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Identifying the environmental conditions that determine the distribution of an endangered estuarine fish to manage risk of entrainment

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Allocation of scarce water resources to meet beneficial but competing end uses has become commonplace in drought-stricken western North America. In the Sacramento-San Joaquin Delta in California, regulatory agencies endeavor to protect the endemic and imperiled delta smelt from entrainment at water-project pumps, while meeting critical water deliveries to agriculture and urban users. The current water management strategy is not effective at or efficient in meeting those dual goals. To improve current management practices, we develop a risk-based strategy that protects delta smelt from population-level impacts from water-project pumping, while enhancing essential water deliveries to consumers. We identify and quantify the environmental factors associated with the presence of delta smelt in the vicinity of water-project pumps. Essential in this process is the identification of "precedent" factor conditions that contribute to determining the distribution of delta smelt. When delta smelt are likely not near the pumps in the south Delta, the risk of entrainment is low, allowing for water deliveries to be increased with *de minimis* losses of delta smelt. We present predictive management-guidance models that identify the environmental-factor conditions influencing rates of take for three delta smelt life stages. In a simulation for a 22-year period of water-project operations, the implementation of a risk-based strategy keeps losses of delta smelt under specified limits in all years, while increasing water deliveries by an average of more than 250,000 acre-feet (306,000 ML) per year. The models allow resource managers to identify in real time the ecological circumstances that signal impending heightened risks to delta smelt, thereby triggering appropriate conservation responses.

KEYWORDS

delta smelt, imperiled species, entrainment risk, precedent conditions, resource-management strategy, predictive model

Introduction

Natural resource managers are frequently challenged with difficult allocation decisions necessitating tradeoffs between environmental and social benefits (National Research Council, 1996, National Research Council, 2004, National Research Council, 2005). With freshwater required to meet diverse demands and competing needs, its allocation in estuaries inevitably provokes dilemmas for decision-makers and is frequently controversial. When those needs include in-stream flow requirements to maintain healthy fisheries and water diversions for human uses, such as irrigation and human health and safety, options may be few and constrained. Those competing needs inevitably vary by season and water supplies vary with weather, forcing a dynamic and stochastic decision framework. Add mandated obligations to protect threatened and endangered species and decision making by resource managers can face intense scrutiny. Here we examine a fraught situation wherein the need to protect the endangered delta smelt from entrainment at water-project pumps in the Sacramento-San Joaquin Delta competes with the need to supply freshwater to meet public benefits there and elsewhere in California.

Delta smelt inhabit a greatly fragmented and highly manipulated ecosystem – a relatively narrow zone of low salinity in an estuary populated with non-native competitors and predators and subjected to ever-increasing anthropogenic disturbances (IEP MAST, 2015). In particular, the estuary facilitates the conveyance of water from northern California, where water is typically plentiful, to southern California where water for agricultural and urban uses is frequently in short supply. Large state and federal water-project pumps divert water from the upper San Francisco Estuary, but despite facilities and interventions that salvage and relocate fish, existing protective measures are not entirely effective. The diminutive delta smelt can be vulnerable to losses at the export pumps. Because delta smelt are imperiled, protected under federal and state Endangered Species Acts, regulations have been implemented to protect them from entrainment events (USFWS, 2008; USFWS, 2019; CDFW, 2020).

Losses or "take" of delta smelt at water-project pumps vary in response to hydrologic and other abiotic conditions and with the delta smelt's habitat needs and patterns of occupancy, which vary by life stage. As such, a variety of environmental conditions have been hypothesized to increase or to reduce rates of take of delta smelt. The purpose of this study is to develop a response strategy that protects delta smelt from population-level impacts due to water-project pumping, while enhancing essential water deliveries to California's agriculture and to urban consumers.

Here we explore the role of environmental factors affecting rates of take. Critically, we begin by identifying "precedent" factor conditions that contribute to determining the distribution of delta smelt. The presence and timing of those environmental conditions actuate entrainment-risk levels for delta smelt, therefore are essential in triggering and prescribing water-project operations. With the identification of high-risk periods and estimates of rates of take, water-project operations can be modified to prevent losses of delta smelt that could have population-level consequences.

Currently resource managers meet weekly through the winter and spring to assess real-time risk of entrainment and modify water-project operations in efforts to protect delta smelt and other endangered fishes that reside in or migrate through the Delta. That "risk assessment" process utilizes a variety of information, including changing environmental conditions and delta smelt presence-absence data generated from trawl surveys (CDFW, 2020). But delta smelt appear infrequently in general fish surveys and probability of detection decreases as abundance decreases (Peterson and Barajas, 2018). Accordingly, a single fish near the pumps might indicate a substantial and consequential entrainment event is imminent. Then again, a single fish may be a lone stray, the take of which at the pumps would essentially have no impact on the dwindling population.

Resource managers need to differentiate between those two circumstances for two reasons. First, because the once-abundant delta smelt are so rarely sampled in long-term trawl surveys, its population is currently being supplemented with the release of thousands of hatchery fish annually (Bland, 2022). Second, regulations intended to protect delta smelt from entrainment require curtailing water exports from the Delta, resulting in significant reductions in water deliveries. With few naturally occurring delta smelt observed in surveys, managers have moved away from specifying allowable take of the fish at the pumps (referred to in the operating permits as "incidental take levels") based on observed abundances in surveys. In place of that approach to informing management actions, implemented regulations now rely on a flow-based strategy that defaults to limits on water exports under a wide range of flow conditions (CDFW, 2020). That pragmatic strategy comes at significant costs to water users, with benefits for delta smelt that are challenging to quantify (Smith et al. (2021).

The purpose of this study is to develop a "risk-based" strategy that protects delta smelt from population-level impacts of water-project pumping, while enhancing essential water deliveries to California's agriculture and urban consumers. The strategy differentiates between high-risk conditions, when delta smelt are likely to be proximate to the export pumps, requiring more restrictive water-project operations, from low-risk conditions when delta smelt are distant from the pumps, providing opportunities for increased water deliveries. The predictive approach to water-resource management allows for increased protection for the imperiled delta smelt while providing for increased water deliveries in many situations. Additionally, the approach offers defensible quantitative support for policy makers and resource managers who must make controversial decisions that simultaneously have great ecological and economic consequences.

Methods

To develop and evaluate a risk-based strategy to improve the efficacy of water-project operations in minimizing losses of delta smelt – 1) we identify the environmental conditions that predictably precede high rates of delta smelt take at water-export pumps, 2) we explore differences in rates of delta smelt take at the pumps in years with differing hydrodynamic conditions across delta smelt life stages, and 3) we develop a model that can inform real-time management decisions to minimize entrainment of delta smelt and lessen reductions in water exports. Here we briefly describe relevant attributes of the upper San Francisco Estuary and relevant delta smelt ecology before presenting a conceptual ecological model, which we use as a foundation for the quantitative analyses.

An extensive inland delta exists upstream of the confluence of Sacramento and San Joaquin rivers in California. Downstream of the rivers' confluence is Suisun Bay and Suisun Marsh. Those areas of open water and wetlands form the upper estuary of the San Francisco Bay, providing habitat for the endemic delta smelt, a fish protected under federal and state Endangered Species Acts. The estuary is tidally influenced and has been greatly altered during the past century and a half. The dendritic sloughs, extensive marshlands, and floodplains that surrounded them dominated the Delta before European settlement but have been nearly completely replaced by agriculture and managed wetlands set behind fortified levees (Whipple et al., 2012). Within this highly manipulated and fragmented ecosystem, the endangered delta smelt persists in aquatic communities that are populated with non-native competitors and predators, are embedded in highly altered food webs, and are subject to ever-increasing anthropogenic disturbances (IEP MAST, 2015).

The Delta also is the hub of a vast infrastructure system in which water is conveyed from rivers and reservoirs in the Sacramento River watershed at distances of up to 500 miles (800 km) to arid central and southern California. In years with greater precipitation, the water system can convey more than 6.5 million acre-feet (8 million ML) from the Delta (DWR Dayflow, 2024). Reservoirs in the Sacramento River watershed capture runoff, reregulating river flow to the Delta. Water is then conveyed across the Delta through rip-rapped channels to pumps at its southern end, where the water is pumped into canals that deliver the water southward. The capacity of these pumps is massive – with an installed capacity of 15,000 cfs (425 ML/s) (DWR, 1997; USBR, 2024). As water is exported from the Delta, fish screens upstream of the pumps divert fish into fish-salvage facilities. But, with predation at fish screens and a salvage process that is not entirely effective, many fish die. Several endangered fish species along with delta smelt are subject to entrainment at the water-project pumps, including spring-run and winter-run chinook salmon (*Oncorhynchus tshawytscha*), steelhead (*Oncorhynchus mykiss)* and longfin smelt (*Spirinchus thaleichthys)*. The diminutive delta smelt are particularly vulnerable. Because delta smelt are protected as endangered, regulations have been implemented to protect them from entrainment (USFWS, 2008; USFWS, 2019).

The delta smelt is restricted to the upper San Francisco Estuary in California. Its range extends from the Napa River in the west through Suisun Bay and Marsh, the northern Delta, northeast to Yolo Bypass and the Sacramento deep water ship channel (Figure 1). Most delta smelt live for just one year. Their annual life cycle can be parsed into life stages, in part to facilitate analysis – eggs (January to June), larvae (April to June), sub-juveniles (April to August), juveniles (June to December), subadults (September to December), pre-spawning adults (January to April), and spawning adults (January to May) (see Merz et al., 2011). It is understood that delta smelt disperse throughout the upper estuary and are most frequently found in areas that exhibit narrow ranges of salinity, turbidity, temperature, and food availability, requirements for which vary by the fish's life stages (Simonis and Merz, 2019; Hamilton and Murphy, 2020). Storm events in the Central Valley and surrounding watersheds are major drivers of those environmental conditions in the Delta (IEP MAST, 2015), with hydrologic conditions in the Delta strongly influenced by large changes in through-Delta flows from the east and tidal forcing from the west.

