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RESEARCH

Re-Examining Factors That Affect Delta Smelt (*Hypomesus transpacificus*) Entrainment at the State Water Project and Central Valley Project in the Sacramento–San Joaquin Delta

Lenny F. Grimaldo*[1], William E. Smith[2], Matthew L. Nobriga[2]

ABSTRACT

Managing endangered species is challenging when increased rarity leads to an inability to detect their responses to environmental conditions. In the San Francisco Estuary, the state and federally listed Delta Smelt (*Hypomesus transpacificus*) has declined to record low numbers, elevating concern over entrainment at the State Water Project (SWP) and Central Valley Project (CVP) water export facilities. The objective of this study was to: (1) revisit previous work on factors that affect adult Delta Smelt collected at the SWP and CVP fish collection facilities using updated conceptual models and a new statistical approach; and (2) to determine factors that affect salvage at time-scales of interest to management. Boosted Regression Tree (BRT) models were applied to salvage data at the SWP and CVP, aggregated into two response categories: a "first flush" response that represented daily salvage from the start of the entrainment window to the 50% midpoint of observed salvage, and a "seasonal" response that included daily salvage from the entire entrainment window. Precipitation, sub-adult abundance, Yolo Bypass flow, and exports best explained first flush salvage at both the SWP and CVP. The seasonal models included a similar set of influential variables, but the relative influence of precipitation was lower compared to the first flush models., Yolo Bypass flow was more influential for seasonal salvage at the SWP, compared to the CVP; Old and Middle River flow was more influential for seasonal salvage at the CVP. Although the rank of variable importance that explains salvage differed slightly between first flush and seasonal time-scales, this study suggests that salvage is most influenced by hydrodynamics, water quality, and population abundance. The application of BRT models to predict salvage is limited, because salvage has been low since federal protections were implemented in 2008. Forecast models that integrate real-time variables with fish behavior models may improve Delta Smelt management.

KEY WORDS

San Francisco Estuary, Delta Smelt, entrainment, water diversion, boosted tree regression

INTRODUCTION

Since the turn of the 21st century, fisheries management has redirected its focus from individual species to broader ecosystem objectives to address inherent complexities of aquatic environments (Link 2005; Hall and Mainprize 2004; Pikitch et al. 2004). For rare species, management objectives that focus on restoring ecosystem functions are considered desirable because they emphasize mechanisms that influence species survival and growth rather than counts of individuals, which may be difficult to detect as population numbers decline. For species listed under the federal Endangered Species Act (ESA), the law allows for recovery actions to be carried out through robust adaptive management plans that include consideration of habitat quality and quantity, reduced exposure to predators and contaminants, and improved access to rearing habitats. However, the ESA also requires that incidental take[1] of endangered species be reasonably minimized or avoided where possible. Conservation plans that can confidently assess and predict when listed fish species are likely to be encountered may help speed species recovery (Pikitch et al. 2004).

In the upper San Francisco Estuary, (California), national attention has been drawn to Delta Smelt (*Hypomesus transpacificus*), a small endangered fish whose numbers have declined to record low levels (Sommer et al. 2007; Moyle et al. 2018). Found nowhere else in the world, Delta Smelt seasonally reside within the hydrodynamic influence of two large water diversions that respectively provide municipal water for over 25 million Californians—the State Water Project (SWP)—and support a multi-billion-dollar agricultural industry: the Central Valley Project (CVP). When Delta Smelt are located near the SWP and CVP (hereafter also referred to as the "water export facilities"), water-diversion restrictions under state and federal ESAs are implemented to minimize entrainment losses (Reis et al. 2019; USFWS 2019; CDFW 2020). Substantial proportions of the population are

estimated to have been lost to entrainment (i.e., the fraction of the population that is entrained) in some years (i.e., > 10 %; Kimmerer 2008; Kimmerer 2011; Miller 2011; Korman et al. 2021; Smith et al. 2021). Modeled evaluations suggest that entrainment losses—along with food supply, water temperature, predators, and freshwater flow—have adversely affected Delta Smelt's population growth rate (Mac Nally et al. 2010; Kimmerer 2011; Rose et al. 2013). An improved understanding of the mechanisms and factors that affect Delta Smelt entrainment is very important to natural resource managers, scientists, and stakeholders who seek to both protect rare species and provide a reliable water supply to the people and agricultural communities of California (Brown et al. 2009; Cowin and Bonham 2013; Moyle et al. 2018).

Delta Smelt is an annual species whose relative abundance has been estimated for decades during the fall by the California Department of Fish Wildlife Fall Midwater Trawl Survey (FMWT; Thomson et al. 2010). This survey has usually concluded shortly before adult Delta Smelt begin to become lost to entrainment (Kimmerer 2008; Grimaldo et al. 2009), which prohibits a direct assessment from the long-term monitoring data of entrainment risk relative to real-time distribution and abundance concurrently with diversions from the SWP and CVP(termed "exports"). Also, a major decline of Delta Smelt observed in this survey has made it difficult to determine abundance and distribution trends from this long-term survey (Latour 2016). This difficulty provides challenges in assessing how distribution before the winter may affect entrainment risk during the winter when Delta Smelt move into the Delta and become vulnerable to entrainment. Thus, managers and scientists must also consider conditions that are likely to produce higher entrainment risk based on historical relationships between fish observed at the screens at the SWP and CVP intakes (known as "salvage") and physical-biological factors (Brown et al. 2009; Grimaldo et al. 2009). In more recent years, to assess real-time entrainment risk, new targeted surveys of adult Delta Smelt distribution and abundance have been implemented as long-term

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1. Federal ESA incidental take is defined as "to harass, harm, pursue, hunt, shoot, wound, kill, trap, capture, or collect any threatened or endangered species" (USFWS 1973)

monitoring programs during the winter, when they become vulnerable to entrainment (Polansky et al. 2018; USFWS 2019); however, these newer surveys provide a limited annual time-series from which to investigate long-term relationships, compared to the annual fall survey, which began in 1967 (Feyrer et al. 2007).

In this paper, to test the ability of a modern statistical approach to predict the conditions that most influence Delta Smelt entrainment risk, we revisit the factors known to affect adult Delta Smelt salvage at the SWP and CVP (Kimmerer 2008; Grimaldo et al. 2009; Miller 2011; Miller et al. 2012) with new information. The goal here is not to determine proportional entrainment losses or the effects of entrainment losses to the population—both of which have been examined previously (Kimmerer 2008; Kimmerer 2011; Maunder and Deriso 2011; Miller 2011; Rose et al. 2013). Rather, the goal is to determine how well entrainment risk, as indexed by salvage, could be quantified at time-scales relevant to management. Our study questions were the following: (1) What subset of factors best predict salvage at the SWP and CVP? (2) Does analysis at a seasonal time-step similar to Grimaldo et al. (2009) produce different results than an analysis that focuses on the onset of winter storms (also known as first flush periods)? (3) How well can SWP and CVP salvage be forecasted? Our hope was that addressing these questions would help resource managers improve real-time management actions to limit the entrainment of Delta Smelt, while also potentially increasing operational flexibility for the SWP and CVP per recent regulatory permit requirements (USFWS 2019; CDFW 2020).

