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RESEARCH MONOGRAPH

Synthesizing Relationships Between Winter-Run Chinook Salmon Out-Migration Survival and Water Operations in the Sacramento–San Joaquin Delta

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ABSTRACT

Sacramento River winter-run Chinook Salmon (*Oncorhynchus tshawytscha*) are an endangered population that faces numerous challenges across its life cycle, including juvenile out-migration through the heavily anthropogenically modified Sacramento–San Joaquin Delta, or Delta. Water exports from pumping facilities in the Delta can alter local hydrology and influence movement of out-migrating juveniles, some of which are observed in or near pumping facilities. Monitoring and regulations, intended to protect out-migrating fish through restrictions on pumping, are predicated on assumed relationships among fish observations, water operations, and through-Delta migratory survival. In this study, we use a new conceptual model to review the current state of science for winter-run Chinook Salmon out-migration survival in the Delta, and use simulation modeling to address pertinent knowledge gaps. Results of this study highlight varying support for the influence of Sacramento River flow, temperature, and water exports on routing and survival in different regions of the Delta. The contributions of specific routing pathways to the interior Delta (e.g., through Threemile Slough) to survival, and the relationship between fish entrainment at pumping facilities and overall migratory survival, remain uncertain. Recommended future work includes continued fine-scale acoustic telemetry studies throughout the Delta, novel integrated modeling of monitoring data, and contextualizing the relevance of Delta-based survival to population viability by incorporating explicit uncertainties about survival into existing life-cycle models.

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INTRODUCTION

When managing natural resources such as fish populations, elements of the ecosystems are often manipulated to achieve certain desired societal goals (e.g., species recovery, self-sustaining population). In California, extensive construction of dams and water diversions, along with invasions of non–native species and modification of habitats and food webs, have combined to imperil many fish species and populations endemic to the state (Yoshiyama et al. 1998). Substantial time, effort, and money have been invested into regulating the rivers of California's Central Valley and the Sacramento–San Joaquin Delta (Delta) to provide both a reliable habitat for declining native species and water supply for human uses. Among some of the most controversial actions and regulations is the management of water exports from the large pumping facilities in the Delta to reduce fish entrainment into the facilities and less desirable habitat nearby. Reduction of pumping from the Delta for environmental purposes creates a perception that water for agriculture and water for the health of fish populations will inevitably be at odds; however, the reality of water management is much more complex and nuanced (Reis et al. 2019). The socio-political context of water operations for fish highlights the need to continue evaluating the science that underpins management actions and its linkage to species recovery targets.

Although the Delta was historically dominated by floodplains and dendritic tidal marsh that provided rearing habitat for juvenile salmon, less than 3% of such habitat remains, and approximately 80% of the Delta's tidal wetlands are diked and altered for agriculture and other human uses (SFEI 1998; Sommer et al. 2007; SFEI–ASC 2014; Brophy et al. 2019). The Delta currently exists as a network of channelized and dredged waterways, with pumping operations toward its southern end where tidally averaged flows can often be reversed (i.e., flows landward) in some of the channels; these operations are managed by the Central Valley Project (CVP) and State Water Project (SWP) (Figure 1). Anthropogenic alterations to habitat and hydrology are hypothesized stressors of fishes that reside in and utilize the Delta as a migratory corridor (Feyrer et al. 2007; Sommer et al. 2007; Johnson et al. 2017).

Chinook Salmon (*Oncorhynchus tshawytscha*) in the Central Valley display a diverse set of life-history strategies, yet all must migrate through the Delta twice in their life cycle: once as juveniles as they migrate to the ocean, and another as adults on their way to spawning grounds in the tributaries. Studies observed generally low survival for out-migrating juvenile Chinook Salmon through the Delta, and especially so if they enter the interior portion south of the Sacramento River (i.e., interior Delta) (Kjelson and Brandes 1989; Brandes and McLain 2001; Buchanan et al. 2018; Perry et al. 2018). Additionally, juvenile salmon may be entrained into the South Delta (i.e., the portion of the interior Delta south of the San Joaquin River) by high rates of diversions from the water export facilities, with multiple expected mortalities for every fish observed (i.e., salvaged) at these facilities because of elevated risk of predation in the area (NMFS 2009, 2019; Jahn and Kier 2020).

Although four distinct runs of Chinook Salmon use the Delta as a migratory corridor, Sacramento River winter-run Chinook Salmon (hereafter, SRWRC or winter-run Chinook Salmon) often garner the most interest. Named after the season in which adults return to freshwater, winter-run Chinook Salmon are genetically distinct from other populations in the Central Valley and exhibit a unique life history (Banks et al. 2000; Moyle 2002; Van Doornik et al. 2024). Although winter-run Chinook Salmon conduct their adult spawning migration in wintertime, they remain in freshwater and delay spawning until the summer. Juveniles rear in freshwater for 5 to 10 months before they migrate toward the ocean, with detections of out-migrating winter-run at the entrance of the Delta (i.e., Knights Landing) occurring between October and April (del Rosario et al. 2013). The cold-water-adapted winter-run Chinook Salmon historically spawned in the upper reaches of Sacramento River, where cool spring-fed water provided refuge in the hot, dry summers of the Central Valley. Constructions of the Shasta and Keswick dams around the 1940s blocked access to most of this cooler spawning habitat, possibly initiating the downward trajectory of winter-run Chinook Salmon numbers.

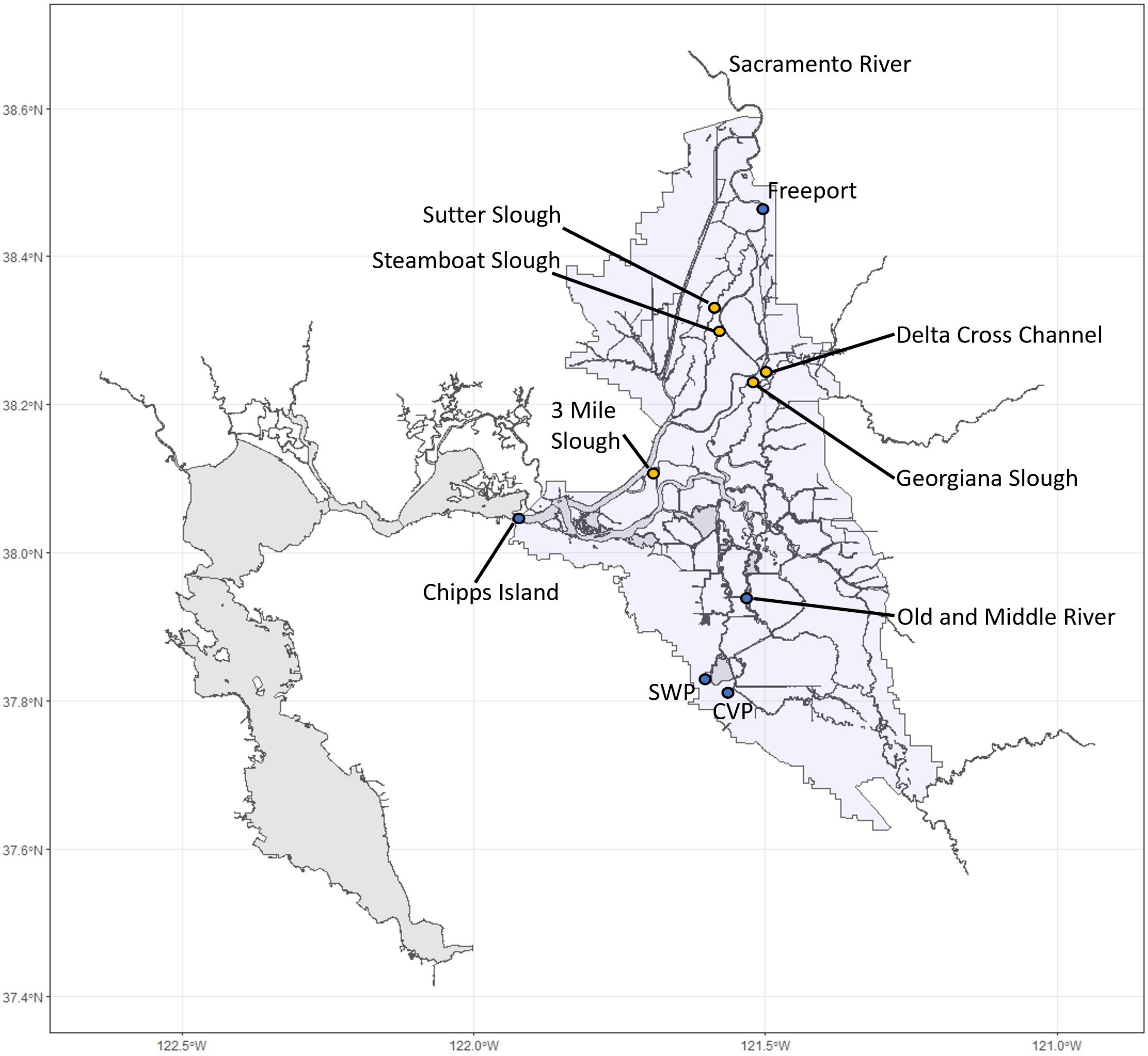

Figure 1 Map of the Sacramento–San Joaquin Delta. The *highlighted region* represents the legal boundary of the Delta, *yellow points* indicate migratory routing junctions with the Sacramento River, and *blue points* indicate relevant reference locations in the Delta.

