One-Dimensional Particle Tracking with Streamline Preserving Junctions for Flows in Channel Networks

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Abstract: A pseudo-three-dimensional particle tracking model of drifter paths has been developed to study the movement of scalars through a complex network of tidal channels and junctions. To better simulate dispersion caused by bifurcation and merging at junctions, a localized model is proposed in which particles move along potential flow streamlines through junctions. The model is applied to the Sacramento–San Joaquin Delta in the California Central Valley, and the approach reproduces the observed ultimate fate of the endangered native fish Delta smelt more accurately than a model that fully randomizes particle positions at junctions. The new model also reproduces the very large dispersion that has been previously inferred from Delta-wide heat balances; this large dispersion appears to be associated with flow splits at junctions. Overall, the streamline-following model is likely to be more accurate for long-term planning and management simulations of such complex estuaries than more commonly used cross-sectionally averaged Lagrangian transport equation solvers, which randomize concentration distributions of scalars at junctions, and thereby do not reproduce the increased dispersion mechanisms. **DOI: 10.1061/(ASCE)HY.1943-7900.0001399.**

Author keywords: Particle tracking model; Saint Vénant equations; Surface water transport and mixing; Dispersion; Channel junctions; Streamlines; Branched network; Tidal estuary; Sacramento–San Joaquin Delta.

Introduction

The complex geometry of tidal estuaries with branched channel networks can lead to large horizontal dispersion because of flow splits at numerous junctions (Monismith et al. 2009), a mechanism that appears to be similar to the chaotic dispersion in coastal waters with complex bathymetry (Ridderinkhof and Zimmerman 1992) and large river systems with channel braiding and junctions (Bouchez et al. 2010). In essence, when streamlines split at channel junctions, scalars and parcels of water (referred to here as *particles*) can enter one downstream channel or another depending sensitively on the location of the particle in the cross section upstream of the junction. The dependence of particle trajectories on spatial and temporal variability in flow velocities as they traverse the system gives rise to the chaotic behavior that leads to large dispersion.

To represent these complex flows, sophisticated three-dimensional hydrodynamic and transport models such as SUNTANS (Wolfram et al. 2016), UNTRIM (Gross et al. 2010), or SCHISM (Zhang et al. 2016) have been used to resolve transport and mixing processes at multiple scales. However, the challenge of using them for a whole system for long enough timescales and for enough different scenarios of hydrologic variability restricts their use for long-term operational and management planning as well as the design of engineered facilities (MacWilliams et al. 2016). Herein, we improve on a practical alternative to two-dimensional (2D) and three-dimensional (3D) circulation models based on particle tracking, and apply it to one such complex system, the Sacramento–San Joaquin Delta (hereafter, the Delta).

The Delta, a complex network of tidal and fluvial channels with several hundred junctions serves multiple water needs, providing with habitats for threatened fishes and also serving as a conduit for the export of freshwater from Sacramento Valley watersheds to San Joaquin Valley agriculture as well as the urban areas of Southern California (Nichols et al. 1986). The need to meet the coequal goals of water supply and ecosystem protection has necessitated the development of several modeling approaches to evaluate how changes in water operations might affect transport and thus water quality, water supply, ecosystem function, and fish populations (NRC 2010). As a particle (or fish egg, etc.) moves through the Delta, it can do so through many different flow paths; thus, the Delta spreads an initially compact cloud of particles over a large region.

A practical alternative to 2D and 3D circulation models is one in which the system is represented by a network of one-dimensional channels, an approach first developed by Fischer in the 1970s [see, e.g., (Gartrell 1993)]. In this type of model, unsteady flows through a channel network are computed by solving the cross-sectionally averaged St. Vénant equations, whereas transport of scalars is performed using a Lagrangian scheme (Fischer 1972). For the last 20 years, the California Department of Water Resources (DWR) has used such a model, referred to as the Delta Simulation

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Note. This manuscript was submitted on September 8, 2016; approved on July 11, 2017; published online on November 29, 2017. Discussion period open until April 29, 2018; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Hydraulic Engineering***, © ASCE, ISSN 0733-9429.

Model II (*DSM2*), in its planning and design studies [e.g., (Liu and Ateljevich 2011)]. *DSM2* is based on the Preissman method (DeLong et al. 1997) and uses a variant of Fischer's model called the Branched Lagrangian Transport Model (BLTM) scheme (Jobson 2001) to model scalar transport (Hutton and Enright 1993). Lagrangian schemes like BLTM keep track of discrete parcels of water that are transported through a channel network, eliminating numerical diffusion. Thus, mixing in the model arises entirely from two mechanisms: (1) shear flow dispersion represented by exchanges between adjacent boxes and (2) mixing of parcels as they pass through junctions. While the former can be specified using extant descriptions of dispersion in open channel flows [e.g., (Fischer et al. 1979)], the latter, while computationally necessary, is unphysical.

DSM2 has been used extensively with a *Java*-based particle tracking model (henceforth, J-PTM) to model the transport of organisms, notably small Delta smelt (Kimmerer and Nobriga 2008), particularly to evaluate the effect of water project operations on entrainment of fish at the water project pumps (NRC 2010). J-PTM uses *DSM2*-computed flows to advect particles through the Delta. Particles are allowed to occupy different positions in the cross section at a given location and thus to move at speeds determined by empirical representations of open-channel flow structure such as the 1/7th power law (Prandtl 1935). Cross-sectional mixing is accomplished via a random walk [e.g., (Hunter et al. 1993; Visser 1997)]. However, as with scalar transport, junctions are challenging: the J-PTM randomizes particle positions as they pass through each junction rather than define individual paths through the junction; these paths can be quite complicated (Gleichauf et al. 2014; Wolfram et al. 2016). This is important because it can be shown that this randomizing accomplishes far more dispersion than does the explicit dispersion resulting from turbulent mixing because of shear in the mean flows [cf., (Fischer et al. 1979)].

As an alternative to J-PTM, we developed the *Stanford three-dimensional augmented random walker* (*STARWalker*), which keeps particles on approximate streamlines of flow through channel junctions. This model is general enough to be applied to extremely complex junction topologies with multiple channels. Like the J-PTM, *STARWalker* uses *DSM2*-computed 1D flow fields. As discussed below, besides a novel, simple treatment of flows through junctions, *STARWalker* also includes refinements to the random walk formulation, time step size criteria (Ross and Sharples 2004; Visser 1997), and minimum sample size requirement (Hunter et al. 1993). We subsequently outline the development and validation of *STARWalker* with a description of (1) the hydrology of the Delta, (2) model physics, (3) model validation, and (4) a discussion of the model performance and applications.

