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Sensitivity of Larval Fish Transport to Location, Timing, and Behavior Using a Particle Tracking Model in Suisun Marsh, California

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Abstract.—We used a coupled hydrodynamic-particle tracking model to assess the relative importance of factors affecting transport and entrainment risk for generalized fish larvae in Suisun Marsh in the San Francisco Estuary, California. Factors examined included location of particle release, time of particle release, vertical migration behavior, and combinations thereof. Model sensitivity was evaluated by observing particle entrainment into a water diversion in Suisun Marsh under various scenarios and compared to randomized input cases. Scenarios combining two or more factors indicated nonlinear interactions, including evidence of tidal pumping on neap tides near our test diversion. Our study suggests that accurate modeling of larval transport depends on accurate determination of fish locations, tidal and residual time scale circulation simulation, and fish behavior during early life stages. We also examined appropriate approaches to modeling these factors.

Introduction

Successful transport of eggs or larvae from spawning to rearing habitats is critical to the recruitment success of many estuarine fishes (Dew and Hecht 1994; Barthem and Goulding 1997; Moriyama et al. 1998). In the San Francisco Estuary, California, eggs and early life stages of several species, such as striped bass *Morone saxatilis*, longfin smelt *Spirinchus thaleichthys*, and threatened delta smelt *Hypomesus transpacificus*, are spawned in freshwater and are subsequently transported downstream to brackish water nursery habitats (Moyle 2002). Although mechanisms are not well understood, quantitative relationships between freshwater flow into the estuary and recruitment of estuarine organisms have been demonstrated (Jassby et al. 1995; Kimmerer 2002). Numerous water diversions distributed throughout the estuary can alter transport flows and entrain young fish potentially impacting recruitment success (Arthur et al. 1996; Bennett and Moyle 1996).

Larval fish mortality is influenced by numerous, often interacting mechanisms (Houde 1987; Bennett and Moyle 1996), making quantitative descriptions of individual sources of mortality difficult. The complexity of fish recruitment processes often necessitates modeling approaches for understanding population dynamics (Letcher et al. 1996). Here, we use a coupled hydrodynamic-particle tracking model to assess the sensitivity of location, timing, and behavior on entrainment risk in an unscreened water diversion. Model scenarios were based on generalized fish larvae during spring (April–May), when native fishes typically spawn in Suisun Marsh (Meng and Matern 2001).

We used the Delta Simulation Model-2 Particle Tracking Model (PTM; CDWR 2002) as the analysis tool. Our goal was to assess the sensitivity of early life stage fish transport assumptions to PTM input parameters, rather

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than a quantitative assessment of entrainment risk for any particular species. As such, this study is less concerned with specifying exact initial release conditions and behavior than with developing an appropriate approach to modeling fish larvae through analysis of model sensitivity.

Sensitivity analysis allows prioritization of model parameters, forcing functions, or submodels to state variables of greatest importance in the model (Jorgensen and Bendoricchio 2001). The process is inherently iterative and provides the opportunity to conduct thought experiments based on simulation responses. The description of simulation experiments given here reflects how this approach guided use of the PTM to address the following questions of fish larvae entrainment risk in Suisun Marsh: (1) what are the relative influences of timing, location of hatching (or transport into the marsh), and vertical migration patterns on entrainment risk? (2) do combinations of these factors interact to influence entrainment risk? and (3) how is the PTM best used to model larval fish and diversion risk within the estuary?

Study Area

Our study focused on Suisun Marsh, where the California Department of Water Resources (CDWR) is required to characterize entrainment risk at several diversions (Figure 1). Suisun Marsh is the largest contiguous brackish marsh (~30,000 ha) on the West Coast of the United States. The marsh represents approximately 12% of California's remaining wetland habitat and is a significant nursery area for many fish species (Meng et al. 1994; Meng and Matern 2001; Matern et al. 2002). The majority of Suisun Marsh (~22,000 ha) is managed for waterfowl.

There are 366 known water diversions distributed throughout Suisun Marsh (Herren and Kawasaki 2001). Nearly 80% of the diversions operate via floodgates, and 2% are screened to exclude fish. Typical intake diameters for Suisun Marsh floodgate diversions are 0.9–1.2 m. In the present study, we simulated the influence of a single diversion, the Morrow Island Distribution System (MIDS; Figure 1). The MIDS fits the above description of a typical Suisun Marsh water diversion and is being used in this study as a representative diversion to evaluate influences on larval fish entrainment. We limit our analysis to this one diversion to clearly discern factors influencing entrainment risk. The MIDS is located in Goodyear Slough, a 20–30-m-wide channel fringed with bulrushes *Scirpus* spp., cattails *Typha* spp., and common reed *Phragmites australis*. The MIDS intake includes three 1.2-m gated culverts that are operated to allow water to enter the distribution system. The CDWR operates and maintains MIDS jointly with the U.S. Bureau of Reclamation.

