The Use of Stable Isotope-Based Water Age to Evaluate a Hydrodynamic Model

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Abstract: Transport time scales are common metrics of the strength of transport processes. Water age is the time elapsed since water from a specific source has entered a study area. An observational method to estimate water age relies on the progressive concentration of the heavier isotopes of hydrogen and oxygen in water that occurs during evaporation. The isotopic composition is used to derive the fraction of water evaporated, and then translated into a transport time scale by applying assumptions of representative water depth and evaporation rate. Water age can also be estimated by a hydrodynamic model using tracer transport equations. Water age calculated by each approach is compared in the Cache Slough Complex, located in the northern San Francisco Estuary, during summer conditions in which this region receives minimal direct freshwater inflow. The model’s representation of tidal dispersion of Sacramento River water into this backwater region is evaluated. In order to compare directly to isotopic estimates of the fraction of water evaporated (“fractional evaporation”) in addition to age, a hydrodynamic model-based property tracking approach analogous to the water age estimation approach is proposed. The age and fractional evaporation model results are analyzed to evaluate assumptions applied in the field-based age estimates. The generally good correspondence between the water age results from both approaches provides confidence in applying the modeling approach to predict age through broader spatial and temporal scales than are practical to assess using the field method, and discrepancies between the two methods suggest aspects of both approaches that may be improved. Model skill in predicting water age is compared to skill in predicting salinity. Compared to water age, salinity observations are shown to be a less useful diagnostic of transport in this low salinity region in which salt inputs are poorly constrained.

Keywords: San Francisco Estuary; Sacramento–San Joaquin Delta; water age; transport time scales; hydrodynamic model; tidal hydrodynamics; stable isotopes

1. Introduction

Time scales are metrics of the time associated with processes such as physical transport or biogeochemical reactions [1]. Comparison of transport time scales with biogeochemical time scales provide insight to the relative importance of transport. When the time scale of a biogeochemical process is much shorter than a transport time scale, the biogeochemical process is typically more important than transport processes in determining constituent concentrations. Intermediate cases in which transport time scales and biogeochemical time scales are similar can have desired ecological
outcomes. For example, primary and secondary productivity can be maximized when these time scales are similar [2].

Water age is a transport time scale quantifying the time elapsed since a water parcel entered a study area [3]. In contrast, residence time quantifies the time required for a water parcel starting at a specific time and location to leave the study area [3]. Water age can be directly useful in estimating biogeochemical rates [4]. Water age can be estimated based on the fractional evaporation of water inferred from variation in the stable isotopes of hydrogen ($^2$H) and oxygen in water ($^{18}$O) along transects through the Cache Slough Complex (CSC) in the northern San Francisco Estuary (SFE) [4]. These estimates showed a broad range of water ages across the region. However, the analysis was based on several approximations, including a constant and uniform water depth and an evaporation rate averaged over the two-months prior to data collection.

A tracer based modeling approach [5,6] has been widely applied to estimate water age. A specific application of this flexible approach provides the algebraic mean age of all water parcels from a specific source present at a given time and location. This approach is generally used to represent the age of water volume or conservative substances. The mean water age will generally be larger than the “radio age” of decaying tracers such as a radioactive tracer [7] (Delhez et al., 2003). Since the observational data uses stable isotopes (not decaying isotopes) whose ratio is influenced by evaporation, the mean water age and isotopic age are believed to be conceptually consistent. We specifically estimate the mean age (“age”) of Sacramento River water advected down the Sacramento River to the seaward (downstream) end of the CSC and mixed through the CSC by tidal mixing processes during the summer and early fall of 2014. We compare this “predicted” age from the hydrodynamic model with the “isotopic age” estimated from the water isotope data. In addition, we estimate fractional evaporation using an extension of the published age approach [6] and compare these to estimates from stable isotope measurements [4].

