Chapter 7: Using the Conceptual Model–Why did Delta Smelt abundance increase in 2011?

In this Chapter, we further explore Delta Smelt responses and habitat attributes as depicted in the driver and life stage transition conceptual model diagrams presented in Chapter 5. The purpose is to demonstrate the utility of our conceptual model framework for generating hypotheses about the factors that may have contributed to the 2011 increase in Delta Smelt abundance. For each life stage transition, we explore a series of hypothesized linkages among ecosystem drivers, habitat attributes, and Delta Smelt responses. We evaluate these hypotheses by comparing habitat conditions and Delta Smelt responses in the wet year 2011 to those in the prior wet year 2006 and in the drier years 2005 and 2010.

In this Chapter we briefly describe the comparative approach and the hydrological conditions during the four years that are the focus of our comparisons. We then state and explore each hypothesis for the adult, larval, juvenile, and subadult life stages of Delta Smelt using data sources described in Chapter 3. Key points from these evaluations, as well as previous report Chapters, along with benefits and limitations of the comparative approach are summarized and discussed in Chapter 8. In several cases, we lacked suitable data or other necessary information to evaluate our hypotheses; these data and information gaps are described in Chapter 9. Chapter 9 also includes a brief review of some of the more complex mathematical analyses used in recent peer-reviewed publications, such approaches currently being used by others, and three examples of additional mathematical modeling approaches that can be used to further explore some of the linkages and interactions in our conceptual model and complement previously published and other ongoing mathematical modeling efforts for Delta Smelt.

Comparative Approach

The comparative approach used for evaluating the hypotheses stated in this Chapter is similar to the approach taken in the FLaSH investigation (Brown et al. 2014, see also http://deltacouncil.ca.gov/science-program/fall-low-salinity-habitat-flash-studies-and-adaptive-management-plan-review-0). This allowed us to place the results of the FLaSH investigation in a year-round, life cycle context as recommended by the FLaSH Panel (FLaSH Panel 2012). Specifically, we compared data from the two most recent wet years, 2006 and 2011, and the two years that immediately preceded them, 2005 and 2010. To conduct our comparisons, we determined how Delta Smelt responses or habitat attributes would be expected to respond in the different years and then compared the expected response to the observed response. If the expected and observed responses were similar, the hypothesis was considered to be supported.

Moderate to wet hydrological conditions tend to benefit many estuarine organisms, including Delta Smelt (Sommer et al. 2007). But low recruitment or low survival at any point in the predominantly annual Delta Smelt life cycle can lead to low abundance even in a wet year. Identifying the reason(s) for low abundance in a wet year may give important insights into key habitat attributes and environmental drivers that could be managed in a way that would improve the likelihood of abundance increases in all wet years.

The two wettest years after the onset of the POD were 2006 and 2011 (Fig. 58). Delta Smelt abundance increased substantially in 2011, but not in 2006 (Fig. 3). The failure of the Delta Smelt population to increase in the wet year 2006 and the increase of Delta Smelt in the wet year 2011 provides an opportunity to compare and contrast habitat attributes in these two years and possibly identify new options for management actions. As stated in Chapter 3, our working assumption is that different Delta Smelt abundances in 2006 and 2011 should be attributable to differing environmental conditions, in some cases attributable to management actions, and subsequent ecological processes influencing the Delta Smelt population.

Preceding habitat conditions may have important implications for the response of a population to the environmental conditions present during a wet year; therefore, we also consider data from 2005 and 2010. Further, we also consider adult and larval abundance in 2012 following the wet year of 2011. We did not include any years predating the POD period in this analysis. This was done to prevent the possibly more subtle, but management-relevant, environmental changes occurring during the POD period from being overwhelmed by effects of the strong POD step changes in the early 2000s as well as similarly strong changes that occurred before the POD (e.g., after the invasion of the clam *Potamocorbula amurensis*).

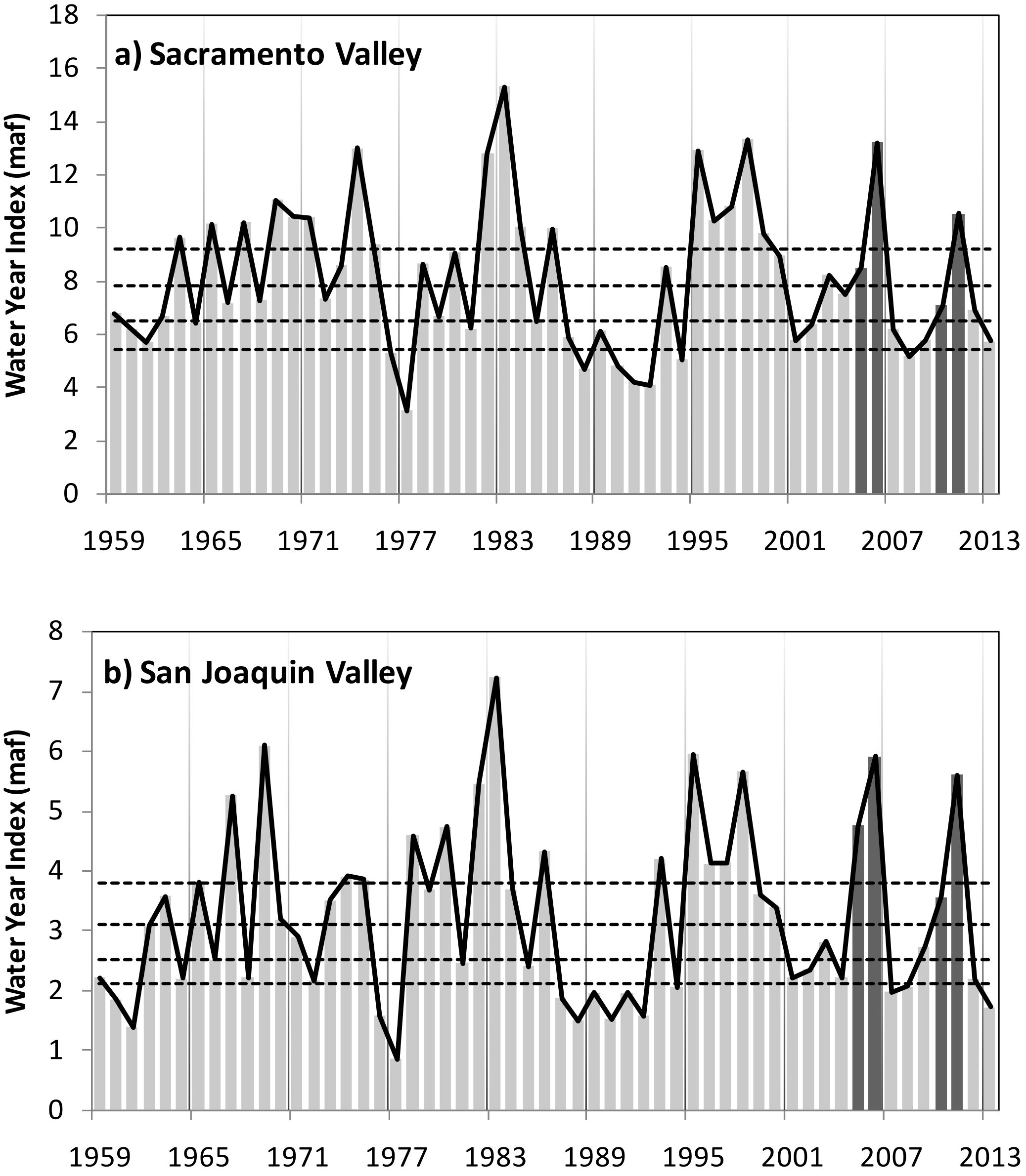
For the purpose of this report, we call 2005, 2006, 2010, and 2011 our “study years.” We use “year” rather loosely because the Delta Smelt life cycle does not follow the calendar year. As already explained, life stages can overlap and can be observed during different months in different years. Mature adults of a cohort produced in one year are generally not observed until the following year. Similarly, the life cycle does not strictly follow the water year type. We do our best to explain these mismatches when they occur and keep the presentation focused on the life cycle and the conceptual models.

Note that we do not examine the complex interactions that may occur when more than one hypothesis is true (or false), nor do we rule out that a hypothesis may be true in some years and false in others. Therefore, it is important to recognize that data contrary to a hypothesis may indicate that the habitat attribute was not controlling in the selected years, or that complex interactions among multiple habitat attributes (and corresponding hypotheses) contributed to the observed effects. Addressing such complexities is more appropriate for quantitative models as discussed in Chapter 9.

Hydrological Conditions

According to annual water year indices and classifications for overall hydrological conditions in the Sacramento and San Joaquin Valleys that provide the freshwater inflow into the Delta, 2005, 2006 and 2011 were the wettest years of the POD period (Fig. 58, see also http://cdec.water.ca.gov/cgi-progs/iodir/WSIHIST). In the San Joaquin Valley, 2010 was the fourth wettest year of this period. In the Sacramento Valley, 2003 and 2004 were wetter than 2010. Specifically, water year 2010 was classified as “below normal” in the Sacramento Valley and “above normal” in the San Joaquin Valley and 2011 was classified as wet in both areas, according to the water year index classifications. Water year 2005 was classified as “above normal” in the Sacramento Valley and “wet” in the San Joaquin Valley and 2006 was classified as wet in both areas. (Fig. 58). Water year 2012 was classified as “below normal” in the Sacramento Valley and “dry” in the San Joaquin Valley.

Figure 58. Annual water year indices for the a) Sacramento and b) San Joaquin Valleys since the initiation of the Summer Townet Survey in 1959. Horizontal dashed lines: threshold levels for water year type classifications as wet (W), above normal (AN), below normal (BN), dry (D) and critically dry (C). Darker grey bars indicate the four study years (2005, 2006, 2010, 2011) examined in Chapter 7 of this report. (Data are from http://cdec.water.ca.gov/cgi-progs/iodir/WSIHIST).



The overall wet hydrological conditions in the Sacramento and San Joaquin Valleys in 2005-6 and 2010-11 resulted in relatively prolonged periods of high Delta inflow and outflow and low X2 values in the winter and spring months of the four study years (Fig. 59). In the first half of the year, 2006 had the highest outflow and lowest X2 values followed by 2011, 2005, and 2010. In the second half of 2011, outflow was higher and X2 values were lower than in the second half of 2006 and of all other years during the POD period. In spite of having the lowest spring X2, 2006 had the highest fall X2 (September to October) of all study years, followed by 2005, 2010, and 2011 (Fig. 60).

The overall high flows during these four years allowed for periods of very high fresh water exports from the Delta (Fig. 59). This led to record high volumes of fresh water exported in water year 2011 (6.7 maf) and in water year 2005 (6.5 maf) and a somewhat lower export volume in water year 2006 (6.3 maf). The total water export volume was substantially lower in water year 2010 (4.8 maf) because 2010 immediately followed a three-year drought and the below normal hydrological conditions in the Sacramento Valley (Fig. 58) were not sufficient to rapidly replenish reservoirs and allow for greater exports.

Hypotheses

Individual hypotheses are indicated in the life stage transition conceptual model diagrams next to the arrows depicting each hypothesized linkage or outcome (figs. 46-49). While all linkages are considered important, we only developed hypotheses for selected linkages. We developed hypotheses for linkages with sufficient data for quantitative assessments and where there is disagreement or uncertainty regarding the outcome resulting from a driver. We also developed hypotheses for linkages considered important but where we found critical information was missing; thus, highlighting topics where new work is needed. For each of these hypotheses, we then considered the available data to examine whether the Delta Smelt response expected under the hypothesis was consistent with the observed trends in habitat attributes or population dynamics. While we would have liked to test hypotheses about the linkages between habitat attributes and the specific life stage transition processes shown in the life stage transition conceptual model diagrams, the available data often only allowed us to test "lower tier" hypotheses about the linkages between ecosystem drivers and habitat attributes.

Note that we have not examined the complex interactions that may have occurred when more than one hypothesis was true (or false), nor have we ruled out that a hypothesis may be true in some years and false in others. Therefore, it is important to recognize that data contrary to a hypothesis may indicate that the habitat attribute was not controlling in the selected years, or that complex interactions among multiple habitat attributes (and corresponding hypotheses) contributed to the observed effects. Addressing such complexities is likely more appropriate for quantitative models as discussed in Chapter 9. Our overall objective in this Chapter is to provide a demonstration of how the conceptual model can be used to generate and test hypotheses and highlight data gaps while addressing a specific topic of management interest—the increased Delta Smelt abundance index in 2011.

Adult Hypotheses

Hypothesis 1: Hydrology and water exports interact to **influence entrainment risk for adult Delta Smelt.**

As discussed earlier, we do not currently have a reliable measure of actual entrainment of fishes by the SWP and CVP export pumps. We also do not have actual population abundance estimates for Delta Smelt. As discussed by Kimmerer (2008, 2011) and Miller (2011), it is thus difficult to estimate proportional population losses due to entrainment. We consider the published

Figure 59. **Net daily flows in cubic feet per second for a) Delta inflow from all tributaries, b) Delta outflow into Suisun Bay, and d) total freshwater exports from the Delta. Also shown are daily values for c) X2 (see Chapter 4 for explanation). Flow data are from Dayflow (http://www.water.ca.gov/dayflow/). X2 values are calculated from daily Delta outflow with the equation in Jassby et al. (1995.)**

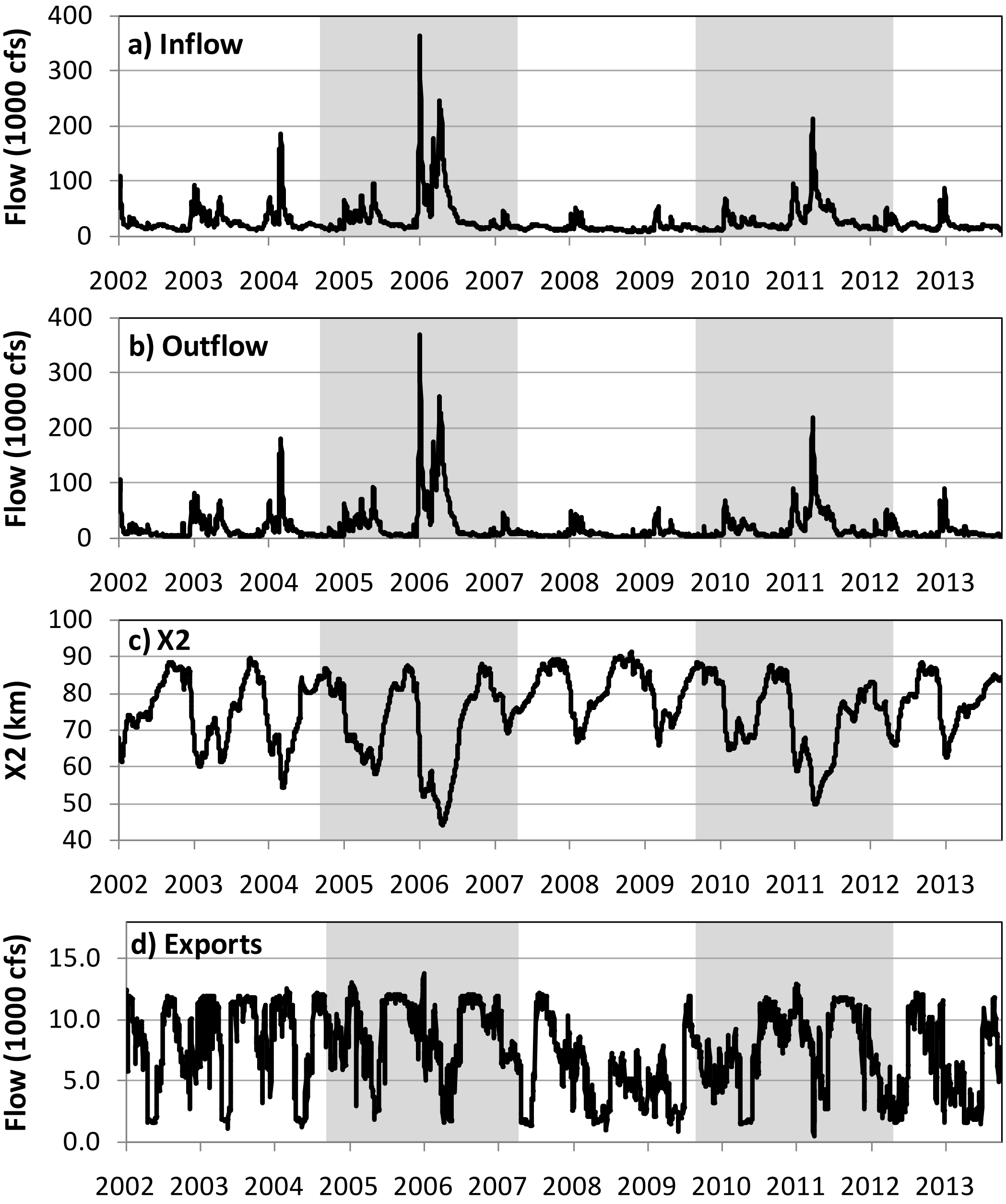
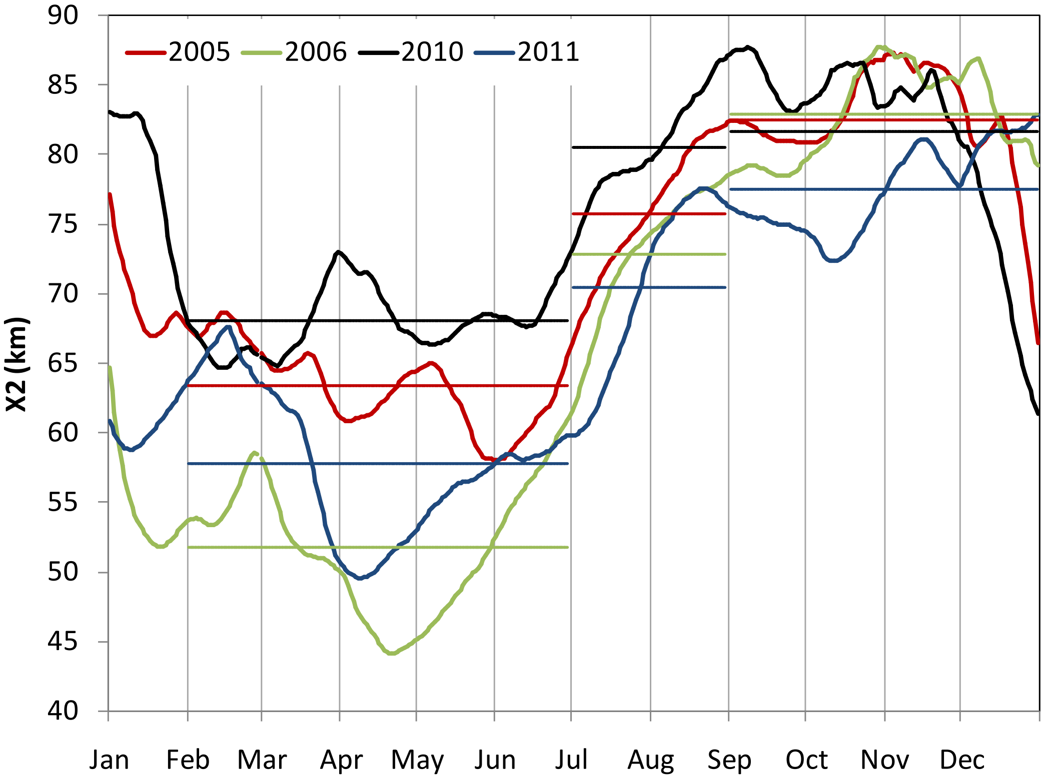


Figure 60. **Daily X2 values in January to December for each of the four study years. Seasonal X2 averages are indicated by horizontal lines for spring X2 (February to June), summer X2 (July and August), and fall X2 (September to December). See Fig. 15 for seasonal X2 in other years.**



proportional loss estimates for adult Delta Smelt entrainment losses for the two years for which they are available (2005 and 2006; Kimmerer 2008). However, we otherwise restrict our analysis – and this hypothesis – to an assessment of entrainment risk based on salvage and OMR flow data. Note that high entrainment risk for an individual fish does not automatically lead to a high proportion of the population lost to entrainment mortality. For example, in wetter years when large numbers of fish are present but most of the population is distributed farther away from the pumps, a large number of fish can be entrained but only a small percentage of the entire population.

Adult (December-March) Delta Smelt salvage was highest in 2005 followed by 2006 and 2010 and lowest in 2011 (Fig. 61). In 2005, most salvage occurred in January, while in the other three years it occurred in February and March (Fig. 62). Overall, adult Delta Smelt salvage in the four comparison years was on the very low end of the historical time series starting in 1980 (Fig. 26). On the other hand, the ratio of adult salvage divided by the previous year's FMWT index was high in 2005 (6th highest on record since 1979), but much lower in 2006 and 2010, and lowest in 2011 (Fig. 26).

Low salvage levels in these years and especially in 2010 and 2011 were not particularly surprising due to the low FMWT levels of the POD years along with more active management of OMR flows for Delta Smelt and salmonid protection after 2008 in accordance with the USFWS (2008) and NMFS (2009) BioOps. For management purposes, the onset of increased adult Delta Smelt entrainment risk is inferred from distributional patterns of Delta Smelt detected by the SKT survey, Delta Smelt salvage and, more recently, consideration of Delta conditions, including turbidity patterns. Since 2009, net OMR flows during periods of increased adult Delta Smelt entrainment risk are now always less negative than they were in years prior to the BioOps. Prior to 2008, net OMR flows often reached -8,000 to -10,000 cfs (see Fig. 31, Kimmerer 2008, Grimaldo et al. 2009), when outflow was low. An exception to these strongly negative flows occurred during April-May export curtailments associated with the Vernalis Adaptive Management Program (VAMP, 2000-2012). These curtailments were especially pronounced in the first half of the VAMP period (2000-2005). During the four comparison years, winter (December-March) net OMR flows were least negative in 2006 followed by 2011 and 2010 with the most negative net OMR flows in 2005 (Fig. 63). High inflows particularly from the San Joaquin River during 2005, 2006 and 2011 moderated effects of negative OMR flows, while export pumping generally remained high. In 2010 at the end of a three-year drought, there was little water in storage to provide for Delta exports prior to the first substantial inflows in mid-January. Subsequently, export levels had to be curtailed to achieve the desired OMR flows. Average winter-time net flows past Jersey Point on the San Joaquin River were positive in all four study years and greatest in 2006 followed by 2011, 2005, and 2010 (Fig. 63).

Kimmerer (2008) used salvage, OMR flows, and fish survey data to estimate proportional population losses due to entrainment for the years 1995-2006. The years 2005 and 2006 represent some of the lower loss estimates in the years examined by Kimmerer (2008); mean population losses reached up to 22% of the adult population in some years when OMR flows were more negative than -5000 cfs (Kimmerer 2008). Even if Kimmerer's estimation method provides a potential overestimate of loss (Miller 2011), proportional losses of the adult population were less than 10% in the two years that coincide with our comparison years (2005 ≈ 3% , 2006 ≈ 9%; from Fig. 12 in Kimmerer 2008). These types of proportional loss estimates are not available for

Figure 61. **Annual adult (December-March) Delta Smelt salvage at the CVP (blue bars) and SWP (green bars) fish protection facilities for 2005-2012.**

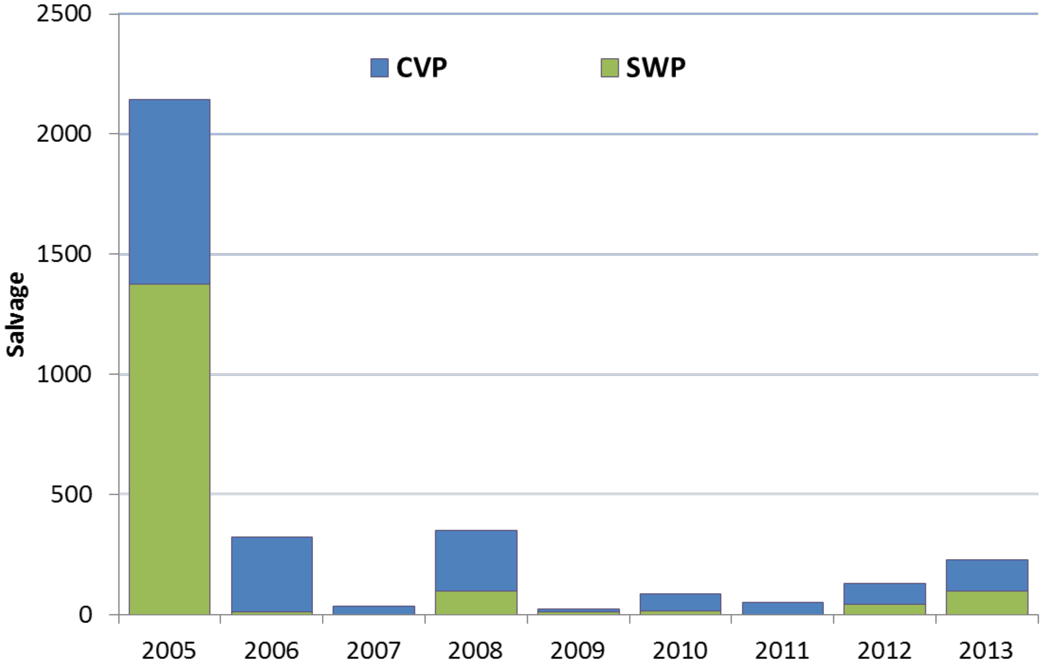
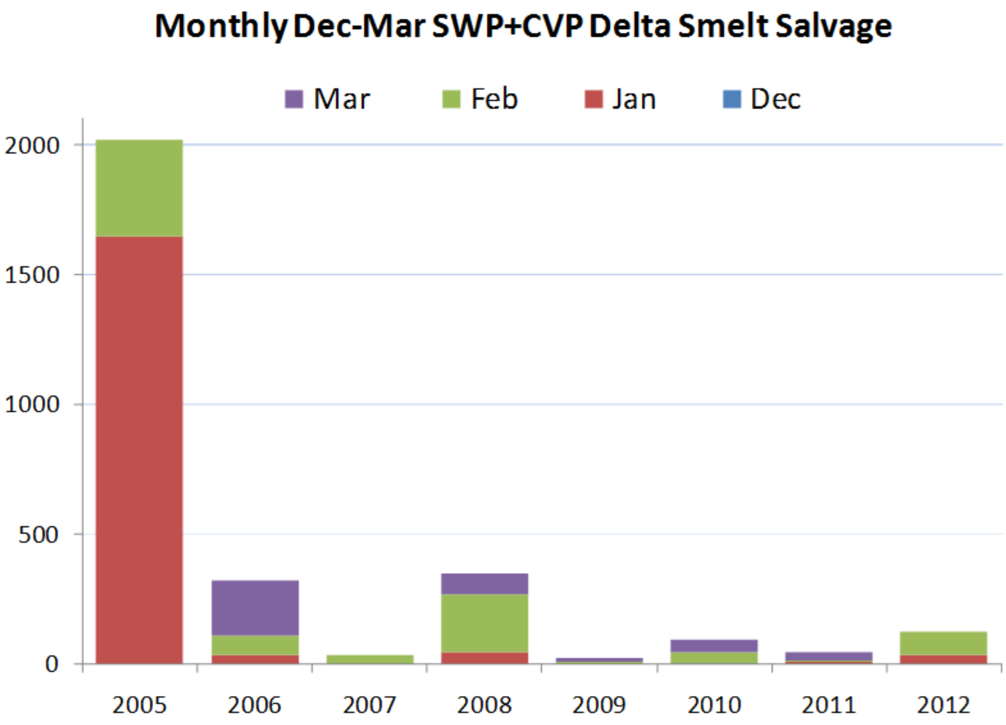


Figure 62. **Annual combined adult (December-March) Delta Smelt salvage at the CVP and SWP fish protection facilities by month for 2005-2012.**



2010 and 2011, but would likely be even smaller than for 2005 due to less negative OMR flows and fish distributions away from the CVP and SWP pumps. Salvage was also lower in these two years than in 2005 and 2006.

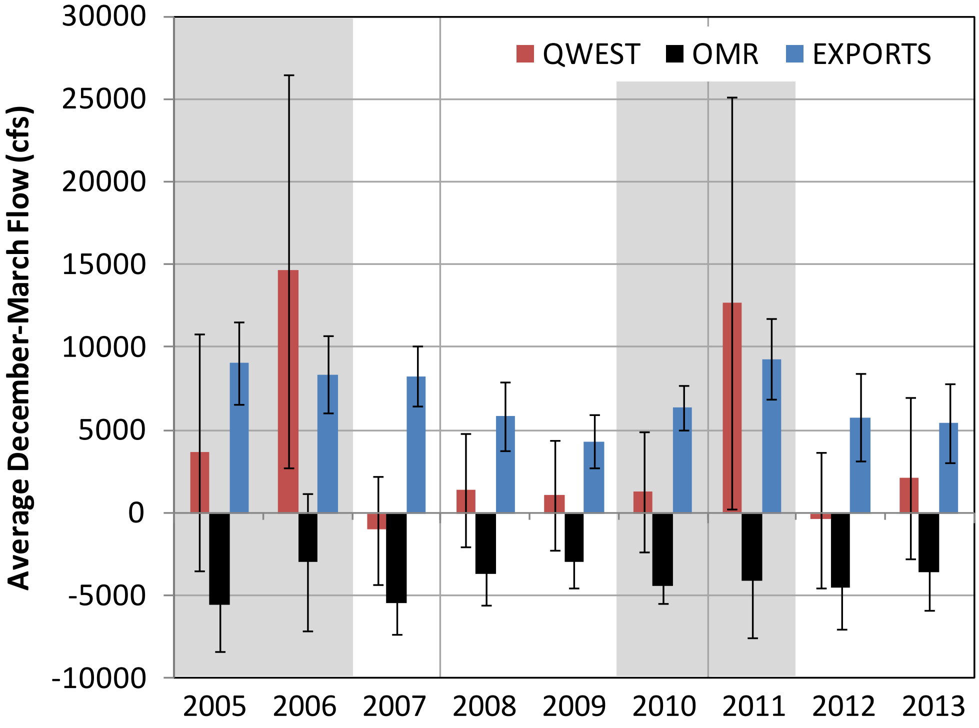
In summary, we conclude that hydrology and water exports do interact to influence entrainment risk for adult Delta Smelt and that adult Delta Smelt entrainment risk during the four comparison years was perhaps higher in 2005 than in the other years, but was low relative to historical levels in all four years.

Hypothesis 2: Hydrology interacting with turbidity **affects predation risk for adult Delta Smelt.**

At present, we do not have information about differences in actual predation mortality between the comparison years. As with entrainment, we thus limit this hypothesis and our analysis to to a general discussion of predation risk. Fully characterizing predation risk is exceptionally complicated, making it difficult to generate simple hypotheses that describe associated losses of all life stages of Delta Smelt. We thus limit our hypotheses about predation risk to a few factors for each life stage. For adults, we consider hydrology and turbidity as well as overlap with predators (next hypothesis).

Because Delta Smelt migrate during higher flow conditions when the water is generally turbid, it is assumed that losses to visual predators are lower or at least not substantially higher during the migration period than during other periods. First flush studies led by the USGS and UC Davis

Figure 63. Annual average daily net flows for December through March in cubic feet per second (cfs) in Old and Middle River (OMR), past Jersey Point on the lower San Joaquin River (QWEST) and total exports in millions of acre feet (MAF), 2005-2013. Error bars are 1 standard deviation.



suggest that Delta Smelt aggregate in the water column away from channel edges during daytime flood tides during upstream migration events (Bennett and Burau 2014), but it is not known if Striped Bass or Sacramento Pikeminnow *Ptychocheilus grandis*, the most likely predators of Delta Smelt in the water column, can detect and exploit these aggregations.

In the winters of 2005, 2006, 2010, and 2011 the highest Secchi depths (lowest turbidity) were found in the freshwater regions of the estuary (< 1 salinity), except for the Cache Slough region in the north Delta which was as turbid as the saltier regions of the estuary (Fig. 64). Winter-time Secchi depths in the freshwater region recorded during the SKT surveys (Fig. 64) were often higher (water clearer) than the average Secchi depths across all IEP EMP monitoring sites during these months since 2003 (about 60 cm) and especially when compared to pre-POD winter Secchi depths (around 50 cm on average) recorded by the EMP (Fig. 25). Winter-time Secchi depths in the other salinity regions were generally lower (water more turbid) than the EMP Secchi depth averages for the POD years and more similar to historical averages. In all four comparison years, predation risk associated with turbidity levels was thus likely not different from the historical risk in the more saline regions and the Cache Slough complex, but possibly higher in the freshwater regions, except for the Cache Slough region.

The salinity region differences were much more pronounced than the interannual differences between the four comparison years. Based on these data, it is not clear that higher flows in 2006 and 2011 contributed to higher turbidity in the winter months. The exception might be near the end of the Delta Smelt spawning season in early April when Secchi depths in the freshwater region were often substantially lower in the two wetter years 2006 and 2011 than in the two drier years 2005 and 2010 (Fig. 64). This will be discussed further in the report section about larval Delta Smelt. For adults, we conclude that interannual differences in turbidity between the wetter and drier of the four comparsion years did not likely contribute substantially to reduced predation risk and increased survival in the two wetter years.

Hypothesis 3: Predator distribution affects predation risk of adult Delta Smelt

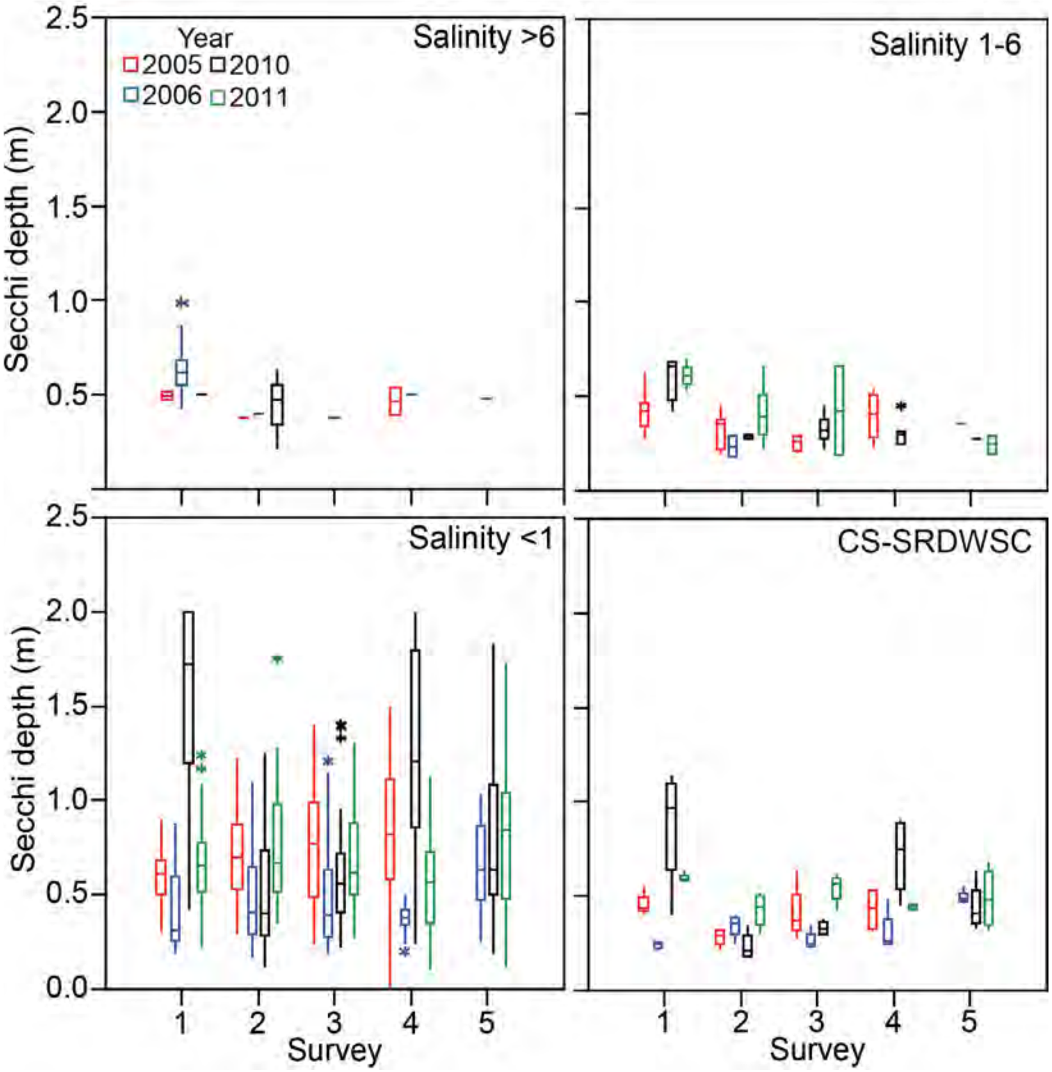
Spatial and temporal overlap with predators is a likely factor contributing to predation risk for all life stages. At present, we do not have information about how predator distribution varied between our comparison years but it is recognized that adult Delta Smelt could be vulnerable to predation if the distributions of predators and Delta Smelt populations overlapped. As already mentioned, Striped Bass and Sacramento Pikeminnow are the most likely open-water predators of adult Delta Smelt. If Delta Smelt utilize littoral habitats to a greater extent than presently assumed, then increased overlap with the distributions of Largemouth Bass and other centrarchid populations is possible. Results of field studies (Feyrer et al. 2013, Bennett and Burau 2014), described for Adult Hypothesis 2, found that adult Delta Smelt did move nearshore on a tidal basis to avoid displacement or move upstream during the “first flush.” Such movements would increase proximity to shoreline predators like Largemouth Bass, albeit during periods of increased turbidity when such visual predators would be at a disadvantage. Clearly, Hypothesis 2 and Hypothesis 3 are closely linked because predation risk is a function of predator presence and prey vulnerability. More information about predator presence is needed to evaluate this aspect of predation risk.

Hypothesis 4: Variability in prey availability during winter and spring affects growth and fecundity (eggs per clutch **and number of clutches) of female Delta Smelt.**

The hypothesis is that increased food availability leads to not only increased adult survivorship, but also growth, which in turn increases reproductive output (number of eggs per female increases with size; Bennett 2005). In addition, with cooler temperatures and lower metabolic rates, sufficient food resources during winter can contribute to energetically demanding multiple spawning events (three spawns possible in wild fish; L. Damon, CDFW, written communication 2012).

