THREE-DIMENSIONAL HYDRODYNAMIC MODELING OF THE SAN FRANCISCO ESTUARY ON AN UNSTRUCTURED GRID

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ABSTRACT

Three-dimensional simulations of circulation in the San Francisco Estuary were performed with the three-dimensional unstructured grid hydrodynamic model UnTRIM. The model was developed to support the Delta Risk Management Strategy (DRMS) funded by the California Department of Water Resources. The model applications build on previous TRIM and UnTRIM applications. A model grid consisting of quadrilaterals and triangles was developed that extends from the Pacific Ocean through San Francisco Bay and further into the Sacramento-San Joaquin Delta than previous TRIM and UnTRIM applications. In addition, a state-of-the-art turbulence closure was incorporated into the UnTRIM model from the TRIM model. This paper describes a portion of the hydrodynamic and salinity calibration of the resulting San Francisco Estuary UnTRIM model.

Keywords: three-dimensional, unstructured grid, estuary, salinity, UnTRIM, San Francisco Bay, Sacramento-San Joaquin Delta, turbulence closure, generic length scale, calibration

1 INTRODUCTION

The Sacramento-San Joaquin Delta is a critical resource to the state of California because the Delta is a source of drinking water for roughly 2 out of 3 Californians. However, the 2,800 km^2 of islands in the Delta region are at risk of inundation from levee failures. These deeply subsided islands are protected by levees typically 4 to 5 meters high which are, in most cases, not engineered levees and are constructed partially with peat and other weak and compressible soils. The Delta Risk Management Study has been funded by the California Department of Water Resources (DWR) to “look at sustainability of the Delta, and … assess major risks to the Delta resources from floods, seepage, subsidence, and earthquakes.” Part of this effort involves the application of hydrodynamic models to estimate the effect of levee failures on salinity in the Delta. Levee failures in the Delta generally result in increased salinity as islands flood and brackish water from Suisun Bay is entrained into the Delta. Increased salinity can result in exceedence of water quality objectives for drinking water causing interruption of water exports, resulting in a large economic impact.

Several hydrodynamic and water quality simulation tools are applied in the DRMS project, ranging from a tidally-averaged advection-dispersion model, which can perform a year of salinity projections in 1 minute of computation time, to the sophisticated and computationally intensive three-dimensional model described here. The first phase of the DRMS work involves quantification of risk and consequences of Delta levee failures while the second phase will evaluate risk reduction actions that can be taken to reduce risks of levee failures and the impacts of levee failures.

2 METHODS

The primary tool used in this study was the three-dimensional hydrodynamic model UnTRIM (Casulli and Zanolli, 2002). The governing equations, numerical discretization, and numerical properties of UnTRIM are described in Casulli and Zanolli (2002, 2005), Casulli (1999), and Casulli and Walters (2000). The UnTRIM model solves the three-dimensional Reynolds-averaged Navier-Stokes (RANS) equations on an unstructured grid in the horizontal plane. The boundaries between vertical layers are at fixed elevations, and cell heights can be varied vertically to provide increased resolution near the surface or other vertical locations. Volume conservation is satisfied by a volume integration of the incompressible continuity equation, and the free-surface is calculated by integrating the continuity equation over the depth and using a kinematic condition at the free-surface, as described in Casulli (1990). The governing equations are discretized using a finite difference – finite volume algorithm. The numerical method allows full wetting and drying of cells in the vertical and horizontal directions. All details and numerical properties of this state-of-the-art three-dimensional model are well-documented in peer reviewed literature (Casulli and Zanolli, 2002; 2005).

The TRIM3D model (Casulli and Cheng, 1992) and UnTRIM model have been applied previously to San Francisco Bay (Cheng and Casulli, 2002; MacWilliams and Cheng, 2007). The TRIM3D model (Casulli and Cattani, 1994), which follows a similar numerical approach on structured horizontal grids, has been widely applied in San Francisco Bay (e.g., Cheng et al. 1993; Cheng and Casulli, 1996; Gross et al., 1999; Gross et al., 2006), and a 2D version, TRIM2D, is used in San Francisco Bay Physical Oceanographic Real-Time System, SFPORTS (Cheng and Smith, 1998). Thus, the UnTRIM numerical approach has been well-tested in the San Francisco Estuary.

The turbulence closure model used in these simulations is the generic length-scale (GLS) closure, with parameters chosen to yield the *gen* closure proposed by Umlauf and Burchard (2003). The Kantha and Clayson quasi-equilibrium stability functions (Kantha and Clayson 1994) are used. All parameter values used are identical to those used by Gross et al. (2006), except for the minimum vertical eddy diffusivity and eddy viscosity, which are both 5×10^{-5} m^2/s.

