Delta Diversion (NDD) and associated structures, construction of the Gate (HORG), construction of the Contra Costa Water District (CCWD) settlem facilities, future maintenance, future monitoring, and compensatory mitigation a construction of the above-mentioned facilities. Effects of construction of the CW expansions and other modifications of Clifton Court Forebay; associated infrast explorations; compensatory mitigation associated with construction except the N CCWD settlement agreement facilities; and specific construction-related conser including preconstruction surveys for listed terrestrial species were addressed u consultation and do not require additional consultation unless any of the reinitia (50 CFR §402.16). Because CWF has already undergone section 7 consultation, it is part of the Env however, because the effects of operations are not proposed to occur during the LTO, those effects do not contribute to the current condition of the species or cr action area and will not be added to the effects of ROC on LTO for the purposes adverse modification analysis.
South Delta Temporary Barriers Project	The SDTBP consists of three rock barriers that DWR uses to increase water leve water quality in the southern Delta for local diverters, and a fourth barrier at the (HORB) intended to incentivize salmonid fishes to migrate through the Delta vi

	Joaquin River. The three ag barriers are in place from April 15 to September 30 HORB has been seasonally installed most years since 1963 in the fall, and 1992 to explicit limits on OMR flows, the installation of the HORB during spring cou delta smelt salvage because the barrier resulted in more negative OMR if export The OMR flow limits in the ROC PA will continue to help minimize the entrain with the south Delta barriers. On March 7, 2018, the Service completed a biological opinion to the U.S. Army and DWR on the seasonal installation of temporary barriers, including the HOR consultation includes replacing the HORB with a permanent operable gate (HO PA, DWR and Reclamation propose to not install the HORB for the duration of
NMFS 2009 Biological Opinion	NMFS issued its current coordinated operations of the CVP and SWP BiOp on J NMFS BiOp covers: Central California Coast steelhead and its critical habitat; S winter-run Chinook salmon; Central Valley spring-run Chinook salmon; Central Southern Distinct Population Segment (DPS) of Northern American green sturg resident DPS of killer whales. NMFS determined that the action was likely to je species and destroy or adversely modify their critical habitat, except the Central steelhead, and included an RPA. Key elements of the NMFS RPA in the 2009 BiOp are: ● A new temperature management program for Shasta Reservoir and the S below Keswick Dam; ● Long-term passage prescriptions at Shasta Dam to allow re-introduction ● Flow and temperature criteria in Clear Creek below Whiskeytown Dam; ● A new screened pumping plant in Red Bluff to replace the Red Bluff Di (completed in 2012); ● Improved juvenile salmonid fish rearing habitat in the lower Sacramento ● Delta Cross Channel gate closure beyond the mandates of D-1641; ● An OMR flow limit of -5000 cfs from January 1 through June 30 with sa that can limit OMR flow to less negative values; ● A limit on the ratio of exports to San Joaquin River inflow during April

	● Required studies of acoustic tagged steelhead in the San Joaquin Basin to effectiveness of the RPA and refinements as necessary; ● New flow management standard, temperature management plan, addition fixes to temperature control structures, and long-term fish passage above steelhead on the American River; ● New minimum flow regime for steelhead in the Stanislaus River and lon evaluations above Goodwin, Tulloch, and New Melones Dam; and A hatchery genetics management plan for Nimbus Hatchery for steelhead and fa salmon (which is an important prey base for listed Southern Resident DPS killer
Water Quality Control Plan	The State Water Resources Control Board (SWRCB) has issued numerous order regarding water quality and water right requirements. The current Water Quality Bay-Delta (WQCP) including the water quality objectives in D-1641 (issued De and subsequent revisions in 2000 and 2006. The various flow objectives and exp are designed to protect the estuary ecosystem, in-Delta agriculture and regional quality. These objectives include salinity and minimum outflow requirements th and an 'X2 standard' and export to inflow ratio limits in February through June. objectives vary within and between years according to the Sacramento Valley 40 These water quality standards were incorporated into the ROC BA. The SWRCB is currently considering a petition to change points of diversion in The SWRCB is also in the process of updating the WQCP. The update has been phases, some of which are proceeding concurrently. Phases 1 and 2 are currently involves updating San Joaquin River flow and southern Delta water quality requ focuses on the Sacramento River basin and the Delta. Phase 3 will involve imple 1 and 2 through changes to water rights and other measures. This phase will requ hearings to determine the appropriate allocation of responsibility between water the scope of the Phase 1 and Phase 2 plans. Phase 4 will involve developing and objectives for priority Delta tributaries upstream of the Delta.
Central Valley Project Improvement Act	In 1992, the CVP was reauthorized through the Central Valley Project Improven (Public Law 102-575, Title 34) adding mitigation, protection, and restoration of project purpose. Further, the CVPIA specified that the dams and reservoirs of th be used "first, for river regulation, improvement of navigation, and flood control irrigation and domestic uses and fish and wildlife mitigation, protection and rest and, third, for power and fish and wildlife enhancement."