Methods

Delta Simulation Model-2 Hydrodynamics and Particle Tracking Model

The primary modeling tool used for this study is PTM (CDWR 2002). The PTM simulates transport and fate of individual particles moving throughout Suisun Marsh and the Sacramento–San Joaquin Delta. The model uses velocity, flow, and stage output from a one-dimensional hydrodynamic model, DSM2 HYDRO (CDWR 2002). DSM2 HYDRO was adapted for the delta and marsh from the unsteady, open-channel flow USGS FourPt Model (DeLong et al. 1997). Time varying boundary conditions for the hydrodynamic model include river and stream inflows, State Water Project and Central Valley Project water diversions, agricultural water diversions, irrigation and leach water drainage flows, tide stage in Suisun Bay at Carquinez Strait (Figure 1), and delta water control operations. Fixed inputs include channel and flooded island geometry and roughness coefficients. The system geometry is modeled as a network of channel segments and openwater areas connected by junctions (Figure 1; additional information on the model is available online at http://modeling.water.ca.gov/delta/models/dsm2/index.html).

The PTM uses the same system geometry as DSM2 HYDRO. The PTM was originally developed as a two-dimensional model and subsequently modified to a quasi-three-dimensional model (CDWR 2002). Particles are transported within the network under the influence of tidal flows and random mixing dynamics.