2.1 MODEL SETUP AND INPUT

The model domain for the San Francisco Estuary simulations includes San Francisco Bay, San Pablo Bay, Suisun Bay, the western and central portions of the Sacramento-San Joaquin Delta, and a portion of the Pacific Ocean extending to approximately 22 km west of the Golden Gate (Figure 1). The ocean portion of the model domain uses a simplified geometry, and unresolved portions of the Sacramento-San Joaquin Delta are approximated using rectangular “false delta” areas sized to produce the appropriate tidal prism of the unresolved areas following the approach of Gross et al. (2006). An unstructured grid for the model domain was developed using the grid generator JANET (Lippert and Sellerhoff, 2007). The grid was developed such that the main channels of the estuary are discretized using “orthogonal curvilinear” quadrilaterals which are aligned with the principal flow directions, while the remainder of the mesh is constructed using a mixture of triangles and quadrilaterals (Figure 1). The grid resolution varies as necessary to resolve bathymetric variability. Grid cell side lengths are approximately 400 m at the Golden Gate and in the Central Bay and become gradually smaller eastward, with resolution of 50 to 75 m in the western and central Delta (Figure 1). This approach takes advantage of the full flexibility of unstructured grids, and offers significant advantages both in terms of numerical efficiency and accuracy.

The primary bathymetry data source for the model grid of South San Francisco Bay, Central Bay, and San Pablo Bay was NOAA DEM (Digital Elevation Model) data. The DEM data were generated by NOAA using NOS soundings and other bathymetry data collected in