	The CVPIA includes actions to benefit fish and wildlife. Section 3406(b)(1) is in the Anadromous Fish Restoration Program (AFRP). Section 3406(b)(1) provides the CVP operations to meet the fishery restoration goals of the CVPIA, so long a not in conflict with the fulfillment of the Secretary's contractual obligations to p for other authorized purposes. The DOI decision on Implementation of Section 3 CVPIA, dated May 9, 2003, provides for the dedication and management of 800 CVP-water each year. This water has been used to augment flows below CVP da temporarily reduce CVP exports in the spring. DOI manages and accounts for (b to its May 9, 2003 decision and court decisions, including *Bay Institute of San F States*, 66 Fed. Appx. 734 (9th Cir. 2003), as amended, 87 Fed. Appx. 637 (2004 is authorized to acquire water to supplement (b)(2) water, pursuant to Section 34 seldom done so.
2014-2016 Drought Operations	The drought conditions during 2014-2016 resulted in low reservoir storages whi of the CVP and SWP to meet their obligations and comply with the WQCP. Dur 2016, Reclamation and DWR petitioned the SWRCB on several occasions to te terms of their water rights permits. The SWRCB Executive Director approved O urgency changes to D-1641 standards to help Reclamation and DWR deliver mi supplies. The granted requests and information related to the drought workshops at: http://www.waterboards.ca.gov/waterrights/water_issues/programs/drought/t An emergency drought barrier was installed in False River between Jersey and E during May and June 2015 to prevent salinity intrusion into the central Delta du extremely low (sometimes net negative) Delta outflow. The barrier allowed the meet salinity standards revised per the TUCPs while conserving limited water su reservoirs. The barrier was removed in the fall of 2015. The barrier was installe typically the peak of delta smelt larval density. The barrier may have prevented from utilizing False River for migration or dispersal, possibly increasing the risk in Franks Tract. Similar drought operations could be considered in the future wh conditions return to California.
Channel Maintenance Dredging and Sand Mining Projects	The Corps has consulted annually with the Service to conduct maintenance dred Bay Federal Navigation Channels (SBFNC). The SBFNC include several reache Channel, Suisun Bay Main Channel and New York Slough. Maintenance activit use of hydraulic suction dredging and mechanical clamshell dredging. Delta sm been entrained with the hydraulic suction dredging. Thus, the Corps has used cl since 2015 to minimize its incidental take.

	The Corps has also annually consulted with the Service to conduct its operations dredging in the Sacramento River Deep Water Ship Channel (SRDWSC) and St Ship Channel (SDWSC). Portions of each channel are dredged annually to main navigational depths. The SRDWSC begins in the city of West Sacramento and e Collinsville. The SDWSC extends from New York Slough near Pittsburg to Sto Joaquin River. The SRDWSC varies in width from 200 to 400 ft. The ship chan be deepened and widened as authorized under the Water Resources Developme (Public Law 99-662). The channel was proposed to be deepened along its entire to bottom widths ranging from 250 to 400 ft. Due to funding and other constrain been completed. Since 2014, only the reach from RM 35 to the turning basin of been deepened and the only widening that occurred was that necessary to maint for the deeper channel segment. The shipping channel maintenance projects use head suction dredge. In 2016, operational changes were made to reduce delta sm 2015, the Service requested cessation of fish monitoring surveys associated with minimize incidental take of delta smelt. Jerico Products, Hanson Marine Operations, and their joint-venture partnership commercial sand mining companies that have leases in Suisun Bay and the west for construction-related materials using hydraulic dredging methods. The Corps Service in 2014 on their ten-year marine sand-mining lease project proposal. Th seasonal timing of sand mining are largely dictated by demand for sand and the sand mining peaks in the summer and early fall when commercial and residentia at its annual peak. July – October sand mining historically makes up over 43% o volume. The Service's biological opinion prohibits mining near the shoreline an help protect delta smelt spawning habitat and fringing marsh habitats. Bathymet basis for routine monitoring of subtidal conditions in areas where mining takes p used to detect and assess biologically significant changes in subtidal habitat. Thi monitoring is required as part of the Corps permit. Tracking mining locations se mining occurs only within designated lease areas.
Levee Projects	In March of 2015, the Corps completed a draft general reevaluation study of the Common Features project for the City of Sacramento and surrounding areas. Th the flood risk management system for the American and Sacramento Rivers and channels which are sources of potential flooding. These areas overlap the action PA. The Common Features project will remediate levee seepage along approxim American River. It will also strengthen and raise 12 miles of Sacramento River Lastly, the authorization included seepage remediation and higher levees along American River and 5 miles of the Natomas Cross Canal levee.