The main objective of this study is to investigate the utility of water isotope-based age estimates in evaluating the representation of transport processes by a hydrodynamic model. The isotopic-age is a potential alternative to salinity observations to calibrate or validate a hydrodynamic model. In dominantly freshwater systems with agricultural return flows, conductivity (and thus practical measurements of salinity) can be substantially influenced by local sources of salts, nitrate, and phosphate [8]. These sources are often poorly quantified, limiting the utility of salinity observations for model calibration. In this study, we compare predicted water age and isotopic water age to the CSC. An additional objective is the evaluation of depth and evaporation rate assumptions applied to estimated isotopic water age [4]. The desired outcome of this study is that both the modeling and field approaches can be used with increased confidence to study relationships between water age and biogeochemical concentrations and transformation rates.

2. Materials and Methods

2.1. Site Description

Our study area includes the Cache Slough Complex (CSC) and neighboring regions at the northwest extreme of the San Francisco Estuary and within the Sacramento–San Joaquin Delta. While the contemporary Delta has little of the historic marsh and other wetland habitat present during historical conditions [9], the northwest portion of the Delta is unique due to the presence of extensive freshwater tidal wetlands and adjacent floodplain habitat. The CSC (Figure 1) comprises several largely natural channels including Cache Slough, Lindsey Slough, and Prospect Slough; straight manmade conveyance channels including Shag Slough, Liberty Cut, the Toe Drain and the Sacramento Deep Water Ship Channel; and former agricultural land restored to tidal action, including Liberty Island and Little Holland Tract (Figure 1). Within it are varying habitats including subtidal channels, intertidal mudflat areas, and vegetated marsh. Both the geometry and bathymetry of the CSC continue to evolve due to deliberate tidal restoration and slow deterioration of unmaintained levees.
The CSC has mixed diurnal and semidiurnal tides with a typical greater diurnal range of 1.2 m. The climate is Mediterranean, classified as dry-summer subtropical (Csb) in the Köppen Climate classification. The wet season is typically November through April. During the dry season, the CSC receives low direct freshwater input, while during the wet season, episodic flood events deliver large inflows. Consumptive use by agriculture in neighboring regions results in net landward flow in portions of the CSC. Due to low net flows in dry periods, landward sediment fluxes are noted in this region, dominantly consisting of Sacramento River-associated sediment arriving via Miner Slough [10].

2.2. Isotopic Water Age

The isotopic composition is defined by the ratio of stable isotopes in a water sample. Specifically, $\delta^{2}H$ quantifies the normalized deviation in the ratio of $^{2}H$ (Deuterium) to $^{1}H$ (hydrogen) relative to a standard ratio and, similarly, $\delta^{18}O$ quantifies the normalized deviation in the ratio of $^{18}O$ to $^{16}O$ from a standard ratio. Lighter isotopes are preferentially evaporated, leading to an evaporative signal in $\delta^{2}H$. 

![Figure 1. The bathymetry and names of channels in the Cache Slough Complex. The inset image in the upper left shows the northern portion of the San Francisco Estuary with relevant geographical labels. The location of the estuary in the state of California is shown in the small inset image in the upper left corner.](image-url)
and δ\textsuperscript{18}O used to infer the amount of evaporation undergone by a water sample. In the dataset used in this study [4], δ\textsuperscript{2}H varied by approximately 20%\textsubscript{o}, while δ\textsuperscript{18}O varied by approximately 4%\textsubscript{o}.

The fractional evaporation represents the fraction of water that has evaporated relative to water with a known original isotopic composition. Water age (\(\tau\)) is estimated from a given fractional evaporation (\(\chi\)) as

\[
\tau = \chi \frac{H}{E}
\]

where \(H\) is a representative water depth and \(E\) is a representative evaporation rate. In [4], \(H\) was assumed to be 3 m and \(E\) was calculated as 0.0054 m d\textsuperscript{-1} from a two-month average evaporation rate measured at the Hastings Tract station of the California Irrigation Management Information System [11].

2.3. Hydrodynamic Model

The three-dimensional UnTRIM model engine [12,13] was applied to simulate flow and transport in the CSC. UnTRIM solves the discretized Reynolds-averaged shallow water equations on an unstructured grid. It resolves the relevant physical processes resulting in transport of dissolved constituents such as salt, allows for wetting and drying of computation cells [14], and sub-grid scale representation of bathymetry [13]. Vertical turbulent mixing in the model is parameterized using a \(k-\varepsilon\) closure, which solves one equation for turbulent kinetic energy (\(k\)) and another for turbulent dissipation (\(\varepsilon\)) using published parameter values [15]. Bed friction is parameterized using a quadratic stress formula and bed roughness height, \(z_0\).