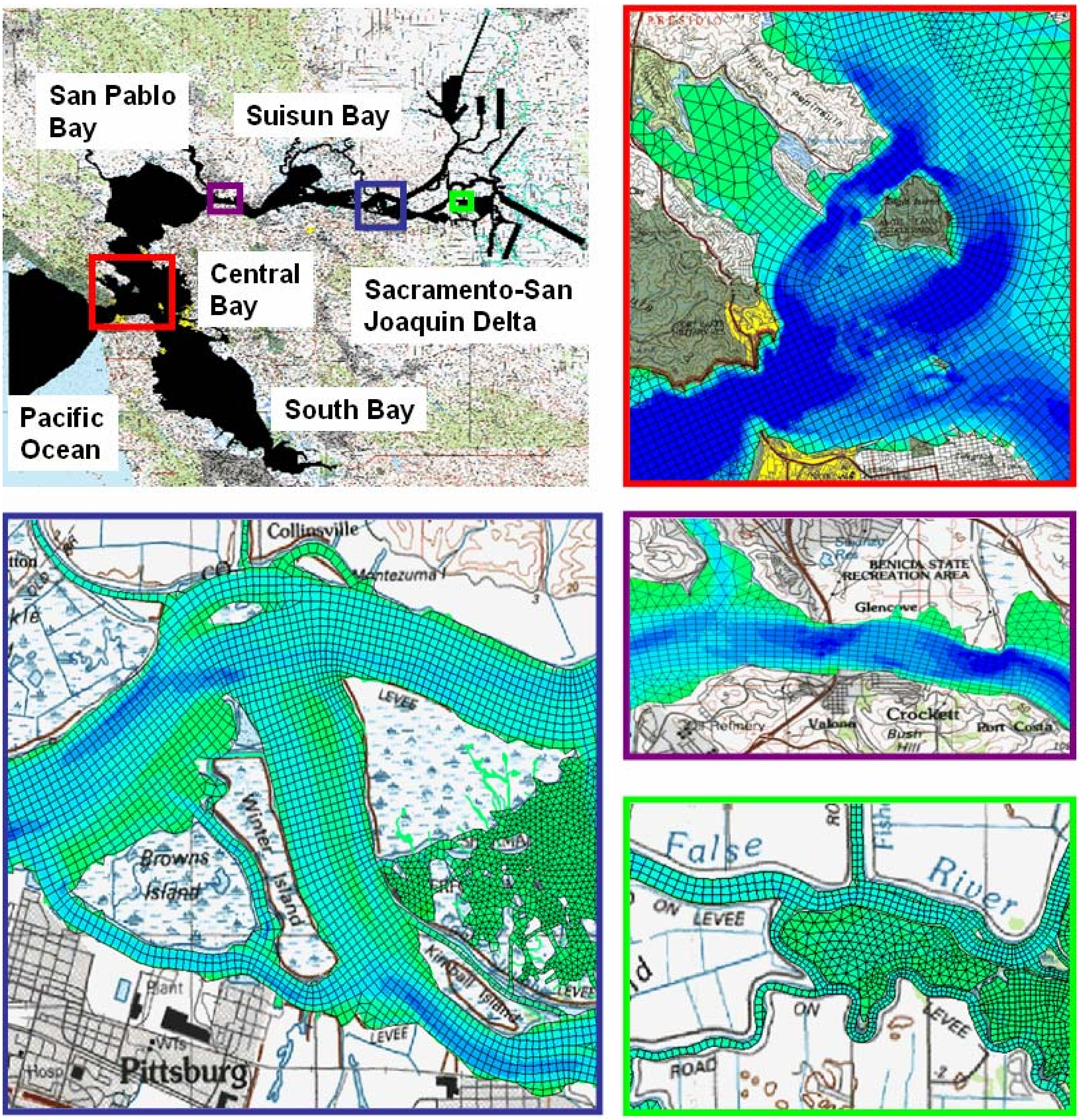

Figure 1. San Francisco Estuary model domain (top left), showing selected portions of the model grid in the Central Bay (top right), Carquinez Strait (middle right), and Sacramento-San Joaquin Delta (bottom left and bottom right).

San Francisco Bay. Coastal ocean bathymetry was also derived from NOAA NOS sounding data. In Suisun Bay and the Sacramento-San Joaquin Delta the model bathymetry was developed using the USGS 10 m horizontal resolution bathymetric grid based on nearly one million depth soundings augmented by contours and aerial photography (Smith et al., 2003). The resulting model bathymetry is shown on Figure 2.

Observations of water surface elevation at Fort Point, near the southern end of the Golden Gate, were used to drive the tidal (ocean) boundary of the model domain. These observations were multiplied amplification factor of 0.9544 to account for the difference in tidal range between observed Fort Point tides and tides along the model boundary, and a phase lead of 30 minutes was applied to account for the phase difference between Fort Point and the model boundary, following the approach used by Gross et al. (2006). The salinity at