	The Small Erosion Repair Program (SERP) provides a streamlined process for D obtain regulatory authorization for, and construct minor levee repairs on levees r within the Sacramento River Flood Control Project area. The SERP covers appro of levees and represents an initial five-year effort. After the first phase, the Intera Management Collaborative Program Group will evaluate the program's success a SERP may be expanded to include sites repaired by local agencies throughout th Joaquin watershed. Similar to previous initiatives, these small levee repairs will levee riprapping along the Sacramento River, further degrading the quality of ha
Aquatic Weed Control	The California Division of Boating and Waterways (DBW) is the lead agency fo weeds in the Delta, its tributaries, and Suisun Marsh. This includes controlling w Brazilian water weed, curly-leaf pondweed and Spongeplant. These programs ar eradicate these species, rather they attempt to control their spread and to seasona intensity of infestations. Thus far, the program has not been successful. Herbicid Delta are authorized to occur from March 1 through November 30. DBW is perm acres in the following areas over a 5-year increment. Much of this acreage is wit habitat boundaries for delta smelt.
Suisun Marsh Plan	On June 10, 2013, the Service issued a biological opinion for the *Suisun Marsh I* *Management, Preservation, and Restoration Plan* (Suisun Marsh Plan). This bio covers the continued operation and maintenance of managed wetlands in the Sui an important component of the Pacific Flyway and habitat for several resident E animals. The Suisun Marsh Plan also covered new managed wetland activities; d protection, including new riprap; and the installation of fish screens. The opinion programmatic restoration plan for restoring 5,000 to 7,000 acres of natural tidal Marsh. Details of the project-level activities associated with the managed wetlan online at: https://www.fws.gov/sfbaydelta/documents/2012-F-0602- 2_Suisun_Marsh_Solano_County_Corps_programmatic.pdf.
Scientific Monitoring and Research	Numerous State and federal agencies and their partners conduct scientific monito the Bay-Delta. Most of the incidental take of delta smelt is covered under a biolo Interagency Ecological Program for the San Francisco Estuary (IEP). However, years, limited its incidental take to much lower numbers that what was authorize biological opinion. The rest of the directed scientific take of delta smelt is covere permits held by other entities. Some sampling occurs year-around throughout the delta smelt and several IEP monitoring programs target delta smelt in particular. running monitoring programs (described in more detail in section X.1.2) were no delta smelt but historically have routinely collected them and over time, they bec delta smelt abundance indexing programs.

Use of cultured delta smelt for scientific research purposes	On December 7, 2018, the Service issued a framework programmatic biological issuance of a section 10(a)(1)(A) permit to the Fish Conservation and Culture La providing cultured delta smelt for scientific studies in the Delta. These studies ar answer questions about how delta smelt that were spawned and reared in captivit being released into the wild for population augmentation purposes.

References that were not cited in the CWF BiOp

Alpine, A.E. and Cloern, J.E., 1992. Trophic interactions and direct physical effects control phytoplankton biomass and production in an estuary. *Limnology and Oceanography*, *37*(5), pp.946-955.

Andrews, S.W., Gross, E.S. and Hutton, P.H., 2016. A water balance model to estimate flow through the Old and Middle River corridor. *San Francisco Estuary and Watershed Science*, *14*(2).

Andrews, S.W., Gross, E.S. and Hutton, P.H., 2017. Modeling salt intrusion in the Bay-Delta prior to anthropogenic influence. *Continental Shelf Research*, *146*, pp.58-81.

Bouley, P. and Kimmerer, W.J., 2006. Ecology of a highly abundant, introduced cyclopoid copepod in a temperate estuary. *Marine Ecology Progress Series*, *324*, pp.219-228.

Brown, L.R., Kimmerer, W. and Brown, R., 2009. Managing water to protect fish: a review of California's environmental water account, 2001–2005. *Environmental management*, *43*(2), pp.357-368.

Brown, L.R., Kimmerer, W., Conrad, J.L., Lesmeister, S. and Mueller–Solger, A., 2016. Food webs of the Delta, Suisun Bay, and Suisun Marsh: an update on current understanding and possibilities for management. *San Francisco Estuary and Watershed Science*, *14*(3).

Brown, L.R., Komoroske, L.M., Wagner, R.W., Morgan-King, T., May, J.T., Connon, R.E. and Fangue, N.A., 2016. Coupled downscaled climate models and ecophysiological metrics forecast habitat compression for an endangered estuarine fish. *PloS one*, *11*(1), p.e0146724.

