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WHY FLOW IS A NECESSARY ELEMENT OF DELTA SMELT HABITAT

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Background: For many fish species, research suggests that the major factors influencing recruitment occur during the first year of life. Delta Smelt is a small fish that only lives one year, so it should be expected that factors affecting habitat conditions throughout its short life span will be important to its success or failure. In addition to its short life span, Delta Smelt lives in only one part of one estuary, so it should also be expected that factors affecting habitat conditions throughout its narrow range will be important to its success or failure.

Delta Smelt is likely on the brink of extinction. Like almost all imperiled species, the major threat is, in the broadest sense, loss of habitat. The Critical Habitat Rule for Delta Smelt[1] has both spatial components and water quality components. The spatial component defines all waters of Suisun Bay, Goodyear, Suisun, Cutoff, First Mallard, and Montezuma sloughs in Suisun Marsh, and the contiguous waterways of the Delta. The water quality components focus on salinity, and in particular the 2 parts per thousand salinity isohaline (X2), which was the low-salinity zone habitat indicator that emerged from scientific workshops in the early 1990s (Jassby et al. 1995).

Year to Year Variation in Delta Outflow is Associated with Delta Smelt Population Increase and Decrease: It is of particular relevance to the following summary analysis that some of the historical Delta Smelt abundance indices may be more reliable than others. In addition, the statistical life cycle models published by Maunder and Deriso (2011) and Miller et al. (2012), as well as other recent life cycle modeling efforts (Rose et al. 2013a,b) and the model under development by Dr. Ken Newman and colleagues, have made it abundantly clear that data analyses which do not account for Delta Smelt abundance at a prior life stage when analyzing environmental effects on abundance are very likely misleading and should no longer be considered best available science.

The Interagency Ecological Program has two sampling programs that target Delta Smelt: the 20-mm Survey[2] (since 1995) and the Spring Kodiak Trawl Survey or SKTS[3] (since 2002). Because these surveys were designed to target Delta Smelt, they are considered by the Service to represent best available scientific information on relative abundance trends of Delta Smelt. The Service and many others have also traditionally relied on Delta Smelt abundance indices derived from longer-term juvenile Striped Bass surveys, specifically the Summer Townet Survey or TNS[4] (since 1959) and the Fall Midwater Trawl Survey or FMWT[5] (since 1967). These longer-

[1] https://www.gpo.gov/fdsys/pkg/FR-1994-12-19/html/94-31063.htm
[2] https://www.wildlife.ca.gov/Conservation/Delta/20mm-Survey
[3] https://www.wildlife.ca.gov/Conservation/Delta/Spring-Kodiak-Trawl
[4] https://www.wildlife.ca.gov/Conservation/Delta/Townet-Survey

term abundance index time series have documented the decline of Delta Smelt over time and they have also been used to evaluate environmental influences on Delta Smelt trends and population dynamics (e.g., Stevens and Miller 1983; Moyle et al. 1992; Jassby et al. 1995; Kimmerer 2002a; Bennett 2005; Sommer et al. 2007; Kimmerer et al. 2009; Mac Nally et al. 2010; Thomson et al. 2010; Maunder and Deriso 2011; Miller et al. 2012; Nobriga et al. 2013; La Tour 2016). These citations represent a substantial body of published scientific work conducted over four decades.

The fundamental question explored below and throughout this memo is whether there is support for the hypothesis that Delta outflow has a positive influence on Delta Smelt abundance. We first test this hypothesis statistically, then review the existing literature regarding specific habitat elements and mechanisms that could contribute to our finding that Delta outflow is associated with Delta Smelt population growth and decline. We used a binary variable based on the ratio of the FMWT index to its value the prior year, coded as 1 if the index declined between years and 2 if it increased. This accounted for the influence of prior population size on current population size, but removed the excessive influence of the 1970, 1993, 1995, and 2011 data points; four Wet or Above Normal years with very high single year increases in relative abundance (Figure 1). We tested two versions of the null hypothesis Delta outflow does not affect delta smelt abundance:

(1) FMWT index ratio (termed "Grow" in Appendix A) ~ log(Delta outflow in the birth year) + Month,
(2) FMWT index ratio (termed "Grow" in Appendix A) ~ log(Delta outflow in the birth year) + Month + interaction term of outflow and month

We find that increasing outflows through the San Francisco Bay-Delta increases the likelihood of Delta Smelt, a fish that only lives one year, surviving to propagate the species. The results of both tests provided very strong statistical support for rejection of the null hypothesis. The *P*-value of the flow term was 0.0007 in equation 1 and 0.0002 in equation 2; (Appendix A). Stated another way, the results provide strong support for a role of Delta outflow on the population trend of Delta Smelt when its abundance the year prior has been accounted for. The parameter estimates for the flow term are positive numbers supporting a positive influence of Delta outflow on the year over year growth of the Delta Smelt population. A graphical look at this analysis shows that Delta outflow has often been higher from January through August or September when the Delta Smelt population grew larger than it had been the prior year (Figure 2).

The analysis described above is based on FMWT data, which is likely less reliable than the newer, but shorter-term SKTS. The analysis presented in Appendix B tests for an influence of Delta outflow and several other flow, food, and temperature variables on the production of juvenile Delta Smelt using estimates of Delta Smelt abundance derived from the 20-mm Survey

[5] https://www.wildlife.ca.gov/Conservation/Delta/Fall-Midwater-Trawl

and the Spring Kodiak Trawl Survey. As such, it focuses on conditions occurring during the spring. Our analysis found similar explanatory power for both X2 during April and May, and water temperature during April, both of which had $r^2 > 0.70$ (Table 2 in Appendix B). The relationship with Delta outflow per se had a lower r^2 due to very low recruitment during the 2014-2015 drought years, which resulted in a nonlinear relationship (Figure 1 in Appendix B). We conclude that since 2002, near the change point of an ecosystem regime shift in the upper estuary, in which pelagic fish abundance declined and littoral fish abundance increased (Thomson et al. 2010; Conrad et al. 2016; Mahardja et al. 2016), the production of juvenile Delta Smelt has largely been a function of the size of the adult spawning stock interacting with physical habitat conditions experienced by the egg through early juvenile stages. These mechanisms make biological sense – egg supply is predominantly a function of adult stock size and water temperature (Rose et al. 2013a), and flow variables affect X2, which in turn affects from where in the estuary individual fish are able to successfully produce young (Hobbs et al. 2007; Kimmerer 2008) because X2 indexes the intersection of several important habitat components (Kimmerer 2002b; Bever et al. 2016) and as such has the capacity to influence Delta Smelt mortality rates via numerous individual pathways (per Figure 2 in Miller et al. 2012).