Winter-run Chinook Salmon were listed as endangered under the California Endangered Species Act and federal Endangered Species Act (ESA) in 1989 and 1994, respectively (CCR 1989; Fed Regist 1994). Recovery actions for SRWRC largely have been implemented through regulatory actions by the National Marine Fisheries Service (NMFS) (e.g., Biological Opinions) and the State Water Resources Control Board (SWRCB; Meyers 2021). In the Delta, efforts to promote juvenile survival have focused on hydrodynamically-mediated effects by varying the amount of freshwater flow entering the Delta, varying the amount of freshwater diverted from the Delta, and using barriers to route fish to migratory pathways associated with higher survival (NMFS 2009, 2019). Furthermore, counts of salvaged fish at the CVP and SWP water pumping facilities, in addition to corresponding estimates of loss, are used as regulatory triggers for additional weekly or seasonal restrictions on pumping, and salvaged fish are re-released downstream in the western Delta (i.e., away from export facilities). Estimates of fish loss at facilities are based on counts of salvaged fish, and rely upon numerous estimated survival terms and assumptions, such as pre-screen near-field survival and the efficiency of directing fish already entrained in facilities to collection areas (Jahn and Kier 2020).

The use of estimated facility loss to trigger export restrictions, with the intention of improving SRWRC survival and corresponding population viability, necessarily relies on an assumed positive relationship between exports and fish loss, and a negative correlation between loss at facilities and through-Delta migratory survival, such that decreasing exports will increase SRWRC survival. However, our understanding of processes that affect through-Delta migratory survival—including relationships among Delta hydrology, water exports, and survival and routing throughout the Delta—remains incomplete. To address these uncertainties and the potential efficacy of recovery actions for SRWRC in the Delta, we identified and accomplished the following objectives: (1) inventory available resources for understanding juvenile SRWRC through-Delta migratory survival, (2) introduce a new conceptual model to characterize effects of Delta hydrology on survival, (3) characterize the current state of the science regarding migratory survival in the Delta using the conceptual model, and (4) address pertinent knowledge gaps using simulation modeling.

MATERIALS AND METHODS

Overview

We utilized a combination of literature, observations, and simulation models to characterize and improve our understanding of juvenile SRWRC through-Delta migratory survival. Specifically, we proposed a new conceptual model to organize our understanding of through-Delta migratory survival, inventoried available data and models that can inform this process, populated the conceptual model by synthesizing findings and knowledge gaps from relevant literature and data sources, and partially addressed identified gaps by simulating the effects of Delta hydrology on fish routing survival using the particle-tracking model (PTM) and ecological particle tracking model (ECO–PTM).

Study System

There are several CVP and SWP water operations conducted annually with the goal of increasing juvenile through-Delta survival by influencing out-migration routes and rates. Both physical and non-physical barriers are used to retain juvenile SRWRC within the mainstem Sacramento River and reduce their entrainment into the interior Delta. The first junction with the Sacramento River at which juveniles can enter the interior Delta is the Delta Cross Channel (DCC), a diversion channel that connects the Sacramento River with the Mokelumne River (Figure 1). The DCC increases the flow of freshwater from the Sacramento River (i.e., inflow)—the primary source of freshwater through the interior Delta coming from the north—away from the western saline Delta and toward the CVP and SWP diversion facilities in the South Delta. A set of gates exists at the upstream end of the DCC that are closed most of the year to prevent routing of SRWRC and other juvenile salmonids toward the interior Delta through the DCC. Under existing regulations, the DCC gates are typically closed starting in December until mid-June (NMFS 2019). However, the DCC gates can be closed earlier in the months of October and November, based on juvenile salmon catch at a rotary screw trap monitoring location near the city of Knights Landing, or at beach seine and trawl surveys around Sacramento. Further attempts to increase survival by modifying juvenile routing through the Delta have included experiments with different migratory barriers at other junctions along the Sacramento River. Results from multiple deployments suggested the most promising action is a Bio-Acoustic Fish Fence (BAFF) at the entrance to Georgiana Slough, which is another possible route to the interior Delta (e.g., Perry et al. 2014; Romine et al. 2016; CDWR 2022). A multi-year deployment of this type of barrier was started in 2024.

When the interior Delta's hydrodynamics are altered by its freshwater being diverted to CVP and SWP's pumping facilities, fish may be directly entrained. (Figure 1). The effect of pumping on interior Delta tidally averaged flows is typically expressed as the calculated combination of flow at the Old and Middle River (Old and Middle River Index, or OMRI), in which negative values indicate landward flows. Both the CVP and SWP pumping stations contain fish salvage facilities, where fish are collected and re-released downstream near the Delta exit. For every fish "salvaged," it is presumed that more individuals went undetected and have experienced mortality in or near the export facilities. One study suggested that once juvenile salmon enter the South Delta, survival can even be higher for fish that were salvaged and re-released, highlighting the poor conditions and survival in this part of the Delta (Buchanan et al. 2013). Since 2009, OMRI has been managed to be more positive than -5,000 cfs (cubic feet per second) in the months between January and June, for the purpose of protecting listed fish species such as SRWRC from entrainment into the South Delta and loss at pumping stations (NMFS 2009, 2019). Values of OMRI more positive than -5,000 cfs are hypothesized to affect movement and survival of salmonids in the South Delta relatively little, and it is further hypothesized that management of OMRI to more positive values (e.g., -3,500 cfs, -2,500 cfs) when observations of listed salmonid species at salvage facilities are higher than expected can further minimize movement effects and improve survival.

Conceptual Model for Characterizing State of the Science

We propose a spatially-explicit conceptual model for characterizing the state of the science regarding SRWRC migratory survival in the Delta, in which we separately consider the effects of water operations on the following demographic processes: (1) routing into the interior Delta, (2) survival of juveniles routed into the interior Delta, and (3) survival of juveniles not routed into the interior Delta (Figure 2). The intent of this conceptual framework is to summarize available studies and current understanding in a streamlined manner, identify critical uncertainties, and facilitate future discussion about these processes and their implications for water management. This conceptual model complements and expands upon information presented in recent reviews of salmonid migration in the Delta, aided by an exclusive focus on SRWRC and application of simulation models (Perry et al. 2016; SST 2017). Perry et al. (2016) reviewed new scientific findings related to multiple biological processes in the Delta between 2006 and 2016 for multiple salmonids but did not provide a unifying conceptual model; SST (2017) applied a conceptual model based on classes of hydrodynamic and biological drivers of biological outcomes for multiple salmonids but did not consider survival outside the interior Delta in detail.

We separately consider survival of fish through routes that do and do not include the interior Delta based on differences in reported effects of exports on survival through each, as well as estimated differences in survival (Brandes and McClain 2001; Perry 2010; Perry et al. 2018; Hance et al. 2022). Furthermore, the Delta is recognized as highly heterogenous, with regions characterized by different forcing factors, and this conceptual model accounts for this variability (SST 2017). We acknowledge there is an abundance of studies that have examined survival of juvenile salmonids released directly into the interior Delta or San Joaquin River (e.g., SJRGA 2007; Holbrook et al. 2009; Buchanan et al. 2013, 2015; Wohner et al. 2022). However, because these release locations do not represent locations expected to be frequently occupied by migrating SRWRC, we do not report on them in detail.

Review of Available Literature, Data, and Models

We inventoried relevant literature, data sources, and models through a combination of professional knowledge and expertise, outreach to colleagues with relevant expertise, and review of available secondary literature. Subsequent summaries within the conceptual model are not intended to serve as formal literature reviews or quantitative meta-analyses, but rather to provide both a current

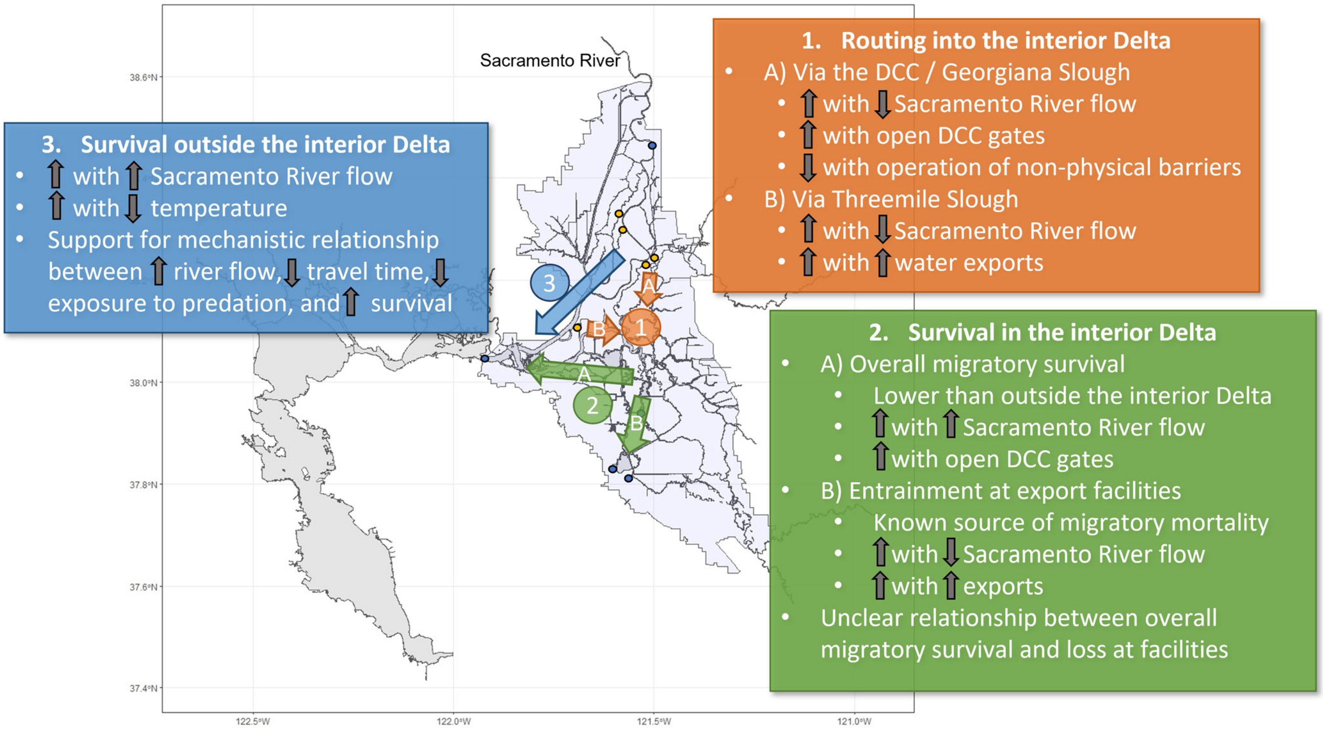

Figure 2 Conceptual model for SRWRC migratory survival in the Sacramento–San Joaquin Delta. The *highlighted region* represents the legal boundary of the Delta, *yellow points* indicate migratory routing junctions with the Sacramento River, and *blue points* indicate relevant reference locations in the Delta.

inventory of scientific resources and a unifying framework for characterizing effects of water operations on the migratory survival of juvenile SRWRC. The presented information represents an update to previous reviews that characterized influences on through-Delta migratory survival of Chinook Salmon (Williams 2006; Perry et al. 2016; SST 2017; Windell et al. 2017).