Bush, E.E., 2017. *Migratory life histories and early growth of the endangered estuarine Delta Smelt (Hypomesus transpacificus)*. University of California, Davis.

Cloern, J.E. 2019. Patterns, pace, and processes of water quality variability in a long-studied estuary. Limnology and Oceanography 64:S192-S208. doi: 10.1002/lno.10958

Cloern, J.E., Alpine, A.E., Cole, B.E., Wong, R.L., Arthur, J.F. and Ball, M.D., 1983. River discharge controls phytoplankton dynamics in the northern San Francisco Bay estuary. *Estuarine, Coastal and Shelf Science*, *16*(4), pp.415-429.

Cloern, J.E. and Jassby, A.D., 2012. Drivers of change in estuarine- coastal ecosystems: Discoveries from four decades of study in San Francisco Bay. *Reviews of Geophysics*, *50*(4).

Cole, B.E. and Cloern, J.E., 1984. Significance of biomass and light availability to phytoplankton productivity in San Francisco Bay. *Marine ecology progress series. Oldendorf*, *17*(1), pp.15-24.

Connon, R.E., Beggel, S., D'Abronzo, L.S., Geist, J.P., Pfeiff, J., Loguinov, A.V., Vulpe, C.D. and Werner, I., 2011. Linking molecular biomarkers with higher level condition indicators to identify effects of copper exposures on the endangered delta smelt (Hypomesus transpacificus). *Environmental Toxicology and Chemistry*, *30*(2), pp.290-300.

Connon, R.E., Deanovic, L.A., Fritsch, E.B., D'Abronzo, L.S. and Werner, I., 2011. Sublethal responses to ammonia exposure in the endangered delta smelt; Hypomesus transpacificus (Fam. Osmeridae). *Aquatic toxicology*, *105*(3-4), pp.369-377.

Connon, R.E., Geist, J., Pfeiff, J., Loguinov, A.V., D'Abronzo, L.S., Wintz, H., Vulpe, C.D. and Werner, I., 2009. Linking mechanistic and behavioral responses to sublethal esfenvalerate exposure in the endangered delta smelt; Hypomesus transpacificus (Fam. Osmeridae). *BMC genomics*, *10*(1), p.608.

Damon, L.J., Slater, S.B., Baxter, R.D. and Fujimura, R.W., 2016. Fecundity and reproductive potential of wild female delta smelt in the upper San Francisco Estuary, California. *California Fish and Game*, *102*(4), pp.188-210.

Davis, B.E., Cocherell, D.E., Sommer, T., Baxter, R.D., Hung, T.C., Todgham, A.E. and Fangue, N.A., 2019. Sensitivities of an endemic, endangered California smelt and two non-native fishes to serial increases in temperature and salinity: implications for shifting community structure with climate change. *Conservation Physiology*, *7*(1), p.coy076.

Dettinger, M., Anderson, J., Anderson, M. Brown, L.R., Cayan, D., and Maurer, E. 2016. Climate change and the Delta. San Francisco Estuary and Watershed Science 14(3): http://escholarship.org/uc/item/2r71j15r

Dugdale, R.C., Wilkerson, F.P., Hogue, V.E. and Marchi, A., 2007. The role of ammonium and nitrate in spring bloom development in San Francisco Bay. *Estuarine, Coastal and Shelf Science*, *73*(1-2), pp.17-29.

Dugdale, R., Wilkerson, F., Parker, A.E., Marchi, A. and Taberski, K., 2012. River flow and ammonium discharge determine spring phytoplankton blooms in an urbanized estuary. *Estuarine, Coastal and Shelf Science*, *115*, pp.187-199.

Dugdale, R.C., Wilkerson, F.P. and Parker, A.E., 2016. The effect of clam grazing on phytoplankton spring blooms in the low-salinity zone of the San Francisco Estuary: a modelling approach. *Ecological modelling*, *340*, pp.1-16.

Eder, K.J., Kaufman, R.C., Cocherell, D.E., Lindberg, J.C., Fangue, N.A., and Loge, F.J. 2014. Longfin and delta smelt food consumption and bioenergetics assessments. Report to U.S. Bureau of Reclamation for grant R10AC20107.

Feyrer, F., Cloern, J.E., Brown, L.R., Fish, M.A., Hieb, K.A. and Baxter, R.D., 2015. Estuarine fish communities respond to climate variability over both river and ocean basins. *Global change biology*, *21*(10), pp.3608-3619.

Feyrer, F., Herbold, B., Matern, S.A. and Moyle, P.B., 2003. Dietary shifts in a stressed fish assemblage: consequences of a bivalve invasion in the San Francisco Estuary. *Environmental Biology of Fishes*, *67*(3), pp.277-288.