When delta smelt were more abundant, their presence in fish salvage facilities varied greatly from year to year, from fewer than 100 individuals (from 2014 to 2018) to more than 150,000 (in 1999) (CDFW, 2024). Within a given year, salvage of delta smelt generally starts slowly and exhibits a bell-shaped curve. In some years, two salvage maxima can occur for adults. The starting date of salvage also varies annually, ranging from early December to mid-March. Managing water-project operations to protect delta smelt given this intra- and inter-year variability has challenged resource managers. Entrainment of delta smelt can occur during some or all of three delta smelt life stages: pre-spawning adults, spawning adults, and juveniles.

Conceptual ecological model

Several conceptual ecological models addressing delta smelt entrainment have been referenced by resource managers in their efforts to mitigate delta smelt mortality at the water-project pumps (see USFWS, 2008 Attachment A and Figure B-13, Grimaldo et al., 2009; IEP MAST, 2015; Grimaldo et al., 2021). Those conceptual models include common elements.

The first major inflow event (colloquially, the "first flush") resulting from winter and early spring storms generates a pulse of freshwater, increasing turbidity and decreasing salinity throughout the Delta. The first flush allows delta smelt to expand their distribution into previously unsuitable areas of the Delta, including into areas of the central and south Delta nearer to water-project pumps in the extreme south of the Delta (Grimaldo et al., 2009; IEP MAST, 2015). Those pumps can create southward flows, net of tidal influences, in the channels leading to the pumping facilities, which are in the opposite direction of the natural downstream flow on more than 80% of days between January and June (USGS, 2024). Delta smelt entering the central and south Delta are vulnerable to entrainment because some stay located in areas that experience turbidity and salinity conditions that are suitable to the fish, allowing them to be drawn toward the water-project pumps.

Delta smelt that have even a small probability of being entrained are said to be in the "zone of influence" of the pumps (also referred to as the "vicinity of the pumps"). That entrainment-risk zone is not a static geographic area, rather it increases in extent as flows toward the pumps increase. If delta smelt are entrained, they were previously located within the zone of influence.

The take of delta smelt at water-project pumps is dependent on the density of delta smelt in the vicinity of the project pumps and the volume of water pumped. The density of delta smelt in the zone

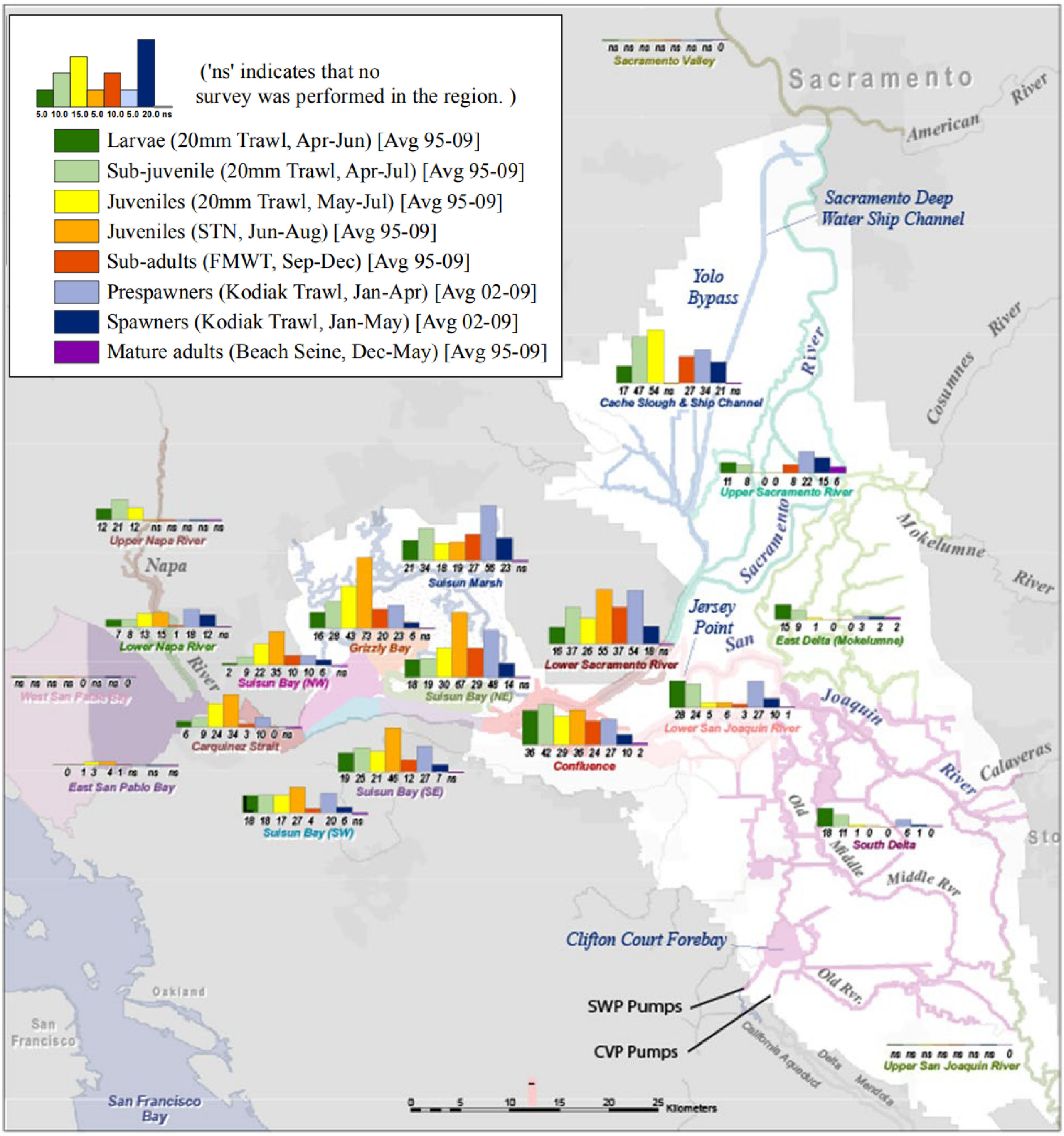

FIGURE 1
Map of the Sacramento-San Joaquin Delta and Suisun Marsh (white background) showing average frequency of detection of delta smelt by life stage and subregion (adapted from Merz et al., 2011). The numbers underneath the columns represent the percentage of times delta smelt have been observed in trawl surveys in each subregion from 1995 through 2009. "ns" indicates that no surveys were conducted for that life stage in the subregion. Waters generally flow through the Delta from east to west but disrupted by flows in Old and Middle rivers to the pumps in the south Delta.

of influence of the pumps, is hypothesized to be influenced by interactions among several ecological factors –

1. the size of the delta smelt population – the greater the abundance of delta smelt, the more of them may be entrained,
2. abiotic conditions (water temperature, turbidity and salinity), influenced by gross volume of inflow into the Delta, which determines areas within the Delta that are suitable for delta smelt,
3. the magnitude of southerly flows in Old and Middle rivers, which draw delta smelt towards the pumps, and

4. the magnitude of San Joaquin River flows that move delta smelt downstream and away from the pumps.

Our conceptual ecological model (Figure 2) expands on earlier conceptual models that were narrative in nature (Kimmerer, 2008, IEP Grimaldo et al., 2009; IEP MAST, 2015; Korman et al., 2021) and better characterizes the distribution of delta smelt in response to inter-annual differences in through-Delta flows. It does so in two essential aspects. First, our conceptual model recognizes that certain environmental conditions – or "precedent conditions" – in addition to a first flush, are necessary stimuli for delta smelt to move into and reside within the zone of influence of the pumps. Absent those precedent conditions, rates of take at the pumps are very low, independent of other environmental factors. Second, our model recognizes important differences in the responses of delta smelt life stages to varying environmental conditions. Delta smelt respond to environmental conditions differently in each of their life stages as they physiologically shift from feeding and growth to reproduction (Hamilton and Murphy, 2020).

Identifying precedent environmental conditions and inferring their effects

Identifying the environmental factors and factor thresholds that precede high rates of delta smelt salvage is the first step in informing a conceptual model with requisite predictive capability. Years with very high or very low Delta inflows have historically been associated with lower levels of salvage of delta smelt (IEP MAST, 2015). Very high flows are hypothesized to move delta smelt downstream, away from the pumps. Very low flows, it is hypothesized, fail to produce the diffuse turbidity and salinity conditions necessary to stimulate delta smelt dispersal into the south Delta. If very high flows on the San Joaquin River occur during the period when juveniles are present, those flows likely move the juveniles downstream away from the pumps (USFWS, 2019; IEP MAST, 2015). Other environmental factors that influence the distribution of delta smelt include water temperature, turbidity, salinity, and prey availability (Bever et al., 2016; LaTour, 2016; Mahardja et al., 2017, Peterson and Barajas, 2018; Polansky et al., 2018; Simonis and Merz, 2019; Hendrix et al., 2022).

Those factors are considered in evaluating the first of two hypotheses that must be confronted with available data on delta smelt and the environmental conditions they encounter:

> *Hypothesis H1: Identifiable hydrologic and abiotic environmental conditions that can inform management decisions precede high salvage (mortality) rates in delta smelt.*

This hypothesis is relevant because, if such conditions must necessarily precede delta smelt moving into the vicinity of the water-project pumps, their absence indicates low risk of take. Also, from a statistical perspective, if such conditions are necessary and sufficient, ignoring their relevance will confound statistical analyses.