For adult females, the ability to meet the bioenergetic demands of reproductive development with sufficient food consumption may be particularly important for fish that spawn multiple times in a year. Preliminary findings from January through April 2012 indicated that adult Delta Smelt are indeed consuming large prey items, such as amphipods, mysids, and larval fish during their spawning period (Fig. 44) with feeding incidence near 98% for the period (Table 2). For this report, we cannot address whether food limitation is a relevant factor during the late winter-spring spawning period because we do not have sufficient data about adult Delta Smelt feeding, but we hypothesize that it may be a critical issue for spawners that need energy for multiple egg clutches. Evidence in support of this hypothesis comes from the modeling simulation experiment by Rose et al. (2013b) who found that food availability along with water temperature affected fall and winter growth and egg production prior to spawning and ultimately population success.

Figure 64. **Secchi depth data collected during the Spring Kodiak Trawl Survey. Surveys are conducted monthly January-May. See Chapter 3: Data Analyses for explanation of boxplots.**



Based on trajectories in adult fork lengths, it appears that adult growth may have been somewhat higher in 2005 and 2011 than in 2006 and 2010, although differences were not pronounced (Fig. 17) and as noted in Chapter 6, annual fork lengths of Delta Smelt collected in the SKT were similar in the four study years (Fig. 55). From these data we infer that environmental conditions were generally good, supporting both continued growth in length and maturation of eggs, except perhaps in 2010. In 2011, only 13 mature females were collected, so growth estimates are uncertain. In general, the number of mature females collected each year reflected year-class strength as measured by the SKT (Fig. 3), except in 2011 when only 13 ripe or ripening females were collected. Adults may use more energy for egg production than for continued somatic growth, but we do not have data on clutch sizes to evaluate this for the four study years.

Data on prey availability for current IEP sampling locations is also limited. Adult Delta Smelt diet is varied (Fig. 44) and includes pelagic and demersal invertebrates, as well as larval fish. Current mesozooplankton (copepod and cladoceran) and mysid sampling by the EMP

Table 2. **Percent of age-1 Delta Smelt captured during the Spring Kodiak Trawl Survey with food present in the stomach collected January through May 2012 for three salinity regions and the freshwater Cache Slough-Sacraramento River Deepwater Ship Channel (CS-SRDWSC).**

		Month					
YEAR	REGION	JAN	FEB	MAR	APR	MAY	GRAND TOTAL
2012	> 6	100%	100%				100%
	1 - 6	100%	100%	100%	100%	0%	99%
	< 1	100%	93%	100%	90%	89%	94%
	CS-SRDWSC	100%	100%	100%	96%	100%	99%
GRAND TOTAL	**100%**	**99%**	**100%**	**95%**	**90%**	**98%**	

Zooplankton Study and invertebrate sampling by the EMP Benthic Monitoring Study does not sample the full geographic range occupied by adult Delta Smelt, including Cache Slough and the Sacramento River Deep Water Ship Channel. In addition, epibenthic cumaceans and amphipods consumed by Delta Smelt might not be effectively sampled with current methods (substrate grabs using a Ponar dredge), which are more suited to sampling organisms in or attached to the substrate. Amphipods found in stomachs of adult Delta Smelt collected January 2012-May 2012 (Fig. 44) were 95% *Corophium* spp., and of those, 90% were juveniles ranging 0.8 to 1.3 mm in body length. These amphipods are believed to be mostly juvenile *Americorophium spinicorne* and *A. stimpsoni*, which as adults are tube building amphipods (Hazel and Kelley 1966). Dirt, substrate debris, and tube pieces were not found in Delta Smelt stomachs with the amphipods, so it is possible these juveniles amphipods are epibenthic or pelagic prior to settling and building tubes. Size distribution of amphipods collected by the DWR EMP Benthic Monitoring Study is not currently available. The IEP Smelt Larva Survey does collect larval fish data during winter (January-March) over a wide section of the estuary, but comparisons with larval fish consumption by adult Delta Smelt are limited because this survey is still new; it was initiated in 2009.

Data were insufficient to conclusively test the hypothesis that variability in prey availability affects growth and fecundity of adult Delta Smelt. More data are needed on growth, clutch number and size, and prey availability.

Larval Hypotheses

Hypothesis 1: Delta Smelt larvae numbers are positively affected by increased duration of the temperature spawning window

To evaluate this hypothesis, we developed two water temperature measures. The first is the number of days in the temperature spawning window as indexed by mean daily water temperatures at Rio Vista between 12 and 20 °C. This temperature range was selected as representing a reasonable balance between the various temperature ranges observed in laboratory and field studies (Wang 1986, Baskerville-Bridges et al. 2004b, Bennett 2005) and reviewed in earlier sections of this report. Presumably, a longer duration spawning window would result in more repeat spawning for individual females and greater total fecundity. The second water temperature measure is the number of days in the optimal temperature for egg survival to hatch. We referred to Fig. 10a in Bennett (2005) and selected the temperature range of 12-17 °C as optimal for egg survival. As explained in previous sections, adult abundance, based on SKT sampling, peaked in 2012 as the 2011 year-class of Delta Smelt reached maturity (Fig. 3). In contrast, the spawning stock (i.e., 2011 SKT) that produced the 2011 year-class ranked second lowest to 2006 (Fig. 3, Adults). Despite this low level, the 2011 spawning stock produced the highest adult abundance observed to date in 2012. This suggests that adult stock size has not limited subsequent adult recruitment from rebounding to levels comparable to those of immediate pre-POD years (see Fig. 3, Subadult). As mentioned in Chapter 6, this suggests that even a severely depleted adult stock can still produce a substantial number of larvae and a rebound in the Delta Smelt population, albeit with potentially lower genetic variability than before (Fisch et al. 2011). It also suggests that factors acting on the survival of larval, juvenile and later stages have a substantial effect on recruitment of adults, because relatively low larval abundance in 2011, was associated with the high 2012 adult abundance (Fig. 3).

As mentioned in the adult section, mature adult female Delta Smelt appeared to grow throughout the spawning seasons of the years compared, except 2010 (Fig. 17). We used water temperatures at the Rio Vista Bridge as a surrogate for temperatures experienced by spawning Delta Smelt (Fig. 65) and calculated the duration of the spawning window and of optimal temperatures to hatch. We calculated each as the number of days between the date of first achieving the lower temperature and the date of first achieving the upper temperature. The onset of the spawning window occurred earliest in 2010, followed by 2005 and 2011 (Fig. 65; Table 3). The spawning window occurred latest in 2006 (Fig. 65; Table 3). The spawning window was broad in both 2005 and 2010 at 128-129 days, intermediate in 2011 at 113 days (20 °C not achieved until July 4, not shown), and was shortest in 2006 at 85 days (Fig. 65; Table 3). Assuming that female Delta Smelt undergo a 35-day refractory period, based on a 4-5 week refractory period (J. Lindberg, U.C. Davis, personal communication, 2013) between each spawning, even in 2006 three spawning events were possible, assuming fish were mature and ready to spawn at the initiation of the spawning window. In all other years, four spawning events were possible, so this measure does not discriminate among years well. The duration of optimal hatch temperature was also lowest in 2006, but other durations ranked differently across years than did spawning window duration (Table 3).

The data for the four study years do not provide conclusive support for the hypothesis that the duration of the spawning window or duration of optimal hatching temperature affected larval production. Relatively high larval abundance in 2005 was consistent with a long spawning window and moderate duration of optimal hatch temperatures (129 days and 68 days, respectively; not shown). However, 2006 with the shortest spawning window (85 days) and shortest optimal hatch duration among the 4 study years also had relatively good larva abundance (Fig. 3). In contrast, larval abundance was low in 2010 although the spawning window and optimal hatch duration were both relatively long. Other factors likely contributed to poor larval abundance in 2010, because ripening and ripe females were not detected after early April 2010 and female growth through the winter was poor (Fig. 17). Finally, both the spawning window and optimal hatch duration were fairly long in 2011 as compared to 2006, so slightly lower larval production in 2011 is inconsistent with these durations. This hypothesis was not supported.

Figure 65. Mean daily temperatures (°C) at Rio Vista from February 1 through June 30, 2005, 2006, 2010, 2011. The green lines enclose the spawning window, which represents temperatures at which successful spawning is expected to occur.

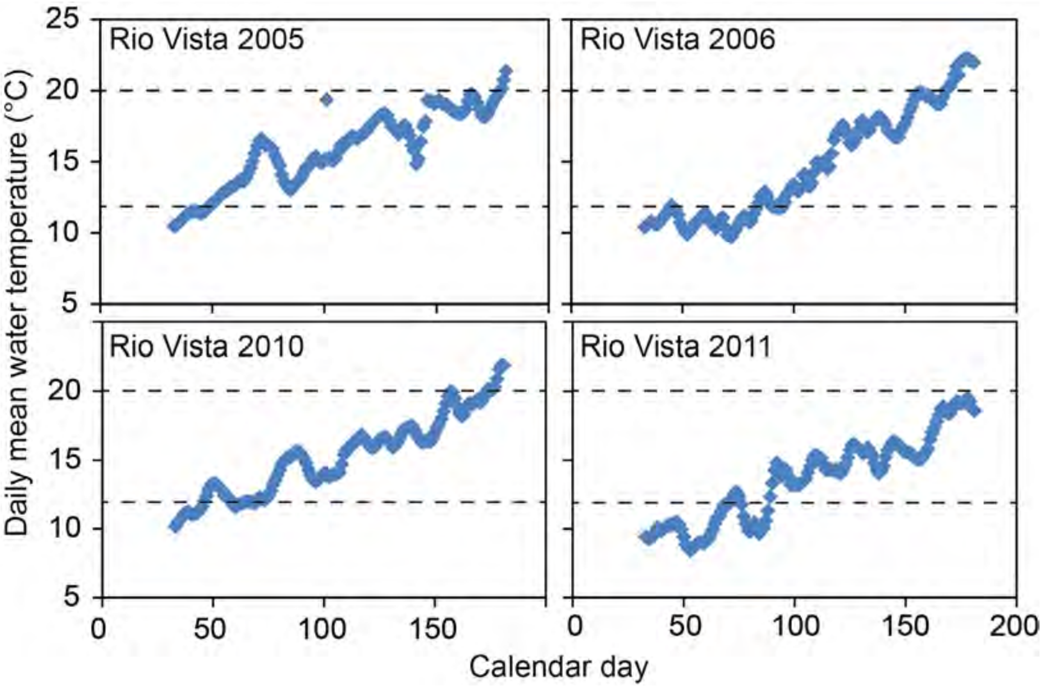


Table 3. Delta Smelt spawning window (12 to 20 °C inclusive) and optimal hatching period (12 to 17 °C inclusive) for 2005, 2006, 2010, and 2011, defined as number of days of water temperatures, based on mean daily water temperatures measured at Rio Vista. Data are calendar day when water temperature achieved 12, 17, and 20 °C and the duration (days) between those calendar days. The upper limit in 2011 was not reached until July 4, outside the spring season.

Year	Day 12 °C Achieved	Day 17 °C Achieved	Day 20 °C Surpassed	Duration 12-20	Duration 12-17	Duration 17-20
2005	50	118	179	129	68	61
2006	84	120	169	85	36	49
2010	46	136	174	128	90	38
2011	72	163	185	113	91	22

Hypothesis 2: Increased food availability results **in increased larval abundance and survival.**

This hypothesis focuses on seasonal changes in phytoplankton biomass and the zooplankton community and resulting changes in abundances of food items most often consumed by Delta Smelt larvae. Phytoplankton biomass data (chlorophyll-*a*) collected at 10 stations by the IEP

EMP show that the highest spring biomass levels were observed in May of 2010 and 2011 (Fig. 66). Median biomass levels were lower in April and May of 2005 and 2006 than in April and May of 2010 and 2011. This suggests that more food was available for zooplankton growth in the spring of 2010 and 2011 than in 2005 and 2006. In all four years, however, chlorophyll concentrations were lower than 10 ug/L at almost all stations, suggesting that zooplankton may have generally been food limited in these years (see Chapter 4). Nevertheless, greater phytoplankton biomass in late spring of 2010 and 2011 may have contributed to overall greater food availability and better survival of late larvae and early juveniles in these years.

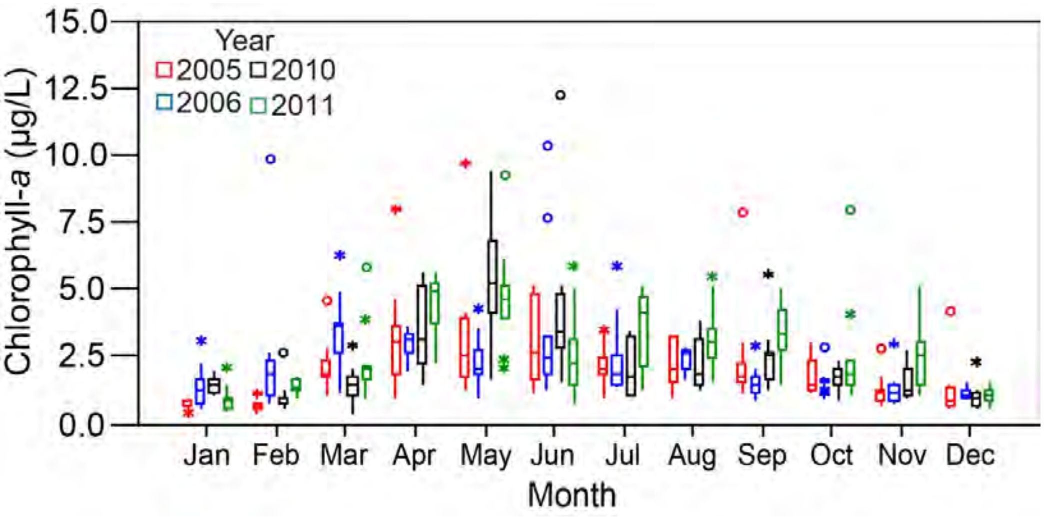
Juvenile and adult calanoid copepods, particularly *E. affinis* and *P. forbesi*, comprise most of the larval diet through June (Nobriga 2002, Slater and Baxter 2014). *E. affinis* is moderately abundant only during winter and spring and rare in summer and fall, whereas *P. forbesi* is abundant only in summer and fall (Durand 2010, Hennessy 2010, 2011, Winder and Jassby 2011). It is not clear whether the seasonal decline in abundance of *E. affinis* is related to temperature, potential competitive interactions with *P. forbesi*, differences between the species in vulnerability to consumption by *P. amurensis* (Miller and Stillman 2013), or a combination of such factors. The transition between high abundances of the two species, may create a seasonal “food gap” during late spring or early summer. This food gap has been hypothesized to be an important period for Delta Smelt larval survival (Bennett 2005, Miller et al. 2012).

To assess whether a gap in prey availability existed between periods of high abundance of *E. affinis* and *P. forbesi*, we evaluated abundance patterns in 20 mm Survey copepod data for stations with and without Delta Smelt. The food gap hypothesis was only weakly supported by the data. The density of *E. affinis* (in the presence of Delta Smelt larvae) typically reached 100 m^3 by week 16 (Figs. 67 and 68). Assuming 100 m^3 as a baseline density for *E. affinis*, this baseline was generally maintained until about week 22, when they declined at about the same time that *P. forbesi* densities increased to 100 m^3 (Figs. 67 and 68). After combining the densities of both *E. affinis* and *P. forbesi* and tracking them through time, we detected a gap in food during week 22 (late May – early June) of 2005 (Fig. 67), which is inconsistent with 2005 exhibiting the highest larva abundance among our comparison years (Fig. 3). Such density gaps were not observed in the other three comparison years (Figs. 67 and 68), which exhibited lower abundance than 2005 (Fig. 3). Survival of larvae to juveniles was very low in 2005, but was also low in 2006 (Fig. 51) with no evidence for a food gap in 2006. Survival of larvae to juveniles was relatively high in 2010 and 2011 (Fig. 51). This analysis does not support the hypothesis that differences in zooplankton availability affected larval abundance and survival in the four study years, but higher phytoplankton biomass in April and May of 2010 and 2011 could have contributed to overall greater food availability and better survival of late larvae and early juveniles in these years.

Hypothesis 3: Distributional overlap of Mississippi Silverside with Delta Smelt and high abundance of Mississippi Silverside increases predation risk/rate on larval Delta Smelt, whereas, increased turbidity, **decreases predation risk/rate on larval Delta Smelt.**

Silversides are ubiquitous within the Delta (Brown and May 2006) and have long been proposed (Bennett 1995) and more recently confirmed as a predator of Delta Smelt larvae (Baerwald et al. 2012). We do not have estimates of predation losses to Silversides during the four study years and thus focus on assessing predation risk by evaluating fish distributions, predator and prey sizes, and prey growth, which is related to temperature.

Figure 66. Trends in chlorophyll-*a* concentrations (µg/L) in samples collected by the IEP Environmental Monitoring Program during each the four study years (2005, 2006, 2010, and 2011). Sample site locations shown in figure 15. See Chapter 3: Data Analyses for explanation of boxplots.

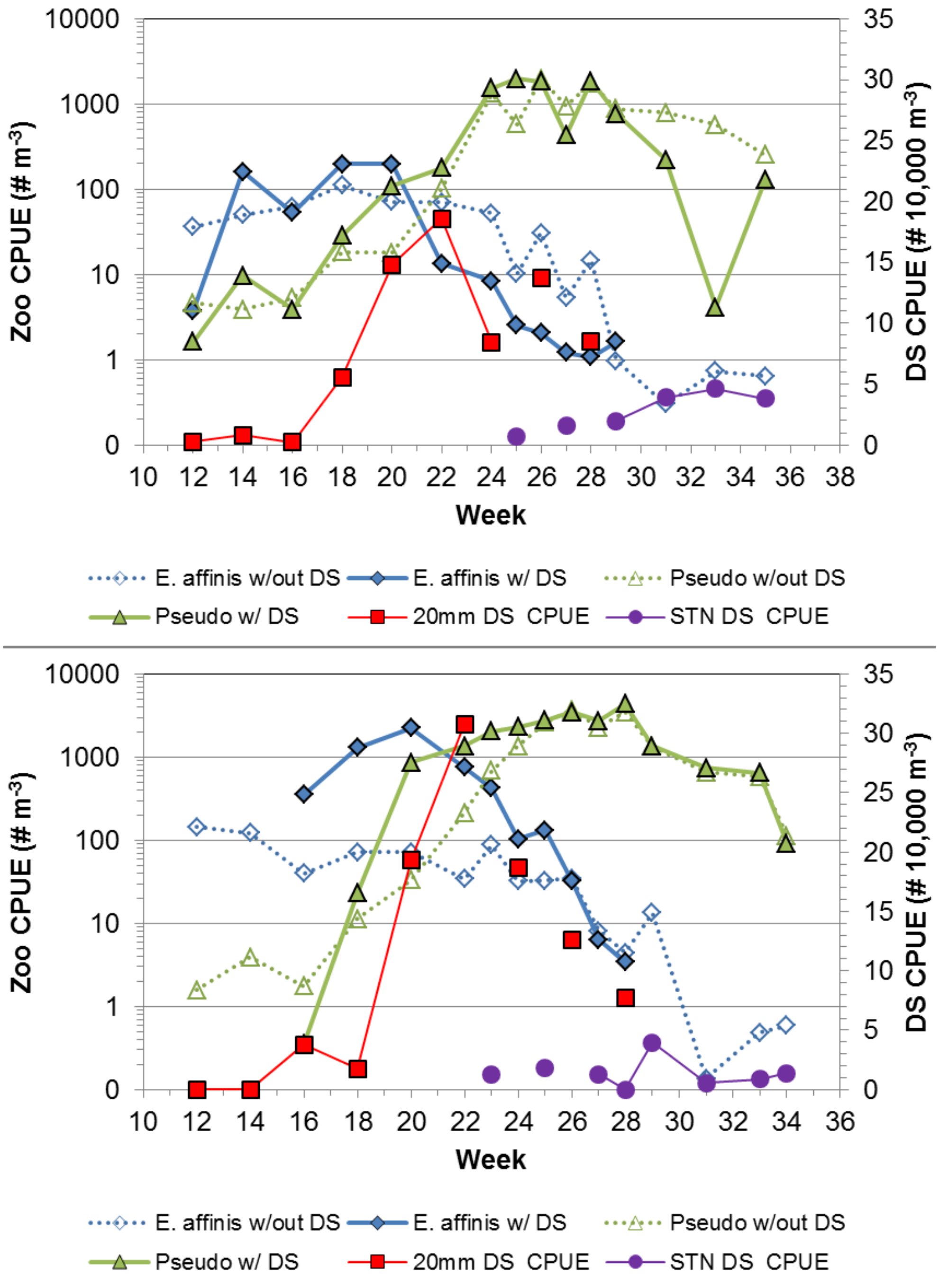


Silversides large enough to consume fish larvae are present in the Delta during spring and are likely to prey upon Delta Smelt larvae. Silverside habitat has been characterized as open water shoals and shoreline (Brown and May 2006, Grimaldo et al. 2012); however, the species also occurs in low density in deep open water primarily in summer (Grimaldo et al. 2012). Catches in the SKT confirm silverside presence in open water in spring as well, though catches tended to be low. However, SKT sampling does not occur at night when offshore Silverside densities may be higher, if foraging patterns follow those observed in Clear Lake, California (see Wurtsbaugh and Li 1985). Compared to the open embayments, SKT Silverside catches were higher in channels such as Montezuma Slough, Cache Slough, the San Joaquin River, and especially the Sacramento Deepwater Ship Channel (Table 4). This Silverside distribution matched higher March through May regional catches of Delta Smelt larvae (Table 4, see http://www.dfg.ca.gov/delta/data/20mm/CPUE_map.asp), except that larvae catches in Suisun Bay and the lower Sacramento River were occasionally high and Silversides catches were usually low. Delta Smelt larvae were found in significantly higher densities in offshore-open water habitats (Grimaldo et al. 2004), which corresponds to the habitat where Silversides consuming Delta Smelt larvae were captured (Baerwald et al. 2012). As discussed above, the relatively large-sized silversides present in the Spring Kodiak Trawl indicates some offshore movement and overlap of predator-sized foraging silversides with Delta Smelt larval habitat.

The frequency and magnitude of Silverside catches by the Spring Kodiak Trawl increased as Secchi depths approached and dropped below 50 cm (Fig. 69), suggesting that Silversides may venture offshore more frequently and in higher numbers in turbid water. This might also represent a displacement effect resulting from high flows, but high catches were most common in Montezuma Slough and the Sacramento Deepwater Ship Channel (Table 4) where displacement by flow should not have been a factor.

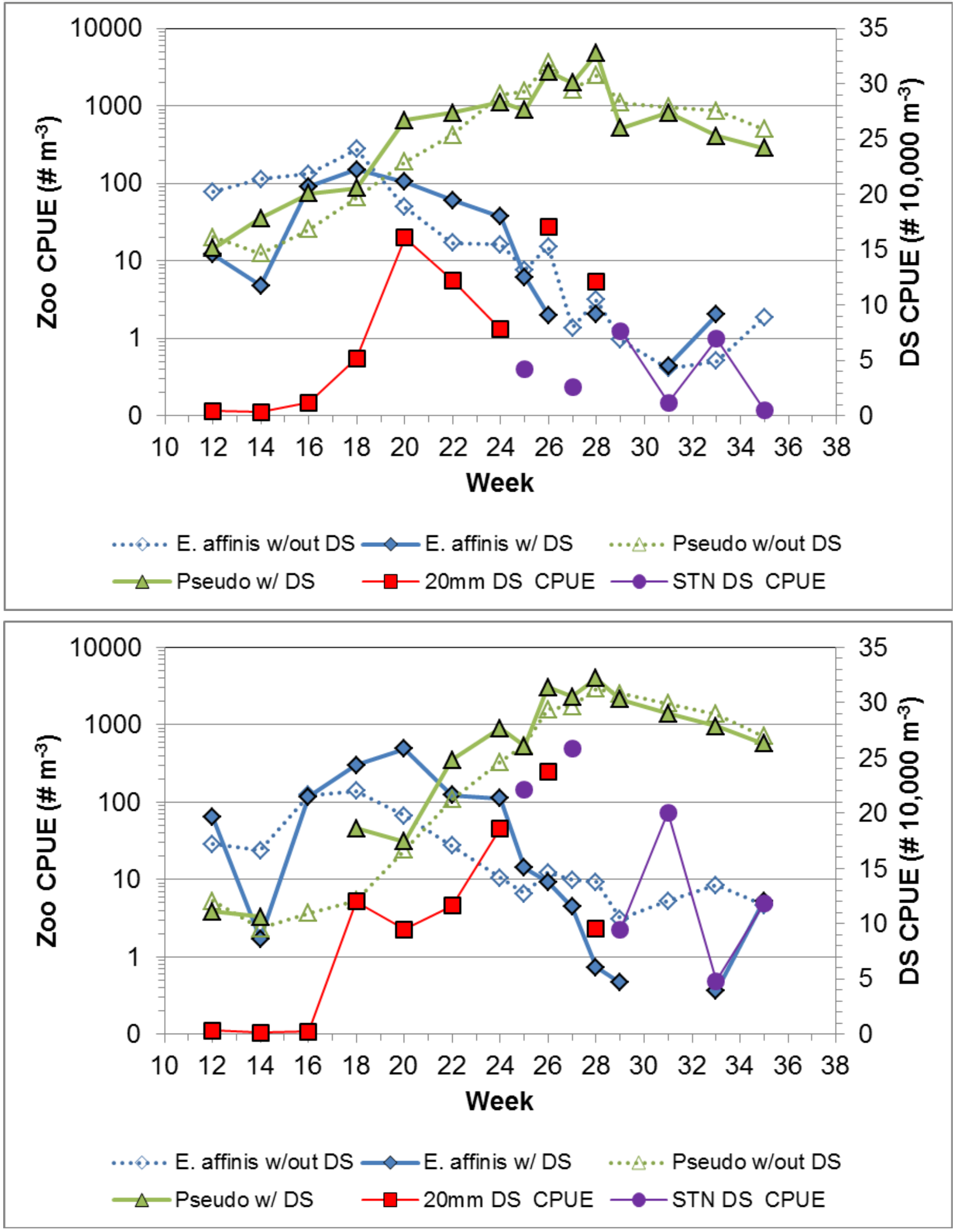
The hypothesis is somewhat supported in that: 1) Silversides are captured in Spring Kodiak Trawl in March and April (Fig. 70), when early stage Delta Smelt larvae are common; 2) Silverside

Figure 67. **Catch per unit effort (CPUE) of adult *Eurytemora affinis* and *Pseudodiaptomus forbesi* (Zoo; number individuals/m^3 sampled) and Delta Smelt (DS; number individuals/10,000 m^3 sampled) by calendar week from mesozooplankton sampling and Delta Smelt catch by the 20 mm and Summer Townet surveys, 2005 (top) and 2006 (bottom)**



catches offshore increase with increased turbidity (i.e., declining Secchi depth; Fig. 69), and 3) there is regional overlap in Cache Slough and the Sacramento Deepwater Ship Channel, and some in Montezuma Slough (cf. Table 4 and http://www.dfg.ca.gov/delta/data/20mm/CPUE_

Figure 68. Catch per unit effort (CPUE) of adult *Eurytemora affinis* and *Pseudodiaptomus forbesi* (Zoo; number individuals/m^3 sampled) and Delta Smelt (DS; number individuals/10,000 m^3 sampled) by calendar week from mesozooplankton sampling and Delta Smelt catch by the 20 mm and Summer Townet surveys, 2010 (top) and 2011 (bottom).



map.asp), known larval rearing regions. It is also possible the nighttime offshore foraging by silversides is a more common strategy (Wurtsbaugh and Li 1985), but one that goes undetected by current sampling. Silverside catch per trawl (Table 4) indicates low offshore densities and the same turbidity that facilitates offshore movement may also inhibit predation effectiveness.

Table 4. Mississippi Silverside catch by region (monthly sample number in parentheses) and year by the Spring Kodiak Trawl Survey sampling monthly March through May (months when Delta Smelt larvae are present), 2005, 2006, 2010 and 2011; distribution survey data only. Annual sampling effort summarized consisted of 3 surveys and 37 stations. Tow volume varied substantially, but averaged 6,300 m^3 per tow for the 4 years.

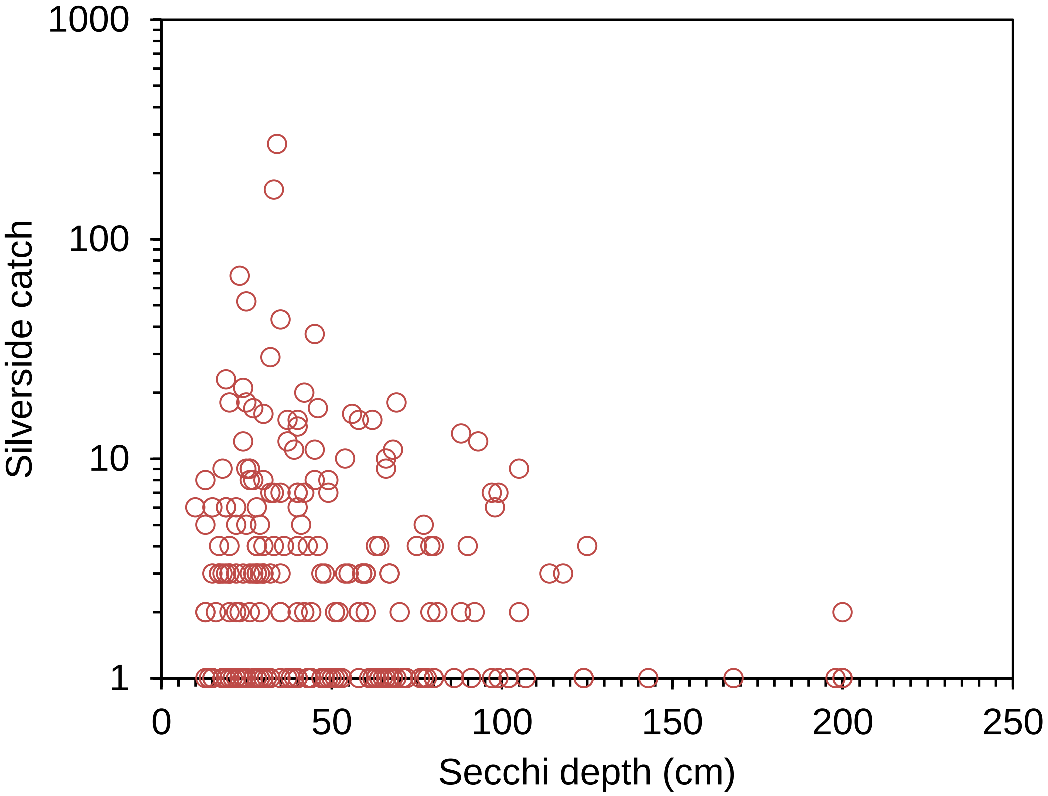
Region	2005	2006	2010	2011	Total Catch	Total Catch per Trawl
SUISUN BAY (N=10)	1	1	2	1	5	0.04
MONTEZUMA SL (N=3)	51	4	17	22	94	2.61
LOWER SACRAMENTO R (N=4)	10	1	1	3	15	0.31
CACHE SL (N=3)	9	2	4	2	17	0.47
SAC DEEPWATER SHIP CHANNEL (N=1)	14	20	45	22	101	8.42
SAN JOAQUIN R (N=8)	39	9	11	14	73	0.76
MOKLEMNE R. (N=5)	1	1	1	8	11	0.18
SOUTH DELTA (N=3)	1	0	1	1	3	0.08
ANNUAL TOTAL FOR REGIONS	126	38	82	73	319	

Overall, the conclusion regarding the effects of species distributions and abundances on predation risk is unclear. If there is an effect, it is most likely to occur in smaller channels, such as Montezuma Slough and those in the Cache Slough and the Sacramento Deepwater Ship Channel where Silversides are present in high numbers along the shoreline and larval Delta Smelt occur offshore.

Hypothesis 4: Hydrology and water exports interact **with one another to influence direction of transport and risk of entrainment for larval Delta Smelt.**

As for adults, we do not have proportional entrainment estimates for all four study years, so the entrainment portion of this hypothesis cannot be directly evaluated. Also, larvae (< 20 mm fork length) entrained in the State and federal water export systems are generally not quantified. To test this hypothesis we use data for the distribution and density of larvae (≥ 20 mm fork length)

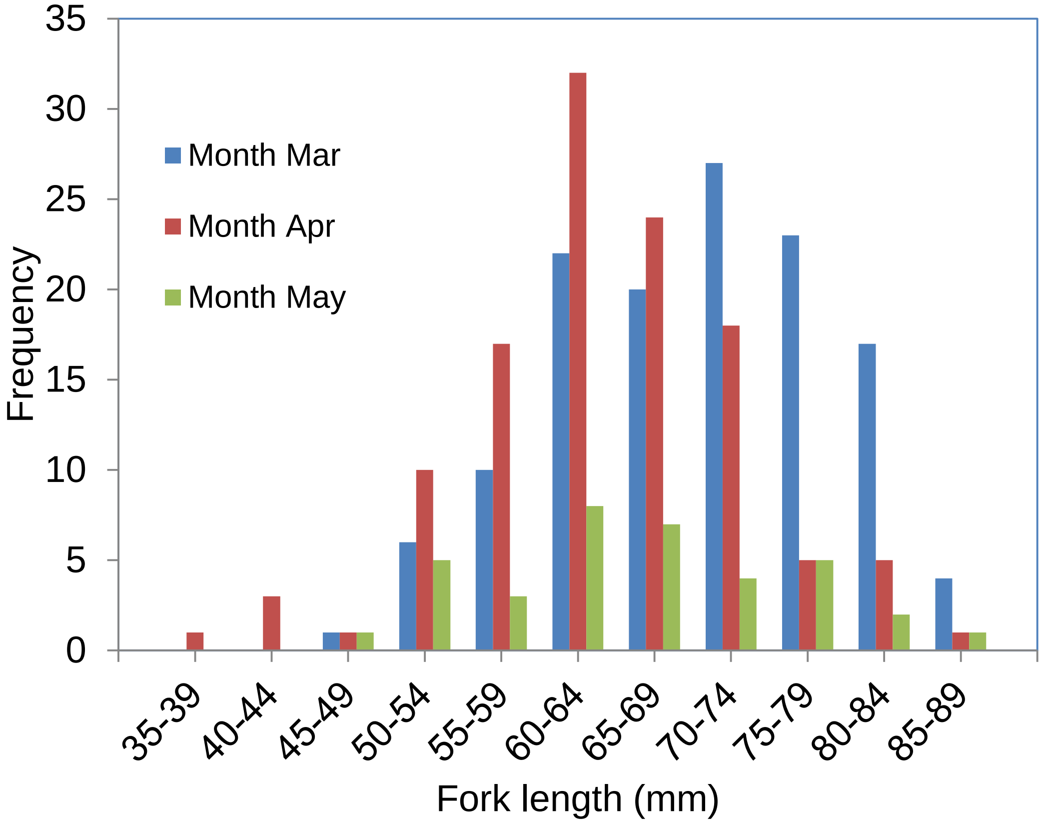
Figure 69. **Scatter plot of Mississippi Silverside catch plotted on Secchi depth (cm) at location of capture from the Spring Kodiak Trawl Survey, 2005, 2006, 2010 and 2011.**



in the central and south Delta and estimates of channel flows to infer risk of entrainment. Among the study years only 2005 larval entrainment was estimated by Kimmerer (2008), and loss to the population was relatively low. However, Delta Smelt density and distribution in the central and south Delta were greater in 2005 than in the three other study years (Table 5). This simple analysis suggests that in our 4-year comparison, entrainment risk for larval Delta Smelt may have been highest in 2005. Hardly any larval Delta Smelt were caught in this region in the two wet years, 2006 and 2011.

As for adults, we also used OMR flows (Fig. 31) to assess larval entrainment risk. Mean March through May OMR flows were positive during the two wet years 2006 and 2011 (8,221 cfs and 3,560 cfs respectively) and negative during the two dry years 2005 and 2010 (-417 cfs and -1,302 cfs, respectively). These OMR values suggest little if any risk during 2006 and 2011, and at most moderate risk in 2005 and 2010. Grimaldo et al. (2009) found that juvenile salvage was a function of abundance in the 20 mm Survey (positive) and OMR flows (negative). Looking more closely at various net daily flows from March to June of 2005, we find that OMR flows were moderately negative (i.e., toward the export pumps) only in March, and were zero to weakly positive in April and May, except for a brief period in mid-April (Fig. 31); also in 2005, Qwest was strongly positive from late March through early June, promoting downstream transport in the San Joaquin River, and exports were low from late April through late May (Fig. 31). The other dry year, 2010 exhibited a similar pattern, but lower inflows resulted in the magnitude of exports more directly influencing OMR flows (Fig. 31), and leading to moderately negative OMR flows

Figure 70. Monthly length frequency of Mississippi Silversides captured by the Spring Kodiak Trawl during distribution sampling March – May in the Sacramento River and Cache Slough sampling stations only, 2002-2012. The months and geographic range were selected to overlap with that of Delta Smelt larvae as they hatch and begin to grow.



in March and again in June, but only weakly negative flows in April and most of May coincident with positive Qwest. In the high outflow years 2006 and 2011, few larvae were detected in the central or south Delta (Table 5) and Qwest flows were strongly positive from March through at least early June, while OMR flows were near zero or weakly negative in March and positive to strongly positive by April and continuing to early June of both years (Fig. 31). Thus, for our comparison years, it appears that the available data generally support our hypothesis, but entrainment of larvae was unlikely to be an important factor during either wet year and was probably not a substantial factor in either dry year.

Table 5. Mean monthly catch of Delta Smelt per 10,000 m^3 by station for stations in the south and central Delta for the 20 mm Survey, 2005, 2006, 2010, 2011. Non-zero values are bolded.