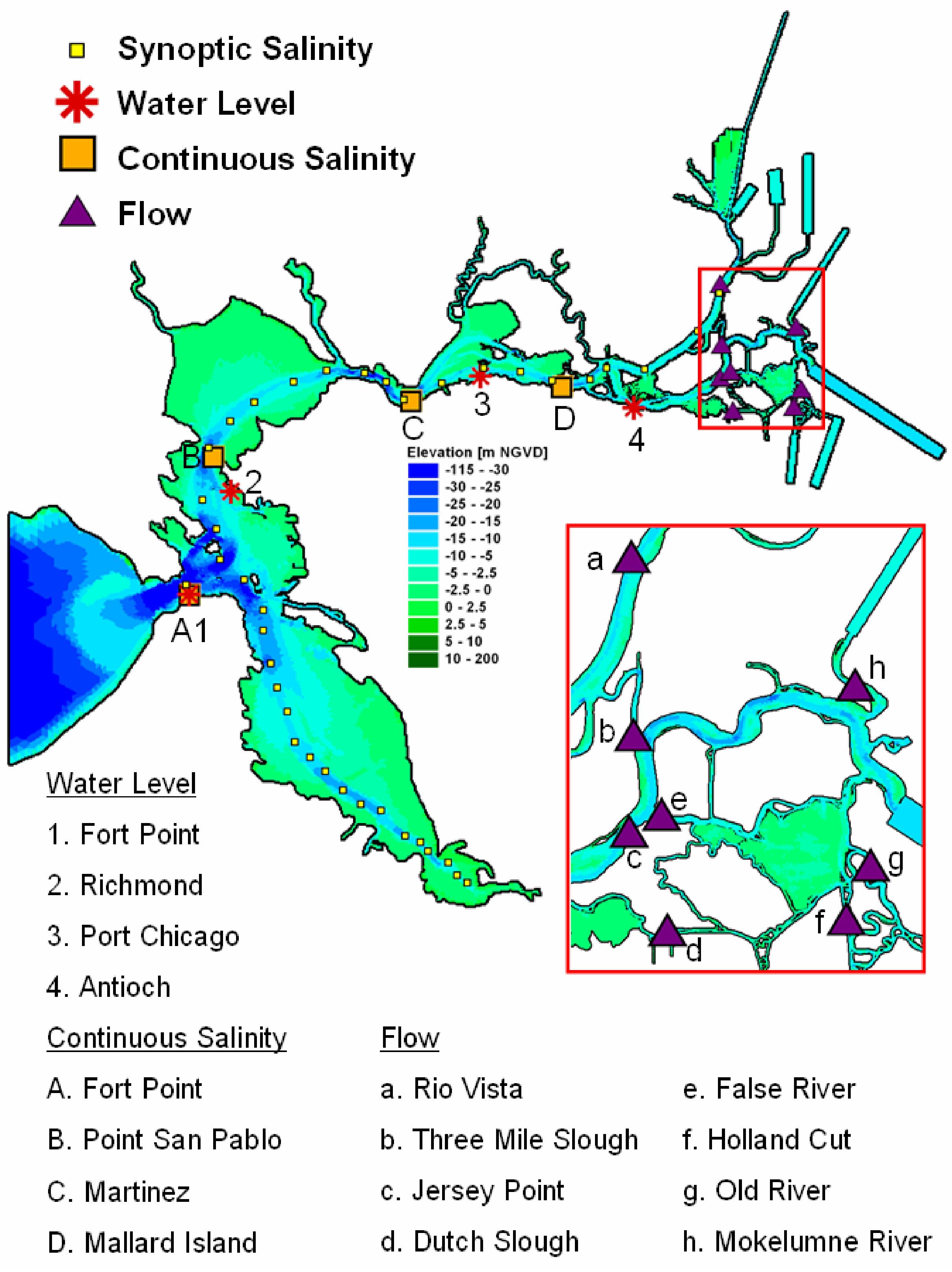

Figure 2. The San Francisco Estuary UnTRIM model domain, model bathymetry and locations of observations used in model calibration.

the ocean boundary is assumed to be 33.5 psu, which is a typical of observed salinity in the coastal ocean near San Francisco Bay (Dever and Lentz, 1994).

At most of the landward boundaries of the Delta in the UnTRIM model, flow boundary conditions were applied to account for the primary freshwater inflows to the San Francisco Estuary. Daily-averaged flows are estimated at several locations in the Delta by the "DAYFLOW" program (CDWR, 1986). The flows are estimated using a volume balance approach incorporating the principal Delta stream inflows, Delta precipitation, Delta exports, and Delta gross channel depletions (CDWR, 1986). During the periods simulated in 2002, typical summer inflows into the northern portion of the Delta are on the order of 400 to 500 m^3/s while there is a net export on the order of 100 to 300 m^3/s from the southern portion of the Delta. The estimates of flows produced by the "DAYFLOW" program contain substantial uncertainty, particularly during low Delta flow conditions, because several terms in the water balance are quite uncertain. Flow monitoring data collected since 1997 (Oltmann, 1998) suggests that the actual daily-averaged Delta outflows can be very different from the "DAYFLOW" values. In addition to the Delta flows, freshwater inflow from several rivers, creeks and water pollution control plants (WPCPs) are included in the simulations. The additional flows considered in the simulations are Napa River, Petaluma River, Alameda Creek, Guadalupe River, Coyote Creek, and flows from the San Jose/Santa Clara WPCP. Local sources of salt, such as agricultural return flows are not accounted for by the model.

Wind forcing was applied at the water surface as a wind stress. Hourly wind speed and direction observations from the Bay Area Air Quality Control District were used from three locations to account for spatial variability in wind velocities. The wind drag coefficient is varied based on local wind speed according to the formulation of Large and Pond (1981).

Daily evaporation and precipitation data collected by the California Irrigation Management Information System at 3 stations bordering the San Francisco Estuary were used to specify spatially variable evaporation and precipitation.

3 MODEL RESULTS

The San Francisco Estuary UnTRIM model described above was first applied to a hydrodynamic calibration period in 2002 when a large number of flow observations were available in the Delta (Figure 2). Then the model was applied during a period in 1994 when a large salinity and hydrodynamic dataset was available in Suisun Bay and the western Delta (Burau et al., 1998).

3.1 HYDRODYNAMIC CALIBRATION

The hydrodynamic calibration period spans from May 7, 2002 through the end of July 2002. Salinity initial conditions for the 2002 simulation were specified based upon a dataset collected by the USGS at the synoptic monitoring stations (Figure 2) on May 7, 2002. This period was selected due to the availability of a large number of flow and stage observations in the Sacramento-San Joaquin Delta. Water level calibration was conducted at continuous NOAA observation stations throughout the San Francisco Estuary. The observed and predicted water levels at four locations along the northern axis of San Francisco Bay are shown in Figure 3. At Fort Point (Figure 3a), the observed and predicted water levels are nearly identical, indicating that the applied offset and amplification at the simplified ocean boundary is accurately propagating tides into the estuary. A similar level of agreement is achieved at Richmond (Figure 3b), Port Chicago (Figure 3c), and at Antioch (Figure 3d), demonstrating that the model is accurately propagating tides along the axis of the estuary.

During the calibration period an extensive USGS monitoring program collected data on flow and stage at a large number of temporary stations in the Sacramento-San Joaquin Delta. Additional data were available at a smaller number of permanent DWR stations. Predicted