The computational mesh and bathymetry for the UnTRIM San Francisco Estuary model are shown in Figure 2. Cell side lengths range from less than 5 m to more than 1000 m, and 1 m layer spacing was used in the vertical. Bathymetry was specified using a digital elevation model of the San Francisco Estuary developed using a large number of bathymetric surveys [16–19]. The model grid was refined substantially in the CSC relative to the grids applied in previous applications [19,20]. The higher resolution in the channels of the CSC allows better representation of tidal and residual velocities.

The simulation period was chosen as 12 May 2014 through 2 October 2014. This allows over four months for Sacramento River water to mix into the CSC prior to comparison to the continuous underway measurement observations collected on 1 October 2014. The model spin-up period is more than twice as long as isotopic water age estimates for the region [4]. Water year 2014 was classified as dry in the Sacramento Valley [21]. The net flows were quite small prior to the data collection with substantial contributions from agricultural withdrawals and return flows (Table 1). River and diversion boundary conditions were prescribed at locations shown in Figure 2 using data obtained from United States Geological Survey [22] and California Department of Water Resources [21] monitoring sites. Local agricultural diversions, return flows, and groundwater seepage (collectively referred to as net channel depletions) were prescribed at 257 locations throughout the Delta, shown in Figure 2, using estimates from [23]. Observed water levels at Point Reyes were used as the offshore boundary condition, and specified offshore salinity was 33.5 psu (practical salinity unit; 1 PSU equals 1%). Spatially variable evaporation, precipitation and wind speed were applied based on observations at several meteorological stations (Figure 2).

Table 1. Average observed flows during September 2014, immediately prior to isotope data collection.

| Flow Category                        | Flow (m\textsuperscript{3}s\textsuperscript{-1}) |
|--------------------------------------|-------------------------------------------------|
| Total Delta inflow                   | 251.29                                          |
| Total Delta exports                  | -100.91                                         |
| Total Delta agricultural withdrawals | 32.84                                           |
| Total Delta agricultural returns     | 23.46                                           |
Figure 2. San Francisco Estuary model extent and bathymetry. Model boundary condition locations are shown for river inflows, diversions, agricultural flows, and hydraulic structures. Station locations used in setting regional wind and evaporation-precipitation model inputs are also shown.

Model output was compared against observed flow, stage, and salinity data collected at continuous monitoring stations throughout the estuary [12] (Figure 3). A model skill metric [24] was computed at each calibration location, as in previous San Francisco Estuary calibration efforts [25]. The skill metric is calculated as

$$Skill = 1 - \frac{\sum_{i=1}^{n}|P_i - O_i|^2}{\sum_{i=1}^{n}(|P_i - \bar{O}| + |O_i - \bar{O}|)^2}$$

where $P$ are the predicted values, $O$ are the observations, $n$ is the total number of observations and $\bar{O}$ is the average of the observations.

We also summarize model performance using target diagrams [26], also used in San Francisco Estuary applications [27]. The predicted longitudinal and vertical salinity structure was compared to monthly observations collected by the USGS on a longitudinal transect from the Golden Gate to Rio Vista [28].
2.4. Predicted Water Age Calculation

In order to estimate mean age of a source of water, the transport of two conservative tracers was simulated in the UnTRIM model [6]. The first tracer is used to tag water entering at the Sacramento River flow boundary condition and is calculated using a three-dimensional advection diffusion equation

$$\frac{\partial C}{\partial t} + \nabla \cdot (u C) = \frac{\partial}{\partial z} \left( K_T \frac{\partial C}{\partial z} \right)$$

(3)

where $C$ is the tracer concentration with dimensions mass per volume, $u$ is a three-dimensional velocity vector with dimensions length per time, and $K_T$ is the vertical eddy diffusivity with dimensions length squared per time. Horizontal eddy diffusion is neglected.
This equation is discretized with a conservative finite volume approach [29]. The discretized equation can be represented as

\[ C^{n+1} = \mathcal{A}(C^n) \]  

where \( \mathcal{A} \) represents a discrete advection-diffusion operator [29].