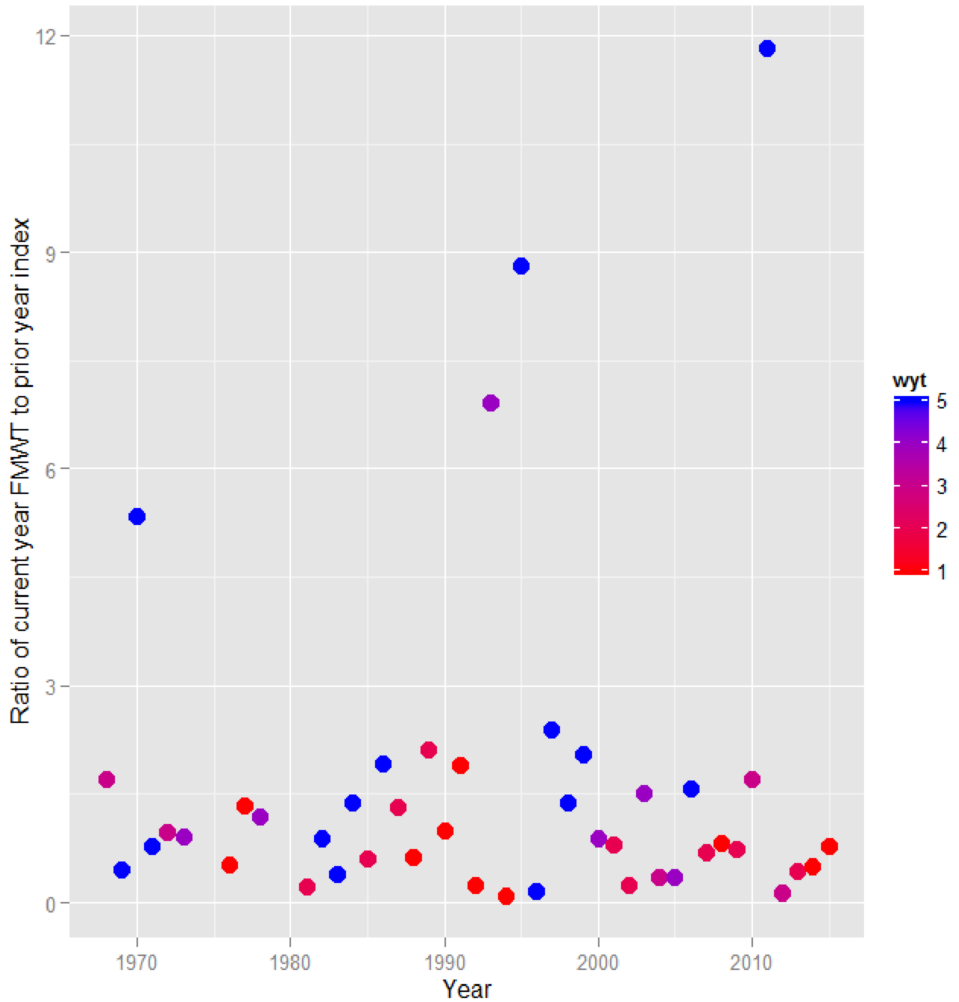

Figure 1. Time series of the Delta Smelt Fall Midwater Trawl indices as a fraction of their prior year value (1968/1967 through 2015/2014). Data points are color-coded by the DWR Water Year Type classification (see lengend).

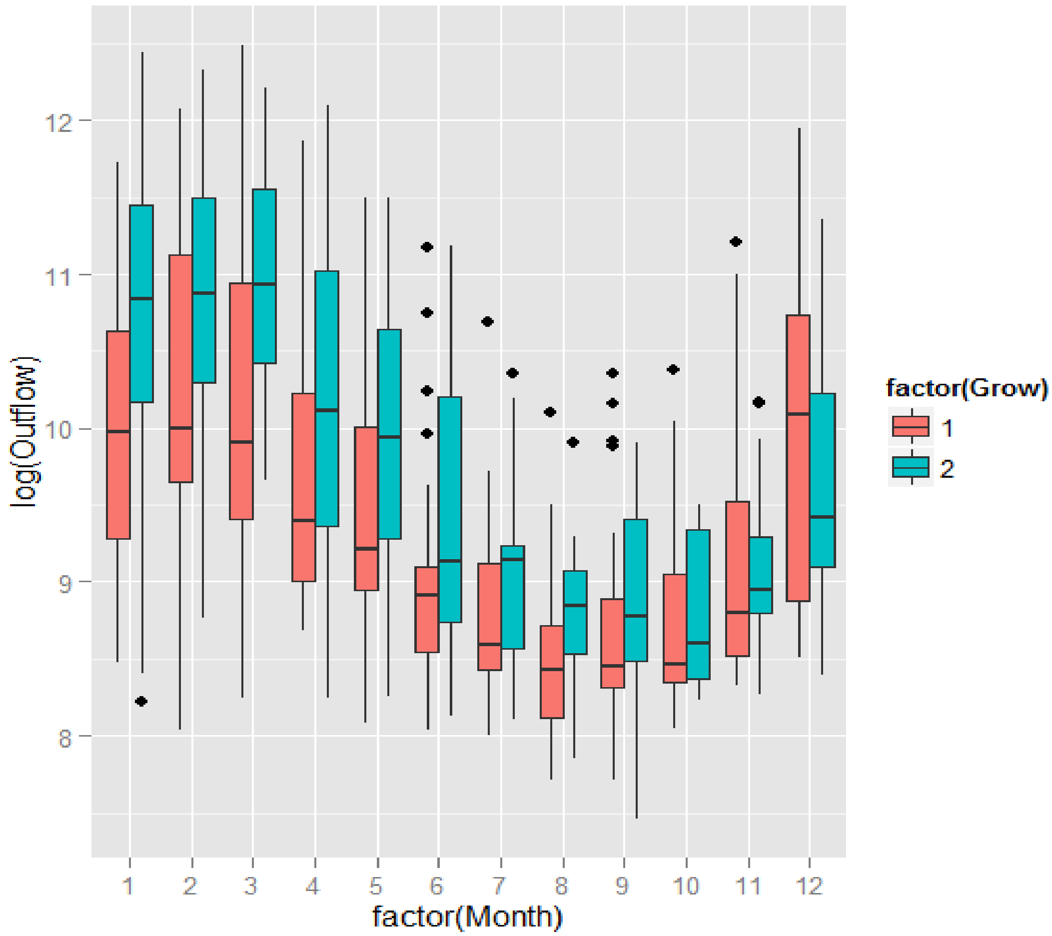

Figure 2. Boxplot of Delta outflow by month of the year (January = 1) for years the Delta Smelt population decreased, meaning Fall Midwater Trawl index was smaller than the prior year index (orange), and increased meaning Fall Midwater Trawl index was larger than the prior year index (teal). When this pattern was tested using an ANCOVA (Appendix A), the Delta outflow term was positive and statistically significant, the month term was not significant. When an outflow:month interaction term was included in the model, that term was also statistically significant because not every month contributed to the overall result.

Overview of the Low-Salinity Zone: Due to its historical importance as a fish nursery habitat, there is a long research history into the physics and biology of the San Francisco Estuary's low-salinity zone (LSZ). Researchers have defined the LSZ as a mobile habitat of varying size and location where salinity ranges from about 0.5 parts per thousand up to about 5 or 6 parts per thousand (Kimmerer 2004; Kimmerer et al. 2013). The USEPA recently finished a comprehensive set of maps that show how the LSZ changes in size and shape when freshwater flows increase or decrease[6]. The 0.5 to 5 parts per thousand and similar salinity ranges reported by other authors were chosen based on analyses of historical peaks in phytoplankton and

6 http://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/docs/cmnt081712/karen_schwinn.pdf

zooplankton abundance. The choice of X2 as the indicator location for the broader salinity range was based on two observations about the physics of the San Francisco Estuary: (1) it is possible to estimate the distribution of all estuary salinities knowing only X2, and (2) X2 is a boundary upstream of which, salinity tends to be the same from the surface of the water to the bottom, and downstream of which, salinity varies from top to bottom (Jassby et al. 1995). That variability in salinity from surface to bottom waters helps to aggregate turbidity and plankton near X2. Larger invertebrates and fish also aggregate near X2, but their aggregations represent a combination of physics and swimming (Bennett et al. 2002; Kimmerer et al. 2002). The force of the tides, river flows, and exports, disperses some of the turbidity, plankton, and fish away from X2 causing the peak densities to correspond to the broader range of salinities mentioned above. Recent pairing of three-dimensional hydrodynamic and particle tracking models is enabling researchers to explore the mechanisms by which physics and biology interact to generate observed distributions of plankton and fish (Kimmerer et al. 2014; Bever et al. 2016).

