Literature Review of EFDC Applications Demonstrating Capability for Use in the Jacksonville Harbor Feasibility Study

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Background

The USACE Jacksonville District (SAJ) requested that a DOTS study be performed by ERDC-EL to determine the following information.

1. How accurately does the Environmental Fluid Dynamics Code (EFDC) model predict changes in a water body due to a deepening project? This would require post-construction monitoring and comparison of predictions with what actually happened.

2. How accurately do other hydrodynamic models predict changes in a water body due to a deepening project? This would require post-construction monitoring and comparison of predictions with what actually happened.

3. How accurately does EFDC predict changes in a water body due to any type of project? This would require post-construction monitoring and comparison of predictions with what actually happened.

4. How accurately do other hydrodynamic models predict changes in a water body due to any type of project? This would require post-construction monitoring and comparison of predictions with what actually happened.

This report is provided through the Engineer Research and Development Center (ERDC), Dredging Operations Technical Support (DOTS) Program in response to a request for assistance made by the Jacksonville District. The DOTS program provides a mechanism for USACE navigation operations managers to access technical expertise for immediate, short-term needs.

Method

A comprehensive literature search revealed a few papers that contained comparisons of EFDC simulations with data, but none of these dealt directly with comparing model results to data after a deepening project. Most of the papers describe modeling studies performed using EFDC and other models (*e.g.*, ECOMSED, CH3D, ROMS) in which only a minimal model calibration was performed, often without any validation. Those papers/reports were not included in this report.

Secondly, John Hamrick (developer of EFDC), Paul Craig (developer of EFDC_Explorer), Craig Jones (who added his SEDZLJ sediment bed model to EFDC), and a few other EFDC users were contacted, but none were aware of a comparison of model results to data of any kind that were collected post-deepening or post-remediation. A brief summary of the reviewed papers/reports is given next, followed by conclusions.

Description of EFDC

The Environmental Fluid Dynamics Code (EFDC) is a public domain modeling package. EFDC simulates multi-dimensional flow, transport, and biochemical processes in surface water systems including lakes, rivers, estuaries, reservoirs, wetlands, and coastal regions. Hamrick (2011; 2007a; 2007b; 2007c) provides extensive information on EFDC. This model, currently maintained by Tetra Tech with support from the U.S. Environmental Protection Agency (USEPA), has a history of extensive use in the United States (*e.g.*, Wool *et al.*, 2003; Sucsy and Morris, 2002; Jin *et al.*, 2000; and Hamrick *et al.*, 1995). The EFDC model has undergone extensive tests, documentation, and applications in more than 200 modeling studies worldwide by research institutions, governmental agencies, and consulting organizations (Hamrick, 2007a).

EFDC contains dynamically linked hydrodynamic, sediment transport, contaminant, and water quality modules. The hydrodynamic model in EFDC can simulate barotropic and baroclinic flow in a water body due to astronomical tides, wind, density gradients, and river inflow. It solves the three-dimensional (3-D), vertically hydrostatic, free surface, turbulence averaged equations of motion. EFDC is extremely versatile, and can be used for 1-D, 2-D-laterally averaged (2-DV), 2-D-vertically averaged (2-DH), or 3-D simulations of rivers, lakes, reservoirs, estuaries, coastal seas, and wetlands.

Monitoring Studies

Leonard *et al.* (2011) described a monitoring and modeling study of the effects in the Cape Fear River estuary due to deepening of Wilmington Harbor. As described in a later section, McAdory (2000) performed a modeling study of the proposed deepening and in certain areas widening of the Cape Fear River deep-draft channel using the USACE RMA10-WES model. The monitoring studies found that the project impact to tidal range throughout the estuary was comparable to the results from the RMA10-WES modeling, that being 0.2 ft or less. The variability in the tide range was found to be due to flow and tidal epochs that were for the most part offsetting trends. This study showed the utility and accuracy of using a surface water model to simulate the effects of, among others, deepening projects.

Modeling Studies Conducted using EFDC

EFDC Navigation Projects with Deepening

The Jacksonville Harbor Navigation Study Integrated General Reevaluation Report II and Supplemental Environmental Impact Statement (IGRR II/SEIS) employed the Environmental Fluid Dynamics Code (EFDC), the three-dimensional (3D) numerical model developed by John Hamrick (Tetra Tech, 2001; Hamrick, 2007a) to evaluate the potential impacts of the navigation project on circulation and salinity of the Lower St. Johns River Estuary. Recently, the) St. Johns River Water Management District (SJRWMD) St. Johns River Water Supply Impact Study (WSIS) (2012) completed application of the model to quantify the effects of water withdrawals on hydrodynamics throughout the St. Johns River (Sucsy *et al*. 2011; SJRWMD, 2012). More specifically, "the goal of the WSIS was to provide a comprehensive and scientifically rigorous analysis of the potential environmental effects to the St. Johns River associated with annual average surface water withdrawals as high as 262 mgd (155 mgd from the St. Johns River and 107 mgd from the Ocklawaha River)" (SJRWMD, 2012).

Calibration and validation (conformation) were evaluated by statistical comparison of measured and simulated time series of different state variables (Sucsy *et al*. 2011). The metrics used were r^2, RMSE, the average relative error (ACRE), the average absolute error (AVAE), the slope of the linear regression line, and the Nash-Sutcliffe coefficient (NS). Table 6-17 (from SJRWMD, 2012) shows a comparison of simulated and measured water surface elevations at 10 stations along the estuary during the calibration period from August 1997 to April 1999. These results show the model was able to accurately simulate the longitudinal variation in the water level. Table 6-21 (from SJRWMD, 2012) shows a comparison of simulated and measured salinities at 5 stations along the estuary during the calibration period. The importance of this comparison is stated by SJRWMD (2012) to be the following:

> "Accurate prediction of salinity is a key skill for the EFDC-LSJR hydrodynamic model because salt, as a conservative tracer, provides a means to assess the integration of all forces acting on the model that results in transport, circulation, and mixing processes. In addition, salinity is a key parameter that affects the biology of estuaries, and the response of salinity to water withdrawals and other factors must be quantified for the present study."

As seen in Table 6-21, the model correctly represented the temporal variability of salinity at all five stations, with the period of comparison ranging from intra-tidal to

Table 6–17. Comparison of observed and simulated hourly water level during the calibration period, August 1997 to April 1999.

Station	*NRECS*	r^2	*m*	*RMSE* (cm)
Bar Pilot Dock	15,337	0.97	0.95	8.7
Dames Point	11,410	0.97	0.98	7.9
Long Branch	12,343	0.97	1.00	5.9
Main Street Bridge	15,257	0.95	0.97	5.3
Buckman Bridge	14,910	0.94	1.00	4.2
Shands Bridge	13,101	0.91	0.97	4.8
Racy Point	12,833	0.93	0.98	4.7
Palatka	14,352	0.92	0.96	5.6
Buffalo Bluff	14,111	0.92	0.94	5.3
Welaka	15,337	0.95	0.94	3.9

NRECS = Number paired observed and simulated values
r^2 = Coefficient of determination
m = Slope of regression line
RMSE = Root-mean-square error

seasonal. In addition, the model also correctly simulated the differing ranges of salinity between stations, including the frequent intrusion of seawater at Acosta Bridge, the infrequent intrusion at Buckman Bridge, and the complete absence of intrusion of seawater at Shands Bridge and Dancy Point. “These results show that the model is successfully predicting the response of river salinity to seasonal variations in discharge and the dynamic mechanisms that result in upstream transport of ocean salt into the river” (SJRWMD, 2012).

Model validation (confirmation) was performed using the complete 10-yr model simulation period of 1996 to 2005. This period contains more extreme events than found in the calibration period. As stated by SJRWMD (2012), “The goal of model confirmation is to demonstrate that the model is a robust and reliable tool for predicting hydrodynamic variables over a wide range of conditions so that the model can be used for model forecast of altered future conditions. This goal is achieved by examination of a 10-yr record that contains both extreme dry and wet periods over a wide range of durations.” Comparative statistics, as seen below in Table 7-1 (from SJRWMD, 2012) for measured and simulated water levels over the confirmation period show a high correlation ($r^2 > 0.93$) at all stations. The correlation coefficients and RMSE statistics are nearly identical to the calibration statistics (see Table 6-17).

Table 6–21. Comparison of observed and simulated hourly salinity at USGS continuous salinity stations over the calibration period, August 1997 to April 1999.