A second equation is used to represent “age-concentration” [6]. The governing equation of age-concentration can be written in a manner similar to Equation (3)

\[ \frac{\partial \alpha}{\partial t} + \nabla \cdot (u \alpha) = \frac{\partial}{\partial z} \left( K_T \frac{\partial \alpha}{\partial z} \right) + C \]  

where \( \alpha \) is the age-concentration with dimensions time-mass per volume. Its discretized form can be written as

\[ \alpha^{n+1} = \mathcal{A}(\alpha^n) + \Delta t C^n \]  

where \( \Delta t \) is the computational time step [30]. Then the age can be estimated as the ratio of the age-concentration and concentration.

\[ a = \frac{\alpha}{C} \]  

where \( a \) has dimensions of time. In our application, the concentration \( C \) in each cell and time step represents the portion of water at that location that entered the domain as Sacramento River inflow and \( a \) is the mean age of that water. This is referred to as the “mean age” because the age calculated at any cell and any time step represents the algebraic mean of the water parcels of the source water present at that time and location [6]. The initial conditions of the scalar transport equations are zero concentration and age-concentration throughout the domain. The boundary conditions of \( C \) are zero at all boundaries except for the upstream Sacramento River boundary where concentration is 1. The boundary conditions of age-concentration are zero at all boundaries. After concentration \( C \) and age-concentration \( \alpha \) are predicted throughout the domain and simulation period, the mean age \( a \) is then calculated in a post-processing analysis.

### 2.5. Fractional Evaporation Calculation

In order to estimate the mean experience of a water quality property (e.g., depth, light level, or temperature) experienced by the tracer \( C \), a property tracking equation is used in addition to the equations in the age calculation. The property-age-concentration is governed by the equation

\[ \frac{\partial \beta}{\partial t} + \nabla \cdot (u \beta) = \frac{\partial}{\partial z} \left( K_T \frac{\partial \beta}{\partial z} \right) + \psi C \]  

where \( \beta \) is the property-age-concentration and \( \psi \) is the instantaneous value of the property. Its discretized form can be written as

\[ \beta^{n+1} = \mathcal{A}(\beta^n) + \Delta t \psi^n C^n \]  

where \( \Delta t \) is the computational time step. Then the mean property experienced by the tracer can be estimated as the ratio of the property-age-concentration and age-concentration.

\[ b = \frac{\beta}{\alpha} \]  

where \( b \) is the mean property experienced by the tracer. The initial condition of the property-age-concentration transport equation is zero throughout the domain. The boundary conditions of \( \beta \) are zero at all boundaries.

We will use this approach to estimate what has been referred to as the evaporation to inflow (E/I) ratio [4] and we refer to as fractional evaporation, represented by \( \chi \) in Equation (1). This can also be
understood as fractional evaporation from a water source with a specific isotopic composition. In our specific application $\psi$ in Equation (9) represents the fraction of the water column that evaporates in one day. For example, an evaporation rate of $0.01 \text{ m d}^{-1}$ and a water column depth of 1 m, would result in $\psi$ of 0.01. The value of $\psi$ is updated at each time step and water column in the simulation. In our application, $\beta$ in Equation (9) is the daily fractional evaporation-age-concentration with dimensions time-mass per volume. $\beta$ divided by the age-concentration in Equation (10) is an estimate of mean daily fractional evaporation ($b$) that the tracer at a given location has experienced since entering the domain. In order to convert this to a total fractional evaporation we multiply by the age ($a$) from Equation (7). This estimate can be directly compared to the fractional evaporation estimated from isotope data in [4].