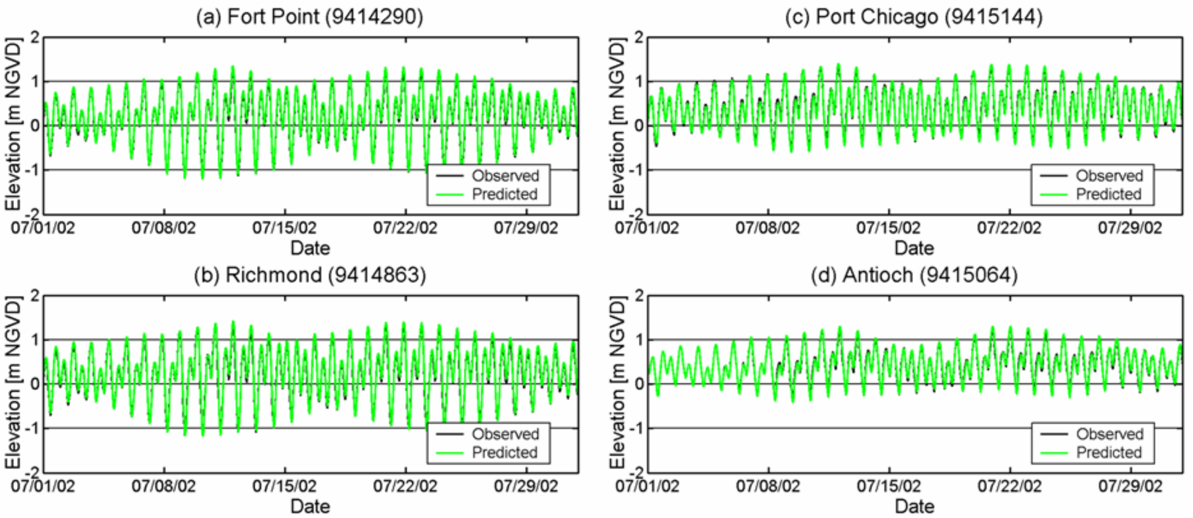

Figure 3. Observed and predicted water level during the hydrodynamic calibration period at (a) Fort Point, (b) Richmond, (c) Port Chicago, and (d) Antioch.

flow at each of these locations was compared with the observed flow to fine-tune the model calibration in the Delta portion of the domain. This calibration involved adjusting the size of the "false delta" geometries to accurately represent the prism of unresolved portions of the Delta, and adjusting the distribution of net flow export between the southern channels of the Delta. In addition, it was found that applying daily-averaged export flows did not produce satisfactory agreement with the phase of observed flows and, subsequently, time varying exports were used to account for operation of gates and pumps and produced noticeably better agreement with observed flows.

The observed and predicted flows at eight stations in the Sacramento San Joaquin-Delta for a two-week period in July 2002 are shown in Figure 4. At Rio Vista on the Sacramento River (Figure 4a), the observed and predicted flows show good agreement, with typical peak flood discharges ranging from 3000 to 4000 m^3/s and typical peak ebb discharges ranging from 2500 to 3000 m^3/s. At Three Mile Slough (Figure 4b), observed and predicted peak flows are typically 500 to 1000 m^3/s with the model predicting slightly larger negative (south) flows. Observed and predicted flows at Jersey Point (Figure 4c) and Dutch Slough (Figure 4d) show very good agreement, with typical observed and predicted peak flows of 4000 and 250 m^3/s, respectively. Observed and predicted flows at False River (Figure 4e) show good agreement, with typical peak flows of 1500 m^3/s. The agreement between observed and predicted flows at these five stations demonstrate that the magnitude and distribution of flow into and out of the western portion of the Sacramento-San Joaquin Delta is being accurately predicted by the model. The observation stations at Holland Cut (Figure 4f) and Old River (Figure 4g) are located near the southern extent of the resolved Delta in the model. The agreement between observed and predicted discharges at these stations demonstrate that the rectangular "false delta" geometries applied on the southern end of the domain are accurately representing the tidal prism of the unresolved portions of the Delta, and that the model is accurately predicting the net export of water from the Delta at these stations. At both of these stations the net peak flows south (negative) exceed the peak positive flows as a result of water exports. Observed and predicted flows on the Mokelumne River (Figure 4h) also show good agreement, with strongly positive net observed and predicted outflows, as a result of significant flow diversions from the Sacramento River into the Mokelumne River.

