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RESEARCH

Integrating Hydrodynamics and Fish Vital Rates into Indices of Entrainment for Endangered Smelts at the Barker Slough Pumping Plant

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ABSTRACT

Fish losses to entrainment in water diversions in the Sacramento–San Joaquin Delta have been a long-standing conservation concern. We evaluated Delta Smelt (*Hypomesus transpacificus*) and Longfin Smelt (*Spirinchus thaleichthys*) entrainment risk associated with the Barker Slough Pumping Plant (BSPP) by integrating hydrodynamic, growth, survival, and fish-screen-selectivity information into indices of entrainment risk for nine locations in the Cache Slough Complex (CSC). Our fundamental question was: *How does risk of entrainment into BSPP vary in space and time?* We found the predicted risk of entrainment into BSPP is extremely high from the adjacent Lindsey Slough. From elsewhere in the CSC, entrainment risk into BSPP is approximately zero in both wet and dry years, such that local irrigation diversions are the only potential source of entrainment loss. We estimated Delta Smelt outgrow vulnerability to entrainment through the BSPP fish-screens in 35 to 53 days while Longfin Smelt remain vulnerable for 90 to 98 days. Research indicates some impingement is probable even after fish outgrow risk of being entrained through the screens if they continue to be passively transported. Our entrainment indices sometimes deviated considerably from hydrodynamic transport predictions within Lindsey Slough because larval fish have high natural mortality rates and, at least for Delta Smelt, growth rates high enough to modify the transport predictions. Since 1989, the predicted entrainment risk at BSPP has declined in the winter but increased in April through May as a result of long-term trends in how much water is seasonally diverted at BSPP. If the one-dimensional model we used to estimate fish transport is accurate, then Delta Smelt and Longfin Smelt would need to be spawned in Barker or Lindsey sloughs to face a meaningful risk of entrainment at BSPP. This conclusion does not appear to be affected by Yolo Bypass flow as had been hypothesized previously.

KEY WORDS

Delta Smelt, Longfin Smelt, entrainment, Particle Tracking Model

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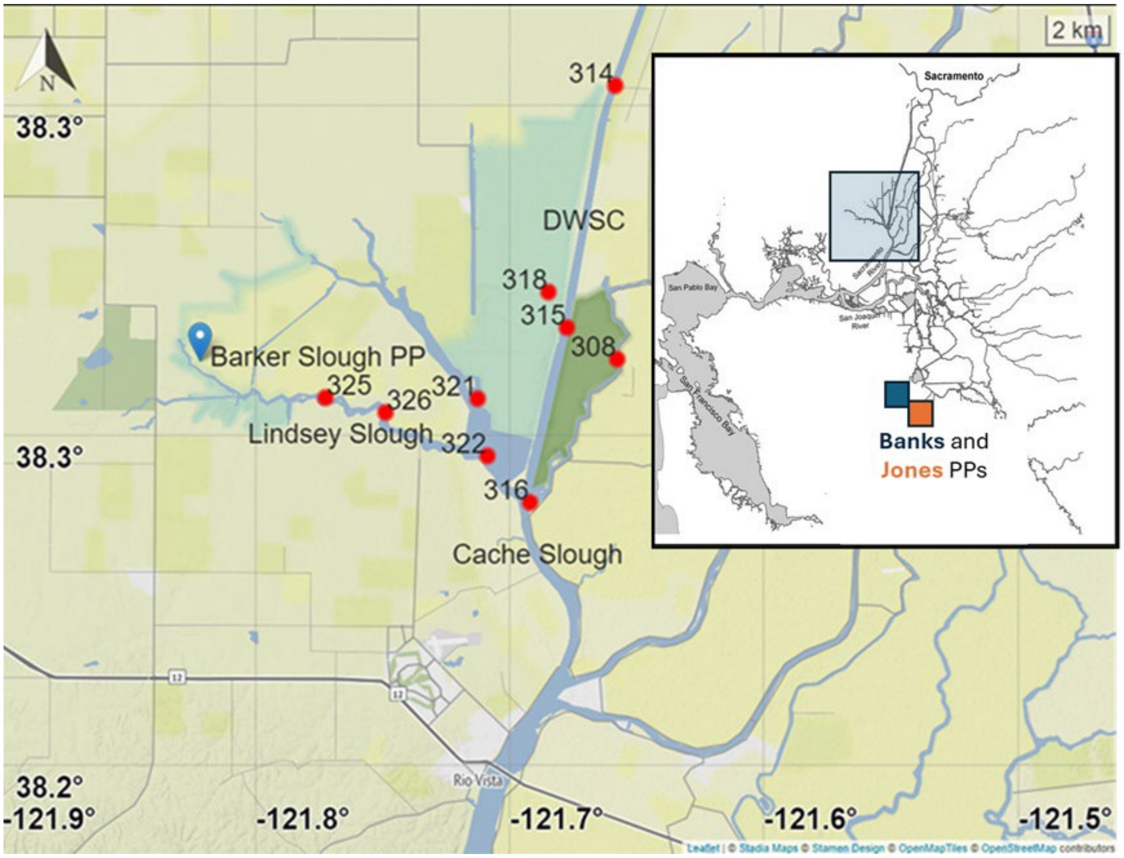

Figure 1 Map of the Cache Slough Complex in the northern Sacramento–San Joaquin Delta. The main map location is shown in *shaded blue* in the *inset map*, which also shows the locations of the larger South Delta Pumping Plants (labeled as Banks and Jones PPs). The location of the Barker Slough Pumping Plant (PP) is shown in the main map with a *blue tag symbol*. The particle release locations used in this study are numbered according to their node number in the DSM-2 hydrodynamic model, and shown with *red circles*. *Sources:* Base map, *https://leaflet-extras.github.io/leaflet-providers/preview*, and DSM2 node locations, *https://github.com/fishsciences/dsm2-map/blob/master/shapefiles/Nodes_EPSG_4326.shp*.

INTRODUCTION

The Sacramento–San Joaquin Delta (hereafter, "the Delta") has thousands of water diversions that range in size from relatively small, privately-owned siphons used to irrigate local farm tracts, up to the Central Valley Project (CVP) and State Water Project (SWP) pumping plants, which are some of the world's largest diversions, serving tens of millions of people (Herren and Kawasaki 2001; Moyle and Israel 2005; Moyle et al. 2018; Figure 1, *inset*). Not surprisingly, fish losses to water diversions in the Delta have been a long-standing conservation concern. Water diversions can kill fish directly by entraining them from waterways and redistributing them into inhospitable habitats, and indirectly by extracting water and changing aquatic habitat function (Moyle and Israel 2005). Scientific and regulatory focus has been on the combined effects of the CVP's Jones Pumping Plant and SWP's Banks Pumping Plant because of their large size and substantial hydrodynamic influence. These diversions annually export about 3.1 and 3.6 km^3 of water from the South Delta and are powerful enough to generate water- elevation gradients and tidal asymmetries (stronger flood than ebb tides) that can create a net flow of water toward the diversions (Kimmerer and Nobriga 2008). This redistribution of water can result in entrainment, and expose fish to low-suitability habitat conditions, increasing their mortality whether they are ultimately entrained or not (Kimmerer

2008; Brown et al. 2009; Grimaldo et al. 2009, 2021; Smith et al. 2021; Buchanan et al. 2021; Kimmerer and Gross 2022; Sridharan et al. 2023).

