Comparison of Two Hydrodynamic Models of Weeks Bay, Alabama

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Abstract. This paper presents a comparison of two hydrodynamic models of the Weeks Bay sub-estuary (Alabama, USA). One model was developed using the Environmental Fluid Dynamic Code (EFDC). The resulting model was compared to an existing hydrodynamic model (of the same water body) that was developed using the Adaptive Hydraulic modeling system (ADH). Comparisons were performed in terms of predicted water surface elevations in Weeks Bay. The computational grid was created using GEFDC (a mesh generator for EFDC) and NOAA's coastline and bathymetric data. The results showed that the EFDC model provides comparable water surface elevation (WSE) estimations for five out of seven control points located in the Weeks Bay study area. R^2 values for those points range between 0.88 and 0.99. Root mean square error values are shown to be lower than 0.15 m in those cases. For the rest of the control points, R^2 values range from 0.73 to 0.87 (RMSE range: 0.2 - 0.35), showing that the EFDC model provides acceptable estimations of WSE when compared to the ADH model WSE output. A finer computational mesh may improve EFDC WSE estimations for Weeks Bay as reported in the literature.

Keywords: Weeks Bay, Hydrodynamics, EFDC, ADH, modeling, grid generation, unstructured, structured.

1 Introduction

Estuaries and bays are water bodies semi-enclosed by land formations that cause the water to form a relatively shallow body. Although coastal waters such as estuaries and bays receive fresh water inputs from rivers draining to the water body, tidal influences (in the form of water surface elevation and water speed and direction) are felt miles upstream the incoming rivers.

The use of mathematical models by regulatory environmental agencies to set up waste load allocations, estimate Total Maximum Daily Loads (TMDLs), estimate impacts of remediation of contaminated sediments, and a variety of other purposes, is well established. Models of open waters and Gulf estuaries most commonly include

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both hydrodynamic and water quality models, due to the importance of transport on the fate of water quality constituents [1].

Measured water surface elevation (WSE) data are critical for establishing initial and boundary conditions for hydrodynamic models. The water surface elevations and water velocities calculated by hydrodynamic models for estuaries, bays and coastal rivers are strongly dependent on boundary conditions provided at open-ocean boundaries. However, the lack of tidal stations that collect WSE and other data, oftentimes forces modelers to interpolate or extrapolate these critical data, generating undesired uncertainty in the output of hydrodynamic models.

One other approach is to use calibrated predictions from existing models to compare the results of the new model. Nevertheless, this comparison is not straightforward. Existing models could be of bigger or smaller scale than the new model, or the new model could have been developed using a different numerical strategy.

This paper reports a comparison of two different hydrodynamic models of Weeks Bay, Alabama. A new model for Weeks Bay was developed using the Environmental Fluid Dynamic Code (EFDC). This code solves a 2-D finite-difference algorithm. Its estimations of water surface elevation values were compared to simulations of an existing model for Weeks Bay developed using the Adaptive Hydraulic Modeling system (ADH). ADH is a finite-element code. The specific objective of this exploration was to determine if the EFDC model for Weeks Bay, developed using the same datasets as the ADH model, could generate the same estimations of water surface elevations estimated by the ADH model.

2 Methods

2.1 Study Area

Weeks Bay is a sub-estuary located on the eastern shore of Mobile Bay (Alabama) in the northern Gulf of Mexico (Fig. 1). Its longitudinal axis is approximately 3.4 km long, running nearly north-south. Its widest point (3.1 km) is located near the center of the estuary [2][3]. The average depth is close to 1.5 m [2], although there are two areas where depths could reach 6 m. Tides are principally diurnal, and have a mean range of 0.4 m. The estuary receives waters from the Fish and Magnolia Rivers.

The Fish River watershed covers 14300 hectares and contributes approximately 73% to the total incoming freshwater flow, with the Magnolia River supplying the rest [4]. The combined discharge of both rivers averages approximately 9 cubic meters per second.