Station	*NRECS*	r^2	*m*	*b*	*AVAE*	*AVRE*	*RMSE*
Dames Point Top	11,116	0.84	0.91	1.48	1.85	9.1	2.40
Dames Point Middle	10,810	0.86	0.95	2.72	2.23	10.3	2.79
Dames Point Bottom	10,769	0.83	0.96	3.49	3.03	13.6	3.66
Acosta Top	12,160	0.93	0.99	-0.07	0.87	18.0	1.32
Acosta Middle	12,893	0.93	1.07	0.01	0.95	19.5	1.46
Acosta Bottom	12,436	0.93	1.11	0.00	1.05	21.8	1.63
Buckman Top	13,048	0.85	0.93	0.04	0.25	22.9	0.59
Buckman Middle	12,224	0.91	1.24	-0.14	0.33	30.9	0.69
Buckman Bottom	10,528	0.90	1.19	-0.08	0.43	32.8	0.94
Shands Top	13,473	0.90	0.71	0.07	0.06	13.9	0.08
Shands Middle	13,257	0.90	0.71	0.07	0.06	13.9	0.08
Shands Bottom	13,353	0.90	0.71	0.07	0.06	13.9	0.08
Dancy Point Top	10,693	0.82	0.79	0.04	0.05	11.3	0.05
Dancy Point Bottom	10,700	0.93	0.79	0.04	0.05	11.3	0.05

NRECS = Number of paired values of simulated and observed salinity
r^2 = Coefficient of determination
m = Slope of regression line
b = Intercept of regression line
RMSE = Root–mean–square error
AVRE = Average relative error (%)
AVAE = Average absolute error

Validation of simulated salinities over the model confirmation period (1996 to 2005) was performed using measured values at 13 stations. Table 7–5 (from SJRWMD, 2012) shows the results. The correlations between the measured and simulated salinities were high at all stations, with r^2 ranging from 0.83 to 0.94. In this comparison, simulated vertically averaged salinity is compared to measured salinity regardless of measured depth. The slopes and intercepts of the regression lines seen in this table indicated no systematic bias in the model. Comparisons performed at other stations likewise showed good agreement between measured and simulated salinities (Sucsy *et al*. 2011).

Table 7–1. Comparative statistics for observed and simulated hourly water level during the confirmation period, 1996 to 2005.

Station	*NRECS*	r^2	*m*	*RMSE* (cm)
Bar Pilot Dock	87,649	0.98	0.96	7.8
Dames Point	43,327	0.96	0.98	8.5
Long Branch	47,433	0.97	0.99	6.0
Main Street Bridge	75,982	0.96	0.97	4.9
Buckman Bridge	79,640	0.96	1.00	4.1
Shands Bridge	76,745	0.95	1.00	4.2
Racy Point	34,580	0.94	0.96	5.1
Palatka	47,338	0.93	0.97	5.6
Buffalo Bluff	41,153	0.93	0.94	5.2
Welaka	79,609	0.95	0.95	4.7

NRECS = Number paired observed and simulated values
r^2 = Coefficient of determination
m = Slope of regression line
RMSE = Root–mean–square–error

Table 7–5. Comparison of Observed and Simulated Salinity at Water Quality Monitoring Network (WQMN) Stations, 1996 to 2005.

Station	*NRECS*	r^2	*m*	*b*	*AVAE*	*AVRE*	*RMSE*
JAXSJR17	188	0.92	1.01	0.41	1.74	14.0	2.48
JAXSJR40	154	0.92	1.06	-0.28	0.83	20.6	1.44
MP72	128	0.94	1.05	0.03	0.33	20.7	0.69
DTL	255	0.93	0.85	0.06	0.40	19.6	0.72
SJRHBP	173	0.93	0.95	-0.08	0.28	21.6	0.56
SJSR16	122	0.91	0.88	0.00	0.11	16.9	0.30
SJWSIL	94	0.83	0.67	0.11	0.07	13.9	0.17
SRP	123	0.84	0.86	0.03	0.05	10.7	0.06
SJM37	107	0.86	0.87	0.03	0.04	8.9	0.05
FP42	71	0.88	0.85	0.04	0.04	9.4	0.05
BB22	137	0.84	0.90	0.02	0.04	9.8	0.05
GF33	67	0.89	0.86	0.06	0.04	15.2	0.05
LAG	58	0.91	0.91	0.03	0.04	8.0	0.05

NRECS = Number of paired values of simulated and observed salinity
r^2 = Coefficient of determination
m = Slope of linear regression line
b = Intercept of linear regression line
RMSE = Root–mean–square error
AVRE = Average relative error (%)
AVAE = Average absolute error

The conclusions from the WSIS performed by the SJRWMD are significant within the context of this literature review. As such, they are copied below.

> "Quantification of the effects of water withdrawals on hydrodynamic variables is central to the goals of the WSIS. Evaluation of the effects of water withdrawals requires knowledge of how these withdrawals will affect water level, discharge, velocity, salinity, and discharge at many different locations and for a range of time scales. In addition, this evaluation needs to consider the interactions of water withdrawals with other future factors that will affect hydrodynamic variables, such as land use and structural changes within watersheds and sea level rise.
>
> The EFDC hydrodynamic model application of the lower and middle St. Johns River, as developed for the WSIS, is the best available tool for assessing the effects of water withdrawals and other future hydrologic changes on river hydrodynamics. This model is demonstrated to provide robust simulations of hydrodynamic variables over a wide range of meteorological conditions that include winter and tropical storm events, periods of extended drought, and extreme wet periods. The ability of the model to dynamically simulate hydrodynamic variables over a wide range of conditions indicates that the model will correctly simulate perturbations to the system needed to test water withdrawal scenarios, both alone and in conjunction with other expected future conditions.
>
> In the tidal portions of the St. Johns River, the model successfully captures tidal dynamics for water level, discharge, salinity, and salinity stratification. Importantly, the model correctly hindcasts the timing, strength, duration, and upstream extent of intrusions of seawater into the oligohaline and fresh segments of the river. The possible encroachment of salinity into normally oligohaline or fresh areas caused by flow reduction was an important question for several of the WSIS evaluations. The ability of the model to properly simulate intrusions of seawater results from its ability to integrate downstream freshwater transport, upstream tidal transport, estuarine circulation, and mass movements generated from low frequency ocean water level variability.
>
> In the nontidal middle St. Johns River, the model correctly simulates daily variability of water levels, discharge, and salinity. Frictional resistance is calibrated using observed slope–discharge relationships. The ability of the model to correctly capture the slope–discharge relationships over a wide range

> of hydrologic conditions ensures that the model will accurately predict the reduction of river stage caused by water withdrawals in this area. Observed water level data are used to show that stage in the middle St. Johns River is dominated by low frequency ocean water level for periods when river discharge is below the median discharge. Below the median river discharge, then, river stage is independent of river discharge. This result partly justifies the use of a hydrodynamic model in the non-tidal middle St. Johns River. The model is shown to correctly propagate the low frequency ocean signal throughout the middle St. Johns River.
>
> An additional important model skill for the WSIS is the ability of the model to simulate sea level rise. Because the model accounts for ocean effects throughout the lower 300 km of river, it implicitly accounts for sea level rise also. A long-term record of observed stage at DeLand shows that the rate of sea level rise in the middle St. Johns River is comparable (1 to 3 mm yr-1) to sea level rise at the river mouth near Mayport. The WSIS is designed to assess hydrodynamic changes over a 35-yr period (1995 to 2030) for which sea level rise would minimally be 3.5 to 10.5 cm. This total rise is the same order of magnitude as expected stage reductions caused by water withdrawals (1 to 6 cm), illustrating the importance of considering sea level rise over the time frame established for the study.
>
> Finally, the hydrodynamic model is a good predictor of salinity in the middle St. Johns River. This result shows that (a) salinity can reliably be used as a conservative tracer in the middle St. Johns River even though salinity levels are low (0.1 to 1.5), (b) the overall chloride budget of the middle St. Johns River, which depends greatly on groundwater inflows, is well-constrained, and (c) simulated water ages, a measure of flushing, are correct."

A National Research Council (NRC) Peer Review Group provided a comprehensive review of the SJRWMD WSIS. Their review can be found at: http://floridaswater.com/surfacewaterwithdrawals/NRCreports.html ; http://dels.nas.edu/Report/Review-Johns-River/13314). The NRC stated that the WSIS was an "unusually comprehensive examination of the hydrologic and hydrodynamic changes that would occur as a result of water withdrawals from the rivers and a wide range of environmental and ecological consequences that could ensure." They also state the following:

> "The Committee found the work of the hydrology and hydrodynamics (H&H) workgroup on building, testing, and analyzing its hydrologic and hydrodynamic models, including efforts to quantify the propagation of data uncertainty into hydrodynamic model uncertainty, to be state-of-the-art

> science. The District is building their WSIS analyses on a hydrodynamic foundation that is well-tested, robust, and well-understood."

One of the NRC's conclusions from their extensive review is copied below.

> "In the end, the District did a competent job relating the predicted environmental responses (including their magnitude and general degree of uncertainty) to the proposed range of withdrawals. The overall strategy of the study and the way it was implemented were appropriate and adequate to address the goals that the District established for the WSIS."