Feyrer, F., Newman, K., Nobriga, M. and Sommer, T., 2016. Delta Smelt Habitat in the San Francisco Estuary: A Reply to Manly, Fullerton, Hendrix, and Burnham's "Comments on Feyrer et al. Modeling the Effects of Future Outflow on the Abiotic Habitat of an Imperiled Estuarine Fish". *Estuaries and Coasts*, *39*(1), pp.287-289.

Feyrer, F., Sommer, T. and Harrell, W., 2006. Managing floodplain inundation for native fish: production dynamics of age-0 splittail (Pogonichthys macrolepidotus) in California's Yolo Bypass. *Hydrobiologia*, *573*(1), pp.213-226.

Fisch, K.M., Henderson, J.M., Burton, R.S. and May, B., 2011. Population genetics and conservation implications for the endangered delta smelt in the San Francisco Bay-Delta. *Conservation genetics*, *12*(6), pp.1421-1434.

Glibert, P.M., Fullerton, D., Burkholder, J.M., Cornwell, J.C. and Kana, T.M., 2011. Ecological stoichiometry, biogeochemical cycling, invasive species, and aquatic food webs: San Francisco Estuary and comparative systems. *Reviews in Fisheries Science*, *19*(4), pp.358-417.

Gross, E.S., Hutton, P.H. and Draper, A.J., 2018. A Comparison of Outflow and Salt Intrusion in the Pre-Development and Contemporary San Francisco Estuary. *San Francisco Estuary and Watershed Science*, *16*(3).

Hamilton, S.A. and Murphy, D.D., 2018. Analysis of limiting factors across the life cycle of Delta smelt (Hypomesus transpacificus). *Environmental management*, *62*(2), pp.365-382.

Hammock, B.G., Hartman, R., Slater, S.B., Hennessy, A. and Teh, S.J., 2019. Tidal Wetlands Associated with Foraging Success of Delta Smelt. *Estuaries and Coasts*, pp.1-11.

Hammock, B.G., Slater, S.B., Baxter, R.D., Fangue, N.A., Cocherell, D., Hennessy, A., Kurobe, T., Tai, C.Y. and Teh, S.J., 2017. Foraging and metabolic consequences of semi-anadromy for an endangered estuarine fish. *PloS one*, *12*(3), p.e0173497.

Hasenbein, M., Fangue, N.A., Geist, J., Komoroske, L.M., Truong, J., McPherson, R. and Connon, R.E., 2016. Assessments at multiple levels of biological organization allow for an integrative determination of physiological tolerances to turbidity in an endangered fish species. *Conservation physiology*, *4*(1), p.cow004.

Hasenbein, M., Werner, I., Deanovic, L.A., Geist, J., Fritsch, E.B., Javidmehr, A., Foe, C., Fangue, N.A. and Connon, R.E., 2014. Transcriptomic profiling permits the identification of pollutant sources and effects in ambient water samples. *Science of the Total Environment*, *468*, pp.688-698.

Hirose, T. and Kawaguchi, K., 1998. Spawning ecology of Japanese surf smelt, Hypomesus pretiosus japonicus (Osmeridae), in Otsuchi Bay, northeastern Japan. *Environmental biology of fishes*, *52*(1-3), pp.213-223.

Hobbs, J.A., Bennett, W.A., Burton, J. and Baskerville-Bridges, B., 2007. Modification of the biological intercept model to account for ontogenetic effects in laboratory-reared delta smelt (Hypomesus transpacificus). *Fishery Bulletin*, *105*(1), pp.30-38.

Hobbs, J., Moyle, P.B., Fangue, N. and Connon, R.E., 2017. Is extinction inevitable for Delta Smelt and Longfin Smelt? An opinion and recommendations for recovery. *San Francisco Estuary and Watershed Science*, *15*(2).

Hutton, P.H., Chen, L., Rath, J.S. and Roy, S.B., 2019. Tidally- averaged flows in the interior Sacramento–San Joaquin River Delta: Trends and change attribution. *Hydrological Processes*, *33*(2), pp.230-243.

Hutton, P.H., Rath, J.S. and Roy, S.B., 2017a. Freshwater flow to the San Francisco Bay- Delta estuary over nine decades (Part 1): Trend evaluation. *Hydrological Processes*, *31*(14), pp.2500-2515.

Hutton, P.H., Rath, J.S. and Roy, S.B., 2017b. Freshwater flow to the San Francisco Bay- Delta estuary over nine decades (Part 2): Change attribution. *Hydrological Processes*, *31*(14), pp.2516-2529.