Overview of Delta Smelt Distribution: Because Delta Smelt only lives in one part of one estuary, its general distribution is well understood, and field observations are increasingly being supported by high tech laboratory research that explains how Delta Smelt respond physiologically to variation in salinity, turbidity, water temperature, and other aspects of their habitat that can vary with freshwater flow (Hasenbein et al. 2014; 2016; Komoroske et al. 2014; 2016).

At some time or other, Delta Smelt have been observed as far west as San Francisco Bay, as far north as Knight's Landing on the Sacramento River, and as far south as Mossdale on the San Joaquin River (Merz et al. 2011; Vincik and Julienne 2012). This full distribution represents a range of salinity from essentially zero parts per thousand up to about 20 parts per thousand, in other words, a salinity range well beyond definitions of the LSZ or the spatial extent of the Critical Habitat Rule. However, most Delta Smelt that have been collected in the extensively surveyed San Francisco Estuary have been collected from the locations included in the Critical Habitat Rule. Captive Delta Smelt can survive indefinitely in freshwater (Lindberg et al. 2013) and in the estuary, are routinely collected in the north Delta where salinity is less than 0.5 parts per thousand (Sommer and Mejia 2013). Delta Smelt have seldom been collected in water where salinity is higher than 10 parts per thousand (Bever et al. 2016; Komoroske et al. 2016) even though many individuals can theoretically survive extended time periods in higher salinities based on laboratory experiments (Swanson et al. 2000; Komoroske et al. 2014). A recent comprehensive physiological and molecular biology study showed that salinities typical of the LSZ are optimal for Delta Smelt and that although the fish can tolerate higher salinity water, it is energetically expensive and would likely decrease their ability to competitively exploit higher salinity habitats, particularly if food is limiting (Komoroske et al. 2016).

Variation in Delta outflow affects the average spatial location of the Delta Smelt population for most of its life. During spring, larval Delta Smelt have centers of distribution in freshwater, typically 20-40 km upstream of X2 (Dege and Brown 2004). By July, as water temperatures in the Delta reach annual peaks, post-larval and juvenile Delta Smelt have centers of distribution very close to X2 (Dege and Brown 2004), but the fish are broadly distributed around that peak (Sweetnam 1999; Nobriga et al. 2008). During the fall, subadult Delta Smelt still have a center of distribution near X2 (Sommer et al. 2011), and remain broadly distributed around that peak (Feyrer et al. 2007; 2011). During the winter, maturing adult Delta Smelt disperse in connection with winter storms following the spread of turbid fresh water (Grimaldo et al. 2009; Sommer et al. 2011; Murphy and Hamilton 2013). After an initial dispersal, our recent analyses suggest the fish's distribution no longer responds strongly to variation in Delta outflow (Leo Polansky, unpublished analysis of Spring Kodiak Trawl data set), though some individuals continue to move (Leo Polansky, unpublished analysis of Early Warning Survey data set).

Some of the spreading out of Delta Smelt around their center of distribution in the LSZ is caused by tides; Delta Smelt are known to change their position within channels in response to tides (Feyrer et al. 2013; Bennett and Burau 2015). However, some of it is probably also caused by other factors including the well-known advection into Old and Middle rivers that can be increased by water exports (Kimmerer 2008; Grimaldo et al. 2009). In addition, recent habitat papers have emphasized Delta Smelt's use of the Cache Slough 'complex' (Liberty Island, Sacramento Deepwater Shipping Channel, and adjacent habitats; Murphy and Hamilton 2013; Sommer and Mejia 2013). These authors have suggested that habitat attributes like tidal marshes and varying channel sizes are possible reasons for the use of these north Delta habitats by Delta Smelt. However, other explanations are also possible. For instance, the north Delta is one of the few remaining parts of the Delta that still has very turbid water and low prevalence of submerged vegetation (Nobriga et al. 2005; Durand et al. 2016). In addition to turbid water, lower Liberty Island and the Sacramento Deepwater Shipping Channel have substantial sandy shoals that likely serve as spawning habitat (Lodi FWO unpublished data).

Long-term changes to Delta Smelt Habitat: The following is a review of both laboratory based science and field based research into aspects of Delta Smelt habitat. It is important to remember that there can be a very large difference between what conditions fish can survive in when held in captivity and what they can competitively accomplish in the wild. Based on our review of past and current literature, Delta Smelt habitat is mostly a mixture of a few key attributes: landscape, turbidity, salinity, temperature, and food.

Landscape: In captivity, water depth is essentially irrelevant. Captive Delta Smelt are typically housed in tanks that hold fewer than 300 gallons of water (Figure 3; Lindberg et al. 2013). In the wild however, Delta Smelt are most frequently collected in water that is somewhat shallow (4-15 ft deep) where turbidity is often elevated and tidal currents exist, but are not excessive (Moyle et al. 1992; Bever et al. 2016). In Suisun Bay, the deep shipping channels are poor quality habitat because tidal velocity is very high (Figure 4), but in the north Delta where tidal velocity is slower, the Sacramento Deepwater Shipping Channel is used to greater extent particularly for spawning and larval rearing (Figure 5).

Figure 3. Photo of Delta Smelt experimental aquaculture facility. Photo credit: Sacramento Bee

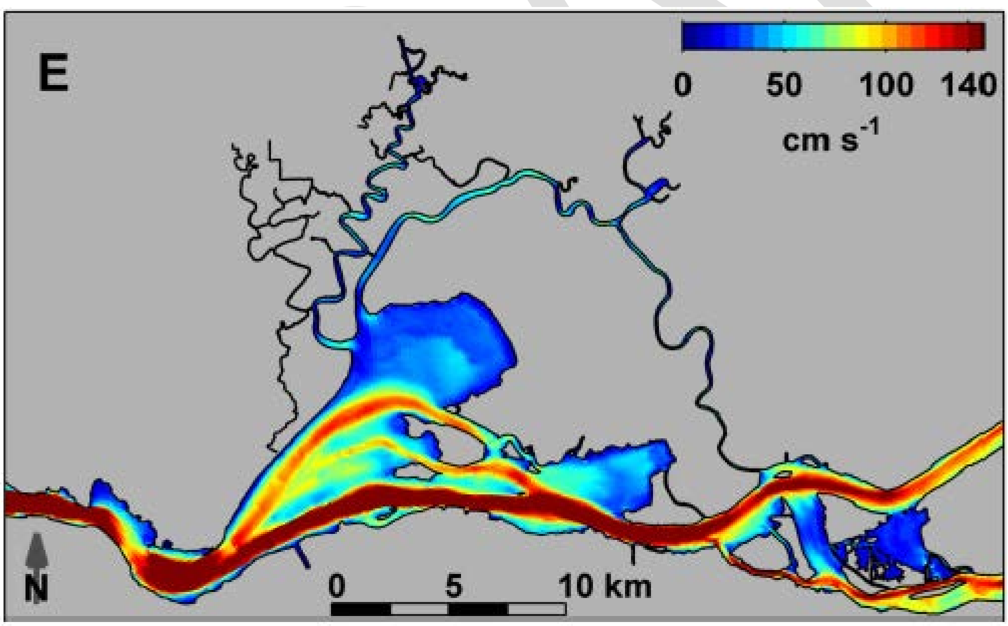

Figure 4. Delta Smelt habitat suitability in terms of tidal current velocity mapped for the Suisun Bay region. Redder colors represent poorer conditions for Delta Smelt and bluer colors represent higher suitability conditions. Note the lower habitat suitability associated with the deep shipping channel cut through southern Suisun Bay. Figure copied from Bever et al. (2016; http://escholarship.org/uc/item/2x91q0fr)