In addition, the EFDC model has recently been applied to assess ecological impacts for water resource management alternative plans, including channel modification, at several harbors. These studies are summarized below.

The Savannah Harbor Expansion Project (SHEP) applied the EFDC model to assess channel deepening impacts to salinity and dissolved oxygen (Tetra Tech, 2006). This project has begun the pre-construction monitoring phase. A review of the pre-channel deepening modeling study is given in the next section.

The EFDC model was applied at Charleston Harbor to evaluate the potential impacts of a proposed port expansion at Charleston, South Carolina on water levels, currents, salinity and sedimentation patterns in the Lower Cooper River (ATM, 2006). A review of this pre-channel deepening modeling study is given in the next section. A Charleston Harbor deepening study is presently being conducted by the USACE, Charleston District.

In a modeling study using EFDC that was performed by Dynamic Solutions LLC for the USACE Sacramento District, a 3D EFDC hydrodynamic, salinity and sediment transport model applied to the Sacramento – San Joaquin Delta was successfully validated (Dynamic Solutions, 2010a; 2010b). This was a technical defensible modeling study of an extremely complicated estuary and delta. While the study did not include the effect of deepening, it did examine the impact of several changes in the operation of the San Joaquin Delta. The study also included an uncertainty and sensitivity analyses that was conducted for the hydrodynamic model of the Sacramento and San Joaquin Rivers. Specifically, the uncertainty analysis was for model input data and the sensitivity analysis was to determine model results response to model inputs. The author of this literature review was a reviewer for the Sacramento Project Manager on this modeling study.

The USACE Seattle District is working on the Seattle Harbor Deepening Project. The author has been funded to modify an EFDC model developed for the Lower Duwamish Waterway –Elliot bay estuary in Seattle (see Arega and Hayter, 2004) to investigate the effects of channel deepening of two waterways in the harbor to -55 ft MLLW on salinity intrusion in that highly stratified salt wedge estuary.

Sucsy and Morris (2002) describe the calibration of a 3D EFDC model of the Lower St. Johns River. Water surface elevation, salinity and flow data from 1995 – 1998 were used in both calibrating and validating the model. Their conclusion, supported by quantitative comparisons given below, was that the model was both satisfactorily calibrated and validated. Table 17 (from Sucsy and Morris, 2002) shows the RMSE and median relative errors between the measured and simulated tidal range at eight stations along the estuary. Table 21 (from Sucsy and Morris, 2002) shows the results from statistical analyses of measured and simulated water surface elevations. Similar results for salinities measured at five stations are shown in Table 23 (from Sucsy and Morris, 2002). After calibration and validation, the model was used to examine alterations to the salinity regime in the model domain caused by deepening of the channel from the mouth to Jacksonville by 2 ft, and by deepening of the west Blount Island Channel by 8 ft.

Table 17: Results of error analysis for differences between simulated and observed harmonic tide. Time-series of harmonic waterlevel were generated using five principal short-period tidal constituents (M_2, N_2, S_2, O_1, and K_1). The error analyses are for differences of simulated and observed hourly harmonic waterlevel over a one-year period.

Station	RMS Error (cm)	Median Relative Error (%)	Observed tidal range (m)	Simulated tidal range (m)
Mayport	3.2	5.3	1.36	1.31
Dames Point	1.5	3.6	1.08	1.07
Long Branch	2.9	10.3	0.76	0.82
Acosta	2.3	11.4	0.54	0.60
Buckman	1.4	12.5	0.24	0.29
Shands	0.9	9.1	0.22	0.23
Racy Point	0.6	0.0	0.33	0.32
Palatka	1.5	9.1	0.37	0.37

Table 21: Statistics from linear regression and error analysis between simulated and observed total hourly waterlevel at 8 stations with continuous observed waterlevel.

Station	N	R^2	Intercept (m)	Slope	RMS Error (cm)	Median Relative Error (%)
Mayport	34080	0.986	0.006	0.968	6.3	8.3
Dames Point	24821	0.971	0.053	0.974	7.3	8.9
Long Branch	27408	0.978	0.041	1.038	5.2	10.7
Main St Bridge	31405	0.970	0.049	1.038	4.8	10.7
Buckman Bridge	28586	0.963	0.069	1.025	3.7	11.0
Shands Bridge	27592	0.953	0.070	1.019	4.4	11.9
Racy Point	26541	0.957	0.062	0.996	4.1	12.3
Palatka	29882	0.935	0.076	0.986	5.4	14.8

Table 23: Statistics used to compare observed and simulated hourly salinity for the period of 1 January 1995–30 November 1998. Comparisons were made for each station and level having continuous hourly salinity.

Station	Sensor Level	Mean Obs.	Mean Sim.	Range Obs.	Range Sim.	R^2	RMS Error	Median Relative Error (%)
Dames Pt	Upper	20.0	18.4	0.4–35.3	0.3–33.9	0.82	3.2	10.8
	Middle	21.5	22.2	0.4–35.3	0.3–35.0	0.72	3.6	11.7
	Lower	21.9	22.9	0.4–35.3	0.3–35.0	0.67	4.0	12.8
Acosta Br	Upper	4.2	4.1	0.1–29.0	0.2–29.9	0.88	1.6	19.8
	Middle	4.5	4.5	0.1–28.7	0.2–29.9	0.87	1.7	19.5
	Lower	4.4	4.6	0.1–28.8	0.2–29.9	0.87	1.8	20.4
Buckman Br	Upper	1.0	1.0	0.2–12.0	0.2–12.2	0.68	0.8	14.9
	Middle	1.0	1.2	0.2–10.7	0.2–14.6	0.64	1.0	14.3
	Lower	1.5	1.4	0.0–18.6	0.2–16.6	0.76	1.2	14.7
Shands Br	Upper	0.39	0.38	0.16–0.69	0.19–1.61	0.53	0.08	8.0
	Middle	0.40	0.40	0.16–0.69	0.19–1.76	0.44	0.09	7.4
	Lower	0.40	0.38	0.16–0.69	0.19–1.61	0.55	0.08	7.8
Dancy Pt	Upper	0.35	0.35	0.15–0.54	0.20–0.51	0.82	0.04	2.9
	Lower	0.35	0.35	0.13–0.54	0.20–0.51	0.82	0.04	2.9

As described by Bowen *et al.* (2009), the University of North Carolina at Charlotte, NC evaluated the impact of both the Wilmington Harbor Deepening Project and loading changes on dissolved oxygen in the Lower Cape Fear River Estuary. They used a calibrated and validated 3D EFDC model for the Lower Cape Fear River Estuary for this purpose. Among other metrics used, the model was able to match very closely the attenuation of the tidal amplitude from the mouth of the Cape Fear River to the upstream boundary of the model domain. The calibration period was from Nov 2003 to Jan 2005, and the validation period was from Jan 2005 – Jan 2006. Quantitative comparisons of observed and simulated tidal constituents at seven stations along the estuary were performed. The constituents used were M2, S2, N2. O1, M4, M6, and K1. The differences between the model predicted and observed tidal amplitudes varied from -0.048 to 0.054 m, while the differences between the model predicted and observed tidal phase varied from -48.3 to 41.8 percent. Differences in measured and simulated tidal phases are usually higher due to small phase differences in the actual forcings that affect the observed tides and those used in the model simulations. Validation results for temperature give the mean error, RMSE, mean absolute error, and r^2 values to be -0.52 ^oC, 1.51 ^oC, 1.08 percent, and 0.964, respectively.

Demirbilek *et al.* (2010) and Hayter *et al.* (2012a) described a project with the USACOE Seattle District (NWS) to address short- to mid-term dredge material management strategies for the Federal Navigation Project at Grays Harbor, WA. This study included the evaluation of a proposed realignment of the navigation channel in the Point Chehalis/Entrance reach. It was hypothesized that relocating the channel to align with natural channel migration would reduce future annual dredging quantities. However, the most heavily used dredged material placement sites lie in proximity to the Federal navigation channel. Thus, the goal of this modeling study was to assess the impact of the three dispersive dredged material placement sites on future channel maintenance dredging. A 2D EFDC model was applied to simulate tide- and wave-induced sediment transport in the well mixed meso-tidal Grays Harbor estuary under four different hydrodynamic and wave forcings that corresponded to 0.5-, 2-, and 5-year events and the most extreme event from a 38-year wave hindcast record. Salinity was also modeled in order to represent the measured longitudinal salinity profile throughout the estuary. Model results using both the existing and realigned channel configurations were analyzed to estimate residence times of dredged placed sediment at the three placement sites and channel infilling rates from sediment eroded from the placement sites for the existing and realigned channel configurations. The findings from the analysis indicated that there were significant differences in the erosion rates of the dredged material between the existing and realigned channel simulations at one of the three placement sites, and that there were no significant differences in the fate of the eroded sediment between the existing conditions and realigned channel configuration. Hayter *et al*. (2012b) describes a follow-up modeling study performed for NWS using the same EFDC model. The EFDC hydrodynamic model was calibrated using measured water surface elevations and velocities. Calibration results gave the RMSE error between the measured and simulated water surface elevations at Tide Station #1 (which was closest to the three placement sites) to be 0.16 m, while it ranged between 0.12 m and 0.19 m for all tide stations. The RMS error between the measured and simulated currents at Current Station #5 was 0.29 m/s, and ranged between 0.24 m/s and 0.35 m/s for all stations. Validation results gave the RMS error between the measured and simulated water surface elevations at Tide Station #1 to be 0.17 m, and ranged between 0.13 m and 0.21 m for all stations. The RMS error between the measured and simulated currents at Current Station #5 was 0.34 m/s, and ranged between 0.28 m/s and 0.40 m/s for all stations. Differences in bathymetry between that incorporated into the model grid and that at the site where the ADCPs were installed is one possible cause for the observed differences in current speeds.