In 2009, Weeks Bay was listed on the Southern Environmental Law Center's 10 Most Endangered Places in the South due to development in the area and lack of zoning laws [3]. Weeks Bay was removed from the top 10 list in 2010 due to Magnolia Springs (AL) adopting runoff control ordinances that promote low-impact development laws which protect the Magnolia River.

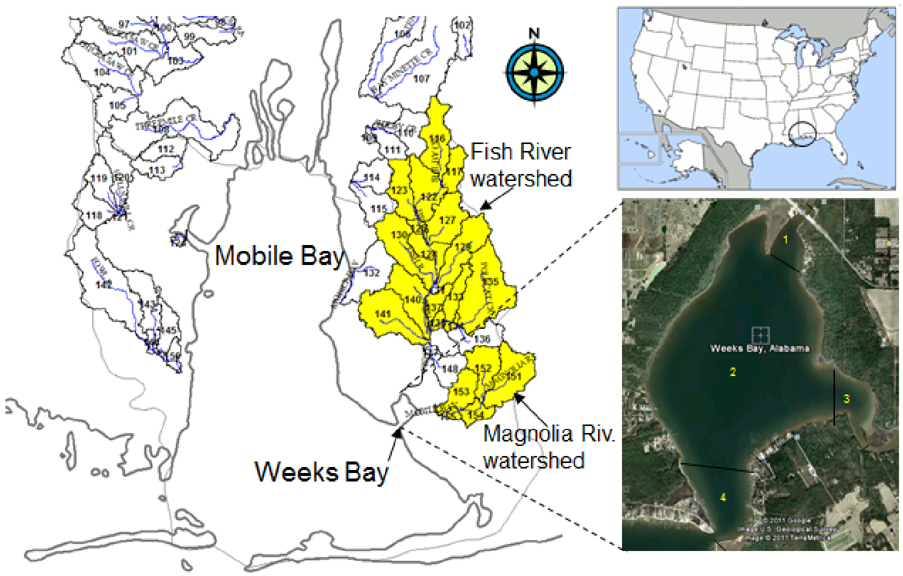

Fig. 1. Study area. Weeks Bay is a sub-estuary located within Mobile Bay, Alabama. Two main rivers drain waters into the sub-estuary: Fish River and Magnolia River. The watersheds for each river are shown.

2.2 Computational Meshes

The grid generator for EFDC (GEFDC), capable of producing structured rectangular and curvilinear meshes [5], was applied for creating a structured grid of Weeks Bay for hydrodynamics modeling. The bathymetry data (detailing the bottom topography with respect to mean sea level) was downloaded from the US National Oceanic and Atmospheric Administration National Geophysical Data Center (NOAA-NGDC) database. NGDC provides datasets of the U.S. coastal zone integrating offshore bathymetry with land topography into a seamless representation of the coast derived from NGDC's hydrographic surveys, multi-beam bathymetry, and track-line bathymetry; the U.S. Geological Survey (USGS); and other federal government agencies and academic institutions [6]. In this research, the US Coastal Relief Model bathymetric data was selected for its fine spatial resolution (84 m x 84 m raster cells), date of production (beginning date: 1999, ending date: present), and accuracy and reliability.

The bathymetric information was downloaded in ASCII raster format and was critical for producing one of the main input data required by GEFDC for the generation of the grid: the cell.inp file. This file specifies the interconnection between finite-difference cells, the type of cell (water, boundary, dry land, etc.), and whether it is a quadrilateral or triangular cell. Manipulation of the raw ASCII bathymetry data was performed using ArcGIS and tailor-made C codes. Other files required by GEFDC such as dxdy.inp (specifying grid coordinates correspondence to actual geographical coordinates), depdat.inp (bottom depths for each finite-difference cell corner), etc., were also produced by those tailor made codes.

All pre-processing for the generation of the required GEFDC input files was performed in UTM Zone 16N coordinates. Figure 2 illustrates the process.

The existing ADH model for Weeks Bay is composed by 9808 triangular elements and 4349 nodes. It is a non-structured finite-element mesh as required by the ADH solver. The mesh is shown in Fig. 3.