Much less scientific effort has been put into understanding the effects of other water diversions *in situ*, for instance, the SWP's Barker Slough Pumping Plant (BSPP; Figure 1). The BSPP is the Delta's fourth-largest diversion, but it diverts less than 2% of the water volumes diverted by the Jones or Banks pumping plants (~0.05 km^3; Kimmerer and Nobriga 2008). According to the Dayflow database (*https://data.ca.gov/dataset/dayflow*), the facility's maximum annual diversion was 60.6 taf (~ 7.5 million m^3) in water year 2007 (i.e., October 1, 2006 through September 30, 2007). However, diversion rates at BSPP can be constrained to protect larval Longfin Smelt and Delta Smelt in the winter and spring of drier water years. In addition to diversion capacity, a second important difference between the Banks and Jones pumping plants and the BSPP is the latter has positive-barrier fish screens in front of its intakes rather than louver systems. Positive-barrier fish-screens diffuse inflowing water over an enlarged surface area to slow down the flow rate as water is drawn into the intake (Poletto et al. 2015). The more slowly water moves toward an intake, the more likely it is that a fish will be able to detect the change in current speed and swim away from it without being harmed (Poletto et al. 2015; Bretzel et al. 2024). The BSPP is operated to meet approach velocities of 0.2 ft s^{-1} (~0.06 m s^{-1}) to 0.4 ft s^{-1} (~0.12 m s^{-1}), depending on the screen bay (CDWR 2017, 2019). The screens have a mesh size of 2.4 mm and are cleaned regularly to maintain the desired approach and sweeping velocities, i.e., the water flow-rates perpendicular and parallel to the screen face, respectively. The fish-screens at BSPP were designed to physically exclude fusiform fish longer than 25 mm. This upper size limit to entrainment vulnerability invokes the potential importance of fish growth-rates, in that fish being transported toward BSPP by tidal and net flows may only be entrained for comparatively short periods of time after they hatch. However, fish larger than 25 mm may still be impinged (pinned against the screens without passing through them).

When the US Fish and Wildlife Service (USFWS) consults on CVP and SWP water operations as part of its obligations under the Federal Endangered Species Act (ESA), the proposed water-diversion rates at BSPP and the anticipated losses of Delta Smelt (*Hypomesus transpacificus*) and Longfin Smelt (*Spirinchus thaleichthys*) are part of the effects analysis. The USFWS' original critical habitat rule listed Barker Slough as a spawning habitat (USFWS 1994). This is presumably one reason that the 1995 Delta Smelt Biological Opinion called for an intensive larval fish-monitoring program that could trigger pumping restrictions at BSPP when catch thresholds were reached (USFWS 1995). However, in subsequent years, the monitoring program caught very few Delta Smelt larvae in Barker Slough (Figure 2), and it was eventually discontinued in favor of an expanded 20-mm Survey (USFWS 2005, 2008). The USFWS listed Longfin Smelt under the ESA in 2024, so it has no comparable federal regulatory history. Recent research into Longfin Smelt spawning distribution has indicated that most spawning

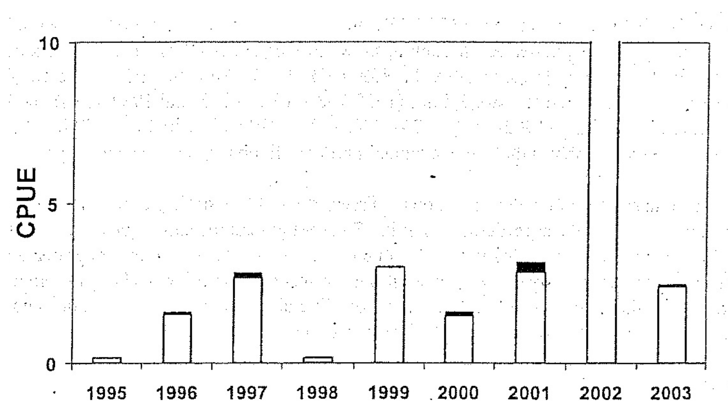

Figure 2 Stacked bar plot summary of larval Delta Smelt catches from the discontinued North Bay Aqueduct Monitoring Program (NBA); image copied from USFWS (2005). The original caption was: "Comparison of delta smelt catch-per-unit-effort (fish/trawl) for NBA monitoring sites in Barker Slough (*dark bars*) to nearby north Delta sites: Lindsey, Cache, and Miner sloughs (*white bars*). The NBA values are the mean annual CPUE for stations 720, 721, and 727. The nearby north Delta sites represent the mean annual CPUE for stations 718, 722, 723, 724, and 726." The locations of the sampling stations that were continued as part of the 20-mm Survey can be seen at the following location: *https://wildlife.ca.gov/Conservation/Delta/20mm-Survey#stationmap*

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occurs seaward of BSPP, but may occur in the Cache Slough Complex (hereafter, "CSC"; Figure 1) in drier years (Grimaldo et al. 2020; Gross et al. 2022).

The data summarized in Figure 2 or any analogous data summary from subsequent fish monitoring surveys cannot be properly contextualized without an understanding of regional transport probabilities, and how hydraulic transport may interact with not just the instantaneous distributions of species but also their fundamental biology. Here we provide a comprehensive analysis of particle transport in the CSC and couple it with information on the early life growth and survival rates of Delta Smelt and Longfin Smelt. We combined several sources of information to develop entrainment risk indices to answer a fundamental question: *How does risk of entrainment into BSPP vary in space and time?* To address this question comprehensively, we answered six others:

1. From where in CSC does hydrodynamic modeling predict transport to BSPP?
2. From where in CSC does hydrodynamic modeling predict transport to local irrigation diversions?
3. Do hydrodynamic transport predictions vary between wet and dry years?
4. How long does it take each smelt species to outgrow risk of entrainment through the BSPP fish screens?
5. How do growth and mortality modify the predicted hydraulic risk of entrainment into the BSPP?
6. How may entrainment risk have varied since the inception of BSPP water exports?

METHODS

Study Area and Background

The BSPP has been in operation since 1988. It is used to deliver water to Travis Air Force Base, Napa County, and the cities of Vallejo and Benicia via the North Bay Aqueduct (CDWR 2017). Water is diverted from Barker Slough, a branch of Lindsey Slough on the west side of the CSC, which is a network of sloughs and open-water habitats in the North Delta generally surrounding the base of the Yolo Bypass (Figure 1). The Yolo Bypass is the largest remaining seasonal floodplain of the Sacramento River and is the only substantial source of freshwater delivery to the area. The Yolo Bypass does not flood every year, but when it does convey floodwaters, the basin has usually drained by May. Thus, the CSC is often an area of very low natural inflow, and much of the water exchange is tidal (Gross et al. 2019; Stumpner et al. 2021). As a result, flow in Barker and Lindsey sloughs is frequently net negative, meaning it is usually moving toward BSPP (see "Results"). Excepting the altered hydrodynamics, the habitat in Lindsey Slough was recently considered one of the better remnant examples of the tidal marsh plains that once dominated the Delta's landscape (Young et al. 2021). However, more recent research has also reported considerable encroachment of submerged aquatic vegetation (SAV), which is associated with poor habitat quality for Delta Smelt and Longfin Smelt (Smits et al. 2025).

Conceptual Model

Historically, most Longfin Smelt have spawned in January and February (Gross et al. 2022) while most Delta Smelt spawned in March and April (Kurobe et al. 2022). Precise spawning locations have not been determined but both species spawn in the CSC, though it is likely that, within the CSC, spawning distributions have changed over time as SAV encroachment has progressed (see "Discussion"). Most Delta Smelt spawn in freshwater (salinity < 0.5 psu; Hobbs et al. 2019), and within the CSC the Deep Water Ship Channel appears to have recently been the most important spawning habitat (Kurobe et al. 2022). Gross et al. (2022) coupled larval Longfin Smelt catch data with particle tracking to infer spawning locations. These authors concluded most Longfin Smelt spawning occurs in the Low-Salinity Zone (LSZ) well seaward of the CSC, but spawning can extend landward into the CSC, especially in winters with low outflow. We focus on the early life stages of both smelts because most Delta Smelt (Hobbs et al. 2019) and all Longfin Smelt (Rosenfield and Baxter 2007) leave the CSC for brackish and marine waters, respectively, beginning in the late spring (~May). In recent years, summertime foraging conditions for Delta Smelt have been poor nearly everywhere in freshwater habitats of the Delta, so it is not clear how effectively the CSC is currently supporting this species from about May or June into October or November (Smith and Nobriga 2023).

Our conceptual model for larval smelt entrainment risk assumed that recently hatched larvae will generally drift passively until they either develop sufficient locomotive function to swim against the river and tidal currents they are experiencing, or they reach salinity of approximately 2 psu where hydrodynamic mixing of fresh and brackish water can help retain weakly swimming organisms (Bennett et al. 2002; Kimmerer et al. 2014). The CSC is upstream of the hydrodynamic mixing that occurs in the LSZ; thus, it is possible that transport can be reasonably indexed by one-dimensional (1-D) hydrodynamic models (Kimmerer 2008; Smith et al. 2020). Aquatic organisms are passively screened at the BSPP intake, preventing all fish larger than 26 mm (Appendix A) from becoming entrained into the North Bay Aqueduct (NBA) and exported from the system, but larval and early post-larval smelts may become entrained by passing through the screen mesh. If a larval smelt can outgrow the screen mesh before it is transported to BSPP, entrainment can be avoided. Thus, entrainment risk is expected to be proportional to transport rate and distance from BSPP. We review the additional risk of fish being impinged in the Discussion.