METHODS

Study Approach

Because one of the goals of this paper was to develop a model or set of models useful for understanding entrainment risk in real-time, we used only independent variables that are measured at daily or sub-daily increments and are readily accessible for download in real-time (~within 14 days of measurement) in the analysis (Table 1). Also, only data that had time-series corresponding to the salvage data going back to 1993 were used in the analyses we present here (see Grimaldo et al. 2009). Physical and biological variables used in statistical models of Delta Smelt salvage included those used by Grimaldo et al. (2009) and new ones identified in more recent conceptual models (Miller et al. 2012). Overall, we designed the analysis to test hypotheses about how Delta Smelt salvage is expected to respond to hydrodynamics, hydrology, distribution, adult abundance, and water quality (Table 1). Food abundance and predator abundance have been identified as potentially important variables that influence adult Delta Smelt salvage (Miller 2011), but data on these variables are not collected in sufficient temporal (i.e., daily) or spatial scales to make them useful for the analyses we present here.

Inspection of the daily adult Delta Smelt salvage data (1993 to 2016) shows that the vast majority of adult Delta Smelt salvage occurs between December 1 and March 31. Thus, consistent with Grimaldo et al. (2009), we applied the same time-period (December 1 and March 31) for the analyses we present in this paper. We also created a first flush response variable for this analysis from the same data set. First flush events occur in association with the first major winter storm of the season (Bergamaschi et al. 2001); these events have been identified as triggers of high salvage in some years (Grimaldo et al. 2009). We constructed the first flush response variable by including only daily salvage from December 1 to the date that daily cumulative salvage reached its 50th percentile for the season (i.e., the seasonal midpoint of salvage). We reasoned the accelerating part of the seasonal salvage trends would best represent the environmental conditions that lead to the onset of entrainment events that are associated with upstream movements of Delta Smelt after the first winter storms of the season (Bennett and Burau 2015). Salvage data on the descending limb of the 50% midpoint may relate to factors that affect Delta Smelt entrainment after they enter the South Delta, such as reverse net Old and Middle rivers (OMR) flow, and less likely related to factors that generate upstream movements, such as tidal dispersion or long-distance upstream movement

Table 1 Variables used for examining adult Delta Smelt salvage dynamics (first flush and seasonal) at the SWP and CVP. Hypotheses about how variables affect (direction and importance) adult Delta Smelt salvage risk are indicated, and also provided with supporting references: ↑/↓ = salvage response with increasing magnitude of variable; explanatory effect is also included as weak (w), moderate (m), or strong (s). "No effect" indicated for variables not believed to have a measured effect on salvage response at the SWP and CVP. See text for response scale definition. Where available, references that support hypotheses are provided.

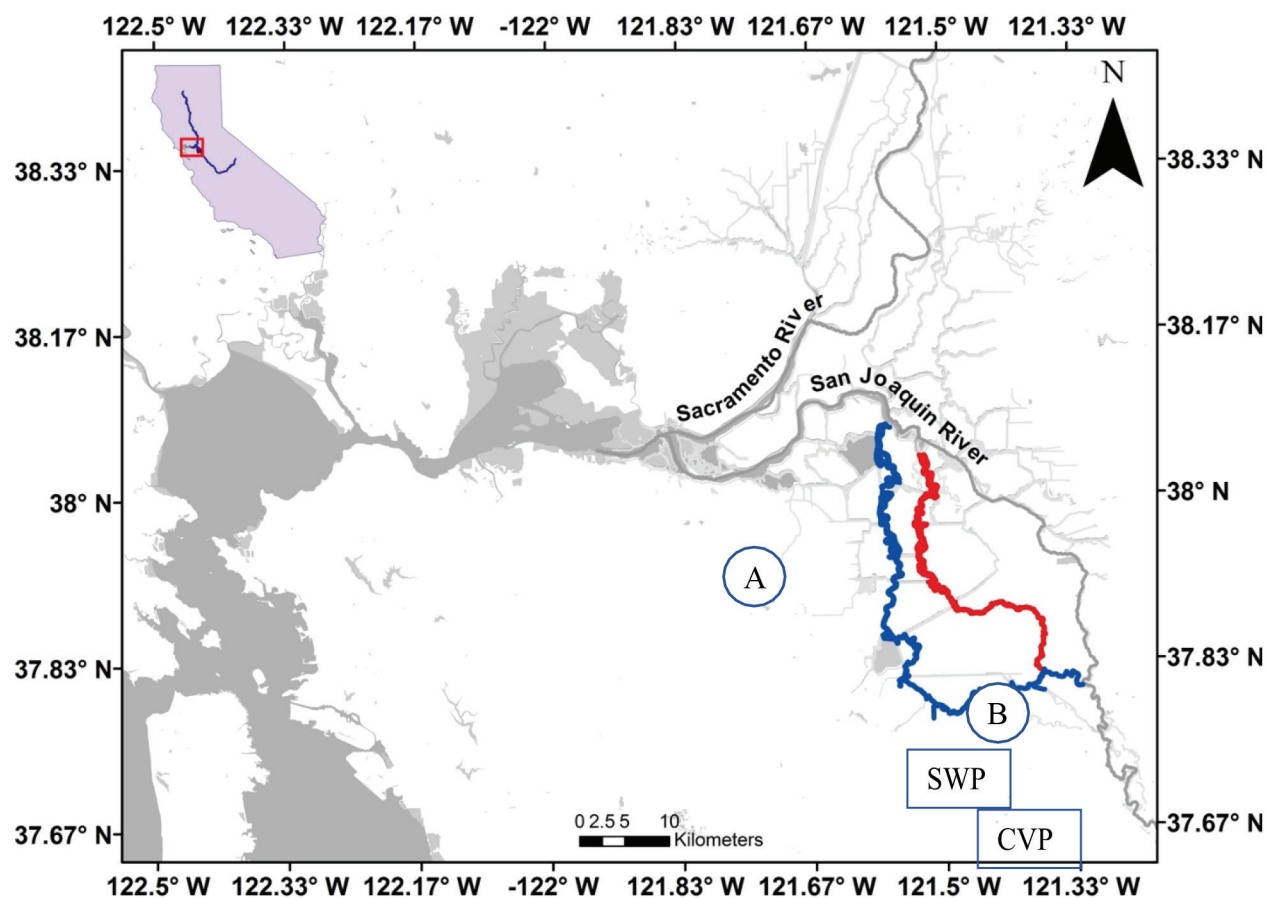| Variable	Abbreviation	Hypothesis (response direction and effect level)	Response scale	Reference
Sacramento River flow (m^{3}s^{-1})	SAC	↑ s	First flush and seasonal	Grimaldo et al. 2009; USFWS 2019; Miller et al. 2012
Yolo Bypass flow (m^{3}s^{-1})	YOLO	↑ m	First flush and seasonal	via turbidity increase Springborn et al. 2011, via flow increase Miller et al. 2012
Cosumnes River flow (m^{3}s^{-1})	CSMR	No effect	n/a	n/a
San Joaquin River flow (m^{3}s^{-1})	SJR	↑ s	First flush and seasonal	Grimaldo et al. 2009; Miller et al. 2012; USFWS 2019; CDFW 2020
Precipitation	PREC	↑ s	First flush and seasonal	Grimaldo et al. 2009; Bennett and Burau 2015; USFWS 2019
Cumulative precipitation since December 1	CPREC	↑ s	First flush and seasonal	Grimaldo et al. 2009
X2 on December 1	DecX2	↑ m	Seasonal	Grimaldo et al. 2009
State Water Project exports (m^{3}s^{-1})	SWP	↑ s	First flush and seasonal	Grimaldo et al. 2009; USFWS 2019; CDFW 2020
Central Valley Project exports (m^{3}s^{-1})	CVP	↑ s	First flush and seasonal	Grimaldo et al. 2009; USFWS 2019; CDFW 2020
Contra Costa exports (m^{3}s^{-1})	CCE	No effect	n/a	
North Bay Aqueduct exports (m^{3}s^{-1})	NBAQ	No effect	n/a	
Gross Channel Depletion (m^{3}s^{-1})	GCD	No effect	n/a	
Old and Middle River flow (m^{3}s^{-1})	OMR	↓ s	First flush and seasonal	Kimmerer 2008, 2011, Miller 2011; Miller et al. 2012; Grimaldo et al. 2009
Mallard Island water temperature (°C)	Temp	↑ w	First flush and seasonal	
Clifton Court Forebay turbidity (nephelometric turbidity units; NTU)	CCF.NTU	↑ s	First flush and seasonal	Grimaldo et al. 2009; Feyrer et al. 2007; Nobriga et al. 2008, Miller et al. 2012
Day index beginning December 1st	Day	↑ w	First flush and seasonal	
Fall Midwater Trawl index	FMWT	↑ s	First flush and seasonal	Kimmerer 2008, 2011; Miller 2011