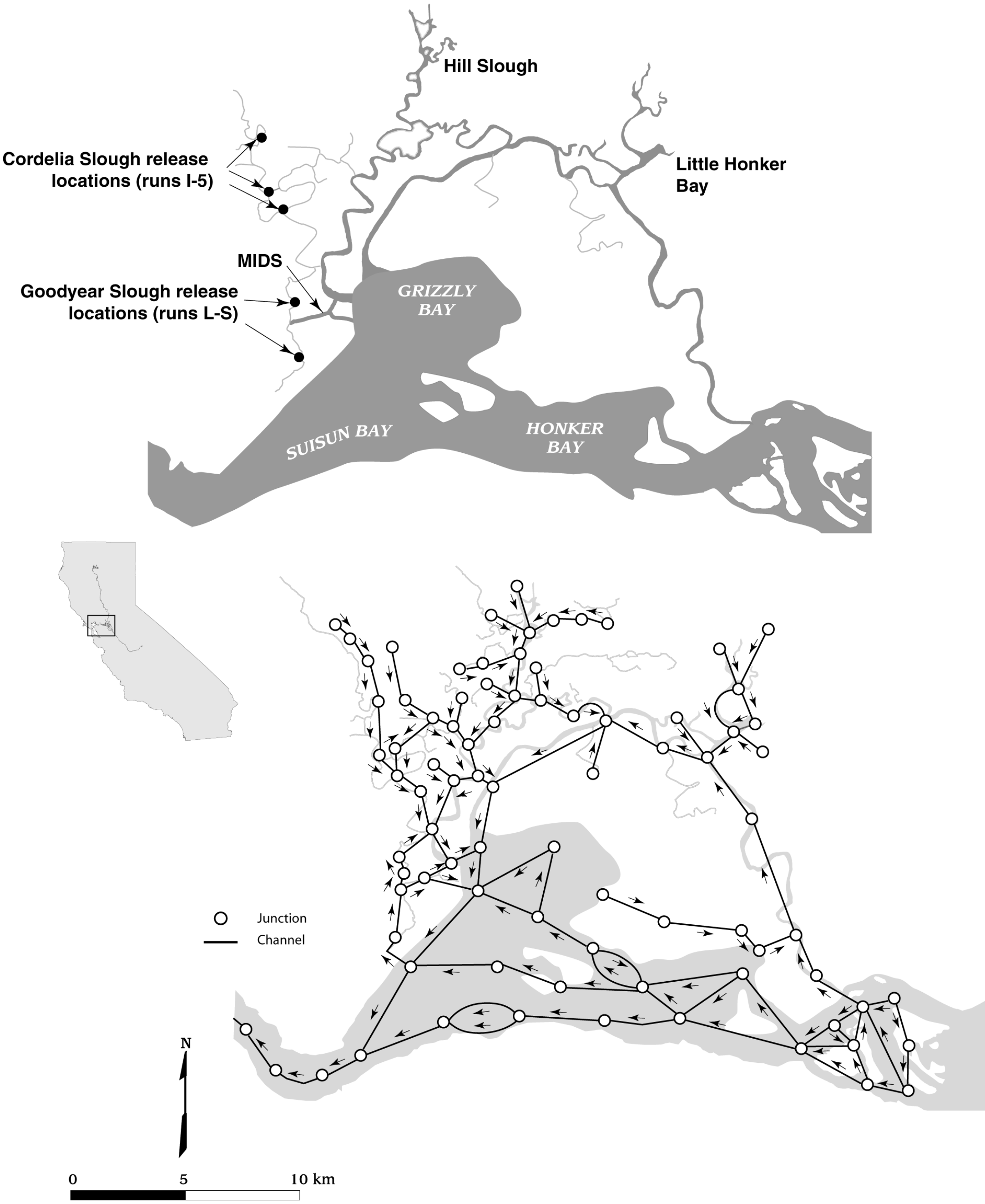

FIGURE 1. Top: Location of the Sacramento–San Joaquin Delta and Suisun Marsh showing the Morrow Island Distribution System (MIDS) and simulated release points. Bottom: Suisun Marsh portion of Delta Simulation Model-2 Hydrodynamics and Particle Tracking model grid map showing graphical relationships between tidal channels and hydrologic junctions.

Deterministic and stochastic longitudinal, transverse, and vertical movements simulate three-dimensional transport of neutrally buoyant particles within channels. Longitudinal velocity experienced by a particle is a function of cross-section average velocity computed by

DSM2 HYDRO, modified by its cross-section position relative to theoretical transverse and vertical velocity profiles. The theoretical transverse velocity profile accounts for lateral velocity shear. Consequently, particles located near shore move slower than those in mid-channel. The vertical velocity profile simulates shear along the channel bottom resulting in a vertical transport gradient with faster particle transport near the surface (CDWR 2000). The DSM2 PTM output data can be viewed as animations that display the movement of particles.

Model input parameters

Particle tracking scenarios were designed to simulate fish larvae hatched upstream of the marsh during the simulation period or larvae hatched from adhesive delta smelt eggs deposited within the marsh. The study period (25 April to 5 May 1996) was chosen to model (1) intermediate flow conditions, (2) a time of year when larval stages of native fish were present (Meng and Matern 2001), and (3) a complete spring-neap tidal cycle. Particle releases were made over a full spring-neap cycle (25 April to 9 May); model runs were extended through 15 May to provide sufficient time for particles released late in the series to disperse. In all scenarios 10,000 individually tracked particles were released to balance the potential bias due to low numbers of simulated particles while remaining computationally feasible.

Particle tracking scenario formulation

Particle release conditions (location and tidal timing) were chosen to simulate appearance of fish larvae in the system. Simulated behaviors mimic vertical migration by larvae (Bennett et al. 2002). To evaluate the model dependence on particle release conditions and behaviors, a random base case was used for comparison (model runs A–K; Table 1). Particle release in the base case was random with respect to location and timing, and particles were simulated as neutrally buoyant.

Scenarios were generated by randomly perturbing base case release conditions. Random variables (particle release location, date, time, and particle release number) for each scenario were generated using Microsoft Excel©. Variability associated with random generation was tested by repeating five scenarios five times, each using different random inputs. The maximum standard deviation of entrainment was 0.9%, indicating that the variability associated with random generation of a scenario was relatively small.

We formulated scenarios in a heuristic fashion using results from initial runs to inform subsequent experiments. Based on results of runs A–K, we generated runs L–S (Table 1), to investigate factor interactions. In runs L–S, particles were released in Goodyear Slough within 4 km of the MIDS intake (same locations as run B; see Figure 1) to amplify the effect on entrainment. Results were compared to run B; thus, run B served as base case for runs L–S. Runs L–O tested independent changes made to run B, and runs P–S combined some of these changes to assess their interactive response.