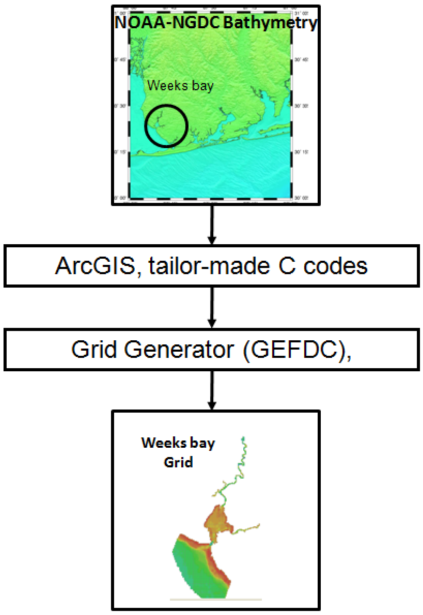

Fig. 2. Processing for the generation of the computational mesh for Weeks Bay for the EFDC solver

2.3 Solvers

The Adaptive Hydraulics (ADH) modeling system is a code that can describe both saturated and unsaturated groundwater, overland flow, 3D Navier-Stokes, and 2-D and 3D shallow-water problems. It is not on the public-domain and is designed to work in conjunction with the commercial software Surface Water Modeling System (SMS) (a Windows application) for building ADH application models, running simulations, and visualizing results [7]. It was developed at ERDC (USACE Vicksburg experimental station), and uses the finite-elements (triangular elements) strategy for solving the equations [7].

The EFDC Model is a public-domain surface water modeling system incorporating fully integrated hydrodynamics. It is used for 1D, 2D, or 3D simulations of rivers, lakes, reservoirs, estuaries, coastal seas, and wetlands [5]. EFDC was developed by

John Hamrick at Virginia Institute of Marine Science (VIMS) with primary support from the State of Virginia. Additional support has been provided by EPA and NOAA and it is presently maintained by Tetra Tech, Inc. It is currently used by federal, state and local agencies, consultants and universities [5].

3 Results

3.1 EFDC Computational Mesh

Fig. 3 (right-hand side) shows the EFDC grid developed for Weeks bay. The mesh consists of approximately 6300 square cells. Efforts were made to generate a grid as similar as possible to the ADH grid (left-hand side of Fig. 3).

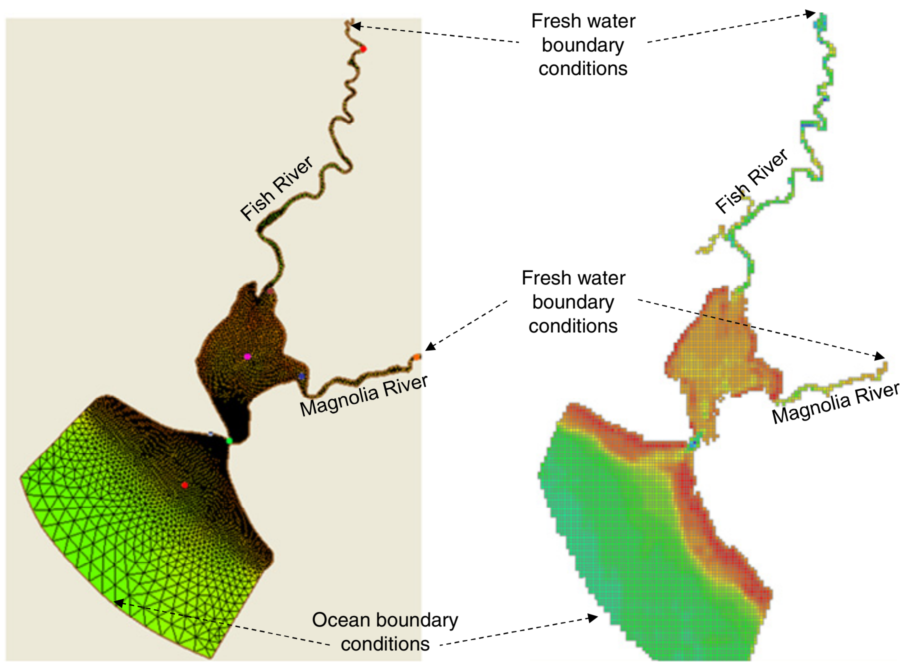

Fig. 3. EFDC and ADH computational meshes. A 6300-cell structured grid for EFDC input (right-hand side) was generated using the EFDC grid generator (GEFDC). The left-hand side of the figure shows the existing ADH grid.