Figure 1 Map of the San Francisco Estuary and study region. State Water Project (SWP) and Central Valley Project (CVP) exports and fish facilities are located in the southern region of the Sacramento–San Joaquin Delta. Old River and Middle River are indicated by blue and red lines respectively. Monitoring stations for (**A**) water temperature and (**B**) turbidity used in statistical models are shown on map.

(i.e., related to spawning) that brings them into the South Delta during first flush (Bennett and Burau 2015). The selection of the 50% midpoint of salvage for a first flush response variable is supported by findings of Polansky et al. 2018, who showed that adult Delta Smelt movements are limited after their initial movement upstream. In contrast, we used a "seasonal" response variable, which included all the daily data from December 1 to March 31, to examine factors that explained daily salvage over the entire period of risk. Both response variables could have important implications for management in reducing entrainment risk when first flush conditions materialize, and for understanding entrainment risk once Delta Smelt are located in the South Delta, near the SWP and CVP.

Finally, we applied models to each fish facility separately, to examine if patterns that underlie salvage were influenced by different factors, because the SWP's export capacity ($292\,m^3s^{-1}$) can be up to two and half times greater than the CVP's export capacity ($130\,m^3s^{-1}$). Also, although the SWP and CVP intakes are located relatively close to each other ($<3\,km$; Figure 1), the SWP differs from the CVP in having a large reservoir known as the Clifton Court Forebay (CCF) that temporarily stores water from the Old River to improve SWP pump operations. Pre-screen losses of entrained fish to milling predators are higher at the SWP compared to the CVP because the CCF supports high predator densities, which can result in poor survival of fish through the water that leads up to the fish screens (Gingras 1997;

Castillo et al. 2012). Thus, the SWP and the CVP can exhibit different responses in salvage. Understanding the factors that affect salvage at each water export facility separately may shed light on finer-scale dynamics that are useful for management application.

Data Sources

Intakes for the SWP and CVP are located in the southern Sacramento–San Joaquin Delta (Figure 1). As previously mentioned, both the water export facilities have large fish screens at their intakes that are designed to facilitate salvage of entrained fish. The SWP Skinner Fish Protective Facility (SFPF) and the CVP Tracy Fish Collection Facility (TFCF) direct fish through a complex louver system into collecting screens, where they are eventually trucked and released back into the western Delta, beyond the hydraulic influence of both facilities. A sub-sample of the salvaged fish are identified and measured. A variable fraction of Delta Smelt may survive the capture, handling, trucking, and release process (Miranda et al. 2010; Morinaka 2013).

The fish salvage facilities have been operating almost daily since 1958 (TFCF) and 1968 (SFPF; Brown et al. 1996), and arguably are two of the largest freshwater fish sampling systems in the world. Up until the early 1990s, salvage counts and identification were focused on salmonids and Striped Bass (*Morone saxatilis*). However, after Delta Smelt were listed in 1993, salvage count frequency increased from twice per day (1978 to 1992) to every 2 hours (Morinaka 2013). Daily salvage for each species per day for each facility is calculated by the following equation:

$$Sd = \sum_{i=0}^{n} si = Ci * \left(\frac{mpi}{ti} \right)$$

where *Sd* is the total daily salvage, *si* is the salvage in sample *i*, and *Ci* is the number of fishes in sample *i* defined by the minutes of water pumped (*mpi*) per the counting time (*ti*). Typically, there are six sample periods per day, and twenty individuals per species greater than 20-mm fork length (FL) are measured. Salvage data for Delta Smelt

and other species used in the analysis were obtained from the California Department of Fish Wildlife (CDFW) ftp site (*ftp://ftp.dfg.ca.gov/Delta%20Smelt/*). Delta Smelt adult abundance estimates from the CDFW's FMWT monitoring survey were obtained from the same ftp site.

Flow and water quality data were obtained from the California Department of Water Resources (CDWR) and US Geological Survey website portals (*http://www.water.ca.gov/dayflow/*; *http://cdec.water.ca.gov*; *http://waterdata.usgs.gov/ca/nwis/*).