Jeffries, K.M., Connon, R.E., Davis, B.E., Komoroske, L.M., Britton, M.T., Sommer, T., Todgham, A.E. and Fangue, N.A., 2016. Effects of high temperatures on threatened estuarine fishes during periods of extreme drought. *Journal of Experimental Biology*, *219*(11), pp.1705-1716.

Jeffries, K.M., Komoroske, L.M., Truong, J., Werner, I., Hasenbein, M., Hasenbein, S., Fangue, N.A. and Connon, R.E., 2015. The transcriptome-wide effects of exposure to a pyrethroid pesticide on the Critically Endangered delta smelt Hypomesus transpacificus. *Endangered Species Research*, *28*(1), pp.43-60.

Jin, J., Kurobe, T., Ramírez-Duarte, W.F., Bolotaolo, M.B., Lam, C.H., Pandey, P.K., Hung, T.C., Stillway, M.E., Zweig, L., Caudill, J. and Lin, L., 2018. Sub-lethal effects of herbicides penoxsulam, imazamox, fluridone and glyphosate on Delta Smelt (Hypomesus transpacificus). *Aquatic toxicology*, *197*, pp.79-88.

Kammerer, B.D., Hung, T.C., Baxter, R.D. and Teh, S.J., 2016. Physiological effects of salinity on Delta Smelt, Hypomesus transpacificus. *Fish physiology and biochemistry*, *42*(1), pp.219-232.

Kayfetz, K. and Kimmerer, W., 2017. Abiotic and biotic controls on the copepod Pseudodiaptomus forbesi in the upper San Francisco Estuary. *Marine Ecology Progress Series*, *581*, pp.85-101.

Kimmerer, W.J., 2011. Modeling Delta Smelt losses at the south Delta export facilities. *San Francisco Estuary and Watershed Science*, *9*(1).

Kimmerer, W.J., Burau, J.R. and Bennett, W.A., 1998. Tidally oriented vertical migration and position maintenance of zooplankton in a temperate estuary. *Limnology and Oceanography*, *43*(7), pp.1697-1709.

Kimmerer, W.J., Gartside, E. and Orsi, J.J., 1994. Predation by an introduced clam as the likely cause of substantial declines in zooplankton of San Francisco Bay. *Marine ecology progress series*, *113*, pp.81-93.

Kimmerer, W. and Gould, A., 2010. A Bayesian approach to estimating copepod development times from stage frequency data. *Limnology and Oceanography: Methods*, *8*(4), pp.118-126.

Kimmerer, W.J., Gross, E.S. and MacWilliams, M.L., 2014. Tidal migration and retention of estuarine zooplankton investigated using a particle- tracking model. *Limnology and Oceanography*, *59*(3), pp.901-916.

Kimmerer, W.J., Gross, E.S., Slaughter, A.M. and Durand, J.R., 2019. Spatial Subsidies and Mortality of an Estuarine Copepod Revealed Using a Box Model. *Estuaries and Coasts*, *42*(1), pp.218-236.

Kimmerer, W.J., Ignoffo, T.R., Slaughter, A.M. and Gould, A.L., 2014. Food-limited reproduction and growth of three copepod species in the low-salinity zone of the San Francisco Estuary. *Journal of Plankton Research*, *36*(3), pp.722-735.

Kimmerer, W., Ignoffo, T.R., Bemowski, B., Modéran, J., Holmes, A. and Bergamaschi, B., 2018. Zooplankton Dynamics in the Cache Slough Complex of the Upper San Francisco Estuary. *San Francisco Estuary and Watershed Science*, *16*(3).

Kimmerer, W.J., Ignoffo, T.R., Kayfetz, K.R. and Slaughter, A.M., 2018. Effects of freshwater flow and phytoplankton biomass on growth, reproduction, and spatial subsidies of the estuarine copepod Pseudodiaptomus forbesi. *Hydrobiologia*, *807*(1), pp.113-130.

Kimmerer, W.J., MacWilliams, M.L. and Gross, E.S., 2013. Variation of fish habitat and extent of the low-salinity zone with freshwater flow in the Bay-Delta. *Bay-Delta and Watershed Science*, *11*(4).

Kimmerer, W.J. and Orsi, J.J., 1996. Changes in the zooplankton of the San Francisco Bay Estuary since the introduction of the clam Potamocorbula amurensis. *San Francisco Bay: The Ecosystem*, pp.403-424.

Kimmerer, W.J. and Rose, K.A., 2018. Individual- Based Modeling of Delta Smelt Population Dynamics in the Upper San Francisco Estuary III. Effects of Entrainment Mortality and Changes in Prey. *Transactions of the American Fisheries Society*, *147*(1), pp.223-243.

Kimmerer, W.J. and Thompson, J.K., 2014. Phytoplankton growth balanced by clam and zooplankton grazing and net transport into the low-salinity zone of the San Francisco Estuary. *Estuaries and coasts*, *37*(5), pp.1202-1218.