Analytical Approach

We calculated a species-specific entrainment risk index E for each of the nine particle release locations (Figure 1). The particle release locations were intentionally spread throughout the CSC because, as mentioned above, precise spawning locations are not known. In each month–year combination, we estimated E as the sum of the product of the daily probabilities of transport $P_{TR_{id}}$, fish-screen selectivity P_{SL_d}, and survival P_{SV_d}, given size on day d

$$E_{is} = \sum_{d=1}^{60} P_{TR_{id}} P_{SL_{ds}} P_{SV_d} \qquad \text{Eq 1}$$

where i denoted specific combinations of particle release locations, years, and months; d denoted the day of the simulation; and s denoted species. E_{is} indicated the cumulative probability of surviving advection to BSPP and passing through the intake screens (i.e., becoming entrained) if a fish had hatched at a specific node on the day of the particle release. We developed models to characterize the uncertainty in $P_{TR_{id}}$ and size on day d. We developed alternative models of P_{SL_d} to characterize uncertainty regarding entrainment through the screens, but we did not model uncertainty in survival, P_{SV_d}.

We estimated $P_{TR_{id}}$ using the DSM2 Particle Tracking Model version 8.2.2 (PTM) (*https://data.cnra.ca.gov/dataset/dsm2-v8-2-2*). The PTM runs on the California Department of Water Resources (CDWR's) Delta Simulation Model II, a 1-D hydrodynamic modeling tool that predicts tidal and advective water movement in the upper estuary among a network of simulated channels, reservoirs, and junctions or nodes (*https://data.cnra.ca.gov/dataset/dsm2-georeferenced-model-grid*). The PTM tracks the transport and fate of virtual releases of neutrally buoyant particles using the historical hydrology and tides. We tracked particle transport from each release node to BSPP and to agricultural diversions. The latter are privately owned and are not part of CVP and SWP water operations, but they affect local hydrodynamics and intercept particles in the model, so we needed to consider their influence when interpreting the PTM results. Particle movements are tracked among user-defined locations for specified amounts of time. We chose to track particle fates for ~60 days. This choice balanced our interest in applying fish vital rate information with the potential for propagating model error, which compounds the longer the model is run. The 60-day run times were long enough for Delta Smelt to reach sizes that would no longer physically fit through the screen mesh

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at BSPP, but not Longfin Smelt, which has much slower early-life growth rates (see "Results"). For all nine release nodes shown in Figure 1, we released particles randomly over 24-hour time-periods to minimize the potential for bias caused by releasing particles on flood vs. ebb tides (Kimmerer and Nobriga 2008). We released particles monthly on the first day of January through April of 2 wet years (2017 and 2019) and 2 dry years (2020 and 2021). Each run lasted 59 to 61 days, ending on the last day of February through the last day of May of each year. This release timing covers the spawning seasons of both smelts while also lessening the likelihood of a consistent longer tidal bias related to the spring–neap cycle.

The 2 wet years had Yolo Bypass flooding, while the 2 dry years had little to no Yolo Bypass flooding (data not shown). Floodplain flow was higher and more prolonged in 2017 than in 2019. Between 10 January and 03 March, 2017, there were 44 days with Yolo Bypass flow >1,416 $m^3 s^{-1}$ (50,000 cfs), while in 2019 there were 14 days that exceeded this flow between February 16 and March 11. This range of Yolo Bypass flow conditions provided enough contrast in system conditions for us to test a hypothesis mentioned by USFWS (2008): "During years when the Yolo Bypass floods, the entrainment risk of larvae into the NBA was also probably extremely localized under historical pumping conditions because of a hydrodynamic "plug" that forms between Barker and Lindsey sloughs with Cache Slough." The implication of this hypothesis is that hydraulic transport into Lindsey Slough from areas outside of it is blocked when the Yolo Bypass is discharging flood water, and as a result only smelt larvae already in Barker or Lindsey sloughs are vulnerable to entrainment. Thus, we expected to see more transport to BSPP and higher risk of entrainment from locations outside of Lindsey Slough in the 2 dry years.

We tracked predicted particle entrainment into BSPP and agricultural diversions. The latter are generally unscreened and individually much smaller than BSPP. However, these unscreened diversions are often aggregated in the DSM2 model grid (i.e., they are represented in DSM2 as a smaller number of larger diversions). We were able to use the predicted loss to these distributed diversions to get a sense of where they are aggregated in the model representation of the CSC. Particle transport and loss to agricultural diversions generates variation in $P_{TR_{id}}$ but is not included in it.

The PTM simulated the number of particles transported from one area to another, on each day. To estimate the probability $P_{TR_{id}}$ and associated uncertainty, we assumed that $P_{TR_{id}}$ were beta-distributed, with some number of particles arriving each day α_{id} and some number failing to arrive β_{id}

$$P_{TR_{id}} \sim \mathrm{Beta}(\alpha_{id}, \beta_{id}) \quad \text{Eq 2}$$

On day one of the simulation, the total number of particles available $\alpha_{id} + \beta_{id}$ was 1,000, and after day one, the total number of particles available declined by the total number arriving on previous days, $\alpha_{id} + \beta_{id} = 1{,}000 = \sum_{1}^{e=d-1} \alpha_{ie}$ for $d > 1$.

Uncertainty in $P_{TR_{id}}$ was characterized using a Monte Carlo simulation with 10,000 draws from the beta distribution, given each and α_{id} and β_{id}

To estimate P_{SL_d} for Delta Smelt, we first estimated length at age from a von Bertalanffy growth model, fit to daily otolith-based ages a, and fork lengths FL_a

$$FL_a = FL_\infty * \left(1 - e^{-k*(a-t_0)}\right) \quad \text{Eq 3}$$

where FL_a were predicted from asymptotic length FL_∞, growth coefficient k, and age a at $FL = 0$ t_0. We estimated these growth parameters using a sample of 153 Delta Smelt that were ≤60 days old based on evaluation of their otoliths (2016 pers. comm., see "Notes"). By rearranging Equation 2 and substituting an estimate of length at hatch, FL_0 ($a = 0$; $FL_0 = 5.3$ mm; Romney et al. 2019), t_0 was calculated directly