A supplementary series of sensitivity runs (runs 1–15) was developed to focus on the influence of tidal pumping observed using the PTM animation tool. The branched and looped nature of Suisun Marsh geometry interacts differentially with tidal strength to generate tidal pumping and trapping phenomena (Fischer et al. 1979). To investigate the effects of tidal pumping throughout the spring-neap cycle, particles were released into Cordelia Slough (Figure 1) over 24-h periods for each day of the spring-neap cycle (25 April to 9 May). In particular, particle flux into Goodyear Slough was observed over time and associated with tidal amplitude, an indicator of tide strength.

We assume the percentage of particles diverted into MIDS represents the likelihood of entrainment. Cumulative particle entrainment percentages were used to compare the results of individual runs. The MIDS discharges water into Grizzly Bay (Figure 1). However, we assumed that all particles entering MIDS were lost (i.e., complete mortality). Thus, particles that entered MIDS were removed and did not subsequently re-enter the diversion.

Results

The MIDS intake is flap-gated, allowing only unidirectional flow into the system. Maximum flow into MIDS varied slightly through the spring-neap cycle, but was about 6 m^3/s,

TABLE 1. List of Delta Simulation Model-2 Particle Tracking model runs. Entrainment is the percentage of released particles entrained at Morrow Island Distribution System. Entrainment values in parentheses for runs A–K are the percent differences in entrainment relative to the completely randomized base case scenario (2.6% entrainment). Entrainment values in parentheses for runs L–S are the percent differences in entrainment relative to run B, the proximate release base case scenario.

Run	Release location	Release timing	Particle behavior	Entrainment
A	Patchy[a]	Random	Neutrally buoyant	1.2 (–55)
B	Proximate[b]	Random	Neutrally buoyant	37.5 (1,342)
C	Remote[c]	Random	Neutrally buoyant	0.0 (–98)
D	Random	Low tide[d]	Neutrally buoyant	3.6 (38)
E	Random	High tide[e]	Neutrally buoyant	1.8 (–33)
F	Random	Night	Neutrally buoyant	1.9 (–25)
G	Random	Day	Neutrally buoyant	2.9 (10)
H	Random	Spring tide[f]	Neutrally buoyant	2.3 (–13)
I	Random	Neap tide[g]	Neutrally buoyant	3.8 (47)
J	Random	Random	Reverse diel[h]	2.9 (11)
K	Random	Random	Diel[i]	3.4 (32)
L	Proximate	Spring tide	Neutrally buoyant	35.7 (–5)
M	Proximate	Neap tide	Neutrally buoyant	45.6 (22)
N	Proximate	Random	Reverse diel	35.5 (–5)
O	Proximate	Random	Diel	47.6 (27)
P	Proximate	Spring tide	Reverse diel	30.7 (–18)
Q	Proximate	Spring tide	Diel	44.7 (19)
R	Proximate	Neap tide	Reverse diel	45.2 (21)
S	Proximate	Neap tide	Diel	55.8 (49)

[a] Particles released in Cordelia Slough, Hill Slough, and Little Honker Bay.
[b] Particles released in Goodyear Slough within 3.7 km upstream or downstream of MIDS.
[c] Particles released in Sacramento River at Rio Vista.
[d] Particles released within $\pm$1 hour of peak low tide.
[e] Particles released within $\pm$1 hour of peak low tide.
[f] Particles released day before, during, and following full or new moon.
[g] Particles released day before, during, and following quarter moon.
[h] Particles move to upper 20% of water column by day and lower 20% by night.
[i] Particles move to lower 20% of water column by day and upper 20% by night.

while peak flow in Goodyear Slough varied between 11.5 and 22.5 m^3/s (Figure 2).

Depending on location, animations of individual particle tracks showed that tidal timescale excursions were between 2 and 5 km. This distance is comparable to characteristic channel and slough lengths between distributary confluences. As a consequence, rapid dispersion from initial particle release locations was observed in all scenarios.

Random marsh-wide particle release (base case)

Particles distributed randomly throughout the marsh exhibiting neutrally buoyant behavior were unlikely to become entrained (2.6% of total particles) in MIDS (Table 1). The model predicted nearly half of the particles exited Suisun Bay through Carquinez Strait (Figure 1) within 3 weeks.