<u>EFDC Tidal (non-Navigation) Modeling Studies</u>

Ji *et al*. (2001) is a journal paper of the modeling study performed at Morro Bay, whereas Ji *et al*. (2000) is a conference proceeding paper. Error analyses of the comparison of measured data and simulated model results are included in this paper. The range of RMS errors for elevation, velocity, temperature, and salinity are 5.6 – 13.8 cm, 13.09 – 17.52 cm/s, 0.40 – 1.11 ^{o}C, and 1.19 psu, respectively. The authors concluded that the Morro Bay model satisfactorily simulates tidal elevation, tidal velocity, temperature, and salinity. They also performed harmonic analysis using five major tidal constituents (M_2, S_2, N_2, K_1, and O_1) of the data and model results. Differences between the data and model results were less than 5.2 cm for tidal amplitudes for all five constituents and less than 9 degrees (approximately 18 minutes for semi-diurnal tides) for tidal phases.

Tetra Tech (2001) applied EFDC to the Lower Cape Fear River estuary. The model was validated using water surface elevation and salinity data. Table 3-1 through Table 3-9 present extensive error measures for water surface elevations, errors and relative errors between observed and predicted tidal harmonic constituents, and error measures for salinity. Overall, these error measures show that the hydrodynamic and salinity transport model was successfully calibrated.

Wool et al. (2003) developed a 3D EFDC hydrodynamic, temperature, salinity and water quality model of the Neuse River Estuary, NC. The hydrodynamic and water quality models were calibrated using data measured in 1998, and confirmed (validated) using data measured in 1999 and 2000. Comparisons of the simulated results with the extensive dataset show that the models are accurately simulating the longitudinal/seasonal distribution of the hydrodynamics, temperature and salinity. At four stations in this estuary, statistical analyses of the measured and simulated salinities were performed to calculate the mean error, percent mean error, RMSE, and percent RMSE. The mean error ranged from -0.33 to -1.19 psu, the percent mean error ranged from -42.4 to 63.9 percent, the RMSE ranged from 0.05 to 0.28 psu, and the percent RMSE ranged from 5.45 to 10.5 percent. For temperature, The mean error ranged from -0.13 to 0.56 ^{o}C, the percent mean error ranged from 0.03 to 0.45 percent, the RMSE ranged from 0.01 to 0.09 ^{o}C, and the percent RMSE ranged from 0.03 to 0.45 percent. These results indicate the model was able to correctly simulate the spatial and temporal variations in salinity and temperature (and therefore density) in this partially stratified estuary.

Mehta and Hayter (2004) describe a study performed for the St. Johns River Management District to evaluate proposed remedial dredging works for contaminated fine-grain sediment in the Cedar and Ortega Rivers, both tributaries to the St. Johns River (SJR). The study involved physical measurements of sediment properties (*e.g.*, settling velocities, erosion rates), and simulating the proposed remedial measures using a 3D EFDC model of this estuarine system. The model domain included the Ortega and Cedar Rivers and the reach of the SJR between the Main St. Bridge and the Buckman Bridge. The model simulated the 3D hydrodynamics, salinity transport, and sediment transport. The hydrodynamic model was calibrated and validated using measured water surface elevations at two tide stations and ADCP measured discharges at three transects in the Ortega-Cedar River estuary. No salinity measurements were available to calibrate and validate the simulated salinities. The sediment transport model was calibrated and validated by comparing measured and simulated sediment fluxes at the same three transects. Satisfactory agreement was obtained between the measured and simulated water levels, discharges, and sediment fluxes. No statistical analysis was performed as a component of the calibration and validation.

ATM (2006) developed a 3D EFDC hydrodynamic, salinity and sediment transport model of Charleston Harbor, SC. An extensive calibration and validation was performed for the primary state variables. Statistical analysis of measured and simulated water surface elevations at seven stations throughout the estuary yielded calculations of mean error, absolute mean error (AME), relative mean error (RME), absolute relative mean error (AREM), and RMSE. The RMSE, REN, AREM, and AME ranged from 0.05 - 0.15, -0.01 – 0.01, 0.01 – 0.18, and 0.04 – 0.12. These results indicate there was good agreement between measured and simulated water elevations at these stations. Velocity measurements were made with ADCPs, and measured and simulated depth-averaged currents were graphically compared. Their conclusion from this comparison was “Overall, there is reasonable agreement between the measured and simulated current patterns. For example, the model replicated the smaller currents along the channel banks and the higher currents in the center of the channel, and the model replicates the formation of gyres downstream from the contraction dikes.” “The model is capturing the larger scale process, which is what is important for evaluating the project related impacts.” Calibration of salinity yielded the following results at 10 stations: the RMSE, REN, AREM, and AME ranged from 0.10 – 3.39, -0.21 – 0.11, 0.03 – 0.85, and 0.09 – 2.88. These results indicate good overall agreement between measured and simulated salinities under the wide ranging flow and salinity regimes found in this stratified estuary.

Validation of the hydrodynamic and salinity transport models was also performed. Analyses of the measured and simulated water surface elevations, current velocities, and salinities gave the following results. For water surface elevations at six stations, the RMSE, REN, AREM, and AME ranged from 0.08 - 0.24, 0.00 – 0.01, 0.00 – 0.08, and 0.05 – 0.19. For current velocities at three station, the RMSE, REN, AREM, and AME ranged from 0.12 - 0.17, -0.04 – 0.04, 0.95 – 93.8, and 0.13 – 0.15. It is noted that the high AREM at one of the stations is the result of a near zero measured mean current, and as such, it does not indicate a large difference between measured and simulated currents since near zero measured values produce large relative errors. For salinities measured at nine stations, the RMSE, REN, AREM, and AME ranged from 0.09 – 3.64, -0.10 – 0.12, 0.01 – 0.57, and 0.04 – 2.95. As with the calibration results, the validation results indicate good overall agreement between measured and simulated water surface elevations, current velocities, and salinities.

Tetra Tech (2006) describes the development of a 3D EFDC hydrodynamic, salinity, temperature and water quality model for the Savannah Harbor Expansion Project. Calibration and validation of the model was performed by comparing measured and simulated water surface elevations, currents, temperatures and salinities. The statistics calculated were mean absolute error (MAE), RMSE, mean predicted (MP), standard deviation predicted (SDP), mean observed (MO), standard deviation observed (SDO), and coefficient of determination, r^2. Comparisons were made at 29 stations throughout this estuary. For calibration, the summary statistics for water surface elevation at 19 stations are given in Table B-2 (from Tetra Tech, 2006) below. Overall, very good comparisons were obtained. For currents, the differences in the 5^{th}, 50^{th}, and 95^{th} percentiles between the measured and simulated velocities at two stations (and at top and bottom of the water column at both stations) were the following: -10, 64, and 2 percents for the 5th, 50th and 95th percentiles for the surface measurements at one station; 56, 9, and 8 percents for the 5th, 50th and 95th percentiles for the bottom measurements at the same station; 4, 38, and 8 percents for the 5th, 50th and 95th percentiles for the surface measurements at the second station; 3, 16, and -67 percents for the 5th, 50th and 95th percentiles for the bottom measurements at the second station . While only for two stations, these results indicate the model was adequately calibrated for currents. Comparisons of measured and simulated temperatures during the calibration period are shown below in Table H-2 (from Tetra Tech, 2006). As seen, very good agreement was obtained. Similar quantitative comparisons between measured and simulated salinities at 29 stations during the calibration period are seen in Table J-2 (from Tetra Tech, 2006).