Simulating the Effects of Delta Hydrology on SRWRC Survival

We applied two simulation models—the particle tracking model (PTM) and the ecological particle tracking model (ECO-PTM)—to evaluate previous findings and address knowledge gaps identified by the synthesis of available literature using the new conceptual model. We specifically applied the PTM and ECO-PTM here because (1) the simulation frameworks were responsive to systemic modifications in hydrology throughout the Delta as a function of exports and (2) the code could be successfully run using available hardware and software.

Particle Tracking Model (PTM)

The PTM simulates the passive movement of particles throughout the Delta, in association with the Delta Simulation Model-2 hydrodynamic model (DSM2 HYDRO), and can track particle fates at numerous nodes, including direct entrainment at pumping facilities and passage past Chipps Island (i.e., Delta exit). The DSM2 HYDRO is a one-dimensional (1D) model for simulating Delta hydrodynamics, and PTM is a quasi-3D extension that assumes a given velocity profile in a given cross-section and allows simulation of particle movement (Culberson et al. 2004). Particles can be released at multiple insertion points and subsequently tracked throughout the Delta. The model has been applied to examine the movement and fate of fish through the Delta (Kimmerer and Nobriga 2008). Advantages of the model include the relative ease and speed of model analyses, in addition to an extensive history of model development, calibration, and testing. The model, however, does not allow direct estimates of particle mortality or broader through-Delta survival. We also note that PTM represents passive particle movement only and is not expected to capture the active swimming and resting behaviors of juvenile salmon.

We applied the PTM model to characterize the expected effects of different levels of pumping on particle routing through alternative migratory routes and the entrainment of simulated particles into both the interior Delta and export facilities. Entrainment of particles in the interior Delta and at facilities is hypothesized to reflect patterns and magnitudes of survival of out-migrating fish, assuming they passively follow the water. Specifically, we characterized the fate of neutrally buoyant particles released in the Sacramento River mainstem near Freeport, California (DSM2 node 330) at the beginning of the months of December, January, February, and March, for water years 1922–2003, and under a range of different OMRI values (i.e., -3000 cfs to -7000 cfs, in 1000 cfs increments; Figure 1). For management purposes, a water year is defined as the period from October 1 of the previous year to September 30 of a given year, such that water year 2024 spans October 1, 2023 through September 30, 2024. Water years 1922–2003 represent the default years modeled in CALSIM II—a water resources modeling system with a monthly time-step and the underlying hydrologic model for DSM2 HYDRO and PTM—and encompass a wide variety of possible hydrological conditions; corresponding model runs also represented regulations and actions that have been implemented since 2019–2020 (NMFS 2019; CDFW 2020). A total of 4,000 particles were inserted over a 24.75-hour tidal cycle on the first day of the month for each simulated combination of month, water year, and monthly OMRI value, and tracked using 15-minute time-steps. The different monthly average OMRI values were achieved for each CALSIM II run by imposing limits on negative flow, such that OMRI is specified to be no more negative than the specified threshold (i.e., -3000 cfs to -7000 cfs). Under conditions in which the monthly OMRI value was exactly equal to the threshold, the OMRI threshold was acting to constrain CVP and SWP pumping. We only retained PTM results for month and water-year combinations in which all OMRI values were equal to their corresponding threshold, to ensure we were comparing results based on identical OMRI values for each specified threshold. Water-year and month combinations in which OMRI values differed from the threshold occurred either when OMRI-based regulations were not yet triggered (i.e., only in December) or when the threshold OMRI value were not feasible as a result of hydrologic (e.g., too dry) or capacity-based (e.g., too wet) limitations on pumping.

We quantified particle fate 30 days after insertion for each month, water-year, and OMRI value to capture hydrologic conditions represented by monthly CALSIM II outputs. Specifically, we quantified the number of particles that entered the interior Delta via multiple routes. Entrainment at facilities was indicated by particles passing proxy model locations near CVP and SWP facilities. More information is provided in Appendix A.

Ecological Particle Tracking Model (ECO–PTM)

The ECO–PTM is an individual-based model of movement in the Delta, again relying in part on the 1D DSM2 HYDRO (Wang et al. 2024). In additional to simulating the movement of neutrally buoyant particles through the Delta, ECO–PTM incorporates individual fish behavior including swimming speeds, upstream or downstream directionality in movement, probabilistic holding, routing probabilities at select junctions (i.e., junctions of Sutter Slough, Steamboat Slough, Georgiana Slough, and DCC with the mainstem Sacramento River), and reach-specific survival using the predation-based XT model (Anderson et al. 2005). Model outputs include proportional routing through distinct migratory pathways (i.e., Sutter Slough, Steamboat Slough, interior Delta via either Georgiana Slough or DCC, and mainstem Sacramento River), route-specific travel times based on those particles that pass Chipps Island, and through-Delta migratory survival (i.e., from the release point to Chipps Island) based on travel time for each route. In contrast to PTM, ECO–PTM allows estimation of overall migratory mortality, as a function of travel time and assumed predation, and greater biological realism in particle routing. However, ECO–PTM does not readily allow characterization of additional particle fates throughout the Delta, such as entrainment at pumping facilities.

We applied ECO–PTM to characterize the expected effects of different levels of pumping on the routing of simulated fish into the interior Delta as well as travel time and survival of fish through all routes. It is hypothesized that if out-migrating fish behave similarly to the simulated neutrally buoyant particles with added swimming behaviors, estimated survival should reflect realized patterns and magnitudes of survival. Specifically, we characterized the estimated survival of neutrally buoyant particles, with added swimming behaviors, released in the Sacramento River mainstem near Freeport at the beginning of the months of December, January, February, and March, for water years 1922–2003, and under a range of different OMRI values (i.e., -3,000 cfs to -7,000 cfs, in 1,000-cfs increments). A total of 9,600 particles were inserted over a period of 24 hours (100 particles every 15 minutes) on the first day of the month for each simulated combination of month, water-year, and monthly OMRI value. The DSM2 HYDRO and ECO–PTM runs again were based on CALSIM II runs representing regulations and actions that have been implemented since 2019–2020 (NFMS 2019; CDFW 2020), and we only retained ECO–PTM results for month and water year combinations in which the OMRI values were equal to specified thresholds (i.e., ranging between -3000 cfs to -7000 cfs) (see Appendix A). We summarized route-specific routing proportions and survival for each month, water year, and OMRI value.

RESULTS

Inventory of Relevant Data and Models

Numerous sources of fish and environmental data, collected over decades of sampling in the Delta, have the potential to inform SRWRC migratory mortality. Tagging of Central Valley Chinook Salmon hatchery smolts from multiple run types—including SRWRC—using both coded-wire tags (CWTs) and acoustic-telemetry tags has informed migratory survival through the Delta (e.g., Kjelson and Brandes 1989; Perry et al. 2018). While CWTs require lethal recovery of tagged fish, acoustic-telemetry tagging uses dedicated receivers to detect passing fish without physical recapture (e.g., Cordoleani et al. 2024). In addition to the application of acoustic tagging to other run types, acoustic tagging has been applied to SRWRC hatchery smolts annually starting in 2013 (O’Farrell et al. 2018), and has provided fine-resolution information on routing and survival (Hance et al. 2022). Both hatchery- and natural-origin smolts are captured at multiple locations along their migratory route in the Sacramento River and Delta, including at rotary screw traps at multiple locations upstream of the Delta, in trawls in the Delta near Sherwood Harbor (i.e., just upstream of Freeport) and Chipps Island, and at fish salvage facilities near CVP and SWP pumping facilities (University of Washington c2024). Upstream estimates of juvenile fish passage, based on rotary screw trap sampling at Red Bluff Diversion Dam, are used to generate annual estimates of SRWRC smolt abundance entering the Delta, and estimates of juvenile abundance exiting the Delta past Chipps Island may be generated from tag data collected with the trawl at Chipps Island (O’Farrell et al. 2018; 2023 data file from R. Perry, USGS, to A. Jensen, unreferenced, see “Notes”). Environmental water-quality data—including turbidity, nutrient concentrations, flow, export rates, and temperature—are collected throughout the Delta by numerous agencies (e.g., CDWR 2024; USGS 2024).