Influence of particle release location

Particle release location had the largest influence on entrainment risk. Releasing particles in a noncontinuous patchy distribution decreased entrainment from 2.6 to 1.2% (Table 1; run A). By contrast, 37.5% of particles released within 4 km of MIDS were entrained (Table 1; run B). Conversely, particles released in the Sacramento River near Rio Vista had almost

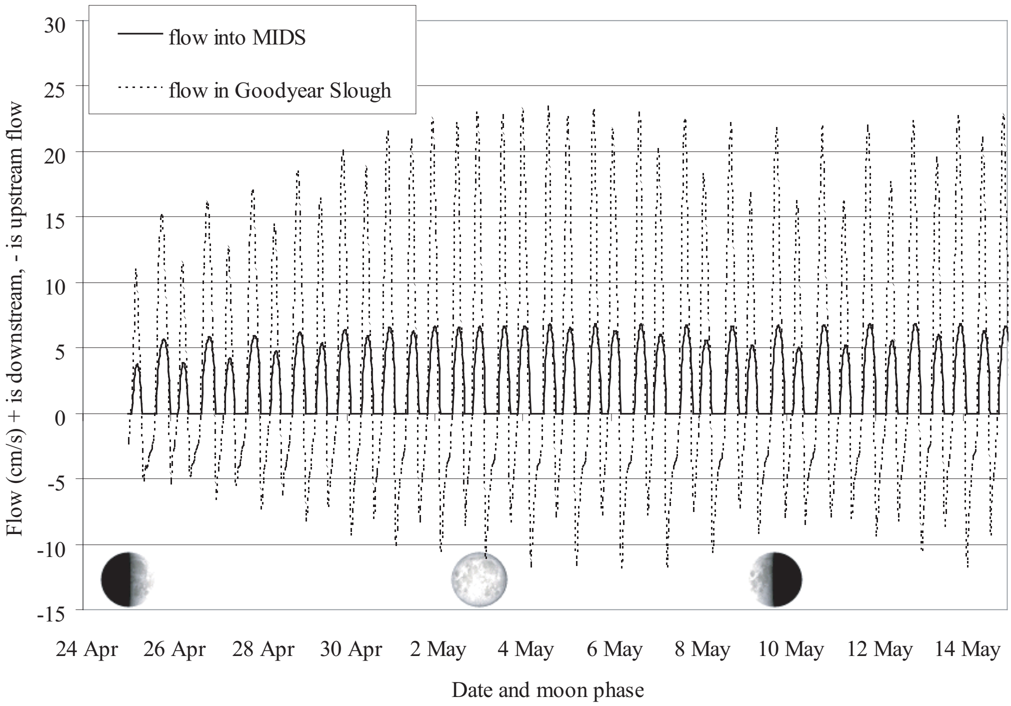

FIGURE 2. Modeled flows in Goodyear Slough and the Morrow Island Distribution System (MIDS). Also shown are corresponding moon phases.

no chance (<0.1%; Table 1; run C) of entering MIDS.

Influence of particle release timing

Particles released during low tides initially experience flood flows that drove them upstream into the marsh. Flood tide releases resulted in longer residence times and increased entrainment (38% greater than random base case; Table 1; run D). Conversely, particles released on ebb tides initially are more likely to be flushed out of the marsh through Carquinez Strait, thus decreasing entrainment (–33% from random base case; Table 1; run E).

Particles released during night experienced decreased entrainment, whereas day release increased entrainment. (Table 1; runs F and G). Our study period included a tidal cycle when nearly all higher high tides occurred during night. The lowered entrainment during night release is likely due to the correlation between night and stronger ebb flows in the marsh. In general, travel time to MIDS for each of the forgoing scenarios (runs D, E, F, and G) is greater than a tidal cycle allowing extensive mixing prior to entrainment. Tidal mixing tends to minimize the entrainment difference regardless of initial release conditions.

Particle transport response is sensitive to the spring-neap time scale (Table 1; runs H and I). Neap tide release increased entrainment by 47% compared to base, while spring tide release reduced entrainment by 13%. This spring-neap tide influence was further investigated in runs 1–15 (see below).

Influence of vertical migration behavior

Evaluation of particle behavior was limited to vertical migration patterns of diel (depth by day for 14 h, surface at night for 10 h) and reverse diel (depth at night, surface by day) movement of particles in the water column. Diel behavior increased entrainment by 32% whereas reverse diel behavior increased entrainment by 11% (Table 1; runs J and K).

Particle releases proximate to MIDS (proximate base case)

Influence of spring-neap tide on proximate release.—Spring tide releases proximate to MIDS resulted in 5% entrainment decrease relative to run B, whereas neap tide releases resulted in 22% entrainment increase (Table 1; runs L and M). Spring versus neap tide releases proximate to MIDS exhibited the same diversion response pattern as the base case. However, the percentage change was less than the random case (spring random –13%; spring proximate –5%; neap random 47%, neap proximate 22%; Table 1).