Year = 2005	Months				
STATION	MARCH	APRIL	MAY	JUNE	JULY
809	0.00	0.00	**3.14**	**5.17**	0.00
812	0.00	0.00	**3.14**	**6.66**	0.00
815	0.00	**3.06**	**3.39**	0.00	0.00
901	0.00	0.00	**3.21**	0.00	**3.61**
902	0.00	0.00	0.00	0.00	0.00
906	**1.65**	**2.93**	**3.22**	0.00	0.00
910	0.00	0.00	0.00	0.00	0.00
912	0.00	0.00	0.00	0.00	0.00
914	**3.18**	**1.49**	**1.56**	0.00	0.00
915	0.00	0.00	0.00	0.00	0.00
918	**1.52**	**1.41**	0.00	0.00	0.00
919	0.00	0.00	0.00	0.00	0.00

Year = 2006	Months				
STATION	MARCH	APRIL	MAY	JUNE	JULY
809	0.00	0.00	0.00	0.00	0.00
812	0.00	0.00	0.00	0.00	0.00
815	0.00	0.00	**1.24**	0.00	0.00
901	0.00	0.00	0.00	0.00	0.00
902	0.00	0.00	0.00	0.00	0.00
906	0.00	0.00	0.00	0.00	0.00
910	0.00	0.00	0.00	0.00	0.00
912	0.00	0.00	0.00	0.00	0.00
914	0.00	0.00	0.00	0.00	0.00
915	0.00	0.00	0.00	0.00	0.00
918	0.00	0.00	0.00	0.00	0.00
919		0.00	0.00	0.00	0.00

Year = 2010	Months				
STATION	MARCH	APRIL	MAY	JUNE	JULY
809	0.00	0.00	**1.62**	0.00	0.00
812	0.00	0.00	0.00	0.00	0.00
815	0.00	**1.77**	**1.72**	0.00	0.00
901	0.00	0.00	0.00	0.00	0.00
902	0.00	0.00	0.00	0.00	0.00
906	0.00	**3.36**	0.00	**1.64**	0.00
910	0.00	**5.24**	0.00	0.00	0.00
912	0.00	0.00	0.00	0.00	0.00
914	0.00	0.00	0.00	0.00	0.00
915	0.00	0.00	0.00	0.00	0.00
918	0.00	0.00	0.00	0.00	0.00
919	0.00	0.00	0.00	0.00	0.00

Year = 2011	Months				
STATION	MARCH	APRIL	MAY	JUNE	JULY
809	0.00	0.00	0.00	**1.73**	0.00
812	0.00	0.00	0.00	0.00	0.00
815	0.00	0.00	0.00	0.00	0.00
901	0.00	0.00	**3.69**	0.00	0.00
902	0.00	0.00	0.00	0.00	0.00
906	0.00	0.00	0.00	0.00	0.00
910	0.00	0.00	0.00	0.00	0.00
912	0.00	0.00	0.00	0.00	0.00
914	0.00	0.00	0.00	0.00	0.00
915	0.00	0.00	0.00	0.00	0.00
918	0.00	0.00	0.00	0.00	0.00
919	0.00	0.00	0.00	0.00	0.00

Juvenile Hypotheses

Hypothesis 1: High water temperatures reduce juvenile Delta Smelt growth and survival through lethal and sublethal **(bioenergetic stress; reduced distribution) effects.**

High water temperatures have a strong effect on juvenile Delta Smelt survival (Swanson et al. 2000, Komoroske et al. 2014). In addition to the obvious potential for lethal effects, temperature can have sub-lethal effects such as reduced habitat area, higher food requirements, increased susceptibility to disease and contaminants, and increased predation. The potential for increased prey requirements and increased predation is described below for other hypotheses.

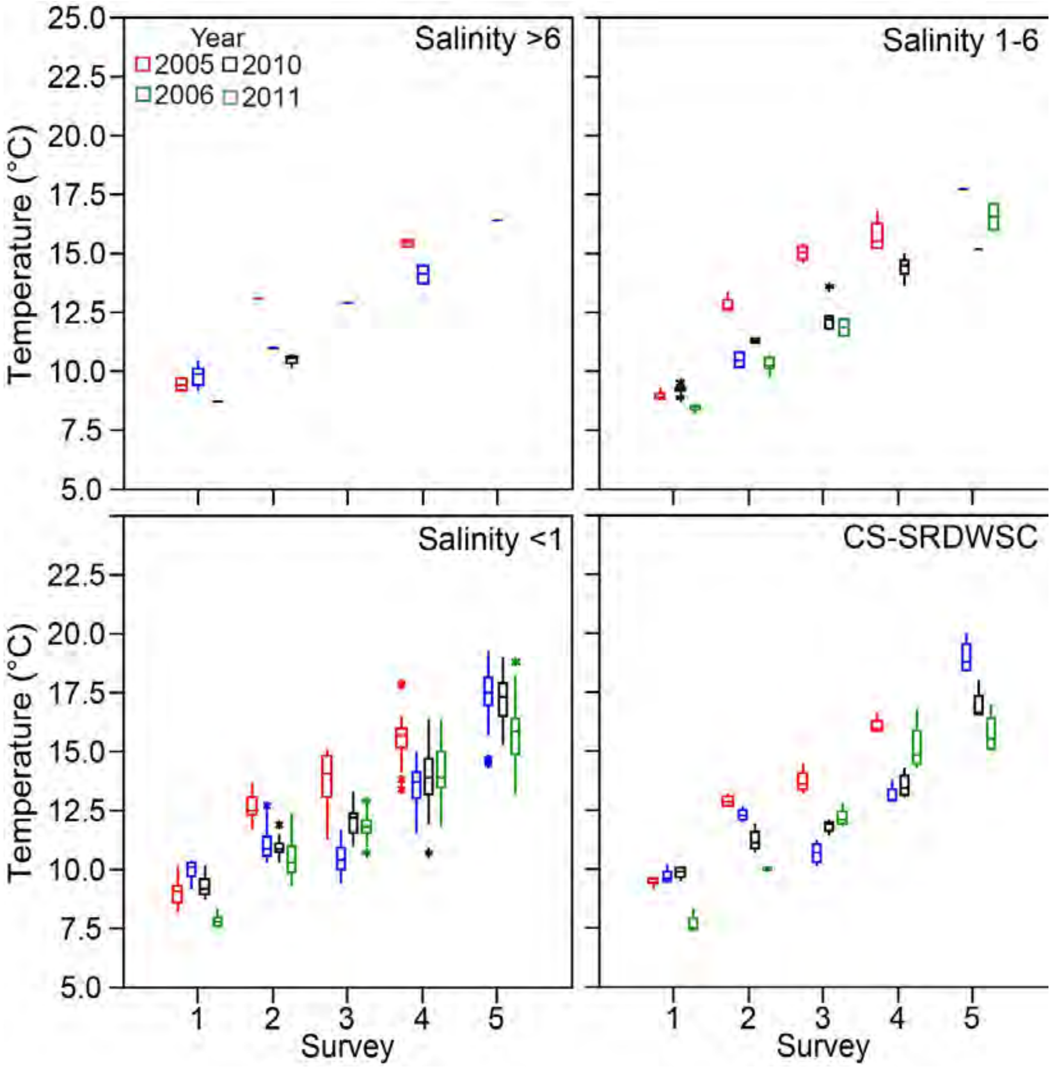
As noted in the adult section, spring water temperature was generally coolest in 2006 and 2011, but warmed up more rapidly toward the end of spring 2006 (May) than in spring 2011. Spring water temperature was overall warmest in 2005 (Fig. 71). Following the high late-spring water temperatures in 2005 and 2006, summer temperatures in 2005 and 2006 tended to be higher than in 2010 and 2011 during July and August (e.g. TNS surveys 3-5; Fig. 72). Temperatures during surveys 4 and 5 may have been particularly important as they exceeded lethal levels in freshwater at some sites, suggesting the potential for mortality. Note that this does not mean that temperatures were universally cooler in 2010 and 2011 than in 2005 and 2006; for example the region around Cache Slough had relatively high temperatures in August 2011. Larval to juvenile survival (ratio of TNS index to 20 mm index) was highest in 2011 followed by 2010, 2006, and 2005, suggesting that the cooler late spring and summer temperatures in 2011 and 2010 may have been beneficial for Delta Smelt. However, juvenile to subadult survival (ratio of FMWT index to TNS index) was highest in 2011 and lowest in 2010 (Fig. 51). While relatively high water temperature in late spring and early to mid summer of of 2005 and 2006 may thus have contributed to low survival of late-stage larvae and early juveniles, water temperature may have been less important to survival in the late summer and early fall. Overall, the results of this analysis of temperature and survival data support our hypothesis that high water temperatures reduce juvenile Delta Smelt growth and survival.

At this point, our data and analyses are inadequate to address temperature effects on juvenile Delta Smelt growth. Although there are some data for Delta Smelt growth during several of the target years, it is difficult to separate the relative effects of improved bioenergetics (see below) versus simple ontogenetic changes in fish size. Juvenile fish growth rates are typically not constant and change with size (“allometric effects;” Fuiman 1983). Specifically, daily growth rates (e.g., mm/day) are often faster for smaller fish and slower for older fish. Hence, cooler years may delay Delta Smelt transitions from faster to slower growth phases, yielding a relatively fast measured growth rate at a specific point in time (e.g., September) because at that specific time the fish are still relatively young and still on the “steepest” part of an idealized growth curve.

Hypothesis 2. Distribution and abundance of Striped Bass, temperature, and turbidity influence predation risk/rate on juvenile Delta Smelt

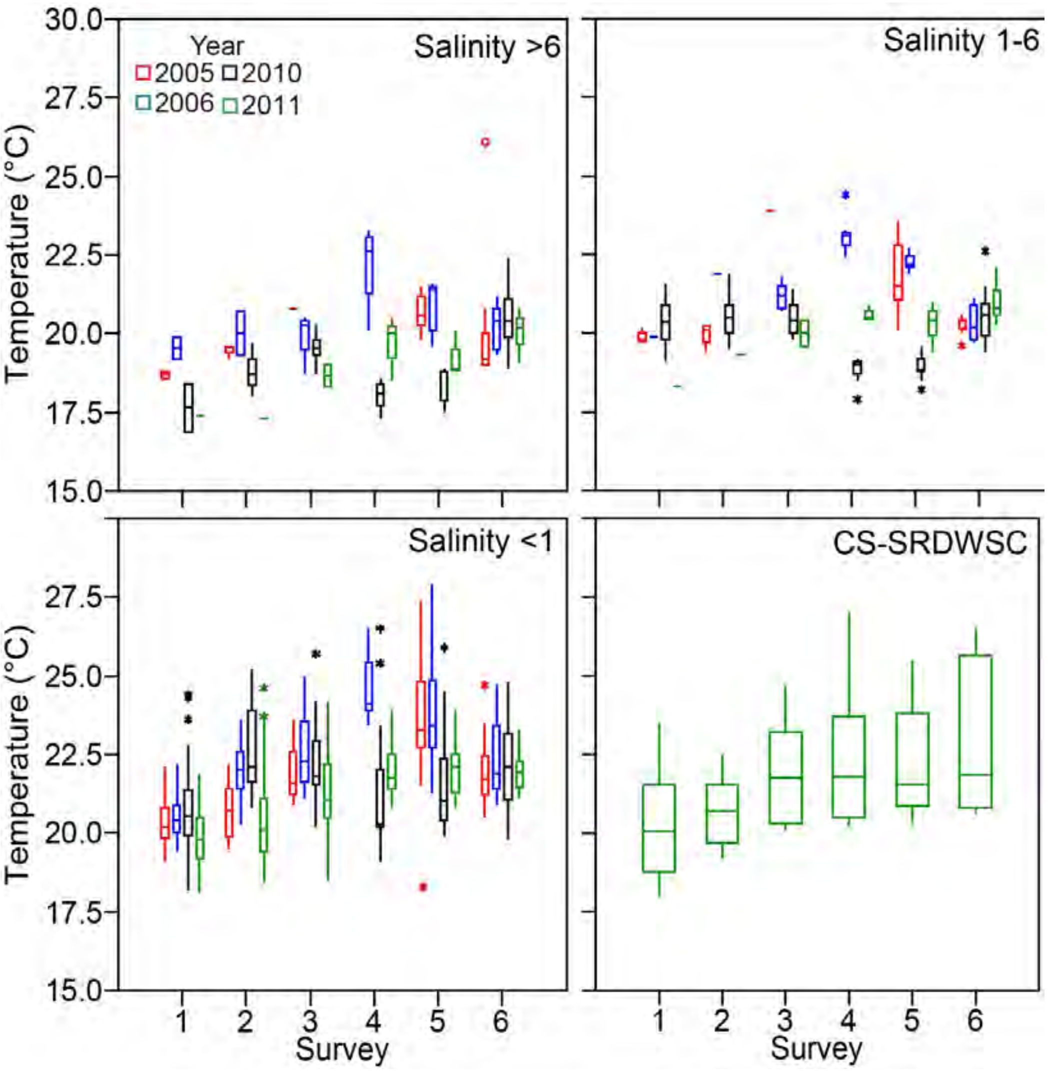
We hypothesize that subadult (age 1-3) Striped Bass are the major predator on juvenile Delta Smelt and that losses are likely affected by temperature and turbidity patterns. However, other factors likely affect predation risk (e.g., other predators such as centrarchids) and several factors

Figure 71. Water surface temperature data collected during the Spring Kodiak Trawl Survey for three salinity regions and the Cache Slough-Sacramento River Deepwater Ship Channel (CS-SRDWSC). Surveys are conducted monthly January-May. See Chapter 3: Data Analyses for explanation of boxplots.



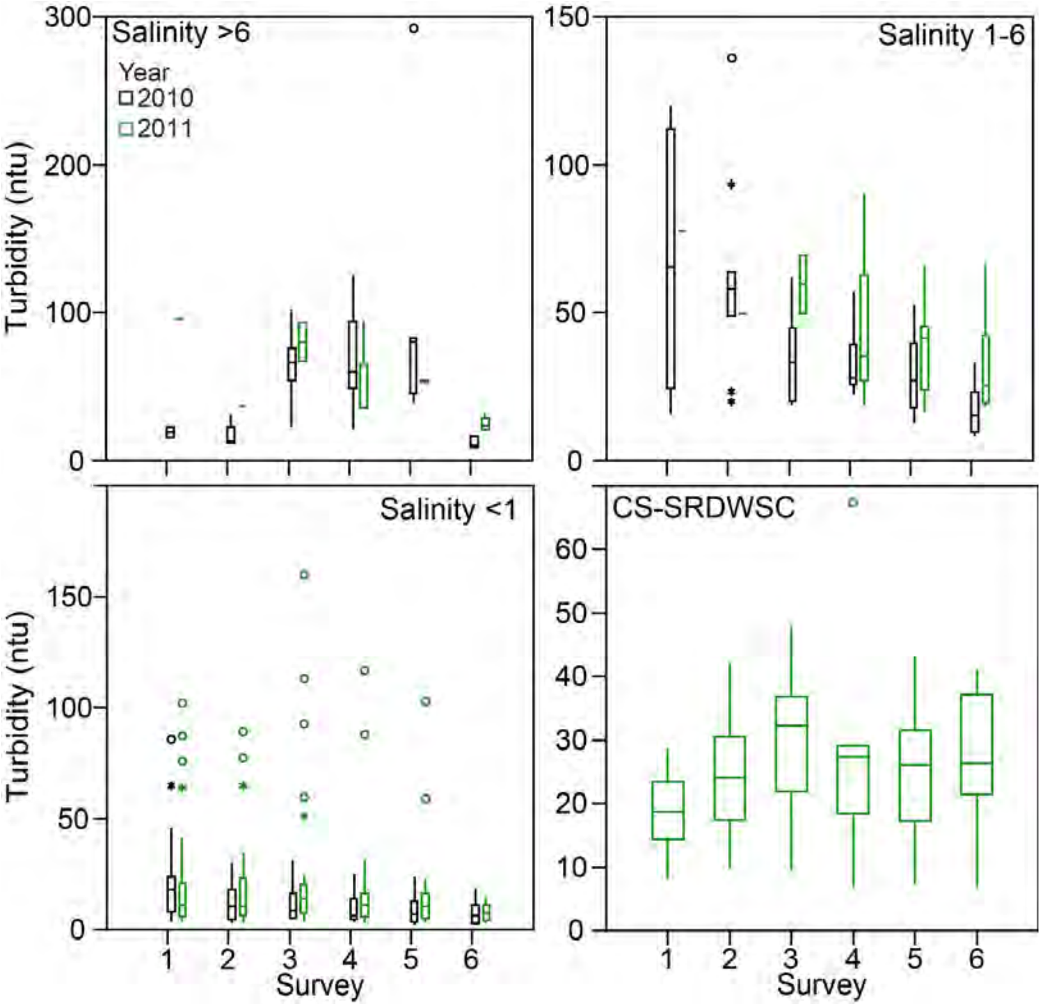
may interact. As noted above for temperature and below for food, high temperatures and low prey density likely lead to bioenergetics problems and increased foraging activity, which might reduce predator avoidance behavior (e.g., Marine and Cech 2004) in Delta Smelt. These effects may be compounded by low turbidity, which makes Delta Smelt more visible to predators in their habitat. Although higher Striped Bass abundance could theoretically result in greater consumption of prey including Delta Smelt (Loboschefsky et al. 2012), changes in habitat variables for both species such as food, temperature, and turbidity mean that predation rates on Delta Smelt periodically may be independent of predator abundance. Although there has been substantial progress in modeling (Lobschefsky et al. 2012, Nobriga et al. 2013) and genetic methods (Baerwald et al. 2012), there is not yet a standardized way to assess the effects of predation on Delta Smelt. Moreover, there are no effective surveys to assess age 1-3 Striped Bass abundance or distribution. Therefore, we are unable to directly evaluate this hypothesis. Lacking this information, we can

Figure 72. Water temperature data collected during the Summer Townet Survey for three salinity regions and the Cache Slough-Sacramento River Deepwater Ship Channel (CS-SRDWSC). Surveys are conducted biweekly June-August. See Chapter 3: Data Analyses for explanation of boxplots.



at least examine turbidity and temperature patterns for the four years. Temperature responses were described for Hypothesis 2. In general, summer 2005 and 2006 temperatures were relatively higher than 2010 and 2011 during key summer months (e.g. TNS surveys 3-5; Fig. 72). We expect that cooler temperatures in 2010 and 2011 may have contributed to reduced predation on Delta Smelt. Turbidity data are limited to 2010 and 2011 (Fig. 73). There were no consistent differences between the two years. Secchi depth data did not suggest major differences among the 4 years except at salinities > 6 when 2005-2006 had higher values in some months (Fig. 74).

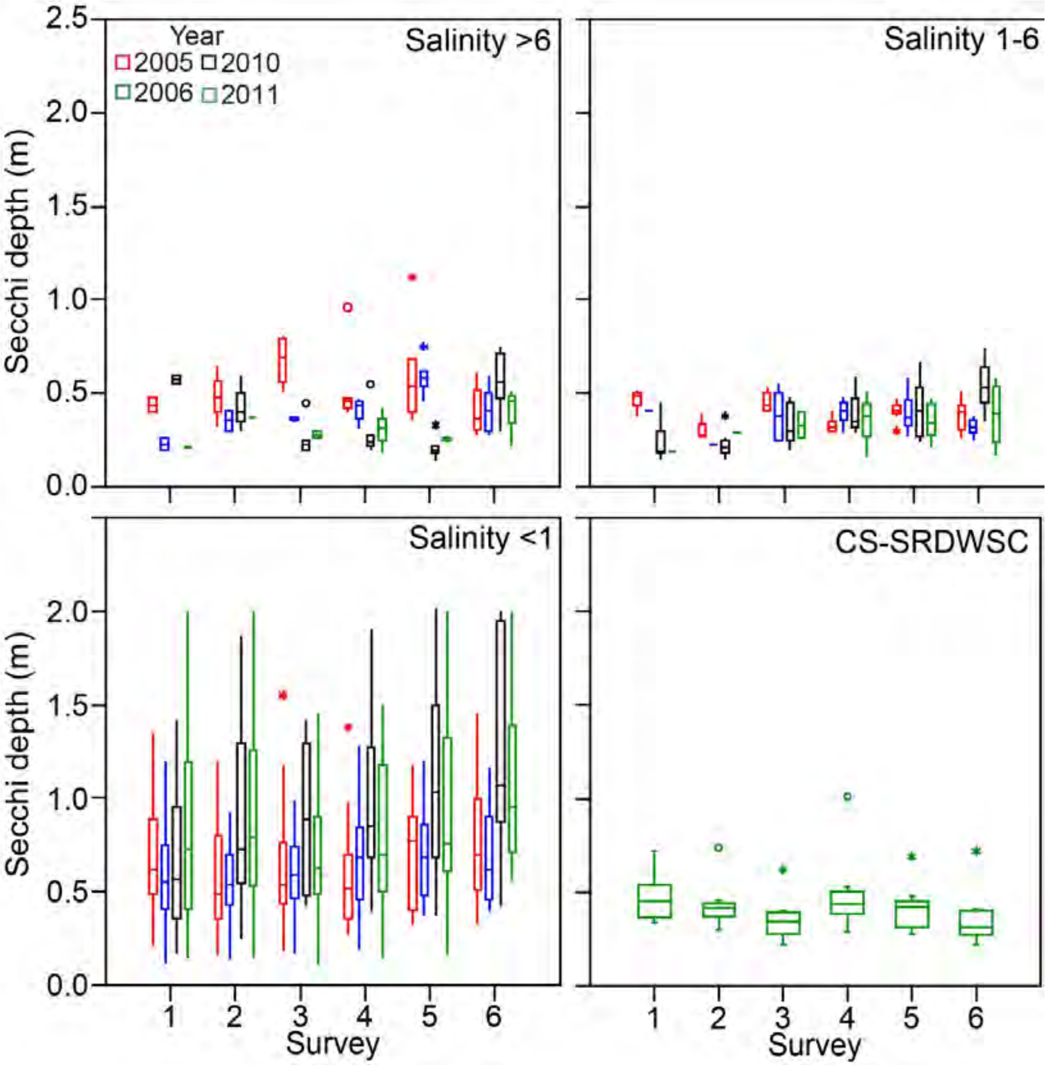
Figure 73. Turbidity data collected during the Summer Townet Survey. Surveys are conducted biweekly June-August. Note different scales among salinity regions. See Chapter 3: Data Analyses for explanation of boxplots.



Hypothesis 3. Juvenile Delta Smelt growth and survival is affected by food availability.

As for Hypothesis 1, we are currently unable to evaluate the growth data because water temperature affects development time, and because growth curves are complicated by allometric effects. The general conceptual model is that higher food abundance results in faster growth rates and larger, healthier fish. In addition, larger, healthier Delta Smelt are presumably less vulnerable to predators because of increased size making them difficult for smaller predators to capture and consume. In general, the median abundance of some of the key prey for juvenile Delta Smelt such as calanoid copepods is highest in summer months (Fig. 75), when juvenile Delta Smelt are present; however, the range of observed densities is broad in all months. As noted previously, Kimmerer (2008) found that Delta Smelt survival from summer to fall was positively associated with calanoid copepod biomass in the low salinity zone.

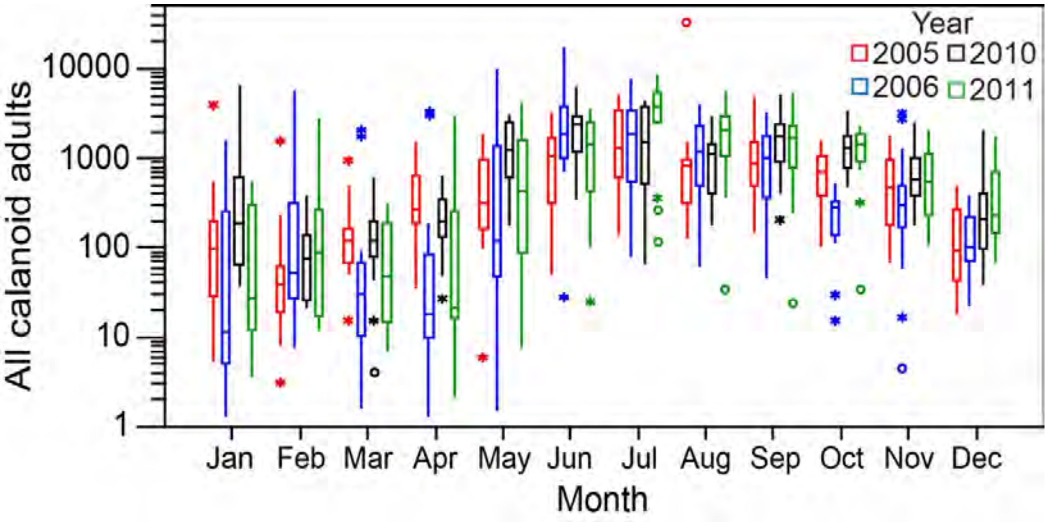
Figure 74. **Secchi depth data collected during the Summer Townet Survey. Surveys are conducted biweekly June-August. See Chapter 3: Data Analyses for explanation of boxplots.**



Interpretation of the field data is complicated because there are no long-term IEP EMP study stations located in some of the core habitats for Delta Smelt, for example, Cache Slough and the Sacramento River Deep Water Ship Channel. Moreover, densities of calanoid copepods vary among regions based on differing habitat (temperature and salinity) requirements of each species (Fig. 76).

Summer-time phytoplankton data (chlorophyll-*a*) suggest that the base of the food web was most enhanced in July and August 2011 and relatively depleted in 2005 (Fig. 66). There is some evidence that these changes may have affected zooplankton abundance. For example, summer densities of calanoid copepods in the LSZ and <1 ppt regions also tended to be highest in 2011 as compared to the other years (Fig. 76). This pattern generally held when individual taxa are considered including two of the most important food sources for Delta Smelt, *Eurytemora affinis* (Fig. 33) and *Pseudodiaptomus forbesi* (Fig. 34).

Figure 75. **Trends in calanoid copepods (number/m^3 for all taxa combined) collected by the IEP Environmental Monitoring Program (EMP) during each the four study years (2005, 2006, 2010, and 2011).**

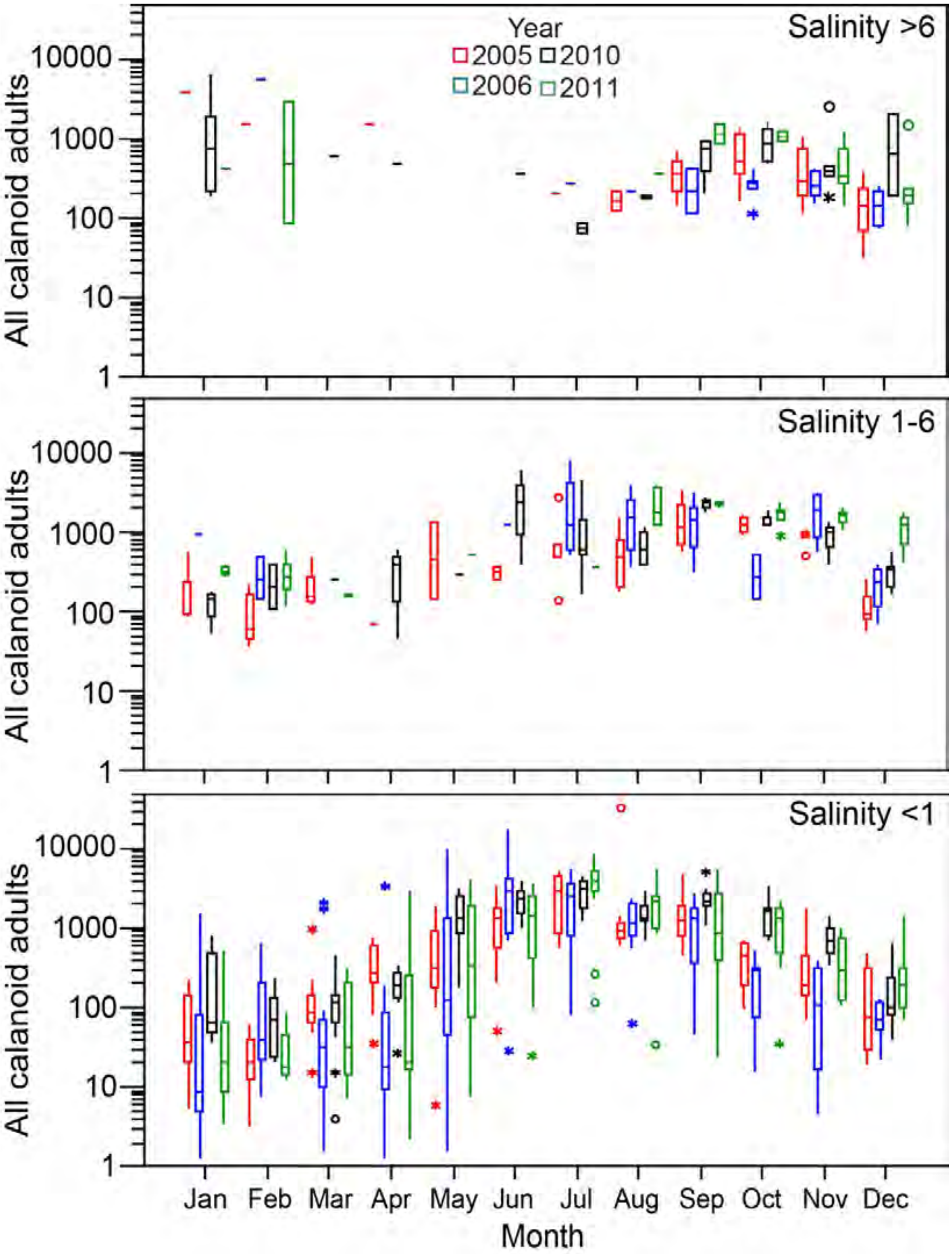


As mentioned above (Hypothesis 1), juvenile to subadult survival was highest in 2011 followed by 2006 and 2005 and lowest in 2010 (Fig. 51). If food availability was the primary habitat attribute driving juvenile survival, our expectation was that summer prey abundance would have been higher in 2011 than 2010. Figure 69 suggests that while differences were not very pronounced, prey levels were indeed somewhat higher in July and August of 2011 than 2010. Calanoid copepod levels varied across the different salinity ranges, but generally followed the same pattern (Fig. 76). In addition, calanoid copepod densities in June and August were higher in 2006 than in 2005 (Fig. 75), which may have contributed to higher juvenile to subadult survival in 2006 compared to 2005 (Fig. 51).

Fish bioenergetics are affected by both food and temperature. As mentioned above, both summer 2010 and 2011 had relatively cool temperatures as compared to 2005 and 2006, which may have affected bioenergetics. In addition, recent studies (S. Slater, CDFW, unpublished data) indicate that Delta Smelt consumption was not just limited to calanoid copepods, so our assessment does not reflect the full dietary range.

In conclusion, our analyses provide some support for the hypothesis that juvenile Delta Smelt growth and survival is affected by food availability; greater food availability may have contributed to greater juvenile survival in 2011 and 2006 compared to 2010 and 2005. However, differences in prey availability among years were not very pronounced and our analyses were limited to calanoid copepods; other species may also be important prey items for Delta Smelt.

Figure 76. Trends in calanoid copepods (number/m³ for all types combined) collected by the IEP Environmental Monitoring Program (EMP) in three salinity ranges (> 6 ppt; 1-6 ppt; < 1 ppt) during each the four study years (2005, 2006, 2010, and 2011). See Chapter 3: Data Analyses for explanation of boxplots.



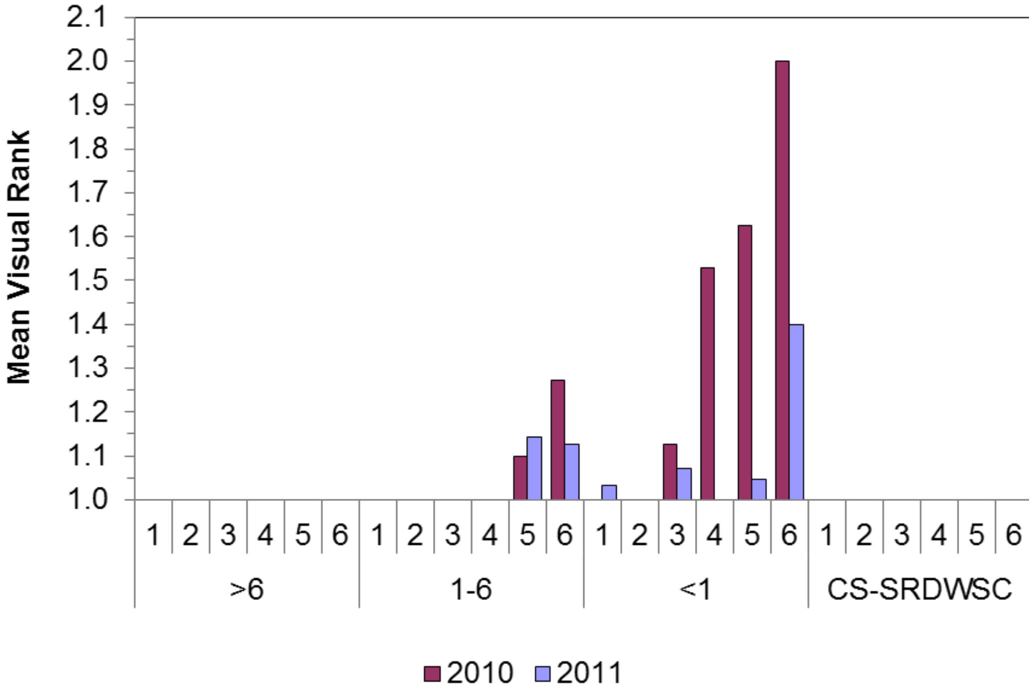
Hypothesis 4. Juvenile Delta Smelt survival and growth is reduced by harmful algal blooms (HAB) because of direct (habitat quality and toxic effects) and indirect (food quality and quantity) effects.

The appearance of late-summer HAB, especially *Microcystis*, is thought to be another component of the decline in habitat quality for Delta Smelt (Baxter et al. 2010, Lehman et al. 2010). Direct effects may include toxicity to Delta Smelt and a reduced area of suitable habitat. There also may be indirect effects on food quantity and quality, particularly with respect to their zooplankton prey (Ger et al. 2009, 2010a,b, Lehman et al. 2010).

The growth responses of Delta Smelt during the four target years are still unclear (see below), but there is evidence that Delta Smelt juvenile to subadult survival was highest in 2011 and lowest in 2010 (Fig. 51). If HABs have a negative effect on survival, we would expect that lower *Microcystis* (or other HAB) abundance would be associated with higher survival in 2011. This seems to have been the case for 2010 and 2011. Densities of *Microcystis* near the water surface were qualitatively assessed (visually ranked) at all TNS stations in these years. In agreement with our expectation, observed levels were low during the TNS in 2011 as compared to 2010 across a range of salinities (Fig. 77).

Unfortunately, we do not have data about other HAB species and more quantitative estimates, nor is similar data available for 2005 and 2006. In general, our expectation is that 2006

Figure 77. **Summer Townet Survey mean visual rank of *Microcystis* spp. (ranks 1-5 possible; 1 = absent) observed at all stations during biweekly surveys (1-6) in various salinity regions (> 6, 1-6, and < 1 ppt) and in the CS-SRDWSC during June through August 2010 and 2011. Observations were not made in Cache Slough-Sacramento River Deepwater Ship Channel (CS-SRDWSC) during 2010.**



Microcystis levels would have been relatively low as a result of higher flow levels that discourage blooms (Lehman et al. 2005). Based on the available qualitative data for 2010 and 2011, this analysis supports the hypothesis that juvenile Delta Smelt survival and growth is better when *Microcystis* does not bloom as intensely, but more data is needed to more conclusively assess this relationship.

Subadult Hypotheses

Hypothesis 1. Subadult Delta Smelt abundance, growth, and survival is affected by food availability.

Similar to juveniles, the general conceptual model is that higher food abundance results in faster growth rates and subsequently, lower predation loss and greater survival (e.g., Houde 1987, Sogard 1997, Takasuka et al. 2003); however the opposite situation in which the fastest growing fishes are most vulnerable to predators has also been observed in at least one east coast estuary (Gleason and Bengston 1996). Fall abundance of Delta Smelt was highest in 2011 followed by 2006, 2010, and 2005 (Fig. 3) while survival of subadults to adults was highest in 2010 followed by 2006 and equal in 2011 and 2005 (Fig. 45). In spite of the lower subadult survival in 2011, the relatively large number of subadults in 2011 gave rise to the highest adult abundance on record in 2012.

In general, fall calanoid copepod abundance and cladocera abundance were higher in 2011 in freshwater and the low-salinity zone compared to the other years, particularly 2005 and 2006 (Fig. 71). However, these data are highly variable, so this conclusion does not apply to each region in every month. With that caveat, the data generally support the hypothesis that food availability affects Delta Smelt abundance and survival; on average, prey density was higher for subadult Delta Smelt in 2011. This may have contributed to the high FMWT abundance index in 2011, although it did not contribute to an equally high survival to adults relative to the other three years. Nevertheless, it seems likely that the relatively good food availability in 2011 also contributed to the high number of adults in 2012. As noted above, we are currently unable to evaluate whether Delta Smelt grew faster in 2011 because water temperature affects spawning and hatch dates, which complicates the interpretation of growth rates.

Hypothesis 2. Distribution and abundance of Striped Bass, temperature, and turbidity influence predation risk/rate on subadult Delta Smelt

As already described for other life stages, predation risk is exceptionally complicated, making it difficult to generate simple hypotheses that describe associated losses of Delta Smelt. The data are not currently available to test this hypothesis (Nobriga et al. 2013). Thus, no firm conclusion can be made.

Hypothesis 3. Subadult Delta Smelt abundance, survival and growth are reduced by harmful algal blooms (HAB) because of direct (habitat quality and toxic effects) and indirect (food quality and quantity) effects.