Sacramento–San Joaquin Delta

The Sacramento–San Joaquin Delta is an inverted fan estuary that is driven at its landward end by freshwater inflow from the Sacramento River in the North, the San Joaquin River in the South, and smaller rivers in the East [Fig. 1; (Moyle et al. 2010)]. The average freshwater flow ranges from about 200 to 2,200 m^3/s. The Sacramento River contributes almost 90% of this flow, while the flow in the San Joaquin River is heavily regulated (Kimmerer 2004). The seaward end of the Delta connects to the San Francisco Bay with semidiurnal tidal forcing, mean tidal range of 1.8 m (Kimmerer 2004) and a net tidal flow at the mouth of the Delta (at Martinez; see Fig. 1) of about 5,000–13,000 m^3/s with typical flood, ebb, and net velocities of 0.5, 0.4, and 0.05 m/s, respectively.

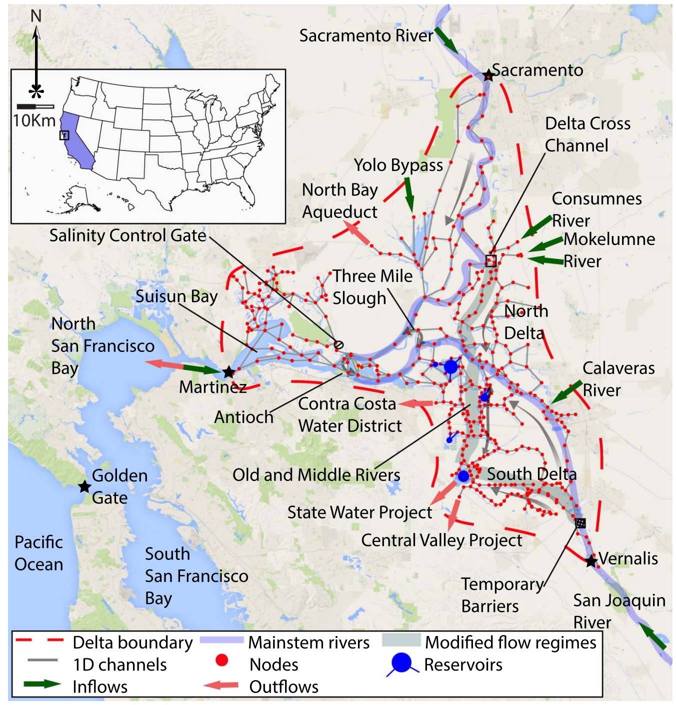

Fig. 1. Map of the Sacramento–San Joaquin Delta and *DSM2* grid (adapted from Anderson and Mierzwa 2002)

The Delta is morphologically complex with numerous shallow (about 0.5 m) and wide channels (about 100 m) with mean velocities of about 0.5 m/s (Monismith et al. 2009). Using these typical values, it can be inferred from scaling arguments that shear flow dispersion is not expected to be a dominant physical process within individual channels of the Delta [see (Fischer et al. 1979)]. Another feature of the Delta is shallow islands that have become submerged owing to levee breaches or land subsistence (Monsen 2000). The seaward end of the Delta (Suisun Marsh) is an intertidal brackish wetland. These islands and the marsh are dead zones wherein tidal trapping may be important.

Another significant feature of circulation in the Delta is engineered alternations to the system. Water is actively managed through (1) the Delta Cross Channel, which when opened supplies freshwater from the Sacramento River to the South Delta; (2) the Central Valley project (CVP) and state water project (SWP) pumps for drinking water supply in the South Delta; and (3) the Suisun Marsh Salinity Control Gate, which is operated to prevent salinity intrusion into the Delta (Monsen 2000). Several temporary barriers are also erected at various locations in the Delta to aid salmon passage (Fig. 1) (Kimmerer 2004; Kimmerer and Nobriga 2008; Monsen 2000). These operations significantly affect flow patterns in the Delta. Lastly, there are about 2,000 uncharted withdrawals for agriculture that remove about 25% of the total inflow and return about 7–10% back to the Delta (Kimmerer 2004).

Model Description

STARWalker is a PTM that uses velocity fields computed from *DSM2* hydrodynamic module, Hydro, developed by the Department of Water Resources (DWR), California, although in principle, it can be used with any 1D channel network model [e.g., HEC-RAS (Brunner 1995)].

DSM2

DSM2 Hydro, described in detail by Anderson and Mierzwa (2002) [see also (Sridharan 2015)], solves the cross-sectionally averaged Saint-Vénant equations on a network of one-dimensional linked channels and reservoirs (DeLong et al. 1997) and has been previously applied to the Delta (Kimmerer and Nobriga 2008). Bathymetry, boundary conditions, and water management structures are included in the model. The channels in *DSM2* are assigned different bottom elevations, slope, and Manning's n values, with their cross-sectional geometry represented by a stage, hydraulic radius, and area lookup table. Channel connections and junctions are represented by nodes (Fig. 1). Flooded islands are treated as continuously stirred tank reactors (CSTRs). Boundary conditions are specified by DAYFLOW, an estimate of net flows in and out of the Delta (Anderson and Mierzwa 2002). Gate operations are made available by DWR. Lateral return flow source and agricultural withdrawal sink flows are incorporated at several internal nodes in the grid as balances of the net flow at the nodes on a monthly timescale.

The numerical solution of the Saint-Vénant equations is performed using the FourPt stencil with two adjacent nodes and two time steps (DeLong et al. 1997). The numerical scheme allows a range of settings from first-order upwinding to second-order quadrature spatial interpolation, and Forward Euler (FE) to Crank-Nicolson (CN) time stepping (Venutelli 2002). Simulations are usually performed centered in space and with slightly more diffusive time stepping than CN for stability (Anderson and Mierzwa 2002).

DSM2 is coupled with J-PTM, a pseudo-three-dimensional model with logarithmic vertical velocity and fourth-order polynomial transverse velocity profiles imposed onto 1D resolved flows. Turbulent diffusivities are assumed constant (Anderson and Mierzwa 2002). Particle trajectories are integrated in time using FE; however, the model does not have any temporal interpolation of hydrodynamic quantities between time steps and does not account for false aggregation of particles near regions of low diffusivity (Visser 1997). J-PTM also randomizes particle positions at the nodes on the *DSM2* grid and routes them to downstream channels according to the fractional proportion of flows through these channels (Anderson and Mierzwa 2002).

STARWalker

STARWalker is a newly developed PTM using *Fortran* designed to run year-long simulations with hundreds of thousands of particles relatively quickly. Like J-PTM, it is a pseudo-3D random walk model operating on rhomboid channels with rectangular cross sections that preserve the hydraulic radius and depth of the water column of the real channel. It allows particles arriving at junctions either to be assigned a randomized cross-sectional position (as is done in J-PTM) or to be advected along their original streamlines.