Statistical Analyses

We analyzed adult Delta Smelt salvage data using Boosted Regression Tree (BRT) models (Elith et al. 2008). Regression trees seek to model a response variable using one or more predictor variables; data is recursively partitioned into a hierarchy of subsets, and the regression tree describes the structure of the hierarchy. The goal is to reduce multi-dimensional space into smaller subsets that can be described by very simple models. Regression trees split into branches at nodes, where nodes represent a value of a single predictor variable. Leaves on the branches represent a single value of predicted response over a range of the predictor variable, until the next node. To fit a regression tree, an algorithm identifies regions of greatest variance in the relationship of response and predictors as potential nodes. Between nodes, model predictions or leaves are simply the response that minimizes residual error (e.g., the mean), conditional on prior tree nodes and the path from the tree root. Regression trees can accommodate many distributions (binomial, normal, Poisson, etc.), are generally insensitive to outliers (Elith et al. 2008), and are suited to non-linearity in the response. Regression trees can be unstable with small data sets, because small changes in training data can result in large changes in tree splits (Hastie et al. 2001).

The boosting paradigm is that model performance is improved by averaging across many moderately fitting models rather than

selecting a single or small group of perfectly fit models (Elith et al. 2008). While traditional model selection approaches seek to identify a parsimonious model with few parameters, boosting approaches seek to fit many parameters and shrink their contribution, similar to regularization methods (Hastie et al. 2001). Boosting is an ensemble method like model averaging, but the process is sequential and iteratively minimizes a loss function (deviance; analogous to sum of squared error). At first iteration, the BRT is the best-fitting regression tree. At second iteration, the regression tree that best fits the residuals of the first is added to the BRT. This sequence proceeds until deviance is minimized and adding more trees results in greater deviance. The contribution of each tree to the BRT is limited or shrunk by the learning rate, and up to several thousand trees are commonly fit and added to produce the final BRT.

Although the BRT allows for inclusion of multiple correlated variables, we screened potential explanatory variables for collinearity ($R^2 > 0.6$; Table 2) to reduce the number of predictors. If two variables were highly correlated, we selected

for further inclusion only the variable with the strongest conceptual link to salvage . We reasoned that this would increase our ability to mechanistically interpret the results. We examined both SWP and CVP exports as well as OMR flows (see Grimaldo et al. 2009) in the BRT because both have potentially important applications for management targets. We explored four alternative combinations of data to determine whether any combination improved model performance above other combinations: (1) SWP and CVP exports as individual effects, (2) combined SWP and CVP exports, (3) OMR flow, and (4) San Joaquin River flow. We used the best combination of variables, as indicated by percent of null deviance explained, for inference.

The BRT model was fit using R package dismo and the gbm.step function (R Development Core Team 2008). The gbm.step function used 10–fold cross validation to determine the optimal number of regression trees to fit. Trees were added until a deviance minimum was reached. Learning rate was set to the lowest rate that reached a deviance minimum with between 1,000 and 2,000 trees

Table 2 Coefficient of determination (R^2) matrix of physical variables. Variable combinations exceeding the threshold for acceptance as predictors to fit in the BRT model are highlighted in *bold*. See Table 1 for variable definitions.

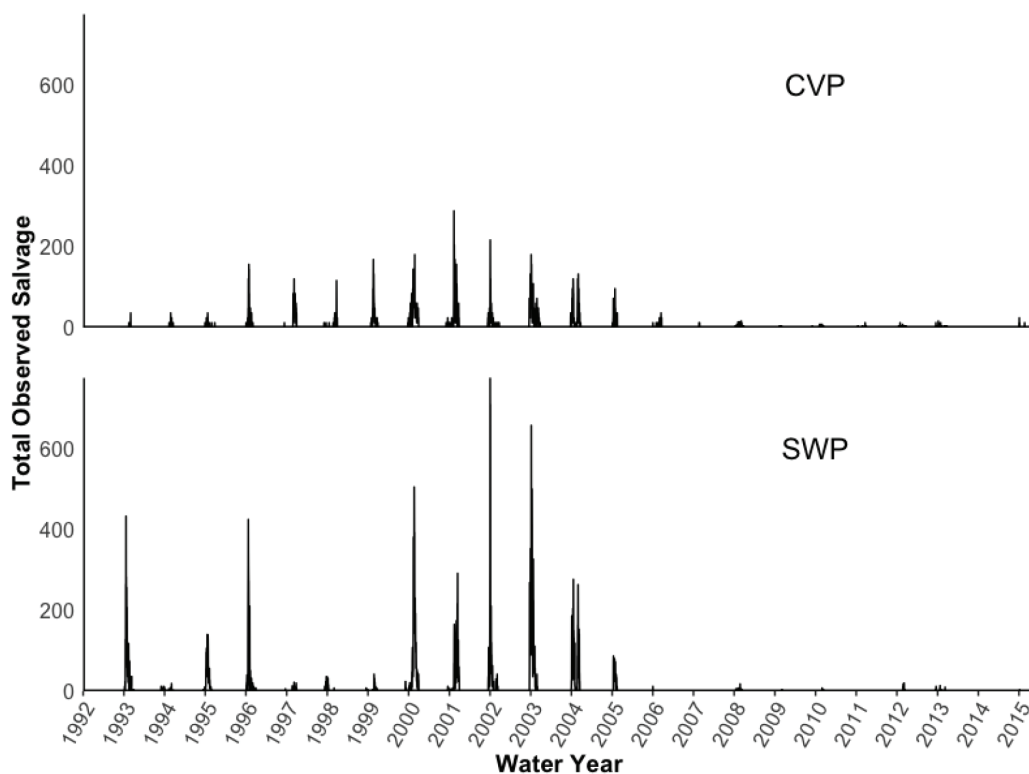|	SAC	YOLO	CSMR	SJR	SWP	CVP	CCE	NBAQ	GCD	PREC	CPREC	OMR	FMWT	Temp	CCF NTU	Dec X2
Day	0.03	0.00	0.02	0.04	0.03	0.00	0.06	0.19	0.41	0.01	0.52	0.03	0.00	0.29	0.02	0.00
SAC		0.37	0.28	0.44	0.01	0.05	0.01	0.09	0.04	0.16	0.31	0.15	0.00	0.00	0.25	0.08
YOLO			0.34	0.34	0.00	0.00	0.01	0.01	0.01	0.10	0.09	0.20	0.00	0.00	0.19	0.01
CSMR				0.16	0.00	0.01	0.01	0.03	0.01	0.16	0.08	0.07	0.00	0.00	0.08	0.02
SJR					0.03	0.00	0.02	0.03	0.04	0.03	0.31	**0.65**	0.00	0.00	0.29	0.13
SWP						0.24	0.00	0.00	0.01	0.01	0.00	0.39	0.02	0.01	0.01	0.02
CVP							0.00	0.00	0.01	0.01	0.01	0.21	0.01	0.00	0.01	0.00
CCE								0.00	0.04	0.04	0.02	0.01	0.00	0.01	0.00	0.01
NBAQ									0.09	0.00	0.18	0.01	0.04	0.06	0.06	0.00
GCD										0.00	0.28	0.03	0.00	0.00	0.04	0.00
PREC											0.01	0.00	0.00	0.00	0.05	0.00
CPREC												0.15	0.01	0.12	0.14	0.00
OMR													0.00	0.00	0.14	0.09
FMWT														0.00	0.00	0.13
Temp															0.01	0.01
CCF NTU																0.02

Figure 2 Daily CVP and SWP salvage from 1993 to 2016

$(0.01 > l_r > 0.1)$, and two-way interactions were modeled (tree complexity = 2). Half of the data were bagged as a training set at each iteration of the regression tree.