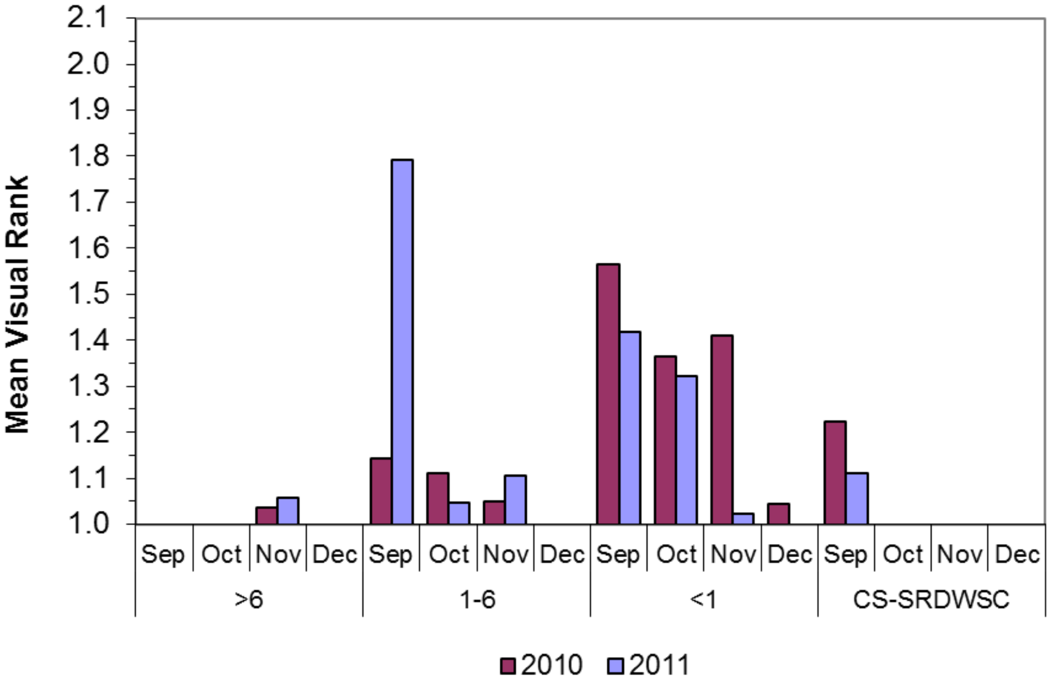
The appearance of late-summer harmful algal blooms (HAB), especially *Microcystis*, is thought to be another detriment to habitat quality for Delta Smelt (Baxter et al. 2010, Lehman et al. 2010). Direct effects may include toxicity to Delta Smelt and a reduced distribution if the fish try to limit their overlap with the bloom. There also may be indirect effects on food quantity and quality, particularly with respect to their zooplankton prey (Ger et al. 2009; 2010a,b, Lehman et al. 2010).

The growth responses of Delta Smelt during the four target years are still unclear (see above), but there is evidence that summer juvenile to subadult survival was highest in 2011, while juvenile survival to adults was highest in 2010 (Fig. 45). Our expectation is therefore that HAB were less prevalent in the summer of 2011 compared to 2010, but more prevalent in fall 2011. As already described for juveniles, the hypothesis that summer *Microcystis* bloom would be less intense in 2011 compared to 2010 was generally supported (Fig. 77). In fall, *Microcystis* levels were also overall lower in 2011 than in 2010, except in September 2011 when a high level of *Microcystis* was observed in the LSZ (Fig. 78). This may be an indication that the higher outflow in September-October 2011 displaced *Microcystis* produced in the Delta seaward into the LSZ. The comparatively high 2011 Delta Smelt FMWT index that coincided with this shift in *Microcystis* distribution is not consistent with the hypothesis; however, the occurrence of fairly high levels of *Microcystis* in the LSZ in 2011 may help explain the lower subadult to adult survival in 2011 compared to 2010. It is also important to remember that the visual survey results presented here are only qualitative and do not necessarily reflect the potential for differences in actual toxicity among years. Overall, these results are inconclusive, although they may provide limited support for the hypothesis that high *Microcystis* levels may have a negative effect on subadult to adult survival; this may help explain the lower subadult survival in 2011 compared to 2010.

Hypothesis 4. Subadult Delta Smelt abundance, survival and growth are affected by the size and position of the low salinity zone during fall.

We do not address this hypothesis in detail because it is the subject of an adaptive management experiment (FLaSH) described earlier (Reclamation 2011, 2012; see also Brown et al. 2014, http://deltacouncil.ca.gov/science-program/fall-low-salinity-habitat-flash-studies-and-adaptive-management-plan-review-0). According to the FLaSH conceptual model, conditions are supposed to be favorable for Delta Smelt when fall X2 is approximately 74 km or less, unfavorable when X2 is approximately 85 km or greater, and intermediate in between (Reclamation 2011, 2012). Surface area for the LSZ at X2s of 74 km and 85 km were predicted to be 4000 and 9000 hectares, respectively (Reclamation 2011, 2012). The data generally supported the idea that lower X2 and greater area of the LSZ would support more subadult Delta Smelt (Table 6). The greatest LSZ area and lowest X2 occurred in September and October 2011 and were associated with a high FMWT index which was followed by the highest SKT index on record, although survival from subadults to adults was actually lower in 2011 than in 2010 and 2006. There was little separation between the other years on the basis of X2, LSZ area, or FMWT index (Table 6). The position and area of the LSZ is a key factor determining the quantity and quality of low salinity rearing habitat available to Delta Smelt and other estuarine species (see Chapter 4 for more detail

Figure 78. **Fall Midwater Trawl mean visual rank of *Microcystis* spp. (ranks 1-5 possible; 1 = absent) observed at all stations during monthly surveys in various salinity regions (> 6, 1-6, and < 1 ppt) and in the CS-SRDWSC during September through December 2010 and 2011.**



and Chapter 8 for additional analysis results). In addition, the complex hydrodynamics produced during higher outflows may alter the lateral mixing environment of the Estuary (especially in shallower areas like Suisun Bay) in ways that improve the quality of Delta Smelt habitat in general (Monismith, personal communication). The limited amount of available data provides some evidence in support of this hypothesis, but additional years of data and investigations are needed.

Chapter 8: Conclusions

As with all reports focusing on conceptual models, this report is intended as a working document, not as the final word on Delta Smelt ecology, because our knowledge will continue to increase. We intend the conceptual model to be used as a framework and tool to further improve our understanding of Delta Smelt ecology and to explore and test management options for improving conditions for the Delta Smelt population. In essence, the updated conceptual model represents a synthesis of our current thinking on the factors affecting vital rates of the Delta Smelt population. We fully expect a wide range of opinion about the relevance of the conceptual models presented here and about the degree of certainty regarding many of its component dynamics and linkages. We have clearly acknowledged that we lack information on many important factors and processes that likely affect Delta Smelt, such as predation and toxicity and their functional relationships

Table 6. **Mean and standard deviation (SD) for X2, surface area of low salinity zone (M. McWilliams, Delta Modeling Associates, unpublished data), and values of the Fall Midwater Trawl index (FMWT) for abundance of subadult Delta Smelt.**

	X2 (km)		Surface area LSZ (hectares)		FMWT index
YEAR	MEAN	SD	MEAN	SD	
2005	83	2	4889	252	26
2006	82	3	4978	320	41
2010	85	2	4635	226	29
2011	75	1	8366	133	343

with survival and growth. The conceptual model incorporates many hypotheses that should be tested via new research, modeling, and ongoing analysis and synthesis of new and previously collected data. This is how science advances.

Conceptual models are increasingly used as tools to develop questions or hypotheses about specific mechanisms through which stressors or other environmental factors drive ecological outcomes. Conceptual models can be used as a basis for communication among managers and scientists to plan research activities and assess outcomes of management actions (Ogden et al. 2005). Because of their broad utility, conceptual models are viewed as a critical element of adaptive management programs (Thom 2000). In the SFE, conceptual models have become common and even required as the community moves toward adaptive management and collaborative science. A primary outcome of conceptual models is the identification of key areas of uncertainty due to lack of information, or areas of disagreement due to different interpretations of the available data and information. Careful examination of these areas often identifies critical data and information gaps, which if filled, would allow a more robust evaluation of the major hypotheses derived from conceptual models. In this way, conceptual models can guide the research community to the topics critical for understanding Delta Smelt biology and formulating effective management actions.

The development of our conceptual model, based on assessment of recent information, identified some key points about conceptual models that are worth highlighting, including the following:

1. Nested and linked conceptual models of increasing specificity provide a useful framework for capturing the dynamics of ecosystem drivers and habitat attributes over a large range of temporal and spatial scales and for providing a comprehensive picture about their effects.

2. Our knowledge about Delta Smelt and the SFE is constantly growing and conceptual models about them have to be regularly updated and revised to properly reflect this knowledge.

3. Construction of our conceptual model and the formulation and evaluation of hypotheses greatly benefitted from the large amount of high-quality ecological data and information available about Delta Smelt and the SFE. The most critical data about Delta Smelt dynamics came from four long-term IEP fish monitoring surveys. Other monitoring

and studies provided key data and information about habitat attributes and ecosystem drivers.

4. Our conceptual model is also useful for identifying important data and information gaps. More data and information is especially needed about predation risk and toxicity, two potentially important attributes of Delta Smelt habitat.

Conceptual models are meant to be useful tools for scientists, managers, and others. But just how useful are the new conceptual models in this report? To find out, we used them to generate and test hypotheses and highlight data gaps while addressing a specific topic of high management interest—the increased Delta Smelt abundance index in 2011.

We found that our conceptual model allowed us to formulate a variety of testable hypotheses about individual components and the linkages among them. Our hypotheses and the analyses we conducted to test them had some clear limitations (discussed below), but highlighted some key points about Delta Smelt and their habitat. In many respects, the points about Delta Smelt seem self-evident from basic biology and earlier conceptual models, but they warrant reinforcement because they are crucial to understanding Delta Smelt and to developing and assessing habitat management actions. Key points about Delta Smelt include the following:

1. Environmental conditions occurring in all four seasons contribute to year-class strength of Delta Smelt - "it takes a year to make a mature Delta Smelt."

2. Survival and recruitment are affected by many factors that interact in complex ways and the importance of these factors and interactions varies from season to season and year to year.

3. Recovery of Delta Smelt depends on better than average larval production (recruitment) and survival in all seasons. The number of eggs and larvae sets an upper limit for the production of mature adults. Low survival between any two life stages can substantially reduce the actual production of mature adults. Success of Delta Smelt in 2011 was related to a high level of larval production (recruitment) followed by moderate to high stage-to-stage survival over the entire year. In contrast, the high level of larval production (recruitment) in 2006 was followed by very low survival from larvae to juveniles which led to low abundance of mature adults.

4. Throughout 2011, Delta Smelt may have benefitted from a combination of favorable habitat conditions: 1) adults and larvae benefitted from high winter 2010 and spring 2011 outflows which reduced entrainment risk and possibly improved other habitat conditions, prolonged cool spring water temperatures, and possibly good food availability in late spring; 2) juveniles benefitted from cool water temperatures in late spring and early summer as well as from relatively good food availability and low levels of harmful *Microcystis*; 3) subadults also benefitted from good food availability and from favorable habitat conditions in the large, westward low salinity zone.

Our hypothesis tests were carried out with the simple comparative approach used in the FLaSH investigations (Brown et al. 2014). Specifically, we compared differences in Delta Smelt responses and in individual habitat attributes during the two most recent wet years and the two years immediately preceding the two wet years. Using this approach allowed us to put the FLaSH results into a year-round context as recommended by the FLaSH Panel (FLaSH Panel 2012).

It also provided an opportunity to further assess the utility of this approach for evaluating the outcome of adaptive management actions such as the fall outflow action.

As with the FLaSH investigations (Brown et al. 2014), we restricted our analyses to simple comparisons among four recent years after the 2002 POD decline for several reasons including the following:

1. Using a comparative approach similar to that in the FLaSH investigation allowed us to place the results of the FLaSH investigation in a year-round, life cycle context as recommended by the FLaSH Panel (FLaSH Panel 2012).
2. This report is intended for a broad audience. Simple comparisons are easily replicated and understood by all.
3. More pertinent data is available for recent years than for earlier years. For example, adult Delta Smelt monitoring began in 2002 with abundance index values available starting in 2003.
4. The POD regime shift (Baxter et al. 2010) changed ecological relationships and the strong pre-POD signals would have likely overwhelmed more subtle, yet meaningful, signals in the period after the POD. For example, it appears that high larval recruitment may now be positively associated with wet hydrology, but that this may not have been the case before the onset of the POD.
5. Clear differences in habitat conditions among years might point to new or refined management strategies aimed at improving specific habitat conditions.
6. More complex modeling approaches take much more time and effort than was available to produce this report. A complex life cycle modeling effort is currently underway (see Chapter 9).

As noted above, our analytical approach yielded some interesting results, but it also raised more questions than it could answer. In many cases this was due to critical data and information gaps; these will be described in more detail in Chapter 9. It also illustrates, however, several limitations of our simple comparative approach as well as difficulties associated with posing and testing hypotheses about ecological phenomena in general. Examples of specific limitations and difficulties include the following:

1. Our hypotheses focused on individual habitat attributes and were tested with a series of separate univariate analyses even though we know that Delta Smelt are affected by multiple interacting habitat atributes. We did not conduct multivariate tests or examine the complex interactions that may have occurred when more than one hypothesis was true (or false), nor did we consider or rule out that a hypothesis may be true in some years and false in others.
2. Our simple comparisons of differences in individual habitat attributes among different years cannot conclusively establish whether these differences are indeed mechanistically linked to the observed differences in Delta Smelt dynamics. In addition, an absence of observed differences does not prove that there is really no effect because actual effects can be masked or counteracted by interactions with other causal factors that differ among years. For example predation in the South Delta may mask actual entrainment

effects and toxicity of anthropogenic contaminants may counteract the effects of abundant food in some years, but not in others.

3. Results contrary to our observations may simply indicate different outcomes in other years or that complex interactions among multiple habitat attributes (and corresponding hypotheses) contributed to the observed effects.
4. We restricted our analyses to observational data collected in a small number of moderately and very wet years during the POD period; including data from additional, more historical, and drier years may have provided more conclusive results.
5. Data available for our analyses were not necessarily collected to test hypotheses similar to the ones in this report; targeted data collections are needed in addition to routine status and trends monitoring.

Many of these difficulties and limitations were expected because hypothesis testing in an ecological context is nearly always problematic. For example, Quinn and Dunham (1983) warned that attempts to follow a strictly hypothetico-deductive scheme (Popper 1959, Platt 1964) to draw “strong inference” from a series of univariate tests aiming to falsify hypotheses about the ecological effects of individual causal factors often lead to inconclusive or even erroneous results. One reason for this is that by design, they generally do not consider non-additive interactions among causal factors. While we did not necessarily set out to strictly follow such a scheme, we nevertheless treated habitat attributes as largely independent from each other and formulated a series of distinct hypotheses about their univariate effects on Delta Smelt. But habitat attributes are not necessarily additive and habitat is indeed more than the “sum of its parts.” A more inductive, multivariate modeling approach with hypotheses about interactive effects and evaluations of the relative contributions of multiple interacting habitat attributes to these effects would have likely been more appropriate, but would have required analyses beyond the scope of this report.

We give some examples of multivariate approaches in Chapter 9, but note that even with the most sophisticated modeling techniques, ecological responses to management manipulations and other changes of the SFE have been notoriously difficult to assess and interpret. Reasons for this persistent difficulty include limited opportunities for experimental control, multiple interacting causal factors, multiple ecological response pathways, and changing environmental conditions due to species invasions, species declines, and the many physical and chemical changes and management manipulations described in this report. In other words, the signal to noise ratio of management actions to environmental variation tends to be low in the SFE because of its size and complexity. The fact that Delta Smelt is now a rare species adds another considerable difficulty. Together, these difficulties are part of the reason why adaptive management actions such as those described in the ongoing Fall Outflow Adaptive Management Plan (Reclamation 2011, 2012) and the now concluded Vernalis Adaptive Management Plan (VAMP, San Joaquin River Group Authority 2013) are planned for a minimum of 10 years, allowing accumulation of data, development of appropriate interpretation of these data, and comparison of observations across as broad a range of conditions as is possible given a 10-year time frame. But even after such a relatively long period of manipulation and observation, questions will likely remain about how some factors interact to affect Delta Smelt abundance.

In summary, we conclude that our new conceptual models can be used successfully to derive testable hypotheses about Delta Smelt responses to changing habitat conditions. Our hypotheses and the analyses we conducted to test them highlighted some key points as well as critical data gaps and the challenges associated with formulating and testing hypotheses in complex ecological contexts. The key points about Delta Smelt and their habitat generally agree with basic biological principles and earlier conceptual models, but warrant reinforcement because they are crucial to understanding Delta Smelt and to developing and assessing habitat management actions. Other results are less conclusive because of data limitations and the shortcomings of our largely univariate hypotheses and simple comparative analysis approach. Next steps should include addressing critical data gaps, modeling that more fully considers the effects of interacting factors on Delta Smelt, and applications of the information in this report in support of management actions. Examples of such efforts are provided in Chapter 9.

Chapter 9: Recommendations for Future Work and Management Applications

The conceptual model in this report can be viewed as a collection of hypotheses. These hypotheses are not limited to the hypotheses posed in Chapter 7 of this report; essentially, each component and linkage in the conceptual models can give rise to meaningful questions and hypotheses by itself or together with other components and linkages. This is one of the main functions of conceptual models.

Some of the hypotheses that can be derived from our conceptual model have already been addressed in the published research reviewed in Chapter 4 of this report. These results provide the knowledge base used to construct our conceptual model as well as previous conceptual models. They also provide the knowledge base for current Delta Smelt management efforts. The results and conclusions in this report add to this knowledge, but they also emphasize the need for additional monitoring, focused studies, and/or additional analysis and synthesis of existing data. These are the information gaps that can be used to guide future research activities to enhance our understanding of how factors interact to control Delta Smelt abundance.

Filling these information gaps is critically important for improving management strategies for Delta Smelt and for constantly adapting them to expected and unexpected future changes. It is clear that ecological changes due to continued growth of California's human population, climate change, new species invasions, and other natural and anthropogenic factors will increase the challenges associated with Delta Smelt management. Moreover, as discussed in the previous Chapter, we will likely never be able to correctly detect or predict all effects of management actions and other changes in an ecosystem as complex and constantly changing as the San Francisco estuary. Science and management have to go hand in hand to constantly identify, implement, evaluate, and refine the best management options for this ever-changing system. In this Chapter, we provide examples of next steps in three major areas where additional work is needed: 1) filling critical data and information gaps; 2) mathematical modeling; and 3) applications to support adaptive management actions. We conclude this report with recommendations for future analysis and synthesis efforts.

Critical Data and Information Gaps

A short list of the most critical data and information gaps identified by the updated conceptual model is given below. It is important to note that this is not an exhaustive list of the potentially productive research questions that could be addressed for Delta Smelt. Instead, these are primary research topics that emerge as major data and information gaps in multiple places within the updated conceptual model. This indicates that additional monitoring and research on these topics may be particularly urgently needed and filling these gaps would provide immediately useful results. The list of critical data and information gaps is organized around the environmental drivers and habitat attributes identified in our conceptual models.

Contaminants and Toxicity

There is a general awareness that exposure to contaminants can impair the health of Delta Smelt and other fishes. A few studies have documented adverse effects, but little is known regarding the thresholds at which most contaminants would be toxic to or otherwise adversely affect Delta Smelt (or their prey). Even less is known about how various contaminants may interact when they co-occur, or how their effects may be enhanced or suppressed by these interactions or by other environmental factors.

1. Focused laboratory studies may provide the most efficient way to assess effects of metals, pesticides, pharmaceutical products, or mixtures of contaminants as long as field-relevant concentrations are used. However, translating results of laboratory tests to the field remains a challenging problem (Scholz et al. 2012).

2. Significant work to understand the effect of nutrient loading from municipal sources on the food web has been done (Weston et al. 2014) (e.g., Sacramento Wastewater Treatment Plant, Parker et al. 2012). A logical next step is to conduct manipulative experiments in which effluent is reduced or shut off. This type of work has recently begun (T. Kraus, USGS, personal communication), but may require multiple iterations during a variety of seasons and environmental conditions in order to understand how such manipulations or future treatment upgrades could be used to provide desired food web responses. Monitoring should continue after any such upgrades to determine if they have the expected outcomes.

Entrainment and Transport

Evaluation of differences in entrainment among years could not be critically evaluated from salvage data; better ways to estimate, monitor, and evaluate entrainment losses due to south Delta exports are needed. Such improved estimates could be derived from experimental research on Delta Smelt and other species along with hydrodynamic modeling. Besides the need to improve the estimates of direct proportional population losses due to entrainment, similarly relevant or more important needs include assessing the influence of entrainment on key population attributes (e.g., genetics, demographics, population dynamics and viability effects).

Predation Risk

The majority of the hypotheses regarding predation risk could not be fully evaluated due to a lack of data regarding co-occurring predator and prey biomass and predation rates of predators on Delta Smelt.

1. The distribution and diet of major predators with respect to the distribution of Delta Smelt needs further investigation. For some predator species, data may already be available that describe distributions over multiple years and one data synthesis effort has already begun (Mississippi Silversides, USFWS Beach Seine Survey; analysis initiated by B. Schreier, DWR). However, data are lacking for several Striped Bass and Largemouth Bass life stages and focused studies are necessary to understand how these species' distributions overlap with the distribution of larval, juvenile, sub-adult, and adult Delta Smelt.
2. The distributional overlaps of Delta Smelt with their predators need to be described over varying conditions of turbidity, salinity, temperature, and hydrology. Linking predation risk to key environmental drivers and habitat attributes will shed light on how Delta Smelt may experience varying degrees of predation across seasons and years.

Food

Food availability is a critical aspect of Delta Smelt habitat throughout the conceptual model. However, many of the hypotheses about effects of food availability in the conceptual model could not be fully evaluated with available observational data due to incomplete information on prey densities and Delta Smelt feeding behavior throughout Delta Smelt habitat.

1. An extension of the IEP EMP into the Cache Slough complex and possibly other areas around the margins of the estuary would allow a fuller regional comparison of prey densities.
2. Another option is to make concurrent zooplankton sampling a routine part of the four major surveys monitoring Delta Smelt (SKT, 20 mm, TNS, FMWT). To varying degrees, this has been ongoing since 2005, but lack of trained staff has resulted in delayed processing of many samples and concurrent zooplankton samples have never been collected during the SKT survey. Adding appropriate zooplankton sampling and sample processing capacity to the fish monitoring surveys would allow for broader and more timely comparisons of pelagic food availability between monitoring stations with and without Delta Smelt present, similar to the analysis conducted in this report for the larvae collected during the 20mm survey (Larval Hypothesis #2).
3. Studies of Delta Smelt growth (from otoliths) and feeding habits (from stomach contents) concurrent with zooplankton sampling would maximize the utility of the concurrent prey sampling by allowing the refinement of functional response models.
4. Studies of Delta Smelt feeding behavior and prey availability with regard to amphipods and other prey that are not well sampled by any of the existing monitoring surveys could help determine the importance of these types of prey to the Delta Smelt population.

Harmful Algal Blooms

While recent research has resulted in improved understanding of the factors influencing the quantity, toxicity and location of HABs, there are still many uncertainties about their direct and indirect effects on Delta Smelt relative to other factors and about what can be done to prevent them. Furthermore and in spite of their importance to ecosystem and human health, there is still no routine quantitative monitoring program in place that specifically targets harmful algae. The TNS and FMWT surveys now include qualitative, visual assessment of *Microcystis*, but more quantitative techniques and techniques that detect additional harmful species and their toxicity would likely provide greater insights. Such techniques are increasingly available (e.g., solid phase adsorption tracking; Wood et al. 2011) and some focused studies that quantify and provide distributions of HABs have been conducted or are underway. These studies should be continued in order to address hypotheses related to the effects of HABs in the conceptual model and evaluate the utility of these techniques for routine monitoring applications.

Delta Smelt Responses

To fully evaluate the interactions of various stressors on Delta Smelt population biology, a quantitative life cycle population model is needed. While such models exist, they can be refined based on research into important aspects of Delta Smelt reproductive biology, including the reproductive output of individual Delta Smelt and the population as a whole, and how it varies with environmental conditions.

In particular, fecundity data on adult female Delta Smelt caught in the SKT have only recently been collected. This is a critical parameter, necessary to assess the reproductive potential of the population in any given year. Continued collection of fecundity data over multiple years and hydrological conditions is crucial to understanding the population response to environmental conditions in the seasons preceding reproduction. In addition, an understanding of variables controlling the number of spawning events in a year for wild Delta Smelt is necessary to understand the full reproductive potential of the population. An exploration of whether spawning events are discernible on otoliths is ongoing (Hobbs group, UC Davis); if so, retrospective analyses relating multiple spawning events to concurrent conditions (e.g., tidal phase, food availability, water temperature) may be possible.

Finally, efforts to better characterize spawning habitat and habitat attributes needed for successful egg hatching should also continue. This is needed to more fully evaluate and understand linkages between environmental drivers such as hydrology and larval recruitment. Of all the life stages of Delta Smelt, we know the least about the egg stage; Delta Smelt eggs have never been found in the wild. Because of this, we were not able to construct a life stage transition conceptual model that specifically focused on eggs. More information about spawning and egg hatching habitat is needed to fill this gap in our conceptual models and to identify management actions that would promote beneficial habitat attributes.

Mathematical Modeling

As demonstrated in this report and by others, conceptual models are useful tools for identifying and understanding key ecosystem components and relationships, but they do not quantify them and cannot be used to quantitatively define functional responses to environmental drivers or make quantitative predictions. Furthermore, as discussed above, the simple univariate and comparative analysis approaches employed throughout this report cannot capture the effects of multiple and often interacting drivers on the Delta Smelt population as a whole and on specific processes such as growth, mortality, and reproduction. The influences of interspecific interactions and abiotic forcing factors on populations and communities in complex ecosystems such as estuaries are also difficult to directly measure in any practical way. Only mathematical models can deal with such complexities and provide quantitative assessments and predictions.

Fortunately, the number of scientific publications about Delta Smelt that include various types of increasingly sophisticated mathematical models is growing rapidly. Recent examples include mathematical models based on statistical approaches (e.g., Bennett 2005, Manly and Chotkowski 2006, Feyrer et al. 2007, Nobriga et al. 2008, Kimmerer 2008, Kimmerer et al. 2009, Feyrer et al. 2010, Thomson et al. 2010, Mac Nally et al. 2010, Miller et al. 2012, Sommer and Mejia 2013, Kimmerer et al. 2013). These efforts generally focused on habitat associations using presence/absence data from the various monitoring surveys or on changes in Delta Smelt abundance based on abundance indices generated by the monitoring surveys and the effects of multiple habitat attributes (covariates) on these changes.

There is also a rapidly developing body of population life cycle models for Delta Smelt and other SFE fish species (e.g., Blumberg et al. 2010, Maunder and Deriso 2011, Massoudieh et al. 2011, Rose et al. 2011, Rose et al. 2013a, b). These models use either a statistically-based “state–space” multistage life cycle modeling approach or a spatially explicit, individual-based simulation modeling approach. Both approaches allow for analysis of the importance of drivers that affect different life stages of Delta Smelt and vary in space and time.

Not surprisingly, results of mathematical modeling efforts to date agree strongly that no single factor can explain the observed Delta Smelt population dynamics and long-term changes in abundance. There is less agreement, however, about which factors are most important (see for example Rose et al. 2013b) and about the exact sequence and nature of their interactions that led to the 2002-3 Delta Smelt POD decline. It is possible, perhaps even likely, that the natural complexity of the estuarine ecosystem coupled with multiple human impacts will prevent definitive answers to these types of questions, especially when they are sought through overly rigid application of formal hypothetico-deductive reasoning and methods (Quinn and Dunham 1983). We agree with Rose et al. (2013b) that the inherent complexity of the system and the challenges it presents for scientists and managers alike “is perhaps the best reason to develop and compare alternative modeling approaches.” Even the most sophisticated modeling oversimplifies complex systems and includes many assumptions. This means that instead of a single modeling approach, multiple alternative conceptual and mathematical modeling approaches, from the simple to the complex, are needed to understand how complex systems work and to predict future changes with sufficient confidence to allow for effective management interventions. The following sections give a brief overview of some of the alternative mathematical modeling efforts currently underway or proposed for the future.

A comprehensive state-space modeling effort that takes advantage of available Delta Smelt abundance data from all monitoring surveys and the even larger monitoring data set about habitat attributes is currently underway (Ken Newman, FWS, personal communication) and future analyses using the individual-based model developed by Rose et al. (2013a) have been proposed (Rose et al. 2013b). As mentioned above, a full description or application of mathematical models is outside of the scope of this report, but to illustrate the utility of additional alternative approaches and further explore some of the linkages and interactions in our conceptual model, we give three additional examples of alternative mathematical modeling approaches that may be used to further test some of the hypotheses in the conceptual models in this report. The first is a qualitative modeling approach, the second a multivariate statistical modeling approach, and the third a numerical simulation modeling approach. Each of these approaches was explored by one of the co-authors of this report. Importantly, these approaches are meant to complement, not replace state-space, individual-based, and other modeling approaches for Delta Smelt. **Furthermore, results are preliminary and included for illustrative purposes only; peer-reviewed publications of these analyses need to be completed before they can be used to draw any conclusions.**

Qualitative Models

Qualitative modeling provides a theoretical foundation for understanding system behavior by minimizing the loss of generality and realism at the expense of model precision (Levins 1974, Levins 1975, Puccia and Levins 1991). Qualitative modeling is based on a mathematically rigorous approach that can be used to gain insight on community level process and to examine the consequences of intended or inadvertent human-induced perturbations in managed systems. Questions often addressed through qualitative modeling include the resilience and stability of the system and the direction of population change (Puccia and Levins 1991), the role of system structure on stability (Dambacher et al. 2003, Fox 2006) and the degree of predictability in the response of populations to perturbations (Montaňo-Moctezuma et al. 2007, Hosack et al. 2009). Such questions have strong implications in terms of stability-complexity relations (May 1972, Pimm 1984, Haydon 1994) and the persistence of populations and communities following regime shifts (Baxter et al. 2010, Brook and Carpenter 2010, Capitán and Cuesta 2010, Cloern and Jassby 2012).

The increased ecological understanding of the upper SFE and the potential drivers and mechanisms underlying the interannual population responses of Delta Smelt reviewed by the FLaSH and MAST syntheses provide a strong rationale to further refine and integrate our knowledge on community level interactions and ecological drivers in this highly altered system. Towards that goal, we envision qualitative modeling as a complementary approach to other types of models to evaluate the response of Delta Smelt and other populations in the upper SFE over several temporal and spatial scales. Qualitative modeling for Delta Smelt can address some relevant system-level knowledge gaps which are usually less amenable to analyses using other modeling approaches, namely, the influence of species interactions and multiple feedback levels on community stability and population changes in response to perturbations on one or more species. For example, understanding the mechanisms leading to Delta Smelt population responses under different hydrological conditions is an area of significant interest.

Signed-digraphs are a useful representation of the structure of a system, as defined by the community matrix, and have been used in qualitative models exploring food webs (Liu et al. 2010), extinction events in communities (Vandermeer 2013), and other ecological topics of theoretical and conservation relevance. Castillo (unpublished data) used this approach to evaluate the predicted response of Delta Smelt to a sustained change in fall outflow as required in the 2008 FWS Biological Opinion. Recognizing that outflows can control X2 and the size and location of the LSZ (see Chapter 4), and affect other segments of the aquatic community supporting Delta Smelt, Castillo (unpublished data) modeled the response of subadult Delta Smelt to low (5,000 cfs; X2 = 85 km), intermediate (8,000 cfs; X2 = 81 km) and high (11,400 cfs; X2 = 74 km) fall outflow scenarios. Community composition for each outflow scenario was determined relative to the geographical distribution of species expected to occupy the LSZ. The high outflow model included six community components: phytoplankton, zooplankton, Delta Smelt, predators of Delta Smelt, the overbite clam *Potamocorbula amurensis*, and outflow. The intermediate outflow scenario included two additional community components: the Asian clam *Corbicula fluminea* and the cyanobacteria *Microcystis aeruginosa*). The low outflow scenario included the same variables as in the intermediate flow scenario, except that the overbite clam was excluded and the Brazilian waterweed, *Egeria densa* was added. For each of these communities, community components could exhibit positive or negative feedbacks and positive or negative interactions with other community components. For each of the assumed flow conditions, the four alternative types of community interactions were assumed and each met the stability criteria, as defined by Puccia and Levins (1991). The predicted response of the Delta Smelt population was: 1) predominantly positive under the high outflow community scenario, 2) ambiguous under the intermediate outflow community scenario and 3) very ambiguous under the low outflow community scenario. According to these preliminary results, both outflow and outflow-induced changes in community composition and structure seem to play a critical role in determining the population response of Delta Smelt. These model predictions supported the hypothesis that a shift in the LSZ towards X2 = 74 km is a necessary condition for the fall outflow action to exert a positive influence on the Delta Smelt population. Qualitative models like these can provide useful assessments when the general direction of community interactions are understood but the data are insufficient to support a quantitative model.

Multivariate Statistical Modeling

In this report we reviewed results from many multivariate statistical modeling efforts such as the multivariate autoregressive modeling (MAR) conducted by MacNally et al (2010) to discern the main factors responsible for the POD declines and the hierarchical log-linear trend modeling by Thomson et al. (2010) that used Bayesian model selection to identify habitat attributes (covariates) with the strongest associations with abundances of the four POD fish species and determine change points in abundance and trends. The state-space life cycle modeling by Maunder and Deriso (2011) is also based on multivariate statistical modeling; an extension of this work is currently underway by Newman and others (Ken Newman, USFWS, unpublished data).

We anticipate that insight from the current conceptual model may be used to facilitate additional multivariate statistical models. As an example, we present preliminary results (Mueller-Solger, USGS, unpublished data) of univariate and multivariate statistical analyses of X2 relationships with annual Delta Smelt abundance indices that follow the approach in Jassby et al. (1995). The purpose is to further explore some of the hypotheses related to hydrology and the size and position of the LSZ included in our conceptual model and to illustrate the importance of considering more than one factor when trying to understand Delta Smelt dynamics. We include this brief exploration in this report because it serves as a useful and relevant example, but as noted above, we advise readers that these are preliminary results from an analysis that has not yet undergone peer review and should be viewed with caution. Moreover, individual and interactive effects of additional factors were not considered in this analysis, but are likely also important (see Chapter 8). As noted in Chapter 7, we recognize that “hydrology” by itself does not affect Delta Smelt, nor does the “X2” index which is used in this analysis as an index of general hydrological (outflow) conditions in the estuary. As shown in our conceptual model (Fig. 38), hydrology affects Delta Smelt through the combined effects of its interactions with other dynamic drivers and stationary landscape attributes (tier 1) on habitat attributes (tier 3). Many of these interactions have been described in this report; others should be explored further in future studies.

This analysis is intended to evaluate the effects of prior abundance, step changes, and concurrent and prior hydrological conditions in the estuary on the relative abundance of larval to early juvenile Delta Smelt (20 mm index, Fig. 3; hereafter referred to as “larval” Delta Smelt). It also considers prior hydrological conditions and the entire available abundance index time series for larval Delta Smelt provided by the 20 mm survey. The 20 mm survey, one of the newest IEP monitoring surveys, was started in 1995. Delta Smelt distribution data from this survey is heavily used to assess and manage entrainment risk. Similar to prior analyses of TNS and FMWT data (Feyrer et al. 2007, Nobriga et al. 2008), Kimmerer et al. (2009, 2013) and Sommer and Mejia (2013) used a generalized additive modeling (GAM) approach to examine the associations between Delta Smelt occurrence or catch per trawl at 20 mm survey stations and habitat attributes (salinity, temperature, turbidity, and calanoid copepod density) measured concurrently at the same stations. There have, however, been few analyses of annual abundance data from this survey. After 19 years, the 20 mm survey now provides barely enough annual abundance data points (indices) to conduct multiple regression analyses with up to two predictor variables. Clearly more years of data collection and more in-depth analyses are needed and the analyses presented here are merely a starting point.

This analysis uses annual abundance indices for larval Delta Smelt (20 mm survey, 1995-2013), adult Delta Smelt (SKT survey, 2003-2013), and subadult Delta Smelt during the previous year (FMWT survey, 1995-2013) (Fig. 3). It also uses larval recruitment indices calculated from the annual abundance indices (20 mm to SKT ratio and 20 mm to $\mathrm{FMWT}_{\mathrm{Year}-1}$ ratio, Fig. 46; see previous chapters for caveats regarding index ratios). Data from the SKT survey was only used for univariate analyses because the SKT index time series only has 11 data points at this time. Spring and fall X2 values were obtained by first calculating mean monthly X2 values calculated from daily X2 values provided by the DWR Dayflow database and then averaging the mean monthly X2 values for the “spring” months February to June and the “fall” months September to December. The 2002-2003 step decline in Delta Smelt abundance (Thomson et al. 2010) was introduced as a before/after factor (“Step”). Details about the data sources are provided in Chapter 3 of this report.

The multivariate analyses presented here were conducted with generalized linear modeling (GLM) following the approach of Jassby et al. (1995) and followed with a classical linear modeling (LM) approach guided by the GLM results. For the GLM, model parameters were estimated with a Poisson error distribution, a log link function describing the relationship between the predictor variables(s) and the mean, and a natural spline to represent non-linearities. The degrees of freedom for the splines were restricted to only 2 (i.e. one interior knot) because of the low number of available data points. Models requiring estimation of more than two independent parameters (aside from the intercept) were not considered for the same reason. Applying the GLM approach avoids the need for log-transforming the abundance data and using natural (quadratic) splines as smoothers allows a more natural representation of non-linearities than using polynomials.

The responses predicted by these models have a fairly high degree of precision as indicated by low values of SE/Mean and residuals were consistent with model assumptions. The results show significant univariate relationships at the $P < 0.05$ level (Table 7) between the 20 mm abundance index and spring X2, prior fall X2, and prior FMWT abundance index. The relationship is strongest with prior fall X2, followed by spring X2 and prior FMWT abundance index (Table

7). The relationship with spring X2 appears unimodal with maximum 20 mm indices associated with spring X2 values between about 55 and 70 km (Fig. 79a). The relationship with prior fall X2 appears negative (Fig. 79b), and the relationship with the prior FMWT abundance index (Fig. 79c) appears positive. Each of these univariate relationships was improved by the inclusion of one of the other predictor variables (Table 7). Relationships with spring and prior fall X2 were also improved by including the 2002-3 step change. As mentioned above, multivariate analyses with more than two predictor variables were not conducted because of the relatively small amount of available data (n = 19, Table 7). Based on AIC comparisons (Table 7), including the 2002 step change (introduced as a before/after factor, “Step”) somewhat improved the relationship of the 20 mm index with spring X2 (Fig. 73a) and with prior Fall X2 (Fig. 79b), but not with the prior FMWT index because that index was the basis for the analyses that detected the step change and thus already includes the step change in the actual data (Fig. 79c, model not included in Table 7). Including the prior FMWT abundance index improved the relationships with spring and fall X2 more substantially, but the model combining the effects of spring and fall X2 fit the 20 mm index data nearly as well as the model combining the effects of spring X2 and prior FMWT (Table 7).