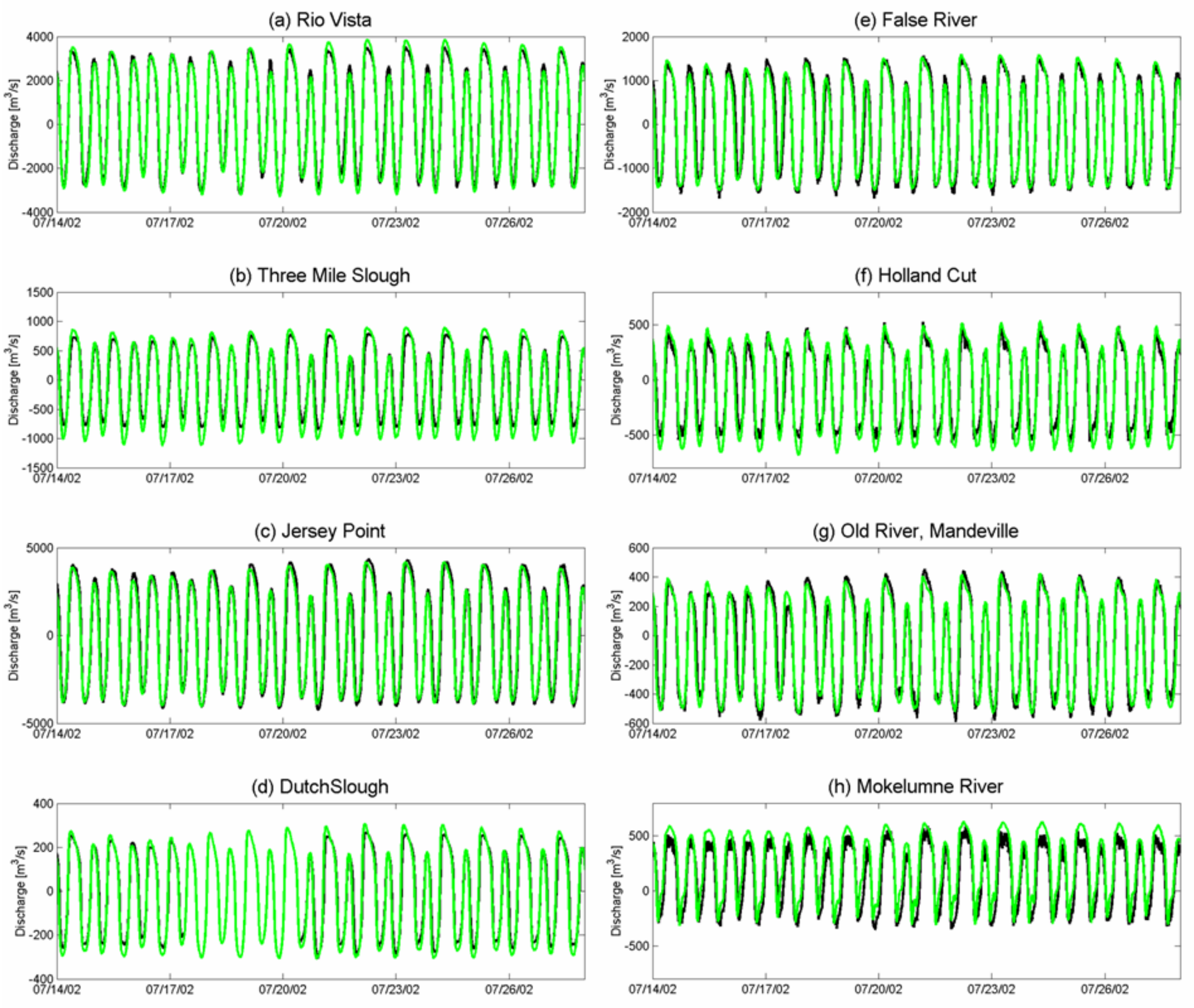

Figure 4. Observed and predicted flow at eight discharge monitoring stations in the Sacramento-San Joaquin Delta.

3.2 SALINITY SIMULATION

Salinity initial conditions for the 1994 simulation period were specified based on United States Geological Survey (USGS) synoptic salinity observations collected on January 18, 1994 (Edmunds et al., 1995). The dataset available on this date consists of vertical profiles of salinity at 1 meter vertical resolution at 38 sampling locations along the axis of San Francisco Bay, shown on Figure 2. Because the dataset does not provide information on lateral variability of salinity, the initial salinity is assumed to be laterally uniform.

The salinity simulation used the same model grid, bathymetry and model parameters as the hydrodynamic calibration. The simulation extended from January 17th 1994 to April 1st 1995, and the first month is considered the spin-up period to minimize the effect of errors in specification of the salinity initial conditions, such as the assumption of laterally uniform salinity. This simulation period was chosen because 1994 was a relatively dry year during which exceedence of water quality objectives for salinity limited water exports. In contrast 1995 was a relatively wet year, so the simulation period spans a large range of Delta outflow.

The predicted salinity was compared to the synoptic salinity observations made by the USGS along the axis of the estuary (Edmunds et al., 1995), at station locations shown in Figure 2, at roughly a monthly interval. Observations and predictions for three cruises