We checked the fit of models and residual error distributions with graphical plots of observed versus predicted salvage, and with graphical plots of model residuals versus observed salvage. To test the predictive capabilities of the model, we performed an annual cross validation by sequentially omitting 5 randomized years of data, refitting the model to the incomplete data set, and predicting the missing salvage observations. The accuracy of the model's predictions of missing salvage observations indicated the model's suitability to forecast salvage.

RESULTS
Salvage Patterns and Variable Selection
In total, the model analyzed 2,911 days of observed salvage and corresponding explanatory variables, representing 24 years of adult Delta Smelt salvage. Salvage at both the SWP and CVP showed a marked decline after 2005 (Figure 2). Correlation analysis of potential explanatory variables indicated that only OMR and San Joaquin River flow exceeded the threshold of $R^2 = 0.6$, so OMR and San Joaquin River flow were not included in the same data set. Variables that represented the day index and cumulative precipitation were somewhat correlated, and multi-collinearity was apparent among all river flow variables (Table 2).

Boosted Regression Trees
Of the four alternative data combinations for deciding which export metrics to include (e.g., SWP plus CVP exports, separate SWP and CVP exports, OMR flow, and San Joaquin River flow), none explained a significantly greater percentage of observed salvage using the data aggregated at 50th percentile or annual (Table 3). Therefore, we used separate SWP and CVP export data to fit the final model because they are more directly linked

Table 3 Percent of null deviance explained by four alternative model water facility export combinations using Boosted Regression Tree analysis. Values in parentheses represent 95% credible intervals over 500 boot-strapped models.

Seasonal data set

	SWP salvage model		CVP salvage model	
	OMR	SJR	OMR	SJR
SWP exports, CVP exports	**94** **(92-96)**	94 (92-96)	**85** **(81-88)**	86 (83-88)
Combined SWP and CVP exports	94 (92-96)	94 (92-96)	86 (77-88)	86 (81-88)

Daily data set

	SWP salvage model		CVP salvage model	
	OMR	SJR	OMR	SJR
SWP exports, CVP exports	**93** **(90-94)**	94 (90-95)	**87** **(84-90)**	87 (84-90)
Combined SWP and CVP exports	93 (90-95)	91 (93-95)	87 (83-90)	87 (84-90

to our study questions for looking at the factors that affect salvage at each project independently. We included OMR flow both because it has been used in previous examinations of adult Delta Smelt salvage (Grimaldo et al. 2009) and because it is currently managed to assess and minimize Delta Smelt entrainment risk, given that it integrates the direct effect of complex South Delta hydrodynamics (USFWS 2019; CDFW 2020).

BRT models of salvage indicated that regardless of time-scale—first flush or seasonal salvage period—the best predictors of salvage at both water export facilities were sub-adult abundance (Fall Midwater Trawl; FMWT index), SWP exports, OMR, and South Delta turbidity (CCF.NTU) (Table 4). Seasonal salvage at the SWP increased with increasing abundance (FMWT index), CCF.NTU, SWP exports, and more negative OMR flow (Figure 3B). SWP salvage also increased sharply with Yolo Bypass flow at the lower end of the distribution, tapering off at higher flows (Figure 3B). Seasonal salvage at the CVP increased with increasing abundance (FMWT

Table 4 Relative influence of all predictor variables in models fit to the seasonal or daily data set. Only variables with at least 5% influence were ranked; other variables were considered insignificant.

Central Valley Project (CVP)			State Water Project (SWP)		
	Relative influence (rank)			Relative influence (rank)	
	Seasonal data set	First flush data set		Seasonal data set	First flush data set
FMWT	0.17 (1)	0.26 (1)	SWP	0.30 (1)	0.22 (1)
CCF.NTU	0.11 (2)	0.07 (6)	YOLO	0.19 (2)	0.20 (2)
OMR	0.10 (3)	0.10 (3)	FMWT	0.11 (3)	0.11 (5)
CVP	0.09 (4)	—	CCF.NTU	0.09 (4)	—
CPREC	0.08 (5)	0.12 (2)	OMR	0.09 (5)	0.12 (4)
YOLO	0.07 (6)	0.08 (5)	CPREC	—	0.19 (3)
GCD	0.07 (7)	—	CSMR	—	—
SWP	0.06 (8)	0.05 (7)	CCE	—	—
CSMR	—	—	Mallard.Temp	—	—
CCE	—	—	CVP	—	—
Temp	—	—	NBAQ	—	—
PREC	—	—	SAC	—	—
SAC	—	—	Spawn.day	—	—
DecX2	—	—	DecX2	—	—
Day	—	0.09 (4)	PREC	—	—
NBAQ	—	—	GCD	—	—

index), CCF.NTU, CVP exports, cumulative precipitation (CPREC), and negative OMR flow (Figure 3A). Salvage was best explained by a combination of variables (Figure 3), and an equivalent level of variation in predicted salvage resulted from various combinations of–or interactions between–predictors (Figure 4).

Comparison of influential predictors between the full data set and the 50th percentile data set indicated a difference in the first flush response observed in CVP salvage, but little difference between the SWP first flush and seasonal salvage data sets (Table 4). CPREC was a more influential predictor of salvage at the SWP and CVP during the first flush period than at the seasonal level, while CCF NTU was somewhat

less influential during the first flush period than when considered across the entire season. Of less influence during the first flush period at the CVP were Cosumnes River flow and CVP exports.