To identify precedent conditions, we evaluated the influence of each component of the conceptual model affecting delta smelt abundance in the zone of influence of the pumps. For each life

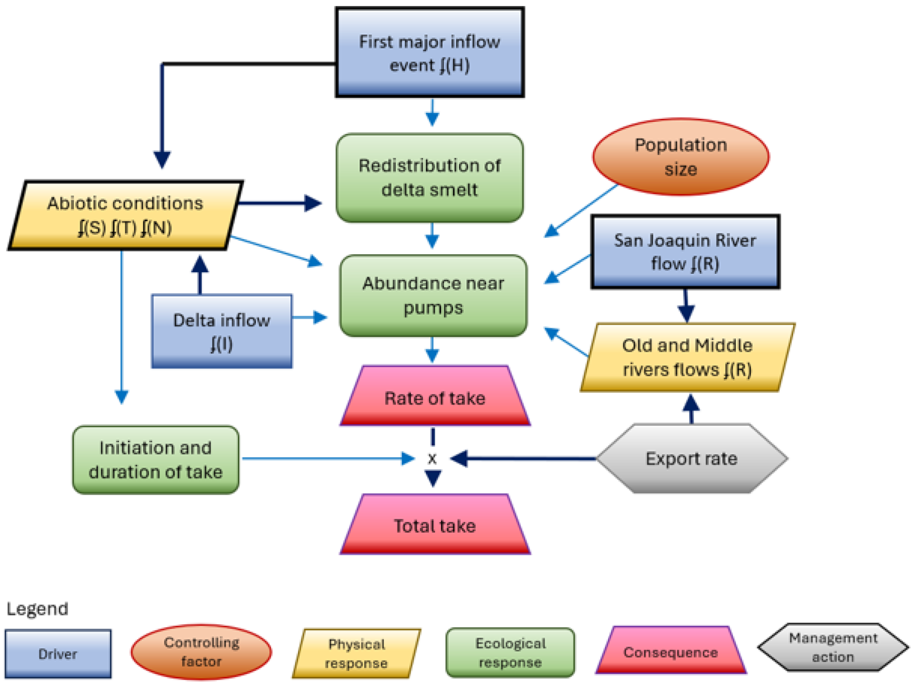

FIGURE 2
Conceptual ecological model of entrainment of delta smelt. Blue arrows reflect biological relationships that vary by life stage. Thick black outlines indicate potential precedent conditions. The function symbols (∫) link to Equation 1.

stage and relevant environmental covariate, we ordered the observations by the magnitude of the covariate and grouped the data into a series of two sets with the number of observations increasing sequentially in one set and decreasing sequentially in the other set. We then calculated the significance of the difference in the means of the dependent variables (the percentage of allowable take per 100,000 acre-feet pumped) between each of the two sets in the series using a t-test, not to determine statistical significance per se, but to provide a statistical basis for comparison between groupings. We then looked to see which grouping provided the greatest t-values and calculated the threshold as the average of the two closest points between the two sets (see Table 1 for an example). We consider the environmental covariate value ranges that correspond to exclusively low rates of take to reflect threshold conditions that prevent delta smelt from entering or remaining in the zone of influence of the pumps, regardless of all other environmental conditions. In instances where the analyses recognize the same high-risk years as associated with more than one environmental covariate, we employ the covariate that appears earliest in the causal chain in the conceptual ecological model. That factor is understood to be the most relevant in management efforts to reduce delta smelt losses at the pumps, because it provides the earliest warning signal and the most time to prepare a management response.

TABLE 1 An example of the analysis to delineate minimal and higher rates of take (column 3) based on the values of a given covariate, in this case, the start day of the first major inflow event (column 2).

WY	Start Day of FMIE	POAT/ htaf	N1	Mean Group 1	Variance Group 1	N2	Mean Group 2	Variance Group2	t value
2014	120	0.00%	1	0.00%					
2009	109	0.00%	2	0.00%	–	19	7.55%	0.01	1.06
2007	103	0.00%	3	0.00%	–	18	7.97%	0.01	1.35
1994	101	0.00%	4	0.00%	–	17	8.44%	0.01	1.64
2012	85	1.20%	5	0.24%	0.00	16	8.89%	0.01	1.85
2000	84	1.78%	6	0.50%	0.00	15	9.36%	0.01	2.05
2010	80	0.00%	7	0.43%	0.00	14	10.03%	0.01	2.39
2001	75	0.91%	8	0.49%	0.00	13	10.73%	0.01	2.71
2008	66	10.65%	9	1.62%	0.00	12	10.74%	0.01	2.38
2006	51	1.82%	10	1.64%	0.00	11	11.55%	0.01	2.69
2004	46	27.72%	11	4.01%	0.01	10	9.94%	0.01	1.44
1996	43	7.60%	12	4.31%	0.01	9	10.20%	0.01	1.42
1993	41	26.69%	13	6.03%	0.01	8	8.13%	0.01	0.48
2005	40	25.42%	14	7.41%	0.01	7	5.66%	0.01	0.38
2011	39	0.33%	15	6.94%	0.01	6	6.55%	0.01	0.08
1997	36	0.34%	16	6.53%	0.01	5	7.80%	0.01	0.25
1995	35	19.33%	17	7.28%	0.01	4	4.91%	0.00	0.43
2002	34	9.38%	18	7.40%	0.01	3	3.42%	0.00	0.65
1998	32	1.67%	19	7.10%	0.01	2	4.30%	0.00	0.38
2013	31	8.42%	20	7.16%	0.01	1			
1999	25	0.17%	21	6.83%					
	n	Average	Std Dev	CV	Min	Max			
Group 1	8	0.49%	0.71%	145%	0.00%	1.78%	DF	19	
Group 2	13	10.70%	10.60%	99%	0.17%	27.70%	P value	0.007	

With this approach the covariate values are ordered in sequence from highest to lowest, and sequentially divided into two groups with the number of observations in group 1 shown in column 4 and the number in group 2 shown in column 7. The t-value for the difference between the two means is shown in column 10. In this example, the t-value is greatest (t value = 2.71) with 8 observations in the first group and 13 in the second group. The rate of take in the first group is 0.49%/htaf and in the second 10.7%/htaf. The delineation is determined by taking the midpoint (70.5) of the adjacent covariate values (75 and 66). Start Day of FMIE – days from October 31 to the start of the first major inflow event, POAT/htaf – percent of allowable take per hundred thousand acre feet of water pumped, CV – coefficient of variation, DF - degrees of freedom.
T values are shaded from lowest (in red) to highest (in dark green).

For each life stage we consider 1) the influence of the first major inflow event into the Delta, 2) temperature, salinity, and turbidity conditions, 3) aggregated inflow into the Delta, and 4) San Joaquin River flows or flows in Old and Middle rivers.

We evaluate the first hypothesis by comparing the hydrologic and other abiotic conditions that precede high rates of take for each life stage and calculate a P value to test for statistical significance in the differences of the means.

Understanding the environmental factors that influence the fraction of the delta smelt population in the entrainment zone during high-risk periods is fundamental to managing water-project operations to limit salvage. Quantifying the relevant factors contributing to precedent conditions is advanced by evaluating a second hypothesis:

> *Hypothesis H2: The average rate of take of delta smelt following a precedent condition is influenced by river flow, water temperature, turbidity, and salinity.*

We evaluate the second hypothesis by testing whether the inclusion of environmental factors in the equation below adds explanatory power using the Bayesian Information Criterion (Schwarz's SBC, Schwarz, 1978). Working from our conceptual model (Figure 2) and the factors known to influence the distribution of delta smelt specified above, we hypothesize that factors affecting rate of take for each of the three delta smelt life stages can be presented as:

$$A = \alpha + \int(H) + \int(S) + \int(T) + \int(N) + \int(R) \quad (1)$$

where A is the percentage of allowable take of delta smelt per hundred thousand acre-feet of water pumped, α is a constant, $\int$ denotes a generalized non-linear functional, H represents hydrodynamic conditions associated with the first major inflow event, including starting day of the first major inflow event (days following 31 October) and a dummy variable for early large inflow events, S is salinity near Clifton Court Forebay (μS/cm), T is water temperature (^{o}C) near Clifton Court Forebay, N is turbidity (NTU) near Clifton Court Forebay, and R is average river flows, including (separately) Delta inflow, net daily flow in Old and Middle rivers, and San Joaquin River flow.

We graphed all covariates individually against the rate of take for each life stage to identify possible non-linear relationships and potential thresholds (conditions with *di minimus* rates of take). Non-linearity, if identified, was addressed by including quadratic or inverse terms when estimating coefficients. Data on river flows were obtained from DWR Dayflow (2024). Data and on abiotic conditions are from DWR (CDEC station "CLC"). Equation 1 is estimated using ordinary least-squares regression analysis. We used BIC rather than an adjusted R^2 as model-selection criteria to reduce the likelihood of overfitting (Brewer et al., 2016). The models for each life stage were validated by calculating a cross-validated R^2 (reported as Q^2 – see Addinsoft, 2024). BIC values were often similar between models. Given the concern of overfitting with small sample sizes, preference was given to models with higher Q^2 and more degrees of freedom, while excluding covariates with low statistical significance. Model residuals were tested for autocorrelation and normality.

The empirical analyses are conducted only for observations where precedent conditions have manifested. To include observations where an individual environmental factor has prevented delta smelt from entering the zone of influence of the pumps, regardless of the values of other covariates, would confound the analysis and produce biased estimates.

Data considerations

Salvage – Efforts are made to salvage fish, including delta smelt, prior to them reaching the water-project pumps. Fish are diverted away from the intake canals that lead to the pumping plants, routing them to salvage facilities. It is useful to distinguish "salvage," the number of fish estimated to be captured at salvage facilities, from "entrainment," which is the total loss of fish due to pumping (Kimmerer, 2008). Salvage is a fraction of entrainment (Kimmerer, 2008; Miller, 2011; Korman et al., 2021). Entrainment includes losses of fish due to upstream predation on delta smelt that would not otherwise have occurred, ineffectiveness of diversion louvers in redirecting delta smelt away from the pumps, and inability of delta smelt to survive the salvage process. The term "salvage" implies a beneficial management measure, but in the context of this analysis it is a proxy for entrainment – a source of delta smelt mortality. We use the term "rates-of-take" when referring to "salvage rates."