The novel approach described by Equations (8)–(10) is analogous to the age calculation approach [6]. Note by inspection of Equations (6) and (9) that if the instantaneous property $\psi$ is constant in time and space then Equation (10) reduces to $b = \psi$. In other words, if the instantaneous property is a constant and uniform value of $\psi$, the mean experience of the tracer ($C$ from Equation (3)) of that property is equivalent to $\psi$. If there is no transport and $\psi(x, y, z, t)$ is variable but $C$ is uniformly 1 everywhere (for example, if the tracer was used to tag water in a lake), then the transport terms in Equations (5) and (8) are zero and Equation (10) is simply the time integrated value of $\psi$ at a given location. Hence, in these simple cases the governing equations (Equations (4)–(10)) produce behavior consistent with an intuitive understanding of the mean experience of a water property by a tracer.

3. Results

3.1. Hydrodynamic Model Calibration

The hydrodynamic model predicted stage, flow and salinity accurately at the majority of stations in the model domain (Table 2). The target diagrams in Figure 3 show less normalized bias and similar normalized unbiased RMSE (unRMSE) in flow and similar normalized bias in water level relative to [31]. However, our results had larger normalized bias in water level with our results tending to underpredict mean water level in the Delta. The tidally-averaged water level is sensitive to the bottom friction parameters chosen. Larger bottom friction decreases bias in water level but increases errors in flow predictions. The salinity target diagram shows larger errors than other applications of the model [25], particularly at the low salinity stations, because the simulation period used here was a dry period of a drought year in which the uncertainty in tributary inflows and agricultural withdrawal and return flows makes salinity prediction challenging. The uncertainty in these flows and in the salinity associated with agricultural return flows makes salinity an imperfect water quality constituent to evaluate model performance in freshwater regions. In contrast to the typically poor salinity predictions in the interior Delta, comparisons to USGS transects in Figure 4 show good prediction of salinity from the Golden Gate to Rio Vista, located in the western Delta. This is consistent with good calibration results achieved with the in other applications, most recently for the two simulation years documented in [32].

Water year 2014 was classified as critically dry in the Sacramento Valley [33]. For this reason, salinity conditions were fairly static during the simulation period with a slow increasing trend (Figure 5). While the spatial pattern of predicted salinity is similar to the observed salinity, largely due to the salinity being set from observed salinity on 13 May, the model predicts more salt intrusion to the Delta than is observed. While this is a small spatial shift as seen in Figure 4, it results in a substantial relative error in salinity in the brackish portion of the estuary. This bias of overprediction of salinity in the northern Delta is more evident by comparison to the USGS continuous underway measurements in the Cache Slough Complex [4] in Figure 6. The mean observed salinity was 0.188 psu while the mean predicted salinity was 0.132 psu, corresponding to a bias of 0.55 psu. However, as seen at Rio Vista in the salinity error in the model that was present outside of the Cache Slough Complex, so the salinity data is of little use to evaluate the representation of transport processes inside the Cache Slough Complex. The correlation coefficient was $-0.06$, indicating that the model also does not capture spatial gradients in salinity which is in part because the estimated flow and salinity associated
with agricultural returns [23] is uncertain. Furthermore, the calculation of salinity from conductivity measurements is uncertain because the mixture of salt ions is different in agricultural return flows and seawater. Partially for these reasons, we turn to the water isotope data [4] to provide a better test of the representation of local dynamics in the Cache Slough Complex.

Figure 4. Observed and predicted salinity transects from the Golden Gate to Rio Vista at all dates available during the simulation period: (A) 10 June 2014, (B) 12 August 2014, and (C) 16 September 2014. The black line indicates model bathymetry along transect.

Figure 5. Observed (solid lines) and predicted (dashed lines) tidally-averaged salinity at four stations along the axis of the northern San Francisco Estuary. Line colors of panel (A) correspond to marker colors of panel (B).
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Figure 6. (A) Observed salinity; (B) predicted salinity; (C) predicted-observed salinity in the Cache Slough Complex during the U.S. Geological Survey (USGS) field study on 1 October 2014.