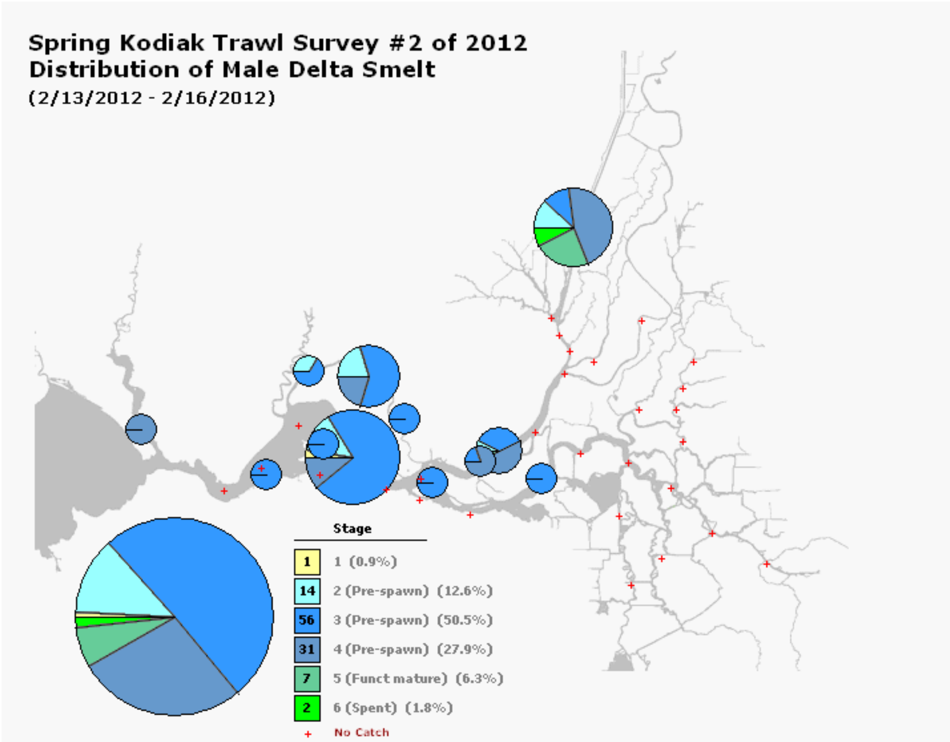

Figure 5. Example distribution map for adult Delta Smelt based on the California Department of Fish and Wildlife's Spring Kodiak Trawl Survey showing collection of Delta Smelt in the Sacramento Deepwater Shipping Channel, particularly at the northernmost site on the map. Figure taken from http://www.dfg.ca.gov/delta/data/skt/DisplayMaps.asp

Turbidity: Delta Smelt require turbidity. Even in captivity, clear water is a source of physiological stress (Lindberg et al. 2013; Hasenbein et al. 2016). Larvae need turbidity to see their prey (Baskerville-Bridges et al. 2004); older fish less so, but older fish feed more effectively in water of moderate turbidity (Hasenbein et al. 2013; 2016) and probably need turbid water to avoid predators (Ferrari et al. 2014). The turbidity of the Delta and Suisun Bay has been declining for a long time (Figure 6) due to dams and rip-rapped levees both of which cut off sources of sediment from rivers flowing into the estuary (Arthur et al. 1996; Wright and Schoellhamer 2004), and due to the spread of Brazilian water weed (Hestir et al. 2015). Water exports from the south Delta may also have contributed to the trend toward clearer water by removing resuspended sediment in the exported water (Arthur et al. 1996). The primary turbid areas that remain in the upper estuary are the semi-shallow embayments in northern Suisun Bay (Bever et al. 2016) and the lower Yolo Bypass region that includes Liberty Island and the upper reach of the Sacramento Deepwater Shipping Channel (Morgan-King and Schoellhamer 2013). Both tidal and river flows, as well as wind speed, affect turbidity in these locations (Figure 7). Many of the estuary's deeper channels tend to have somewhat lower turbidity because water velocity and wind cannot resuspend sediment that sinks into deep water (Ruhl and Schoellhamer 2004).

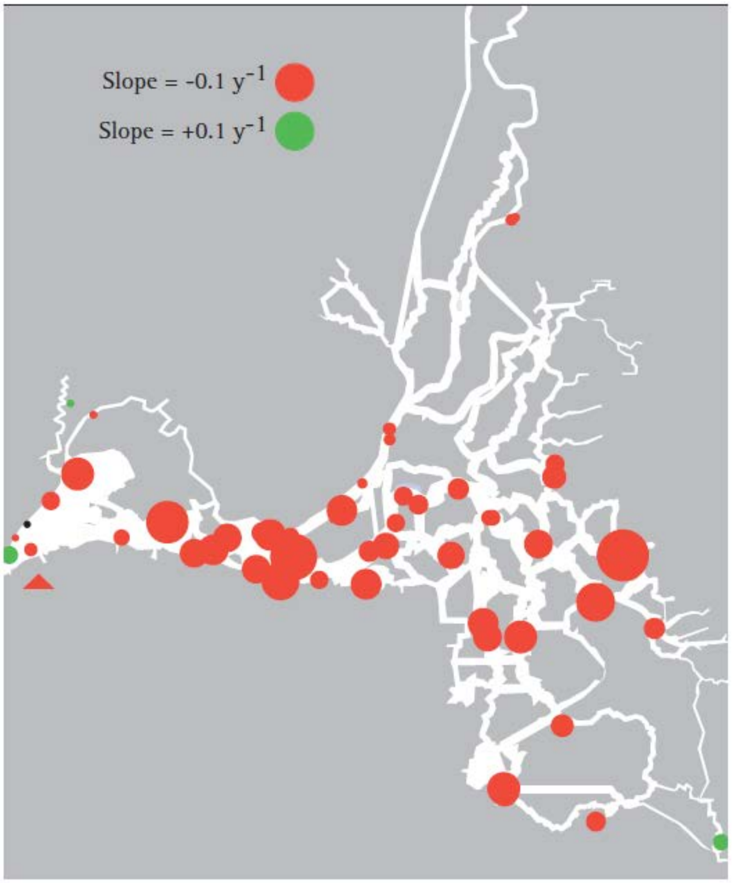

Figure 6. Trend in Secchi disk depth for numerous fish sampling sites in the upper San Francisco Estuary. Red symbols depict increasing Secchi depths (analogous with declining turbidity); the larger the symbol, the faster the rate of turbidity decline. Figure copied from Kimmerer (2004; http://escholarship.org/uc/item/9bp499mv)