Although EFDC works well with curvilinear (orthogonal) grids, the particular geometry of the coastline surrounding Weeks Bay did not allow generating a mesh with optimal orthogonality indicators (assessed by GEFDC). Fig. 4 shows one of the curvilinear meshes that were discarded due to abnormalities in the cells corresponding to the throat of Weeks Bay.

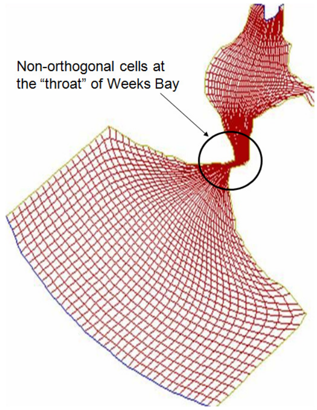

Fig. 4. Curvilinear grids for Weeks Bay. Cells at the "throat" of the estuary presented serious non-orthogonality issues

Ocean boundary conditions were imposed in the form of water surface elevation (WSE) time-series for all boundary cells (or boundary elements in the case of the ADH model) along the boundaries shown in Fig. 3. Due to the geometrical differences imposed by the geometry of EFDC's quadrilateral cells, and the fact that EFDC specifies input to boundary cells per East, North, South or West orientation, the ocean boundary for the EFDC Weeks Bay model was designed such that estimated WSEs at common geographical locations near the boundaries in both models are identical. The temporal resolution of the water surface elevation time-series was hourly.

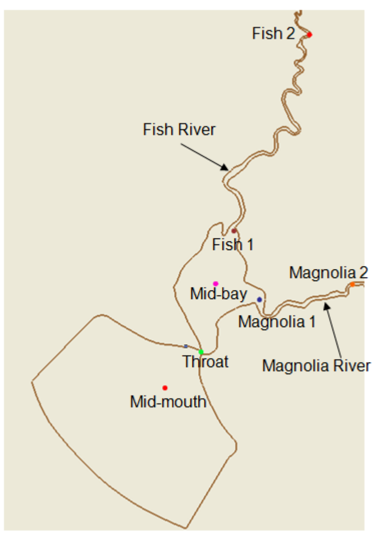

Fig. 5. Control points for which comparisons between EFDC and ADH output were performed

Fresh water boundary conditions were implemented at the most inland EFDC cells or ADH elements of the Fish and Magnolia river portions included in both computational grids (as shown in Fig. 3). Stream flow time-series constituted the fresh water forcings. Those time-series were produced by existing hydrological watershed models of Fish and Magnolia river watersheds from a previous research project [8]. In that research, several hydrological models of the Mobile Bay watershed and other watersheds located in the northern Gulf of Mexico, (Alabama, USA) were developed using the Hydrological Simulation Program Fortran (HSPF). Coastal watersheds of selected streams that drain directly to the Mobile estuary (namely: Fish River, Magnolia River, and Chickasaw Creek) were modeled and their corresponding HSPF models were calibrated. For this research, the existing hydrological models for Fish River and Magnolia River watersheds were updated with current precipitation and evapotranspiration time-series covering the period of hydrodynamic simulation. The temporal resolution of the HSPF-estimated stream flow time-series was daily.

3.2 EFDC vs. ADH Comparison

Fig. 5 shows the location of several control points, in the computational domain, for which water surface elevation estimations from the EFDC and ADH models were compared. These points were chosen because other research efforts for the area collected salinity and other water quality indicators at those points. The results shown in the following comparison charts use the location names specified in Fig. 5.