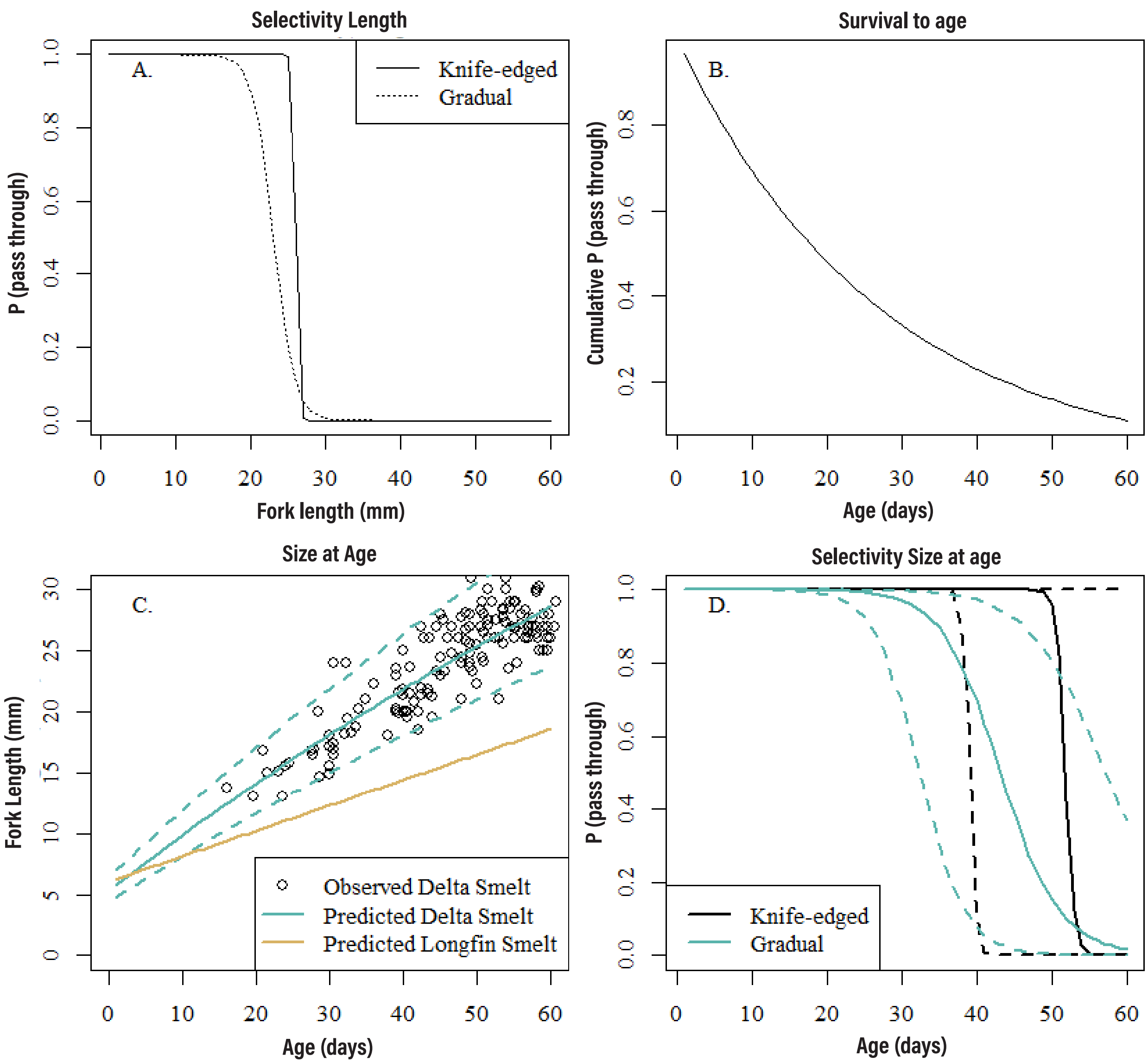

Figure 3 (**A**) (Selectivity) the relationship between fish length and two assumptions about the probability of fish being able to pass through a fish-screen. (**B**) larval fish survival as a function of age. (**C**) (Growth) fish length at age. (**D**) Same as Panel **A** but in terms of age rather than length. Note (**D**) represents only Delta Smelt selectivity, because Longfin Smelt were predicted to be too small to be excluded in their first 60 days post-hatch (i.e., selectivity = 1). *Dashed lines* represent 95% credible intervals for size at age and selectivity, given size at age.

$$t_0 = \frac{1}{k} * \ln\left((FL_\infty - FL_0)/FL_\infty\right) \quad \textbf{Eq 4}$$

and FL_∞ and k were estimated. Because larval growth rates were expected to differ from juvenile and sub-adult growth rates, ages were restricted to 60 days or less to match the length of PTM simulations (Figure 3). Posterior FL_∞ and k were used to predict FL_a on each day of the simulation. Given FL_d, selectivity $P_{SL_{ds}}$ was then calculated.

To estimate Longfin Smelt growth, we applied the model of Gross et al. (2022; see also Supplemental Information therein), who reported that Longfin Smelt hatch over a length range of 5.3 to 6.8 mm and the larvae grow at an average rate of 0.19 mm d^{-1}. The Gross et al. (2022) growth model was in units of standard length. To approximate FL, we multiplied standard length-at-age estimates by the ratio of FL to standard length predictions at a given weight. As length–weight equations for

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Longfin Smelt were unavailable in fork length, we substituted equations of Delta Smelt for the fork- to standard-length conversion (Kimmerer et al. 2005). This generates length predictions remaining under 20-mm after 60 days at both extremes of larval hatch sizes, which is too small to be affected by our selectivity functions (described later), so for Longfin Smelt we simply assumed $P_{SL_{ds}} = 1$.

Existing data show that fish larger than 26 mm FL are physically excluded from entrainment by the BSPP fish-screens (Appendix A); however, these data were insufficient to statistically estimate a selectivity function that would apply to fish smaller than 26 mm. Therefore, we evaluated the sensitivity of our predictions to two selectivity functions based on alternative logistic regression models (Figure 3A). The first was knife-edged, with all lengths less than 26 mm FL passing through the screen ($P_{SL_{ds}} = 1$), and all lengths greater than 26 mm FL being excluded ($P_{SL_{ds}} = 0$). This model assumes fish have no ability to avoid net flow and entrainment until they are physically excluded by the fish-screen. The second selectivity model assumed that 26-mm FL represented the 90th percentile of lengths that passed through the screens, and that selectivity declined gradually from 20 to 26 mm FL. This variant was only applied to Delta Smelt because, as mentioned above, Longfin Smelt do not grow large enough in 60 days to be affected by it. These are very conservative assumptions about screen avoidance as a function of fish size relative to a prior study that indicated a positive-barrier fish-screen on an agricultural diversion in the Delta was limiting entrainment of fish down to at least 12 mm (Nobriga et al. 2004). However, we used the chosen selectivity functions after having discussions with colleagues, who speculated that because BSPP is at the terminus of a dead-end channel, there is little if any sweeping velocity moving parallel to the screen to help fish avoid contacting it.

Cumulative survival, from hatch to day d, was estimated using the daily larval survival estimated by Rose et al. (2013) for Delta Smelt and Gross et al. (2022) for Longfin Smelt, both of which produce essentially identical results (within 0.001), which we summarized as

$$P_{SV_d} = 0.96^d \quad \text{(Figure 3B)} \qquad \textbf{Eq 5}$$

Though publicly available, DSM2 is not easy to compile and apply. To better assist future regulatory evaluations, we used regression techniques to estimate E_{is} using the more accessible Dayflow database. We used beta regression with a logit link to develop statistical models of the relationship between E_{is} and variables that represented pumping rates at BSPP (North Bay Aqueduct diversions; NBAQ), Yolo Bypass flow (Yolo), and the rate of agricultural diversions (Gross Channel Depletion; GCD), using all 16 month–year combinations for the two Lindsey Slough insertion nodes (325 and 326). We used 60-day means of each Dayflow variable to form predictors that matched the time-scale of the PTM data. The full model was

$$\hat{E}_{is} = 1/\left(1 + e^{-(\beta_0 + \beta_1 NBAQ_i + \beta_1 Yolo_i + \beta_1 GCD_i)}\right) \qquad \textbf{Eq 6}$$

where β were regression coefficients. We compared all combinations of predictors—including an intercept-only model—using Akaike's Information Criterion, adjusted for small sample size (AICc), and we estimated $\hat{E}_{is}$ from AICc-model-averaged predictions, among all models. To evaluate historical trends in entrainment risk, we used the AICc-weighted variations of Equation 6 for all years before the period in our analysis (1989–2016). Long-term trends in $\hat{E}_{is}$ were explored by plotting the time-series.

We used R statistical software for all data analyses and visualizations (R Core Team 2021). The growth model was fit using Bayesian methods in JAGS (R package 'R2jags'; Plummer 2003). The Bayesian model used six independent chains, and a large posterior sample of 300,000, discarding the first 25,000 samples as a burn-in. Bayesian methods facilitated the integration of posterior samples of the growth model, with simulated draws of $P_{TR_{id}}$, to characterize how uncertainty in growth and transport propagate into uncertainty in entrainment risk. We fit the beta regression models using nonlinear least squares with the 'betareg' package (Cribari–Neto and Zeileis 2010). We checked models for residual patterns and leverage points, and we removed any outliers or high leverage points to evaluate whether their inclusion or exclusion would change model inference (coefficient estimates or AICc model rankings).

RESULTS

The von Bertalanffy growth model captured the average larval to post-larval Delta Smelt sizes at age (Figure 3C). The fitted model growth parameter, $k = 2.42$ (95% CI: 1.19, 3.80), predicted extremely rapid growth to an asymptotic length $FL_{\infty} = 82.0$ (95% CI: 54.5, 139.1), but this model should not be used to extrapolate beyond the observed lengths included in the analysis, which were all < 35 mm FL. Predicted mean size at age increased from 5.3 mm at hatch to 29.0 mm FL over the 60-day PTM simulation. The 95% CI of FL60 was 23.7 to 34.6 mm, indicating that only larval Delta Smelt growing slower than average would remain vulnerable to entrainment for ≥ 60 days. In contrast, Longfin Smelt were predicted to reach sizes of 18.7 to 20.2 mm FL in 60 days, and if individuals continued growing at this average rate for larvae, they would need about 90 to 98 days to exceed 26 mm FL. In contrast, the selectivity models predicted entrainment of Delta Smelt through the fish-screen would drop rapidly starting 35 days post-hatch if selectivity were gradual, or 53 days post-hatch if selectivity were knife-edged (Figure 3D).