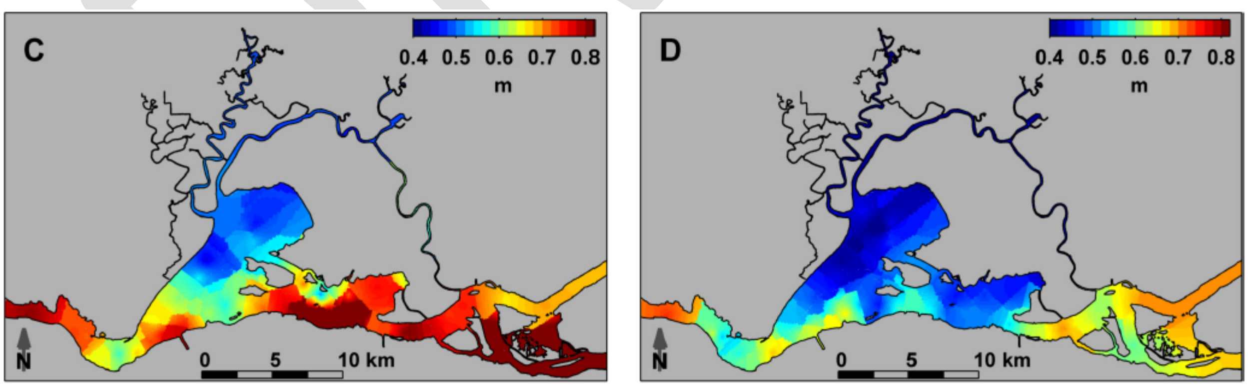

Figure 7. Maps of interpolated Secchi disk depth in the Suisun Bay region for the lower flow fall of 2010 (left panel) and the higher flow fall of 2011 (right panel). The bluer colors represent lower Secchi disk depths (analogous with higher turbidity), which represents higher habitat suitability for Delta Smelt. The redder colors represent higher Secchi disk depths (analogous with lower turbidity), which represents lower habitat suitability for Delta Smelt. Figure copied from Bever et al. (2016; http://escholarship.org/uc/item/2x91q0fr)

Salinity: Older laboratory research suggested that Delta Smelt have an upper acute salinity tolerance of about 20 parts per thousand (Swanson et al. 2000) which is about 60% of seawater's salt concentration of 32-33 parts per thousand. Newer laboratory based research suggests that some individuals can acclimate to seawater, but doing so comes at a high energetic cost that is lethal to about one in four individuals (Komoroske et al. 2014; 2016). In the wild however, Delta Smelt are nearly always collected at very low salinity which recent laboratory research has confirmed is nearer to their physiological optimum (Komoroske et al. 2016). Few individuals are collected at salinity higher than 6 parts per thousand (about 20% of seawater salt concentration) and very few are collected at salinity higher than 10 parts per thousand (about 30% of seawater salt concentration) (Figure 8). As described in more detail above, this well documented association with fresh to low salinity water is the reason for the scientific emphasis on X2 as a Delta Smelt habitat indicator (Dege and Brown 2004; Feyrer et al. 2011). Recent research combining long-term monitoring data with three-dimensional hydrodynamic modeling shows that the spatial overlap of several of the key habitat attributes covered in this memo increases as Delta outflow increases (Bever et al. 2016). This means that higher outflow increases the suitability of habitat in the estuary by increasing the overlap of some, but not all, needed elements (Figure 9). Lower outflows provide less of the necessary overlap and provide it in fewer places.

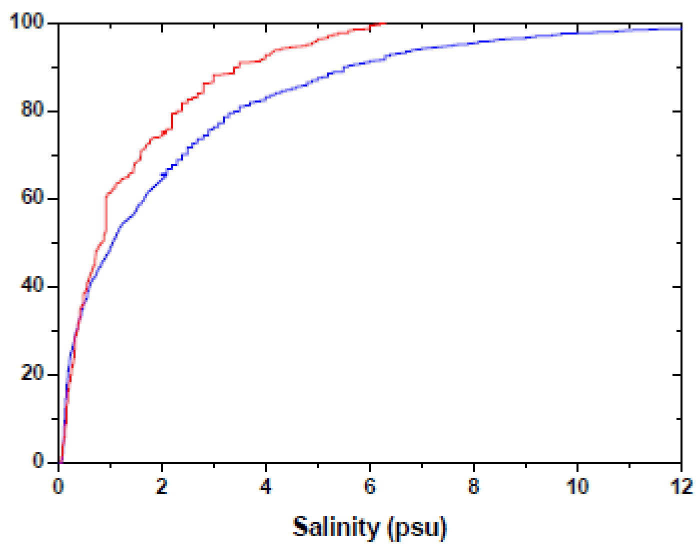

Figure 8. Cumulative percentage of Delta Smelt collected in the California Department of Fish and Wildlife's Fall Midwater Trawl Survey for salinity (top panel) and water temperature (bottom panel). Figure copied from Bennett (2005; http://escholarship.org/uc/item/0725n5vk)