Study period – We use publicly available data on delta smelt and environmental conditions that were gathered from 1993 forward; the identification of delta smelt in salvage operations was reported to be more rigorous starting in that year (Grimaldo et al., 2009). The study period ends in the 2014 water year, the last year in which the Fall Midwater Trawl Index (FMWT) recorded numbers of delta smelt in double digits. The survey after that date recorded delta smelt in numbers so low that just several delta smelt in the FMWT survey could skew coefficient estimates.

Delineating the relevant periods for each life stage – For purposes of this study, we consider three temporal salvage windows – 1) the delta smelt pre-spawning period, the period from first major inflow event to 13 February or until water temperature at Clifton Court Forebay exceeds 10°C after 24 January, whichever occurs first, 2) the spawning period, the period from the end of the previous period to 20 April, and 3) the juvenile period, from 21 April to 7 July. Those temporal windows were delineated based on body length records for delta smelt from salvage data and maturity data from the Spring Kodiak Trawl (see Supplementary Appendix A). Water temperature rather than a calendar date appears to trigger risk of entrainment for spawning delta smelt based on a review of historic data.

Defining the first major inflow event – The first major inflow event in the Delta results from the first major storm or storms of the season that occur in late autumn or early winter. Large first storms modify turbidity and salinity in the Delta, thereby increasing dispersion of delta smelt. Those storm events have been identified as triggers of high salvage in some years (Grimaldo et al., 2009). We identified inflow events large enough to allow dispersion of delta smelt into the entrainment zone by examining historical inflow data from 1993 to 2014 to determine the type of inflow event that preceded salvage.

Consequently, we define a first major inflow event as one that generates daily delta inflows greater than 25,000 cfs on a running 3-day average, at a time when inflows had increased by 12,500 cfs over the previous seven days. This delineation is close to that identified by USFWS (2019), which required flows on the Sacramento River at Rio Vista to exceed 25,000 cfs and turbidity to exceed 50 NTU. We define the "date of the first major inflow event" to be the first day of the three-day sequence. For context, in the years in which the first major inflow event occurred in December or January, the average flow before the event was 17,348 cfs and afterwards was 57,335 cfs, a substantive increase close to 40,000 cfs.

Determining a starting date for delta smelt salvage events – In many years salvage is a continuous event. Once salvage starts, daily take of delta smelt increases up to a peak and then decreases, often resembling a normal distribution (or bell-shaped curve). The date of the start of a salvage event under those circumstances is readily discernable. For analytical purposes in years when delta smelt take was not a continuous event, we use the date at which cumulative take for the season exceeded 5% of the annual salvage.

Developing a metric for water-project take of delta smelt – The abundance of delta smelt can vary significantly from year to year (Polansky et al., 2019). Generally, the take of delta smelt increases when the number of delta smelt in the estuary is greater (Grimaldo et al., 2021). To account for different population sizes in different years we follow the method used by USFWS (2008), calculating a "salvage index" by dividing salvage by the estimated abundance of delta smelt in the prior autumn, using the Fall Midwater Trawl (FMWT) Index (see Peterson and Barajas 2018).

Management target – Ideally, salvage should be managed to prevent water-project operations from having population-level impacts on delt smelt that cannot be mitigated. Determining salvage levels at which population level impacts occur and establishing upper levels of acceptable salvage has been employed in management decision-making previously (USFWS, 2008, USFWS, 2019). For regulatory management purposes, USFWS (2008) established allowable-take levels (referred to as "Incidental Take Levels" or "ITLs") for delta smelt adults (approximately 8 times the prior FMWT Index) and for juveniles (approximately 23 times the prior FMWT Index). It is unclear whether population-level impacts on delta smelt occur when the ITL is exceeded. While two studies offer evidence of such a relationship (Rose et al., 2013; Smith et al., 2021), several others find no significant relationship between salvage numbers and subsequent delta smelt abundance (USFWS, 1996; Mac Nally et al., 2010; Thomson et al., 2010; Maunder and Deriso, 2011; Miller et al., 2012; Hamilton and Murphy, 2018). For this study, we adopt the expansion values of 8 and 23 for adults and juveniles respectively, recognizing that future studies related to population-level take may call for modification of those values.

Nevertheless, the ITL serves as a useful metric for the purposes of this study because the ITL is adjusted in response to contemporary abundance index values and provides a consistent management target across years. We use allowable-take levels (100% of the ITL) here to guide management actions, given their management relevance. The risk-based strategy developed here is readily modifiable should amended take levels be developed by proportionally adjusting rates of take, which are expressed as a percentage of the current take levels, to new take values.

For analytical purposes, we use the percentage of allowable take per 100,000 acre-feet of water pumped (the rate of take) as the dependent variable in equation [1] and as a proxy for the abundance of fish in the zone of influence of the pumps, differentiating adult rates of take from juvenile salvage, since allowable-take levels are established separately for each life stage.

Development and evaluation of a management strategy

The strategy underlying the current regulations is precautionary, that is, intentionally limiting net flows towards the pumps (southerly flows) in Old and Middle rivers at certain times. The strategy is complex, intended to limit movement of delta smelt adults into the south Delta, limit rates of take, and increase protection for juveniles as the risk of entrainment is perceived to increase (described more fully in Supplementary Appendix B).

The alternative "risk-based" strategy proposed here recognizes that higher levels of salvage will not occur until precedent conditions have been met. Until those conditions are met, rates of delta smelt take and the likelihood of population-level impacts are lower. Under the risk-based strategy, rates of take are estimated based on hydrologic and other abiotic conditions in the south Delta, and pumping rates are decreased if salvage limits are likely to be exceeded.

We conducted a simulation analysis to compare a risk-based strategy for reducing delta smelt entrainment with current regulations. The simulation required development and application of three models – 1) a Delta Flow Model to simulate water available for export under existing regulations that are not specific to delta smelt, 2) a Water Project Operations Model in which water available for exports is reduced to recognize the impacts of regulations intended to protect delta smelt, and 3) a Consequences Model that calculates the impacts to delta smelt of those water-project operations. The third model, in the case of the risk-based strategy, modifies water-project operations through a non-linear optimization routine that adjusts water project operations to maximize exports, while not allowing expected take to exceed specified limits. (Additional information is provided in Supplementary Appendix B.) We apply the simulation analysis for each life stage to each year from 1993 to 2014. We impose pertinent regulations on water-project operations and estimate the change in salvage of delta smelt and the change in water deliveries under each management strategy for each year (Figure 3), then compare the effects of the different management strategies on the delta smelt population and water available for export.

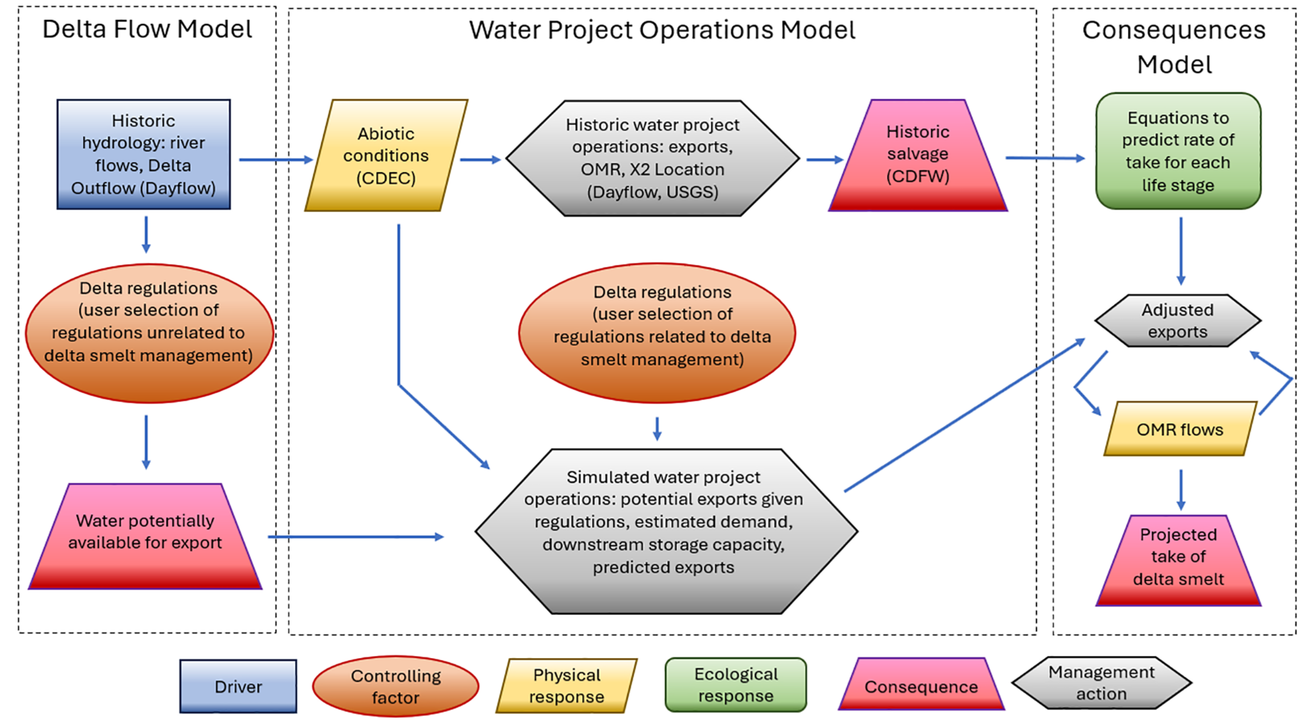

FIGURE 3
Diagram of the model elements used to simulate Delta conditions, water project operations, and the consequences of those operations for the take of delta smelt to evaluate alternative water-management scenarios. The Delta Flow Model simulates water available for export under existing regulations not specific to delta smelt. The Water Project Operations Model simulates the implementation of regulations intended to protect delta smelt, resulting in projected reductions in water available for exports. The Consequences Model calculates the impacts to delta smelt of those water-project operations. In simulating the risk-based strategy, adjusting exports in the Consequences Model modifies flows in Old and Middle rivers, which then influence the rate of take. Recognizing those dynamic interactions, a nonlinear optimization routine is used within the Consequences Model to maximize exports, while not exceeding take limits. See Appendix B for a description of the simulation modeling.