Table 2. Model performance metrics averaged across all continuous monitoring stations.

| Parameter   | $R^2$ | Skill |
|-------------|-------|-------|
| Water level | 0.990 | 0.969 |
| Flow        | 0.969 | 0.985 |
| Salinity    | 0.690 | 0.724 |

3.2. Sacramento River Water Age

The depth-averaged predicted Sacramento River water age has been calculated at the time and location of each isotopic age estimate. The predicted Sacramento River water age is zero where the tracer enters the model boundary at Verona. In contrast, the isotopic water age is relative to the specific isotopic composition at an origin point in Miner Slough, where isotopic water age is correspondingly defined as zero. The predicted water age in Miner Slough is 4.2 days at the origin of isotopic age. In order to allow direct comparison of predicted age and isotopic age, this offset is subtracted from the predicted age (Figure 7). For clarity, when observations were available from both the initial transect and return trip in a channel, only the initial transect data is shown. The distribution of predicted age is similar to the isotopic age. The most notable differences are lower predicted age in the Stairstep channel and higher predicted age in Liberty Cut. There is a bias toward overprediction of age (Figure 8) of 0.7 days and a standard error of 6.9 days.

The predicted water age is the mean age of Sacramento River water tracer that entered the domain during the simulation period. The simulation does not provide information regarding the age of water in the domain at the beginning or before the simulation period. The water in the model domain at any point in time is a mixture of water that was present at the beginning of the simulation which has unknown age and provenance and water that entered during the simulation via the Sacramento River that has an estimated age. Other sources of inflow during this period are small. Figure 8b shows that the Sacramento River water tracer has spread through the study area to become the dominant source of water everywhere except in the Toe Drain.
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3.3. Sacramento River Water Fractional Evaporation

The depth-averaged predicted Sacramento River fractional evaporation has been calculated at each time and locations of isotope data ("isotopic fractional evaporation"). The minimum reported isotopic fractional evaporation is 0.034 in Miner Slough. The model fractional evaporation values are offset to be identical at that one point, which requires subtracting 0.029 from each predicted fractional evaporation value in order to compare directly to the observations. The distribution of predicted fractional evaporation is similar to the isotopic fractional evaporation. The overall bias in fractional evaporation is an overprediction of 0.005 and the standard error is 0.020. Additional performance metrics for comparisons to underway measurement data for salinity and isotopic water age and fractional evaporation estimates are given in Table 3.

The most notable difference in Figure 9 and Figure 10 is higher predicted fractional evaporation in the Toe Drain. Figure 8 indicates that the Sacramento River water tracer has not fully spread through the Toe Drain during the simulation period indicating that both the age and fractional evaporation of the total water mass in that channel cannot be predicted accurately by the model. For example, in parts of the Toe Drain, only 10% of the water in the model derives from Sacramento River water that entered the domain during the simulation. While we can estimate the age and fractional evaporation...
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Table 3. Model performance metrics in comparisons to underway measurements.

| Parameter              | R²       | Skill |
|------------------------|----------|-------|
| Salinity               | 0.00397  | -3.330|
| Water Age              | 0.867    | 0.841 |
| Fractional Evaporation | 0.684    | 0.559 |

The most notable difference in Figures 9 and 10 is higher predicted fractional evaporation in the Toe Drain. Figure 8 indicates that the Sacramento River water tracer has not fully spread through the Toe Drain during the simulation period indicating that both the age and fractional evaporation of the total water mass in that channel cannot be predicted accurately by the model. For example, in parts of the Toe Drain, only 10% of the water in the model derives from Sacramento River water that entered the domain during the simulation. While we can estimate the age and fractional evaporation of the 10% of the water at that location that entered the domain as Sacramento River water, we cannot estimate the age or fractional evaporation of the other 90% of the water volume at that location. Therefore, isotopic and predicted fractional evaporation are not expected to match closely in much of the Toe Drain. Through the Toe Drain and nearby regions, the flow direction and magnitude depend strongly on small but uncertain agricultural diversion and return flows during the study period.