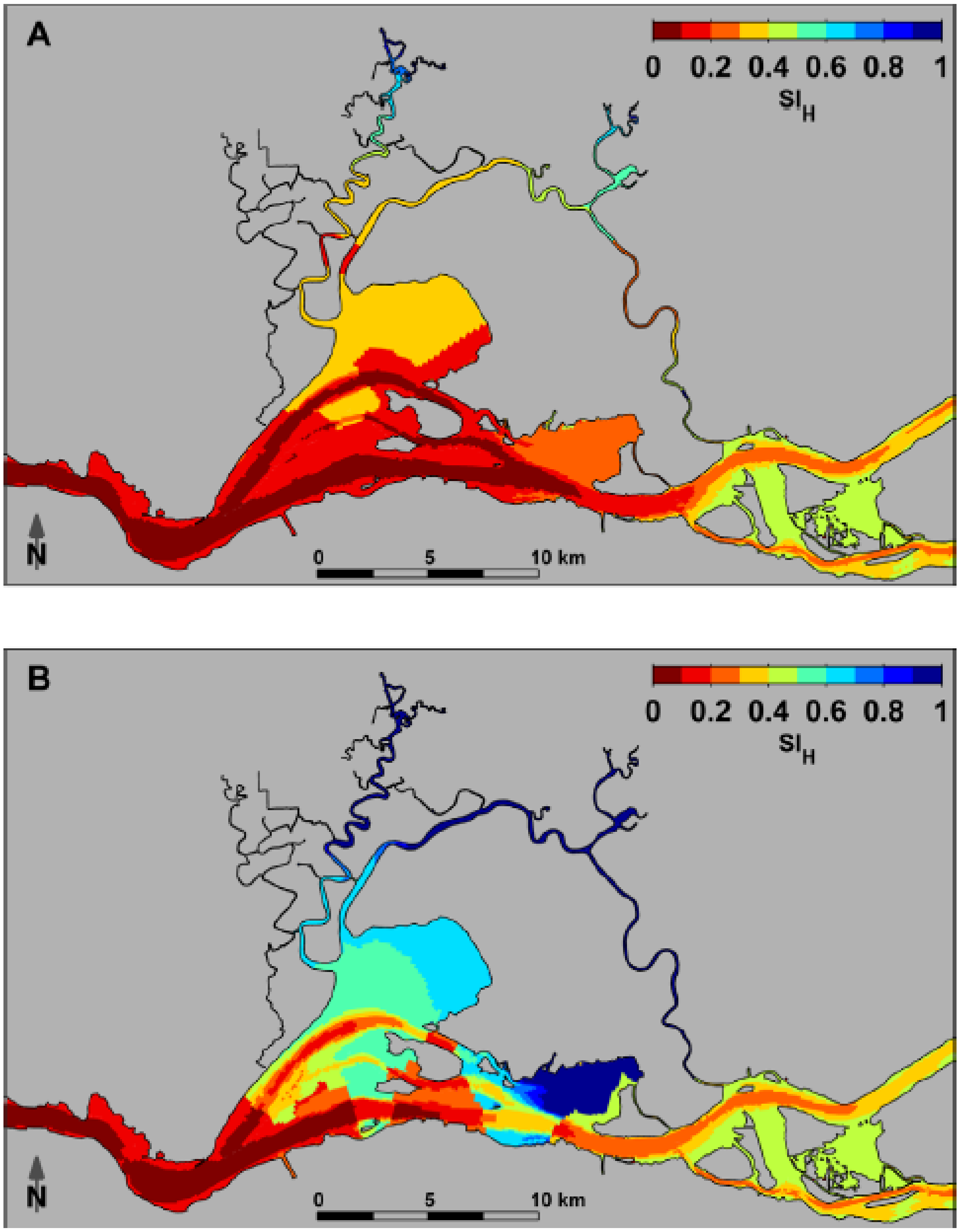

Figure 9. Maps of interpolated Delta Smelt habitat suitability in the Suisun Bay region for the lower flow fall of 2010 (top panel) and the higher flow fall of 2011 (bottom panel). The maps reflect the interacting influences of salinity, turbidity (Secchi disk depth), and tidal velocity. The bluer colors represent higher habitat suitability for Delta Smelt. The redder colors represent lower habitat suitability for Delta Smelt. Figure copied from Bever et al. (2016; http://escholarship.org/uc/item/2x91q0fr)

Water temperature: Older laboratory based research suggested an upper water temperature limit for Delta Smelt of about 25°C, or 77°F (Swanson et al. 2000). Newer laboratory research suggests Delta Smelt temperature tolerance decreases as the fish age, but is a little higher than previously reported, up to 28°C or 82°F in the juvenile life stage (Komoroske et al. 2014). It should be kept in mind that these are upper *acute* water temperature limits meaning they kill one of every two fish tested.

In the laboratory and the wild, Delta Smelt appear to have a physiological optimum temperature near 20°C or 68°F (Nobriga et al. 2008; Rose et al. 2013a; Jeffries et al. 2016); most of the upper estuary exceeds this water temperature from June through September (Wagner et al. 2011). Thus, many parts of the estuary are stressful and energetically costly for Delta Smelt to occupy. Generally speaking, spring and summer water temperatures are cooler to the west and warmer to the east due to the differences in overlying air temperatures between the Bay Area and the warmer Central Valley (Figure 10). In addition, there is a strong water temperature gradient across the Delta with cooler water in the north and warmer water in the south. The higher flows from the Sacramento River probably explain this north-south gradient. Note that water temperatures in the north Delta near Liberty Island and the lower Yolo Bypass are also typically warmer than they are along the Sacramento River (Sommer et al. 2001; Nobriga et al. 2005). Temperatures in this area are not shown in Figure 10 because the area was not part of historical trawl surveys.

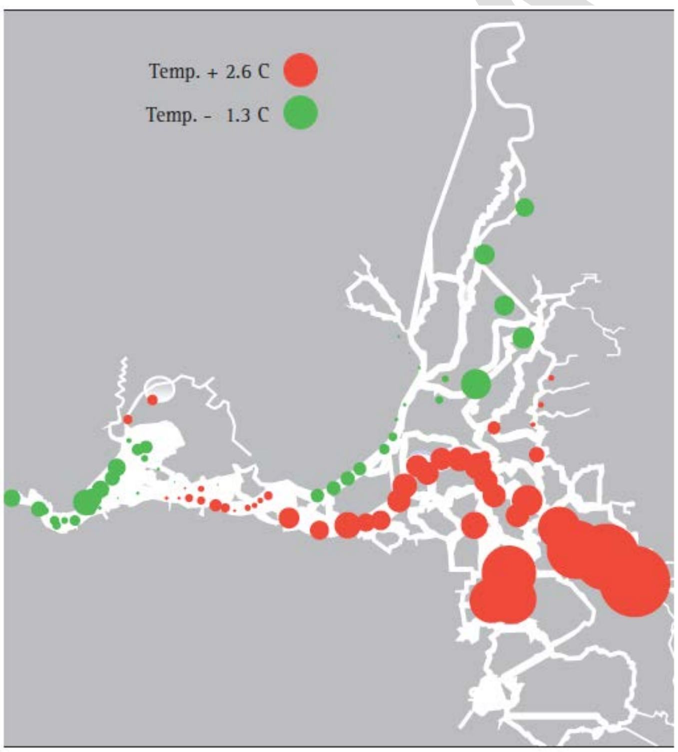

Figure 10. Map of deviations from average water temperature at numerous fish sampling sites in the upper San Francisco Estuary. Red symbols depict higher than average water temperature; the larger the symbol, the more the site exceeded the average of all of the stations. Green symbols represent cooler than average water temperatures; the larger the symbol, the lower the average temperature. Figure copied from Kimmerer (2004; http://escholarship.org/uc/item/9bp499mv)

Food: Small crustaceans make up most of the Delta Smelt diet (Slater and Baxter 2014). Small crustaceans are ubiquitously distributed throughout the estuary, but what prey species are present at particular times and locations has changed dramatically over time (Winder and Jassby 2011; Kratina et al. 2014; Merz et al. 2016). This has likely affected Delta Smelt feeding success, particularly during warm summers. For instance, many of the physical habitat attributes that Delta Smelt require overlap in Suisun Bay when low-salinity water is present (Figure 9). Historically, Suisun Bay also generated a lot of prey production, but this has been badly depleted due to grazing by overbite clams (Kimmerer and Lougee 2015) and high ammonium concentrations in waste water (Dugdale et al. 2012). Recent research suggests Delta Smelt occupying Suisun Bay are in poor nutritional health (Hammock et al. 2015). Delta Smelt occupying the lower Yolo Bypass region are in better nutritional health, but face relatively high contaminant impacts. The southern Delta is among the more productive areas remaining in the upper estuary (Nobriga et al. 2005), but Delta Smelt cannot remain in this habitat during the warmer months of the year (Nobriga et al. 2008) and historically faced high risk of entrainment even when they did occupy it during cooler months (Kimmerer 2008; Grimaldo et al. 2009). The Service's 2008 Biological Opinion for Delta Smelt has reduced the risk of entrainment for fish using the lower mainstem of the San Joaquin River. Delta Smelt that rear in Suisun Marsh seem to fare best in terms of nutrition and contaminant impact (Hammock et al. 2015).

In summary, there appear to be very few locations that consistently provide all of the most needed habitat attributes in the same times and places (Table 1).

Table 1. Summary of habitat attribute conditions for Delta Smelt in six regions of the estuary that are seasonally occupied in most years.