The PTM results showed high variability in particle transport to BSPP and agricultural diversions, ranging from 0 to 100%, depending on release node (Figure 4). Particles released closest to BSPP (node 325) were usually transported there regardless of whether it was a wet or dry year. Particles released at the next closest node (326) usually had high predicted transport to BSPP or agricultural diversions. At node 326,

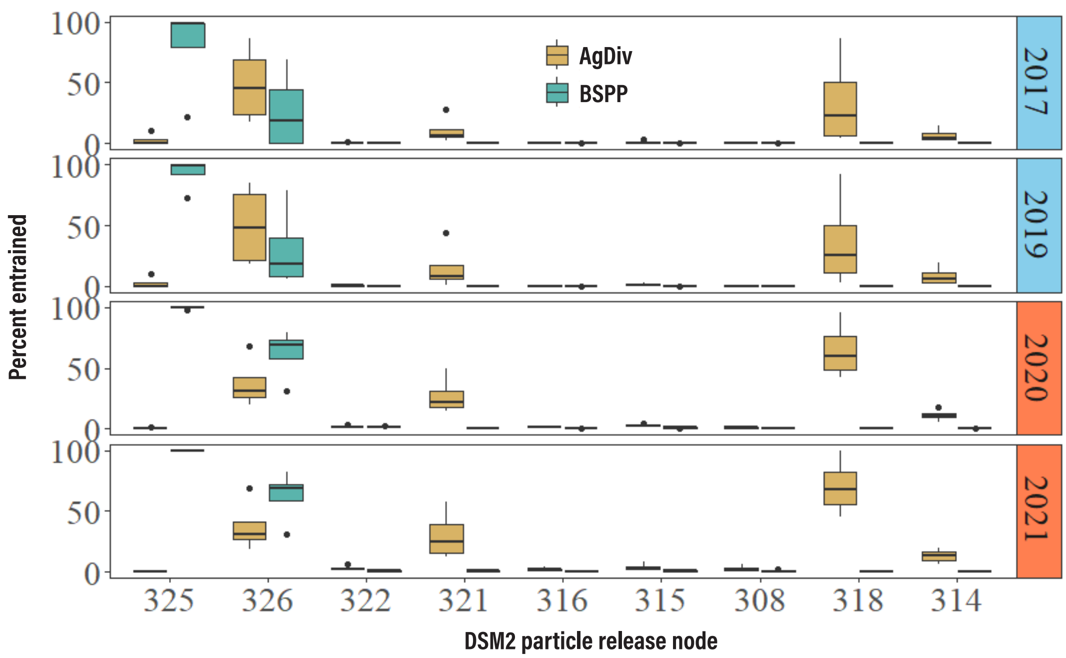

Figure 4 Boxplot summarizing particle fate predictions for n = 144 PTM runs as percent entrainment into either agricultural water diversions (AgDiv) or Barker Slough Pumping Plant (BSPP). The *boxes* depict the median and interquartile range, the *whiskers* depict the 95% confidence interval, and *individual points* are outliers beyond expectations from a normal distribution. Note that the particle release nodes are listed from left to right along the *x*-axis by rank distance from BSPP, and the 2 wet years have *blue banners* while the 2 dry years have *red banners*.

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transport to agricultural diversions was predicted to start faster than transport to BSPP, leaving smaller fractions of particles available to reach the latter (Figure 5). Elsewhere in the CSC the likelihood of hydraulic transport to BSPP within 60 days was zero or very close to zero (Figure 4; maximum = 2.2% for node 322 at the confluence of Lindsey and Cache sloughs in April–May 2021). Predicted loss to agricultural diversions showed no relationship to distance from BSPP but, in addition to node 326, was also relatively high from nodes 318 (Prospect Slough) and 321 (Cache Slough), suggesting that DSM2 has aggregated diversion locations at or near these three release sites. Overall, there was some wet year vs. dry year difference in the variability of predicted transport to BSPP for particles released within Lindsey Slough but not to the east of it. Thus, the PTM results did not support the hydraulic "plug" hypothesis.

For particle releases within Lindsey Slough, point estimates of E_{is} varied widely, ranging from 0.001 to 0.740 for Longfin Smelt, and from 0.000 to 0.807 for Delta Smelt (see Appendix B). The conversion of PTM information into *Eis* using fish vital rate information generally resulted in lower estimates of predicted Delta Smelt and Longfin Smelt entrainment than PTM alone would have indicated (Figure 6). Further, when PTM-based transport predictions were higher than about 0.5, the E_{is} were often uncorrelated with their associated PTM prediction. This reflects the importance of biological vital rates in the estimation of BSPP entrainment risk. Entrainment indices E_{is} were not sensitive to the choice of selectivity function, and were always zero for all particle release locations further from BSPP than node 326 (data not shown).

The best beta regression model of the entrainment index included NBAQ and GCD (i.e., the two Dayflow variables that best represent the amount of water being diverted in the CSC; Table 1; Figure 7). This model had 59% of AICc model weights for both smelts. The scatter around the line in Figure 7 probably represents the imprecision that arises from using Dayflow variables to predict the entrainment indices.

The second-highest AICc-weighted model also included Yolo Bypass flow and had ~29% of AICc model weights (Table 1). The slopes of the Yolo Bypass coefficients were negative, suggesting that entrainment into BSPP declines as floodplain inflow increases, but the *p*-value and coefficient of variation associated with the Yolo Bypass coefficients were relatively high, with *p*-value = 0.13 and CV = 0.66 for the Delta Smelt model, and *p*-value = 0.14 and CV = 0.68 for the Longfin Smelt model. The AICc model-averaged predictions for the historical time-series of the entrainment index, $\hat{E}_{is}$ varied from 0.028 to 0.45, within the range of 2017 to 2021 estimates to which the beta regression models were fit. Over the 28-year hindcast, $\hat{E}_{is}$ declined for all 2-month periods except April–May (Figure 8).

DISCUSSION

The dominant influence of proximity to water diversions has been well-documented in studies evaluating the potential for small fish to be entrained in Suisun Marsh and the Delta (Culberson et al. 2004; Kimmerer and Nobriga 2008). However, integration of physical and biological models has been a valuable tool to improve predictions of the potential consequences of water diversion to Osmerid fish, particularly for life stages that are too small to quantify *in situ* with high accuracy (Kimmerer 2008; Rose et al. 2013; Smith et al. 2020; Gross et al. 2022; Kimmerer and Gross 2022). For BSPP, we found proximity was very important, but even then the inclusion of information about vital rates can cause predictions of larval fish entrainment risk to be considerably lower than what is implied by particle tracking. This results primarily from the low probability of individual fish larvae surviving for extended periods. Larval Delta Smelt may also grow large enough to avoid being pulled through the fish-screens in 35 to 53 days, but the similarity of the Delta Smelt and Longfin Smelt confidence interval widths in Figure 6 indicates that mortality is mathematically the more important process. Thus, we conclude: (1) Barker and Lindsey sloughs can generally be thought of as an ecological sink for larval Osmerid fish production if they spawn there (i.e., a proximity effect), but