As seen in Tables C-2, E-1, I-2 and K-2 (from Tetra Tech 2006), similar quantitative agreement was obtained between measurements and simulation results for these state variables during the validation period. One conclusion that was reached in this modeling study is that as seen by the seven-year water surface elevation and salinity comparisons presented by Tetra Tech (2006), the EFDC model can perform equally well in high flows and summer-time low-flow conditions.

Table B-2 Summary Statistics for Elevation (meters) for July 31 through October 13, 1999

July 31 - October 13, 1999 [Julian Days 212-285]									
Station	N	ME	AME	RMS	Mean Obs	StDev Obs	Mean Pred	StDev Pred	R^2
FR-26	16577	-0.02	0.06	0.08	0.42	0.80	0.39	0.79	0.99
FR-02	6721	-0.04	0.09	0.11	0.35	0.82	0.31	0.80	0.98
SC-03	15516	-0.01	0.09	0.11	0.43	0.84	0.42	0.83	0.98
FR-04	18022	-0.01	0.10	0.12	0.46	0.88	0.45	0.89	0.98
FR-21	15387	-0.02	0.11	0.14	0.48	0.88	0.46	0.89	0.98
BR-05	16665	-0.05	0.15	0.18	0.53	0.86	0.48	0.86	0.96
FR-06	14947	0.00	0.12	0.15	0.49	0.87	0.50	0.89	0.97
FR-22	14993	0.00	0.14	0.17	0.50	0.96	0.50	0.98	0.97
FR-08	19437	-0.03	0.14	0.18	0.53	0.91	0.49	0.95	0.97
FR-09	18431	0.00	0.15	0.18	0.52	0.90	0.51	0.94	0.96
FR-11R	16309	-0.04	0.21	0.29	0.60	0.85	0.56	0.93	0.91
SR-14	11326	-0.08	0.30	0.35	0.72	0.76	0.63	0.93	0.88
SR-16	14912	-0.22	0.38	0.49	0.89	0.93	0.67	0.88	0.79
SR-17	15774	0.04	0.17	0.22	2.50	0.35	2.54	0.36	0.67
USGS02198980 (Ft Pulaski)	3601	-0.02	0.05	0.06	0.43	0.78	0.41	0.78	0.99
USGS02198977 (Broad St)	3601	-0.02	0.10	0.12	0.50	0.89	0.48	0.91	0.98
USGS02198920 (Houlihan Bridge)	2858	0.01	0.13	0.17	0.50	0.91	0.51	0.94	0.97
USGS02198979 (Limehouse Creek)	3601	-0.19	0.27	0.32	0.75	0.83	0.56	0.79	0.90
USGS02198840 (I-95)	3601	-0.10	0.29	0.35	0.73	0.76	0.63	0.93	0.88

Table H-2 1999 Temperature Comparison Statistics

July 31 - October 13, 1999 [Julian Days 212-285]										
Station	**Depth***	**N**	**ME**	**AME**	**RMS**	**Mean Pred**	**StDev Pred**	**Mean Obs**	**StDev Obs**	**R^2**
FR-26	S	13600	-0.1	0.5	0.6	27.4	2.6	27.5	2.8	1.0
FR-26	B	16940	-0.6	0.7	1.0	27.4	2.5	28.0	2.8	0.9
FR-02	S	10346	-0.3	0.5	0.7	26.4	2.4	26.8	2.6	1.0
FR-02	B	2225	-1.4	1.4	1.4	28.8	0.3	30.2	0.3	0.3
FR-04	S	14937	-0.2	0.5	0.6	28.1	2.6	28.2	2.7	1.0
FR-04	B	12963	-0.5	0.6	0.8	28.3	2.8	28.7	3.0	1.0
FR-21	S	18694	-0.3	0.5	0.6	27.2	2.8	27.5	2.8	1.0
FR-21	B	16674	-0.8	0.9	1.2	27.5	2.8	28.3	2.7	0.9
BR-05	B	11806	0.3	0.5	0.6	26.8	2.1	26.4	2.3	0.9
FR-06	S	11862	-0.1	0.5	0.6	26.5	2.4	26.6	2.7	1.0
FR-06	B	15018	0.0	0.5	0.6	26.8	2.1	26.7	2.5	1.0
FR-22	S	18949	-0.1	0.5	0.6	26.9	2.7	27.1	2.7	1.0
FR-22	B	18570	0.3	0.5	0.6	27.6	2.6	27.3	2.8	1.0
FR-08	S	11922	0.1	0.6	0.8	27.4	3.3	27.3	3.6	1.0
FR-08	B	8385	-0.2	0.6	0.7	28.6	2.6	28.7	2.4	0.9
FR-09	S	18337	-0.1	0.6	0.8	27.0	2.7	27.1	2.9	0.9
FR-09	B	18471	0.2	0.6	0.8	27.1	2.7	26.9	3.0	0.9
MR-10	S	15570	0.1	0.5	0.6	26.6	2.6	26.5	2.7	1.0
FR-11R	B	16657	0.1	0.6	0.7	26.2	2.4	26.1	2.4	0.9
SR-14	M	12348	0.0	0.5	0.7	25.9	2.3	25.9	2.3	0.9

* S = Surface
B = Bottom
M = Mid-Depth

Table J-2 Summary Statistics for Salinity (ppt) for July 31, 1999 through October 13, 1999

July 31 - October 13, 1999 [Julian Days 212-285]											
Station	Depth*	N	ME	AME	RMS	Mean Obs	StDev Obs	Mean Pred	StDev Pred	R^2
FR-26	S	13592	-3.77	4.14	4.66	25.68	4.40	21.91	4.60	0.67
FR-26	B	16580	2.34	2.75	3.52	30.17	2.86	32.51	1.92	0.20
FR-02	S	10346	-2.02	3.71	4.37	18.90	4.72	16.89	5.46	0.52
FR-02	B	2225	1.11	2.33	3.17	30.58	2.79	31.68	1.98	0.07
SC-03	B	15516	-1.38	2.10	2.59	18.08	2.11	16.69	1.82	0.15
FR-04	S	14937	-3.00	3.10	3.74	12.85	3.48	9.85	2.83	0.59
FR-04	B	12965	2.84	3.31	4.06	18.98	4.69	21.82	3.43	0.62
FR-21	S	18693	-1.62	2.12	2.63	8.43	3.09	6.81	2.51	0.55
FR-21	B	13045	1.26	2.95	3.69	16.12	4.45	17.39	3.16	0.40
BR-05	B	11817	2.87	3.35	4.09	7.80	4.18	10.67	3.27	0.52
FR-06	S	11886	-0.89	1.44	1.80	6.03	2.77	5.15	2.56	0.69
FR-06	B	14958	2.14	2.93	3.60	14.97	5.39	17.11	4.12	0.72
FR-22	S	18949	-0.66	1.16	1.61	3.53	2.75	2.87	1.88	0.75
FR-22	B	13918	3.75	4.02	4.74	7.68	3.85	11.43	3.51	0.48
BR-07	S	18038	1.18	1.74	2.20	1.48	1.89	2.66	1.73	0.23
FR-08	S	11920	0.19	1.27	1.76	2.11	2.75	2.30	1.82	0.61
FR-08	B	8385	2.29	3.84	5.50	5.44	4.70	7.73	7.02	0.49
LBR-15	S	18893	-0.21	1.29	1.88	1.92	2.40	1.72	1.68	0.40
FR-09	S	18499	1.14	2.08	3.20	3.30	3.98	4.44	4.92	0.63
FR-09	B	15511	-0.17	0.75	1.11	1.66	1.68	1.49	1.32	0.58
MR-10	S	16641	0.75	1.29	2.32	1.30	2.71	2.05	3.43	0.59
FR-11R	B	18453	-0.25	0.46	0.94	0.77	1.16	0.53	0.60	0.41
MR-12R	S	12348	-0.04	0.04	0.04	0.05	0.01	0.00	0.01	0.13
SR-14	B	15588	0.27	0.39	0.71	0.46	0.58	0.73	0.86	0.42
USGS02198920 (Houlihan Bridge)	M	3601	-0.04	0.04	0.05	0.05	0.01	0.00	0.01	0.07
USGS02198840 (I-95)	M	3533	-0.06	0.10	0.13	0.22	0.14	0.16	0.15	0.48
USGS021989784 (Lucknow Canal)	M	3526	0.81	1.36	2.22	2.26	2.37	3.07	3.11	0.56
USGS02198791 (US F&W Docks)	M	3601	0.13	0.24	0.41	0.32	0.34	0.45	0.52	0.44

* S = Surface
B = Bottom
M = Mid-Depth

Tuckey *et al*. (2006) used EFDC to simulate the tidal residual circulation in the Tasman/Golden Bays system in New Zealand. They validated the model by comparing simulated and measured current velocities. They concluded that despite the complexity of the tidal forcing in this system, the model was able to reproduce the gross features of the major tidal flows within these bays.