Results

Precedent environmental conditions

Precedent environmental-factor conditions associated with high rates of take were identified for each delta smelt life stage – pre-spawning stage (Figures 4, 5), spawning adults (Figure 6), and juveniles (Figure 7). We compared rates of take following a precedent condition with rates of take when the condition did not occur (Table 2). Here we note the influence of differing environmental factors between life stages.

Pre-spawning Period – For the delta smelt pre-spawning period, we confirmed that rates of take of delta smelt were significantly higher following the first major inflow event (average rate of take 14.1% per 100,000 acre-feet pumped – htaf) than rates of take before the event (average of 0.02%/htaf, Table 2). The timing and magnitude of the first major inflow event further defined the circumstances associated with high and low rates of take of delta smelt. Inflow events that began before January 10 had higher rates of take (average of 10.7%/htaf) than those later (average of 0.65%/htaf, Figure 4A). Also, years in which inflow in the 14 days following the first major inflow event increased less than 33,700 cfs had an average rate of take 10.8%/htaf, compared to an average rate of take of 0.53%/htaf when the inflow was greater than 33,700 cfs (Figure 4B). Salinity in the range greater than and 500 µS/cm prior to the start of the take event was associated with a higher rate of subsequent take (average of 13.2%/htaf), than when salinity was below that range (average of 0.61%/htaf, Figure 4C).

Having observed that high rates of take for pre-spawning delta smelt adults followed a first major inflow event occurring before January 10, with 14-day change in inflow of more than 33,700 cfs and with EC in a range greater than 500 µS/cm prior to the start of take, we graphed salinity from the start of the first major inflow event until the start of take. We observed that in years with those conditions, take did not start until salinity moved within a range from 550 to 600 µS/cm and then declined (Figure 5). We also graphed temperature and turbidity conditions prior to the start of take but found no consistent patterns.

Spawning Period – For the spawning period, two environmental conditions consistently preceded high rates of take of delta smelt. Years with a first major inflow event that occurred before February 1 had an average rate of take during the spawning period of 10.2%/htaf, compared to years when the first major inflow event was later, at 1.08%/htaf (Figure 6A). Years with turbidity more than 10 NTU in the week prior to the spawning salvage period had an average rate of take during the spawning period of 10.1%/htaf, compared to an average of 1.45%/htaf when turbidity was less than 10 NTU (Figure 6B).

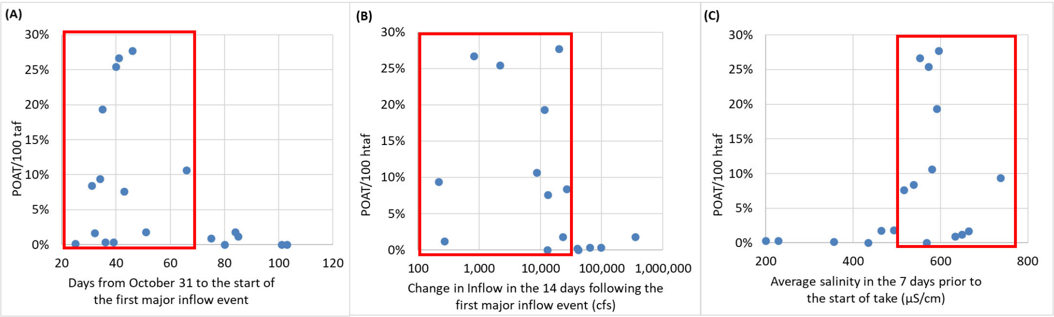

FIGURE 4
Environmental conditions prior to the start of take during the delta smelt pre-spawning period. The vertical axis is rate of take (percent of allowable-take level per 100,000 acre-feet pumped). The red rectangles indicate ranges of environmental factors (horizontal axis) associated with high rates of take of adult delta smelt and depict higher rates of take when **(A)** the start of the first major inflow event occurs before January 10 **(B)** the change in inflow during the first major inflow event is less than 33,700 cfs, and **(C)** average salinity in the south Delta in the seven days prior to the start of take is between 500 and 600 µS/cm.

Juvenile Period – Four environmental conditions preceding the juvenile entrainment period were associated with high rates of take during that period – average inflow less than 60,000 cfs, Old and Middle rivers' flow less than 2,500 cfs, San Joaquin River flows less than 7,800 cfs in the week preceding the juvenile period, and water temperature in the south Delta between 15.6 and 20°C. Those hydrologic conditions occurred in the same years with lower flow, leading to higher rates of take, consistent with the hypothesis that strong outward flows move weak-swimming juvenile delta smelt away from the pumps. Particularly warm water (greater than 20°C at the start of the juvenile entrainment period) was associated with low rates of take. Among those four environmental conditions, San Joaquin River flows less than 7,800 cfs was selected as the most management-relevant metric as the precedent condition for take of juvenile delta smelt. It denotes the same high-risk years as the other hydrologic factors, is consistent with existing regulations, and unlike flows in Old and Middle rivers, is not readily controlled through reoperation of water-project pumps. Water temperature was not employed as a management factor because water temperatures are likely to change through the juvenile entrainment period (April 20 to July 7) due to changes in air temperature; therefore, air temperature is better employed as the environmental factor affecting the rate of take.

Years with San Joaquin River flows less than 7,800 cfs during the week prior to the start of the juvenile period had an average rate of take during the juvenile period of 28.5%/htaf; compared to 0.87%/htaf in years when San Joaquin River flows were greater than 7,800 cfs (Figure 7).

Factors that influence rate of take

We hypothesized that the average rate of take of delta smelt following a precedent condition is influenced by river flow, water temperature, salinity, and turbidity. We used empirical analyses to fit equations to explain the rate of take for each life stage. The goodness-

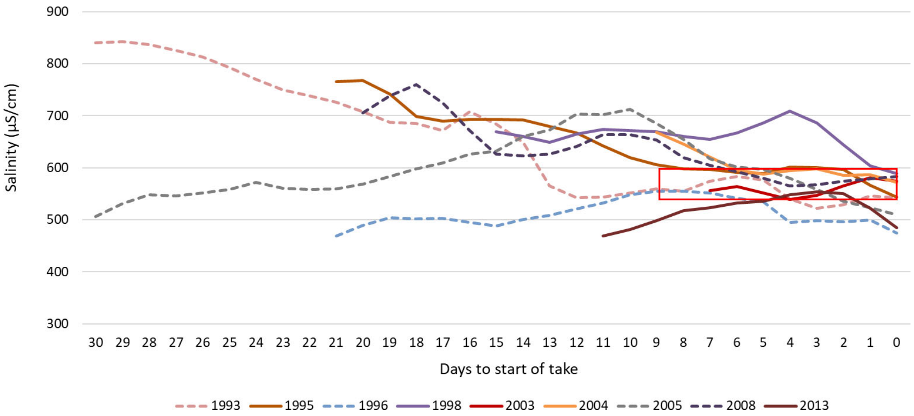

FIGURE 5
Salinity conditions between the start of the first major inflow event and the start of adult delta smelt salvage for years with high salvage rates of pre-spawning adults (the 9 years with precedent hydrologic conditions identified in Figure 4. Year 2002 is excluded because of missing sensor data.). The vertical axis is electrical conductivity near the entrance to Clifton Court Forebay (µS/cm). Solid lines indicate years when salvage started in December. Dashed lines indicate years when salvage started in January. The red rectangle indicates an apparent precedent condition(s) prior to the start of salvage. Salinity in each of these years at Clifton Court Forebay was in the range of 550 to 600 µS/cm and declining for at least three consecutive days.

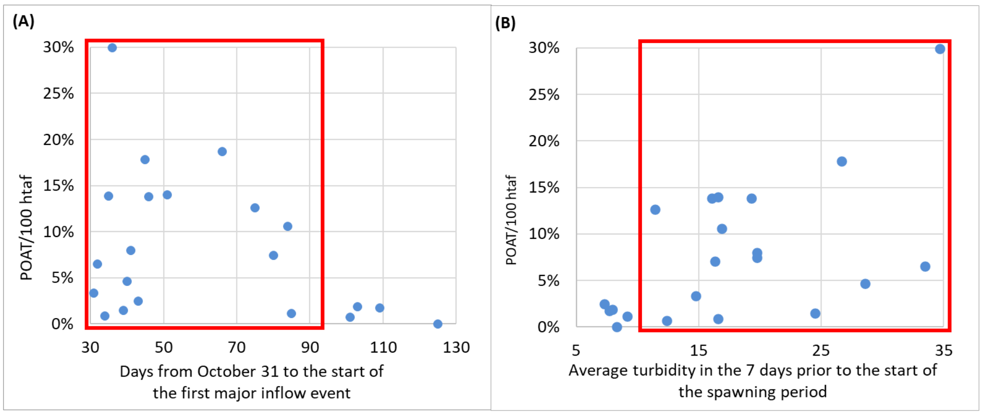

FIGURE 6
Environmental conditions prior to the start of the delta smelt spawning period. The vertical axis is rate of take (percent of allowable-take level per 100,000 acre-feet pumped). The red rectangles indicate ranges of environmental factors (horizontal axis) associated with high rates of delta smelt take during the spawning period and depict higher rates of take when **(A)** the start of the first major inflow event occurs before February 1 and **(B)** when turbidity is greater than 10 NTU in the 7 days prior to the start of the spawning period.

of-fit parameters are reported in Table 3 and comparisons by years of actual and predicted observations are presented in Figure 8.