It is interesting to note that while prior fall X2 by itself was a stronger predictor of the 20 mm index than spring X2, spring X2 was the stronger predictor when the step change or previous fall abundance were taken into account. Baxter et al. (2010) hypothesized that the shift toward higher prior fall X2 values (Fig. 17) may have contributed to an ecological “regime shift” associated with the step decline in Delta Smelt and other species. This means that prior fall X2 and the “step” factor and FMWT decline in this analysis may be related, which could explain the very similar outcomes for the two models combining spring X2 with either prior fall X2 or the prior FMWT index.

Partial residual plots show the relationship between a predictor variable and the response variable given that other independent variables are also in the model; in other words, they show the effect of one predictor variable given the effect of one or more additional predictor variables. Partial residual plots for the relationships of the 20 mm index with the combinations of spring X2 and prior fall X2 (Fig. 80 a and b) and spring X2 and prior FMWT abundance index (Fig 80 c and d) show that the general shape and direction of the relationships of the 20 mm index with each of the individual predictor variables (Fig. 79) remains intact in the models with combined predictors, but the partial residuals do not closely follow the fitted lines. This indicates that while each variable has its own, distinct effect on the 20 mm index that is maintained in the presence of the other variables, interactive effects among these variables are quite strong. In summary, low values of prior fall X2, high prior FMWT abundance, and intermediate values of spring X2 have positive associations with the abundance of larval/postlarval Delta Smelt, but the effects of individual variables are mediated by the presence of the other variables.

Because the spline degrees of freedom were strongly restricted in this GLM analysis, the results are quite similar to the results of classical linear models (LM) with log-transformed abundance data and a quadratic term to represent the unimodal non-linearity in the relationship between the 20 mm index and spring X2 (Fig. 81). We include these models here because they are more easily reproducible than the GLM models and offer simple equations for making predictions about larval abundance that can be used in adaptive management applications. As for the GLM analysis (Table 7), the best fits overall were achieved by combining spring X2 with either the step change or the prior FMWT abundance index (Table 8). All predictor combinations improved the models compared to the univariate relationships (Table 8). Based on a comparison of regression

Table 7. **Summary of relationships between the 20 mm abundance index for Delta Smelt (response variable) and one or more predictor variables: n, number of observations (years); SE/Mean, model standard error (square root of mean squared residual) as proportion of mean response, P, statistical significance level for the model; R^2, coefficient of determination; adjusted R^2, R^2 adjusted for the number of predictors in the model; AIC, Akaike information criterion; Δ AIC, AIC differences; w (AIC), AIC weights. All relationships modeled with generalized linear models (GLM) with a Poisson error distribution, log link function, and a natural cubic spline with two degrees of freedom as a smoother for all predictor variables except "Step."**

Predictor Variable(s)	n	SE/ Mean	P	R^2	Adjusted R^2	AIC	Δ (AIC)	w (AIC)
Spring X2, $FMWT_{year-1}$	19	0.119	<0.001	0.791	0.731	39.5	0.00	0.53
Spring X2, Fall $X2_{year-1}$	19	0.120	<0.001	0.787	0.726	40.1	0.60	0.39
Fall $X2_{year-1}$, $FMWT_{year-1}$	19	0.126	<0.001	0.764	0.697	43.2	3.78	0.08
Spring X2, Step (Factor)	19	0.143	<0.001	0.677	0.612	53.6	14.12	0.00
Fall $X2_{year-1}$, Step (Factor)	19	0.135	<0.001	0.712	0.655	55.8	16.35	0.00
Fall $X2_{year-1}$	19	0.145	<0.001	0.646	0.601	56.0	16.53	0.00
Spring X2	19	0.176	0.006	0.476	0.411	79.9	40.43	0.00
$FMWT_{year-1}$	19	0.187	0.015	0.408	0.334	89.4	49.98	0.00

coefficients and P-values, the LM relationships were statistically weaker (Table 8) than in the GLM analysis (Table 7).

Another way of including prior abundance in statistical relationships of abundance with habitat attributes and environmental drivers is to use abundance indices that are proportional to prior abundance indices, in other words, ratios of present to prior abundance indices. In this report, we used the ratios of 20 mm to SKT and 20 mm to $FMWT_{Year}$-1 abundance indices (Fig. 46; see also caveats about these indices in Chapter 3) as larval recruitment indices from adults and subadults, respectively. We found that recruitment of larvae from adults was linearly related to spring X2 for the entire available time series (2003-2013, Fig.82a and Table 9). The recruitment index for 2013 was higher than expected based on the other data points. The relationship of the recruitment index from subadults to next year's larvae with winter-spring X2 was also linear for the POD period after the abundance step decline in 2002 (Thomson et al. 2010), but with more scatter at higher X2 values. Interestingly, no relationship was apparent at all before the 2002 step decline when the proportional larval recruitment from then more abundant subadults was generally low (Fig. 82b and Table 9). In the current POD regime, larval recruitment from parental stock appears to be highest when flows through and out of the Delta are high and the interface between fresh and brackish water is located to the west (i.e. low X2), although it can occasionally also be high at lower flows, as was the case in 2013.

In late winter and spring 2013, CVP and SWP exports were reduced to comply with OMR flow requirements in the 2008 USFWS Biological Opinion aimed at reducing the risk of adult and

Figure 79. Plots of the Delta Smelt 20 mm survey abundance index as a function of a) spring (February-June) X2, b) previous year fall (September-December) X2, and c) Delta Smelt fall midwater-trawl abundance index in the previous year. Details of general linear models (GLM) used to fit the lines are in Table 7.

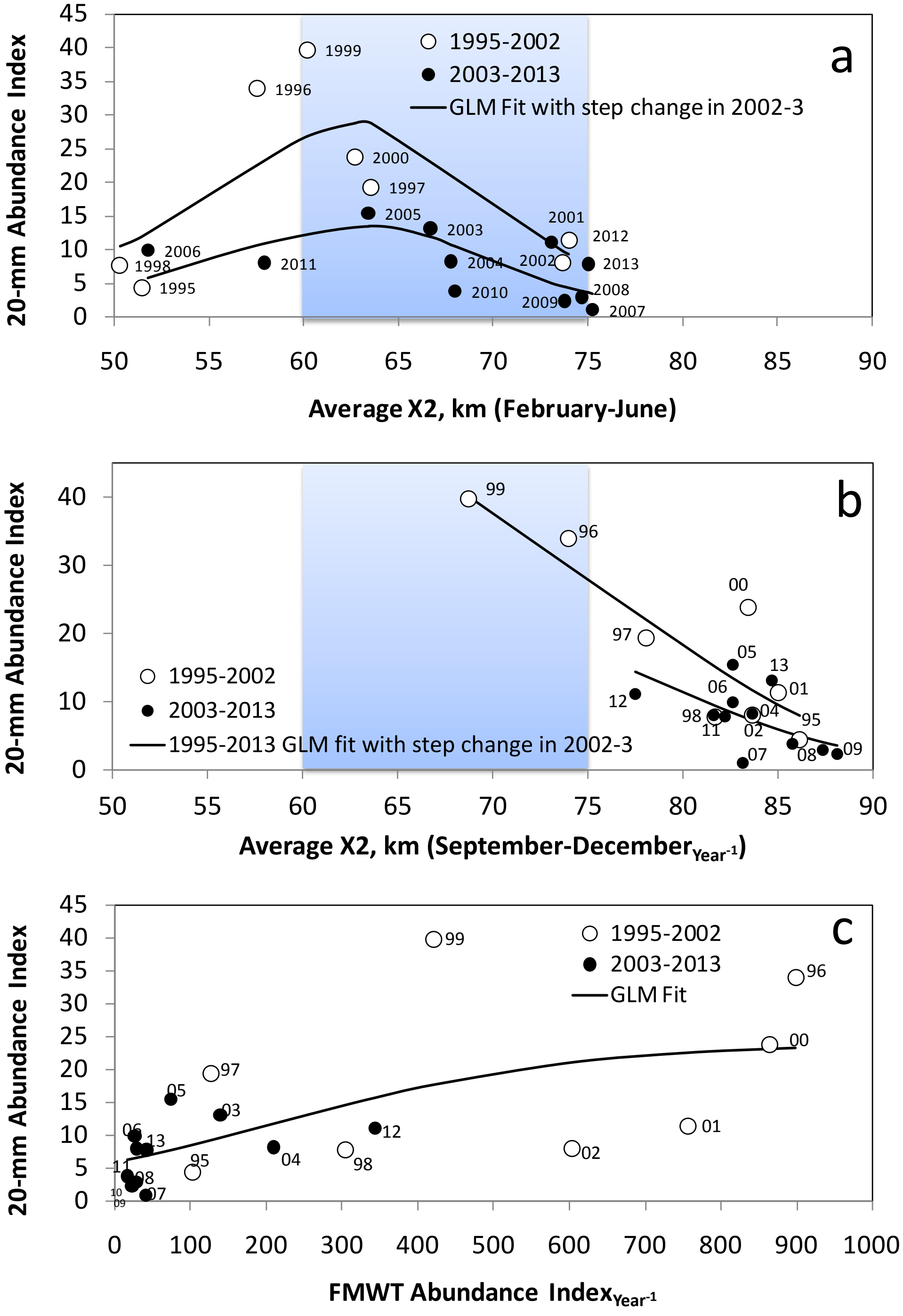


Figure 80. Plots of partial residuals for the relationships of the 20 mm index with the combinations of spring X2, prior fall X2, and prior FMWT abundance index summarized in Table 1 (panels a, b, d, and e). The plots shown here also include partial fit lines and their 95% confidence intervals. Values for the time period of analysis are shown for: c, X2; and f, the fall midwater trawl abundance index from the previous year

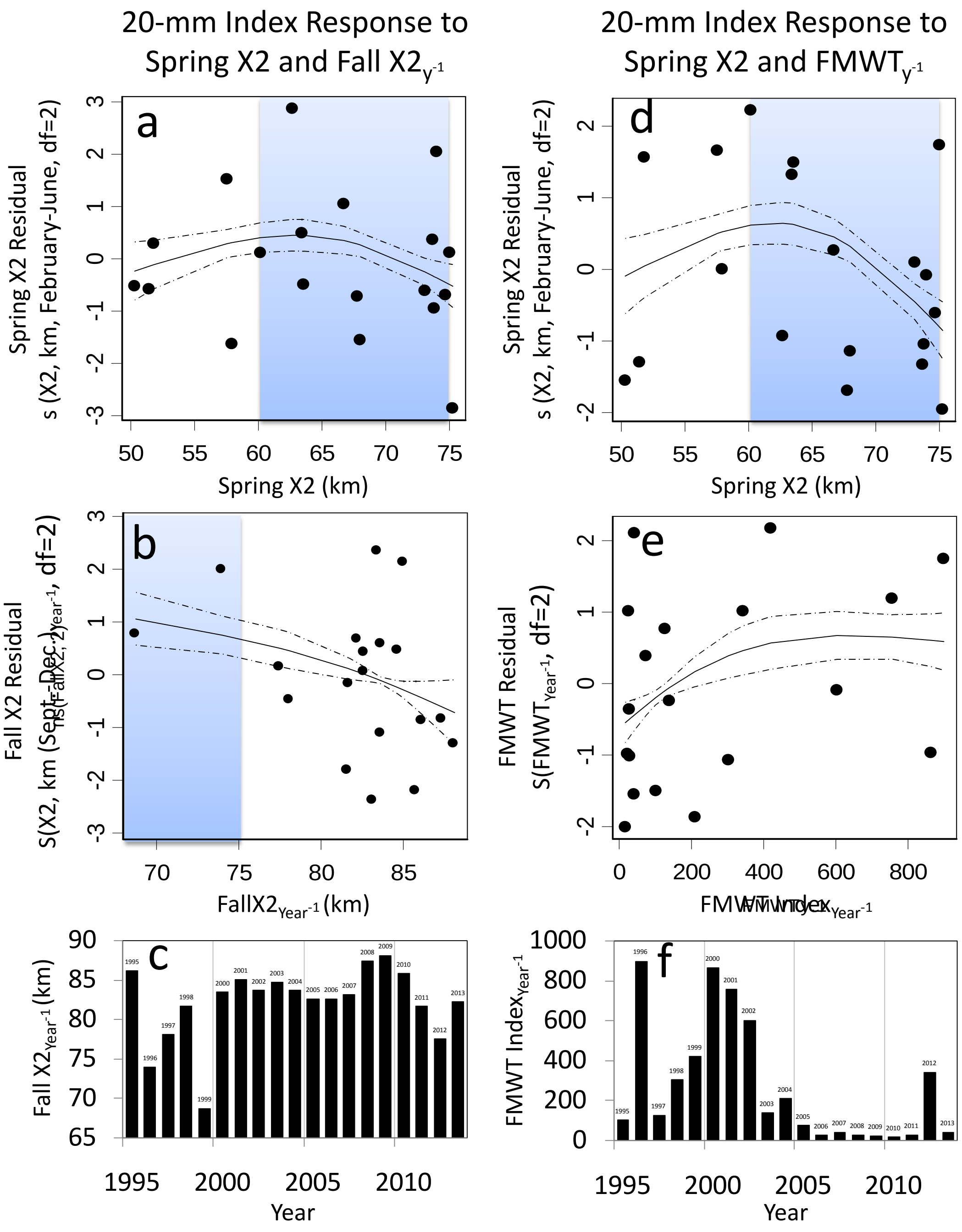
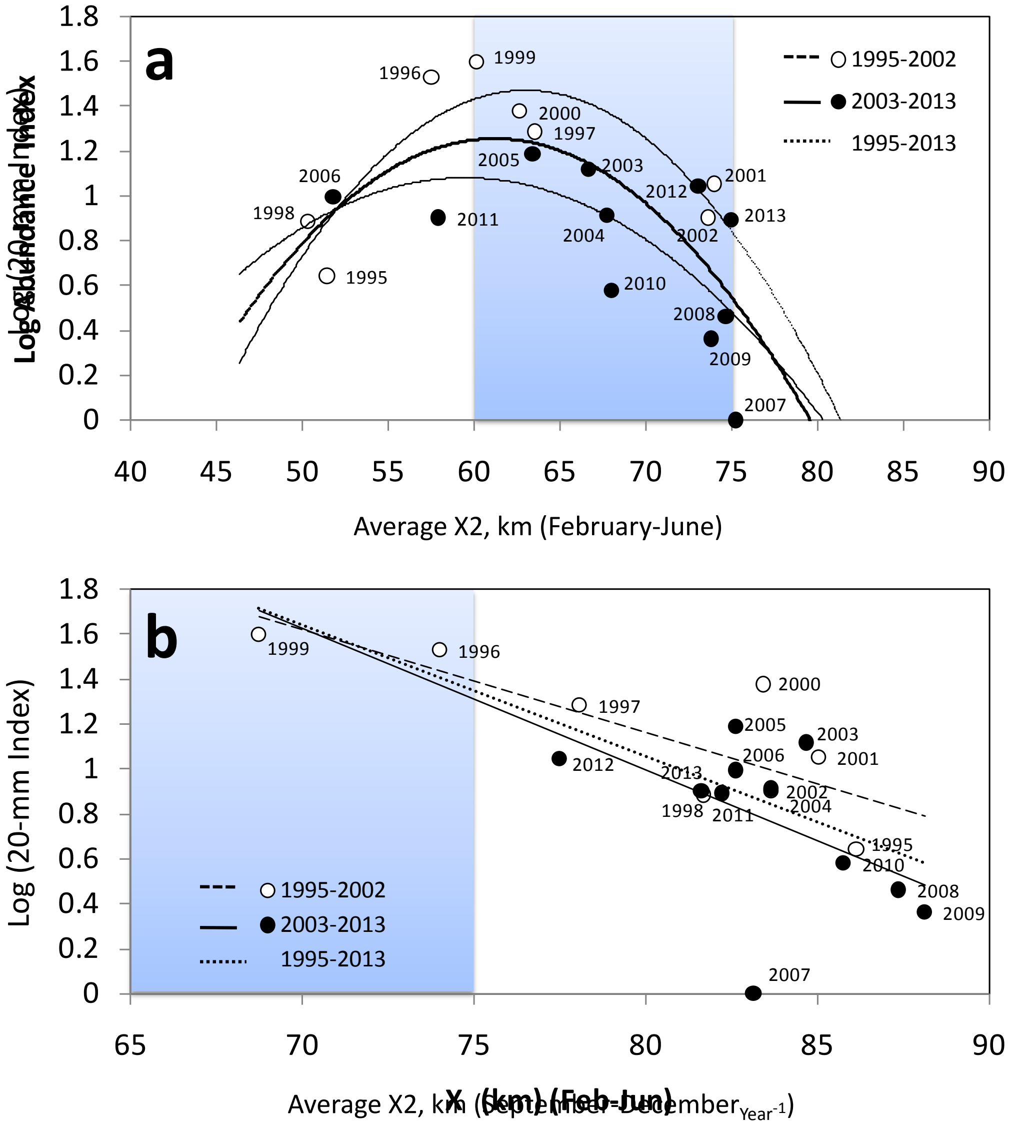


Figure 81. **Plots of the Delta Smelt 20 mm survey abundance index as a function of a) spring (February-June) X2, and b) previous year fall (September-December) X2. Lines are either simple linear least squares regression (lines) or quadratic regression (curves). Details of linear models (LM) used to fit the 1995-2013 lines are in Table 8.**



larval Delta Smelt entrainment into the water export pumps. This was the first time since the 2008 USFWS Biological Opinion was issued that exports were specifically reduced to lower Delta Smelt entrainment risk. In other years, flows were high enough to allow for higher export levels or export reductions to protect salmon were deemed sufficiently protective for Delta Smelt. It is possible that the intentional reduction in Delta Smelt entrainment risk in 2013 contributed to the high larval recruitment from adults during relatively low flow conditions, but additional years with similar conditions and targeted management actions as well as better estimates of entrainment and more in-depth analyses with other flow variables and flow averaging periods

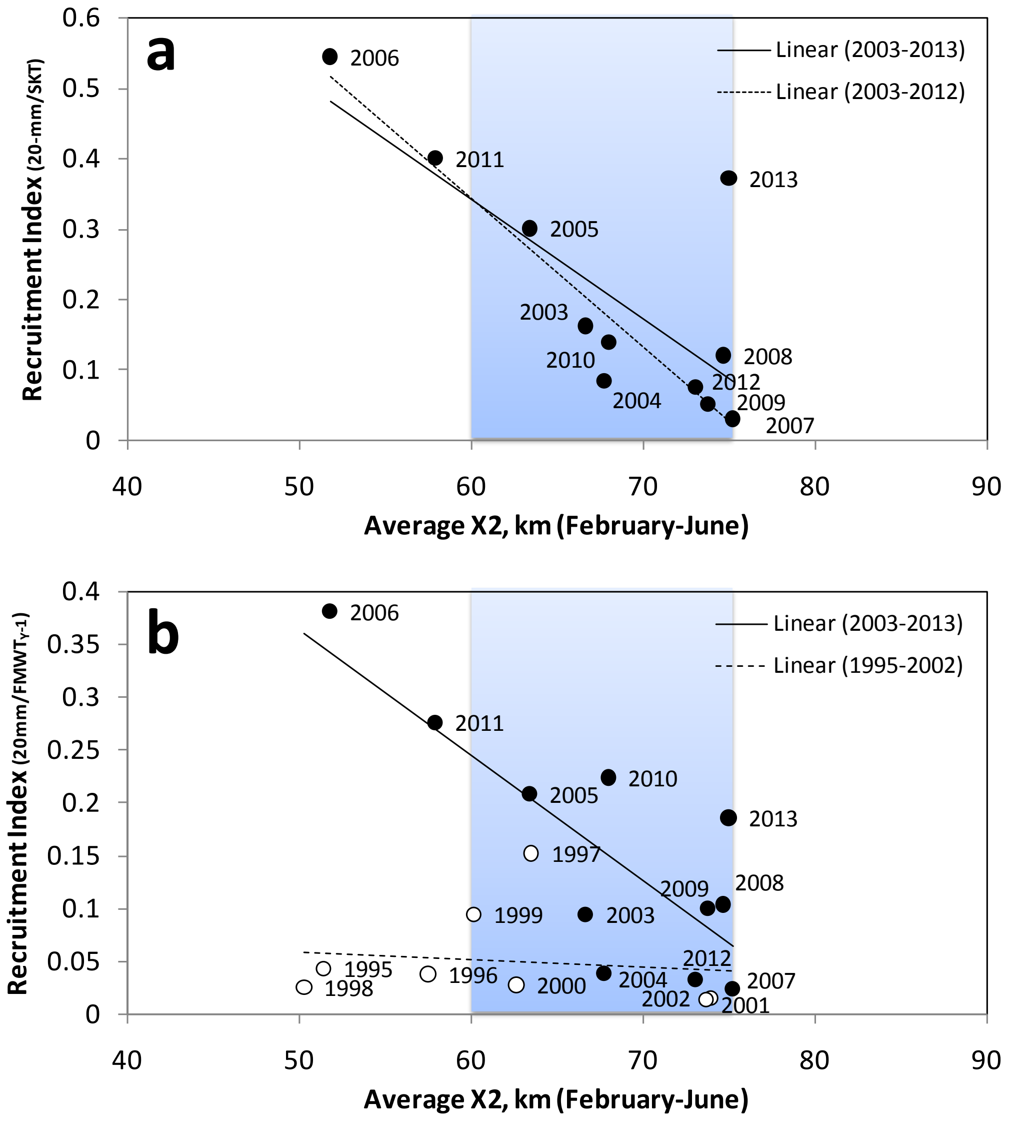
Table 8. **Summary of relationships between the log-transformed 20 mm abundance index for Delta Smelt (response variable) and one or more predictor variables. All relationships modeled with simple least-squares linear models (LM). For explanation of column headings see Table 6.**

Predictor Variable(s)	n	SE/ Mean	P	R^2	Adjusted R^2	AIC	Δ (AIC)	w (AIC)
Spring X2, (Spring X2)^2, log FMWT$_{\text{year-1}}$	19	0.237	0.000	0.745	0.694	2.1	0.00	0.85
Spring X2, (Spring X2)^2, Fall X2$_{\text{year-1}}$	19	0.274	0.001	0.661	0.593	7.5	5.42	0.06
Fall X2$_{\text{year-1}}$, log FMWT$_{\text{year-1}}$	19	0.280	0.000	0.621	0.574	7.7	5.54	0.05
Spring X2, (Spring X2)^2, Step (Factor)	19	0.292	0.002	0.616	0.540	9.9	7.78	0.02
Fall X2$_{\text{year-1}}$, Step (Factor)	19	0.307	0.002	0.544	0.487	11.2	9.06	
Fall X2$_{\text{year-1}}$	19	0.318	0.001	0.479	0.449	11.7	9.58	0.01
Spring X2, (Spring X2)^2	19	0.329	0.006	0.473	0.407	13.9	11.83	0.00
log FMWT$_{\text{year-1}}$	19	0.333	0.002	0.430	0.397	13.4	11.29	0.00

are needed to test this hypothesis and obtain a better understanding of flow effects on larval recruitment.

Overall, these preliminary findings suggest that abundance of the larval to early juvenile life stages of Delta Smelt may respond quite strongly to spring and prior fall outflow conditions. The relationships of the 20 mm index with spring X2 shown in this analysis were much stronger than relationships of the TNS and FMWT indices with spring X2 (Table 1, Fig. 17. Similarly, hydrological conditions in the fall seem to have a greater impact on subsequent abundance of larvae than on subsequent juvenile abundance (TNS index; Mount et al. 2013). This is consistent with the findings by Kimmerer et al. (2009) who noted more pronounced relationships of spring X2 with earlier than with later life stages of Delta Smelt and explained that this was “probably because the earlier life stages occupy areas that are fresher and therefore more responsive to changing flow than the more brackish regions.” While the size and location of the LSZ itself may be important for maturing adults in the fall, its interface with fresh water may be important to larvae and spawning adults. A more westward interface means a larger freshwater habitat for spawning and larval rearing that reaches into the shallow eastern region of Suisun Bay and is well connected with Suisun Marsh sloughs and, in wetter years, the Napa River. It also means a larger distance to the export pumps in the southern Delta and thus a reduced risk of entrainment for spawning adults and larvae. Interactions of flow with other drivers and habitat attributes as shown in the conceptual models in this report are likely also important. This suggests that at least

Figure 82. **Adult (panel a, SKT) and subadult (panel b, FMWT the previous year) to larvae (20 mm Survey) recruitment indices (abundance index ratios) as a function of spring X2 (February-June). For 20 mm/SKT a linear regression was calculated with and without 2013, which appears to be an outlier. For 20 mm/FMWT the previous year separate regressions were calculated for the POD period (2003-2013), the period before the POD (1995-2002), and the entire data record (not shown). See Table 9 for regression results.**



at present, increased Delta outflow and a more westward LSZ in fall, winter, and spring may have important beneficial effects on early life stages of Delta Smelt, but other factors (possibly including summer flows which were not included in this analysis) may be more important for their survival to adults.

Finally, similar to previously published analyses, this analysis strongly suggests that previous life stage abundance should always be taken into account in statistical explorations of habitat effects

Table 9. Summary of relationships of larval recruitment indices (abundance index ratios) for Delta Smelt (response variable) and spring X2 (predictor variable; spring: February-June): n, number of observations (years); SE/Mean, model standard error (square root of mean squared residual) as proportion of mean response, P, statistical significance level for the model; R^2, coefficient of determination. All relationships modeled with least-squares linear models (LM).

Index Ratio	Period	n	SE/Mean	P	R^2
20-mm/ SKT	2003-2013	11	0.556	0.006	0.588
20-mm/ SKT	2003-2012	10	0.270	0.000	0.918
20-mm/ $FMWT_{Year-1}$	2003-2013	11	0.469	0.003	0.648
20-mm/ $FMWT_{Year-1}$	1995-2002	8	1.012	0.771	0.015
20-mm/ $FMWT_{Year-1}$	1995-2013	19	0.981	0.321	0.058

on Delta Smelt. Prior abundance can be introduced into these relationships as actual abundance data (e.g. abundance indices or catch per trawl data), periods of relatively constant abundance (here introduced as a “step” factor), or by combining it with present abundance in proportional abundance indices such as the index ratios used here as recruitment indices. Similar to the relationships of juveniles with spring X2 discussed in Chapter 4, the overall depressed abundance of larval Delta Smelt during the POD period that started in 2002 leads to less substantial larval abundance increases with increasing outflows and decreasing X2 values than before the onset of the POD. However, the association of high larval recruitment with high spring outflow suggests that winter and spring hydrology, through its effects on habitat attributes, may be an important driver of larval recruitment during the current POD period, although it may be less important at higher abundance levels.

In summary, this preliminary analysis provides an example of how relatively simple multivariate modeling can yield intereresting insights, in this case about how prior conditions (prior fall X2), prior abundance (prior FMWT), step changes in abundance, and concurrent environmental conditions (spring X2) may all have important effects on Delta Smelt abundance in the spring. While further analyses, more sophisticated life cycle modeling, and publication in a peer-reviewed journal are needed to draw firm conclusions, these preliminary results support the idea discussed throughout this report that neither scientific understanding nor management effectiveness can be improved by only considering a single effect, or a single season or life stage. High larval recruitment is essential for setting the stage for a strong year class, but higher growth and survival through subsequent life stages are also needed to achieve and sustain higher population abundance levels.

Numerical Simulation Modeling

Quantitative simulations of the multiple factors and processes that affect Delta Smelt life stage transitions in our conceptual model are an obvious next step in the exploration and synthesis of the information presented in this report. The purpose of simulation modeling is to represent a phenomenon or process in a way that allows users to learn more about it by interacting with the simulation (Alessi and Trollip 2001). In particular, simulations allow users to easily control experimental variables and test hypotheses. Guidance from simulation model "dry runs" can make actual laboratory and field experimentation much more efficient and effective. Simulations are also valuable in visualizing outcomes, thus further promoting learning and understanding.

The individual-based Delta Smelt model by Rose et al. (2013a, b) is an example of a complex simulation model specifically created for Delta Smelt. Another simulation modeling option is to utilize "off-the-shelf" simulation software such as the "STELLA" (Structural Thinking and Experiential Learning Laboratory) simulation construction kit (http://www.iseesystems.com/softwares/Education/StellaSoftware.aspx). STELLA is designed to let users easily create their own simulations using system dynamics including positive and negative causal loops, and flows, accumulations and conversions of materials.

Culberson (USFWS, unpublished data) created a simple quantitative simulation model in STELLA that includes several life stages of Delta Smelt and is based on seasonal environmental conditions and stage to stage estimates of survival. While this simulation modeling approach appears to be feasible, it remains to be seen how such an approach will approximate actual population dynamics encountered in the field and how results compare to those of other simulation models such as the individual-based life cycle model by Rose et al. (2013a,b). A user-friendly STELLA-based model can be useful in the interim, however, to explore the relative contribution of lifecycle stage and environmental covariates to the overall status of Delta Smelt abundance from year to year and to test hypotheses derived from the conceptual model. In its fullest expression, this MAST-associated lifecycle model will be useful for illustrating how multiple suites of plausible co-variates can allow for different Delta Smelt abundance outcomes. For example, it may be possible to find high abundance under degraded conditions given low entrainment losses across successive winters and springs. Conversely, it is possible to encounter low Delta Smelt abundance given otherwise good environmental and outflow conditions with significantly warmer temperatures during fall pre-adult maturation periods. Moreover, simulated changes in survival can provide a useful frame of reference to evaluate alternative outcomes of cohort size or population size attained at different life stages. For example, given the reported levels of larva, juvenile and sub-adult Delta Smelt in IEP surveys, what levels of daily survival between life stages would be required to attain the relative abundances corresponding to each of the four years being compared? Could the small anticipated differences in assumed daily survival among those four years be attributed to some combination of habitat attributes? Or, could stage-to-stage survival (e.g., percent of individuals surviving from one stage to the next) provide a more useful frame of reference to address that question? Our proposed STELLA simulation model and associated modeling exercises will comfortably allow exploration of these questions and related ideas.

This type of modeling will best be used iteratively with emerging data and within synthesis reports to identify where important gaps exist in the Delta Smelt lifecycle understanding and demonstrate how disparate information sources might be brought together to inform our smelt population estimates through time. Importantly, our model can be used in combination with the narrative description of "a year in the life" of the Delta Smelt population from the conceptual model to more effectively describe environmental and management effects on population status in the SFE. We are especially interested in using such a model to avoid single-factor outcome discussions where smelt populations are seen as the result of "one versus another" environmental or management-related trade off, particularly when single factor analysis is aggregated over decades of data collection efforts in what we know is a constantly-changing estuary.

Figure 83 shows how output from such a model might be useful for keeping track of the variable influence of factors on overall Delta Smelt abundance across seasons within three hypothetical years. Six factors are plotted according to their sensitivity rank (their relative influence on simulated population outcomes). Specific sensitivity levels can then be identified according to the combinations of factors that emerge as important across succeeding seasons and years. Models built to simulate these influences can then be closely examined to discern how different years, year types, or management practices influence simulated abundance, and to detect where potential data gaps or inconsistencies are among the alternative conceptual models or model modes. The basis for using such an approach is a comparative one, and an absolute resolution of the size or behavior of the real Delta Smelt population is not anticipated – but remains the overall objective. Of real interest here is providing a way to interpret our emerging conceptual model within potential regime-shifts, and to capitalize on previous specifications of this model to organize our ever-improving understanding. Of additional benefit is the ability to use these models easily in “learning sessions,” where users interact with the modelers and species experts to deepen understanding of Delta Smelt biology and its relationship to Delta ecology and management.

Applications to Support Delta Smelt Management

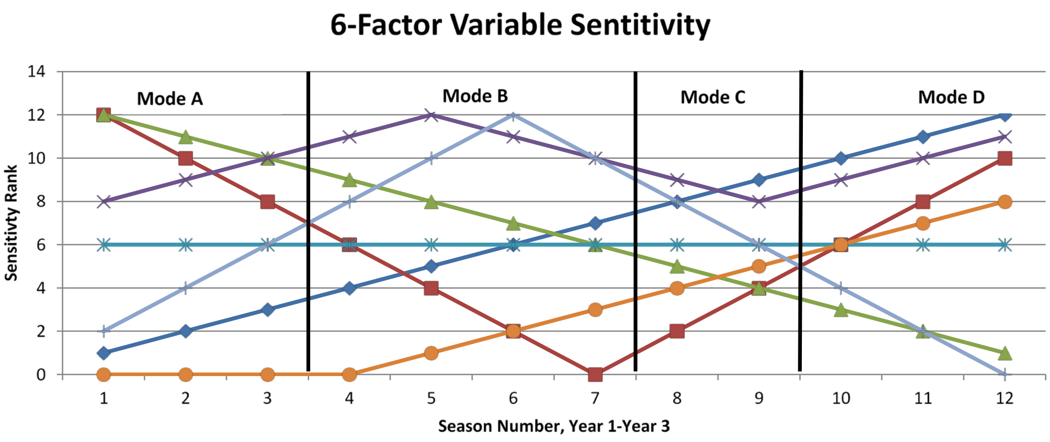
We have shown that the conceptual models in this report provide a reasonable and up to date conceptual framework that can be used to analyze and synthesize existing data and knowledge about Delta Smelt, identify critical data and information gaps, and guide new field and laboratory studies as well as mathematical modeling efforts. We have also discussed many challenges that limit our ability to reach firm conclusions and make highly confident predictions about the effects of management actions and other changes on Delta Smelt. And we have noted that science and management have to go hand in hand to constantly identify, implement, evaluate, and refine the best management options for Delta Smelt in the highly altered and ever-changing estuarine ecosystem that represents the entire range of this species.

Adaptive management is a well-established approach for systematically integrating science and management. As mentioned earlier in this report, it is increasingly required in plans for management of the San Francisco estuary, but to date, the Vernalis Adaptive Management Program (VAMP) and the Fall Ouflow Adaptive Management Plan are among the few clear examples of systematically planned and implemented adaptive management in the estuary.

We end our report with examples of how our conceptual models can be used to adaptively manage and improve Delta Smelt habitat. We conclude with several recommendations for the next analysis, synthesis, and modeling efforts. These efforts are a key ingredient for the more widespread adoption and success of adaptive management strategies; without the conceptual and mathematical models provided by these efforts adaptive management of ecosystems simply cannot proceed.

Table 10 gives examples of adaptive management goals and associated uncertainties to address habitat deficiencies (“habitat problems”) identified and discussed in this report. This table is intended as an illustration of how our conceptual models can be used to inform the first three steps of the nine-step adaptive management framework developed by the DSC Delta Science Program (DSP 2013). These three steps are: 1) definition of the problem; 2) establishment of

Figure 83. **Simulated output from a STELLA model for assessing sensitivity of the model to variation in model variables.**



management goals and actions to address the problem; and 3) modeling of linkages between management goals and actions. The third step specifically requires conceptual or quantitative models for the purpose of evaluating outcomes of alternative management actions and identification of uncertainties and data gaps. Conceptual models are also important in the other six adaptive management steps, for example to design effective adaptive management experiments and appropriate monitoring and to analyze, synthesize and evaluate results.

Table 10 is organized around the habitat attributes identified in the conceptual models. For each habitat attribute, we describe some example categories of management actions that could be considered to improve the status of Delta Smelt. In essence, these actions represent an example “tool box” for the management of Delta Smelt.

Note that the tool box identified in Table 10 is not meant to be exhaustive. Rather, the list is intended as an example set of adaptive management actions suggested by the conceptual models. As such, the list provides no insight into the cost-effectiveness or feasibility of any of the potential actions. Moreover, we acknowledge that there is substantial uncertainty about the potential benefits of actions in the tool box. As mentioned above, identification of uncertainties about the feasibility and benefits of proposed management actions is an important step in adaptive management that can only be accomplished with the help of conceptual or quantitative models. A key point is that these studies are somewhat different than the critical data and information gaps presented earlier in this Chapter. Specifically, Table 10 emphasizes information gaps that are most relevant to specific management questions, while the earlier list focuses on needs to improve the overall scientific understanding that provides the basis for our conceptual models for Delta Smelt. Clearly, efforts to resolve uncertainties and gaps in understanding are needed in both categories. Overlapping uncertainties may highlight especially urgent data and information needs. For Delta Smelt, this includes uncertainties related to contaminants, predation, and entrainment along with interactions of physical habitat attributes with other factors.

Table 10. **Example tool-box for applying the conceptual model to Delta Smelt management.**

Habitat Attribute	Management Actions	Example Study Efforts
Physical Features	Increase habitat area & quality	-Identification of key microhabitats for each life stage and attributes. -Effects of flow/LSZ position on habitat quality, particularly key biotic habitat elements (access to prey, evasion of predators). -Approaches to maintain & expand high turbidity habitat (e.g. supply, habitat design, SAV management). -Approaches to maintain and expand habitat with moderate temperatures (e.g. channel configuration, water depth and velocity). -Evaluation of whether targeted restoration meets habitat needs (e.g. temperature, substrate, turbidity)
Chemical Features	Reduce toxicity	-Identification of chronic effects of contaminants. -Identification of effects of Harmful Algal Blooms. -Approaches to reduce toxicity from contaminants and HABs
Food	Increase pelagic production Increase access to alternative foods (e.g. epibenthic). Reduce sources of loss Manage towards higher quality foods Prevention and control of non-native species	-Role of tidal wetlands as subsidy habitats (not necessarily occupied by smelt) -Ammonia-bivalve interactive effects on diatom, copepod, mysid, amphipod production. -Relative importance (contribution to smelt growth) of epibenthic foods (e.g., mysids, amphipods, aquatic insects). -Effect of bathymetry, vegetation type (and density) on access to epibenthic and pelagic foods. -Role of tidal wetlands and wetland/open-water complexes. -Approaches to reduce losses to benthic grazing (e.g. invasive clams) and/or to the suppression of bivalve populations -Value of different food types to Delta Smelt nutrition. -Effects of habitat conditions (e.g. ammonia, flow) on food quality. -Identification of nutrient sources and sinks. -Improved detection methods for invasive species -Studies to evaluate alternative control methods.
Entrainment	Avoid entrainment region Adjustments to timing and magnitude of exports	-Identification of factors that lead to increased occupancy of South Delta. -Improved measurement of entrainment and its environmental correlates -Effects of exports and entrainment on viability (e.g. abundance, genetics, demographics). -Approaches to reduce entrainment and enhance emigration success.
Predation risk	Reduction of predator population Reduction of predation rate	-Studies on delta smelt responses (behavior, distribution, abundance) to variation in predator abundance. -Identify habitat features that reduce predation rate (e.g. depth, turbidity, food, lower water temperatures).