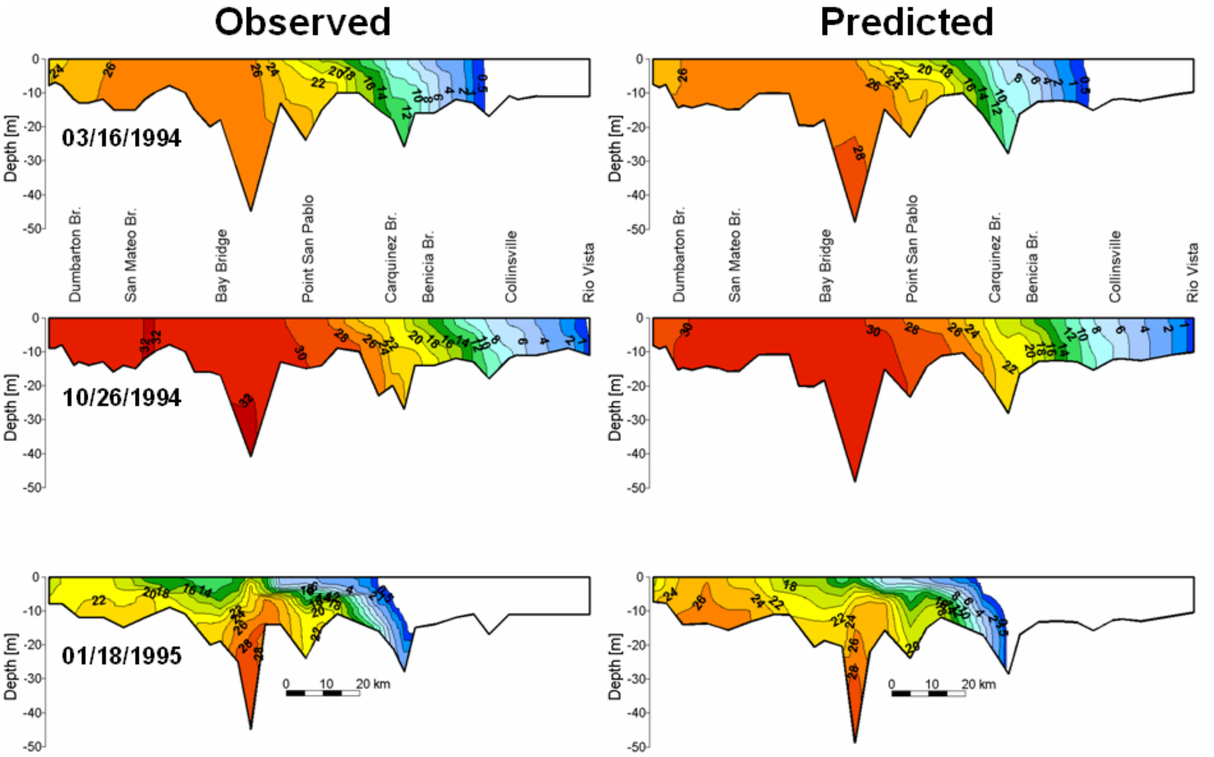

Figure 5. Observed and predicted salinity along the axis of the San Francisco Estuary for 3 data cruises during the 1994 simulation period.

covering the entire estuary during the simulation period are shown in Figure 5. Error measures for all "whole bay" cruises during the simulation period are reported in Table 1. Both the longitudinal and vertical distribution are predicted well by the model, with the predicted salinity typically within 1 psu of the observed salinity. The most notable and persistent errors in salinity prediction occur in South San Francisco Bay, and were expected because flows from several small tributaries in that embayment are not accounted for in the simulation.

In Figure 6, the predicted salinity is compared with observed salinity (Buchanan et al., 1996) at 4 locations shown in Figure 2. These stations span most of the northern portion of the model domain, from Fort Point in Central Bay, to Point San Pablo in San Pablo Bay, Martinez in Carquinez Strait and Mallard Island at the eastern end of Suisun Bay. The salinity observations are near bottom salinity at 3 stations and near surface salinity at the Martinez station, where near bottom salinity data were not available during the simulation period.

Table 1. Average error and standard error for each synoptic sampling cruise covering the axis of the San Francisco Estuary.

Date	Average Error (psu)	Standard Error (psu)
3/16/1994	-0.24	0.49
4/19/1994	0.18	0.33
5/17/1994	-0.37	0.37
6/15/1994	-0.76	0.80
7/28/1994	-0.26	0.73
8/30/1994	-0.74	0.93
9/27/1994	-0.54	0.75
10/26/1994	-0.45	0.98
11/29/1994	-0.35	0.35
1/18/1995	1.03	1.68
2/07/1995	2.49	2.54