Excluding low-risk circumstances for pre-spawning adults – that is, a first major inflow event after January 10 or when salinity is in unsuitable ranges – rates of take of pre-spawning adults increased as turbidity, salinity, water temperature, and OMR flows towards the pumps increase and rates of take decrease when the first major inflow events occur later in the season.

Excluding low-risk circumstances for spawning adults – that is, a first major inflow event after February 1 or when turbidity at the end of the spawning period is less than 10 NTU – rates of take of spawning adults increase as OMR flows toward the pumps increase and when the first major flow event occurs later in the water year. Rates of take for spawning adults decrease as water temperatures increase. While a very large inflow event was associated with low rates of take during the pre-spawning period, it was associated with higher rates of take during the spawning and juvenile periods. That indicates that pre-spawning adults disperse downstream early in the year with very large flows, and return upstream to spawn, despite persisting high outflows.

Excluding low-risk circumstances for juveniles – that is, years when flows in the San Joaquin River exceed 8,700 cfs at the end of the spawning period – rates of take of juveniles increase as OMR flows towards the pumps increase and rates of take of juveniles

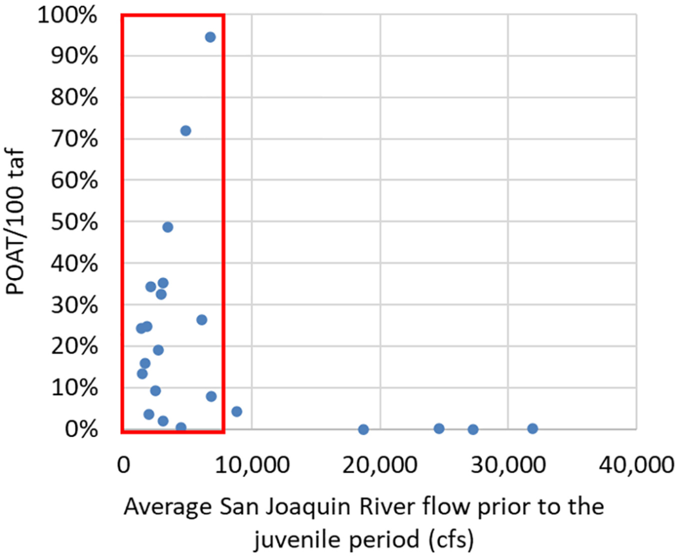

FIGURE 7
Flows in the San Joaquin River in the week prior to the start of the entrainment period for juvenile delta smelt. The vertical axis is rate of take (percent of allowable-take level per 100,000 acre-feet pumped). The red rectangle indicates higher rates of take are associated with San Joaquin River flows less than 7,800 cfs during the week prior to the start of the juvenile period (horizontal axis).

TABLE 2 The influence of precedent conditions on subsequent rates of take of delta smelt by life stage.

Life stage and precedent condition	Rate of take with Precedent Condition	Rate of take without Precedent Condition	P value
Pre-spawning period (November 21 to February 13)			
First major inflow event	14.1% [224%]	0.02% [170%]	0.054
First major inflow event occurs before January 10 (Figure 4A)	10.7% [99%]	0.65% [117%]	0.017
14-Day Increase in Inflow is less than 33,700 cfs (Figure 4B)	10.8% [97%]	0.53% [138%]	0.023
Average south Delta salinity is less than 500 µS/cm in the week prior to the start of take (Figure 4C)	11.6% [91%]	0.74% [112%]	0.013
South Delta salinity is between 550 and 600 µS/cm after first major inflow event and is declining (Figure 5)	13.2% [98%]	0.61% [164%]	<0.01
Spawning period (February 14 to April 19)			
First major inflow occurs before February 1 (Figure 6A)	10.2% [75%]	1.08% [82%]	<0.01
South delta turbidity greater than 10 NTU (Figure 6B)	10.1% [74%]	1.45% [65%]	0.011
Juvenile period (April 20 to July 7)			
Average San Joaquin River flows are less than 7,800 cfs in the week preceding the juvenile period (Figure 7)	28.5% [93%]	0.87% [210%]	0.016

Numbers in square brackets indicate the coefficient of variation. P-values provide the significance of the difference between the means of the two groups.

decrease as temperatures decrease and as the first major inflow event occurs later in the year. Late inflow events were associated with lower rates of take during the juvenile period. Take of juveniles was projected to cease when water temperatures reach 23.5°C. Salinity is projected to have a non-linear relationship with rates of take, reaching a peak at 480 µS/cm.

Higher flows in Old and Middle rivers towards the pumps were associated with increased rates of take for all life stages. Because of the interactive relationship between water-project pumping and flows in Old and Middle rivers, a proportional increase in pumping results in a more-than-proportional increase in take.

Comparison of management strategies

In comparing management strategies, the risk-based strategy has advantages over operations under current regulations. The risk-based strategy results in more than 250,000 acre-feet (305,000 ML) additional water being delivered for human uses per year on average, compared to operations under current regulations (Table 4). Although water deliveries would have to be severely restricted in 50% of years to protect adult delta smelt under the risk-based strategy, annual average deliveries would be increased by 167,000 af/year on average by pumping more water during low-risk periods. Water deliveries would be restricted in 36% of years to protect juvenile delta smelt under the risk-based strategy, but annual average deliveries would be increased by 90,000 af/year by pumping more water during low-risk periods.

Current regulations, as modeled, did not keep the salvage of adults below take limits in 23% of years (Figure 9) and salvage of juveniles below take limits in 6% of years. The risk-based strategy is designed to keep salvage below take limits in all years.

Because the implementation of current regulations involves considerable discretion, it is likely that protections for delta smelt would be increased as take limits are approached. That would result in take limits being exceeded less frequently than modeled, with exports less than projected under the current regulation scenario.

Discussion

California's Delta Reform Act of 2009 directs regulators and resource managers to meet "co-equal goals" that are intended to "improve statewide water supply reliability and protect and restore a vibrant and healthy Delta ecosystem" (Delta Reform Act, 2009). Stakeholder groups representing interests on either side of the co-equal goals claim that the allocation of water entering the Delta from upstream is not reasonably balanced in compliance with the Act and have sought solutions from the courts through litigation. But the courts are not equipped to address complex ecological issues. A series of lawsuits have left listed fish species imperiled and the state's water users in crisis. To help inform decision makers concerned with achieving the co-equal goals, we examined here environmental factors influencing take of delta smelt from water-project operations.

The investigation of environmental factors that influence fish losses due to entrainment or impingement is not a particularly novel endeavor. Factors influencing the magnitude of losses at large water-diversion facilities, such as those for powerplant cooling systems, turbines for hydroelectric plants, and irrigation diversions include hydrodynamics and hydraulics (approach velocities to screens, sweeping velocities, the hydraulic influence of diversions, the proportion of water diverted), abiotic factors near intakes (water clarity, water temperature, time of day, tide, season)

TABLE 3 Regression results for environmental factors that affect the population-adjusted rate of take of delta smelt at water-project pumps for each delta smelt life stage.

Predominate life stage			Pre-spawning period	Spawning period	Juvenile period
Precedent conditions			FMIE occurs before January 10, the following 14-day increase in inflow is less than 33,700 af and EC is between 550 and 600 µS/cm and declining	FMIE occurs before February 1 and turbidity at the end of the pre-spawning period is less than 10 NTU	Average San Joaquin River flows less than 8,700 cfs at the end of the spawning period
No. of annual observations			13	17	18
Degrees of freedom			6	13	10
R^2			0.92	0.66	0.93
Q^2			0.63	0.43	0.74
Covariates			P-values	P-values	P-values
	α	Intercept	**+ 0.048**	- 0.247	+ 0.539
Hydro-dynamic conditions	ʃ(H)	Starting day of first inflow event	n.i.	n.i.	**- 0.001**
		Starting day squared	**- 0.003**	+ 0.131	n.i.
		High inflow dummy	n.i.	**+ 0.001**	**+ 0.003**
		Late FMIE dummy	–	–	- 0.059
Abiotic conditions	ʃ(S)	Salinity (μS/cm)	+**0.003**	n.i.	**+ 0.001**
		Salinity squared	- n.i.	n.i.	**- 0.003**
	ʃ(T)	Water temperature (°C)	**- 0.033**	n.i.	n.i.
		Water temp. squared	**+ 0.029**	- 0.352	**- 0.003**
	ʃ(N)	Turbidity (NTU)	n.i.	n.i.	n.i.
		Turbidity squared	**+ 0.012**	n.i.	n.i.
River flows	ʃ(R)	OMR flows (tcfs)	**+ 0.002**	+ 0.076	**+ 0.010**
Delta inflow	ʃ(I)	Inflow (tcfs)	n.i.	n.i.	n.i.

The equations are fitted to observations after the occurrence of the precedent conditions specified in the second row. The second column under covariates corresponds to environmental factors included in Equation 1. The next column provides the specification of each covariate for each environmental factor. The next three columns provide P-values for each covariate in each life stage with significant values in bold.

Salvage periods for pre-spawning adults – from the start of the first major inflow event until February 13 or when water temperatures exceed 10°C, whichever comes first; for spawning adults – from the end of the pre-spawning period until April 19; and for juveniles - from April 20 until July 7.