	Landscape	**Turbidity**	**Salinity**	**Temperature**	**Food**
Napa River	Appropriate	Appropriate	Too high except during very wet periods	Can be too high during summer	Unknown; likely appropriate
Montezuma Slough	Appropriate	Appropriate	Appropriate *when outflow is sufficient*	Usually appropriate	Appropriate
Suisun Bay	Appropriate except in shipping channel	Appropriate, but declining	Appropriate *when outflow is sufficient*	Usually appropriate	Depleted
West Delta	Limited area 4 to 15 feet deep	marginal, declining	Appropriate	Can be too high during summer	Depleted
North Delta	Appropriate	Appropriate	Appropriate	Can be too high during summer	Appropriate
South Delta	Appropriate except too much	Too low	Appropriate	Too high in the summer	Appropriate

coverage by submerged plants

How Delta Outflow Affects Habitat Quality and Quantity for Delta Smelt: As described above, Delta Smelt habitat is not strictly defined by defintions of the San Francisco Estuary's LSZ, but it strongly overlaps with the LSZ. There are numerous biological reasons that higher outflow, which pushes X2 closer to the Golden Gate Bridge, would improve conditions for Delta Smelt. The following is a synopsis of what is known about each one.

- *Entrainment (winter through spring)*: Delta outflow is correlated with Old and Middle river flow (OMR), with higher outflow generally associated with more postive OMR. With our implementation of the 2008 Biological Opinion, the Service has changed the historical relationship between Delta outflow and OMR, greatly reducing entrainment below pre-2008 levels. To date, this has not been able to overcome the severe effects of drought on Delta Smelt, suggesting that entrainment is not the primary reason for the spring X2 relationship that emerged in the early 2000s. However, the OMR protections in the Biological Opinion are still critical to minimizing entrainment impacts on Delta Smelt.

- *Spawning habitat (spring)*: Delta Smelt are believed to spawn on sandy beaches in fresh and possibly low-salinity water (Bennett 2005). When outflow is high, there are more sandy beaches with tidally-influenced fresh water flowing over them so Delta Smelt sucessfully produce young from more locations (Hobbs et al. 2007). We are unaware of any complete substrate maps of the Bay-Delta that we could use to predict how spawning habitat availability might change as outflow increases. This mechanism is therefore not robustly testable at this time.

- *Water temperature (late spring through early fall)*: For the most part, water temperatures in the estuary are driven by overlying air temperatures (Wagner et al. 2011). However, *very* wet springs are usually cooler than lower flow springs and this could result in at least two beneficial mechanisms. First, persistent cool weather increases the duration of the Delta Smelt spawning season (Bennett 2005). This gives Delta Smelt more opportunities to spawn and more time for spawned eggs to develop and hatch. The longer water temperatures stay near 20°C in the spring and early summer, the better the energetic environment is for young Delta Smelt (Rose et al. 2013a). The likelihood of severe food limitation and other forms of physiological stress increases as water temperatures increase (Komoroske et al. 2014). Our analysis of juvenile recruitment provided almost as much statistical support for water temperature as it did for X2 (Appendix B).

- *Salinity and habitat space (all year, but particularly summer and fall)*: Recent research has confirmed that changes in the amount of fresh- and low-salinity water volume are not a mechanism likely contributing to springtime fish-flow relationships (Kimmerer et al. 2009; 2013). However, other research focused on the fall has shown that increases in outflow cause low-salinity water to overlie areas with appropriate tidal current velocity and turbidity improving habitat conditions for Delta Smelt (Feyrer et al. 2011; Bever et al. 2016). Thus, defining Delta Smelt 'habitat' only in terms of salinity is too simple and it remains possible that greater habitat quality and quantity do contribute to juvenile recruitment or increasing population size. The flow mechanisms described for the fall would also apply to the summer months.

- *Salinity and prey availability (late spring)*: In general, very high outflows dilute plankton and therefore reduce prey density available to small fishes. However, high flow years tend to have moderately high flows by late spring extending into the summer and these moderate flows historically enabled large plankton blooms in Suisun Bay, contributing to the region's importance as a fish nursery (Turner and Chadwick 1972; Cloern et al. 1983; Knutson and Orsi 1983; Jassby et al. 1995). Unfortunately, the overbite clam has greatly changed the way the LSZ food web works which has suppressed the fish nursery value of the LSZ (Kimmerer and Thompson 2014; Kratina et al. 2014). Nonetheless, there are two flow-related mechanisms that may still affect prey availability for young Delta Smelt: (1) Flooding and draining of Yolo Bypass, and (2) suppression of overbite clam recruitment. During very wet springs, Yolo Bypass can still be draining into the north Delta during April and May when large numbers of young Delta Smelt may be able to take advantage of the plankton production that drains off of the bypass (Schemel et al. 2004; Sommer et al. 2004; Lehman et al. 2008). Adult overbite clams can survive in very low salinity water, but young clams settling out of the plankton cannot[7]. Thus, it is also possible that in years when outflow stays elevated through spring, that the impact of grazing by overbite clam on Delta Smelt's prey is delayed long enough to allow the fish to grow large enough to survive mild to moderate summers. Food related mechanisms have been suggested by several authors to influence Delta Smelt recruitment and population growth rate, primarily during summer and fall (Kimmerer 2008; Maunder and Deriso 2011; Miller et al. 2012; Rose et al. 2013a). If the fish can survive the summer and fall, the limited data that exist for Delta Smelt that survive to adulthood indicates they are in good health (Foott and Bigelow 2010).

[7] http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.364.8035&rep=rep1&type=pdf

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Appendix A: R code for statistical tests reported by FWS staff

```
R version 3.1.0 (2014-04-10) -- "Spring Dance"

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Platform: x86_64-w64-mingw32/x64 (64-bit)

R is free software and comes with ABSOLUTELY NO WARRANTY.
You are welcome to redistribute it under certain conditions.
Type 'license()' or 'licence()' for distribution details.

  Natural language support but running in an English locale

R is a collaborative project with many contributors.
Type 'contributors()' for more information and
'citation()' on how to cite R or R packages in publications.

Type 'demo()' for some demos, 'help()' for on-line help, or
'help.start()' for an HTML browser interface to help.
Type 'q()' to quit R.

> data <- read.csv(file.choose("SmeltFlow.csv"), header = TRUE)
> result <- lm(Grow ~ log(Outflow) + Month, data = data)
> summary(result)

Call:
lm(formula = Grow ~ log(Outflow) + Month, data = data)

Residuals:
    Min      1Q  Median      3Q     Max
-0.6469 -0.3894 -0.3295  0.5670  0.7471

Coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept)  0.616969   0.234483   2.631 0.008771 **
log(Outflow) 0.076174   0.022228   3.427 0.000661 ***
Month        0.009978   0.006922   1.442 0.150039
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.4866 on 501 degrees of freedom
Multiple R-squared:  0.0229,    Adjusted R-squared:  0.019
F-statistic: 5.872 on 2 and 501 DF,  p-value: 0.003015

> result2 <- lm(Grow ~ log(Outflow) + Month + log(Outflow):Month, data = data)
> summary(result2)

Call:
```

```
lm(formula = Grow ~ log(Outflow) + Month + log(Outflow):Month,
    data = data)

Residuals:
    Min      1Q  Median      3Q     Max
-0.6871 -0.4067 -0.3176  0.5601  0.8745

Coefficients:
                    Estimate Std. Error t value Pr(>|t|)
(Intercept)        -0.217229   0.432985  -0.502 0.616098
log(Outflow)        0.159602   0.042659   3.741 0.000204 ***
Month               0.148843   0.061088   2.437 0.015177 *
log(Outflow):Month -0.014306   0.006253  -2.288 0.022566 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.4846 on 500 degrees of freedom
Multiple R-squared:  0.03303,   Adjusted R-squared:  0.02722
F-statistic: 5.692 on 3 and 500 DF,  p-value: 0.0007738
```

Appendix B: Assessing Delta Smelt Recruitment Success

Assessing Delta Smelt Recruitment Success
DRAFT

Ken Newman, Lara Mitchell, and Matt Nobriga

June 6, 2016

This note presents initial answers to the following question:

- "How are environmental factors associated with reproductive success, *recruitment*, of delta smelt?"