Recommendations for future analysis and synthesis

Efforts to resolve the management issues listed in Table 10 or carry out the modeling and fill the critical science gaps discussed earlier in this Chapter will not succeed without an organizational commitment to continued systematic and long-term collection, synthesis and evaluation of data and information about Delta Smelt, its habitat, and important drivers of habitat and abundance changes. The importance of Delta Smelt for ecosystem and water supply management in and far beyond the SFE is widely recognized. The impressive rate at which we are learning about Delta Smelt and the estuarine ecosystem and the large amount of existing information about them is less widely recognized by many managers and even by many scientists. Part of the reason for this is that it is difficult to track the large quantity of new (since 2010) information documented in this report and even more difficult to integrate it with the previously existing information in a meaningful way. But without this integration, identification of priorities for additional scientific investigations is ad hoc and piecemeal at best and the value of new information cannot be fully realized in management applications such as those listed in Table 10.

Moreover, comprehensive adaptive management efforts simply cannot succeed without adequate conceptual and mathematical models and important science and management opportunities will be missed. Such efforts currently include the ongoing fall outflow adaptive management for Delta Smelt and new efforts called for by the new "Collaborative Science and Adaptive Management Program" (CSAMP), the California Delta Stewardship Council's Delta Plan, and the multi-agency Bay Delta Conservation Plan (BDCP). The fact that even the incomplete draft version of our report released for public review in June 2013 already played a central role in CSAMP work planning, court documents, and elsewhere bears clear testimony to the fact that there is a great and urgent policy and management need for analysis, synthesis and conceptual models such as those provided in this report.

In consequence, we strongly recommend that there be a continued management, analysis, and synthesis effort, whether carried out by the IEP, the Delta Science Program, or some other scientist, group or agency. While it is possible for individual scientists to take on such efforts (e.g., Bennett 2005), the amount, diversity, and rapid growth of pertinent data and information suggests that team efforts may usually be a more feasible and possibly also a more effective option. Collaborative, multidisciplinary analysis and synthesis teams are also at the core of the National Center for Ecological Analysis and Synthesis in Santa Barbara, CA (NCEAS, http://www.nceas.ucsb.edu/), the newer National Socio-Environmental Synthesis Center in Annapolis, MD (SESYNC, http://www.sesync.org/) and the Delta Collaborative Analysis and Synthesis (DCAS) approach promoted by the Delta Science Program's Delta Science Plan (DSP 2013). Important IEP POD and MAST lessons for future synthesis teams are that the role and responsibilities of all team members need to be very clear, that lines of communication need to always be open and available to all, and that there needs to be strong and fully engaged team leadership with a clearly dedicated lead author and/or lead editor for all major team products. In addition, to complete analyses and reports on schedule, it is necessary for team members to prioritize synthesis efforts for sustained periods of time, without being tasked with additional projects that may be urgent for short-term needs.

Another consideration is the type of publication that results from analysis and synthesis efforts. The IEP MAST and POD teams have written comprehensive agency reports, but would have preferred writing peer-reviewed books or monographs (e.g., published by the American Fisheries Society or by U.C. Press) had the time and resources been available to do so. Such books would be considered better scientific products with greater scientific standing and a longer life span and would reach a much larger audience. Another approach would be to write a series of shorter articles that could be published in a special issue of a peer-reviewed scientific journal. This too would take more time and effort and would also somewhat restrict the types of topics that could be covered. Journal articles are, however, the main target for national analysis and synthesis centers such as NCEAS and SESYNC because they have the greatest scientific standing and are the most widely accepted and well established method of written science communication.

Regardless of which analysis, synthesis, and communication approach is chosen, none of these efforts can succeed without commitment of adequate funding, staffing, and other resources. The IEP MAST team that developed and wrote this report was formed in 2012 for IEP science synthesis and work planning, but it has remained a pilot-level effort that was never adequately supported. MAST work remained a part-time effort for all co-authors of this report, and for most it was an "on the side" task compared to their "regular" agency duties. There is no doubt that completion of this report could have proceeded much more rapidly with greater allocation of resources. Public and independent peer reviews of a draft version of this report (see http://www.water.ca.gov/iep/pod/mast.cfm) greatly improved the structure and content, but were not an original part of the MAST planning. Preparing and conducting the reviews as well as responding to the 355 specific and many more general review comments took considerable time (see also Appendix A). Other MAST tasks also added to the delays. In addition to this report, the MAST completed a synthesis report for the Fall Low Salinity Habitat (FLaSH) investigation component of the Fall Outflow Adaptive Management Program (Brown et al. 2014) and prepared a solicitation package for research proposals, which it then also reviewed.

We strongly recommend that adequate, long-term support for these types of efforts be among the highest science and adaptive management priorities for the region and the entire State of California. Given its pivotal role in adaptive management and the increasingly large amounts of new scientific data and information that are produced every year, the authors of this report, individually and as a team, cannot think of any science activity that is more urgently in need of greater support than analysis, synthesis, and communication of scientific results.

For additional analysis and synthesis efforts about Delta Smelt, we recommend that the next individual or team to take this on should:

- Build on this report by evaluating the conceptual model with more rigorous analyses that include more years of data, developing lifecycle and numerical models as discussed above, and/or using the conceptual model to develop a comprehensive list of data and information gaps and approaches to addressing these gaps in order to inform management strategies;
- Early in the process, make clear decisions about the analytical/modeling approaches to be used, the scope of the synthesis to be done, and approaches for review and communication of results;
- Evaluate additional data and information needs concerning Delta Smelt;
- Consider approaches to understand the effects of the wide variety of management actions targeting Delta Smelt, including adaptive management of fall outflow, entrainment, habitat restoration, etc (e.g., Table 10);
- Develop key "indicator" variables that can be used to track and predict the status of Delta Smelt and its habitat and serve as "performance metrics" to evaluate the success of management actions. Such variables, and a "report card" to summarize them, were considered for this report, but the MAST decided that developing them was beyond the scope of

this report and would require a fairly substantial effort that could be the main focus of an additional effort.

An additional recommendation is that an ultimate goal of these efforts should be the integration of conceptual and mathematical models such as those described in the previous section of this Chapter and the routine use of both types of models in adaptive management. Neither the recently published mathematical models nor existing conceptual models for Delta Smelt have been applied to management issues in a consistent manner. This is likely at least partially due to unfamiliarity of managers with the models and the need for specialists (model developers) to apply the mathematical and in some cases even the conceptual models to management issues in the absence of easy to use and understandable model interfaces and specifications. We also recommend a comprehensive biological modeling forum and/or more specific biological modeling teams and "summits" as recommended by the IEP Science Advisory Group (2010, available at http://www.water.ca.gov/iep/docs/IEPModelWorkshopReview.pdf) and, more recently, the Delta Science Plan (DSP 2013). Such groups would not only facilitate communication among modelers, but could also help make the connection from model development to model applications of interest to managers and policy makers. They would complement and could (and likely should) be integrated with the existing, California Water and Environmental Modeling Forum (CWEMF, see http://www.cwemf.org), which tends to focus on modeling physical processes. As with the overall analysis and synthesis teams, these groups could be implemented by the IEP, The Delta Science Program, CWEMF, or others. The chosen organizational umbrella is less important than actual implementation and involvement of appropriate local and outside scientific and management expertise. Some possible topics for these groups include:

1. Reviews and updates to existing conceptual and mathematical models
2. Further development of mathematical models of Delta Smelt population abundance drawn specifically from the conceptual models described in this report; applications and extensions of recently published models to help make management decisions and guide new modeling efforts; additional modeling efforts and future research projects to improve resolution and understanding of the particular factors identified as critical to reproduction, recruitment, survival, and growth.
3. Review and refinement of new models such as the emerging comprehensive state-space population model (Newman, personal communication); development of additional models or modules of models specifically aimed at estimating effects of inadequately monitored or difficult to measure and evaluate habitat attributes such as predation risk and toxicity; development of new "nested" and/or "linked" mathematical modeling approaches that can accommodate multiple drivers and their interactive effects across temporal and spatial scales.
4. Collaboration among physical and biological modelers, experimental and other scientists, managers, and stakeholders to develop and model management scenarios and strategies that move beyond the current focus on relatively crude distinctions among "water year types" toward a more integrative ecosystem and landscape-based management approach.

We end this report with the hope that the conceptual models and information presented will be used for achieving better management outcomes for Delta Smelt and the estuarine ecosystem on which it depends. These precious natural resources are owned by no one, but are held in public trust by the California and U.S. governments for the benefit of all the people. We are grateful for the opportunity to serve our State and nation in the collaborative manner afforded by working under the interagency umbrella of the Interagency Ecological Program for the San Francisco Estuary.

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Appendix A: How the Delta Smelt MAST Report was Written

The report titled “An updated conceptual model for Delta Smelt: our evolving understanding of an estuarine fish” (hereafter referred to as Delta Smelt MAST report) was written in 2013-2014 by the IEP Management, Analysis, and Synthesis Team (MAST). The Delta Smelt MAST report was developed through a series of report drafts and a public technical review and followed a set of general report guidelines. This report appendix describes the Delta Smelt MAST report guidelines, the report review and revisions, and report milestones.

Delta Smelt MAST Report Guidelines

Report Purpose and Approach

The Delta Smelt MAST report is a technical report intended to synthesize the latest scientific data and information on Delta Smelt, a topic of particularly high relevance to agency managers and decision makers in California. Specifically, it provides an up to date assessment and conceptual model of factors affecting Delta Smelt throughout its primarily annual life cycle and demonstrates how the conceptual model can be used in science and management. The Delta Smelt MAST report updates and redesigns previous conceptual models for Delta Smelt with new data and information since the release of the last synthesis report about the “Pelagic Organism Decline” (POD) by the Interagency Ecological Program (IEP) in 2010. It then uses the conceptual model to generate hypotheses about the factors that may have contributed to the 2011 increase in

Delta Smelt abundance and evaluate them using a simple comparative approach. The Delta Smelt MAST report ends with key conclusions, a discussion of our hypothesis testing approach, and recommendations for future work and adaptive management applications, with examples.

1. **Report Development.** The 2014 MAST report is a synthesis report developed and written by the IEP Management, Analysis, and Synthesis Team (MAST). The MAST is co-chaired by the IEP Lead Scientist and IEP Program Manager and includes senior scientists from IEP member agencies tasked with data analysis, synthesis, and work planning. The MAST report is the collective product of a dynamic and collaborative interagency team process involving focused team discussions at monthly MAST meetings, intensive conceptual model and report development at additional multi-day off-site meetings, presentations and discussions with other scientists, stakeholders, and the public (e.g., at the annual IEP workshop, meetings of the IEP Stakeholder Group and IEP Project Work Teams), and data analysis and synthesis as well as writing, integration, and revisions of report sections by MAST members with written communication via email and the MAST wiki. MAST report authors were expected to follow the MAST report guidelines described here. They were also expected to consider all internal review comments by other MAST members and members of the IEP Management and Coordinators teams as well as external technical review comments received during a 40-day public review period. Details about the public review process are given in II.

2. **Report Authorship.** The “author of record” for the 2013 MAST report is the entire IEP MAST, and the responsibility for authorship lies with the entire MAST as well. Individual authorship of report sections is not credited; the report is a product of the IEP MAST and not of any individual author or an individual IEP member agency. All current MAST members are MAST report authors and are listed alphabetically in the initial pages of the report (see III. below). Former MAST members will not be listed as authors, but will be noted as contributors. Each report section had a lead author who had primary responsibility for writing and revising the section. One designated MAST member (Larry Brown, USGS) functioned as report lead editor who compiled and integrated all sections and sent full draft report versions to the MAST for review by all MAST members. All MAST members sent their edits and comments back to Larry Brown and the section authors for revisions. The report went through multiple draft versions before its finalization.

3. **Report Organization.** The 2014 MAST report is an IEP technical report and follows the same basic organization as other IEP technical reports, including a title page, list of all authors, acknowledgements, table of contents, executive summary, an introductory section with background information and report objectives, and concise sections detailing the analysis and synthesis approach, models and hypotheses, findings, and conclusions as well as illustrative tables, figures, and full references for all citations. In response to reviewer recommendations received during the public technical review (see II.), the report was restructured and expanded from originally six to nine Chapters.

4. **Supporting Evidence.** The 2014 MAST report follows the conventions of IEP and other technical reports regarding supporting evidence, which includes the following. The rationale for any findings, conclusions, and recommendations should be fully explained in the report. Whenever possible, conceptual models and hypotheses should be evaluated through analysis of the available data. Additional supporting information should be obtained from the peer-reviewed literature or from publicly accessible reports. Related or competing hypotheses and models that have been previously published in the peer-

reviewed literature should be acknowledged and discussed in the report and conclusions should be based on even-handed, dispassionate consideration of all available evidence. Sources for all supporting data and information should be clearly identified and cited. Citation of personally communicated unpublished results (e.g. emails, memos) is permissible, but should be used sparingly.

Delta Smelt MAST Report Review and Revisions

1. **What was the purpose of the review?** The purpose of the public technical review of the draft Delta Smelt MAST report was to ensure its scientific credibility, relevance to managers and decision makers, and a transparent and legitimate process that welcomed and considered input and recommendations from other scientists, managers, stakeholders, and the public.

2. **What was expected of draft Delta Smelt MAST report reviewers?** MAST report reviewers were asked to provide written comments on any and all technical aspects of the draft report, but to pay particular attention to review criteria outlined in the MAST report review guidelines.[1]

3. **Who reviewed the draft Delta Smelt MAST report?** The draft Delta Smelt MAST report released for public review on July 23, 2014, was reviewed by invited IEP staff and colleagues as well as by invited external peer reviewers and other scientists who submitted comments during the 40-day public review period, as follows.

    a. IEP Coordinators (1 Reviewer, IEP management review)

    b. Former MAST Members (2 Reviewers, IEP colleague scientific peer review)

    c. Invited Subject Area Expert (1 Reviewer, IEP colleague review of contaminants sections)

    d. Independent Scientific Peer Reviewers (3 Reviewers, external independent scientific peer review facilitated by the Delta Science Program)

    e. Other Scientists, Stakeholders and the Public (7 Reviewers, external public review)

    In addition, the IEP Coordinators were asked to review the revised, near-final version of the Delta Smelt MAST report and the executive summary and to approve the final version. The IEP Directors were briefed and invited to comment on the direction and progress of the Delta Smelt MAST report on a quarterly basis.

4. **How were external draft Delta Smelt MAST report reviewers identified, invited, and informed?** Independent Scientific Peer Reviewers for the draft Delta Smelt MAST report were identified by the Delta Stewardship Council's Delta Science Program (DSP) and Delta Lead Scientist. In accordance with the DSP "Procedures for Independent Scientific Peer Review,"[2] the Delta Lead Scientist determined and invited the independent scientific peer reviewers using the following selection criteria: standing in the scientific community, expertise relevant to the documents being reviewed, and free of conflict of interest.

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[1] http://www.water.ca.gov/iep/docs/mast_report_process_july2013.pdf

[2] http://deltacouncil.ca.gov/docs/2012-11-06/delta-science-program-procedures-conducting-independent-scientific-peer-review

All other review was invited by email and in a notice posted on the IEP website.[3] A draft of the 2013 MAST report, associated figures, and MAST report review guidelines were posted on July 23, 2013, for public technical review. The draft report release for review did not include an executive summary and conclusions. The public review period closed on August 31, 2013.

5. **How many review comments were received and where can they be accessed?** The MAST received 14 sets of review comments on the July 2013 draft MAST report. They included many general comments as well as 355 comments that referred to specific lines in the report, see table A1. All comments by external reviewers (public review comments and the review comments by the three independent scientific peer reviewers) were posted on the IEP website.[4]

6. **How were the review comments addressed?** All review comments received during the 40-day review period were compiled in an Excel spreadsheet and summarized numerically (Table A1). Review comments and procedures for addressing them were discussed by the MAST at its regular monthly meetings and during a one-day offsite meeting in November 2013. The process for addressing review comments included the following:

    a. The lead author for each report section had the primary responsibility for addressing review comments pertaining to that section and for revising the section.

    b. Secondary revision leads were also assigned and assisted the primary revision lead.

    c. For each review comment in the Excel spreadsheet, it was noted whether the comment: (1) Did not suggest a revision and no revision was made; (2) Suggested a revision and a revision was made; or (3) Suggested a revision, but no revision was made, for example because it was outside of the report scope, explained elsewhere, or the lead author did not agree with the recommended revision.

    d. Revised sections and the annotated excel spreadsheet were sent by email to the entire MAST. MAST members were alerted to all major revisions.

    e. Major revisions were discussed with all MAST members during MAST meetings and via email.

    f. Decisions about major revisions were made by the whole MAST; no comment implied consent.

    g. Decisions about more minor revisions were made by the section revision leads and the report lead editor, often in consultation with some or all other MAST members.

    h. The report lead editor (Larry Brown, USGS) compiled, further revised, and integrated all revised report sections and sent full draft report versions to the MAST for review by all MAST members. The final draft versions of the report and executive summary were also sent to the IEP coordinators for their review and approval.

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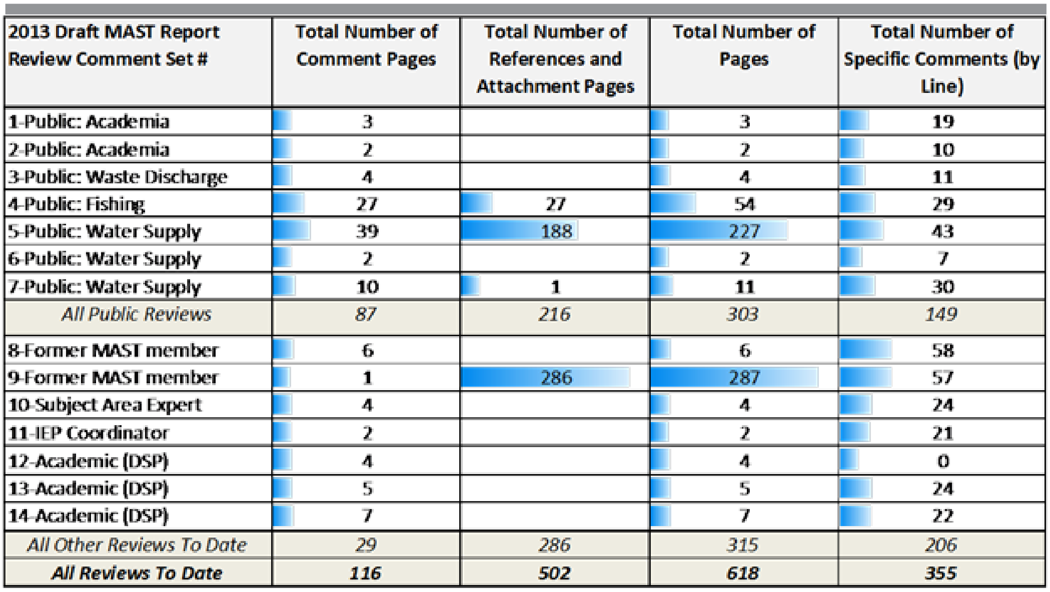
[3] http://www.water.ca.gov/iep/pod/mast.cfm
[4] http://www.water.ca.gov/iep/pod/mast.cfm

Table A1. Numerical summary of review comments for the July 2013 draft MAST report.



2013 Draft MAST Report Review Comment Set #	Total Number of Comment Pages	Total Number of References and Attachment Pages	Total Number of Pages	Total Number of Specific Comments (by Line)
1-Public: Academia	3		3	19
2-Public: Academia	2		2	10
3-Public: Waste Discharge	4		4	11
4-Public: Fishing	27	27	54	29
5-Public: Water Supply	39	188	227	43
6-Public: Water Supply	2		2	7
7-Public: Water Supply	10	1	11	30
All Public Reviews	*87*	*216*	*303*	*149*
8-Former MAST member	6		6	58
9-Former MAST member	1	286	287	57
10-Subject Area Expert	4		4	24
11-IEP Coordinator	2		2	21
12-Academic (DSP)	4		4	0
13-Academic (DSP)	5		5	24
14-Academic (DSP)	7		7	22
All Other Reviews To Date	*29*	*286*	*315*	*206*
All Reviews To Date	***116***	***502***	***618***	***355***

7. **What major changes were made to the draft report in response to review comments?** The draft Delta Smelt MAST report underwent several major changes in response to review comments. Changes include the following:

   a. The report purpose and goals were reconsidered, clarified, and somewhat expanded. Specifically, the four-year comparison of factors that may have contributed to the Delta Smelt abundance increase in 2011 was deemphasized in favor of a broader assessment and conceptual model of factors affecting Delta Smelt throughout its primarily annual life cycle and demonstrations of how the conceptual model can be used in science and management.

   b. The report structure was substantially changed to better fit the revised report purpose and goals and to improve the organization of the large amount of information included in the report. Four new Chapters were added to describe the updated conceptual model (Chapter 5), provide a more thorough overview of Delta Smelt life history and population dynamics (Chapter 6), summarize and discuss findings and conclusions (Chapter 8), and provide recommendations and examples of future work and management applications (Chapter 9). An executive summary was also added, along with this appendix.

   c. The content of the report was expanded to accomplish the somewhat expanded report purpose and goals, reflect previously missing information pointed out by reviewers as well as new information from the latest scientific publications, and provide conclusions and recommendations for future work and management applications.

   d. Several reviewers commented that the simple four-year comparative approach that was used to evaluate factors that may have contributed to the Delta Smelt abundance increase in 2011 was too limited and that more years of data and more in-depth analyses and modeling were needed for this evaluation. The MAST agreed, but decided that these types of analyses would require additional time and resources and were outside the scope of this report which emphasized synthesis of existing information over new data analyses. Instead, the MAST decided to discuss some of the benefits and limitations of analysis and synthesis approaches used in the report in Chapter 8 and existing and ongoing analyses and modeling efforts along with additional, analysis, synthesis, modeling, and other science needs and potential management applications in Chapter 9. Three examples of additional mathematical modeling approaches are also included in Chapter 9. These approaches were explored by individual co-authors of this report. Preliminary results of these analyses are given for illustrative purposes only; peer-reviewed publications of these analyses need to be completed before they can be used to draw firm conclusions.

Delta Smelt MAST Report Milestones

Note: The time line for the development, review, revision and completion of the Delta Smelt MAST report had to be adjusted repeatedly because of numerous new work assignments for individual MAST members, the large number and depth of review comments, the federal government shut-down, personnel changes, etc.

2012

March 13-16	Initial MAST off-site meeting (Marconi Center, CA) to discuss MAST products and direction and start MAST work on the 2012 IEP proposal solicitation[5], the “FLaSH” report[6], and the Delta Smelt MAST report (hereafter MAST report)
Sep 13-14	MAST off-site meeting (Yolo Wildlife Area, CA)
Dec 4-5	MAST off-site meeting (Clarksburg, CA)

2013

March 29	First draft MAST report completed
April 24	MAST presentation (talk) at annual IEP Workshop (Larry Brown, USGS)
May 20	Second draft MAST report completed
June 6	Third draft MAST report completed
July 23 – Aug 31	Fourth draft MAST report completed and posted on the IEP website for a 40-day review period
August 14	Draft MAST report discussion with IEP Stakeholder Group
Sep 11	Special IEP Stakeholder Group meeting about the draft MAST report
Oct 30	MAST report poster presentation at 2013 State of the Estuary Conference
Nov 14	MAST off-site meeting (UC Davis, CA)
Dec 8	Fifth draft MAST report completed

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[5] http://www.water.ca.gov/iep/archive/2012/solicitations.cfm

[6] http://deltacouncil.ca.gov/science-program/fall-low-salinity-habitat-flash-studies-and-adaptive-management-plan-review-0

2014

Feb 3	Sixth draft MAST report completed
Feb 11	MAST presentation (talk) at DSP-SWRCB “Delta Outflows” workshop (Larry Brown, USGS)
Feb 20	MAST presentation (talk) at a meeting of the IEP Resident Fishes Project Work Team (Larry Brown, USGS)
Feb 26	MAST presentation (talk) at annual IEP Workshop (Larry Brown, USGS)
April 16	Seventh draft MAST report completed
April 17	First draft MAST report executive summary completed
April 24	Second draft MAST report executive summary completed and sent to IEP Coordinators for review
May 15	Eight draft MAST report completed and sent to IEP Coordinators for a one-week “red flag” review. This draft includes the executive summary and a description of how the MAST report was written and revised with a list of major report revisions in response to review comments (Appendix A)
June 2	Ninth draft MAST report completed and sent to IEP Coordinators for review and IEP Directors briefings
June 11	IEP Coordinators briefed on MAST report including a review of the major changes.
June 17	Agencies and stakeholders of the CAMT Delta Smelt Scoping Team briefed about the MAST report including major findings and changes since 2013.
July 2	IEP Stakeholder Group meeting to discuss MAST report revisions and completion
July 3	Coordinators approve the final draft MAST report for publication as an IEP Technical Report; when ready the draft final report will be posted on the MAST webpage[7] until the IEP Technical Report publication is completed and report is posted on the IEP Technical Reports webpage[8]
July 14	MAST model presented to IEP Wetlands Conceptual Model Team.
July 29	IEP Directors meeting with presentation and discussion of final MAST report
July 30	MAST model presented to IEP Wetlands Project Work Team.
August 6	MAST briefing to Drought Operations Plan Team

Appendix B: Calculation of Annual Abundance Indices

This Appendix describes the data and methods used by 4 long-term fish monitoring surveys for calculating annual abundance indices for Delta Smelt (*Hypomesus transpacificus*). Descriptions are arranged sequentially beginning with the Spring Kodiak Trawl, which calculates an index of abundance for adult Delta Smelt, followed by the 20 mm Survey, which calculates an index

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[7] http://www.water.ca.gov/iep/pod/mast.cfm

[8] http://www.water.ca.gov/iep/products/technicalrpts.cfm

for late-stage larvae and small juveniles; the Summer Townet Survey calculates an index for juveniles and the Fall Midwater Trawl Survey calculates an index for sub-adults. As mentioned in the main document, abundance indices are not population estimates, but they are believed to increase monotonically with increases in true population size.

Spring Kodiak Trawl

The Department of Fish and Wildlife (DFW) initiated the Spring Kodiak Trawl Survey (SKT) in 2002. The SKT replaced the Spring Midwater Trawl and provided a more effective means to monitor the distribution and reproductive status of adult Delta Smelt. Survey results provide near real-time information on the proximity of adult Delta Smelt to south Delta export facilities and can provide an indication of likely spawning areas.

The SKT includes 5 monthly Delta-wide surveys, January through May (Figure 84). Only the first 4 surveys contribute to the annual abundance index. No index exists for 2002, when only 3 surveys were conducted. The index is calculated after all data have been verified for accuracy.

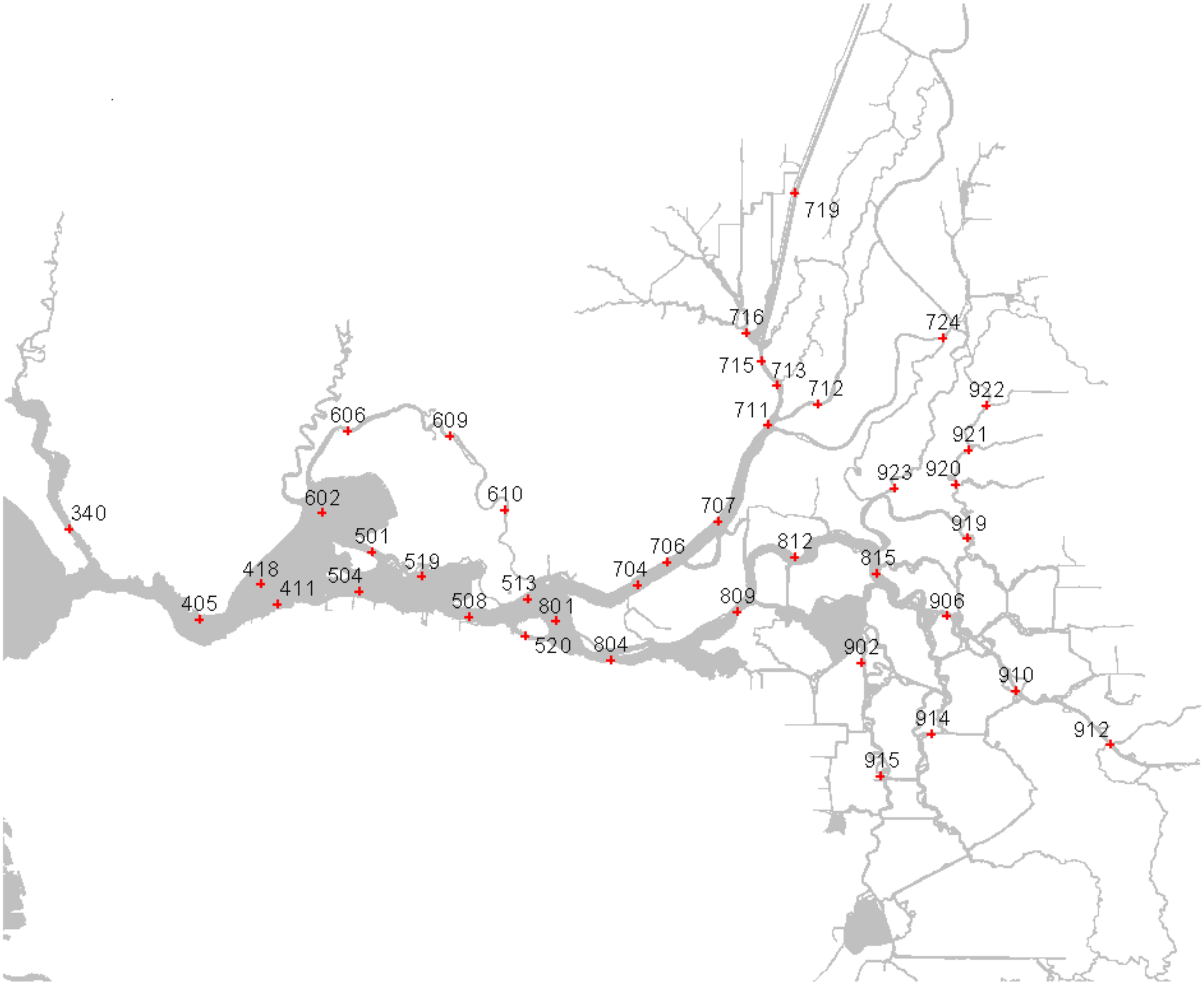
Field crews tow the net at the surface between 2 boats once for 10-min at each station per survey; 5-min surface tows are used at stations with historically high catch to limit excessive Delta Smelt take; a second 5-min surface tow is completed if Delta Smelt catch in the first tow did not exceed 50. A flow meter deployed at the start of the tow and retrieved at the end provides information on distance towed through the water. To calculate fish density, survey personnel assume that the SKT net fishes with the mouth fully opened, an area of 13.95 m^2 (7.62 m wide by 1.83 m deep). Volume filtered is the product of distance towed and mouth area. Volume filtered varies and by convention researchers expand catch per volume filtered (number per m^3) for juvenile and adult fish to catch per 10,000 m^3.

Annual abundance index calculations use adult Delta Smelt data from 39 of the 40 stations (Fig. 84). For each of the first 4 monthly surveys, adult catch per 10,000 m^3 values from each station are grouped into 3 distinct regions based on geographic location: 1) the confluence and Suisun region (sites 340, 405, 411, 418, 501, 504, 508, 513, 519, 520, 602, 606, 609, 610, 801); 2) the Sacramento River and Cache Slough region (sites 704, 706, 707, 711, 712, 713, 715, 716, 719, 724); and 3) the San Joaquin River and Delta region (804, 809, 812, 815, 902, 906, 910, 912, 914, 915, 919, 920, 921, 922, 923). A monthly mean is calculated for each region and the sum of the regional means is the monthly or survey index. The sum of the 4 survey indices is the annual index.

20 mm Survey

DFW initiated the 20 mm Survey in 1995 to monitor the distribution and relative abundance of larval and juvenile Delta Smelt throughout their historical spring range in the upper San Francisco Estuary (Fig. 85), and provide near real-time information on the relative densities and proximities of these young fish to south Delta export pumps. The 20 mm Survey includes sampling on alternate weeks from mid-March through early July, typically resulting in 9 surveys per year. During each survey, field crews complete 3 oblique tows at each of the 47 stations (Fig. 85). The 20 mm Survey added stations over time, but not all contribute to annual abundance index calculation. The survey added 5 Napa River stations in 1996 for a total of 41 core stations, which are included in the annual abundance index calculations (Fig. 85, circles). In 2008, 6 non-

Figure 84. **Map of Spring Kodiak Trawl Survey stations showing all currently sampled stations. Data from all stations except 719 are used in abundance index calculation.**

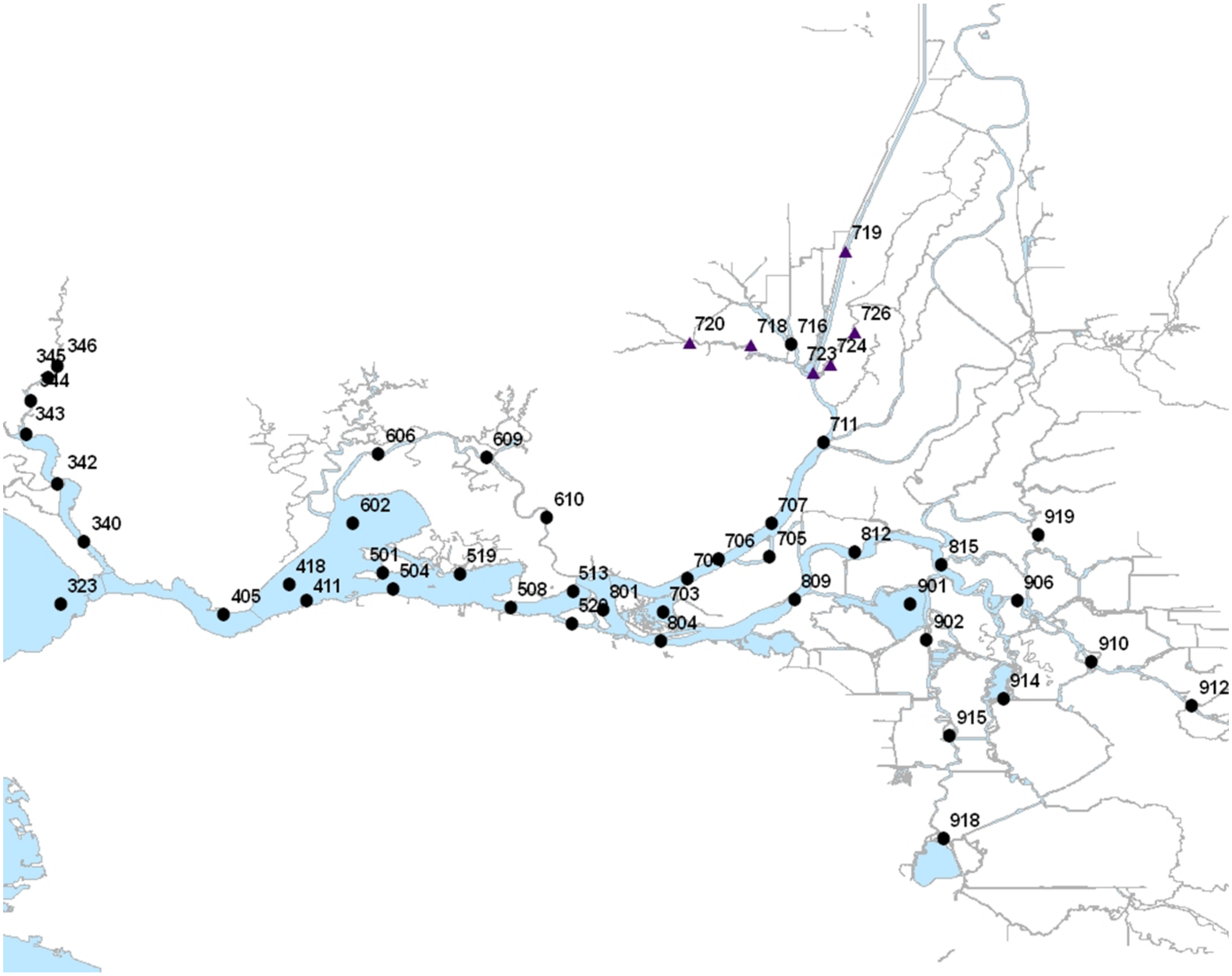


core stations were added, which are not included in the annual abundance index calculations, including Barker Slough (site 720), Lindsey Slough (site 718), Miner Slough (sites 724 and 726), and the Sacramento Deep Water Shipping Channel (n = 2; sites 719 and 723) (Fig. 85, triangles).

The 20 mm net includes a flow meter located within the mouth of the net to measure distance traveled by the net during the tow. This value is then multiplied by the fixed mouth area of the net (1.51 m^2) to provide total volume filtered. The tows are then standardized to catch of Delta Smelt per 10,000 m^3.