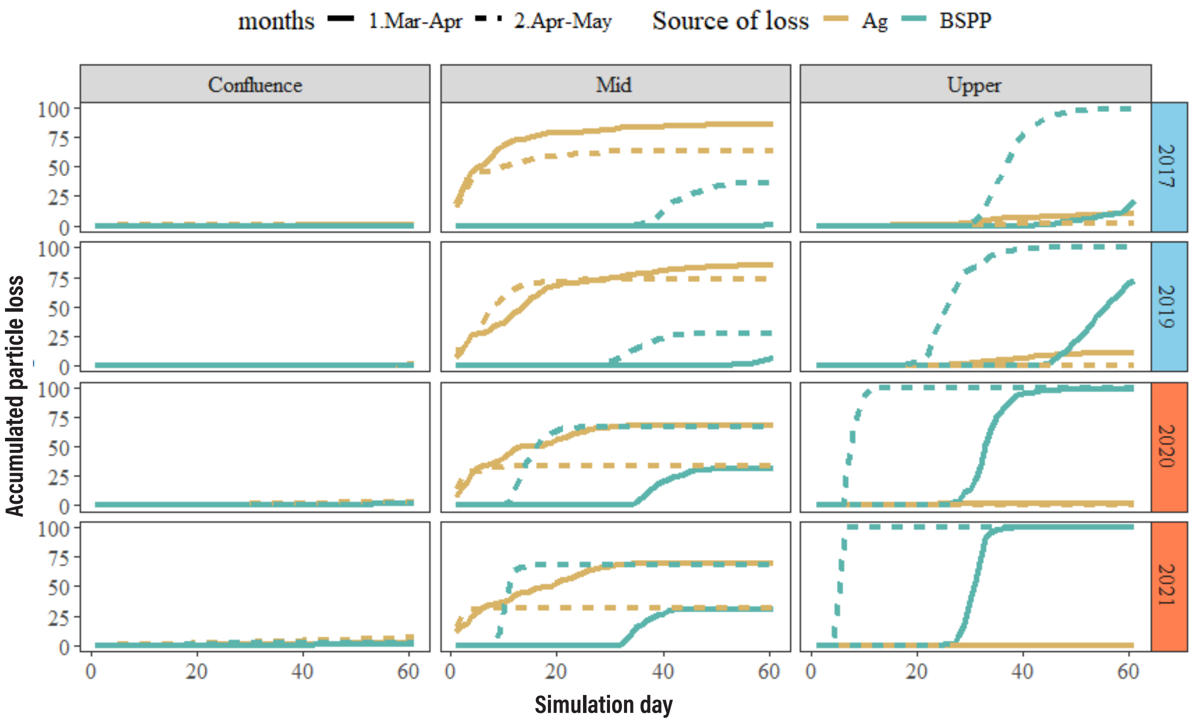

Figure 5 Selected time-series of cumulative particle entrainment into agricultural diversions (*gold*) and the Barker Slough Pumping Plant (BSPP; *teal*) for the three particle insertion nodes closest to BSPP. From left to right, "Confluence," "Mid," and "Upper" represent particle insertion nodes 322, 326, and 325. Day 0–61 are either March 1–April 30 (*solid lines*) or April 1–May 31 (*dashed lines*). The 2 wet years have *blue banners* while the 2 dry years have *red banners*.

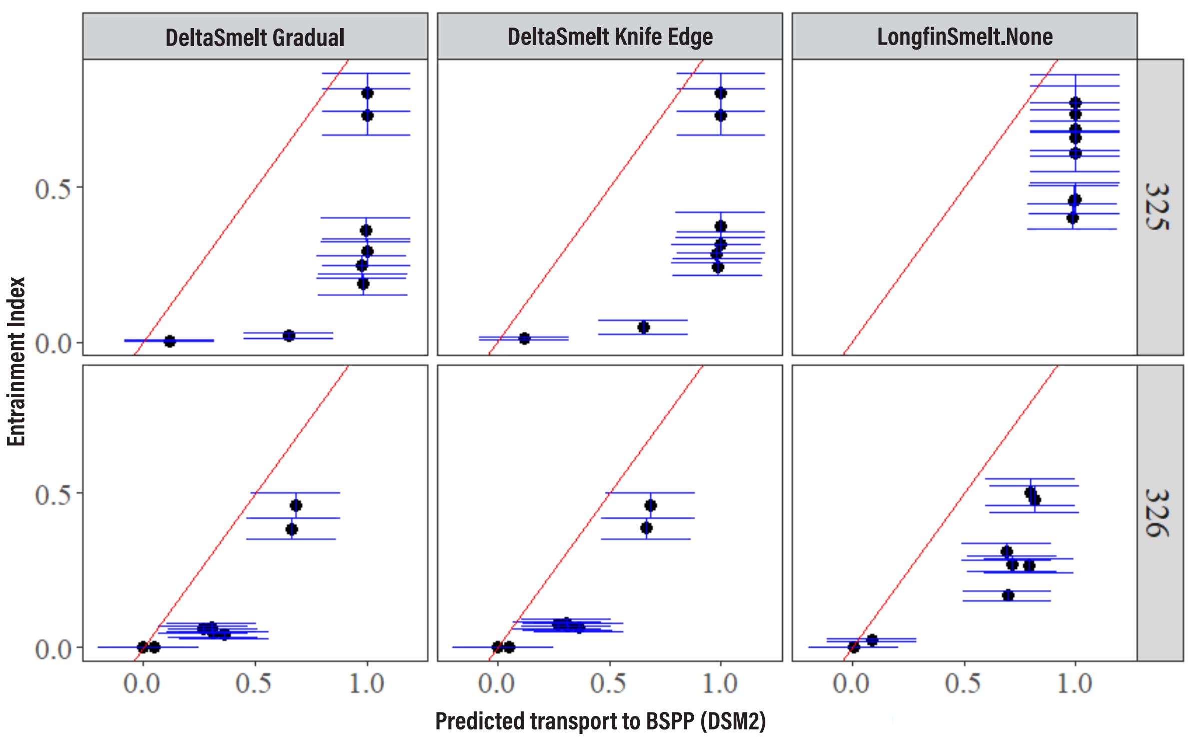

Figure 6 Scatterplots of the predicted transport to Barker Slough Pumping Plant (BSPP) from the DSM2 Particle Tracking Model vs. variations of the entrainment index (E_{is}). The *facet labels* provide the species, associated selectivity-model choice (gradual, knife-edged, or none), and particle insertion node (325 or 326). The 95% confidence intervals around the entrainment index predictions are shown as *blue error bars* and the *red lines* are 1:1 regression lines, demonstrating that most entrainment indices were lower than what was predicted by hydraulic transport.

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Table 1 Akaike information criteria (AICc) scores and model weights for all beta regression models of the Delta Smelt entrainment indices vs. Dayflow variables. NBAQ was North Bay Aqueduct exports; Yolo Bypass outflow, representing Cache Slough complex, and GCD was gross channel depletion, representing agricultural diversions.

				Coefficient p-values		
Model	AICc	ΔAICc	AICc weight	NBAQ	Yolo	GCD
NBAQ+Yolo+GCD	–43.2	1.5	0.285	< 0.001	0.124	< 0.001
NBAQ+GCD	–44.7	0.0	0.591	< 0.001	—	0.001
NBAQ+Yolo	–38.4	6.3	0.026	0.002	0.434	—
Yolo+GCD	–31.3	13.4	0.0007	—	0.002	0.106
NBAQ	–41.0	3.7	0.095	< 0.001	—	—
Yolo	–32.6	12.1	0.001	—	0.01	—
GCD	–28.7	16.0	0.0002	—	—	0.814
Intercept only	–31.3	13.4	0.0007	—	—	—