Numerous models exist for characterizing migratory routing, travel time, and survival of juvenile SRWRC through the Delta, based on varying combinations of hydrological models and empirical tagging data. These include PTM (Kimmerer and Nobriga 2008); Delta Passage Model (DPM; Cavallo et al. 2011); Survival, Travel time, And Routing Simulation model (STARS; Perry et al. 2018); ECO–PTM (Wang et al. 2024); and enhanced particle-tracking model (ePTM; Sridharan et al. 2023). Additionally, models have been developed to characterize and predict the species-specific numbers of fish, including SRWRC, salvaged or lost at the CVP and SWP pumping facilities. These include simple calculations of salvage density (i.e., numbers of salvaged fish per thousand acre-feet of exported water) to predict salvage under future export conditions, and a quantile regression forest approach to predict facility entrainment (USBR 2019; Tillotson et al. 2022). Finally, life-cycle models have been developed for SRWRC that incorporate at least one of the Delta-specific sub-models for migratory survival, including the Interactive Object-Oriented Simulation Model (IOS; Zeug et al. 2012), the Central Valley Project Improvement Act (CVPIA) Science Integration Team (SIT) winter-run Chinook Salmon Decision Support Model (Peterson and Duarte 2020), and the Winter-Run Life Cycle Model (Hendrix et al. 2022).

The summarized data and models were used throughout the available literature on SRWRC through-Delta migratory survival. Findings from these studies are summarized in the synthesis of findings and knowledge gaps, below.

Synthesis of Findings and Knowledge Gaps Using the Conceptual Model

Routing into the Interior Delta

Previously modeled migratory routes of Chinook Salmon juveniles through the Delta, starting in the Sacramento River, include the following, as ordered from the most upstream junction to the most downstream: (1) through the Sutter Slough and back into the mainstem Sacramento River, (2) through the Steamboat Slough and back into the mainstem Sacramento River, (3) through the DCC into the interior Delta, (4) through Georgiana Slough into the interior Delta, or (5) through the mainstem of the Sacramento River only (Figure 1; Perry 2010; Perry et al. 2013; Perry et al. 2018; Hance et al. 2022). Consistent with past studies, this list excludes juveniles routed into the Yolo Bypass further upstream from the Sacramento River, and we do not specifically focus on these juveniles in the conceptual framework. Because survival generally appears to be similarly high between fish routed through Sutter Slough, Steamboat Slough, and the mainstem Sacramento River, and effects of exports are not considered to affect hydrology at the Sutter Slough and Steamboat Slough junctions, we focus our framework on drivers of routing into the interior Delta. Based on acoustic telemetry tagging of late-fall-run Chinook Salmon juveniles, routing to the interior Delta through either Georgiana Slough and/or the DCC can be substantial, varying from approximately 30% to 57% (Perry et al. 2018).

Based on acoustic-telemetry studies, including both late-fall-run and winter-run Chinook Salmon, entrainment of fish into the interior Delta through either the DCC or Georgiana Slough was observed to be influenced by Sacramento River flow, tidal flows, cross-channel position of migrating fish, diel patterns, operation of the DCC gates (i.e., open or closed), and operation of non-physical barriers (Perry et al. 2014; Perry et al. 2015; Plumb et al. 2016; Perry et al. 2018; Hance et al. 2020; Hance et al. 2022). Routing to the interior Delta via the DCC, when the gates are open, appeared to increase with decreasing Sacramento River flow (Plumb et al. 2016; Perry et al. 2018). Meanwhile, routing into Georgiana Slough has been estimated to be approximately proportional to the proportional volume of flow that enters the slough, which is coarsely influenced by Sacramento River and tidal flows, but varies at a finer resolution as a function of characteristics that include the critical streakline position and time of day (Perry 2010; Hance et al. 2020). Overall, studies have reported either insignificant or negative correlation between inflow and routing to the interior Delta via Georgiana Slough, as well as increased routing to the interior Delta with the opening of the DCC gates (Perry et al. 2015; Perry et al. 2018; Hance et al. 2020; Hance et al. 2022). Additionally, the operation of a non-physical barrier (i.e., a bio-acoustic fish fence) at the entrance of Georgiana Slough substantially reduced routing into the pathway, with barrier effectiveness declining with increasing flow (Perry et al. 2014; Hance et al. 2020).

The reported acoustic-telemetry studies did not hypothesize that Delta exports would affect fish routing to the interior Delta. Analyses of hydrology using DSM2 HYDRO observed minor to no distinguishable effects of simulated exports, ranging from 2,000 to 10,000 cfs, on the flow near the junction of the Sacramento

River and Georgiana Slough (Cavallo, Gaskill, et al. 2013). Furthermore, comparison of modeled routing proportions of fall- and late-fall-run juveniles into the Georgiana Slough with the lowest modeled inflow (i.e., 11,227 cfs) showed little difference in routing under varying export conditions (i.e., ranging from 2,119 to 10,594 cfs; Cavallo et al. 2015).

In addition to the well-recognized pathways of the Georgiana Slough and DCC, additional possible routes to the interior Delta have received relatively less attention and study. For example, previous studies have acknowledged the possibility of fish routing through Threemile Slough, a potential routing pathway downstream of the DCC gates, but suggest this route plays a minor role in fish movement (Kjelson et al. 1989; Perry and Skalski 2009; Newman and Brandes 2010; Zeug and Cavallo 2014). More recent modeling studies have not formally considered the role of this or other alternative pathways, including the confluence of the Sacramento and San Joaquin rivers (e.g., Hance et al. 2022). However, acoustic-telemetry tagging data from 2022 may support some routing contribution by Threemile Slough. Four tagged fall-run smolts, out of 83 released fish that made it past the first available receiver in Sutter Bypass, were detected entering Threemile Slough; all fish detections exhibited patterns characteristic of predation shortly before or after detection at Threemile Slough (2023 email between A. Wampler and A. Jensen, unreferenced, see “Notes”).

These findings broadly support the conclusions that routing to the interior Delta through the DCC and Georgiana Slough can be expected to increase with reduced Sacramento River flow and the opening of the DCC gates, decrease with the operation of non-physical barriers, and not respond to variation in water exports. Remaining knowledge gaps include the relative contribution of alternative routing pathways to the routing of SRWRC to the interior Delta, such as Threemile Slough, as well as the role of hydrologic forcing (e.g., Sacramento River flow, water exports) on the contribution of these pathways.

Survival in the Interior Delta

Numerous studies reported reduced survival (i.e., overall probability of surviving) for fish migrating to and through the interior Delta relative to other pathways. Estimated survival of fall-run Chinook salmon smolts released in Georgiana Slough with CWTs was consistently less than half (about 35% to 44%) of those released in the mainstem Sacramento River below the junctions with DCC and Georgiana Slough (Brandes and McClain 2001; Newman 2008; Newman and Brandes 2010). Acoustic telemetry studies similarly estimated lower and less variable survival of late-fall-run juveniles migrating through pathways into and through the interior Delta via Georgiana Slough and the DCC, relative to other pathways (Perry et al. 2013, 2018).

Numerous tagging studies evaluated effects of environmental conditions on Chinook Salmon smolts’ survival through the interior Delta. Studies based on CWT releases observed weak or insignificant relationships between the export-to-inflow ratio and survival for fall-run smolts released in the Delta, a slight positive effect of flow on survival, and a strong, negative effect of release temperature (Newman and Rice 2002; Newman 2008; Newman and Brandes 2010). For CWT fish already entrained in either the interior Delta or routes leading to the interior Delta, opening the DCC gates increased estimated through-Delta migratory survival (Newman and Rice 2002; Cavallo, Merz, et al. 2013), likely from greater flows in the channel decreasing travel times and exposure to predators. Acoustic-telemetry tagging studies including both late-fall-run and SRWRC juveniles identified a positive effect of flow on survival through only the Georgiana Slough, either no effect or a significant positive effect of flow on survival through the interior Delta, and no effect of either temperature or the export/inflow ratio on survival (Perry et al. 2018; Hance et al. 2022).

Researchers also noted that the magnitude of the difference in estimated mortality between CWT fall-run hatchery smolts in the mainstem Sacramento River and in Georgiana Slough was not solely explained by differences in travel distance, and suggested other environmental stressors and loss at CVP and SWP facilities may be driving elevated mortality of fish that enter the interior Delta (Brandes and McClain 2001). Analyses of environmental effects on smolt entrainment at facilities (i.e., as measured by occurrence of salvage or magnitude of loss) observed that SRWRC entrainment had a positive correlation with exports, and negative correlations with both OMRI and flow (Zeug and Cavallo 2014; Tillotson et al. 2022). However, we note that the greatest estimated loss of winter-run at salvage facilities since water year 2001—expressed relative to the estimated number of smolts that enter the Delta—occurred in water years 2011 and 2012, during relatively high-precipitation years in which inflow was higher and OMRI values were relatively positive (Appendix B). These observations suggest there are years with atypical combinations of hydrology, environmental conditions, and winter-run loss at salvage.

Importantly, the relationships between SRWRC loss at facilities and through-Delta migratory survival have not been well established in empirical studies. Evaluating relationships between salvage and migratory survival requires data at appropriate scales for both processes; potentially informative data include estimates of SRWRC salvage and loss at CVP and SWP facilities, CWT release and recovery data, acoustic-telemetry tagging data, estimates of SRWRC smolt abundances entering the Delta, and relatively recent estimates of SRWRC juvenile abundance exiting the Delta. Because these data have not been readily available until recently, no previous studies have documented a correlation between facility loss and overall migratory survival across years. The only dedicated evaluation of both processes used CWT and salvage data to estimate that entrainment mortality contributed less than 5.5% to total juvenile and ocean mortality (i.e., encompassing river, Delta, and ocean survival) for all Chinook Salmon smolt releases (Zeug and Cavallo 2014).

Furthermore, apparently contrasting effects of hydrological alterations on migratory survival and entrainment at pumping facilities further complicate our understanding of this relationship. Migratory survival through both the interior Delta and the Delta as a whole has been observed to be either unaffected or only weakly affected by changing exports, while loss at facilities increases with increasing hydrological alteration caused by exports (Newman and Brandes 2010; Zeug and Cavallo 2014; Hance et al. 2022; Tillotson et al. 2022). However, the contrasting effects of Sacramento River flow on migratory survival and facility entrainment suggest that the two processes may be inversely related as a function of river flow, such that facility entrainment decreases with increasing flow while overall migratory survival increases.