As already noted, the annual abundance index calculation uses only catch per 10,000 m^3 values from the 41 index stations. For each survey, the mean fork length of Delta Smelt is calculated from measurements of the fish captured during each survey. The two surveys just before the average fork length reached 20 mm and the 2 surveys just after the average fork length reached 20 mm are included in the annual abundance index calculation. For these 4 surveys the geometric

Figure 85. Map of 20 mm survey stations showing all currently sampled stations. Data from all core stations are used in abundance index calculation.



mean of the catch of Delta Smelt per 10,000 m^3 is calculated across the 41 core stations. The geometric mean for each survey is calculated as the arithmetic mean of $\log_{10}(x+1)$-transformed values of Delta Smelt catch per 10,000 m^3 across the 41 core stations. The resulting value is then back-transformed (including subtraction of 1) for the calculation of the annual abundance index. The annual abundance index is calculated as the sum of the geometric means of the 4 selected surveys.

Summer Townet Survey

The Summer Townet Survey (TNS) was started by DFW in 1959 to produce an annual index of summer abundance for age-0 Striped Bass (*Morone saxatilis*). In the mid-1990s, DFW staff developed an abundance index calculation for Delta Smelt. Annual abundance indices for Delta Smelt have been calculated for the period 1959 through the present, except for 1966-1968. The

TNS Survey samples 32 historic stations, 31 of which contribute to index calculation (labeled as "core stations," Fig. 86). Currently sampled TNS stations range from eastern San Pablo Bay to Rio Vista on the Sacramento River and to Stockton on the San Joaquin River (Fig. 86). In 2011, TNS added 8 supplemental stations in the Cache Slough and the Sacramento River Deepwater Ship Channel region to increase spatial coverage and better describe Delta Smelt range and habitat (Fig. 86). Historically, TNS sampling began when age-0 Striped Bass achieved a mean fork length of 20 mm based on larval sampling, typically in mid-June to early July, and ended when age-0 Striped Bass surpassed a mean size of 38.1 mm fork length. Since 2003, TNS has consistently included 6 surveys annually, running on alternate weeks from early June through mid- to late August.

Field crews perform at least two 10-min oblique tows at most stations. A third tow is conducted when any fish were caught during either of the first 2 tows. At least 1 tow is completed at each of the new Cache Slough and Sacramento River Deepwater Ship Channel stations. To reduce Delta Smelt take, field crews only perform a second tow at these stations if Delta Smelt catch from the first tow is less than 10. Delta Smelt catch per tow data are used for index calculation.

The annual abundance index for Delta Smelt is the arithmetic mean of the abundance indices from the first 2 surveys conducted each year. Delta Smelt abundance indices for each biweekly survey are calculated by summing catch across all tows for each index station, multiplying the summed catch by a station weighting factor representing the water volume of that station (Table B1); then the volume-weighted catches are summed across all 31 index stations and the sum divided by 1000.

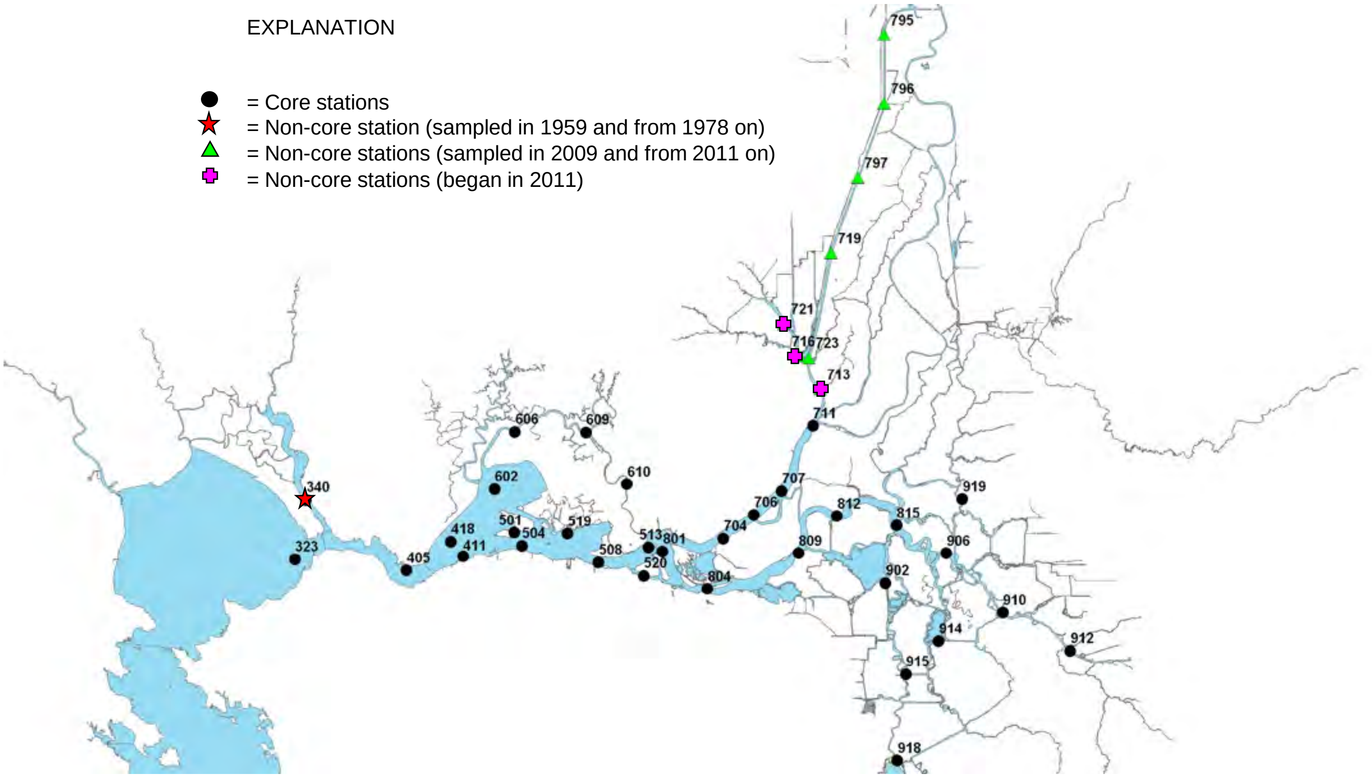
The annual abundance index for age-0 Striped Bass is calculated using similar methods, except the first two surveys are not used. Instead, abundance indices from the 2 surveys that bound the date when the fish reach a mean fork length of 38.1 mm are used; this frequently occurs after several surveys have been completed in a field season.

Fall Midwater Trawl Survey

DFW began the Fall Midwater Trawl Survey (FMWT) in 1967 to provide an annual index of relative abundance and information on the distribution of age-0 Striped Bass for the fall period. Later, DFW staff developed abundance and distribution information for other upper-estuary pelagic fishes, including Delta Smelt. Surveys have been conducted in all years from 1967 to present, except 1974 and 1979. The FMWT survey currently samples 122 stations monthly (Fig. 87), from September through December. Station locations range from San Pablo Bay to Hood on the Sacramento River, and from Sherman Lake to Stockton on the San Joaquin River (Fig. 87). Currently, annual abundance index calculations use catch data from 100 of the 122 stations sampled monthly, but the number of stations used for the index has varied through time. Table 12 contains the complete list of stations used for abundance index calculation for FWMT (n = 117), including historical stations (underlined) that must be included for proper calculation of past indices, but are not included in calculations for recent years. The remaining 22 stations were added in 1990, 1991, 2009, and 2010 to improve our understanding of Delta Smelt habitat use (Fig. 87). At each sampling station, field crews perform a single, 12-min oblique tow monthly.

Delta Smelt catch per tow data are used for calculation of the annual abundance index. Individual survey indices are calculated by first grouping the 100 core stations (Fig. 87) into 14 regions based on their location (Table 12). Survey indices are calculated by averaging Delta Smelt catch

Figure 86. **Map of summer townet survey stations showing all currently sampled stations. Data from all core stations are used in abundance index calculation.**



across index stations within each region, multiplying these regional means by their respective weighting factors (i.e. a scalar based on water volume; Table 12), and summing the weighted values. Annual abundance indices are calculated as the sum of the 4 survey abundance indices (i.e. September through December).

Table B1. Station weighting factors for stations used in calculations of the summer townet survey annual abundance indexes. Regions are geographic areas designated by the California Department of Fish and Wildlife. See fig. 86 for station locations.

Region	Station	Station weighting factor
MONTEZUMA SLOUGH	606	20
	609	15
	610	4
SAN PABLO BAY	323	213
SUISUN BAY	405	13
	411	46
	418	70
	501	49
	504	60
	508	31
	513	43
	519	15
	520	9
	602	44
SACRAMENTO RIVER	704	53
	706	27
	707	35
	711	32
SAN JOAQUIN RIVER	801	26
	804	52
	809	56
	812	22
EAST DELTA	815	40
	906	21
	910	11
	912	8
	919	10
SOUTH DELTA	902	23
	914	15
	915	15
	918	11

Figure 87. Map of fall midwater trawl survey stations showing all currently sampled stations. Data from core stations are used in abundance index calculation.

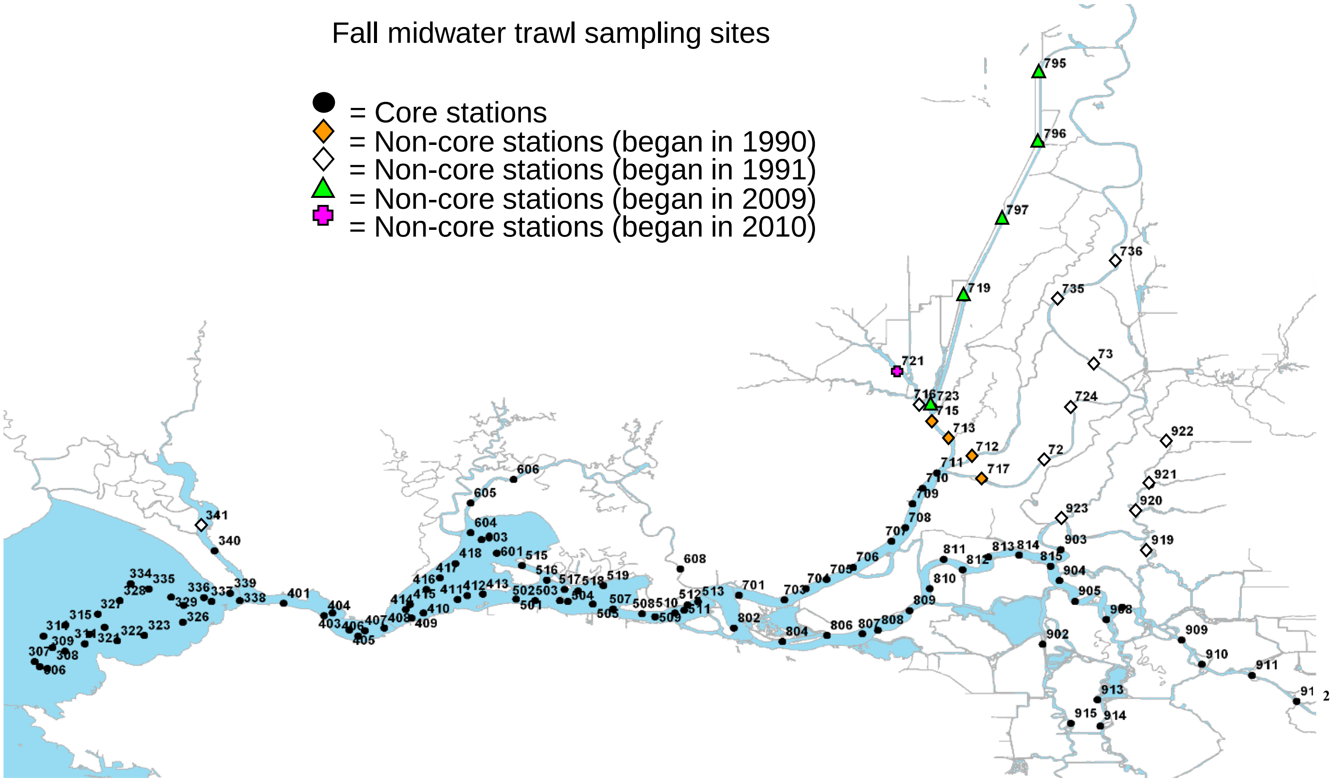


Table B2. Area-regions, weighting factor for each area-region, and stations included within each area-region. Bolded station numbers indicate the current 100 core stations used in calculation of annual abundance indexes. Underlined station numbers indicate stations previously included in calculations but subsequently dropped.

Area-region	Weighting factor	Stations included
1-San Pablo Bay	8.1	**336** **337** **338** **339**
3-San Pablo Bay	11.3	**321** **322** **323** 324 **325** **326**
4-San Pablo Bay	6.5	**327** **328** **329**
5-San Pablo Bay	12.2	330 331 332 333 **334** **335**
7-San Pablo Bay	10.2	312 313 **314** **315** 316
8-San Pablo Bay	18.5	303 304 **305** **306** **307** **308** **309** **310** **311**
10-Napa River	4.8	**340**
11-Carquinez Strait	16.0	**401** **403** 402 **404** **405** **406** **407** **408**
12-Suisun Bay	14.0	**409** **410** **411** **412** **413** **414** **415** **416** **417** **418**

13-Suisun and Honker bays	18.0	**501**
		502
		503
		504
		505
		506
		507
	18.0	**508**
		509
		510
		511
		512
		513
		514
		515
		516
		517
		518
		519
		601
14-Grizzly Bay and Montezuma Slough	5.0	**602**
		603
		604
		605
		606
		607
		608
15-Sacramento River	12.0	**701**
		702
		703
		704
		705
		706
		707
		708
		709
		710
		711
16-San Joaquin River	14.0	**802**
		804
		806
		807
		808
		809
		810
		811
		812
		813
		814
		815
17-South Delta	20.0	901
		902
		903
		904
		905
		906
		907
		908
		909

1.D.2.4 Attachments to Comments of North Coast Rivers Alliance

EXHIBIT
1

Feds scramble to avoid another mass salmon die-off in the Sacramento River

By Phillip Reese and Ryan Sabalow preese@sacbee.com

A year ago, California lost nearly an entire generation of endangered salmon because the water releases from Shasta Dam flowed out warmer than federal models had predicted. Thousands of salmon eggs and newly hatched fry baked to death in a narrow stretch of the Sacramento River near Redding that for decades has served as the primary spawning ground for winter-run Chinook salmon.

Earlier this year, federal scientists believed they had modeled a new strategy to avoid a similar die-off, only to realize their temperature monitoring equipment had failed and Shasta's waters once again were warming faster than anticipated.

In the months since, in what is essentially an emergency workaround, they've revised course, sharply curtailing flows out of Shasta. The hope is that they reserve enough of the reservoir's deep, cold water pool to sustain this year's juvenile winter-run Chinook. But it's meant sacrificing water deliveries to hundreds of Central Valley farmers who planted crops in expectation of bigger releases; and draining Folsom reservoir – the source of drinking water for much of suburban Sacramento – to near-historic lows to keep salt water from intruding on the Delta downstream.

In spite of all this, another generation of wild winter-run Chinook salmon could very well die.

For all the focus on fallowed farm fields and withered lawns in California's protracted drought, native fish have suffered the most dire consequences. The lack of snowmelt, warmer temperatures and persistent demand for limited freshwater supplies have left many of the state's reservoirs – and, by extension, its streams and rivers – hotter than normal. The changing river conditions have threatened the existence of 18 native species of fish, the winter-run Chinook among them.

Chinook are called king salmon by anglers for a reason. They can grow to more than 3 feet in length, and the biggest can top more than 50 pounds. Decades ago, before dams were built blocking their traditional spawning habitat, vast schools of these silver-sided fish with blue-green backs migrated from the ocean to spawn and die in the tributaries that feed the Sacramento River in runs timed with the seasons.

The largest run that remains in the Sacramento River system is the fall run, which survives almost entirely due to hatchery breeding programs below the Shasta, Oroville and Folsom dams. The winter run, in contrast, is still largely reared in the wild, laying its eggs in the gravel beds below Shasta's concrete walls. Their numbers have dwindled in the face of predators and deteriorating river conditions. The federal government declared the run endangered in 1994, and it has flirted with extinction ever since.

Following last year's failed federal efforts, only about 5 percent of the winter-run Chinook survived long enough to begin to migrate out to sea. The species has a three-year spawning cycle, meaning that three consecutive fish kills could lead to the end of the winter run as a wild species. One hatchery below Lake Shasta breeds winter-run Chinook in captivity.

Officials with the U.S. Bureau of Reclamation, which operates both Shasta and Folsom dams, say they believe their emergency efforts at Shasta are working and they anticipate "some" winter-run Chinook will survive this year.

"We believe that we are on track," said bureau spokesman Shane Hunt. "We are sitting in a much better place today than we were a year ago today."

Several biologists interviewed remain dubious. They note that preserving more cold water in Shasta has meant many stretches of the Sacramento River are warmer than they were last year. They worry that salmon eggs and fry will still die – only gradually instead of suddenly.

“We stand a pretty good chance of losing the wild cohort again this year, like we did last year,” said Peter Moyle, a UC Davis researcher and one of the nation’s leading fisheries biologists. “If we get lucky some of those fish will survive. We’re definitely pushing the population to its limits.”

Agricultural leaders, meanwhile, say there’s good reason to suspect the government models will again prove flawed and the fish will die despite the sacrifices farmers have made.

Rep. Jim Costa, a Democrat and third-generation farmer who represents a wide swath of the San Joaquin Valley, is among those who think there’s a good chance farmers have been punished for no benefit to the fish.

“That begs the question: What are we accomplishing?” Costa said. “We are in extreme drought conditions. ... The water districts that I represent in the San Joaquin Valley have had a zero – zero – water allocation. ... Over half a million acres have been fallowed ... It just seems to defy common sense and logic.”

Some members of California’s fisheries industry also have lost confidence in the bureau, arguing the government has badly mismanaged its rivers. Beyond the very existence of a wild population of fish, they say, the government is risking millions of dollars for California’s economy and hundreds of fishing jobs – and a key source of locally caught seafood for markets and restaurants.

Two consecutive fish kills involving an endangered species could lead to more stringent regulation of commercial and recreational fishing. It’s a real possibility, state and federal fisheries regulators said, that salmon fishing could be severely restricted along much of California’s central coast and in the Sacramento River system next year.

Larry Collins, a commercial fisherman operating out of Pier 45 in San Francisco, said that in the fight over water, the fishing industry – and wild fish – lack the political clout compared with municipal and agricultural interests.

“I’ve been around a long time, and I’ve fought the battle for a long time, and I’ve watched the water stolen from the fish,” he said. “The fish are in tough shape because their water is growing almonds down in the valley. To me, it’s just outright theft of the people’s resource for the self-aggrandizement of a few, you know?”

“You got money you can buy anything,” he added. “You can buy extinction.”

Federal models prove faulty

On paper, the requirements for salvaging the winter-run Chinook seem fairly basic. The winter-run Chinook spawn from April to August. Juvenile fish swim downriver from July to March. If the water in the Sacramento River is too hot as the fry emerge from their eggs, they die. Warm water also makes it more difficult for the juveniles to survive their swim downstream to the ocean.

But in practice, there are broad variables to keeping the river cool, involving snowmelt, heat waves, water depths and the temperatures of the tributaries entering the reservoir, as well as conditions in the river downstream.

A year ago, federal and state officials had a plan to keep temperatures in key portions of the Sacramento River below 56 degrees; temperatures above 56 can trigger a die-off. The models built by the Bureau of Reclamation indicated operators could release large amounts of water from Lake Shasta while still maintaining a cool temperature, easing the pressure on farms and cities. According to their calculations, the water would be cold enough at key points in the Sacramento River to ensure survival of 30 percent of the salmon run.

But the models were wrong. The Bureau of Reclamation essentially ran out of cold water reserves in Lake Shasta, limiting its ability to control temperatures in the Sacramento River. Average daily river temperatures rose well above levels needed by salmon to survive. The 5 percent that did transition from eggs to fry were left to navigate to the ocean in tough conditions.

“That 5 percent – I guarantee you they didn’t make it down through the Delta,” said Bill Jennings, executive director of the California Sportfishing Protection Alliance.

Fast forward to this year, and another plan gone awry.

During the spring, government officials again said they would keep winter-run Chinook alive by maintaining water temperatures below 56 degrees. The State Water Resources Control Board signed off on their plan in mid-May.

Only weeks later, Bureau of Reclamation officials told the state that their temperature monitoring equipment wasn’t working. In fact, they said, temperatures in Shasta were warmer than anticipated – and dramatic intervention would be needed to keep winter-run Chinook alive. They asked the board to consider a new plan and immediately restricted flows from Shasta.

The state water board took up the issue at a meeting on June 16. Members of the board bemoaned their lack of good choices and later adopted a plan that left no one happy. Water releases would be curtailed out of Lake Shasta. Folsom Lake would be drawn to historic lows. Deliveries to farmers would be reduced.

And, despite those measures, the average daily temperature in the Sacramento River would rise to 57 degrees on most days and 58 degrees on some days, according to the government models. That’s too high a temperature for all winter-run Chinook to survive, but the Bureau of Reclamation, in documents supporting the change, said its modeling predicted roughly 20 percent of the fish would survive to early adulthood. That would be lower than a typical year – but not a disaster.

But are this year’s models more accurate? Already this summer, average daily temperatures at a key point in the Sacramento River have risen above 58 degrees on seven separate occasions, including several times in late August, state data show.

Federal officials said their models anticipated some temperature spikes, and noted that on each occasion so far, they were able to release cold water into the river and bring temperatures back down.

“It can have an effect” on fish, said Hunt, the bureau spokesman, of river temperatures above 58 degrees. But, he added, “That temperature is not a lethal temperature immediately.”

Jon Rosenfield, a biologist with the Bay Institute, disagreed, saying that many winter-run salmon likely were doomed by the temperature spikes. He offered the analogy of a chicken egg: “If you take an egg and dip it in boiling water, you are jeopardizing its ability to develop into a chick,” he said. “The longer you do that and the hotter the temperatures, the less likely it is to develop.”

Another concern is whether there is still enough cold water in Shasta to keep river temperatures low into the fall. Hunt says yes – that the government projects that Shasta will contain 350,000 acre-feet of cold water, below 56 degrees, at month’s end, far more than in 2014.

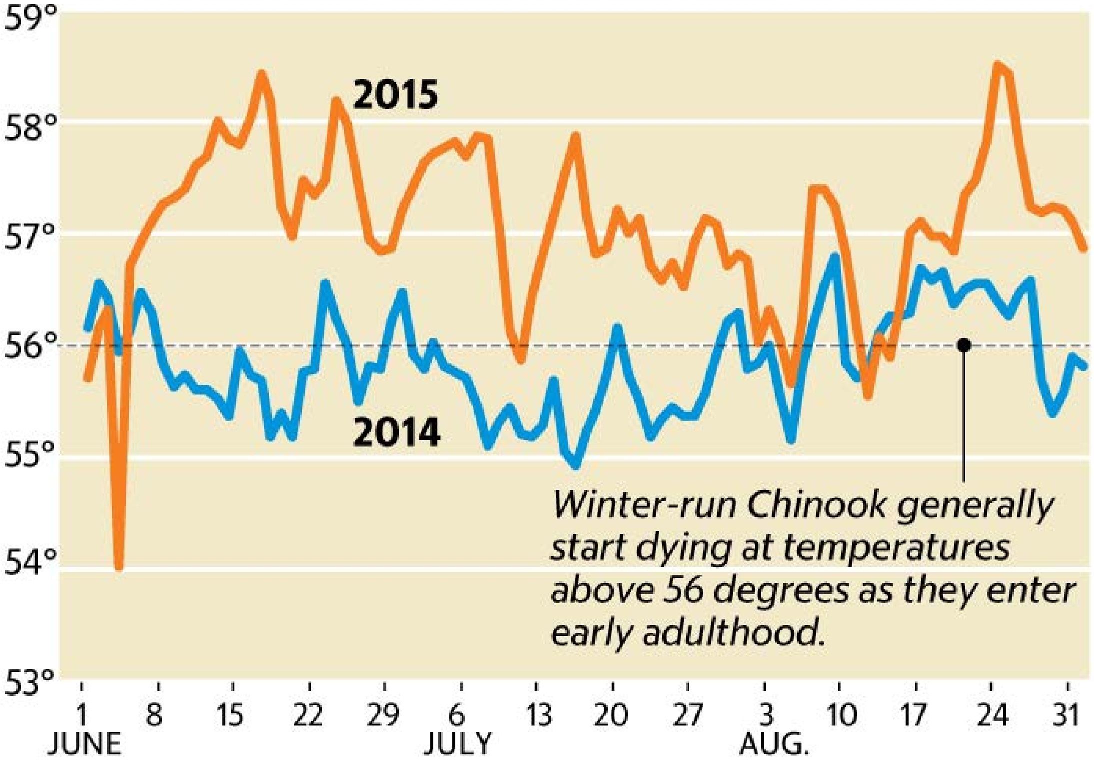
Rosenfield expressed doubts that the bureau is in position to do detailed calculations on its cold water supply. “They are way behind in anything using modern technology in measuring how much cold water they have,” Rosenfield said.

Scientists won’t know whether this year’s plan worked until fish surveys are completed in the winter. In a worst-case scenario, the government could rely even more heavily on its hatchery to sustain winter-run Chinook. Rosenfield called that option a “Band-Aid,” noting it would not preclude the loss of the fish as a wild species. Hatchery fish, he said, tend to come from a limited gene pool and may also have difficulty surviving in warm water.

Higher river temperatures; low lake levels

Under a new plan, federal officials have allowed temperatures in the Sacramento River in Shasta County to rise above 56 degrees consistently throughout the summer. They predict the warmer temperatures will not cause a mass salmon die-off; some biologists are dubious.

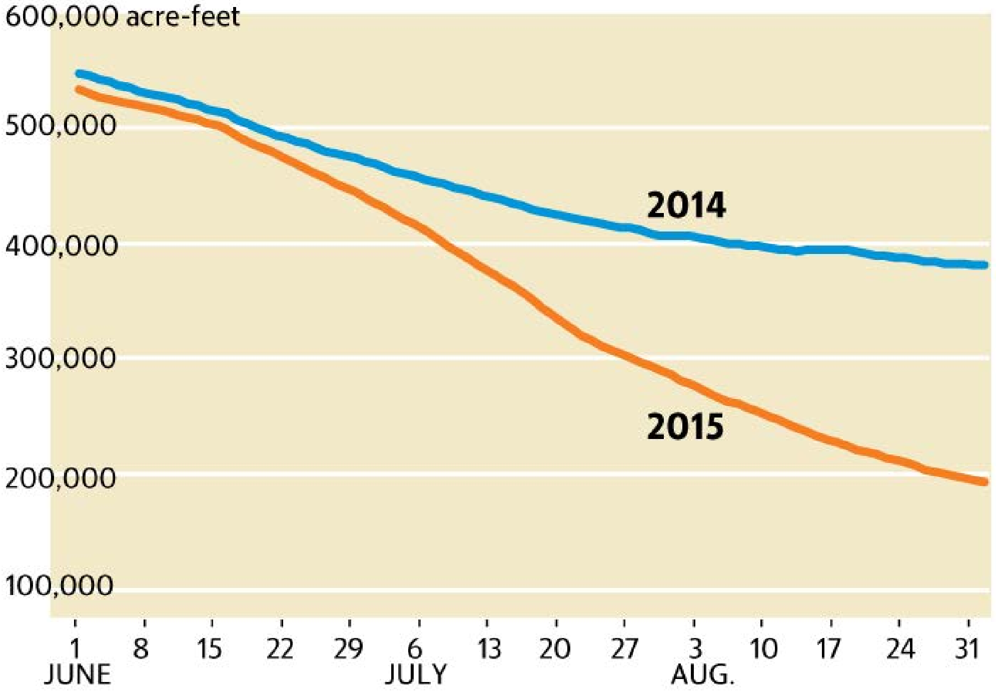
Average daily water temperatures in the Sacramento River above Clear Creek



Winter-run Chinook generally start dying at temperatures above 56 degrees as they enter early adulthood.

One consequence of the temperature plan to keep winter-run Chinook alive has been increased flows out of Folsom Lake.

Daily Folsom Lake storage (in acre-feet)



Source: California Department of Water Resources

The Sacramento Bee

Looking to the future

Jeff Gonzales worries about the ripple effects of another bad salmon season. Gonzales, a retired fire captain from Durham who guides clients on river-fishing trips, remembers when fisheries managers shut down the season for the fall-run Chinook in 2008 and 2009.

In those years, officials closed the fall-run fishing season in response to an unprecedented decline in the numbers of Chinook that had returned to the Sacramento, American and Feather rivers to spawn. The run plummeted amid poor ocean conditions and environmental problems in the Sacramento-San Joaquin Delta.

Gonzales thinks a similar scenario could be well underway, and that this year’s fall run is also in danger. He’s troubled by photos his fellow guides have sent him of fully-grown fall-run salmon floating dead in southern stretches of the Sacramento River. He attributes the deaths to warm water.

On Thursday morning, he was guiding clients on the river near Los Molinos, between Chico and Red Bluff, in search of fall-run salmon. The river is so warm, he said, that it’s been tough to find fish in his normal spots. The fish, he said, have either raced upstream seeking colder water, or are holding off the entrance to the Delta in the Pacific, waiting for a cold water flow.

That means slow-going for him and other guides.

On Thursday, his four clients, all firefighters enjoying an off-day, spent a four-hour stretch watching ospreys, wood ducks and herons glide by as their lures wriggled in the swift current. Every so often, a Chinook would breach the water and slap the surface with its tail, almost tauntingly. That morning, just one client saw his rod bend under the weight of a lunging 15-pound, silver-sided king.

Some clients have canceled trips because of the paltry catches, Gonzales said, and business will only get worse if the salmon seasons get shut down due to yet another winter-run die-off.

Maneuvering through the currents, the river rippling out before him, he lamented not just the loss of the fish but of a cultural heritage.

“You’ve gotta think about our future here, you know?” Gonzales said. “Our children and our grandchildren may not be able to see what we’re seeing here.”

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EXHIBIT
2

Supplemental Informational Report 13
September 2015

STATUS REPORT OF THE 2015 OCEAN SALMON FISHERIES OFF WASHINGTON, OREGON, and CALIFORNIA.

Preliminary Data Through August 31, 2015.[a]

Fishery and Area	Season Dates	Effort Days Fished	CHINOOK Catch	CHINOOK Quota	CHINOOK Percent	COHO[b] Catch	COHO[b] Quota	COHO[b] Percent
			COMMERCIAL					
Treaty Indian[c]	*5/1-6/30*	683	30,916	30,000	103%		Non-Retention	
	7/1-9/15	364	26,944	29,084	93%	2,961	42,500	7%
Non-Indian North of Cape Falcon[d]	*5/1-6/30*	2,118	38,930	40,200	97%		Non-Retention	
	7/1-9/1[e]	1,090	25,248	26,800	94%	2,924	19,200	15%
	9/4-9/22[f]	NA	NA			NA	NA	NA
Cape Falcon - Humbug Mt.	*4/1-8/27*	6,645	82,752	None	NA		Non-Retention	
	9/3-9/30	NA	NA	None	NA		Non-Retention	
Humbug Mt. - OR/CA Border[g]	*4/1-5/31*	161	1,177	NA	NA		Non-Retention	
	6/1-6/26	100	1,528	1,800	85%		Non-Retention	
	7/1-7/31	88	769	1,184	65%		Non-Retention	
	8/6-8/27	23	50	772	6%		Non-Retention	
OR/CA Border - Humboldt S. Jetty	*9/11-9/30*	NA	NA	3,000			Non-Retention	
Humboldt S. Jetty - Horse Mt.				Closed				
Horse Mt. - Pt. Arena	*5/1-5/31, 6/15-6/30, 7/12-8/26*	3,577	59,515	None	NA		Non-Retention	
	9/1-30	NA	NA	None	NA		Non-Retention	
Pt. Arena - Pigeon Pt.	*5/1-31,6/7-30, 7/8-8/29*	2,281	20,775	None	NA		Non-Retention	
	9/1-30	NA	NA	None	NA		Non-Retention	
Pt. Reyes-Pt. San Pedro	*10/1-2, 5-9 &12-15*	NA	NA	None	NA		Non-Retention	
Pigeon Pt. - Pt. Sur	*5/1-31,6/7-30, 7/8-8/15*	2,289	12,176	None	NA		Non-Retention	
Pt. Sur - U.S./Mexico Border	*5/1-31,6/7-30, 7/8-31*	866	4,412	None	NA		Non-Retention	
			RECREATIONAL					
U.S./Canada Border - Queets River[h]	*5/15-16, 22-23, 5/30-6/12*	751	215	10,000	12%		Non-Retention	
Queets River - Leadbetter Poin[h]	*5/30-6/12*	2,080	745				Non-Retention	
Leadbetter Point - Cape Falcon[h]	*5/30-6/12*	499	242				Non-Retention	
U.S./Canada Border - Cape Alava	*6/13-9/3*	13,255	8,199	8,400	98%	3,665	14,850	25%
	9/4-9/30						4,100	0%
Cape Alava-Queets River	*6/13-9/3*	2,685	2,113	2,600	81%	388	3,610	11%
	9/4-9/30						625	0%
	10/1-10/12			100	0%		100	0%
Queets River - Leadbetter Pt.	*6/13-9/3*	36,583	15,946	27,900	57%	22,793	52,840	43%
	9/4-9/30						13,000	0%
Leadbetter Pt.-Cape Falcon	*6/14-9/3*	32,970	8,881	15,000	59%	38,300	79,400	48%
	9/4-9/30						15,300	0%
Cape Falcon - Humbug Mt.	*3/15-10/31*	29,466	1,227	None	NA	Non-Retention except for periods listed		
Cape Falcon to OR/CA Border	*6/27-8/9*	Included Above or Below		NA	NA	14,925	55,000	27%
Cape Falcon to Humbug Mt.	*9/4-9/30*[i]	Included Above		NA	NA	NA	20,700	NA
Humbug Mt. - OR/CA Border (OR-KMZ)	*5/1-9/7*	2,795	321	None	NA	Included Above		
OR/CA Border - Horse Mt. (CA-KMZ)	*5/1-9/7*	8,711	3,640	None	NA		Non-Retention	
Horse Mt. - Pt. Arena (Ft. Bragg)	*4/4-11/8*	11,181	5,023	None	NA		Non-Retention	
Pt. Arena - Pigeon Pt. (San Francisco)	*4/4-10/31*	28,061	12,972	None	NA		Non-Retention	
Pigeon Pt. - P. Sur (Monterey N.)	*4/4-9/7*	12,648	2,547	None	NA		Non-Retention	
Pt. Sur - U.S./Mexico Border (Monterey S.)	*4/4-7/19*	1,996	359	None	NA		Non-Retention	

TOTALS TO DATE (through Aug. 31)	Effort 2015	Effort 2014	Effort 2013	Chinook Catch 2015	Chinook Catch 2014	Chinook Catch 2013	Coho Catch 2015	Coho Catch 2014	Coho Catch 2013
TROLL									
Treaty Indian	**1,047**	1,342	1,232	**57,860**	62,217	49,518	**2,961**	49,625	43,553
Washington Non-Indian	**2,468**	1,887	2,218	**53,564**	37,993	39,361	**1,874**	10,313	5,764
Oregon	**7,757**	9,491	6,473	**96,890**	195,852	74,407	**1,050**	3,997	309
California	**9,013**	11,807	15,401	**96,878**	151,367	285,592	**0**	0	0
Total Troll	**20,285**	24,527	25,324	**305,192**	447,429	448,878	**5,885**	63,935	49,626
RECREATIONAL									
Washington	**82,288**	101,428	70,938	**34,597**	38,290	26,810	**57,820**	96,034	39,387
Oregon	**38,796**	89,147	65,431	**3,292**	15,194	26,865	**22,251**	70,189	11,680
California	**62,597**	103,319	138,490	**24,541**	64,936	112,022	**38**	476	361
Total Recreational	**183,681**	293,894	274,859	**62,430**	118,420	165,697	**80,109**	166,699	51,428
PFMC Total	**203,966**	318,421	300,183	**367,622**	565,849	614,575	**85,994**	230,634	101,054

a/ Inseason estimates are preliminary.

b/ Non-Indian coho fisheries prior to Sept. are mark-selective and non-mark-selective recreational fisheries occur in Sept., (except SOF rec.) see the regulations for details.

c/ Effort is reported as landings. Chinook summer quota of 30,000 decreased by subtracting spring quota overage on an impact neutral basis by 916 fish.

d/ Numbers shown as Chinook quotas for non-Indian troll and rec. fisheries North of Falcon are guidelines not quotas; only the total Chinook allowable catch is a quota.

e/ September quotas to be adjusted due to iimpact neutral trades and rollovers.

f/ Remaining mark-selective coho quota to be converted to non-mark-selective quota on an impact neutral basis.

g/ July and August quotas adjusted from preseason due to impact neutral rollover of

h/ Mark-selective fishery for Chinook

i/ 12,500 preseason quota plus an impact equivalent roll-over from the Cape Falcon to OR/CA border mark-selective recreational coho fishery.

EXHIBIT
3

AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2015GL064924

Key Points:
- Warming since 1901 caused a significant trend toward drought in California
- Recent drought was naturally driven and modestly intensified by warming
- Warming has rapidly amplified the probability of severe drought

Supporting Information:
- Text S1, Table S1, and Figures S1–S7

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Citation:
Williams, A. P., R. Seager, J. T. Abatzoglou, B. I. Cook, J. E. Smerdon, and E. R. Cook (2015), Contribution of anthropogenic warming to California drought during 2012–2014, *Geophys. Res. Lett.*, *42*, 6819–6828, doi:10.1002/2015GL064924.

Received 11 JUN 2015
Accepted 1 AUG 2015
Accepted article online 20 AUG 2015
Published online 31 AUG 2015

Contribution of anthropogenic warming to California drought during 2012–2014

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Abstract A suite of climate data sets and multiple representations of atmospheric moisture demand are used to calculate many estimates of the self-calibrated Palmer Drought Severity Index, a proxy for near-surface soil moisture, across California from 1901 to 2014 at high spatial resolution. Based on the ensemble of calculations, California drought conditions were record breaking in 2014, but probably not record breaking in 2012–2014, contrary to prior findings. Regionally, the 2012–2014 drought was record breaking in the agriculturally important southern Central Valley and highly populated coastal areas. Contributions of individual climate variables to recent drought are also examined, including the temperature component associated with anthropogenic warming. Precipitation is the primary driver of drought variability but anthropogenic warming is estimated to have accounted for 8–27% of the observed drought anomaly in 2012–2014 and 5–18% in 2014. Although natural variability dominates, anthropogenic warming has substantially increased the overall likelihood of extreme California droughts.