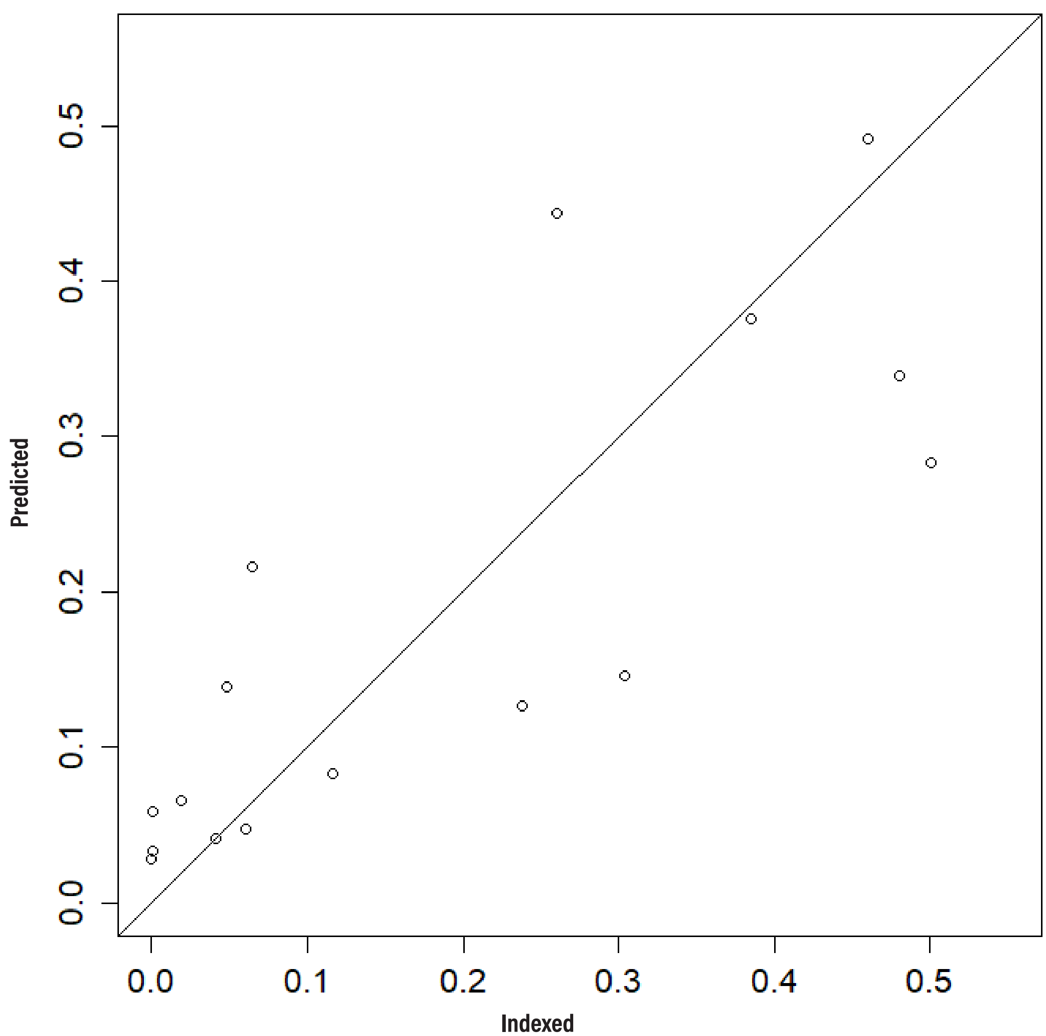

Figure 7 Lower Lindsey Slough entrainment index, calculated as the product of transport, selectivity, and survival (Index) vs. estimated from a regression model (Predicted) with Barker Slough Pumping Plant exports, Yolo Bypass flow, and agricultural diversions as predictors

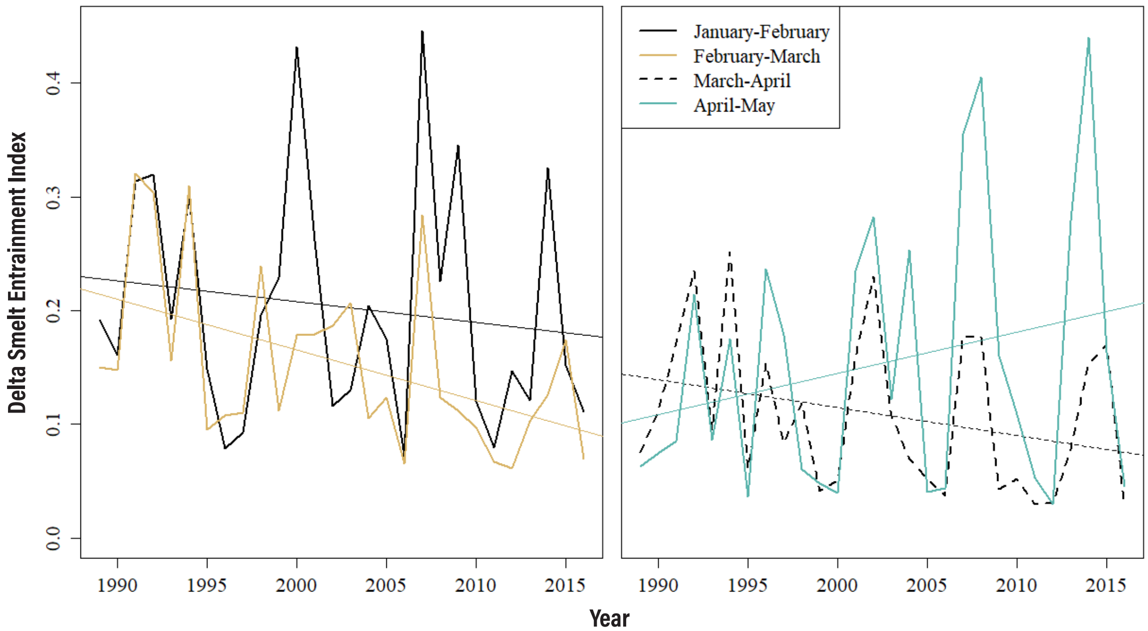

Figure 8 Time-series of entrainment indices from the first year of Barker Slough Pumping Plant operation from 1989 to 2016, including long-term trend lines for the pairs of months indicated in the legend

(2) there is no quantitatively meaningful risk of BSPP entrainment for larval smelts spawned outside of Barker or Lindsey sloughs because of the combined low probabilities of transport and survival. The mouth of Lindsey Slough has been considered as a potential site for stocking hatchery-origin Delta Smelt; however, we think this may be a poor choice of release location for the Delta Smelt supplementation effort as it moves forward, unless these adult fish can be shown to predominantly disperse elsewhere before spawning.

The DSM2 is good at predicting tides, water levels, and net flows in particular channels, but it less accurately predicts mixing at channel junctions and in open-water areas (MacWilliams et al. 2016). It also loses accuracy when inflows are low and tidal flows dominate (Sridharan et al. 2018). Channel junctions, open waters, and low inflows are features of the CSC (Figure 1). Thus, DSM2 may not accurately predict tidal exchange at junctions that are important to our analysis such as the confluence of Cache Slough and Lindsey Slough. The DSM2 PTM distributes particles into channels as a weighted average of the predicted flows in and out of the channel junctions. If DSM2 is getting those exchanges wrong, then that error propagates through the PTM at every modeled time-step. This, in turn, could lead to a relationship between run time and model prediction error. The potential for prediction error is important in our application because the PTM was run for 60 days, and the results suggested limited exchange between Barker and Lindsey sloughs and other parts of the CSC (Figure 4). Our conclusions about entrainment risk are based to large degree on the accuracy of the PTM's prediction of exchange between Cache and Lindsey sloughs. Stumpner et al. (2021) found the longest tidal excursion in the CSC propagates up the Sacramento Deep Water Ship Channel (Sacramento DWSC). This makes intuitive sense because the largest and deepest channels in the CSC are Cache Slough and the Sacramento DWSC, so they would be expected to convey most of the regional water volume being moved by the tides. Further, Stumpner et al. (2021) showed that, given Lindsey Slough's length relative to the extent of the tidal excursion into it, the uppermost 40% of Lindsey Slough—which includes Barker Slough—is essentially a "no exchange zone" relative to

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the slough's lowermost 30%, which regularly exchanges water via tidal flow with Cache Slough. Thus, the PTM results seem at least qualitatively consistent with what is known about CSC hydrodynamics.

Within Lindsey Slough, particle transport to BSPP and modeled entrainment risk were more variable in wet years than dry years. However, we estimated that the risk of entrainment from locations outside Lindsey Slough was zero in all 4 years, suggesting the mechanism for wet vs. dry year differences is not caused by some form of the hydraulic "plug" hypothesis, i.e., floodwaters from Yolo Bypass blocking reverse flow or muting tidal flow into Lindsey Slough. Further, Yolo Bypass flow was an unreliable predictor of our entrainment indices. We speculate that the greater tidal flow flooding and ebbing in Cache Slough and the Sacramento DWSC (Stumpner et al. 2021) may be what limits transport into Lindsey Slough when the Yolo Bypass is not discharging large flood flows such that there is essentially always some form of a hydraulic "plug." The low predictive power of Yolo Bypass flow may also suggest that a more localized mechanism controls entrainment risk from within Barker and Lindsey sloughs. Our best guess at this mechanism is that local rainfall may have increased net flow out of Lindsey Slough in 2017 and 2019 compared to 2020 and 2021. It is logical that more rain across the entire region would associate net flow out of both Lindsey Slough and Yolo Bypass to some degree, but flows from the Yolo Bypass also have a flood-management aspect that can decouple floodplain flow from local rainfall. We suspect that is what generated the weak statistical relationship between Yolo Bypass flow and transport to BSPP in our beta regression models. These hypotheses could be tested more rigorously by combining rainfall data with higher- dimension hydrodynamics models if that was deemed important by others, but it was beyond our scope to do so. For now, we conclude that if there is a mechanism that increases larval smelt losses to BSPP in dry years, it would need to be higher fractions of fish spawning in Barker or Lindsey sloughs in dry years.