Ji *et al*. (2007) describe a modeling study using a 3D model of the St. Lucie Estuary, FL. Model calibration and validation results for water elevation, velocity, temperature and salinity are presented. The RMSE ranged from 0.07 to 0.12 m at six stations, and the relative RMSE ranged from 5 to 10.8 percent. These results indicate good model validation for water elevation. Current measurements were only available at one station. The values of the RMSE range from 0.112 to 0.114 m/s over the 1999-2000 dataset, and the value of the relative RMSE is 14 percent for both years. Statistical analysis for temperatures at five stations found that the RMSE ranged from 0.6 to 1.5 ^{o}C, and the relative RMSE ranged from 5.3 to 13.6 percent. The authors stated that the model simulated water temperatures satisfactorily, and this literature review author agrees with that assessment. Comparison of salinity measurements with model results found the range of RMSE to be 1.5 to 5.2 psu (with a mean of 2.8 psu), and the relative RMSE ranged from 7.4 to 32.2 percent. The largest errors occurred immediately after a large freshwater inflow event. It was pointed out that errors in the estimation of the freshwater inflow (calculated by a watershed model) would affect the accuracy of the predicted salinities.

Ren *et al*. (2009) described a 3D modeling study of Galway Bay, Ireland, using EFDC in which simulated surface currents were compared with measurements made with high frequency radar and by ADCP. They obtained very good correlation between the measured and simulated tide levels within the model domain. The root mean square error between simulated and Coastal Ocean Dynamics Applications Radar (CODAR) measured surface currents varied between 13.1 to 21.5 cm/s in the x-direction and between 8.4 to 13.3 cm/s in the y-direction. While these values seem high, the complexity of the geophysical flows in the modeled bay and the uncertainty in the CODAR measured currents need to be taken into consideration.

One of Ren *et al*.'s conclusions was that model accuracy is strongly dependent on the structure of the vertical sigma layers used in the model. Sensitivity analysis showed that a non-uniform thickness structure is most accurate, especially one in which the layers are the thinnest at the bottom and top of the water column (*i.e.*, in the two portions of the water column with the highest shear) and in which the thickness gradually increases towards the middle of the water column. This allows the shear induced by wind at the surface and friction at the bottom to more accurately propagate to the middle of the water column where the shear is minimum.

Hayter and Smith (2010) describe the application of a 2D EFDC model to simulate hydrodynamics and sediment transport in Upper Cook Inlet, AK, which is a hypertidal well-mixed estuary with tidal ranges between 11 – 12 m during spring tides at Anchorage, AK. Simulation of excessive sedimentation in the Port of Anchorage, which is located close to the mouth of Knik Arm (where it joins Upper Cook Inlet) to quantify changes in sedimentation rates within the port associated with port expansion and deepening was the objective of this study. Knik Arm is a 60 km long hypertidal subestuary of Cook Inlet. The model domain stretched 150 km from the upper end of Knik Arm to the East and West Forelands near Nikiski, AK, and also included Turnagain Arm. ADCIRC simulated tides in the Gulf of Alaska and Cook Inlet were used as the tidal forcing for EFDC at the forelands. Due to the narrowing geometry in Upper Cook Inlet, the tidal range at Anchorage is approximately double that at the forelands, so a radiation free boundary condition had to be used in EFDC to allow for the amplification of the tide as it propagates up the estuary as well as to allow the reflected tidal wave to propagate out of the model domain. The grid cell sizes in the curvilinear orthogonal grid varied from 10m by 30m within the port to 400m by 2,000m near the forelands. The hydrodynamic model was calibrated by comparing measured and simulated tides at Anchorage, and by comparing measured and simulated velocities along several transects lines along which velocity measurements were made using a boat mounted ADCP. The data –simulation comparison of water levels at this station indicates that the tidal amplitude, phase, and semi-lunar (spring/neap) variations, and diurnal inequalities (alternating variations in daily high-low water elevations) at the port were accurately represented. It also indicates that the model correctly represented the tidal wave amplification between the forelands and lower Knik Arm. Satisfactory comparison between the measures and simulated velocities along these transects was achieved, even within the port where two large gyres form (one during flood tides and the other during ebb tides) due to flow separation from prominent headlands (between which the port is located) located on the same side of lower Knik Arm as the port.

Jeong *et al.* (2010) describes a 3D numerical modeling study of salinity intrusion in the Geum River, Korea using EFDC. They used four different flow conditions in the Geum River to quantify the impact of flow on salinity intrusion. The flow conditions simulated were drought, low, normal, and flood flows. Before simulating salinity intrusion up the Geum River they verified the model by comparing measured and simulated water surface elevations at three locations along the 131 km length of the river that was modeled. The root mean square error and the normal root mean squared error ranged from 0.35 to 0.61 percent and from 6.98 to 9.72 percent, respectively. They did not have any salinity data to verify the salinity transport model.

EFDC Non-tidal Sediment Transport and Water Quality Modeling Studies

Ji *et al.* (2000) describe the development of a three-dimensional (3D) hydrodynamic, salinity, temperature and sediment transport model for Morro Bay, CA. The calibrated model was used to determine whether locations of sediment deposition were qualitatively in agreement with historical surveys. The modeling results showed that simulated locations of deposition occurred in the same area as found from the bathymetric survey. Plots showing comparison of measured and simulated water surface elevation, current velocity, temperature and salinity at six stations throughout the bay showed good agreement over 31 days. No quantitative metrics on the results from the calibration were reported. Model validation is not mentioned in this paper.

Jin *et al.* (2002) describe the development and validation of a 3D hydrodynamic and temperature model using EFDC of Lake Okeechobee, FL. Simulated water surface elevations, velocities, and temperatures were compared with data measured at four stations. The statistical analyses performed during model validation included calculation of the mean error, mean absolute error, root-mean-square error (RMSE), maximum absolute error, and the relative RMSE. These analyses showed that the simulated water surface elevations agree well with the data, with the mean absolute errors ranging from 0.01 to 0.02 m, and the RMSE ranging from 0.012 t0 0.027 m. The average absolute value of the relative errors at all stations was 1.4 cm, and the average relative RMSE was 6.89%. The simulated water temperatures also agreed very well with the data. The mean absolute errors and the RMSE range from 0.41 and 0.93 ^{o}C and 0.52 to 1.26 ^{o}C, respectively, and the average relative RMSE was 7.97%. The analyses for measured versus simulated velocities showed good agreement as with the other state variables. The mean absolute errors ranged from 1.93 to 4.31 cm/s, and the RMSE ranges from 2.47 t0 4.57 cm/s. The average relative RMSE was 15.80% at the 16 depths sampled at four stations in the lake. In closing, the 3D EFDC model of Lake Okeechobee was successfully validated for water depths/surface elevations, 3D currents, and water temperature for the chosen validation time period.

Ji *et al.* (2004) describe the development and validation of a 3D EFDC model that simulates the hydrodynamic, eutrophication, and sediment diagenesis in Lake Tenkiller, OK. This lake is a manmade reservoir that has approximate dimensions of 48 km in length, up to 3 km in width, and up to 45 m in depth. Statistical analysis of the measured and simulated water surface elevation was performed at one station in the reservoir. The RMSE is 0.09 m, and the relative RMSE is 3.5 percent. Statistical analyses of the measured and simulated water temperature were performed at 11 stations in the reservoir. The RMSE varies from 1.11 to 1.81 ^{o}C, and the relative RMSE varied from 4.58 to 7.97 percent, with a mean relative RMSE of 5.85 percent. Overall, the model simulated the vertical temperature profiles very well, which as this author knows by personal experience, is not easy to do in lakes/reservoirs.

Jin *et al.* (2004) describes a follow-up modeling study to that described by Ji *et al.* (2002) in which sediment transport modeling in Lake Okeechobee, FL was performed. Both current- and wind wave-induced sediment resuspension was included in this modeling. Model calibration and validation were performed by comparing measured and simulated suspended sediment concentrations (SSC) at four stations. Statistical analysis gave the average RMSE at these four stations to be 27.9 percent, with the range in the RMSE being from 26.8 to 41.7 mg/L. Based on the experience of the author in performing sediment transport modeling studies, these are very good results for a sediment transport model.

Jin and Ji (2005) present a similar paper to that by Jin *et al.* (2002). One difference is that model calibration and validation were performed by comparing measured and simulated SSC at eight stations instead of four. Statistical analysis gave the average RMSE at these eight stations to be 34.4 percent, with the range in the RMSE being from 25.8 to 49.4 mg/L. Not unexpectedly, the range and average RMSE is slightly higher than those found by Jin *et al.* (2002) for four stations. Nevertheless, these are good results for a sediment transport model.