Relevant available studies support the following conclusions regarding the migratory survival of fish through the interior Delta: (1) survival for fish in the interior Delta is lower than that for fish migrating through other routes; (2) survival to and through the interior Delta is likely affected by Sacramento River flow and operation of the DCC gates; may or may not be affected by temperature, based on conflicting findings across studies; and is likely not meaningfully affected by exports; (3) juvenile entrainment by export operations is a known source of mortality in the South Delta and is influenced by Sacramento River flow and exports. Remaining knowledge gaps include the uncertain effects of exports on finer-scale migratory processes in the interior Delta and the poorly resolved relationship between migratory survival and loss at facilities.

Survival Outside the Interior Delta

Several studies have used releases of CWT Chinook Salmon to characterize environmental and operational influences on migratory survival, with varying capacities to differentiate between fish migrating outside or inside the interior Delta. Survival data from fall-run Chinook salmon smolts released in the Sacramento River downstream of junctions with Georgiana Slough and the DCC indicated survival had an inverse relationship with water temperature and with tidal flood stage; no effects of flow were detected (Kjelson et al. 1989). Additional CWT data across multiple release sites both above and below junctions with routing pathways to the interior Delta (i.e., likely encompassing juveniles that migrated through the interior Delta) supported a consistent negative relationship between survival and release temperature, positive relationships between survival and flow with varying strengths, and weak or insignificant effects of exports; these studies also observed a negative effect of opening the DCC gates on through-Delta survival, consistent with directing fish into the interior Delta and further away from the confluence (Newman and Rice 2002; Newman 2003). In contrast, additional analyses of fall-run CWT release data from multiple release sites indicated ocean recovery rate (i.e., encompassing freshwater and marine survival) had the strongest positive relationship with water quality, including measures of ammonium concentration and Secchi depth, but found little support for the influence of exports or inflows (Zeug and Cavallo 2013).

More recent releases of acoustic-telemetry-tagged smolts allowed identification of, and estimation of survival for, fish that migrate only outside the interior Delta. Survival of late-fall-run juveniles migrating through pathways outside the interior Delta—including Sutter Slough, Steamboat Slough, and the mainstem Sacramento River—was estimated to vary widely, from a low of approximately 30% to a high of 80% (Perry et al. 2018). The same study also identified significant positive effects of flow on survival for fish that migrated through these pathways (Perry et al. 2018). Expanded analyses supported positive effects of inflow on SRWRC survival through Sutter and Steamboat sloughs, observed no significant effect of flow on survival in the mainstem Sacramento River below the Rio Vista Bridge, and identified generally negative but insignificant effects of temperature on survival (Hance et al. 2022). The mean free-path theory of predator–prey interactions (i.e., the XT model), which specifies that juvenile Chinook Salmon migratory survival increases with decreasing travel time and/or distance, supports these observations (Anderson et al. 2005). Although previous analyses have not specifically reported on potential possible effects of water exports on survival outside the interior Delta, previous findings of limited effects of exports on simulated flow near the junction of Georgiana Slough and the Sacramento River support a limited effect of exports on survival within the Sacramento River (Cavallo, Gaskill et al. 2013).

The available data generally support the following conclusions for SRWRC that migrate outside the interior Delta (i.e., from the Sacramento River upstream of the junction with Sutter Slough to approximately Chipps Island): although estimated environmental influences varied across both tagging methodologies and studies, migratory survival of fish appears to be affected predominantly by inflow, and to a lesser degree by temperature, with no reported effects of exports or other water operations in the Delta.

Insights from Simulation Models

Routing into the Interior Delta

Modeling results from PTM generally support previous studies that observed a negative correlation between Sacramento River flow and routing to the interior Delta. The PTM-predicted routing through Georgiana Slough varied strongly as a function of inflow, with increased inflow associated with decreased routing (Figure 3). Differences in routing proportions among the OMRI levels were negligible, which is also consistent with previous findings that exports are not expected to affect routing to the interior Delta through Georgiana Slough. Predicted routing percentages through Georgiana Slough varied between 13% and 24% across all combinations of month, water year, and target OMRI.

The PTM also allowed us to quantify expected particle movement into additional migratory pathways, such as Threemile Slough, as a function of hydrology. Simulated routing through Threemile Slough varied widely across simulations, from approximately 2% to 23%. These values were more variable than those predicted for Georgiana Slough but approached similar peak values. Similar to PTM results for Georgiana Slough, routing through Threemile Slough decreased with increasing Sacramento

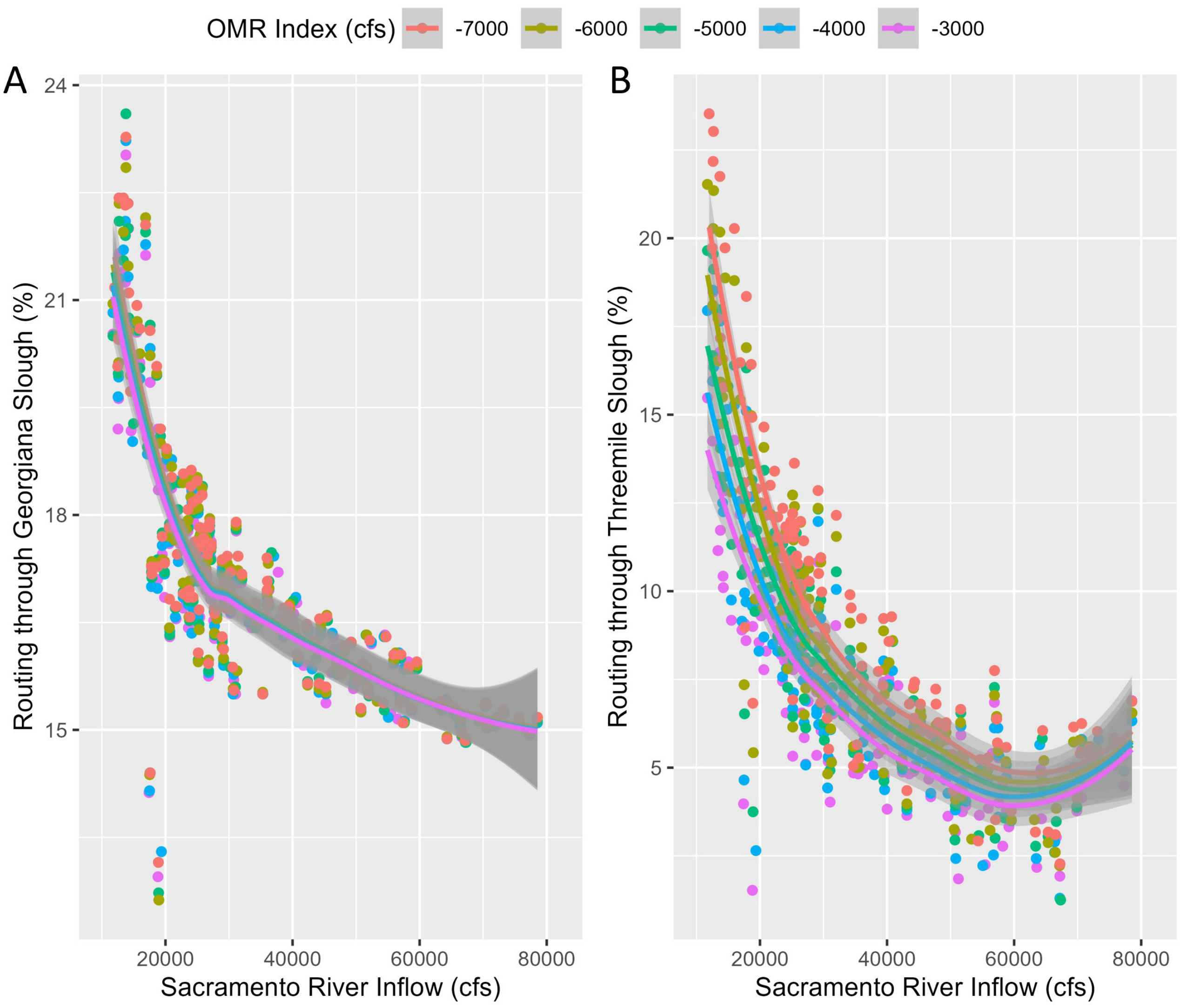

Figure 3 Predicted routing proportions through Georgiana Slough (**A**) and Threemile Slough (**B**), based on PTM, as a function of Sacramento River inflow and target OMRI. *Lines* represent "loess" model fitting in 'ggplot2'.

flow (Figure 3). However, in contrast to the Georgiana Slough results, routing through Threemile Slough increased with progressively negative OMRI (i.e., increasing water exports); this effect of exports on routing was weaker than the effect of inflow. These PTM results suggest a meaningful percentage of particles (i.e., up to 23%) can be routed to the interior Delta via Threemile Slough, and changing exports could influence these routing percentages.