Influence of vertical migration behavior on proximate releases.—A 27% entrainment increase was observed when diel behavior (Table 1; run O) was applied to the proximate release case. Reverse diel behavior resulted in a very small (5%; Table 1; run N) entrainment decrease relative to the proximate release.

Combinations of spring and neap tides in combination with diel or reverse diel behavior on proximate release.—The interaction of spring tide release with reverse diel behavior decreased entrainment 18% (Table 1; run P), while spring tide release with diel behavior increased entrainment 19% (Table 1; run Q). Particle release during neap tide coupled with reverse diel behavior increased entrainment 21% (Table 1; run R). Neap tide release with diel behavior resulted in the largest increase in entrainment of any of the combined factors tested (49%; Table 1; run S). Combined effects were not additive of isolated singular effects indicating interactions among modeled particle behaviors and initial conditions. For example, the interaction of spring tide release with reverse diel behavior decreased entrainment 18% (Table 1; run P), whereas the sum of singular spring tide release and reverse diel behavior was 10%.

Sequential release through the spring-neap cycle

Throughout the foregoing simulations, we observed that particles were increasingly diverted into Goodyear Slough during neap tides. However, based on tide strength alone, we anticipated that the greatest amount of flow into Goodyear Slough would occur during spring tides. The apparent flux dependence on tidal strength suggests tidal or residual flow asymmetry, generally referred to as tidal pumping (Fischer et al. 1979). To investigate this further, we released particles into Cordelia Slough (Figure 1) for each day of the spring-neap cycle (25 April to 9 May; runs 1–15). We observed the highest flux into Goodyear Slough when particle release occurred during neap tide (25 April) and lowest flux during spring tide (4 May; Figure 2). The increased flow into Goodyear Slough during neap tides increased water diverted into MIDS. However, overall particle entrainment into MIDS remained relatively low (<4.5% of total particles released).

Discussion

The early life history of several estuarine fish species includes dispersal as eggs (striped bass) or larvae (longfin smelt and delta smelt) from freshwater spawning grounds to low salinity nursery habitats (Moyle 2002). With continued growth and larval development, these fishes increasingly exhibit tidal-diel behavior combinations to maintain positions along the estuarine salinity gradient (Bennett et al. 2002). We believe that PTM results are most relevant to passively drifting (dispersing) life stages. Furthermore, model results become increasingly less accurate as larvae grow and develop fins and air bladders, structures that improve their ability to maintain positions in favorable habitats.

Acknowledging current model limitations, our results suggest the location of particle release relative to water diversion position has an overwhelming influence on entrainment risk. This was our expectation, and it serves to validate model behavior. Particles released far upstream of MIDS were almost never entrained, whereas particles released within 4 km of MIDS were entrained an order of magnitude greater than base and all other single parameter scenarios. Distribution of particle releases (patchy versus random) was important primarily because it altered the effective release location. Patchy release distribution resulted in decreased entrainment, since all randomly released patches happened to be located greater than 16 km from MIDS. Notably, Herren and Kawasaki (2001) mapped 366 individual diversions distributed throughout Suisun Marsh, demonstrating that nearly any marsh location is near a diversion. Presently, PTM has not been configured to include all Suisun Marsh diversions. It is unclear whether collectively, these diversions represent a 366-fold increase over modeled conditions in entrainment risk, or if collectively, entrainment within the marsh is the result of a combination of factors (e.g., regional and local tidal conditions, diversion characteristics) that results in less than 366-fold increased entrainment risk, as we have suggested. Furthermore, we were unable to determine whether collectively 366 diversions within Suisun Marsh have impacts to fishes at the population level.

Semidiurnal (low or high tides) or diurnal (night or day) release timing affected entrainment. We assumed that diel behavior placed particles near channel bottom for 14 h (daylight) and near surface for 10 h (dark). The simulated quasi-three-dimensional advection and dispersion of particles caused greater retention of near bottom particles due to reduced near bottom water velocities (CDWR 2002). Greater retention likely increased entrainment potential in diel model runs by increasing residence times near the diversion. Significantly, reverse diel releases, distributed both proximately and randomly, resulted in opposing trends. This suggests that water column orientation relates nonlinearly to other factors of interest, especially tides. Further work to determine the relationship between marsh fish spawning episodes and tidal sequence is of paramount importance. If, however, the spawn timing is not known, spring-neap biasing should be examined by selecting a release period lasting at least one spring-neap cycle. The effect of day versus night release timing was confounded by tidal covariation during our study. Thus, apparent day–night differences were partly an artifact of our chosen time period. Investigators need to be aware of potential tidal-diel aliasing when designing particle tracking studies or interpreting results. Implications for predation aside, we believe that given a large number of simulation trials that spanned the range of tidal/diel time scale interactions, differential transport of fish spawned during day or night will likely be explained better by covariance with tidal strength and behavior assumptions.