Cross-sectional diffusion and streamwise dispersion beyond the initial self-similar regime (Fischer et al. 1979) are simulated by randomly diffusing particles in the cross section, and advecting them with the Eulerian flow velocity at their current location in the streamwise direction by a symplectic FE algorithm [e.g., (Sanz-Serna 1992)]. The governing equations for the streamwise (x), lateral (y), and vertical (z) particle trajectories are given by

$$\dot{x} = u \tag{1}$$

$$\dot{y} = R_y\sqrt{(2/r)(\varepsilon_H + D)/\Delta t} \tag{2}$$

$$\dot{z} = R_z\sqrt{(2/r)[\varepsilon_V(z + 0.5(d\varepsilon_V/dz)\Delta t) + D]/\Delta t} + (d\varepsilon_V/dz) \tag{3}$$

where the overdots denote time rates; u = streamwise velocity; R_y and R_z = uniform random processes with standard deviation r; and the vertical and transverse turbulent eddy diffusivities, ε_H and ε_V, are given respectively by parabolic and uniform profiles (Fischer et al. 1979). The vertical and lateral profiles for u are given in Eq. (9) in Appendix I. In the vertical direction, the gradient of vertical diffusivity is added to overcome false aggregation of particles in low diffusivity regions (Dimou and Adams 1993; Visser 1997). Across the cross section, an isotropic diffusion coefficient, $D = 10^{-5}\ \mathrm{m^2/s}$, is added to allow particle movements owing to eddies during slack water. Flooded islands are treated as CSTRs and particles entering them are modeled using forward difference approximations of the reactor mass balance given by Danckwerts (1953) [see Eq. (10) in Appendix I].

Time substeps are chosen as the minimum of (1) the time step required to limit particle displacement at any given time step to within the smallest dimension of the channel, and (2) the constraint for the gradient of vertical diffusivity to adequately capture the deterministic transport away from regions of low vertical diffusivity (Visser 1997), i.e., $\Delta t_S < (1/|\partial^2\varepsilon_v/\partial z^2|)$. A substep size of 10% smaller than this theoretical limit is chosen to improve the accuracy of the deterministic transport mechanism (Ross and Sharples 2004). A particle exits from the upstream or downstream end of a channel when the streamwise displacement of the particle during a time step exceeds the distance between the current position of the particle and the end of the channel.

The channel bottom, banks, and free surface are treated as fully reflecting boundaries. While there are more sophisticated methods for treating boundaries (Ross and Sharples 2004; Thomson and Montgomery 1994), the full reflection is most easily implemented and does not impose significant nonphysical artifacts. In *STARWalker*, a linear interpolation is performed between the vertical eddy diffusivity at 1.5% of the total depth from the vertical boundaries to ensure the existence of the derivative of the eddy diffusivity at the boundaries, a simplification of the method of Ross and Sharples (2004). The interpolation introduces a nonphysical value of the wall shear stress, but does not affect the consistency of the PTM. After each *STARWalker* substep, the particle positions are redistributed to account for the change in free surface elevation and cross-sectional area. The diversion sinks then remove particles within a boundary layer of thickness $0.5(q/Q)W$ from the channel banks.

All the stochastic processes in the model are simulated using the pseudorandom number generation algorithm RAN3 (Press et al. 1992). RAN3 passes various statistical tests of robustness and randomness (Hunter et al. 1993), is machine architecture independent, and is not resource intensive.

The key difference between *STARWalker* and previous 1D models such as J-PTM is that in *STARWalker* flow behavior at junctions can be represented by moving particles along streamlines computed from potential flow theory (PFT). PFT provides a reasonable approximation of flow through a junction at distances sufficiently far upstream or downstream of the junction that the effects of separation, stagnation, and turbulence are no longer important (Huang et al. 2002). Several authors have shown experimentally [e.g., (Hsu et al. 1998)] and numerically [e.g., (Huang et al. 2002)] that for uniform flows through a confluence of two rectangular channels at different relative orientations, the streamwise and lateral velocity profiles become almost uniform, the vertical velocity profile becomes logarithmic, and the streamlines of flow can be approximated by two-dimensional PFT at locations far upstream or downstream of a channel junction. The streamline-following model is a simplification of a realistic junction, and it would only be strictly valid for large distances downstream of a junction. As represented

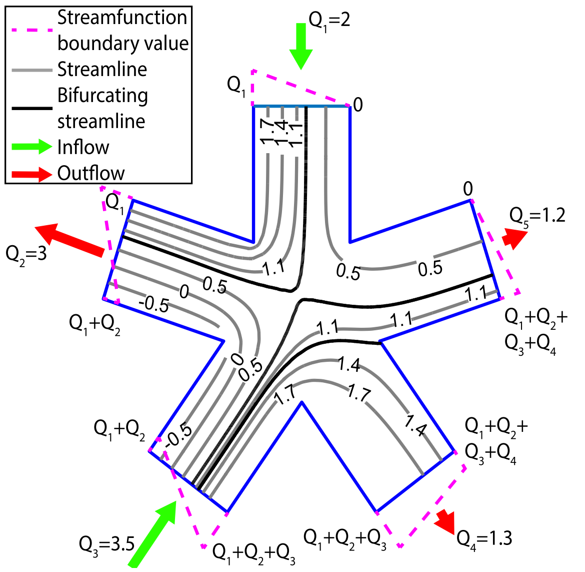

Fig. 2. Junction rule formulation with solution of stream function at a polygonal junction; all quantities are dimensionless

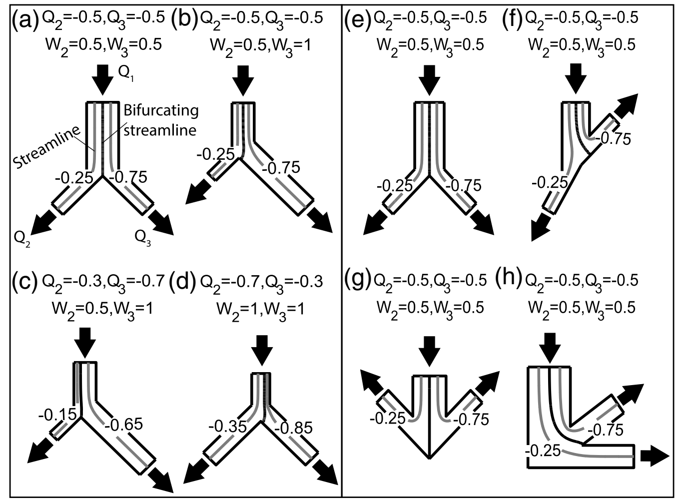

Fig. 3. Stream function for (a–d) different flow and channel width scenarios with flow topology and channel orientations held constant; (e–h) for different channel orientations with flow topology and relative widths of channels held constant at $W_1 = 1$, $W_2 = W_3 = 0.5$; values of the flows, widths, and stream function are dimensionless with $Q_1 = 1$ and $W_1 = 1$

by the *DSM2* grid, the number of channels connecting to each junction varies between three and six. In the grid for this particular system, about 70% of the junctions have three channels with either one inflow and two outflows or vice versa (Type Y), and about 30% of the junctions have four or more channels (Type X).