Although BRT models explained a large proportion of null deviance (94% to 86%), predictive performance was poor when entire years were removed and predicted from a model fit to other years. Of 5 sequentially omitted years, the highest R^2 values were for omitted year 2004 ($R^2 = 0.20 - 0.36$ for SWP and CVP models, respectively); R^2 values for all other omitted years were less than 0.1 (Table 5).
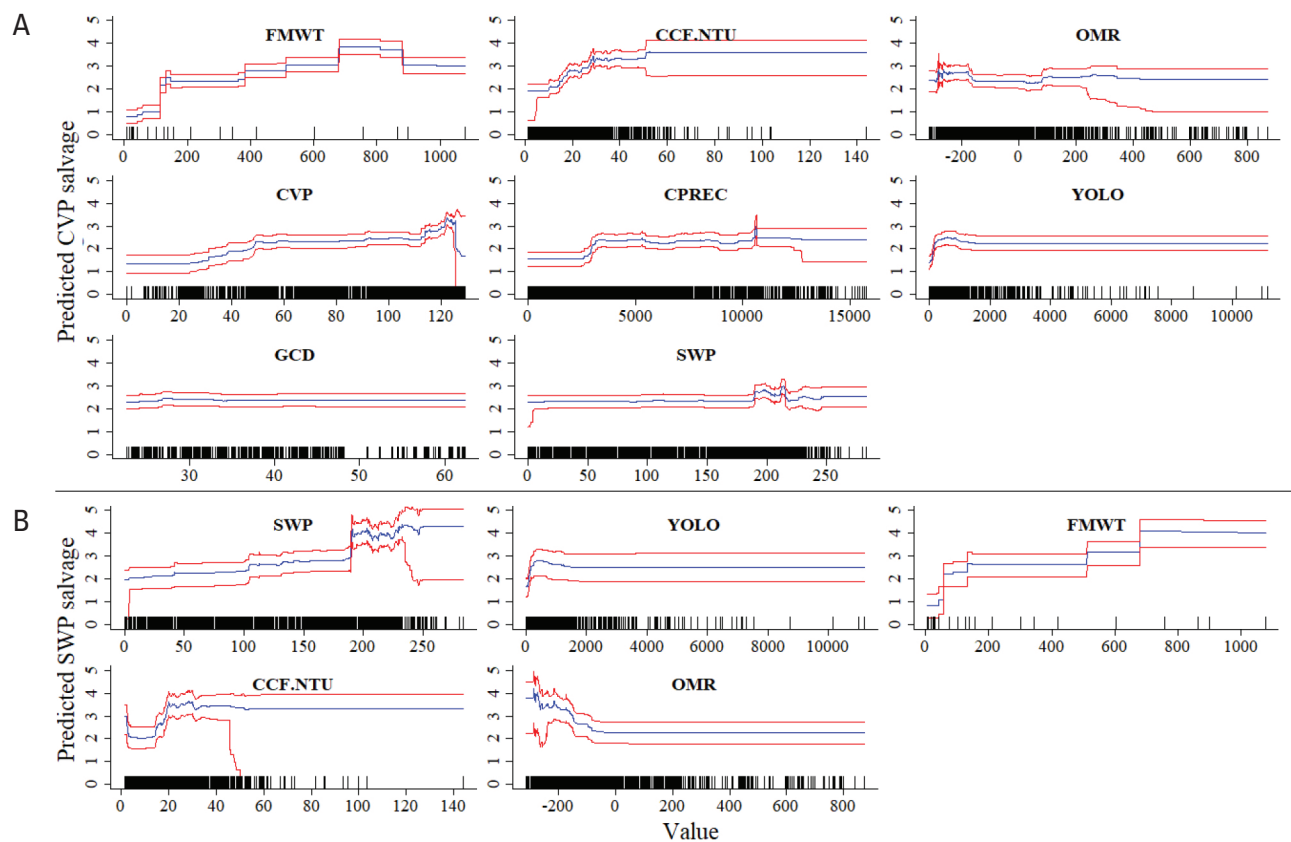

Figure 3   Model predictions of seasonal salvage (number of fish per day) at the (**A**) Central Valley Project and (**B**) State Water Project. Only the most influential variables are shown (see text for details of influential). Predictions represent expected salvage across the range of observed variable values, while holding all other variables at their means. *Blue lines* indicate median model predictions; *red lines* indicate 95% credible intervals of predictions, and *rug plots* indicate observed variable values. See Table 1 for variable units.
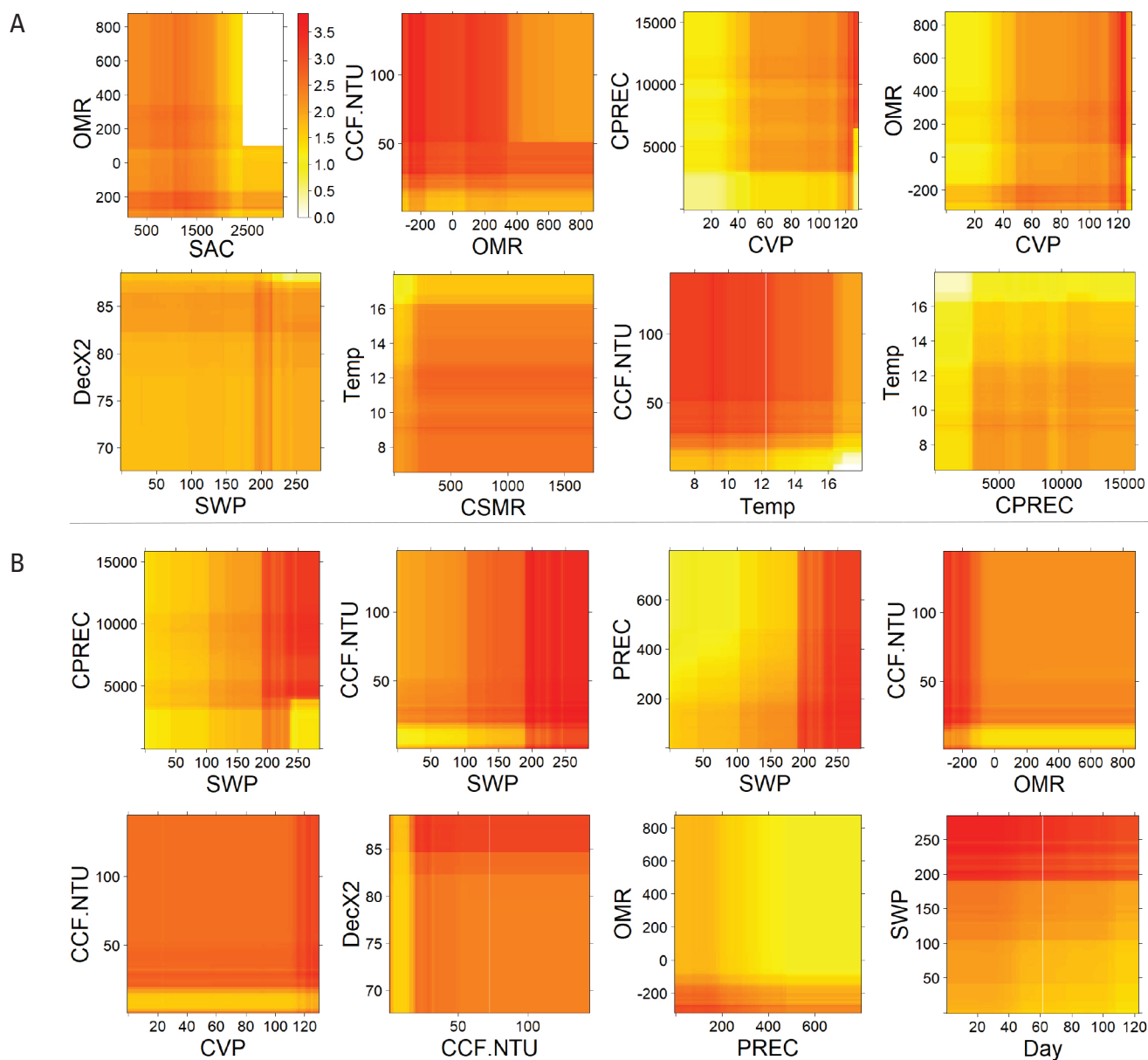
Figure 4 Heat maps of annual (**A**) Central Valley Project and (**B**) State Water Project salvage with variables deemed of most importance from BRT models. *Color range* represents strength of effect from *yellow* being lower to *red* being higher. See Table 1 for variable units.