Recruitment for a given cohort was defined as the ratio of the number of juveniles in June to the number of adults in February. We recognize the imprecision in this definition as the particular times within February and June are not specified.

1 Recruitment estimation

Recruitment was estimated using estimates of adult and juvenile abundances that were based on fish survey data from 2002 through 2015. For both adults and juveniles, stratified random sample ratio expansions were used to estimate abundance. Within a stratum the ratio was total catch at all sampling locations divided by total volume sampled (m^3).

1.1 Juvenile abundance estimation

The abundance of juveniles was estimated using Delta Smelt catches from all samples taken during the month of June by the 20mm survey. 20mm gear was assumed to have the following length-based capture probability.

$$\pi_{20mm}(L) = \frac{\exp(-11.577 + 0.699L)}{1 + \exp(-11.577 + 0.699L)}$$

where $\pi_{20mm}(L) = \Pr(\text{Catch a length } L \text{ fish}|\text{fish was present in 20mm tow volume})$. We think $\pi_{20mm}(L)$ likely overestimates selectivity for fish between 15 and 20mm and perhaps underestimates fish less than 15mm. Somewhat arbitrarily, calculated values < 0.02 were set equal to 0.02. We assumed that juvenile fish occupied a horizontal stratum between 0.5m and 4.5m from the surface. To remove the portion of tow volume that was above or below that stratum, a geometric calculation was carried out assuming an oblique tow from the maximum tow depth to the water surface. A further assumption was that the height of the gear opening was 1.292m (4.2 feet). The formula for estimating juvenile abundance:

$$\hat{n}_{Juveniles} = \sum_{h=1}^{H_{20mm}} V_{h,4m} \frac{\sum_{i=1}^{m_h} \frac{c_{20mm,h,i}}{\pi_{20mm}(\overline{L}_{h,i})}}{\sum_{i=1}^{m_h} v_{adj,20mm,h,i}} \tag{1}$$

where $V_{h,m}$ is the estimated volume to 4m depth in stratum h, $c_{h,i}$ is the catch at location i in stratum h, $\overline{L}_{h,i}$ is the average length, and $v_{adj,h,i}$ is the adjusted volume.

1.2 Adult abundance estimation

The abundance of adults during the month of February was estimated using catches from the SKT surveys taken in January and February, assuming that survival was relatively high during this time period. The Kodiak trawl gear was assumed 100% effective For adult abundance estimation, we assumed that adult fish occupied the top 4m and the fish density declined linearly from the surface to 4m depth. Further assuming that the Kodiak trawl fished the top 2m, the catch densities were biased high by a multiplier of 1.5, thus catches were reduced by a multiplier of $1/1.5 = 2/3$. The formula for estimating "adult" abundance:

$$\hat{n}_{Adults} = \frac{2}{3}\sum_{h=1}^{H_{SKT}} V_{h,4m}\frac{\sum_{i=1}^{m_h} c_{SKT,h,i}}{\sum_{i=1}^{m_h} v_{SKT,h,i}} \quad (2)$$

Strata for the 20mm and SKT surveys differed but both were based on the sub-region partitioning of the DSM2 hydrology model. Sub-regions without sampling locations were merged with neighboring regions which did have sampling. Volume calculations were provided by USGUS who carried out tide-adjusted bathymetric calculations.

1.3 Results

The resulting estimates are shown in Table 1. Standard errors for abundance estimates were calculated assuming design based estimation and ignored error in the 20mm gear capture probabilities. Recruitment, λ, was estimated by dividing the juvenile abundance estimate by the adult abundance estimate.

Table 1: Estimated abundances of juveniles and adults and associated standard errors and estimated recruitment ($\hat{\lambda}$).

Year	$\hat{n}_{adult}$	se_{adult}	$\hat{n}_{juv}$	se_{juv}	$\hat{\lambda}$
2002	597	118	1632	1035	2.74
2003	519	206	3941	3237	7.6
2004	527	154	1029	717	1.95
2005	385	86	3706	2475	9.63
2006	151	28	5109	3338	33.91
2007	235	75	580	934	2.46
2008	262	105	966	1258	3.68
2009	295	128	863	822	2.92
2010	134	33	2336	1962	17.4
2011	234	118	4320	2914	18.42
2012	623	186	5067	5351	8.14
2013	171	52	1548	1571	9.04
2014	167	52	165	255	0.99
2015	112	42	47	98	0.42

2 Modeling recruitment

A multiplicative model for juvenile abundance was assumed.

$$n_{juv,t} \quad = \quad n_{adult,t}\lambda_t \tag{3}$$

where λ_t can be interpreted as the number of juveniles produced per adult. Interest was in the factors that might influence λ_t. Allowing for environmental variation the following univariate models were fit:

$$n_{juv,t} \quad = \quad n_{adult,t}\exp(\beta_0 + \beta_1 X_{j,t} + \epsilon_t) \tag{4}$$

where $X_{j,t}$ denotes a covariate and ϵ_t is environmental variation. Estimates of abundances were substituted for the true abundances and taking a natural log transformation of both sides of equation (4) yielded the following linear regression model.

$$\ln(\hat{n}_{juv,t}) \quad = \quad \ln(\hat{n}_{adult,t}) + \beta_0 + \beta_1 X_{j,t} + \epsilon_t, \quad t = 2002, \ldots, 2015 \tag{5}$$

Table 2 lists some of covariates considered along with R^2 values. Figure 1 shows plots of $ln(\hat{n}_{juv}/\hat{n}_{adult})$ against the first four covariates. Estimated recruitment had the strongest association with the average $X2$ value for the months of April and May (R^2=0.74), although the association with water temperatures during April was nearly the same (R^2=0.71). All these results should be viewed critically given the many assumptions made to construct the recruitment estimate and the relatively small data set of 14 observations. Work is on-going. Specific tasks are to (a) improve the estimates of the 20mm capture probabilities, (b) extend the time period of analysis to 1991, including Spring Midwater Trawl survey data for adult abundance estimation, and (c) integrate estimation of recruitment within the fitting of a life cycle model which connects abundance between cohorts.

Table 2: Covariates used to model recruitment and corresponding linear regression R^2 values.

Covariate		R^2
Label	Definition	
$Outflow.Apr.May$	average daily inflow during April and May	0.55
$Exports.Apr.May$	average daily export volume during April and May	0.49
$OMR.Apr.May$	average daily OMR value during April and May	0.38
$X2.Apr.May$	average daily X2 value during April and May	0.74
$Water.Temp.Apr$	average 20mm survey water temperatures during April	0.71
$Water.Temp.May$	average 20mm survey water temperature during May	0.32
$Secchi.May$	average 20mm survey Secchi measurements during May	0.23
$Prey.NJ.Apr$	measure of nauplii and copepodids in April	0.31
$Prey.JACM.May$	measure of copepodids, copepods, claudicerans, and mysids in May	0.35
$Prey.Eury.May$	measure of *Eurytemora* in May	0.45
$Feb.length$	estimated average length of adults in February	0.21

Figure 1: $ln(\hat{n}_{juv}/\hat{n}_{adult})$ versus Outflow, Exports, OMR, and X2.