In *STARWalker* each junction is modeled as a polygon with small reaches of the connecting channels within which the flow is approximated as locally steady. Flows in the junction are then represented via a planwise 2D stream function with Neumann boundary conditions across the channel widths and Dirichlét conditions on the channel banks (Fig. 2). The junction is then conformally mapped onto a unit circle where the Laplace equation for the stream function is solved using the *MATLAB* Schwarz-Christoffel toolbox developed by Driscoll (1994). The solution is then transformed back onto the original polygon on a triangular grid (Driscoll and Vavasis 1998) (Fig. 2). This process is applied for a junction with various channel widths and orientations for unique flow scenarios (Fig. 3). The bifurcating streamlines are then identified for each scenario and their lateral positions relative to the particle positions determine particle trajectories through the junction. By inverting the flows into each channel, and by using a combination of rotation and mirroring of the unique scenarios, all admissible junction topologies can be obtained. Inadmissible flow scenarios with branch cuts in the stream function are ignored.

For each of these scenarios, the locations of bifurcating streamlines can be prescribed as functions of the flows and relative widths of each connecting channel [see (Sridharan 2015)]. For instance, for a junction with three channels of constant width, W, and two inflows, Q_1 and Q_2, with the assumption that the cross-sectional flow velocities are uniform far downstream of the junction, it can be shown that the location of the bifurcating streamline in the downstream channel would be $[Q_1/(Q_1 + Q_2)]W$ from the bank nearest to the inflow Q_1. These functions are placed in a lookup table for each channel in each scenario for each type of junction. Depending on where in a channel cross section a particle is relative to the position of the bifurcating streamline, it is pushed into a new downstream channel. A particle's horizontal position relative to the position of the bifurcating streamline in the new channel is normalized based on its position relative to the position of the bifurcating streamline in the old channel. Its vertical position is normalized based on the ratio of the depths of flow in the old and current channels. In this manner, it is constrained to approximately follow its original streamline. Only the topology of flows and the relative widths of the connecting channels and magnitudes of flows affect the model for the junction in each scenario. Neither the orientations of the connecting channels nor their depths matter (Kacimov 2000; Ramamurthy et al. 2007).

Model Results

To validate *STARWalker*, model predictions were compared with analytical solutions for typical transport problems. Since the purpose of this paper is to focus on the effects of junction dynamics on transport and the application and performance of *STARWalker*, we omit detailed discussion of *DSM2* Hydro, except to note that after substantial calibration it can accurately model flows and free surface elevations in the Delta (Kimmerer and Nobriga 2008; Rose et al. 2013). We also note that *DSM2* Hydro represents tidal components with higher than semidiurnal frequencies with somewhat less accuracy than diurnal and semidiurnal components (Sridharan 2015).

Validation of STARWalker with Analytical Results

A range of problems for which analytical solutions exist (Fischer et al. 1979) were simulated to establish the validity of the *STARWalker* model. In all cases, an infinitesimal pulse of 10,000 particles was released and tracked over time. First, a pulse released in a still, infinite 3D ocean with isotropic diffusion coefficient of 0.01 m^2/s grew in size with the square root of time as expected [Eq. (11) in Appendix II]. Second, shear flow dispersion in a straight channel 10 km long, 100 m wide, and 10 m deep, simulated with uniformly distributed particles, produced linear growth of variance in particle positions with time after an initial theoretical correlation time of about 3,300 s (see Appendix II). The shear flow dispersion coefficient estimated from the growth of particle

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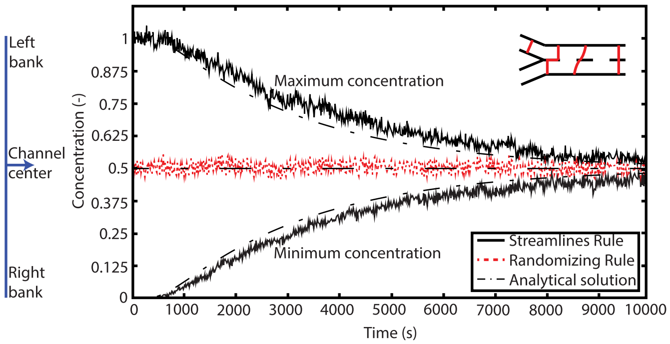

Fig. 4. *STARWalker* validation with mixing at the confluence of two rivers; inset diagram indicates schematic of the test

cloud variance, σ, by $K = 0.5d\sigma^2/dt$ (Fischer et al. 1979) of 83 $\mathrm{m^2/s}$ is comparable to the theoretical value [Eq. (12) in Appendix II].

A third important test of the model's validity is the mixing at the confluence of two channels. In this test, two identical channels 1 km long, 100 m wide, and 10 m deep, with a mean velocity of 0.5 m/s, one of which carried a uniformly released pulse, discharged into a downstream channel of identical dimensions but with mean flow velocity of 1 m/s. The streamline-following junction rule mixed the streams in about 10,000 s (Appendix II), while the randomizing junction rule instantaneously mixed them (Fig. 4). The mixing predicted by *STARWalker* is in excellent agreement with the analytical solution obtained with the method of superposition of image sources (Fischer et al. 1979) [Eq. (13) in Appendix II].

Model Performance

The criteria of convergence, consistency, stability, accuracy, time step size restriction, and minimum number of particles to achieve statistical convergence are discussed below. Hydro is nearly first-order accurate in time, while *STARWalker* gradually converges at O(Δt) owing to the complexities of the branched domain. Hydro is unconditionally stable for the time steps it is run with (Venutelli 2002), as is *STARWalker* whose time step restriction is stricter than the stability requirement for FE time marching (Ketcheson et al. 2008). The error in computations of particle trajectories is small, O(1 m), compared to the particle displacement, O(10–100 m). Also, because of its strict time step restriction, *STARWalker* does not allow runaway particle tracks owing to chaotic amplification of small errors with time. The truncation error is O(Δx^2, Δt) in Hydro and O(Δt) in *STARWalker*.