Kjelson, M.A. and Brandes, P.L., 1989. The use of smolt survival estimates to quantify the effects of habitat changes on salmonid stocks in the Sacramento-San Joaquin rivers, California. *Canadian special publication of fisheries and aquatic sciences/Publication speciale canadienne des sciences halieutiques et aquatiques. 1989.*

Knutson Jr, A.C. and Orsi, J.J., 1983. Factors regulating abundance and distribution of the shrimp Neomysis mercedis in the Sacramento-San Joaquin Estuary. *Transactions of the American Fisheries Society*, *112*(4), pp.476-485.

Komoroske, L.M., Connon, R.E., Jeffries, K.M. and Fangue, N.A., 2015. Linking transcriptional responses to organismal tolerance reveals mechanisms of thermal sensitivity in a mesothermal endangered fish. *Molecular ecology*, *24*(19), pp.4960-4981.

Kratina, P., Mac Nally, R., Kimmerer, W.J., Thomson, J.R. and Winder, M., 2014. Human- induced biotic invasions and changes in plankton interaction networks. *Journal of applied ecology*, *51*(4), pp.1066-1074.

Lopez, C.B., Cloern, J.E., Schraga, T.S., Little, A.J., Lucas, L.V., Thompson, J.K. and Burau, J.R., 2006. Ecological values of shallow-water habitats: implications for the restoration of disturbed ecosystems. *Ecosystems*, *9*(3), pp.422-440.

Lucas, L.V., Cloern, J.E., Thompson, J.K. and Monsen, N.E., 2002. Functional variability of habitats within the Sacramento–San Joaquin Delta: restoration implications. *Ecological Applications*, *12*(5), pp.1528-1547.

Lucas, L.V., Thompson, J.K. and Brown, L.R., 2009. Why are diverse relationships observed between phytoplankton biomass and transport time?. *Limnology and oceanography*, *54*(1), pp.381-390.

Mac Nally, R., Thomson, J.R., Kimmerer, W.J., Feyrer, F., Newman, K.B., Sih, A., Bennett, W.A., Brown, L., Fleishman, E., Culberson, S.D. and Castillo, G., 2010. Analysis of pelagic species decline in the upper San Francisco Estuary using multivariate autoregressive modeling (MAR). *Ecological Applications*, *20*(5), pp.1417-1430.

MacWilliams, M.L., Bever, A.J., Gross, E.S., Ketefian, G.S. and Kimmerer, W.J., 2015. Three-dimensional modeling of hydrodynamics and salinity in the Bay-Delta: An evaluation of model accuracy, X2, and the low–salinity zone. *Bay-Delta and Watershed Science*, *13*(1).

MacWilliams, M., Bever, A.J. and Foresman, E., 2016. 3-D simulations of the Bay-Delta with subgrid bathymetry to explore long-term trends in salinity distribution and fish abundance. *Bay-Delta and Watershed Science*, *14*(2).

Mager, R.C., Doroshov, S.I., Van Eenennaam, J.P., and Brown, R.L. 2004. Early life stages of delta smelt. Pages 169-180 in Feyrer, F., Brown, L.R., Brown, R.L., and Orsi, J.J. (eds.). Early life history of fishes in the San Francisco Estuary and Watershed. American Fisheries Society Symposium 39, Bethesda, MD.

Mahardja, B., Hobbs, J.A., Ikemiyagi, N., Benjamin, A. and Finger, A.J., 2019. Role of freshwater floodplain-tidal slough complex in the persistence of the endangered delta smelt. *PloS one*, *14*(1), p.e0208084.

Manly, B.F.J., Fullerton, D., Hendrix, A.N. and Burnham, K.P., 2015. Comments on Feyrer et al."modeling the effects of future outflow on the abiotic habitat of an imperiled estuarine fish". *Estuaries and coasts*, *38*(5), pp.1815-1820.

Monismith, S.G., 2016. A note on Delta outflow. *San Francisco Estuary and Watershed Science*, *14*(3).

Moyle, P.B., 2002. *Inland fishes of California: revised and expanded*. Univ of California Press.

Moyle, P.B., Baxter, R.D., Sommer, T., Foin, T.C. and Matern, S.A., 2004. Biology and population dynamics of Sacramento splittail (Pogonichthys macrolepidotus) in the San Francisco Estuary: a review. *San Francisco Estuary and Watershed Science*, *2*(2).

Moyle, P.B., Brown, L.R., Durand, J.R. and Hobbs, J.A., 2016. Delta smelt: life history and decline of a once-abundant species in the San Francisco Estuary. *San Francisco Estuary and Watershed Science*, *14*(2).