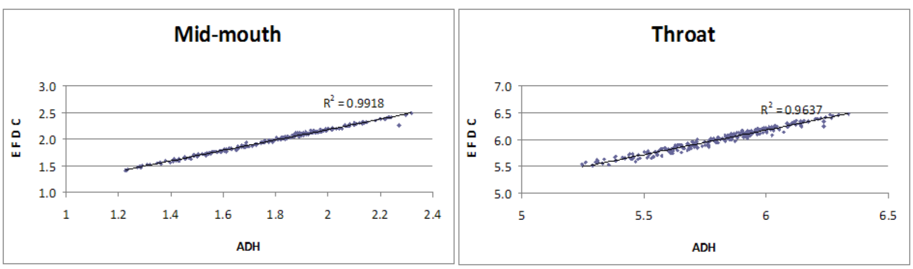

Fig. 6. Scatter plots of water surface elevations (WSE) calculated by the EFDC model of Weeks Bay compared to WSE estimated by the ADH model for the Mid-mouth and Throat control points. R^2 fitting coefficients are shown

A comparison of water surface elevations (WSE) estimated using EFDC against those WSE calculated by ADH are shown in figures 6 through 9. The scatter plots corresponding to the mid-mouth and throat control points (Fig. 6) show that both models estimate similar values of WSE as demonstrated by the high fitting coefficient (coefficient of determination R^2): 0.99 and 0.96, respectively. The plots show that EFDC tends to slightly overestimate WSE values with respect to those calculated by ADH. Overall, however, EFDC seems to produce comparable results.

Figure 7 shows a scatter plot comparing EFDC and ADH simulated output for the mid-bay control point. While the R^2 fitting coefficient is still acceptable (0.88), interestingly EFDC underestimates WSE values, and a spread of the scatter points is present.

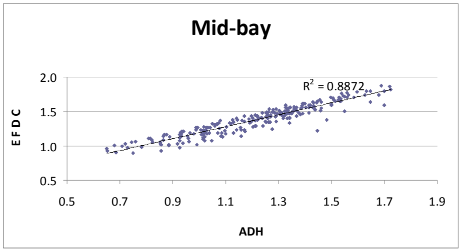

Fig. 7. Comparison scatter-plot of water surface elevations (WSE) calculated by the EFDC model of Weeks Bay versus WSE estimated by the ADH model for the Mid-bay control point

A similar quality in the EFDC simulation for two control points along the Magnolia River (Magnolia 1 and Magnolia 2) is evidenced by the scatter plots shown in Fig. 8. EFDC seems to slightly overestimate WSE values consistently for these control points. However, the R^2 values for both control points (0.88) do not decrease in comparison to the fitting coefficient values for the mid-bay control point, demonstrating that EFDC estimations of water surface elevations are consistent with the ADH estimations.

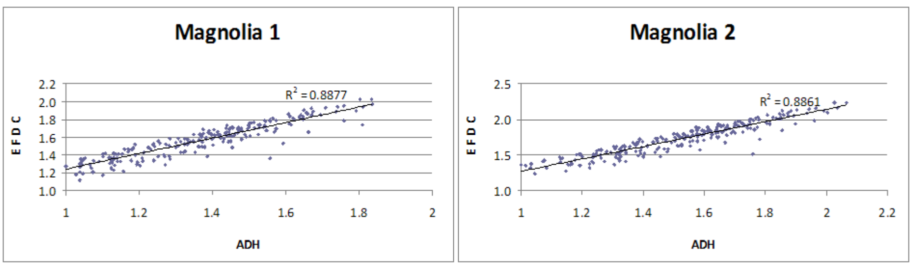

Fig. 8. Scatter-plots of water surface elevations (WSE) calculated by the EFDC model of Weeks Bay compared to WSE estimated by the ADH model for control points along Magnolia Rivers