DISCUSSION

This study reinforces previous work that adult Delta Smelt salvage is largely explained by hydrodynamics (including SWP and CVP exports as well as river flows), water clarity (turbidity), precipitation, and sub-adult abundance (Grimaldo et al. 2009). However, the approach applied here provided an improved understanding of entrainment risk for the SWP and CVP separately, and helped identify differences in the factors that influence salvage during first flush and seasonal time-scales when adult Delta Smelt are vulnerable to entrainment. Moreover, the statistical approach applied here is more robust than previous approaches (Grimaldo et al. 2009), which allows for stronger inference regarding the importance of factors that have led to high salvage events during the previous 24 years. Key study findings are further discussed under category of effects below.

Table 5 Coefficient of determination (R^2) between observed and predicted salvage when years of data were sequentially omitted

Predicted year	State Water Project (SWP)	Central Valley Project (CVP)
1998	0.01	0.01
1999	0.02	0.08
2004	0.20	0.36
2010	0.02	0.08
2013	0.02	0.05

Figure 5 Diagnostic plots for (**A**) Central Valley Project and (**B**) State Water Project salvage data using BRT models. Predicted values are expected to approximate observed values, falling along the diagonal 1:1 line (*left panels*), and residuals are expected to be randomly distributed around 0 (*right panels*).

Hydrodynamic Effects

It is not surprising that SWP exports best explained adult Delta Smelt salvage at the SWP for both first flush and seasonal data sets. SWP exports can be up to two and half times higher than the CVP, contributing to a larger proportion of net reverse OMR flow in the South Delta under high export conditions (Arthur et al. 1996; Monsen et al. 2007). As previously mentioned, in some years, some adult Delta Smelt move into the South Delta where they become more vulnerable to water exports because they become distributed within the hydrodynamic "footprint" of the water export facilities where the net movement of water is southward toward the SWP and CVP (Grimaldo et al. 2009; Gross et al., this volume). The rate at which these fish are observed at the fish facilities accelerates with increased SWP exports or net reverse OMR flow, because the residence time of water in channels that lead to the SWP and CVP—and within the CCF—decreases (Kimmerer and Nobriga 2008; MacWilliams and Gross 2013). During periods of higher exports and elevated turbidities, their exposure to predators likely decreases as both a function of residence time and detection in the water column as well (Castillo et al. 2012; Korman et al. 2021).

OMR flow influenced CVP salvage more than CVP exports for both first flush and seasonal data sets, suggesting an indirect influence of SWP exports through its contribution to reverse OMR flow. But the influence of OMR flow could also be related to San Joaquin River flow dynamics, especially for Delta Smelt that may take multiple routes to the salvage facilities. For
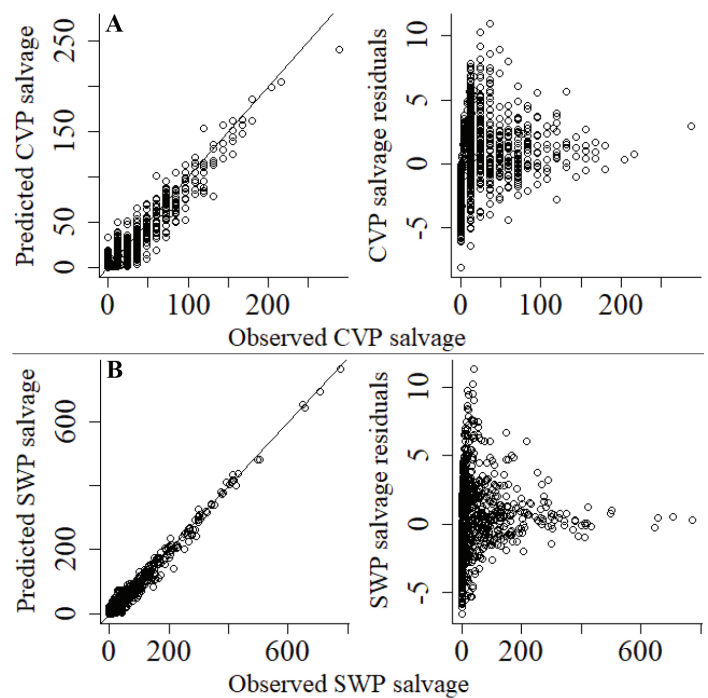
example, it is generally assumed that Delta Smelt largely move to the fish facilities via the Old and Middle rivers (Figure 1). Adult Delta Smelt can take a number of routes to reach the fish facilities, and even local dispersion around the SWP and CVP intakes themselves could influence which fish reach the CVP.

Turbidity Effects

The importance of turbidity as a predictor of seasonal Delta Smelt salvage at the SWP and CVP found here is consistent with previous research that shows entrainment risk increasing with turbidity (Grimaldo et al. 2009). Overlooked in previous attempts to quantify proportional population losses (Kimmerer 2008, 2011; Miller 2011), emerging work shows that turbidity is important for quantifying Delta Smelt pre-screen expansion loss estimates (Korman et al. 2021) and population growth rate estimates (Polansky et

al. 2019). Previous research that examined Delta Smelt abundance and distribution in regional fish monitoring surveys shows that Delta Smelt are caught more frequently when the water is more turbid (Feyrer et al. 2007; Nobriga et al. 2008; Sommer and Mejia 2013). This may be an effect of gear selectivity (Latour 2016) or habitat use that reduces predation risk. Because the SWP and CVP facilities entrain massive volumes of water compared to the monitoring survey trawls, and because water clarity in the South Delta is relatively high at other times of the year (Nobriga et al. 2008; Sommer and Mejia 2013), the association of Delta Smelt salvage and turbid water is unlikely an efficiency issue of the SWP and CVP fish facilities. Rather, it is more likely that adult Delta Smelt are moving with and occupying turbid water consistent with their more general use of pelagic habitat and reduced predation risk, a hypothesis supported by one recent study conducted during first flush periods (Bennett and Burau 2015).