Moyle, P.B., Hobbs, J.A. and Durand, J.R., 2018. Delta Smelt and water politics in California. *Fisheries*, *43*(1), pp.42-50.

Orsi, J.J. and Mecum, W.L., 1986. Zooplankton distribution and abundance in the Sacramento-San Joaquin Delta in relation to certain environmental factors. *Estuaries*, *9*(4), pp.326-339.

Orsi, J.J. and Mecum, W.L., 1996. Food limitation as the probable cause of a long-term decline in the abundance of Neomysis mercedis the opossum shrimp in the Sacramento-San Joaquin estuary. *San Francisco Bay: the ecosystem. American Association for the Advancement of Science, San Francisco*, pp.375-401.

Parker, A.E., Dugdale, R.C. and Wilkerson, F.P., 2012. Elevated ammonium concentrations from wastewater discharge depress primary productivity in the Sacramento River and the Northern San Francisco Estuary. *Marine Pollution Bulletin*, *64*(3), pp.574-586.

Perry, R.W., Skalski, J.R., Brandes, P.L., Sandstrom, P.T., Klimley, A.P., Ammann, A. and MacFarlane, B., 2010. Estimating survival and migration route probabilities of juvenile Chinook salmon in the Sacramento–San Joaquin River Delta. *North American Journal of Fisheries Management*, *30*(1), pp.142-156.

Peterson, M.S., 2003. A conceptual view of environment-habitat-production linkages in tidal river estuaries. *Reviews in Fisheries science*, *11*(4), pp.291-313.

Peterson, J.T. and Barajas, M.F., 2018. An Evaluation of Three Fish Surveys in the San Francisco Estuary, 1995–2015. *San Francisco Estuary and Watershed Science*, *16*(4).

Polansky, L., Mitchell, L., and Newman, K.B. In revision. Using multistage design-based methods to construct abundance indices and uncertainty measures for delta smelt. Transactions of the American Fisheries Society (update when accepted).

Polansky, L., Newman, K.B., Nobriga, M.L. and Mitchell, L., 2018. Spatiotemporal Models of an Estuarine Fish Species to Identify Patterns and Factors Impacting Their Distribution and Abundance. *Estuaries and coasts*, *41*(2), pp.572-581.

Quinn, T., Krueger, K., Pierce, K., Penttila, D., Perry, K., Hicks, T. and Lowry, D., 2012. Patterns of surf smelt, Hypomesus pretiosus, intertidal spawning habitat use in Puget Sound, Washington State. *Estuaries and Coasts*, *35*(5), pp.1214-1228.

Reis, G.J., Howard, J.K. and Rosenfield, J.A., 2019. Clarifying Effects of Environmental Protections on Freshwater Flows to—and Water Exports from—the San Francisco Bay Estuary. *San Francisco Estuary and Watershed Science*, *17*(1).

Schoellhamer, D.H., Wright, S.A. and Drexler, J., 2012. A conceptual model of sedimentation in the Sacramento–San Joaquin Delta. *San Francisco Estuary and Watershed Science*, *10*(3).

Scofield, N.B., and Bryant, H.C. 1926. The striped bass in California. California Fish and Game 12(2): 55-74.

Simonis, J.L., and Merz, J.E. 2019. Prey availability, environmental constraints, and aggregation dictate population distribution of an imperiled fish. Ecosphere info:doi/10.1002/ecs2.2634.

Stevens, D.E. and Miller, L.W., 1983. Effects of river flow on abundance of young Chinook salmon, American shad, longfin smelt, and delta smelt in the Sacramento- San Joaquin River system. *North American Journal of Fisheries Management*, *3*(4), pp.425-437.

Sullivan, L.J. and Kimmerer, W.J., 2013. Egg development times of Eurytemora affinis and Pseudodiaptomus forbesi (Copepoda, Calanoida) from the upper San Francisco Estuary with notes on methods. *Journal of plankton research*, *35*(6), pp.1331-1338.

Wilkerson, F.P., Dugdale, R.C., Parker, A.E., Blaser, S.B. and Pimenta, A., 2015. Nutrient uptake and primary productivity in an urban estuary: using rate measurements to evaluate phytoplankton response to different hydrological and nutrient conditions. *Aquatic Ecology*, *49*(2), pp.211-233.

Winder, M. and Jassby, A.D., 2011. Shifts in zooplankton community structure: implications for food web processes in the upper San Francisco Estuary. *Estuaries and Coasts*, *34*(4), pp.675-690.

Winder, M., Jassby, A.D. and Mac Nally, R., 2011. Synergies between climate anomalies and hydrological modifications facilitate estuarine biotic invasions. *Ecology letters*, *14*(8), pp.749-757.