1. Introduction

During 2012–2014, drought in California (CA) caused water use restrictions, rapid drawdown of groundwater reserves [*Famiglietti*, 2014; *Harter and Dahlke*, 2014], fallowed agricultural fields [*Howitt et al.*, 2014], and ecological disturbances such as large wildfires and tree mortality [e.g., *Moore and Heath*, 2015; *Worland*, 2015]. The ultimate cause of the recent drought was a persistent ridge of high atmospheric pressure over the Northeast Pacific that blocked cold-season storms from reaching CA and stifled precipitation totals [e.g., *Seager et al.*, 2015]. Tree ring reconstructions from CA indicate that the resultant 3 year precipitation shortfall of 2012–2014 has been matched less than once per century over the past several hundred years [*Griffin and Anchukaitis*, 2014; *Diaz and Wahl*, 2015]. Dynamical studies agree that the Northeast Pacific ridge that caused the precipitation shortfall was part of an atmospheric wave train originating from the western tropical Pacific due to warm sea surface temperatures (SSTs) in that region [*Funk et al.*, 2014; *Seager et al.*, 2014a, 2015; *Wang and Schubert*, 2014; *Wang et al.*, 2014; *Hartmann*, 2015]. The observed ridging anomaly was stronger than the modeled response to tropical SST forcing [e.g., *Wang and Schubert*, 2014; *Seager et al.*, 2015], however, and leaves room for contributions from internal atmospheric variability or anthropogenic climate change. Although it has been suggested that anthropogenic emissions enhance the probability of *extreme* Northeast Pacific ridging events without necessarily affecting the long-term mean state [*Swain et al.*, 2014; *Wang et al.*, 2014, 2015], model projections of increased extremes in cold-season precipitation totals do not emerge as relevant until the second half of this century [*Berg and Hall*, 2015]. Furthermore, observed CA precipitation totals indicate no long-term trend despite cooccurring increases in western tropical Pacific SSTs [*Seager et al.*, 2015], climate models do not produce negative CA precipitation trends when forced by observed SST trends [*Funk et al.*, 2014], and future anthropogenic climate change is projected to result in slight *positive* trends in CA precipitation totals [*Neelin et al.*, 2013; *Seager et al.*, 2014b, 2015; *Simpson et al.*, 2015], all arguing against the likelihood of an anthropogenic role in the recent CA precipitation shortfall.

Importantly, there is widespread consensus that warmth has intensified the effects of the recent precipitation shortfall by enhancing potential evapotranspiration (PET) [*AghaKouchak et al.*, 2014; *Griffin and Anchukaitis*, 2014; *Diffenbaugh et al.*, 2015; *Mann and Gleick*, 2015; *Shukla et al.*, 2015]. Because warming is a well-understood and robustly modeled response to anthropogenic emissions of greenhouse gases, it is expected that warming-induced drying will continue for centuries to come [e.g., *Cook et al.*, 2015; *Diffenbaugh et al.*, 2015]. However, the degree to which anthropogenic warming and resultant increases in PET were responsible for the recent drought severity in CA is unknown.

Griffin and Anchukaitis [2014] used the Palmer Drought Severity Index (PDSI), a proxy for near-surface soil moisture [*Palmer*, 1965], to investigate the role of temperature in the recent drought, but they did not separate the influence of anthropogenic warming from natural temperature variability and their employed version of PDSI (from the National Oceanic and Atmospheric Administration (NOAA)) uses a simplified formulation of PET. *Mao et al*. [2015] attempted to isolate the anthropogenic component of warming using a more physically based PET calculation but focused only on the Sierra Nevada Mountain region and spring snowpack, and simply characterized anthropogenic warming as the observed linear trend in daily minimum temperatures. Other studies investigate the effect of warming on the likelihood of severe drought events in CA [e.g., *AghaKouchak et al*., 2014; *Diffenbaugh et al*., 2015; *Shukla et al*., 2015] but do not directly address the anthropogenic contribution to recent drought severity. Each study noted above considers only a single climate data product without addressing the structural uncertainty across different data products.

Here we quantify the severity of recent CA drought using an ensemble of data products and multiple PDSI formulations, determine the relative roles of individual components of the water balance, and determine the proportion of recent drought severity that can be attributed to increases in PET due to anthropogenic warming.

2. Methods

2.1. Palmer Drought Severity Index

We calculate monthly PDSI to characterize temporal and spatial variations in CA drought from 1901 to 2014: most humidity, wind speed, and insolation data sets do not extend prior to 1901. The PDSI is based on a simple two-layer soil moisture model and is locally normalized to reflect moisture anomalies relative to long-term mean conditions. PDSI is a primary tool used for drought monitoring in the United States [*Heim*, 2002; *Svoboda et al*., 2002] and generally agrees well with modeled and observed soil moisture anomalies [*Dai et al*., 2004; *Cook et al*., 2015; *Smerdon et al*., 2015; *Zhao and Dai*, 2015] and tree ring records [*Cook et al*., 2007]. While some recent studies have taken more complex modeling approaches to investigate the recent CA drought [*Mao et al*., 2015; *Shukla et al*., 2015], we use the PDSI because it allows efficient calculations of centennial-length records at high spatial resolution, which can be computed many hundreds of times with different climate variables, input data sets, and methodological schemes. The PDSI only reflects drought variability from a climatological perspective. Our results therefore do not explicitly reflect human water demand, stream flow and reservoir storage, or accessibility of groundwater. The PDSI also considers all precipitation to occur as rain, neglecting snow storage and subsequently delayed inputs to soil moisture and runoff. To assess implications of this latter simplification, PDSI is compared to modeled soil moisture by *Mao et al*. [2015] for the snow-dominated Sierra Nevada mountains.

Other studies also have used the PDSI to examine recent CA drought [*Griffin and Anchukaitis*, 2014; *Diffenbaugh et al*., 2015; *Robeson*, 2015]. A key difference between these studies, which use data developed by NOAA, and our study is the formulation of PET. The NOAA calculations involve the simplified Thornthwaite formula [*Thornthwaite*, 1948] that considers monthly mean temperature to be the only climatological driver of PET variability. This approach can overemphasize the influence of warmth when temperatures are high, and further inaccuracies are introduced by ignoring the nontemperature components of PET [e.g., *Hobbins et al*., 2008; *Hoerling et al*., 2012; *Sheffield et al*., 2012]. The more physically based Penman-Monteith (PM) formula [*Penman*, 1948; *Monteith*, 1965] considers the suite of variables affecting PET: mean daily maximum temperature ($T_{\max}$), mean daily minimum temperature ($T_{\min}$), humidity, wind speed, and net radiation. We use the PM formula and repeat calculations using Thornthwaite in some cases for comparison. Additionally, we use the newer self-calibrated PDSI (PDSI$_{sc}$), developed to make drought severity comparable among locations [*Wells et al*., 2004].

Consistent with several prior studies [e.g., *Cook et al*., 2004, 2007, 2010; *Griffin and Anchukaitis*, 2014], we focus on June–August (JJA). PDSI$_{sc}$ is an integration of hydroclimate over multiple months to several years [*Guttman*, 1998] and summer is the ideal season for characterizing drought intensity in CA for two reasons: (1) it is when drought effects tend to be most critical; and (2) it is when PDSI$_{sc}$ is most accurate in mountain regions because snowpack has melted or is at a minimum [e.g., *Dai et al*., 2004]. To facilitate interpretation, each grid cell's annual record of JJA PDSI$_{sc}$ is normalized so that two PDSI$_{sc}$ units equal a 1 standard deviation departure from the 1931–1990 mean, retaining a similar variance in the records of JJA PDSI$_{sc}$ as is in the monthly records. Again for interpretability, we renormalize statewide mean JJA $\mathrm{PDSI_{sc}}$ records. We use a 1931–1990 calibration interval in all $\mathrm{PDSI_{sc}}$ calculations to be consistent with NOAA methodology.

2.2. Climate Data

We calculate $\mathrm{PDSI_{sc}}$ records for all 432 combinations of four precipitation, four temperature, three vapor pressure, three wind speed, and three insolation data sets. Data sets are listed with references in Table S1 in the supporting information and described in Text S1. We bilinearly interpolate each monthly climate field for each data set to the spatial resolution of the PRISM data set (0.04167°) [*Daly et al.*, 2004]. For each climate variable, data sets were calibrated so that climatological means and variances match during 1961–2010 (see Text S1). Uncertainties are high for humidity, wind speed, and insolation because they are largely based on models or observations of other variables [e.g., *Dai*, 2011]. Although consideration of multiple data products helps to characterize some of this uncertainty, data products are not all produced independently. Errors therefore may be recurrent in multiple data products (see Text S1).

2.3. Decomposition of PET and $\mathrm{PDSI_{sc}}$

We calculate the influence of a given variable, or subset of variables, on PET as the PET anomaly calculated while holding all other variables at their mean annual cycles [e.g., *Cook et al.*, 2014; *Scheff and Frierson*, 2014; *Zhao and Dai*, 2015]. Mean annual cycles were always defined over 1961–2010. For $\mathrm{PDSI_{sc}}$, the contribution of precipitation was defined as $\mathrm{PDSI_{sc\_P}}$, calculated by holding PET at its mean annual cycle and only allowing precipitation to vary. The contribution of PET was calculated as the difference between $\mathrm{PDSI_{sc\_P}}$ and a recalculation of $\mathrm{PDSI_{sc}}$ in which both precipitation and PET vary. We isolated the influences of the temperature and nontemperature components of PET by applying versions of PET in which only the component of interest varies. Contributions of subcomponents of PET and $\mathrm{PDSI_{sc}}$ anomalies were nearly perfectly additive, but all relative anomalies were rescaled to sum to exactly 100% of the total anomaly.

2.4. Effect of Anthropogenic Warming

Anthropogenic warming was isolated from that of natural temperature variability by considering four warming scenarios that are described in detail in the next two paragraphs. For each scenario, natural temperature variability is calculated as the observed temperature minus the anthropogenic trend. All records of anthropogenic warming and natural variability were calculated independently for T_{max} and T_{min}, each grid cell, and each month. For each warming scenario, we recalculated PET twice: once considering only the anthropogenic warming record and once considering the residual record of natural temperature variability. Methods were repeated from above to assess $\mathrm{PDSI_{sc}}$ anomalies caused by anthropogenic warming and natural temperature variability.

The four anthropogenic warming scenarios are defined as follows: (1) linear trend, (2) 50 year low-pass filter (using a 10-point butterworth filter), (3) unadjusted mean trend from an ensemble of climate models, and (4) an adjusted version of #3. The first two warming scenarios represent empirical fits to the observed temperature records during 1895–2014. Although a linear trend is commonly used to represent the anthropogenic effect, a linear fit to a centennial temperature record may underestimate the human effect on temperature in recent decades because radiative forcing during this period has increased relatively rapidly [e.g., *Myhre et al.*, 2013]. The 50 year low-pass filter partially addresses this issue, but multidecadal natural temperature variability inhibits complete isolation of the anthropogenic effect with either the linear trend or the 50 year filter. Additionally, trends toward the end of the 50 year filter record are affected by boundary constraint assumptions. Although continued warming is likely, we pad the end of the temperature record with a repetition of the last 25 years in reverse order, likely leading to an underestimation of anthropogenic warming in the most recent years.

In the third and fourth warming scenarios, we use modeled records of T_{min} and T_{max} produced for the Coupled Model Intercomparison Project Phase 5 (CMIP5) [*Taylor et al.*, 2012] to represent anthropogenic warming trends for each month. Thirty-six models in the CMIP5 archive are used, based on the availability of T_{max} and T_{min} data for the historical (1850–2005) and future (2006–2099, RCP 8.5 [*van Vuuren et al.*, 2011]) simulations. For each model, T_{min} and T_{max} are each averaged across all available runs for the historical and future periods, bilinearly interpolated to the geographic resolution of PRISM, and bias corrected for each grid cell so that monthly means during 1961–2010 matched observational means. We calculate 50 year low-pass filtered time series for each month during 1850–2099 and average across the 36 models. The resultant ensemble mean records for 1895–2014 represent the CMIP5 records of anthropogenic warming used in the

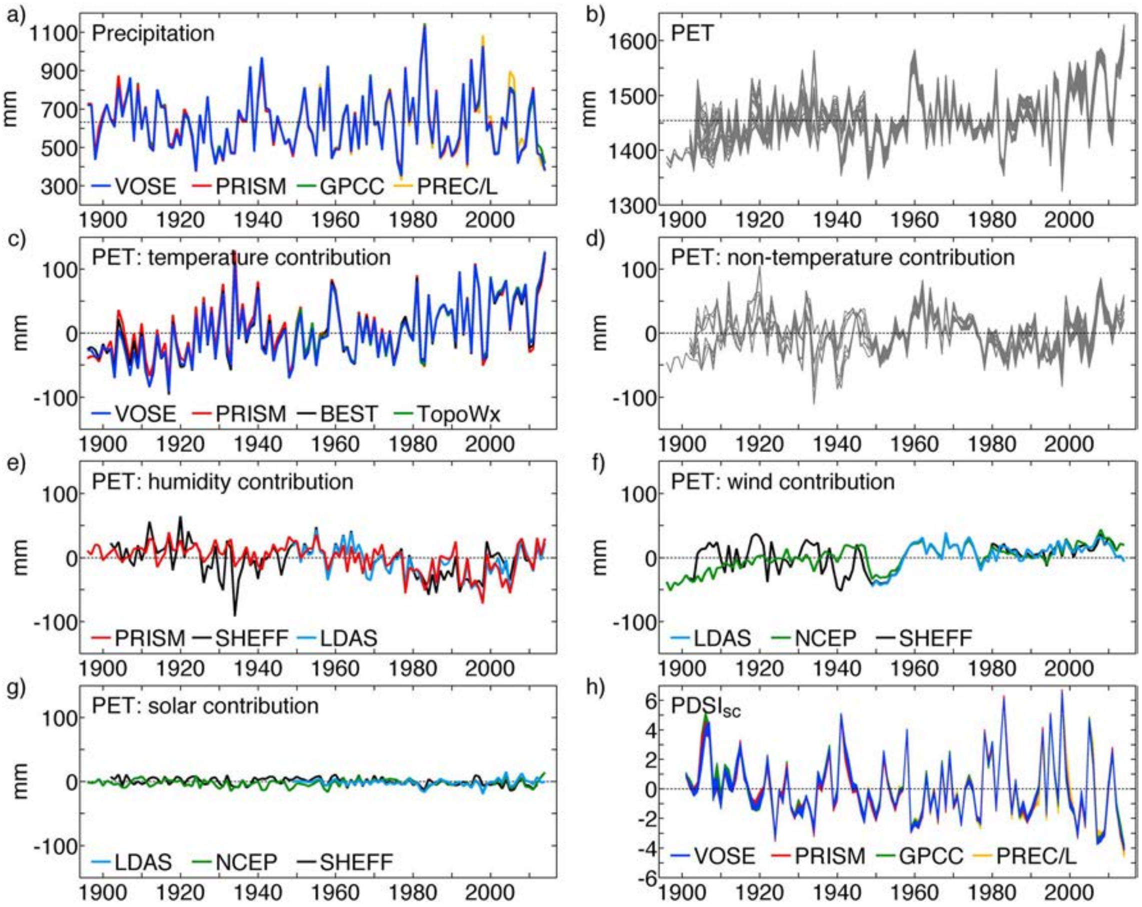

Figure 1. Contributors to interannual (water year) drought variability in CA, calculated from multiple data sets. (a) Precipitation. (b) PET totals, calculated using the PM equation for all combinations of four temperature, three humidity, three wind velocity, and three insolation data sets. (c) Temperature contribution to PET anomalies. Contributions of (d) all nontemperature variables, (e) humidity, (f) wind velocity, and (g) insolation to PET anomalies. (h) JJA PDSI$_{SC}$ calculated with all 432 combinations of the climate-variable data sets. Horizontal black lines: 1931–1990 means. Colors distinguish data products.

third warming scenario. For the fourth scenario, we linearly adjust these records to best fit the observations from 1895 to 2014. This approach reduces biases in the modeled trends but carries the implicit assumption that observed temperature trends are entirely anthropogenic in origin, which is a questionable assumption. For example, *Johnstone and Mantua* [2014a] indicate that some of the observed warming trend may be due to warming in the Northeast Pacific that is not linked to anthropogenic climate change, but also see *Abatzoglou et al.* [2014] and *Johnstone and Mantua* [2014b].

3. Results and Discussion

3.1. Recent Drought Conditions

Figure 1a shows annual water year (WY: October–September) CA precipitation totals for 1896–2014 and demonstrates general agreement among the four gridded data sets. The WY 2014 precipitation total was the third lowest (fourth lowest for Global Precipitation Climatology Centre (GPCC) [*Schneider et al.*, 2014]) on record (behind WYs 1977 and 1924) and WY 2012–2014 precipitation was the lowest (third lowest for GPCC) 3 year running average on record (Figure S1a). The effects of the recent precipitation deficit have been amplified by positive PET anomalies. Figure 1b shows the 108 records of WY PET, calculated from all combinations of temperature, humidity, wind, and insolation data sets. Among the PET records, 32 include data for 2014. WY 2014 PET was 9–12% above average and the highest on record in every case. PET for WY 2012–2014 was 7–9% above average and either the highest or second highest (behind WY 2007–2009) on record (Figure S1b).

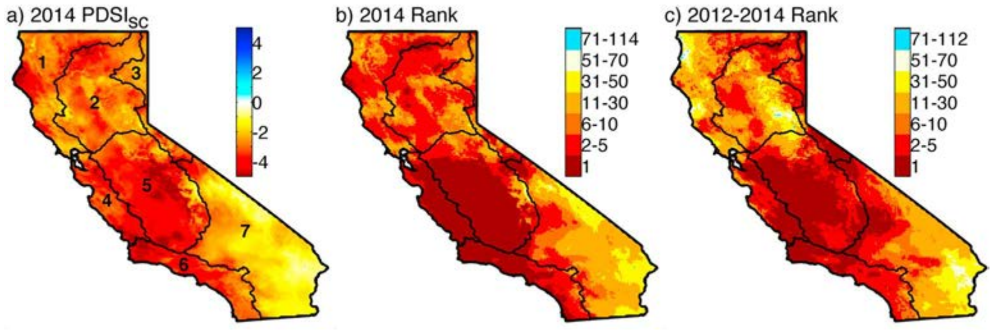

Figure 2. Maps of (a) JJA PDSI$_{sc}$ and ranking for (b) 2014 and (c) 2012–2014. Rankings are based on all years between 1901 and 2014, and a ranking of 1 indicates record-breaking drought. PDSI$_{sc}$ in this figure is based on VOSE precipitation and temperature, PRISM humidity, and LDAS [*Mitchell et al.*, 2004; *Rodell et al.*, 2004] wind speed and insolation. Polygons bound the seven NOAA climate divisions (division numbers shown in Figure 2a).

All PET data sets indicate positive and significant trends during WY 1949–2014, ranging from 8.2 to 13.7 mm/decade when considering linear trends. These trends are almost entirely due to warming. Since WY 1949, warming positively forced PET by 10–12 mm/decade (65–82 mm total), equivalent to 10–13% of the mean WY precipitation (Figure 1c). The VOSE [*Vose et al.*, 2014], BEST [*Rohde et al.*, 2013], and TopoWx (which only goes back to 1948 [*Oyler et al.*, 2015]) data sets indicate that the temperature contribution to PET was highest on record in 2014 while PRISM indicates that the temperature contribution was higher in 1934. All four data sets agree that the temperature contribution to PET during WY 2012–2014 was substantially higher than that of any other 3 year period on record (Figure S1c).

Nontemperature variables account for approximately one third of WY PET variability (Figure 1d), although much uncertainty exists among the nontemperature data sets. Nearly all interannual variability and inter–data set spread in nontemperature PET (Figure 1d) are due to contributions from vapor pressure and wind speed (Figures 1e–1g). According to the data sets considered, positive wind speed trends contributed positively to PET (4.5 to 4.8 mm/dec), positive humidity trends contributed negatively (−3.5 to −4.0 mm/dec), and insolation had a minimal influence due to very low interannual variability in warm-season insolation relative to the mean. Prior to 1948, trends in the nontemperature components of PET are much less certain due to a nearly complete lack of pre-1948 observational data [e.g., *Dai*, 2011].

Within CA, PET trends were spatially heterogeneous, with much of the Central Valley experiencing reduced PET during the second half of the twentieth century due to suppressed daytime warming and increased humidity, consistent with the effects of increased irrigation [*Lobell and Bonfils*, 2008]. These results are broadly consistent with observed decreases in warm-season pan evaporation at sites in the Central Valley during 1951–2002 [*Hobbins et al.*, 2004]. These agricultural trends appear distinct from the well-known global declines in pan evaporation that appear to have been caused by pollution-induced solar dimming during the 1950s–1980s and reductions in wind speed [*Roderick et al.*, 2009]. While long-term records of insolation and wind speed are sparse in CA, those that exist indicate insignificant wind trends of inconsistent sign [*Pryor et al.*, 2009; *Pryor and Ledolter*, 2010] and twentieth century insolation decreases that were too small to substantially affect statewide mean PET, similar to prior findings in Australia [*Roderick et al.*, 2007].

Figure 1h shows all 432 records of JJA PDSI$_{sc}$ for 1901–2014 (128 records extend through 2014). Colors in Figure 1h indicate the precipitation product; spread among colors reflects disagreement among precipitation products and spread within colors reflects disagreement among PET products. All records indicate that 2014 JJA PDSI$_{sc}$ was the lowest on record (−4.64 to −3.67), with 25–37% of CA experiencing record-breaking drought locally. The year 2014 had the highest proportion of record-breaking drought area on record for all data sets, with the most severe anomalies centered in the southern Central Valley and the central and southern CA coasts (Figures 2a and 2b).

Considering 3 year running average PDSI$_{sc}$, 2012–2014 JJA drought intensity was found to be similar to, but generally not as severe as, that of 2007–2009 when averaged across CA, regardless of data sets used (Figure S1h). The similarity of mean PDSI$_{sc}$ during these two periods is interesting given that WY 2012–2014 had the lowest precipitation total on record and PET levels were comparable during each period. The difference

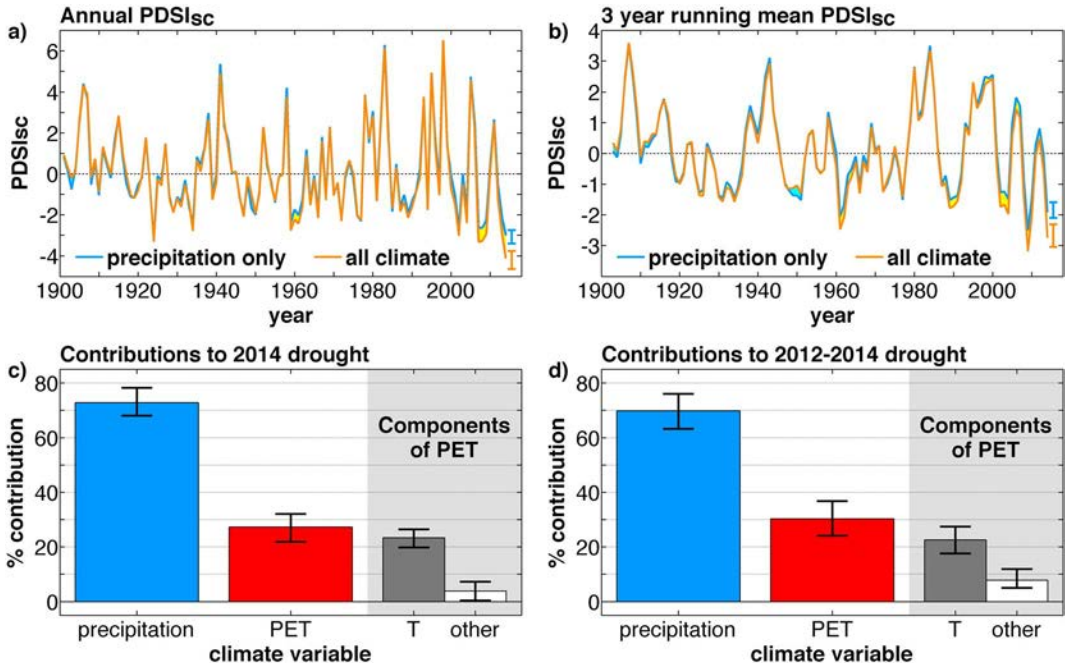

Figure 3. Contributions of precipitation and PET to drought variability. (a) Annual and (b) 3 year running mean JJA $\mathrm{PDSI_{sc}}$ records calculated when (blue) only precipitation is allowed to vary from the climatological mean and (orange) when both precipitation and PET vary. Thus, departures of the blue line from zero are due to precipitation variability and departures of the orange line from the blue line are due to PET variability. Shading between lines in Figures 3a and 3b indicate periods when (cyan) low PET reduces drought and (yellow) high PET intensifies drought. Percent contributions of precipitation and PET to the (c) 2014 and (d) 2012–2014 $\mathrm{PDSI_{sc}}$ anomalies. The bars in the shaded area of Figures 3c and 3d break the contribution of PET into contributions from temperature (*T*) and nontemperature (other: humidity, wind, and solar). Time series and bars represent mean conditions across all combinations of climate data products and whiskers bound all values from all combinations of data products.

was in the timing of precipitation. Unlike the 2012–2014 drought, which intensified over time, the 2007–2009 drought was most intense at the onset and the moisture deficit established in 2007 partially propagated into 2008 and 2009. Additionally, spring months for WY 2012-2014 were generally wetter than WY 2007–2009, contributing to soil moisture at a critical time immediately prior to summer (Figure S2).

The finding that the 2012–2014 $\mathrm{PDSI_{sc}}$ was not as severe as that of 2007–2009 conflicts with prior findings based on NOAA PDSI (which is based on VOSE precipitation and temperature) that 2012–2014 was the most severe 3 year drought on record in CA [*Griffin and Anchukaitis*, 2014; *Robeson*, 2015]. This is attributable to the NOAA calculation of PDSI, which amplifies the effect of extreme heat anomalies in 2014 via the Thornthwaite PET equation (Figures S3 and S4). Importantly, while our calculations indicate that 2012–2014 was probably not a record-breaking drought event when averaged across CA, 2012–2014 drought severity *was* record breaking in much of the agriculturally important Central Valley (Figure 2c). In contrast, drought in 2007–2009 was most severe in the sparsely populated and already dry desert region of southeastern CA.

$\mathrm{PDSI_{sc}}$ does not account for snowpack effects, which are important for human water supply, and our calculations of statewide $\mathrm{PDSI_{sc}}$ may therefore not always accurately reflect drought from the perspective of human water supply, which is disproportionately linked to the Sierra Nevada Mountains. For that region, *Mao et al.* [2015] used the Variable Infiltration Capacity (VIC) hydrologic model [*Liang et al.*, 1994] to simulate hydrological dynamics during 1920–2014. Using the *Mao et al.* [2015] meteorological forcing to calculate $\mathrm{PDSI_{sc}}$ for the Sierra Nevada Mountains, we find strong agreement ($r = 0.93$) with VIC JJA soil moisture (Figure S5). VIC soil moisture nevertheless indicates slightly more severe drought than $\mathrm{PDSI_{sc}}$ during the most extreme drought years, likely due to early disappearance of snowpack [e.g., *Mote*, 2006; *Mankin and Diffenbaugh*, 2015] and subsequently reduced spring and summer melt-driven soil moisture inputs (Figure S6). Given that the calculation of $\mathrm{PDSI_{sc}}$ neglects snowpack and therefore cannot capture the effect of early snowmelt on summer soil moisture, the warming effect on summer $\mathrm{PDSI_{sc}}$ presented in the next section is likely conservative for snow-dominated areas.

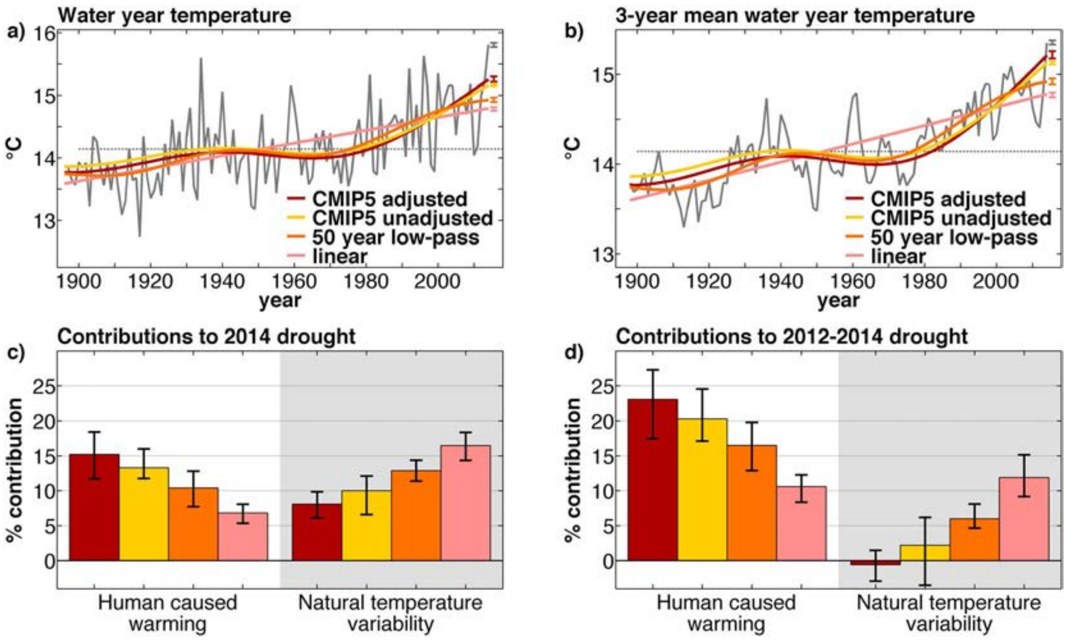

Figure 4. Contributions of anthropogenic warming and natural temperature variability to recent temperature and drought. (a) Annual and (b) 3 year running water year temperature records with four alternate scenarios of anthropogenic warming. Contributions of anthropogenic warming versus natural temperature variability to (c) 2014 and (d) 2012–2014 JJA $PDSI_{sc}$ anomalies, where bar colors correspond to the colors of the four anthropogenic warming trends in Figures 4a and 4b. For each of the anthropogenic warming scenarios, natural temperature variability is calculated as the observed temperature minus the warming trend. All time series and bars represent mean conditions across all combinations of climate products. Whiskers bound all values for all combinations of data products.

3.2. Effect of Warming on Recent Drought

Figures 3a and 3b compare $PDSI_{sc}$ (orange) to an alternate calculation in which only precipitation varies and PET is held at its mean annual cycle (blue). While there is no long-term trend in precipitation-driven $PDSI_{sc}$ since 1948 or 1901, trends in actual $PDSI_{sc}$ are significant and negative ($p < 0.05$ according to Spearman's Rho and Kendall's Tau) due to increasing PET. During 2014 and 2012–2014, PET anomalies accounted for 22–32% and 24–37% of the JJA $PDSI_{sc}$ anomalies, respectively (Figures 3c and 3d). Recalculating $PDSI_{sc}$ considering the temperature and nontemperature components of PET separately, we find that the intensifying effect of high PET on recent drought was nearly entirely caused by warmth (Figures 3c and 3d). High temperatures accounted for 20–26% and 18–27% of the JJA $PDSI_{sc}$ anomalies in 2014 and 2012–2014, respectively (Figures 3c and 3d).

The contribution of temperature is further separated into contributions from natural temperature variability and anthropogenic warming in Figure 4. Figures 4a and 4b show the WY temperature record and the four anthropogenic warming scenarios, which indicate an anthropogenic warming contribution in WY 2014 of 0.61–1.27°C relative to the 1931–1990 mean. The empirically derived trends suggest a weaker anthropogenic warming contribution in recent years than the CMIP5 trends because (1) the linear trend does not account for the nonlinear increase in anthropogenic forcing and (2) the 50 year low-pass filter trend indicates slowed warming in the past two decades that is partly due to our conservative smoothing approach and partly due to decadal climate variability. The CMIP5 trends represent the nonlinear increase in radiative forcing without being affected by decadal climate variability or smoothing artifacts. The similarity between the adjusted and unadjusted CMIP5 warming trends suggest that the CMIP5 provides a reasonable representation of the anthropogenic warming influence in CA despite having stronger warming trends than the conservatively designed empirical trends.

Breaking the temperature contributions to $PDSI_{sc}$ into anthropogenic and natural components, the four anthropogenic warming trends account for 5–18% of the JJA $PDSI_{sc}$ anomaly in 2014 and 8–27% of the anomaly in 2012–2014 (Figures 4c and 4d). Despite differences in these relative contributions of warming to drought during 2014 versus 2012–2014, the *absolute* contributions of anthropogenic warming to drought during these two periods were virtually identical. The absolute anthropogenic contribution does not change much interannually but instead acts as a gradually moving drought baseline upon which the effects of natural climate variability are superimposed (Figure S7a).

As of 2014, the anthropogenic warming forcing accounted for approximately -0.3 to -0.7 standardized PDSI_{sc} units, depending on the anthropogenic warming scenario and combination of climate data sets considered (Figure S7a). To illustrate how this trend in background drought conditions affected the probability of severe drought as of 2014, we compare the probability distribution of 1901–2014 PDSI_{sc} values calculated in the absence of anthropogenic warming to the same distributions shifted negative by 0.46, the 2014 PDSI_{sc} forcing by the 50 year low-pass filter warming trend (Figure S7b, based on VOSE temperature and precipitation data). Comparing the two distributions, we find that severe summer droughts with $\mathrm{PDSI}_{sc} \leq -3$ were approximately twice as likely under 2014 anthropogenic warming levels (Figure S7c). Although uncertainty in probabilities of extreme events is large when based on observed records [e.g., *Swain et al*., 2014], and the anthropogenic trend may not result in a perfectly uniform shift in the PDSI_{sc} distribution, this analysis illustrates the general fact that the anthropogenic drying trend, while still small relative to the range of natural climate variability, has caused previously improbable drought extremes to become substantially more likely, consistent with the conclusions of other recent studies [e.g., *AghaKouchak et al*., 2014; *Cook et al*., 2015; *Diffenbaugh et al*., 2015; *Shukla et al*., 2015; *Williams et al*., 2013, 2014, 2015].

Regarding anthropogenic contributions, there are some important caveats. First, anthropogenic climate change has potentially affected more than just temperature in CA [e.g., *Swain et al*., 2014; *Wang et al*., 2014, 2015]. Lack of long-term observational data on wind speed and humidity in CA, and uncertainties in existing data, make it difficult to quantify anthropogenic influences on these variables. For CA precipitation, current models project a weak overall increase [*Neelin et al*., 2013; *Seager et al*., 2014b, 2015; *Simpson et al*., 2015], but no such precipitation trend has emerged. Hence, we only characterize anthropogenic effects on temperature in this study. Second, observed warming trends are affected by processes not related to greenhouse gas emissions such as land use (e.g., agriculture, urbanization) and natural low-frequency climate variability. While climate models provide a definition of anthropogenic warming that should be unbiased by observations, the accuracy of this approach, as in other attribution studies [e.g., *Bindoff et al*., 2013], is confined by the accuracy of climate models. Finally, our analyses do not account for snowpack, making our results a likely underestimation of the contribution of heat anomalies to recent drought in snow-dominated mountain areas and should be interpreted conservatively regarding the effects of warming on water resources for systems strongly affected by the timing of seasonal runoff from mountains.

4. Conclusions

Anthropogenic warming has intensified the recent drought as part of a chronic drying trend that is becoming increasingly detectable and is projected to continue growing throughout the rest of this century [e.g., *Cook et al*., 2015]. As anthropogenic warming continues, natural climate variability will become increasingly unable to compensate for the drying effect of warming. Instead, the soil moisture conditions associated with the current drought will become increasingly common. Impacts of drought on society may be increasingly intensified due to declining availability of groundwater reserves [e.g., *Famiglietti*, 2014]. The Central Valley may be particularly vulnerable to warming-driven drought if reductions in water supply cause reductions in irrigation, as irrigation has slowed warming in this region [*Lobell and Bonfils*, 2008]. The dramatic effects of the current drought in CA, combined with the knowledge that the background warming-driven drought trend will continue to intensify amidst a high degree of natural climate variability, highlight the critical need for a long-term outlook on drought resilience, even if wet conditions soon end the current drought in CA.

Acknowledgments
We thank Y. Mao for sharing VIC meteorological forcing and soil moisture data from *Mao et al.* [2015]. We thank J. Sheffield for making the SHEFF data set available at http://hydrology.princeton.edu. We thank R. Vose for providing the VOSE data set. PRISM data were obtained from the PRISM Climate Group, Oregon State University (http://www.prism.oregonstate.edu, created 4 February 2004). PRISM dew point data were obtained from http://oldprism.nacse.org. TopoWx data were obtained from ftp://mco.cfc.umt.edu/resources/TopoWx-source/. LDAS data were obtained from http://disc.sci.gsfc.nasa.gov/hydrology/data holdings. GPCC data through 2013 come from ftp://ftp.dwd.de/pub/data/gpcc/html/fulldata_v7_-doi_download.html. PREC/L, NCEP2, NCEP/NCAR, NOAA twentieth century reanalysis, and GPCC for 2014 were accessed from http://www.esrl.noaa.gov. A spatially continuous map of soil moisture holding capacities for the United States came from the Web Soil Survey data set (http://websoilsurvey.nrcs.usda.gov). This work was supported by NSF award AGS-1243204 and NOAA award NA14OAR4310232. Lamont–Doherty publication number 7924. Thanks to K.J. Anchukaitis and two anonymous reviewers for comments that improved this manuscript. The climate and PDSI_{sc} data sets compiled for this study are available at http://www.ldeo.columbia.edu/~williams/ca_drought_2015_grl.html.

The Editor thanks two anonymous reviewers for their assistance in evaluating this paper.

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