"FMIE" denotes first major inflow event, "n.i." indicates that the inclusion of the covariate did not improve adjusted R^2, "–" indicates the covariate was not a candidate for the equation, "NTU" - nephelometric turbidity units, "EC", electrical conductivity (μS/cm), "OMR", flows in Old and Middle rivers towards the pumps, "tcfs", thousand cubic feet per second.

and salient aspects of fish ecology (the abundance of fish near intakes, their life stages, and their foraging behavior) (Nobriga et al., 2003; Grimaldo et al., 2009; Sechrist and Zehfuss, 2010; Mussen et al., 2013; Martins et al., 2014; Cooke et al., 2020; Grimaldo et al., 2021; Kock et al., 2024).

The findings from this study support the relevance of 1) Delta hydrodynamics – the timing and magnitude of the first major inflow event, Delta inflow during the spring and summer, flow in Old and Middle rivers, and San Joaquin River flow, 2) abiotic conditions (turbidity, salinity, and water temperature) and 3) biological factors (delta smelt life stage) in determining risk of delta smelt entrainment at water-project pumps. The management challenge where losses of the imperiled delta smelt occur with water exported, is not limited to minimizing fish losses by recognizing influential factors. California's Delta Reform Act mandates that equal importance be given to enhancing the environment and protecting water supplies. Achieving a reasonable balance among disparate management mandates requires sensitive application of relevant data in appropriate spatial and temporal context.

Here we have proposed and tested a risk-based strategy for managing water-project operations based on empirical analysis of 22 years of data on delta smelt. We found that certain environmental conditions historically have preceded high levels of take, which can lead to population-level impacts if water exports are not properly managed. Absent those conditions, the abundance of delta smelt in the vicinity of project pumps is very low or non-existent and pumping can continue at efficient levels.

The risk-based strategy presented in Figure 10 emerged from a conceptual ecological model (Figure 2) that identified environmental factors that potentially influence the abundance of

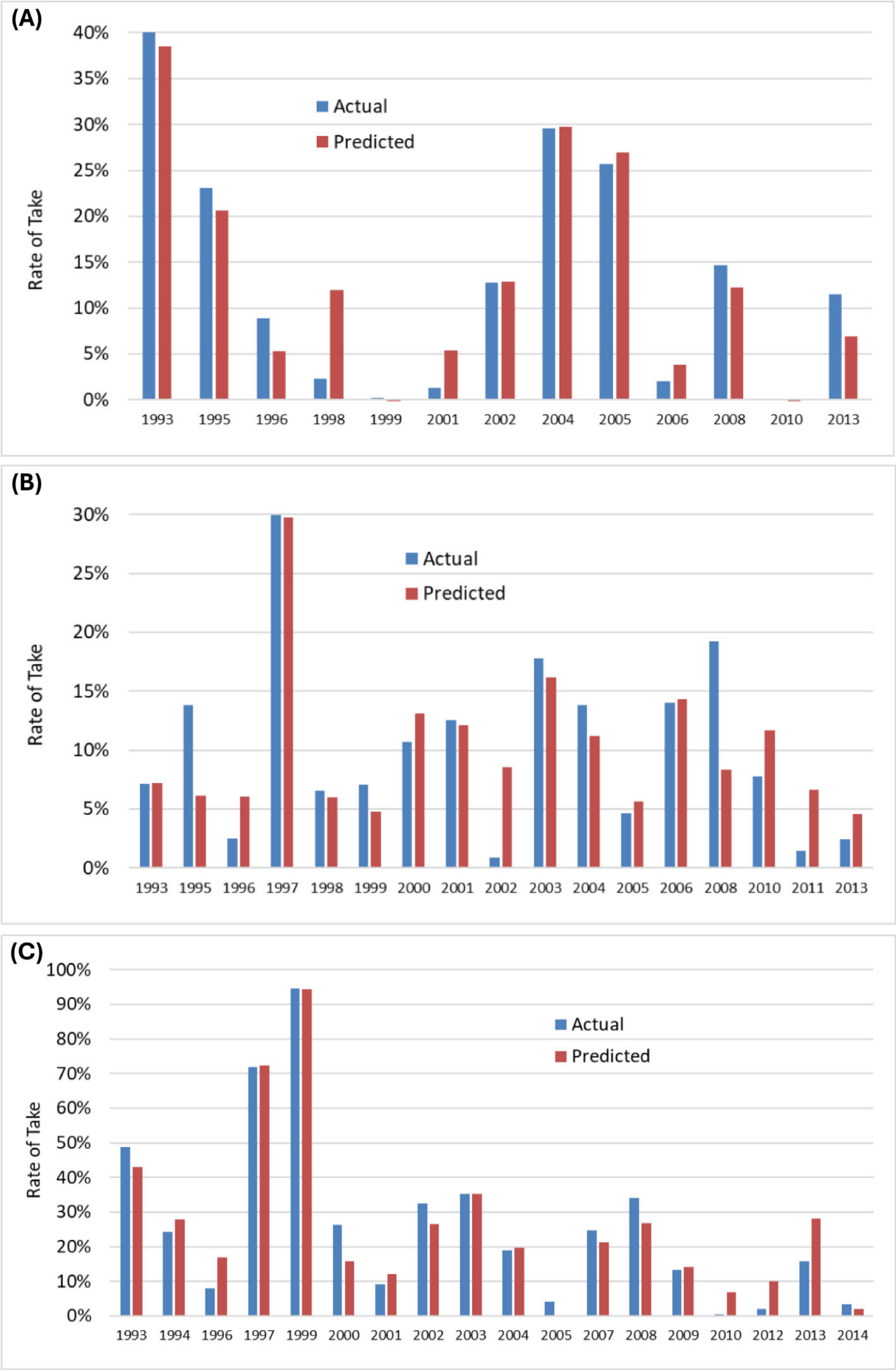

FIGURE 8
The accuracy of predictions of rate of take across years from the models presented in Table 3 for **(A)** pre-spawning adults, **(B)** spawning adults, and **(C)** juvenile delta smelt. The vertical axis is rate of take – the percent of allowable take per hundred thousand acre-feet of water pumped. The models predict high rates of take when water operations should be operated conservatively to reduce take of delta smelt with poorer explanation for moderate rates of take for spawning adults in 1995 and 2008. Only years that manifest precedent conditions are represented in each of the life-stage-specific graphs.

delta smelt at each life stage in the vicinity of the water-project pumps. Employing historical data in an analysis of salvage rates of delta smelt allowed for identification of environmental conditions that consistently precede high rates of delta smelt take – for adults 1) the occurrence, timing, and magnitude of the first major inflow event, 2) salinity in a narrow range in the zone of influence of the pumps, 3) turbidity prior to the start of the spawning period, and for juveniles 4) low and moderate flows on the San Joaquin River.

With circumstances preceding high rates of take identified, we developed predictive models for each delta smelt life stage to estimate rates of take given prevailing environmental conditions. Those models can be used to predict whether continuation of

TABLE 4 Simulated average annual impacts under the current regulatory strategy and risk-based strategy scenarios.

Period	Current Strategy	Risk-based Strategy	Change
Total take (average % of allowable take)			
Adults	87%	66%	-21%
Juveniles	58%	56%	-2%
Average water deliveries during entrainment period (thousand acre-feet)			
Adults	1,703	1,870	+167
Juveniles	491	581	+90
Total	2,387	2,928	+257
Percentage of years allowable-take levels are exceeded			
Adults	23%	0%	-23%
Juveniles	6%	0%	-6%

pumping at prevailing levels is likely to lead to exceedance of take limits, and how pumping could be adjusted to prevent those levels of take being reached. Of importance, flows in Old and Middle rivers have a non-linear impact on salvage rates of all life stages once precedent environmental conditions have manifested. Water-project pumping levels have a direct impact on flows in Old and Middle rivers. Combined, those factors suggest that a proportional decrease in pumping volumes will produce more than a proportional decrease in the rate of delta smelt take.

The results from this study indicate that the current regulations may be unsuccessful in keeping management outcomes below allowable-take targets for delta smelt adults in one- fifth of the years. The risk-based strategy was more protective, and it was projected to increase water available for export by more than 250,000 acre-feet per year. Not considered in this study was whether the allowable-take levels specified in the 2008 Biological Opinion (USFWS, 2008) and used in this study reflect take levels leading to population-level impacts. Recent studies offer mixed assessments regarding whether and under what conditions population-level impacts occur (Rose et al., 2013; Smith et al., 2021; USFWS, 1996; Mac Nally et al., 2010; Thomson et al., 2010; Maunder and Deriso, 2011; Miller et al., 2012; Hamilton and Murphy, 2018). If the allowable-take levels used in this study were to increase, the availability of water for human uses under the risk-based strategy would also increase because allowable-take levels would be reached less frequently.

The major difference between the two strategic approaches is the trigger used to initiate protective measures for delta smelt – at the start of the first major inflow event in the case of current regulations and at the onset of prerequisite conditions in the case of the risk-based strategy. Following initiation of protective measures, both strategies propose adjustments to water-project operations based on perceived risk. In the case of the current regulations by using emerging delta smelt presence data from fish surveys and in the case of the risk-based strategy using real time data on environmental conditions and modeled rates-of-take estimates. Both strategies would employ further restrictions on exports in cases of actual salvage of delta smelt. Consequently, the current regulations likely would have been more protective than we have estimated here because water-project operators would strive to avoid approaching allowable-take levels. However, with delta smelt now rare in salvage at the project operations, a protective strategy that depends on observations of delta smelt in the south Delta surely is less reliable and less defensible.