The 1995 Delta Smelt Biological Opinion mandated an intensive larval fish monitoring program that sampled several locations in the CSC every other day during the Delta Smelt spawning season (USFWS 2005). Despite the intensity of the sampling effort, the program collected few Delta Smelt larvae from Barker Slough during 1995–2003 (Figure 2), a time when SAV was less abundant and Delta Smelt were relatively more abundant (Nobriga et al. 2005). This led to the program's eventual discontinuation, although no attempt to synthesize across relatable sources of information occurred at the time. Therefore, what remained unclear was whether the low catches were a result of entrainment quickly cropping recently hatched fish in the near-field environment, or the result of only small numbers of Delta Smelt spawning in Barker or Lindsey sloughs. We think our results suggest that the information collected by the discontinued North Bay Aqueduct monitoring program reflected infrequent use of Barker and Lindsey sloughs for spawning because the hydraulic transport times predicted by PTM are generally longer than the 2-day sampling interval (Figure 5).

Was Lindsey Slough an important spawning habitat in more recent decades? We know that Delta Smelt historically spawned in the CSC (Kurobe et al. 2022) and may continue to do so. Longfin Smelt are also thought to spawn in the CSC during low-outflow winters (Gross et al. 2022), but how much that has applied to Lindsey Slough *per se* is unknown because the primary larval Longfin Smelt monitoring program does not currently sample there (Eakin 2021). Beds of SAV have expanded considerably in the CSC over the past 10 to 20 years, and by 2018 appeared to have resulted in the disuse of Lindsey Slough and upper Cache Slough by both Delta Smelt and Longfin Smelt (Smits et al. 2025). This is also reinforced by the catch of only a single Delta Smelt larva and no Longfin Smelt larvae in two seasons of extensive sampling behind the BSPP fish-screens (Appendix A). Thus, current information suggests that habitat conditions may not even support spawning by these species close enough to BSPP to result in meaningful entrainment into it.

Our entrainment indices, which are composites of different models, were estimatable using publicly available Dayflow data, which might reduce the need for separate hydrodynamic modeling when proposed changes to BSPP operations during the winter and spring are evaluated. However, there are several caveats in addition to the habitat trends reviewed above. First, these indices are not population-scale predictions, they are predictions of the likelihood that fish hatching from within Lindsey Slough will be entrained into BSPP based on the assumption that transport from outside of Lindsey Slough is essentially zero. Second, the wetted geography of the CSC is being changed by habitat-restoration projects (Hartman et al. 2024). This will, in turn, change regional hydrodynamics, which may increase the prediction error of our regression model. Third, the model has a relatively low sample size ($n = 16$) given its three to four estimated parameters, so overfitting is possible. Future efforts to refine a statistical surrogate for our BSPP entrainment index should expand the number of years modeled with DSM2 or other hydrodynamic modeling tools.

The application of our Dayflow-based regression model to historical conditions suggested that BSPP entrainment risk has declined during winter but increased in the spring. Longfin Smelt spawn in the winter, so their entrainment risk has probably declined irrespective of the habitat changes reviewed above. The direct application of this result to Delta Smelt may be more nuanced. Delta Smelt spawn later, so their risk may have increased because of the trend of increasing BSPP exports in April–May. However, this conclusion depends on whether they can still spawn in Lindsey Slough. Further, if current pumping trends persist, Delta Smelt entrainment risk may decrease as climate change drives earlier spawning (Brown et al. 2016).

The combination of Lindsey Slough habitat trends reviewed above and lack of predicted entrainment risk from areas outside of Lindsey Slough also serves to limit concern about impingement of fish that outgrow the risk of entrainment. Nonetheless, for completeness, we review this risk. Fish approaching screened water diversions may still be pinned against the screen by intake flow (i.e., become impinged). Swanson et al. (2005) observed impingement causing the death of 25- to 40-mm Delta Smelt in a laboratory setting. Impingement and subsequent mortality were related to screen contact rates and durations, which were, in turn, related to flow velocity. These "fish treadmill" experiments contributed to the regulation of approach velocities down 0.2 ft s^{-1} (~0.06 m s^{-1}) to 0.4 ft s^{-1}(~0.12 m s^{-1}) for fish-screens deployed on water diversions in the Delta, and these criteria have turned out to be protective of a wide range of aquatic taxa and life stages (Bretzel et al. 2024). Nonetheless, the screen vulnerability models we used for Delta Smelt may not be predicting decline in vulnerability to mortality at BSPP but a transition from entrainment to impingement related to increasing body size and mass that limit passage through the screen. For instance, the data shown in Figure A1 in Appendix A could reflect three phenomena that are not mutually exclusive: (1) an average early life mortality rate experienced by the assemblage of fish that was collected behind the BSPP fish-screens; (2) an ability of fish more than ~8 to 10 mm to begin avoiding entrainment, or (3) a transition from entrainment to impingement that starts at sizes smaller than what could theoretically be pulled through the screen mesh.

Stocks et al. (2024) evaluated the entrainment and impingement of Murray Cod *Maccullochella peelii*, through wedge-wire fish screens in a laboratory setting. Unfortunately, they only evaluated impingement of fish that were too large to fit through their experimental fish-screens, so their dataset cannot confirm how often larvae may be impinged without being pulled all the way through a fish-screen. However, they did find that once screen approach velocities equaled or exceeded 0.1 m s^{-1}, Murray Cod larvae ranging from 10.0 to 11.4 mm in length would be entrained at rates comparable to an unscreened water diversion, which suggests the larvae were not frequently impinged. They also found that impingement of 23- to 29-mm Murray Cod increased approximately linearly, given any non-zero approach velocity; at approach velocities

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comparable to BSPP operation (0.06 to 0.12 m s^{-1}), the impingement rate was ~10% to 25%. We note that in this experiment, the fish were corralled to within 80 mm of the experimental fish-screen, so how well these results would translate to *in situ* conditions is extremely uncertain.

Small unscreened water diversions such as most of the Delta's agricultural diversions, and water diversions with positive barrier fish-screens, such as BSPP, can introduce spatial scale dependencies that may lead to overestimation of entrainment loss in 1-D models (e.g., Nobriga et al. 2004; Kimmerer and Nobriga 2008). Unlike the South Delta pumping plants, the diversions considered in this study have a much more localized hydraulic influence, which affects entrainment risk differently. In unscreened water diversions typical of those in the Central Valley, the hydraulic influence is on the order of 2 m or less from the intake mouth (Ercan et al. 2017). Similarly, in the laboratory flumes deployed by Stocks et al. (2024), the approach velocity toward the screen was zero only 300 mm (approximately 1 foot) away from the screen face at approach velocities comparable to BSPP operations. As a result, fish must approach these diversions very closely, often within just 1 or 2 meters to face a meaningful risk of entrainment or impingement. Whether this occurs depends on how fish interact with habitat near the diversion site (Nobriga et al. 2004). The early life stages of Delta Smelt and Longfin Smelt are unlikely to exert much influence over their distribution, but as they grow and can swim more strongly, they can change their position in the water column relatively quickly and use tidal transport to maintain position or disperse (Bennett et al. 2002; Kimmerer et al. 2014). Once they begin to metamorphose into juveniles, both smelts are believed to generally avoid in-water structures and SAV (e.g., Smits et al. 2025). It is not known at what sizes they can reliably do this, but it very likely depends on local current velocities and the availability of habitat gradients they can perceive. These potentially important but small-scale interactions of fish with their open-water habitats could further decouple hydrodynamics-based entrainment (and impingement) predictions such as those developed or reviewed here from how often the fish will get within e.g., 1 foot of an in-water structure such as the BSPP fish-screens. If further research into fish entrainment or impingement at BSPP is deemed warranted, we recommend focusing on the near-field micro-habitats and associated fish behaviors related to entrainment and impingement in the context of larger-scale patterns of fish habitat use, which have changed rapidly over the past 2 decades (Mahardja et al. 2017; Smits et al. 2025).

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