Survival in the Interior Delta

Results from ECO–PTM simulations generally supported the following findings from previous studies: (1) Sacramento River flow affects migratory survival within Georgiana Slough and possibly through the interior Delta, and (2) exports do not affect through-Delta migratory survival of fish routed to the interior Delta. Simulation results indicated higher through-Delta survival for fish routed through Georgiana Slough with increasing Sacramento River flow, but no obvious differences in survival among OMRI values (Figure 4). These results suggest that changing OMRI values do not affect hydrology in a manner that meaningfully influences simulated particle travel time (i.e., travel time to Chipps Island), because (1) particle movement in ECO–

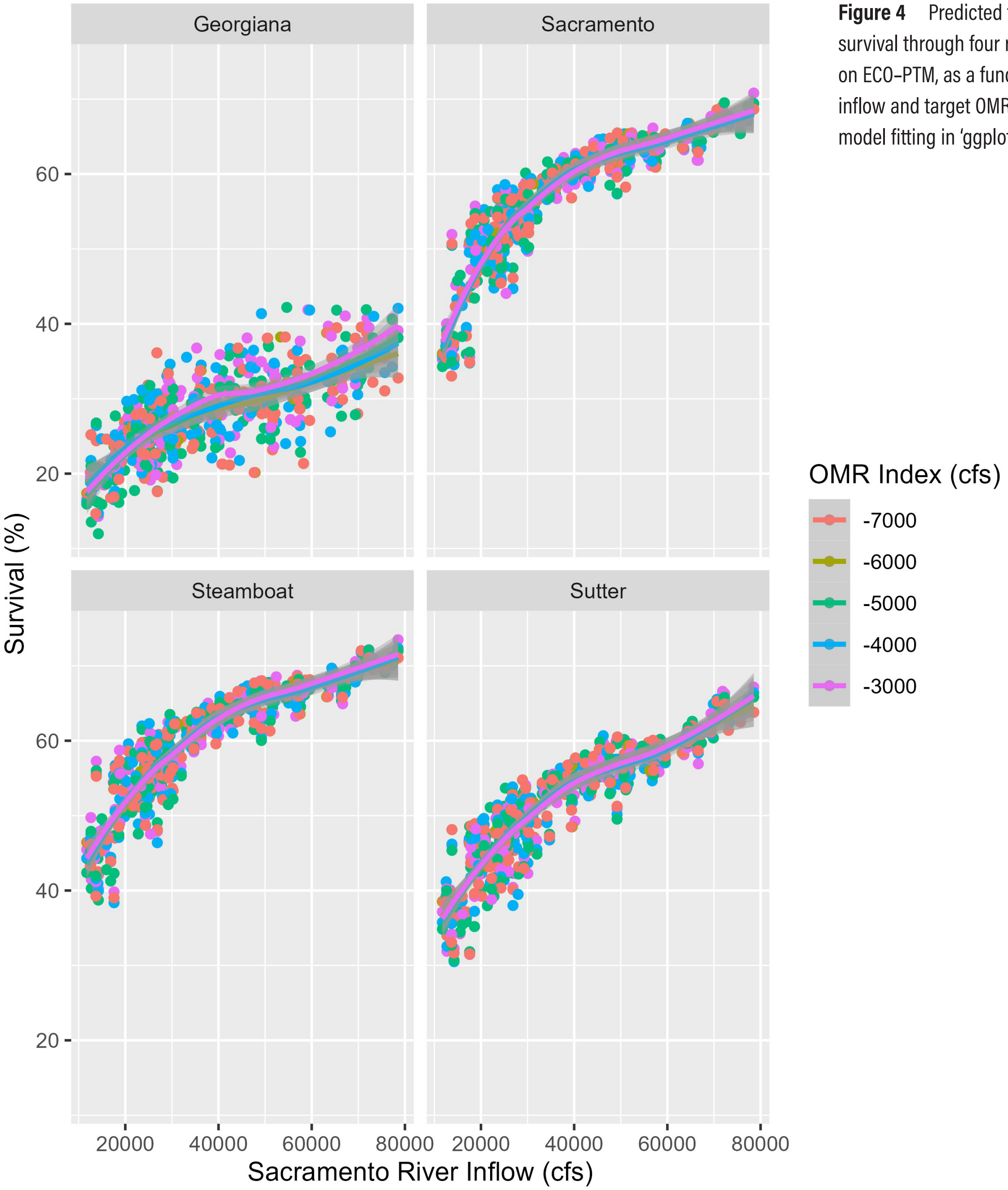

Figure 4 Predicted through-Delta migratory survival through four routing pathways, based on ECO-PTM, as a function of Sacramento River inflow and target OMRI. *Lines* represent "loess" model fitting in 'ggplot2.'

PTM is determined in part by hydrology, (2) travel time is determined by simulated particle movement, and (3) survival is calculated as a function of simulated travel time.

Results from PTM simulations also supported previous findings of increased SRWRC entrainment at CVP and SWP facilities with increased exports and decreased river flow. Simulated particle entrainment at facilities decreased with increasing Sacramento River flow, and increased with increasingly negative OMRI (Figure 5A). These results are the same when facilities entrainment is expressed relative to the proportion of particles routed through the interior Delta, suggesting that both OMRI and inflow specifically affect the entrainment of particles already present in the region (Figure 5).

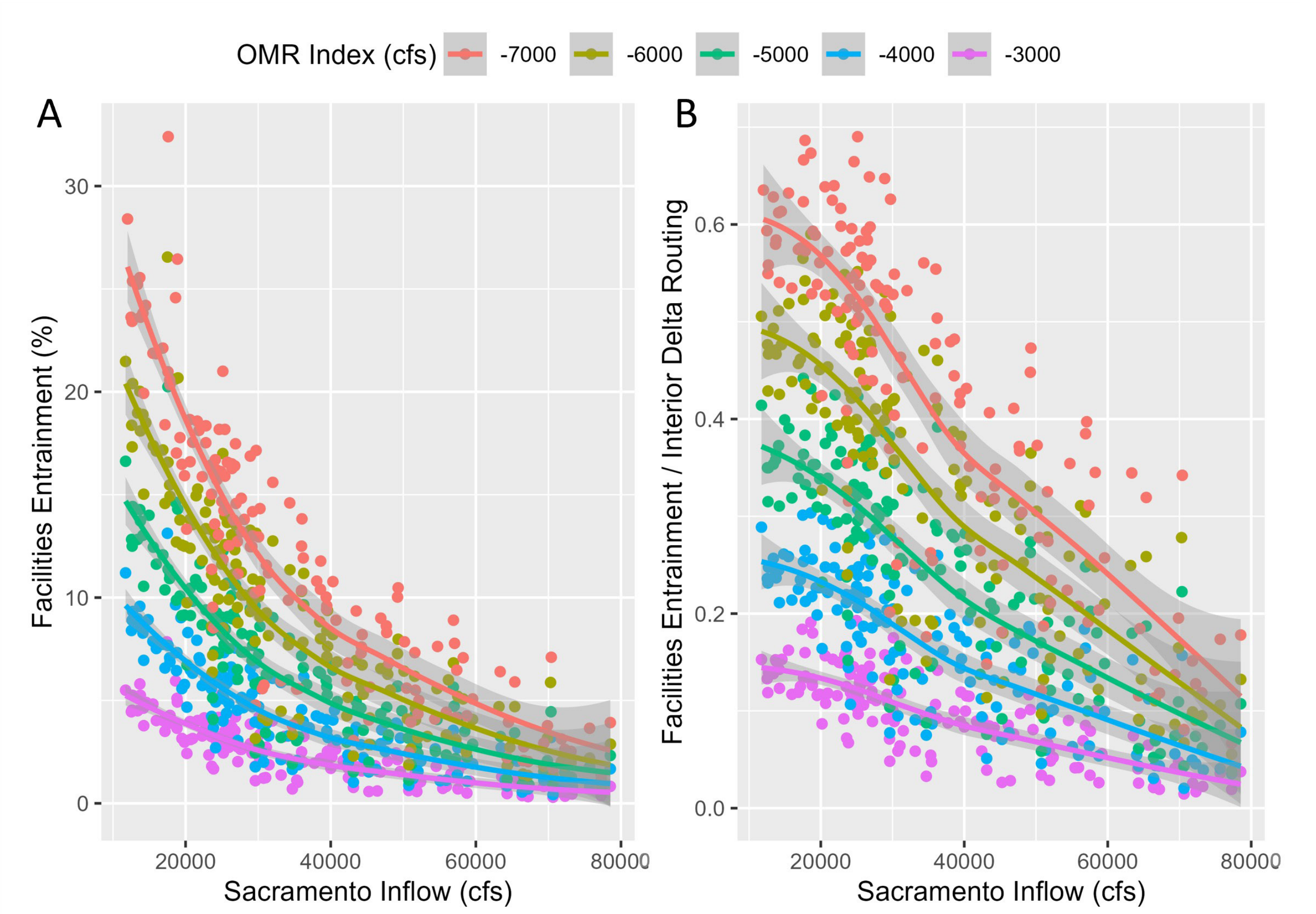

Figure 5 Predicted proportional entrainment at the CVP and SWP facilities, both independent from (**A**) and relative to (**B**) the number of particles routed to the interior Delta via Georgiana Slough, the DCC, and Threemile Slough. Results are based on PTM. *Lines* represent "loess" model fitting in 'ggplot2.'

Finally, comparisons of PTM and ECO–PTM simulations may help resolve uncertain relationships between SRWRC loss at facilities and overall migratory survival. Similar to findings in previous studies, simulation results suggest that loss at facilities and overall migratory survival may be inversely related as a function of inflow, such that facility entrainment decreases with increasing inflow, while overall migratory survival increases (Figures 5 and 6). These results also suggest that hydrologic alterations caused by exports have contrasting effects on entrainment at pumping facilities and overall migratory survival. Exports do not affect simulated migratory survival through both the interior Delta and overall Delta, but, due to increasing hydrological alteration, exports do increase facility entrainment. (Figures 4 through 6).

Survival Outside the Interior Delta

Model results from ECO–PTM reflect previous findings that increasing Sacramento River flow increases migratory survival outside the interior Delta, while exports have little influence on survival. Specifically, simulation results indicate a positive influence of Sacramento River flow on through-Delta migratory survival through Steamboat Slough, Sutter Slough, and the mainstem Sacramento River, with increased flow corresponding to increased survival (Figure 4). These findings are unsurprising, given the ECO–PTM model incorporates the XT model to translate simulated travel times to expected migratory survival. More interestingly, ECO–PTM results also show negligible differences in survival among the different OMRI values for fish routed primarily through the Sacramento River, Sutter Slough, or Steamboat Slough (Figure 4).