Figure 9. (A) Fractional evaporation estimated from stable isotope observations; (B) predicted fractional evaporation of Sacramento River water; (C) predicted minus isotopic fractional evaporation.
3.4. Evaluation of Assumptions in Age Estimates

The water isotope-based age estimate approach \[4\] requires specification of a representative depth and evaporation rate. A fixed depth of 3 m was assumed and a two-month average of an observed evaporation rates \(0.0054 \text{ m d}^{-1}\) was applied. These assumptions can be examined. The predicted daily evaporation rate is calculated as a moving average over the period of the predicted age preceding the field study. For example, if a point in Cache Slough has a predicted age of 10 days at the time of the field study on 1 October 2014, the observed evaporation rate would be the average from 22 September 2014 through 1 October 2014 to estimate the average evaporation rate experienced by that water parcel since entering the study area at Miner Slough. The averaged evaporation over the period associated with the age at each point is shown in Figure 11A. The bias in assumed evaporation rate was \(-0.00059 \text{ m d}^{-1}\) and the standard error was \(0.00048 \text{ m d}^{-1}\). The evaporation rate over the period corresponding to age was smaller than the assumed evaporation rate at most locations.

The representative depth (Figure 11B) is estimated from Equation (1), reorganized to solve for \(H\), the water depth that the water parcel at that location has experienced over the period corresponding to the water age, which we have referred to as “representative depth”. This representative depth uses the tracer-based predictions of age in Figure 7B, fractional evaporation shown in Figure 8B and the evaporation rate shown in Figure 11A. The average predicted representative depth is 2.99 m in close agreement to the assumption of 3 m in \[4\]. However, as expected, the predicted representative depth is larger than 3 m in the deep portions of the model domain including the Sacramento Deep Water Ship Channel and shallower than 3 m in the Stairstep region and the Toe Drain because the local depths are different than 3 m and the water in those regions has relatively high age, thus has experienced the local depths for a substantial amount of time.

**Figure 10.** Relationship between predicted and isotopic fractional evaporation at the time and location of continuous underway measurements.
predictions in the CSC may be inaccurate even if local mixing processes are represented accurately by the model. Therefore, the isotopic water age estimates [4] provide a unique opportunity to evaluate the ability of a hydrodynamic model to represent tidal mixing processes in the CSC. The results presented here suggest that the hydrodynamic model represents these mixing processes well.

Furthermore, errors in oceanic salt intrusion can accumulate far from the region of interest. For example, if estuarine circulation processes are not well represented at any point between the ocean and the CSC, salinity predictions in the CSC may be inaccurate even if local mixing processes are represented accurately by the model. Therefore, the isotopic water age estimates [4] provide a unique opportunity to evaluate the ability of a hydrodynamic model to represent tidal mixing processes in the CSC. The results presented here suggest that the hydrodynamic model represents these mixing processes well. The significant error in the Stairstep Channel and Liberty Cut may be occurring due to inaccurate prediction of tidal residual flows or uncertainty in agricultural withdrawal and return flows. Ongoing observational and modeling studies in the CSC may provide further insight.

Figure 6 indicates that observed salinity from the continuous underway measurements [4] is typically lower than hydrodynamic model predicted salinity. However, the substantial overestimate of salinity at the seaward end of the domain suggests that the errors in predicted salinity may be largely due to errors outside the study area, leading to too much salt intrusion into the Sacramento River and Cache Slough. Estimating salt intrusion in these dry summer conditions in the San Francisco Estuary is generally difficult because uncertain agricultural diversions are roughly as large as net inflows to the Delta leading to small and uncertain net Delta outflow as well as uncertainty in the distribution of flows throughout the Delta [34]. In contrast the age analysis indicates the extent to which landward