The minimum number of particles needed to ensure statistical convergence was determined by comparing the summary statistics of the arrival time distributions at the export pumps of quintuplicate runs of duration 30 days with a time step size of 100 s for (1) 1,000–10,000 particles and (2) 100,000 particles (Fig. 5). The quantities that were compared are the mean arrival time, $\mu_{\text{Arrival time}}$, and spread in arrival times, $\sigma_{\text{Arrival times}}$. The decrease in percentage error between $\mu_{\text{Arrival time}}$ and $\sigma_{\text{Arrival times}}$ of the 10,000 particle runs and the 100,000 particle runs was about 1% (percentages in Fig. 5), and the reduction in the standard deviations between $\mu_{\text{Arrival time}}$ and between $\sigma_{\text{Arrival times}}$ among the quintuplicate 5,000 and 10,000 particle runs was less than 1% (extent of the error bars relative to the mean values in Fig. 5). These results indicate that at least 5,000 particles and ideally 10,000 or more particles are required to achieve statistical convergence.

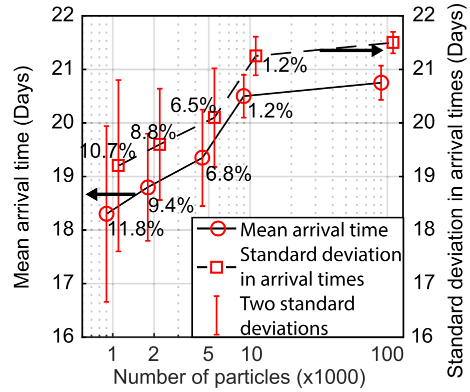

Fig. 5. Convergence of summary statistics of arrival times at export pumps for quintuplicate runs with different numbers of particles for mean arrival time, and standard deviation in arrival times; the numbers indicate percentage difference from 100,000 particles runs

Application to the Sacramento–San Joaquin Delta

STARWalker results can be used to infer small channel scale as well as large delta scale transport and mixing mechanisms and particle fates in complex systems. Different applications to the Delta are described below.

In-Channel Longitudinal Dispersion

The longitudinal dispersion coefficient is used as a parameter in several transport models [e.g., the Water Allocation Model described by Fleenor and Bombardelli (2013)]. While it is small, O(1 $\mathrm{m^2/s}$), within channels and may not be important to the overall transport and fate of scalars in the Delta (Sridharan 2015), it is useful as an indicator of the local mixing within channels and can be useful in determining scalar exchange between localized habitats.

In order to determine the magnitude of in-channel longitudinal dispersion, 500 particles were released per hour for 24 h at each of nine locations within the Delta (Sridharan 2015) and tracked in the period between June 1 and August 31, 1996. The in-channel dispersion coefficient in a given channel was then estimated as

$$K_C = 0.5\left[\sum_{i=1}^{RR} N_i\sigma_{\xi,i}^2 \bigg/ \sum_{i=1}^{RR} N_i\right] \bigg/ \Delta t \tag{4}$$

which is the average value of the mean of the tidally filtered rate of growth of stream-wise spread, $\sigma_{\xi,i}$, given by

$$\sigma_{\xi,i}^2 = (1/N_i)\sum_{j=1}^{N_i}\xi_j^2 - \left[(1/N_i)\sum_{j=1}^{N_i}\xi_j\right]^2 \tag{5}$$

within the channels for each i of RR releases, weighted by the number of particles, N_i, passing through that channel from that release. This was a period of low flow in the Sacramento and San Joaquin Rivers, and the computed dispersion coefficients were very small with peak values not exceeding 10 $\mathrm{m^2/s}$. The dispersion coefficient was largest at O(1 $\mathrm{m^2/s}$) in the Sacramento and San Joaquin rivers. In the central and western Delta, it was very small, i.e., ≤O(0.1 $\mathrm{m^2/s}$). In this region, the typical cross-sectional mixing timescale is O(10^5 s), while the semidiurnal tidal timescale is O(10^4 s). These values therefore correspond to the lower limits of the expected oscillatory shear flow dispersion coefficient in tidal open channels constrained by the tidal period (Fischer et al. 1979).

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The dispersion coefficients computed here are dependent on the hydrology and vary for other time periods.

Particle Tracking at the Scale of the Delta

The ultimate fate of particles following streamlines at junctions is very different from that of particles whose positions are randomized at junctions. To demonstrate this difference, a 3-month simulation was performed with uniform inflows of 292 and 40 m^3/s respectively in the Sacramento and San Joaquin rivers, outflow of 57 and 20 m^3/s at the pumps, and a semidiurnal 2.1 m range tide at Martinez in which 5,000 particles were released uniformly at Vernalis every 15 min at the beginning of the run. *STARWalker* was the first run with complete randomization (as in the J-PTM), and then run by progressively using the streamline-following model at first the Type Y junctions and then the Type X junctions, until all junctions were represented with the streamline-following model. This progressive adaptation of the condition was applied to show the relative importance of modeling the more common Type Y junctions correctly over the rarer Type X junctions in the model performance.

We observed spurious mixing and consequent path-independent dispersion in the J-PTM mode. More than twice the number of particles escaped to the San Francisco Bay via Martinez in the J-PTM mode than with the streamline-following model (Fig. 6). The effect is that in the J-PTM mode, the increased dispersion owing to junction mechanisms along transport pathways is not captured, but particles can access portions of the Delta that they would not be able to reach with a more realistic junction model. In the J-PTM mode, the almost sevenfold larger inflow in the Sacramento River than the San Joaquin River caused a large fraction of particles to leave the system downstream of their confluence in the western Delta. With the streamline-following model, such flow-based movement into downstream channels did not occur; a larger fraction of particles remained in the central Delta and were exported slowly by the tides [Figs. 6(b, d, and e)]. Increased subtidal dispersion was recorded with the streamline-following model than in the J-PTM mode. The dispersion was computed using Eqs. (4) and (5), but with the east-west variance of the cloud of particles. The dispersion coefficient between Vernalis and Jersey Island was within a range of 85–345 m^2/s with the streamline-following model and 13–50 m^2/s with the J-PTM junction model.

Clearly, the few Type X junctions were more important in the central and western Delta where they are largely prevalent, than in the Old and Middle River corridor (OMRc) and south Delta. The decreased importance of Type X junctions compared to Type Y is evident in the decrease in difference in breakthrough curves at various locations as increasingly complex junctions are modeled using the streamline-following model (Fig. 6). As discussed below, these differences in movements created by the junction model can significantly affect key predictions of the model: routes taken, dispersion along those routes, entrainment of particles at the export pumps, and escapement to San Francisco Bay.