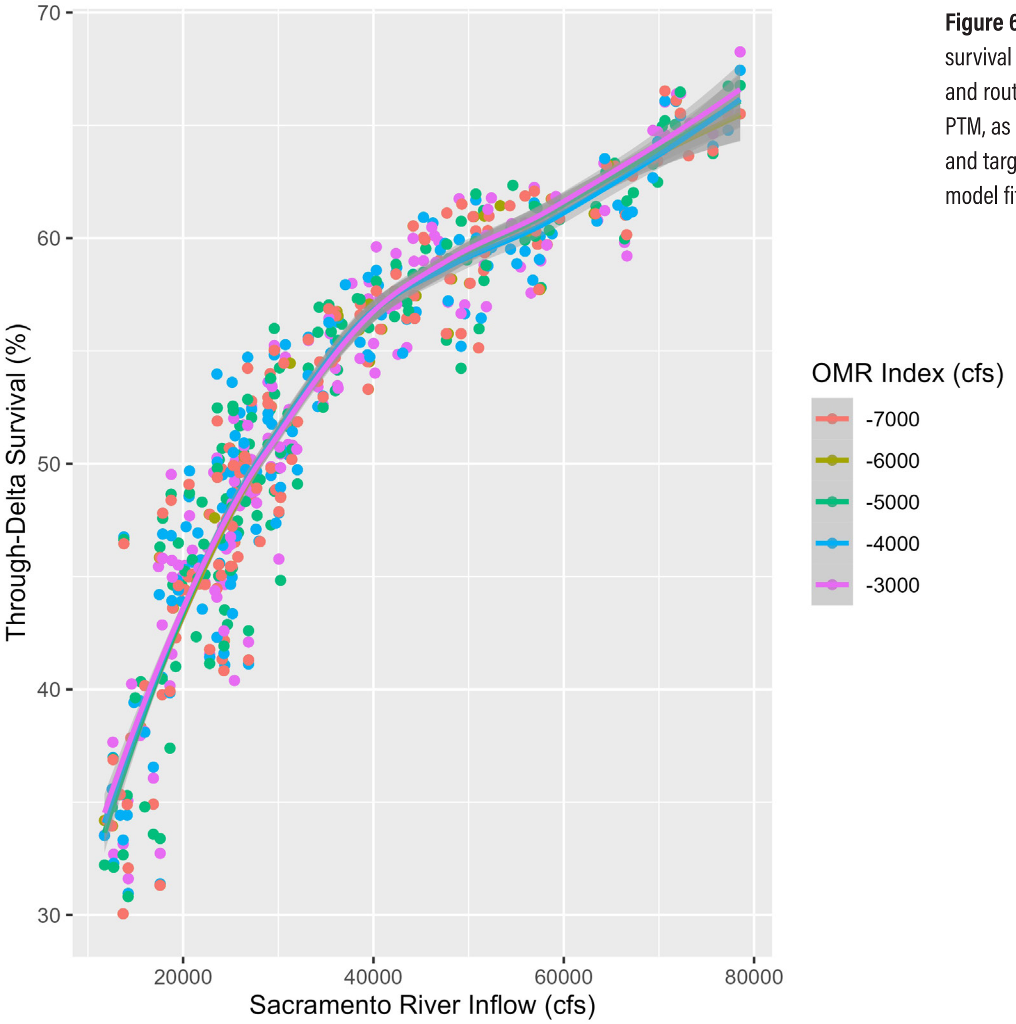

Figure 6 Predicted through-Delta migratory survival integrating both routing proportions and route-specific survival, based on ECO–PTM, as a function of Sacramento River inflow and target OMRI. *Lines* represent "loess" model fitting in 'ggplot2.'

Given the model's reliance on travel time to estimate survival, this suggests that changing water exports—within the constraints of the simulated OMRI values—does not meaningfully affect particle travel time along these migratory routes.

DISCUSSION

In this study, we proposed a new conceptual model for understanding SRWRC juvenile migratory survival in the Sacramento–San Joaquin Delta, synthesized data and modeling resources to characterize the current state of knowledge and uncertainty of factors that affect migratory patterns and survival, and applied simulation modeling to address identified uncertainties. The spatially-explicit conceptual model provided a practical framework for characterizing drivers of demographic processes in heterogenous Delta regions. Syntheses of available studies, organized using the conceptual model framework, support the role of Sacramento River flow in mediating the routing of juveniles through the Delta and their survival across multiple routing pathways. Estimated migratory survival is consistently lower in the interior Delta relative to alternative migratory pathways. Water temperature and DCC gate operations affect localized routing and survival along varying portions of migratory routes, while support for the influence of water exports on routing and survival is mixed, ranging from insignificant to weak, and with increased evidence of an effect closer to export facilities. Particle-based simulation analyses also supported many of these previous findings and helped address data gaps, including the role of alternative migratory pathways and effects of flow and exports on migratory processes. However, how water exports affect demographic processes such as out-migration survival remains uncertain, in part because of the under-studied relationship between entrainment at export facilities and overall migratory survival, and the unknown contribution of alternative migratory pathways such as Threemile Slough to fish routing.

Strategies for managing inflow and water exports in the Delta have evolved over the past 50 years as managers learned more about effects on fish and aquatic habitats and—more recently—imperiled species. Early approaches focused on water quality necessary for beneficial uses, including fish and wildlife (SWRCB 1978, 1999), but these criteria did not result in improving fish and wildlife population abundance. The subsequent listing of winter-run Chinook Salmon has required additional export reduction requirements that use prescriptive approaches based on a potential amount of mortality at the CVP and SWP export facilities, accompanied by corresponding monitoring of salvaged fish and estimated loss at these facilities. Daily, weekly, and seasonal loss criteria have been scaled to the SRWRC juvenile production estimate (i.e., JPE: the estimated number of smolts that enter the Delta), and have constituted 1% or less of this annual production over the past 15 years (NMFS 2009, 2019; O'Farrell et al. 2018). The regulatory framework implicitly assumes that loss estimates represent or contribute to overall through-Delta survival, such that increasing facility loss is anticipated to decrease overall survival. While numerous multi-day, weekly, and seasonal reductions in exports have occurred over the past 15 years because loss thresholds have been exceeded, no clear relationship has been observed between loss of SRWRC near export facilities and through-Delta migratory survival. Furthermore, conflicting results from the reviewed empirical studies—which reported no strong relationships between migratory survival and water exports but statistically significant relationships between facility entrainment and exports—indicate that the relationship between loss at facilities and overall migratory survival remains poorly understood (e.g., Hance et al. 2022; Tillotson et al. 2022).

Multiple hypotheses may address these apparent contradictions. One possible explanation is that mortality that occurs near facilities from changes in exports is compensatory, such that overall mortality of fish in the interior Delta does not increase when exports are increased but is instead being re-distributed toward the facilities. More specifically, it is possible that mortality rates are similar throughout the interior Delta (i.e., both close to and distant from export facilities), but increasing exports cause proportionally more fish to end up near export facilities where they can be observed and counted as loss. If this is the case, we would expect exports to affect entrainment near facilities but have little effect on the survival of both the overall juvenile population and juveniles routed to the interior Delta, as has been observed in both previous studies and new simulation results (Figures 4 through 6). Alternatively, it is also possible that mortality at the facilities is additive for through-Delta survival (i.e., mortality is higher near facilities, changing exports shift the distribution of fish relative to the facilities, and increasing loss at facilities decreases survival) but has a weak enough effect that there is insufficient statistical power to detect it with available data. These hypotheses are illustrated with a detailed example in Figure 7. Resolving these uncertainties through additional research could increase the effectiveness of management actions such as export modifications to improve Delta migratory survival.

In models of fish routing, the possible contribution of alternative pathways such as Threemile Slough to the number of fish entrained in the interior Delta also merits further consideration. Previous analyses of fish movement and survival through the Delta quantified the joint movement and survival of fish through Threemile Slough but concluded the pathway contributes only slightly in the Sacramento River; however, the contribution of Threemile Slough has not been revisited in subsequent studies (Perry and Skalski 2009).