Decreased tidal strength during neap tides increased particle entrainment due to increased residence time near MIDS. In our experience, tidal excursions in Suisun Marsh are comparable to characteristic channel bifurcation lengths allowing rapid tidal dispersion. Therefore, we hypothesize that intensified tidal mixing during spring tides (Stacey et al. 1999) is more likely to transport particles out of Suisun Marsh within the fortnight time scale. Consequently, there were fewer opportunities for particles to encounter MIDS. Particles released near MIDS were more likely to be entrained (1–2 d). As a result, these particles have less time to experience tidal mixing and are more affected by release timing. The influence of spring-neap release timing in a multiple diversion scenario remains unknown and should be explored after all Suisun Marsh diversions have been incorporated into the PTM.

The imbalance between spring (–13%) and neap tide entrainment (+47%) suggests that mechanisms other than fortnightly varying tidal strength and tidal excursions influence particle movement. Based on tide strength alone, we expected a priori that the largest flow volumes into Goodyear Slough would occur during spring tides. We found the opposite to be true, suggesting the influence of tidal asymmetry as the flux-forcing mechanism. Channel and slough networks create opportunities for tidal waves to reach the same location by different path lengths. Tidal patterns on the spring-neap time scale can generate nonlinear interactions between tide stage and channel geometry at the tidal time scale. Particular tide strength and channel length combinations can interact nonlinearly to tidally pump water (Fischer et al. 1979). Results of sequential releases through the spring-neap cycle demonstrated this nonlinear interaction (Table 1; runs 1–15; Figure 3). Tidal pumping increased flow into Goodyear Slough during neap tides, incrementally increasing entrainment into MIDS. Complex geometry of Suisun Marsh and the Sacramento–San Joaquin Delta likely creates many interrelated tidal pumps