It was not surprising that turbidity was not an important predictor of salvage of the first flush data. The CCF turbidity gauge is located at the entrance of the SWP and more or less represents South Delta turbidity until sediment gets mobilized into the Delta from upstream tributaries (Wright and Schoellhamer 2005). Hence, the CCF gauge is not the best measure of Delta-wide turbidity given an apparent time-lag between when the Delta becomes turbid and when this turbidity registers at the CCF gauge. But it is the only source of turbidity data that is readily available at a daily time-step going back to the start of the time-series analyzed here (1993). In short, the analysis presented here does not yield different results about the importance of turbidity in affecting salvage (Grimaldo et al 2009) because it was considered of high importance in the seasonal time-series. Emerging work by Gross et al. (this volume) suggests that turbidity is a key variable that influences behavior of Delta Smelt during first flush periods, though the actual cue that triggers upstream movements of Delta Smelt is unresolved (Bennett and Burau 2015).

The Yolo Bypass drains several smaller river tributaries and an inundated floodplain under high Sacramento River flow (Sommer et al. 2001) that transports massive sediment loads into and through the Yolo Bypass into the Delta (Springborn et al. 2011). The finding that Yolo Bypass flow ranked high in Delta Smelt first flush models at the SWP (second) and CVP (fifth) is likely not related to a hydrodynamic affect, but rather to an effect of increased turbid inflow associated with upstream movements of Delta Smelt (Sommer et al. 2011; Bennett and Burau 2015).

Adult Abundance

The apparent strong influence of sub-adult Delta Smelt abundance on SWP and CVP salvage was as hypothesized. When there are more fish, there is a greater chance of detecting them at the fish facilities, especially when a greater proportion of the population moves into the hydrodynamic footprint of SWP and CVP exports (Kimmerer 2008; Smith et al. 2019; Korman et al., this volume). It should be recognized that natural mortality that arises from spawning activity increases as the spring progresses (Polansky et al. 2018). Thus, the stock size vulnerable to entrainment risk decreases substantially by the end of March, when most adult Delta Smelt die after spawning—age 2 Delta Smelt are now extremely rare in the wild (Bennett 2005). This may explain why salvage of adult Delta Smelt is lower during March of most years, even after storms when turbidity increases, compared to December and January when most adult Delta Smelt are salvaged.

Fish Flush

Adult Delta Smelt movement during the winter is likely linked to a major change in their environment and pre-spawning activity (Bennett and Burau 2015; Gross et al., this volume). For the first flush data, cumulative precipitation was ranked of high importance at the combined SWP (third) and CVP (second) but was not important at the SWP, and ranked fifth in importance in the CVP model. This suggests that cumulative precipitation is a key indicator of the first flush response exhibited by Delta Smelt in some years. Mechanisms that underlie

cumulative precipitation as an indicator for Delta Smelt salvage during first flush remain unclear. Modeling Delta Smelt entrainment during first flush is complicated, and not explained by simple behaviors generated by singular cues (Gross et al., this volume; Korman et al., this volume). Researchers in other estuaries have found osmerid spawning behavior to be influenced by lunar phases (Hirose and Kawaguchi 1998), semidiurnal tides (Middaugh et al. 1987), and water temperature (Nakashima and Wheeler 2002). Note that Delta Smelt show little movement after first flush events (Polansky et al. 2018). This may explain the high year-to-year variation in observed salvage patterns (Grimaldo et al. 2009; Smith et al. 2019).

Management Implications

Managing Delta Smelt entrainment risk at the SWP and CVP during the winter can create conflict between resource managers responsible for protecting Delta Smelt and water operators who want to increase water diversions when river inflows increase into the Delta (Brown et al. 2009). Information generated from this study using either first flush or seasonal timescales reinforces previous work suggesting that adult Delta Smelt salvage risk can be assessed (and managed) using a combination of factors that represent Delta Smelt abundance, water quality (e.g., turbidity) and hydrodynamics (SWP and CVP exports and river flows) (Grimaldo et al. 2009). Hence, real-time monitoring of Delta-wide turbidity and river inflows remain useful tools for assessing when first flush conditions will materialize.

Endangered species regulations imposed under the US Fish and Wildlife Service Biological Opinion (USFWS 2019) and California Department of Fish and Wildlife Incidental Take Permit (ITP; CDFW 2020) require that Delta Smelt entrainment risk at the SWP and CVP be managed directly through manipulation of OMR flow. By analyzing salvage independently at the SWP and CVP, we found that OMR flow had a smaller explanatory influence on Delta Smelt salvage at the SWP than SWP exports. However, given the correlation of OMR with SWP and CVP models (Table 3), we

see no need to suggest an export metric other than OMR for managing Delta Smelt entrainment or entrainment risk at the SWP. The BRT model indicates that management must also consider sub-adult abundance, turbidity and precipitation—factors already considered in the evaluation matrix of the USFWS biological opinion and CDFW ITP.

Our attempt to use the BRT for forecasting was not fruitful (Table 5), in part, because the analysis included recent years (since 2006) when salvage has been low or zero. Future development of coupled biological-hydrodynamic models could also prove useful as a management tool, especially if behavioral hypotheses can be reconciled with existing data on the species' distribution and historical salvage patterns (Bennett and Burau 2015; Korman et al., this volume; Gross et al., this volume). A coarser aggregation of time (i.e., weekly or biweekly) or different response (i.e., presence vs. absence) should be explored in future forecast efforts.

New tagging techniques for cultured Delta Smelt (Wilder et al. 2016) could also be applied by releasing tagged fish during first flush periods to evaluate fish movement in the South Delta, and could further link movement of entrained fish to hydrodynamic conditions, similar to approaches used with Chinook Salmon (Oncorhynchus tshawytscha; Perry et al. 2010; Buchanan et al. 2013). These studies could also help quantify one source of variation that could not be explored in the BRT models: predation rates within the CCF across a range of exports and transport times (Castillo et al. 2012). Tagging studies could also provide more accurate pre-screen loss estimates (Smith et al. 2019; Korman et al., this volume) in the channels that lead to the SWP and CVP during first flush periods, as has been done for salmonids in the Delta (Cavallo et al. 2015).

Finally, the ultimate objective for managing Delta Smelt entrainment should not focus solely on reducing entrainment risk. Rather, the management objective—akin to typical fishery management—should be to determine how entrainment and other stressors affect population

growth rates (Ricker 1975; Hilborn and Walters 1992; Maunder and Deriso 2011; Rose et al. 2013; Hamilton and Murphy 2018). The results presented in this study can help scientists and resource managers identify circumstances when those large entrainment losses are likely to occur, which can ultimately be used to develop population-risk assessment models. The question about whether the Delta Smelt population can rebound from record-low abundances, even with improved entrainment management during the winter, remains outstanding, given the apparent importance of other factors (i.e., poor food supply, growth, and water temperatures; see Maunder and Deriso 2011; Rose et al 2013). Managers and scientists should focus on developing linked management actions that promote population growth within and between years (Bennett 2005; Maunder and Deriso 2011; Rose et al. 2013; Murphy and Weiland 2016).

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