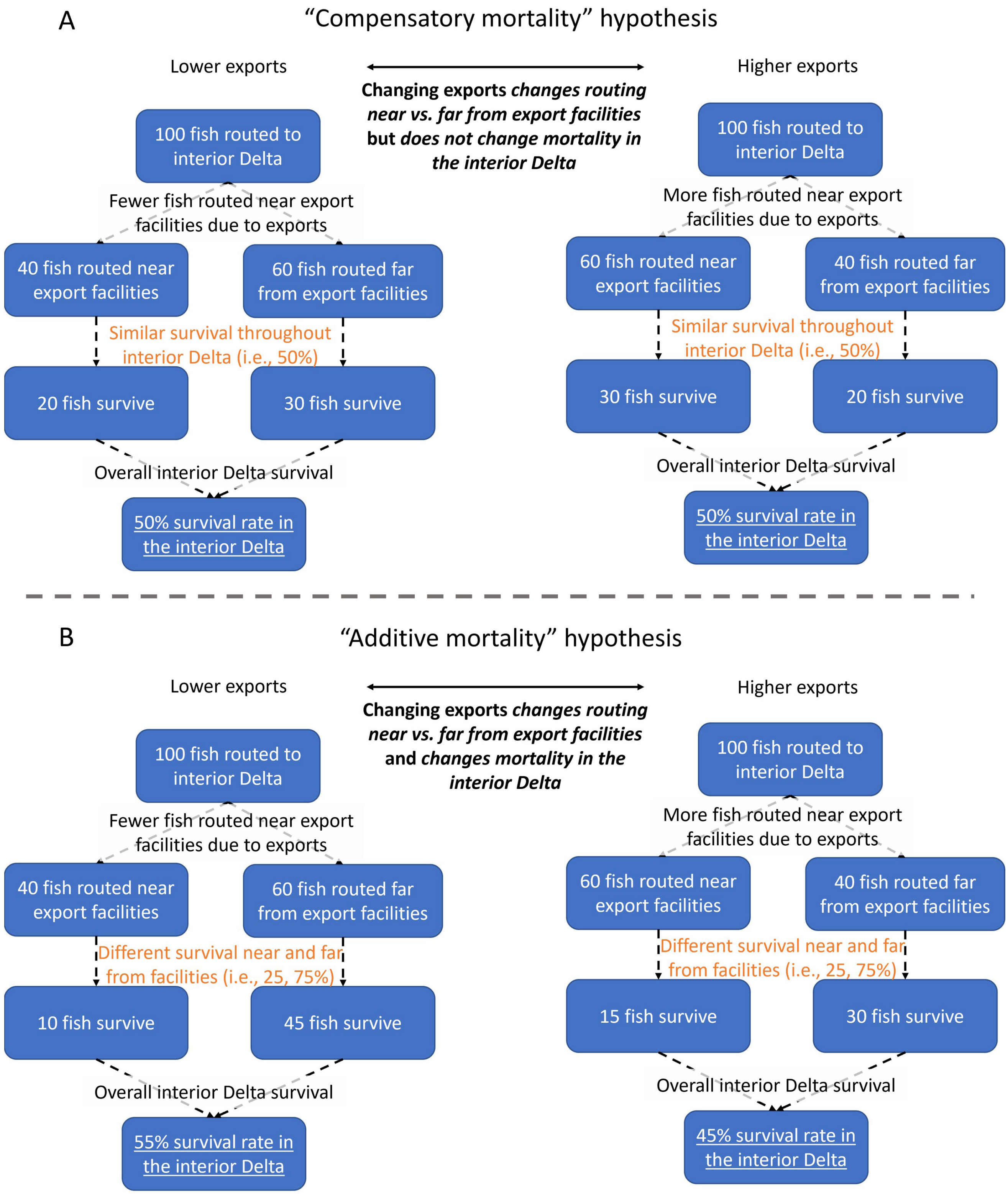

Figure 7 Visualization of the "compensatory mortality" (**A**) and "additive mortality" (**B**) hypotheses to explain uncertainty in the relationship between SRWRC entrainment at facilities and through-Delta migratory survival. Example values for routing proportions and survival are simplified for demonstration purposes only and do not represent empirical values. The example scenarios assume that hydrologic conditions other than exports (e.g., river inflow) are held constant.

The particle-based simulations presented here suggested that routing through Threemile Slough is possible, can operate on a scale similar to routing through more recognized pathways such as Georgiana Slough, and may be altered by changing water exports (Figure 3). Substantial fish routing through Threemile Slough could affect traditional estimates of survival through the mainstem Sacramento River (i.e., assuming no alternate routing), depending on the fate of these fish. Furthermore, although we primarily evaluated routing through Threemile Slough, we note hydrological alterations from exports may also influence routing at the confluence of the Sacramento and San Joaquin rivers on the western end of the Delta. Additional research is necessary to validate the realized contribution of routing pathways such as Threemile Slough to both fish routing proportions and through-Delta migratory survival.

Sacramento River flow appears to affect through-Delta migratory processes and overall population viability substantially more than water exports, which highlights the importance of basin-scale water management. New simulation results showed that higher Sacramento River flow tends to route fish down migratory pathways with greater survival and increase survival across all modeled migratory routes. Across the ranges of modeled exports and inflow, routing and survival responded far more to differences in inflow than exports. Therefore, it is important to recognize that basin-scale management decisions regarding Sacramento River flow (e.g., through releases at Shasta Dam) will affect Delta migratory survival more than solely modifying water exports in the Delta. Basin-scale water-management actions may also synergistically affect multiple SRWRC life stages. For example, increasing inflow during months of peak through-Delta migration could also increase in-river rearing and migratory survival of juveniles that have not yet entered the Delta, and subsequently increase population productivity. Water-management actions both inside and outside the Delta are therefore relevant to through-Delta migratory survival and population viability.

To integrate protective Delta water operations into the broader context of SRWRC life-history processes and conservation, we contend there is value in developing a comprehensive management framework that relates management decisions to population-scale recovery objectives. The proposed management framework includes the following components: (1) identification of water-management actions and their effects on Delta hydrology, (2) understanding of relationships among SRWRC Delta survival, loss at facilities, and hydrology, (3) continued and re-designed monitoring to assess survival, loss, and environmental conditions in the Delta, (4) identification of conservation and recovery objectives, and (5) application of life-cycle models that can aid evaluation of through-Delta survival in the context of population growth or species recovery targets. Management actions in or near the Delta that could affect SRWRC are primarily water export rates at pumping facilities and operation of barriers to route water and fish, including the DCC gates and non-physical fish barriers. The effects of these actions can be readily estimated with existing models (e.g., DSM2 HYDRO) and are typically constrained by other hydrological conditions, such as flow from the Sacramento River and San Joaquin River. Our current understanding of relationships among Delta survival, loss at facilities, and hydrology is summarized above, and enhanced monitoring can improve our incomplete understanding of these relationships. Previous recommendations (e.g., Allendorf et al. 1997; NMFS 1997; Botsford and Brittnacher 1998; Lindley et al. 2007). can inform selection of recovery objectives. Finally, life-cycle models, in turn, can integrate proposed management actions, our understanding of SRWRC life-history process, and simulated monitoring processes to generate expected population trajectories relative to species-conservation outcomes. Existing life cycle models—including the SIT winter-run decision support model and winter-run life-cycle model—can be modified to more explicitly incorporate the newly synthesized relationships and uncertainties about Delta survival, and translate our knowledge to expected population viability (Peterson and Duarte 2020; Hendrix et al. 2022).

There are numerous limitations to the reported modeling approaches and data summaries described in this study. First, modeling results do not consider the effect of exports or hydrological alterations on juvenile fish rearing in the Delta. Past research has shown that some brood-years of fall-run Chinook salmon include a significant number of adults that had spent time rearing in the Delta as fry or parr (Miller et al. 2010; Sturrock et al. 2015; Perry et al. 2016). Understanding how inflow and water exports affect survival of these early life stages for all runs of Chinook salmon is an important knowledge gap. Further, referenced studies and models were based on data collected across decades of varying environmental and regulatory conditions. We expect fish responsiveness to the hydrological effects of exports varied between periods of generally high exports with large amounts of variability (i.e., years before 2009) and periods of tightly regulated hydrological conditions. The PTM and ECO–PTM also relied on varying and possibly contradictory assumptions of fish behavior, with PTM assuming passive fish movement and ECO–PTM assuming swimming behavior estimated from empirical data. Although analyses from ECO–PTM calibrations suggest juveniles do not move passively, the flexible specification of PTM uniquely allowed us to explore the importance of alternative migratory routes, and evaluate drivers of entrainment. Finally, in addition to these recognized limitations in the PTM and ECO–PTM models, we acknowledge that the regulatory rules and hydrologic assumptions embedded in the underlying CALSIM II hydrological model do not necessarily reflect current requirements or future infrastructure changes in the watershed (e.g., required annual operation of the BAFF at Georgiana Slough, installation of the Big Notch project, etc.; CDWR 2022; Huntsman et al. 2024; USBR 2024).

Several research opportunities can help resolve critical uncertainties about SRWRC through-Delta survival. As part of recent Chinook Salmon acoustic-telemetry studies throughout the Central Valley, new receivers have been added near entrances to and throughout the interior Delta; these receivers facilitated detection of fish that entered Threemile Slough in 2022. Continued or expanded deployment of receivers throughout this region—accompanied by appropriately detailed mark–recapture models—may help elucidate fine-scale movement of juveniles through routing pathways such as Threemile Slough and within the interior Delta. These data may be particularly valuable to understanding how exports influence the routing of fish after they enter the interior Delta. Integration of new and existing monitoring could also provide novel estimates of overall through-Delta survival, and inform the relationship between survival and entrainment at facilities. Specifically, integration of genetics, CWT, and acoustic- telemetry data collected in association with the Chipps Island trawl can provide estimates of total annual SRWRC abundance leaving the Delta (2023 data file from R. Perry, USGS, to A. Jensen, unreferenced, see "Notes"). Combined with existing estimates of the number of smolts entering the Delta (i.e., the JPE), estimates of overall through-Delta survival then can be generated for comparison with estimates of facility loss. Improved estimation of loss at facilities using observed salvage, (i.e., the current basis for triggering export-based regulatory actions) also remains a research need that can be addressed with directed mark–recapture studies (Jahn and Kier 2020). Once current computational challenges are resolved, other modeling methods, including the enhanced PTM, could be used to further explore relationships among inflow, exports, routing, entrainment, and survival. Finally, value of information analyses, such as those conducted by Stantial et al. (2023), may be useful to determine the extent to which funding future studies to resolve identified sources of uncertainty could improve management outcomes.

CONCLUSIONS

We conducted new model simulations and reviewed available studies to characterize the current understanding of through-Delta migratory survival for SRWCS juveniles, with corresponding implications for monitoring and regulatory efforts. We developed a new conceptual framework to summarize environmental influences on spatially-explicit migratory routing and survival. We also identified several pressing uncertainties, including the role of alternative routing pathways on out-migration survival, as well as the relationship between entrainment, loss at pumping facilities, and through-Delta survival. Resolving these uncertainties may inform the continuation or optimization of existing Delta water operations to include actions that improve juvenile salmonid through-Delta survival. Numerous research approaches can address these uncertainties, including continued fine-resolution acoustic-telemetry studies, integration of existing data sources, and expanded simulation modeling. Furthermore, existing life-cycle models may be modified and applied to help translate the implications of these Delta-based uncertainties to expected population outcomes, within the broader context of other life-history processes and management actions in both freshwater and marine environments. Ultimately, these approaches, findings, and recommendations can inform the management of salmonids in general in the Central Valley, all of which must out-migrate through the Delta as juveniles.

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