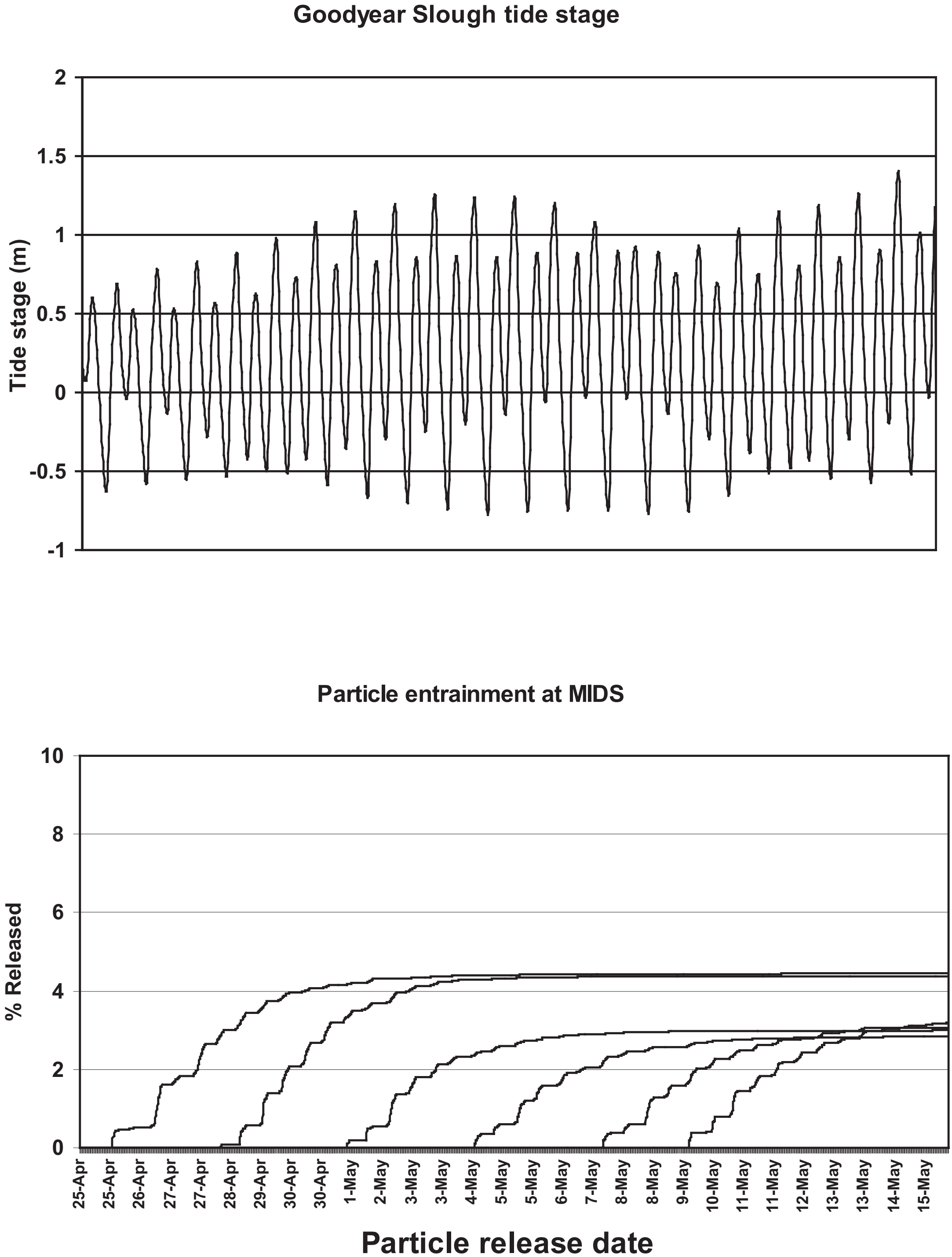

FIGURE 3. Cumulative particle flux into the Morrow Island Distribution System for a series of runs with indicated release dates. Upper pannel displays tide stage information for Goodyear Slough over the same time period.

that influence hydrodynamics in the San Francisco Estuary. Obtaining a better understanding of tidal pumping could greatly enhance the ability to predict estuarine transport processes for physical (e.g., salt, contaminants) and biological (e.g., fish larvae) variables of management interest.

The PTM produced nonadditive outputs when combinations of independent factors were modeled simultaneously. Although derived from a limited set of combinations, this result suggests nonlinear interaction of tidal pattern and particle behavior. Presently, the PTM is not capable of modeling complex fish behaviors that may influence entrainment risk. For instance, depending on hydrologic conditions, larval fish in the San Francisco Estuary have been shown to switch between vertical and horizontal migrations to maintain position within favorable habitats (Bennett et al. 2002). Further understanding of fish behaviors and continued model development can improve the applicability of these PTM results to greater segments of fish life history and to a wider array of species.

Conclusions

The most important result of this study is that diversion of larval fishes largely depends on their proximity to the diversion location. Within this general conclusion, several more subtle results emerged. First, spring-neap timescale tidal strength differences and diel behavior have a significant impact on particle residence time and entrainment potential. Second, nonlinear interactions of tidal strength and system geometry tidally pump water, thus further increasing entrainment during neap tides. Sloughs converging at the head of Goodyear Slough apparently pump water more readily into Goodyear Slough during neap tides. We believe that this system characteristic may have important management implications for protecting larval fish.

We also underscore the need for models that are able to correctly simulate tidal movement over a range of time and space scales—attributes that the PTM has been demonstrated to possess. Nonlinear interactions between tidal strength and system geometry require wave propagation to be simulated with accurate phasing and stage amplitudes. Accurate measurement of system bathymetry and geometry and translation to model input are also required to produce a locally accurate and regionally effective modeling tool. The neap tide pumping observed in Goodyear Slough is a subtle consequence of tidal strength, and phasing outputs of the model for nearby regions should be verified by field measurements.

Heuristic application of this mechanistic hydrodynamic and particle tracking model is useful for sharpening study questions and discovering exceptions to general conclusions. By conducting the modeling exercises as a collaborative analysis between fish biologists and hydrodynamicists, we were able to generate hypotheses about local and regional fish survival related to interactions of local and regional tides, hydraulic geometries, and larval fish responses to these variable environmental conditions. Feedback between particle tracking model applications and larval fish field data collection will improve the capabilities of particle tracking models and inform monitoring programs investigating early life stages of fish.

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