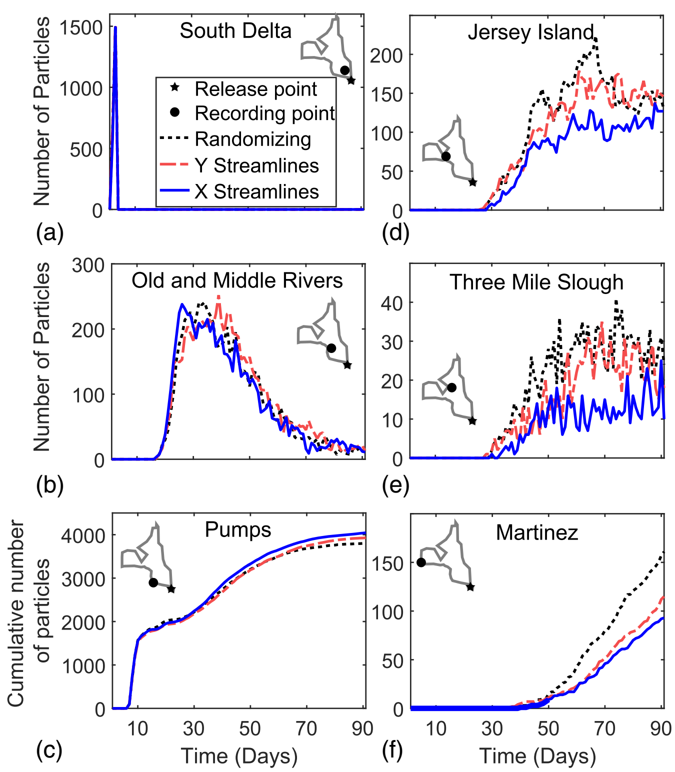

Fig. 6. Number of particles recorded at different locations for different junction models; locations in the south Delta are shown in the first column and locations in the central and western Delta are shown in the second column; top and middle plots indicate daily total number of particles passing through a location within the Delta, and bottom plots indicate cumulative number of particles exiting the system

Transport Pathways and Increased Dispersion Owing to Junctions

It is typically assumed that transport occurs through the Delta along preferred geographical pathways, e.g., the OMRc [e.g., (Perry et al. 2014)] (Fig. 1). Regulations for minimizing entrainment of at-risk fish species are designed using this idea (NRC 2010). However, there may be multiple pathways depending on hydrologic conditions, gate operations, and export flows. *STARWalker* was used to carry out several simulations to objectively identify these paths by tracking particles released at Sacramento and Vernalis. Particle passage through key locations within the Delta conditional upon passage through other locations was used to determine the transport pathways (Sridharan 2015). Here we present a few examples to illustrate the value of the approach.

Analysis of particle tracks for different flow conditions shows that pathways occur in many categories and depend on flows in the Sacramento and San Joaquin Rivers, exported through the South Delta pumps and operations of the Delta Cross Channel and South Delta barriers. Here we focus on three particular pathways occurring in December 1995 [Figs. 7(a–c)]: (1) advection by the Sacramento River to Martinez, bypassing the Delta; (2) from the Sacramento River to the export pumps through the central Delta via the Delta cross channel; and (3) from the San Joaquin River to Martinez via the central Delta. These pathways have been observed in mark-recapture studies of acoustic-tagged juvenile salmon, whose downstream routing at channel junctions is strongly affected by the local hydrodynamics (Perry et al. 2013).

Large-scale subtidal dispersion along these pathways was computed using Eq. (2), but with the rate of tangential along-pathway and normal-to-pathway growth of variance of the cloud of particles moving along these pathways. To compute the tangential and normal variances, the UTM coordinates of the particles were mapped onto the pathway centerline following grids using the *xy2sn* toolbox in *MATLAB* (Dugge 2015) and the subsequent analysis was performed with these coordinates. In order to demonstrate only the key temporal attributes of the dispersion coefficient, the variance was low-pass filtered (7 days) to remove both tidal variations as well as peaks and troughs owing to bifurcating and recombining

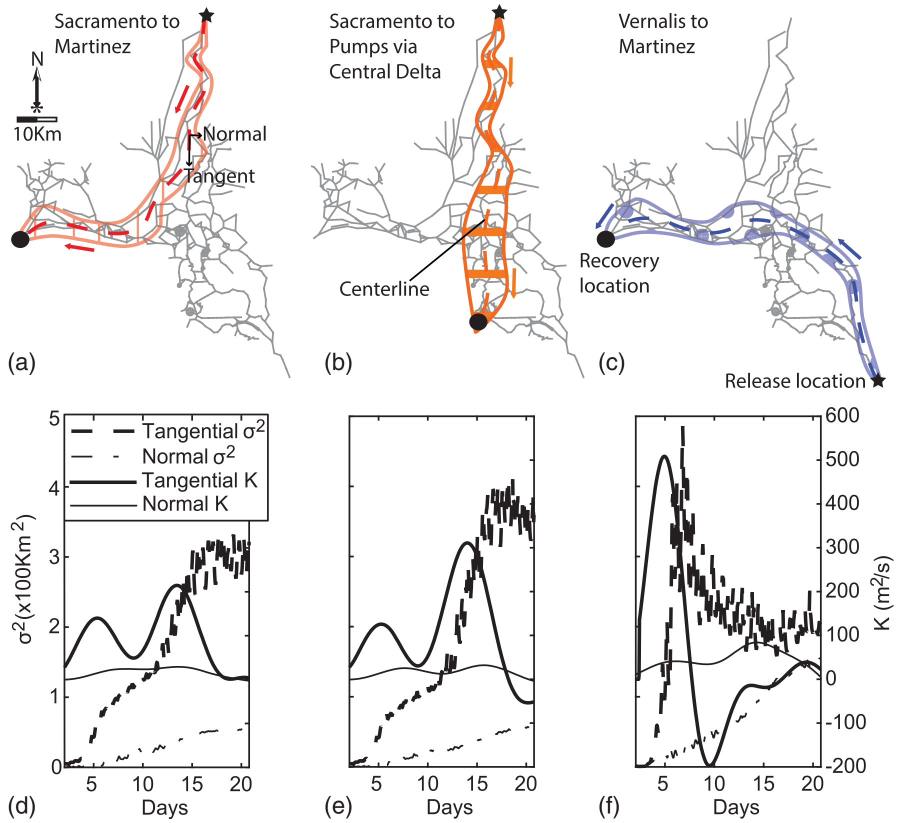

Fig. 7. Primary transport pathways and mixing mechanisms in the Delta: (a–c) indicate three transport pathways with colored arrows indicating direction of subtidal transport; (d–f) respectively show the temporal growth of tangential-to-pathway and normal-to-pathway variance and 7-day low-pass filtered dispersion coefficient in the whole Delta of particles traveling along the pathways in (a–c)

junctions. In all pathways, the tangential component of variance increases nonlinearly with time at a faster rate compared to the linear growth of the normal component. The tangential component of variance subsequently levels off [Figs. 7(d and e)] and even begins to decrease [Fig. 7(f)] as the cloud of particles exits the system. This period of exit is marked by negative values of the dispersion coefficient. The normal component grows slowly in the mainstem rivers [initial flat parts in Figs. 7(d–f)] and increases owing to multiple junctions in the central Delta [middle parts in Figs. 7(d–f)] before becoming constrained by the funneling effect of the western Delta [final flat parts in Figs. 7(d and e)] and the OMRc [final part in Fig. 7(f)]. Here also, as in the case of in-channel dispersion, the dispersion coefficients depend on the hydrology and vary for different time periods.