Jain *et al.* (2005) describe a study performed by the University of Florida for the St. Johns River Water Management District (SJRWMD) on the resuspension of fine-grain sediment and subsequent release of nutrients from Newnans Lake, FL. This study included the use of a 3D EFDC model of the hydrodynamics and sediment transport model to simulate current- and wind wave-induced resuspension of sediments and their subsequent transport by wind-generated circulation in the lake. The hydrodynamic model was validated by comparison of measured and simulated water surface elevations at a station in the lake and by comparison of measured and simulated discharge from the lake over a 50 day period. The difference between the measured and simulated water levels varied between -2 to 8 cm, and the difference between the measured and simulated discharges was less than 2 percent. This was appropriately viewed as a very satisfactory validation.

Ji and Jin (2006) describe the use of their validated 3D Lake Okeechobee model as well as theoretical analysis and statistical methods to investigate gyres and seiches in the lake. Their study found that the seiche range is usually around 10 cm. Both the theoretical analysis and their model showed that circulation in the lake is dominated by a two gyre pattern, especially in the winter. Both northwest and southeast winds generate cyclonic gyre in the southwest and an anti-cyclonic gyre in the northeast.

Jin *et al.* (2007) presents the application of the previously described 3D EFDC model of Lake Okeechobee to simulate water quality and the spatial and temporal variations of SAV in the lake. It was verified, calibrated, and validated using three years worth of water quality and SAV data. Results from the modeling were consistent with data indicating that algal growth in the lake is primarily nitrogen limited in the summer and nitrogen and light co-limited in the winter. It also showed that lower lake levels lead to larger SAV areas, and that SAV positively impacts water quality by reducing algae concentrations. Reported error analyses included RMSE, relative RMSE, and relative absolute error for seven water quality parameters at one station for Water Year (WY) 2000. The mean relative RMSE and relative absolute error for these seven parameters were 22.6 and 25.1 percent, respectively. Other reported comparisons included the station-averaged relative RMSE over two WYs for 23 stations. The mean relative RMSE for the 23 stations over the three years was 31.8 percent.

Elçi *et al.* (2007) describe a study that included use of a 3D EFDC model of the main pool, *i.e.*, downstream, portion of Lake Hartwell, which is the USACE reservoir at the head waters of the Savannah River. The objective of the study was to evaluate the influence of stratification and shoreline erosion on sedimentation patterns in the reservoir. This study revealed probable zones of sediment deposition in the thermally stratified reservoir and presented a methodology for integrating shoreline erosion into sedimentation studies that can be used in any reservoir. Velocities and depths at selected transects in Lake Hartwell were measured using an ADCP and fathometer. Since the depths in Hartwell are up to 50 m, the bottom was out of range of the ADCP, and only the velocities for the top 10–15 m of the water column could be measured. Comparison of simulated and measured velocities indicated differences of less than 20% (4–6 cm/s) of the maximum measured values for all transects without any calibration of model parameters. After adjustment of the top layer thickness from 10% of the water column depth to 5%, the maximum errors in the simulated velocities were reduced to 3 cm/s. Jin *et al.* (2000) reported velocity errors up to 5 cm/s when measuring mean flows via similar techniques in lakes with fetches ranging from 15–45 km. In this study, the simulated values were typically lower than the measured velocities, but still in good agreement even without any calibration.

Hayter *et al.* (2007) describe an evaluation of a two-dimensional (2D) application of EFDC to simulate the transport and fate of sediment PCBs in a 19.0 mile reach of the Housatonic River, MA. The latter is a shallow, piedmont river in western

Massachusetts that empties into Long Island Sound. This application involved the use of the EFDC model that had been calibrated and validated for the 10.7 mile reach of the Housatonic upstream of the modeled 19-mile reach with no additional calibration for the 19 mile reach. The modeling study of the 10.7 mile reach of the Housatonic is described in the Modeling Framework Document (WESTON, 2004a), the Model Calibration Report (WESTON, 2004b), the Model Validation Report (WESTON, 2006a), and the Final Model Documentation (WESTON, 2006b). The evaluation of this application of EFDC showed that EFDC is capable of simulating the transport and resultant concentrations of SSC and PCBs in this reach of the Housatonic River within specified model performance measures for both relative bias and median relative error of ± 10 percent at the downstream boundary of the model domain (*i.e.*, Rising Pond Dam) for discharge. The model performance is also within the specified performance measure of ± 30 percent for median relative error for both TSS (-28.3%) and PCB (-14.4%) concentrations. However, the EFDC model did not satisfy the model performance measure of ± 30 percent for relative bias for either TSS (61.4%) or PCB concentrations (-71.1%). Factors that contributed to the failure to satisfy the performance measure for relative bias include a) phasing differences between the simulated results at Rising Pond Dam and the data collected one-mile downstream of the dam at the USGS Gauging Station at Great Barrington, MA; b) phasing and volumetric differences between the actual flows (from direct runoff and seven tributaries) and HSPF-simulated flows and loadings; and c) a higher detection limit for one group of PCB data than for the other data that caused the model-data comparison for PCBs to be extremely poor. Nevertheless, considering the fact that the EFDC model was not recalibrated for this 19-mile reach, and that the 19 mile reach had widely varying hydraulic and morphologic regimes (more so than the upstream 10.7 mile reach), the EFDC model's overall performance is considered satisfactory. This demonstrates the robustness of EFDC.

Hayter *et al.* (2011) and Mehta and Hayter (2011) describe the application of a 3D EFDC model to simulate the wind-driven circulation and current- and wave-induced sediment resuspension and transport in Lake Apopka, which is a shallow 125 km^2 lake located 24 km northwest of Orlando, FL. A detailed report of the entire study performed by the University of Florida for the SJRWMD is presented elsewhere (Mehta *et al.*, 2009). Measured wind velocities, daily average discharges from the lake into the Apopka-Beauclair Canal, and daily average discharges from Apopka Springs located in the southwest arm of the lake, were used for the hydrodynamic boundary conditions. Measured water levels and flow velocities at a mid-like station were used to calibrate and validate the hydrodynamic model. Results from the error analysis performed for measured and simulated velocities during both model calibration and validation are given in the table below.

Model –Data Comparison Statistics for Velocities at Mid-Lake Measurement Station in Lake Apopka, FL

Error or Bias	Model Calibration	Model Validation
Average Error (cm/s)	0.32	-0.08
Relative Error (%)	62.7	94.5
Average Absolute Error (cm/s)	0.85	0.73
RMSE (cm/s)	1.3	1.0
Relative Model Bias (%)	-23.2	10.8

As seen above, the relative bias for the calibration runs is -23.2%. The average error indicates that the simulated current speeds were on average 0.32 cm/s lower than the measured values. The small average error and the RMS error of 1.3 cm/s indicate an acceptable level of agreement between the measured and simulated current speeds. The relative bias for the validation run is 10.8% which is less than half that obtained for calibration. The relative bias is positive which means that the average simulated current speed was 10.8% higher than the average measured speed, whereas the average error indicates that the simulated speed was on average 0.08 cm/s higher than the measured speed. Overall, the results from validation are comparable to those from calibration, and both were judged to be acceptable.

Jin and Ji (2013) present a 10 year simulation using the 3D EFDC model of Lake Okeechobee described by Jin *et al*. (2007) of the water quality and SAV growth in the lake as well as a comparison with data collected in the lake's nearshore zone. Error analysis of the model results and data over the 10 year simulation period at one station was presented for eight water quality parameters. The mean relative RMSE for all eight parameters over this 10 year period was 17.1 percent. This is a very good result considering the length of the model simulation and the complexity of the biological, chemical, and physical processes that control the water quality in this large shallow lake. In addition, the mean relative RMSE at 15 stations over this 10 year period was 22.6 percent, which also shows excellent agreement between the model results and data.

Ji and Jin (2014) used their 3D EFDC model of Lake Okeechobee to investigate the impact of wind waves on sediment transport throughout the lake. Their findings from both data analysis and model simulations include the following: 1) significant wave heights and SSC are closely correlated to the local wind speed; 2) interaction of high-frequency wind waves with low-frequency currents in the bottom boundary layer in this shallow lake has a significant effect on deposition and resuspension of sediment;

and 3) the formation of seven distinct sediment zones in the lake is controlled at least in part by the long-term averaged current- and wave-generated bed shear stress.

Modeling Studies Conducted using Other Models

There are many modeling studies that fall into this category. One of the earliest was a model study performed by Johnson *et al.* (1987) of the impact of salinity intrusion of deepening the Lower Mississippi River Navigation Channel. It was performed using a laterally averaged hydrodynamic and salinity transport model called LAEM. They simulated the effect of 40, 45, 50 and 55 ft channels (with over depth dredging) in conjunction with historic low flow conditions. Using the 1953-1954 hydrograph and the 55 ft channel depth, the simulated position of the salinity wedge agreed closely to field data of salinity profiles.