4. Discussion

The Cache Slough Complex is an ecologically important region that receives little direct freshwater inflow during summer and fall. Most of the water in the CSC in that period arrives from the Sacramento River and has mixed landward from the confluence of Miner Slough, Cache Slough and the Sacramento River. Therefore, water age is almost entirely dependent on tidal mixing processes in this region. Furthermore, model calibration using salinity data is difficult in the CSC because it is influenced by agricultural withdrawals and return flows. Uncertainty in these agricultural flows and the salinity associated with agricultural return flows is large [22]. For this reason, any calibration errors in salinity in that region likely derive from errors in boundary conditions in the hydrodynamic model. Furthermore, errors in oceanic salt intrusion can accumulate far from the region of interest. For example, if estuarine circulation processes are not well represented at any point between the ocean and the CSC, salinity predictions in the CSC may be inaccurate even if local mixing processes are represented accurately by the model. Therefore, the isotopic water age estimates [4] provide a unique opportunity to evaluate the ability of a hydrodynamic model to represent tidal mixing processes in the CSC. The results presented here suggest that the hydrodynamic model represents these mixing processes well. The significant error in the Stairstep Channel and Liberty Cut may be occurring due to inaccurate prediction of tidal residual flows or uncertainty in agricultural withdrawal and return flows. Ongoing observational and modeling studies in the CSC may provide further insight.

Figure 11. (A) Evaporation rate estimated using predicted age, with assumed evaporation rate of 0.00054 m d\(^{-1}\) shown with a black line in the colorbar. (B) Predicted representative depth estimated from predicted fractional evaporation, evaporation rate and predicted age, with the assumed depth of 3 m shown with a black line in the colorbar.
transport of water entering the CSC from Miner Slough are represented by the model, thus is less
sensitive to errors in flow in other parts of the model domain.

While the isotope-based age estimates require assumptions of a representative water depth,
evaporation rate, the fractional evaporation (E/I) can be estimated directly from the isotope data with
no additional assumptions. The reduced number of assumptions in the fractional evaporation data
allows a more confident evaluation of model performance. In order to predict fractional evaporation
from tracer results a novel approach was suggested as an extension of the tracer based mean water age
approach of [6]. The predicted fractional evaporation generally matched the observations well but
was less accurate in the portions of the CSC furthest landward. The circulation in these regions and
isotopic composition may be substantially influenced by small agricultural diversion and return flows.

It should be noted that the field-based isotopic method also has significant potential sources
of uncertainty. The isotopic ratio of agricultural return flows is uncertain and may contribute to
differences between isotopic and predicted fractional evaporation.

The work here emphasizes that the term “water residence time” as used in [4] is consistent with
the definition of “mean water age” as defined in [6]. Furthermore, the model results confirm that the
dominant water source in the CSC is the Sacramento River. Therefore, a single end-member of isotopic
composition for the water source, as assumed in [4] is appropriate. However, this assumption may be
less accurate in some of the landward reaches of the CSC due to agricultural return flows of different
isotopic composition.

The evaporation rate over the period associated with predicted water age is typically smaller than
the two-month average evaporation rate used in [4]. This is because predicted age was lower than
2 months in most of the domain and observed evaporation at Hastings Tract was lower prior to the
field data collection on October 1, 2014 than it was in August and September.

With the predicted evaporation shown in Figure 11, the model predictions include all variables in
Equation (1), except for the depth. Therefore, the depth that is consistent with the predicted factional
evaporation and age estimates can be calculated from Equation (1). This depth estimate is typically
larger than the assumed depth of 3 m [4] in deep regions such as the Sacramento Deep Water Ship
Channel and lower in shallow regions like the Toe Drain. Note that the equivalent depth of evaporation
increases with distance up the Sacramento Deep Water Ship Channel not because of local depth changes
but because the fraction of evaporation that has occurred within the Sacramento River Deep Water
Ship Channel increases with landward distance.

5. Conclusions

Our comparison demonstrates that the isotope-based water age approach in [4] is useful for
validating model-based transport time scale estimates. The water isotope-based approach is useful
for estimating transport time scales in regions with a clearly defined source of water and substantial
fractional evaporation over relevant time scales of transport. The information from isotopic composition
of the water is more useful than salinity data for evaluation of representation of transport processes
in these far landward reaches of the estuary because it is less sensitive to representation of mixing
processes seaward of the study area. Similarly, in freshwater regions with negligible salinity and
salinity gradients, age remains a practical diagnostic of transport. Finally, this validation of the
model-predicted age of source water suggests the approach can be used to relate age of source water
and associated biogeochemical constituents with local observed concentrations of those constituents
to estimate biogeochemical rates to extend the estimates in [4] over broader spatial and temporal scales.

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