The subtidal dispersion along these pathways owing to passage through multiple junctions is significantly higher than in-channel dispersion: $O(100\ \mathrm{m}^2/\mathrm{s})$ in the tangential and $O(10\ \mathrm{m}^2/\mathrm{s})$ in the normal directions [Figs. 7(d–f)]. The increased dispersion coefficient is attributable to several mechanisms: (1) interaction of tidal currents with residual circulation patterns [(Banas et al. 2004); see also (Sridharan 2015)], (2) in-channel dispersion by tidal currents (Fischer et al. 1979), (3) trapping in side channels (Okubo 1973), and (4) increased shear flow dispersion through multiple junctions [(Wolfram et al. 2016); see also (Sridharan 2015)]. These mechanisms were collectively attributed to junction mixing in a 3D model of the Delta (Monsen 2000) and in observed thermal energy balance in the San Joaquin River by Monismith et al. (2009), to account for the increased dispersion they observed in those studies.

As in the case of in-channel dispersion, the randomizing junction model produced dispersion coefficient values of only about $O(10\ \mathrm{m}^2/\mathrm{s})$; propagation and amplification of perturbations in particle positions at near junctions are negated by the randomizing process. The streamline-following model is essential for capturing the chaotic mixing mechanisms in systems such as the Delta. Since neither Hydro nor *STARWalker* incorporate gravitational circulation, this model should be applied to stratified estuaries with caution.

Using STARWalker to Model Delta Smelt Salvage at the Export Pumps

STARWalker is well suited to modeling export pumping effects on the population of the endangered Delta smelt (Moyle et al. 2010), a fish that is thought to have very simple behavior (Bennett 2005), and one that at times significantly limits export pumping to prevent take (Wright 2001). The approach used to test *STARWalker*'s ability to model Delta smelt entrainment at the pumps follows that of Gross et al. (2010), who used a 3D circulation model and 3D particle tracking. In this approach, fish counts between April 12, 1999, and July 22, 1999 (the Delta smelt spawning period), collected by the California Department of Fish and Wildlife (CDFW) 20-mm Townet Survey (CDFW 2015b)—a periodic set of triplicate surveys of small fish in the Delta—were used to release particles simulating the Delta smelt onto the *DSM2* grid. These particles were then transported through the Delta by *STARWalker*. The accuracy of the model was then evaluated by comparing the number of particles recovered at the CVP pumps with the total salvage of fish recorded there (CDFW 2015a).

In this approach, the spatial distribution of the rate of particle releases was based on fish surveys assumed to be constant in time.

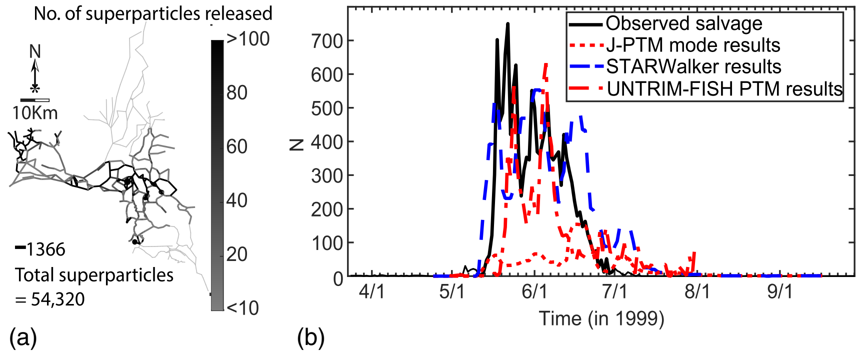

Fig. 8. Delta smelt salvage modeling: (a) total number of superparticle releases in each *DSM2* channel reach; scale indicates number of superparticles released in a specific reach of a channel, where the number of fish represented by each superparticle is given in Eq. (3); no delta smelt were found in the trawls and so no superparticles were released in the very light-colored thin channels; (b) comparison of *STARWalker* and J-PTM mode model results to delta smelt salvage at CVP in the year 1999; the validation for passive particles from Gross et al. (2010) is plotted for comparison with the ordinate axis scale changed to reflect the assumptions of Eq. (7)

Every 6 h for each location where fish had been found in the townet survey, a superparticle was released over T time steps representing n_b fish in channel b in a given region, computed as

$$n_b = (V_b/T)\left(\sum_{a=1}^{m} N_a \Big/ \sum_{a=1}^{m} V_a\right) \tag{6}$$

where m = number of trawling stations in a given region; V_a = mean volume trawled at station a; and V_b = mean volume of channel b during the spawning period. N_a is the sum of all fish caught at station a during the three townet surveys. In all, 54,320 superparticles were released during the run [Fig. 8(a)]. Hydro was run with DAYFLOW initial and boundary conditions for this period with a time step of 1 h. *STARWalker* was run with all enhancements (streamline-following, corrections to the random walk for spatial variations in diffusivity, etc.) in operation and again with enhancements turned off so as to emulate the J-PTM. To model mortality prior to entrainment, the strength of each superparticle was reduced so that survival was 97.1%/day as estimated from observations by Kimmerer (2004). To evaluate the quality of the various simulations, the arrival of particles at the export pumps was compared to salvage at CVP, S, estimated from the raw salvage, S_R, as

$$S = [(1+\gamma)/\eta]S_R \tag{7}$$

where γ, the prescreen loss, is assumed to be 15% and η, the salvage efficiency, is assumed to be 14.2% prior to May 15 and 38.9% after May 15 (Gross et al. 2010).

Qualitatively, even given the simple nature of the fish model (i.e., no behavior), *STARWalker* with the streamline-following junction model performs significantly better than does *STARWalker* emulating the J-PTM. In particular the model with streamline-following at junctions captures the general characteristics of the salvage reasonably well [Fig. 8(b)], although it does significantly err at times, e.g., mid-May when substantial salvage was recorded although not predicted by the model. The quantitative accuracy in computing salvage was evaluated using a model skill score [cf. (Gross et al. 2010)]

$$\mathrm{MSS} = 1 - \left\{\left[\sum_{n=1}^{T_s}(B-S)^2\right]\Big/(N\sigma_S^2)\right\} \tag{8}$$

where σ_S = standard deviation in the estimated salvage; N = number of fish salvaged; T_s = duration of the salvage in days; and B = number of simulated delta smelt recovered. For *STARWalker*, MSS = 0.63 with $R^2 = 0.52$ between observed and modeled salvage, whereas for *STARWalker* in J-PTM mode, MSS = −0.16 and $R^2 = 0.23$. For comparison, similar high quality 3D modeling reported in Gross et al. (2010) gave MSS = 0.6, although more complicated releases were prescribed that involved tuning to match the extent of the townet survey data. Thus, it would appear that the 1D modeling approach of *STARWalker* represents a substantial improvement over the simpler J-PTM representation and may not be significantly less accurate than a full 3D model.