McAdory (2000) performed a modeling study of the proposed deepening and in certain areas widening of the Cape Fear River deep-draft channel. RMA10-WES was used to perform this modeling. RMA10-WES is a 3D finite element hydrodynamic and transport model that invokes the hydrostatic assumption. This model is a modified version of the RMA-10 code developed by King (1993). A quantitative comparison of measured versus simulated relative tidal amplitude and phase at 12 stations from the river mouth to the upper reaches of the model domain was performed. The comparison of relative tidal amplitudes showed very good agreement at all 12 stations. The comparison of relative tidal phases as well showed good agreement, with the largest difference occurring at the upstream boundary. Comparison of root mean square (RMS) values of measured and simulated velocities also compared very well at 10 of the 12 stations. At one of the two stations where a good comparison was not obtained was due to fouling of the current meter. At the other station, the model underpredicts the measured value by 18 percent.

Ahsan *et al*. (2002) describe the calibration and validation of a Mississippi Sound /Bight modeling system developed using the ECOMSED model (HydroQual, 2001; Blumberg and Mellor, 1987). ECOMSED was used simulated the hydrodynamics, and the salinity and temperature fields in the model domain that stretched from east of Mobile Bay to the eastern side of the Mississippi River delta. The southern boundary of the model domain follows the 200m isobaths, which represents a natural barrier between the Mississippi Bight and the remainder of the Gulf of Mexico. Like the southern open water boundary of the model domain, the eastern open water boundary runs perpendicular to the coastline east of Mobile Bay. The primary purpose of this modeling study was to assess the performance of the modeling system in order to identify the dominant physical processes throughout the model domain.

Another purpose was to assess the modeling system's sensitivity to variations in different model input parameters such as bathymetry, freshwater flows, wind forcing, and temperature and salinity boundary conditions. Calibration and skill assessment of the modeling system was accomplished by comparing simulated results with observed water levels at Waveland, MS and temperature and salinity at five near coast CTD stations. Good comparison of data and model tidal harmonics for the K1, O1, N2, M2, and S2 tidal constituents at Waveland were achieved. Specifically, it was found that the modeling system performed very well in reproducing diurnal tidal signals, but it underestimated the low energy semidiurnal signals. In comparing measured and simulated temperature and salinity at the five CTD stations, very good correlation was achieved. In most cases, the r^2 values were greater than 0.8 for temperature. For salinity, the r^2 values are a little lower at three of the five stations. At the two stations located near freshwater sources, the simulated salinity values are lower than the data, which was attributed to possibly use of higher freshwater flows at these two locations than actually occurred. Overall, the Mississippi Bight/Sound modeling system was assessed to reproduce the overall circulation and mixing characteristics of the coastal seas and estuaries in the model domain based on the reasonably good model results to data comparisons.

Warner *et al.* (2005) describe a modeling study of the stratified Hudson River estuary using the Regional Ocean Modeling System (ROMS). They performed a thorough comparison of a series of model simulations against an extensive set of measurements over a 43 day period that contained large variations in tidal forcing and river discharge. They found that ROMS could predict the temporal and spatial evolution of momentum and salt transport with predictive skills that vary for 0.68 to 0.95. The skill metric is based on a measure of quantitative agreement between data and model simulations using the method given by Wilmott (1981). Not surprisingly, they note that the proper specification of boundary conditions, especially that for bottom stress and the open boundary condition for salinity, is crucial for increased model skill.

MacWilliams *et al.* (2008) developed a 3D hydrodynamic model that extends from offshore through the entire Sacramento-San Joaquin Delta using the UnTRIM model (Casulli and Zanolli, 2002, 2005). They performed calibration, followed by validation by comparing observed and predicted water levels and flows at stations in San Francisco Bay and the Sacramento San Joaquin Delta. For water level validation, the observed and predicted water levels were compared at five NOAA stations in San Francisco Bay and at forty-three stations in the Sacramento-San Joaquin Delta. The quality of fit between model results and observed water levels, flows, and salinity time series data were assessed using a cross-correlation procedure similar to that used by

RMA (2005). The procedure involves repeatedly shifting the predicted time series at one minute increments relative to the observed time series and computing the correlation coefficient at each time shift. The correlation is maximum when the shifted predicted time series best matches the observed time series. The time shift when the maximum correlation occurs represents the phase difference in minutes between the predicted and observed data. Positive values indicate that the predicted time series lags the observed time series. Linear regression is then performed between the time shifted predicted results and observed data record to yield the amplitude ratio, best-fit line, and correlation coefficient. The coefficient of determination, r^2, for stage stations in San Francisco Bay, North Delta, Central Delta, and South Delta ranged from 0.998 – 0.999, 0.959 – 0.991, 0.979 – 0.997, and 0.901 – 0.995, respectively. These results indicate that the model was more than satisfactorily validated with respect to simulating water levels throughout a very large, stratified, estuary and delta complex.

The Bay-Delta UnTRIM model was also calibrated and validated for flow using flow measurements made at 23 flow monitoring stations in the Sacramento-San Joaquin Delta. The same cross-correlation procedure was used to quantitatively measure the degree of validation achieved. At 6, 12, and 5 flow stations in the North Delta, Central Delta, and South Delta regions, respectively, the r^2 values ranged from 0.929 – 0.994, 0.692 – 0.996, and 0.808 – 0.989. Out of the 23 flow monitoring stations, only three stations had values of r^2 less than 0.929, and 19 had values greater than 0.96. These are unusually high for flow measurements, especially in a tidal water body, and indicate that the model was validated to a very high degree with respect to simulating flows throughout the Bay-Delta model domain.

Sheng and Kim (2009) describe a study that evaluated the predictive skills of an integrated physical–biogeochemical modeling system (CH3D-IMS) for shallow estuarine and coastal ecosystems are assessed using available field data measured in 1998-2000 in the Indian River Lagoon estuarine system, FL. Model skills for hydrodynamic and water quality simulations were assessed in terms of the absolute relative errors and the relative operating characteristic (ROC) scores. The ROC test, which has been used for such studies as weather forecasting, medical imaging, material testing, and other scientific disciplines, is a representation of the skill in which the true positive fraction and false positive fraction are compared. True positive fraction is the same metric as Sensitivity, and false positive fraction is the same as 1-Specificity. Specificity is defined as the ratio of the number of true negative decisions to the number of negatives cases, while Sensitivity is defined as the ratio of the number of true positive decisions to the number of positive cases. The ROC curve (or function) is generated by plotting Sensitivity against the corresponding 1-

Specificity. The area under the curve is the ROC score. If the area under the curve is greater than 0.5, the model system is determined as skillful. The ROC score ranges from 1.0 (for a perfect model system) to 0.0 (for a perfectly bad model system), with 0.5 indicating no skill. Both methods indicate that the modeling system has skills in simulating water level, salinity, dissolved oxygen, chlorophyll, and dissolved nutrients, with the ROC score between 0.60 and 0.86, indicating skills for most of the variables. The RMSE for water level and salinity were generally less than 10% and 20%, respectively, of the observed values.

Bever *et al.* (2013) modeled sediment transport in San Pablo Bay, a tidal sub-embayment of the San Francisco estuary, using the 3D UnTRIM model of San Francisco Bay and the Sacramento-San Joaquin Delta. The model was validated using water level, velocity, wind waves and suspended sediment data collected in San Pablo Bay. They obtained skill scores ranging from 0.99 for water level to 0.63 for SSC at a location in San Pablo Bay.

Song *et al.* (2013) and Song and Wang (2013) performed an extensive model study of the hydrodynamics and sediment transport in the Deepwater Navigation Channel (DNC) in the North Passage of the Yangtze River estuary in China. The model was validated with *in situ* data (water surface elevation, and profiles of velocities, temperature, salinity, and density) measured in the DNC. They obtained good skill scores and correlation coefficients during the validation. Tidal elevation, velocities, and salinity all had skill scores greater than 0.80, which is very good. The skill score from the SSC comparison was not very good. It was less than 0.4, but that is not surprising when modeling such a high energy estuary with very high sediment loads.

Conclusion

The documented EFDC modeling studies, most of which involved both calibration and validation, along with hundreds of other modeling studies that have been performed by the USEPA and the USACE, and Tetra Tech, Inc.; Dynamic Solutions, LLC; AnchorQEA, LLC; LimnoTech, Inc.; Applied Technology and Management, Inc.; and Integral Consulting, Inc., all who use EFDC as the hydrodynamic and transport model in their consulting practices, support the conclusion that EFDC is a very credible modeling system that has been successfully applied in many modeling studies, not only in this country but worldwide as well. Those modeling studies have ranged from investigating the impact on the salinity regime and water levels throughout estuaries due to deepening of the navigation channel to investigating changes in water quality in inland lakes and reservoirs.

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