Management of water-project operations to avoid losses of delta smelt during the first half of each year requires conservation planners and water managers to meet weekly to consider the

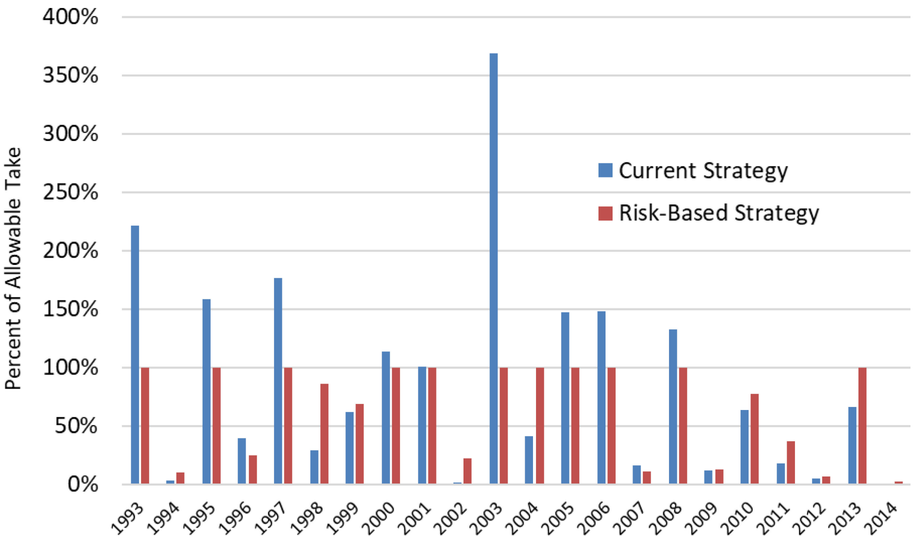

FIGURE 9
Comparison of simulation results for take of adult delta smelt under the current strategy and the risk-based strategy.

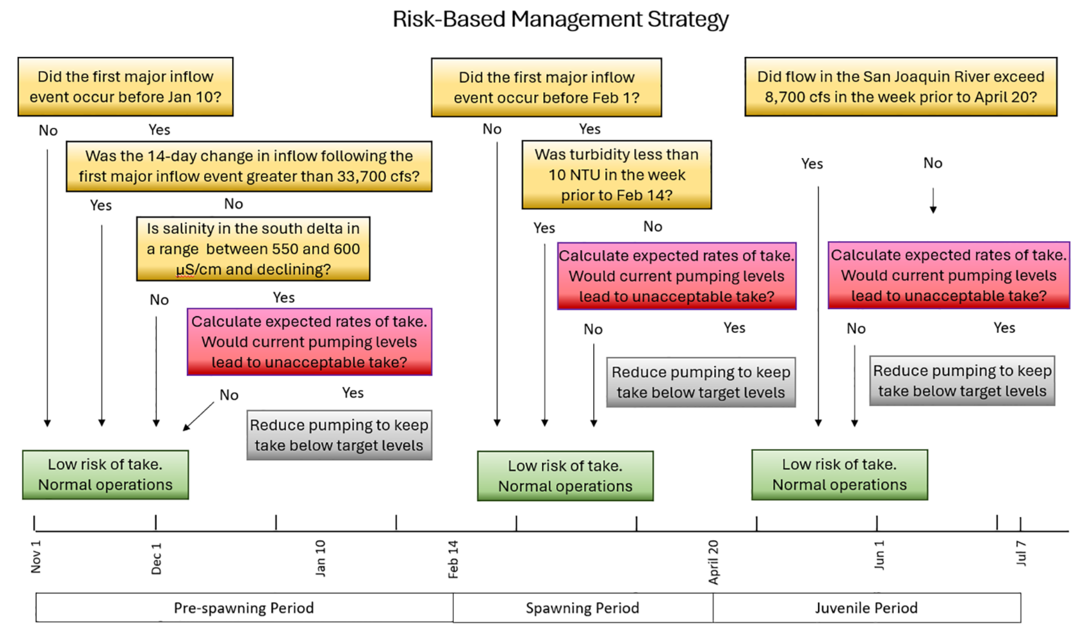

FIGURE 10
Risk-based management strategy. For each delta smelt life stage, certain conditions (yellow rectangles) precede potentially high rates of take (red rectangles). When those conditions manifest and predictive models (see Table 2) indicate population-level impacts are likely, water-project operations may need to be adjusted (grey rectangles), otherwise risk of take is low and increased water deliveries can be considered (green rectangles).

possible impact of the operations on imperiled fish species, including delta smelt (CDFW, 2020). Those decisions are made using real-time fish survey data and prevailing conceptual models, but they are subjective. The use of the findings and management guidance from this study provides empirical support for decisions that provide increased protection for delta smelt, while simultaneously providing an opportunity for increased water deliveries. The thresholds identified here as differentiating high-risk and low-risk circumstances should not at this point be interpreted as having elevated precision. For example, an increase in Delta inflows in the 14 days following the first major inflow event of less than 33,700 indicates that a high rate of delta smelt take may follow. But flow volumes slightly above that level should be viewed with caution and other real-time environmental factors influencing rates of delta smelt take should be considered.

It should also be noted that this study focused exclusively on the re-management of water-project operations to protect delta smelt. Additional restrictions are placed on water-project operations to protect other imperiled fishes, including longfin smelt and out-migrating salmon. In the absence of modeling and accounting for water-export restrictions targeting those species, the modeling of risk-based strategy likely overestimates the water-supply benefits.

The results of this study indicate that certain management actions targeting delta smelt under the current regulations appear to be triggered at inappropriate times. For example, current regulations require that pumping always be restricted following a first major inflow event, but the analyses here suggest that very large inflow events, those in which inflows increase by more than 33,700 cfs in 14 days, move delta smelt away from the pumps. In that circumstance, pumping limitations to protect delta smelt are unnecessary. Similarly, first major inflow events occurring after January 10 historically have produced low rates of take, indicating that pumping restrictions from January 10 to February 14 in certain years would not be warranted.

The US Fish and Wildlife Service recognizes the presence of delta smelt in the upper estuary is frequently associated with areas of high turbidity. Current regulations are intended to prevent turbidity from the Sacramento River from entering the south Delta during or following a first major inflow event (CDFW, 2020). Review of historical data indicates that attempts to manage turbidity in the central Delta are likely to be infeasible or unnecessary (Supplementary Appendix B). Furthermore, in this study we found no threshold for turbidity below which there is minimal take for pre-spawning adults. Rather, delta smelt salvage during the pre-spawning period is observed to occur years when turbidity levels were low (less than 10 NTU) and take was projected to increase as turbidity increased. However, that was not the case during the spawning period when mature adults appear to avoid clear water (turbidity less than 10 NTU). Rates of take during the spawning period are also low when the first major inflow event occurred after February, again indicating that pumping restrictions would not be warranted.

Given the absence of delta smelt since 2017 in long-running trawl surveys, starting in 2021 the fish and wildlife agencies in the Delta began releasing laboratory-propagated delta smelt. (Delta Smelt Supplementation | U.S. Fish & Wildlife Service (fws.gov)). Since then, hundreds of thousands of delta smelt have been released into Delta waters. The conclusions presented here would be accompanied by increased uncertainty if propagated delta smelt have different behaviors and patterns of movement than wild delta smelt. However, the propagation of delta smelt, combined with the rare occurrences of delta smelt in salvage, provides an opportunity to mitigate entrainment of delta smelt at water-project pumps by increasing the number of propagated delta smelt that are reintroduced annually. That possibility is yet to be considered by the regulatory agencies and is likely to be controversial.

Alternative methods for reducing entrainment risk to delta smelt are not yet available. Conventional vertical screen technologies that employ large physical barriers continue to improve, but none that are currently available protect particularly small fishes, like the early-life-stage delta smelt. Having minimal swimming abilities, the young fish are likely to be impinged on screen structures, even at very low approach velocities. A solution to the dilemma of diverting water without harming fish could involve the use of infiltration galleries, which draw water from the bottom of the water column through perforated pipes buried in gravel. Such designs take advantage of the natural buoyancy properties of the fish to keep them suspended in the water column away from the screens. These infiltration galleries could be constructed at strategic locations in the Delta to minimize delta smelt losses from predation. Infiltration galleries have been designed and installed for river applications in California, but not yet for tidally influenced estuarine systems, such as the Sacramento-San Joaquin Delta. In the near-term then, best management practices for the imperiled delta smelt are limited to adjusting export volumes in real time to reduce fish numbers subject to entrainment.

Long-standing complications challenge those who seek to understand the response of delta smelt to changing environmental conditions in the Sacramento-San Joaquin Delta, particularly the conditions that precede entertainment. First, with numbers of delta smelt decreasingly small (see Polansky et al., 2019) and patchily distributed, gauging the distribution of the fish and their proximity to water-project pumps is challenging. Second, the number of delta smelt taken at the water-project pumps is not knowable because it is not possible to estimate with any accuracy the number of fish that die before reaching fish salvage facilities or the number that manage to survive the salvage process. Third, the 22-year salvage dataset is relatively small, limiting the degrees of freedom in statistical analyses. Importantly, precedent conditions have been identified in only a fraction of those years, so the identification of precedent conditions could in some cases be coincidental rather than reflecting enduring biological phenomena. Accordingly, the results of the analyses herein are constrained by the availability of data, therefore the risk-based strategy should be implemented in an adaptive management framework, supported with rigorous monitoring.

The consequences of management errors in the Sacramento-San Joaquin Delta are potentially significant. The very survival of the delta smelt is at risk. At the same time, California as the fifth largest economy in the world has millions of people and thousands of industries that depend on Delta waters for their well-being. With both considered, here we have presented a method that can provide data-based support for water-allocation decisions necessarily made at critical times in the delta smelt's cycle of growth and reproduction, allowing those decisions to be made with empirical defensibility.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

SH: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Writing – original draft, Writing – review & editing. DM: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. EM: Formal analysis, Methodology, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fevo.2025.1411994/full#supplementary-material

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