Conclusions

A new PTM, *STARWalker*, designed to study the movement of particles through complex branched network tidal estuaries, has been developed with the incorporation of a simple, physically based model of channel junctions. Used with a 1D hydrodynamic model, this PTM is much less computationally intensive than more complex multidimensional circulation models that have been previously used to study the linkage of hydrodynamics and ecological processes in the Delta (Kimmerer et al. 2009, 2013). The assumptions inherent to the streamline-following junction model are (1) statistical stationarity of flow through the junction at a given point in time and (2) channel morphology independence. The former condition is quite accurate as water parcels usually take at most only a few minutes to traverse junctions in the Delta (Gleichauf et al. 2014), whereas the latter can be shown analytically in the absence of secondary flows and flow separation (Debnath and Chatterjee 1979).

As documented using two- and three-dimensional modeling by Wolfram et al. (2016), complete mixing by randomization of particle positions after passage through junctions can produce significant errors. Thus, the simple junction model we present here—a useful compromise between accuracy and computational effort—provides an effective means for modeling over long timescales the transport processes of channel networks in tidal estuaries such as the Delta, systems where complex geometries with multiple junctions can produce significant horizontal dispersion.

As seen in our application to the Delta, the advantages of using a simple model like *DSM2-STARWalker* stem from the ability to run multiple simulations covering long timescales. This allows the user to identify system-level processes that might be difficult to determine from the shorter-term and smaller-scale (e.g., 1–3 months over particular reaches of the Delta) simulations using multidimensional models. For example, as we demonstrate, it can be used to identify important pathways of transport through the channel network, information that can be especially useful for developing regulations or designing facilities or project operations.

Appendix I. Details of *STARWalker*

The treatment of in-channel velocity profiles and reservoirs is described below.

For a channel with dimensions ($W \times H$) with mean velocity U, the streamwise velocity u is

$$u = U f_V f_H; \quad v = 0; \quad w = 0$$
$$f_V = \begin{cases} 1 + 2.4\sqrt{C_D}[1 + \ln(z/H)]; & z > \delta_v \\ 1 + 2.4\sqrt{C_D}[1 + \ln(\delta_v/H)]; & z \leq \delta_v \end{cases};$$
$$\delta_v = 30(v/u_*)|_{u_* \neq 0}; \quad u_* = \sqrt{C_D}U; \quad C_D \approx 0.03$$
$$f_H = 1.2 + 0.3[(2y - W)/W]^2 - 1.5[(2y - W)/W]^4 \tag{9}$$

where the vertical friction term $\nu(\partial^2 u/\partial z^2) \approx C_D[(U|U|)/H]$ [e.g., (Wang et al. 2009)]; C_D = bottom drag coefficient; and δ_ν = bed roughness height.

The number of particles entering, N_{IN}; in, N_R; or leaving, N_{OUT}, a flooded island with V_R and V_R^0 volumes of water in the current and previous time steps is given by

$$N_{\mathrm{IN}} = \sum_{i=1}^{n_{\mathrm{In}}} N_i^{CC}[(Q_i^{\mathrm{In}}\Delta t)/V_R];$$
$$N_{\mathrm{OUT}} = N_R\left[\left(\sum_{j=1}^{m_{\mathrm{Out}}} Q_j^{\mathrm{Out}}\Delta t\right) \Big/ V_R\right]$$
$$N_R = N_0 + N_{\mathrm{IN}}; \quad V_R = V_R^0 + \sum_{i=1}^{n_{\mathrm{In}}} Q_i^{\mathrm{In}} - \sum_{j=1}^{m_{\mathrm{Out}}} Q_j^{\mathrm{Out}} \tag{10}$$

where N_0 particles are initially in the reservoir, N_i^{CC} particles enter the reservoir from the ith of n_{In} channels with flow Q_i^{In}, and particles leave through the jth of m_{Out} channels with flow Q_j^{Out}.

Appendix II. Analytical Solutions for Validating *STARWalker*

The analytical solutions for the validation problems described in the main text are given below.

For diffusion in a 3D ocean, the concentration of an initial pulse C_0, of volume $\Delta x\Delta y\Delta z$, is (Fischer et al. 1979)

$$C = [(C_0\Delta x\Delta y\Delta z)/(4\pi Dt)^{3/2}]e^{-[(x^2+y^2+z^2)/(4Dt)]} \tag{11}$$

For shear flow dispersion in steady, uniform flow in a straight channel the concentration of an initial pulse C_0 of length, Δx, is (Fischer et al. 1979)

$$C = [(C_0\Delta x)/\sqrt{4\pi Kt}]e^{-[(x-Ut)^2/(4Kt)]};$$
$$K = 0.011[(U^2W^2)/(Hu_*)] \tag{12}$$

and the time to complete cross-sectional mixing for uniformly released concentration is $T_{\mathrm{Mix}} \approx 0.1W^2/\varepsilon_H$.

For mixing at the confluence of two channels, it can be shown using the method of superposition of images (Fischer et al. 1979) that the concentration owing to the confluence of two streams with concentration C_0 in one is

$$C = 0.5C_0 \sum_{n=-\infty}^{\infty} (-1)^{n+1}$$
$$\times \{\mathrm{erf}[(y - (n + 0.5(-1)^n)W)/\eta] - \mathrm{erf}[(y - nW)/\eta]\};$$
$$\eta = \sqrt{4\varepsilon_H t} \tag{13}$$

and the time taken to completely mix the two streams is typically about $T_{\mathrm{Mix}} \approx 0.3W^2/\varepsilon_H$.

Acknowledgments

Initial funding for this work was provided by the CALFED science program. Later support for VKS was provided by the Singapore Stanford Partnership; Stanford University through a Leavell Fellowship for the Sustainable Built Environment; and by the National Marine Fisheries Service, National Oceanographic and Atmospheric Administration. The authors are grateful to Dr. Eli Ateljevich at DWR for his assistance with using the *DSM2* suite of models. The authors also acknowledge the constructive feedback of two anonymous reviewers; an anonymous associate editor; and Chief Editor, Thanos Papanicolaou, for greatly improving the quality of the manuscript.

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