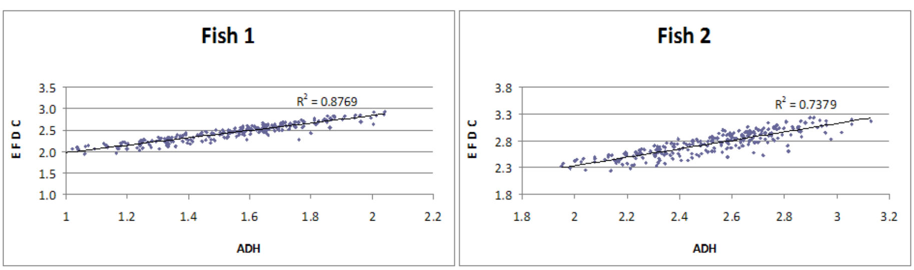

Fig. 9. Scatter plots of water surface elevations (WSE) calculated by the EFDC model of Weeks Bay compared to WSE estimated by the ADH model along Fish River

The comparison of EFDC water surface elevation estimations against ADH estimations for the two control points along the Fish River (Fish 1 and Fish 2 control points) is shown in Figure 9. R^2 fitting coefficients are 0.87.and 0.74, respectively. There exists a decrease in fitting quality directly proportional to the distance from the ocean boundary. The decrease, however, is not big, as evidenced by the still high R^2 value for the northern-most control point (R^2 value for Fish 2 is 0.74).

In order to further explore the actual quality of EFDC estimations, root-mean square-error values (RMSE) were computed. Also, since it seems that greater decrease in fitting quality is bigger with latitude than with longitude, RMSE and R^2 values are plotted against horizontal and vertical distances.

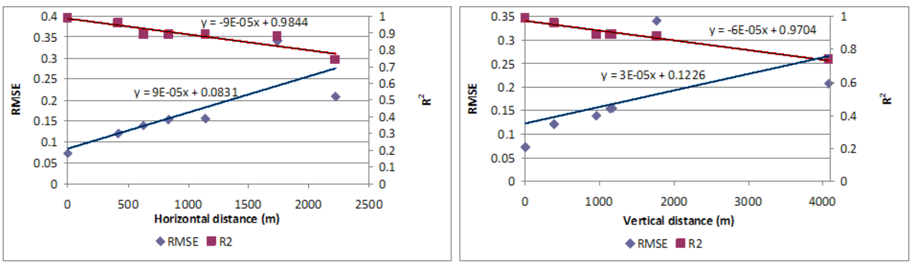

Fig. 10. R^2 and RMSE values against horizontal and vertical geographical distances, measured from the mid-mouth control point to the rest of the control points

Fig.10 presents a summary of fitting coefficients (R^2) and corresponding root-mean-square errors (RMSE) for all the control points. The values are plotted against horizontal and vertical spatial distances measured from the mid-mouth control point.

RMSE and R^2 values in Figure 10 show that the fitting inconsistencies increase with distances along the horizontal and vertical directions of the grid. The rate of error increase with respect to either direction is similar, probably due to the fact that the grid cells are square so the error propagates at the same rate vertically or horizontally. What is more important is that RMSE values range from 0.025 m to 0.15 m for most of the control points (Mid-mouth, Throat, Mid-bay, Magnolia 1, and Magnolia 2), showing that EFDC estimates water surface elevation values with small errors. For control points Fish 1 and Fish 2, although RMSE values are bigger (0.2 and o.35 respectively), EFDC estimations are still within acceptable error ranges.

4 Conclusions

The results of this computational exploration show that the EFDC model provides comparable water surface elevation (WSE) estimations for five of the seven control points located in the Weeks Bay study area. R^2 fitting coefficients for those points are greater than 0.88. Although EFDC slightly overestimates WSE for those points, the root mean square error is lower than 0.15 m. For the rest of the control points, R^2 values range from 0.73 to 0.87 (with RMSE values of 0.2 to 0.35 respectively), showing that the EFDC model also provide acceptable estimations when compared to the ADH model output. Providing EFDC of a finer computational mesh representing Weeks Bay seems may improve EFDC estimations for Weeks Bay. This conclusion is consistent with comparisons of finite-element and finite differences schemes reported in the literature [10] when applied to oceanographic modeling studies. However, the results show that the current grid will work well (RMSE < 0.2) for most of the cells within the computational domain.

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