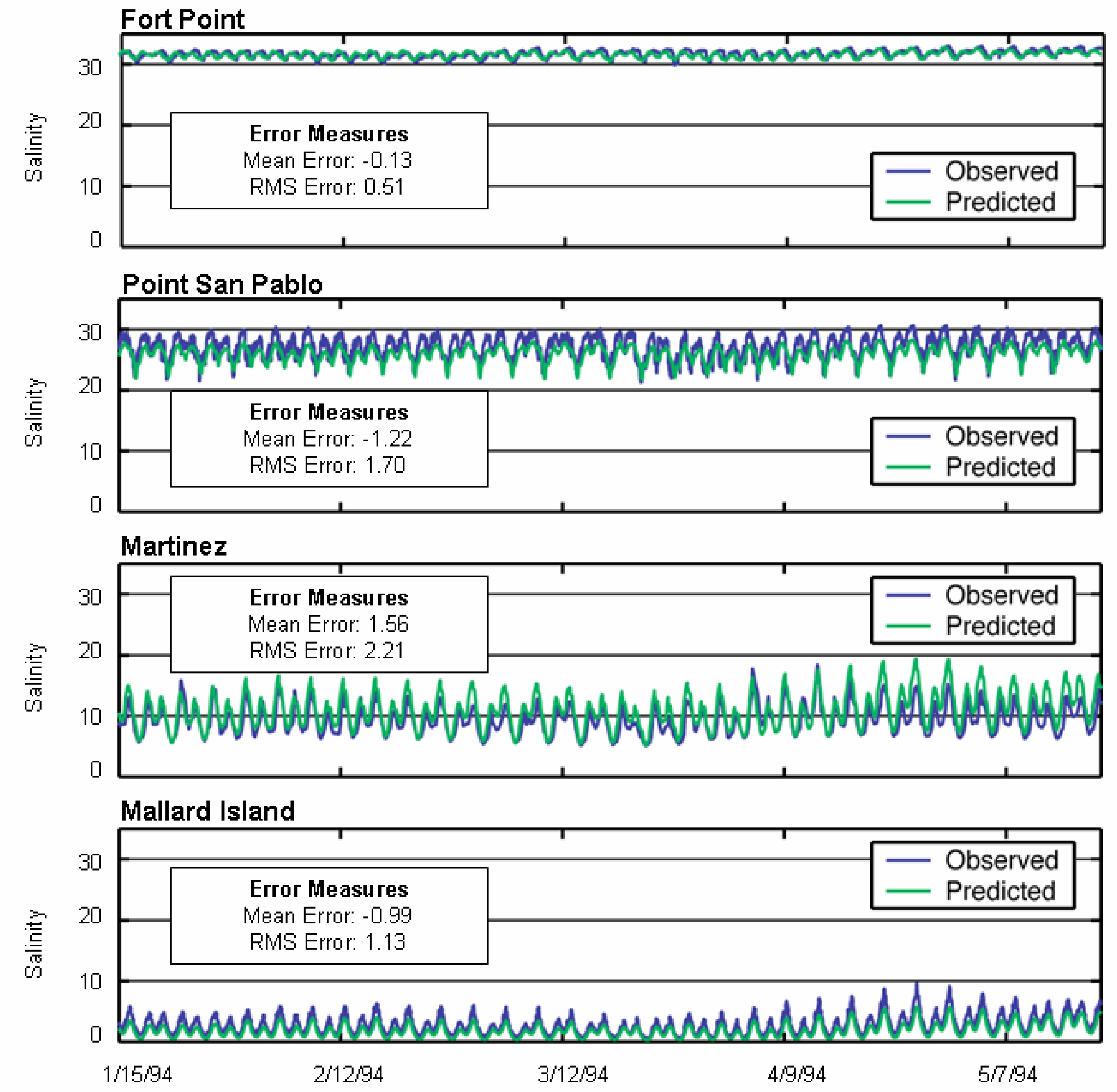

Figure 6. Observed and predicted salinity at 4 locations in the San Francisco Estuary during the 1994 simulation period.

The salinity is predicted well at all stations though the model tends to under predict salinity significantly at Mallard Island. The period chosen for the comparison is based upon availability of observations. The model accuracy is typically higher during early spring at stations where observations are available and decreases towards summer. This trend may result from substantial uncertainties in Delta Island Consumptive Use (DICU) by farms in the Delta during summer.

4 CONCLUSIONS

The UnTRIM model has been successfully calibrated to reproduce observed tides, flows and salinity in the San Francisco Estuary. This three-dimensional unstructured grid model with over 600,000 active grid cells runs on a standard PC at roughly 10 times faster than real time. The good quality of the calibration depended largely on the development of an adequately resolved unstructured grid that meets orthogonality criteria and other numerical constraints, the incorporation of a sophisticated turbulence model, and proper representation of Delta inflows and exports.

The UnTRIM model applications have already proven useful in understanding the role of stratification and baroclinic circulation in salt transport for historic conditions, levee failure scenarios and sea level rise scenarios. In addition, results from the model applications have been analyzed to develop parameterizations of dispersion that are used in a one-dimensional tidally-averaged model which can simulate a decade of salinity conditions in 1 minute of computational time. The simplified model is being applied in the risk-based framework to evaluate the consequences of thousands of Delta levee failure scenarios. In the next phase of the DRMS work the UnTRIM model and other hydrodynamic models will be applied to additional scenarios to evaluate measures to reduce the risks and consequences of levee failures.

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