

MIKE21 Modeling to Evaluate Shoaling Reduction Alternatives near Matanzas Inlet in Florida

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Abstract

This study describes the field measurements and MIKE21 numerical modeling of tides, waves, sediment transport, and bed morphological changes in the Intracoastal Waterway (ICWW) near Matanzas Inlet in St. Johns County, Florida. The model results generally agree well with measured water levels, current speeds, current direction, and observed morphological patterns in the area. The models applications provided the means to (1) understand the transport of sediments and formation of the shoals in the ICCW, (2) identify various alternatives that could reduce ICCW shoaling rates, and (3) evaluate the performance and the associated cost and frequency of maintenance dredging for alternatives that show potential to reduce the ICCW shoaling. Model results show flood slows as it flows south around the northern tip of Rattlesnake Island. This rapid decrease in flow velocity explains the observed sediment deposition (shoaling) in the ICWW. Model results also show sediment basins located in the north arm of Matanzas River and north of Fort Matanzas will likely reduce shoaling in the ICWW and reduce maintenance dredging from the current once every three years to once every four years.

INTRODUCTION

Matanzas Inlet lies 2.5 miles (4.0 kilometers) north of the St. Johns/Flagler county line in Florida. The ICWW near Matanzas Inlet exhibits an extremely high shoaling rate. Historical dredging records indicate that the ICWW requires maintenance dredging, on average, every 2.7 years. Each operation requires the removal of over 175,000 cubic yards (133,797 cubic meters) of material and placement of the dredged material on the beach south of Matanzas Inlet. This high maintenance requirement exists primarily for two reasons. First, the ICWW in this area lies relatively close to an exposed, active, natural sandy inlet. Second, unlike virtually all other inlets on Florida's east coast, no inlet management program exists at Matanzas Inlet to manage the littoral material introduced through the inlet to the interior channels. Further, no agency maintains the inlet for navigation.

The area of modeling interest or the primary area of sediment deposition, as Figure 1 shows lies at the confluence of Matanzas River and the ICWW. The confluence is

1.5 miles (2.4 kilometers) northwest of Matanzas Inlet. Because of the proximity of the area of interest to the dual inlet system of Matanzas and St. Augustine Inlets and the small drainage area from upland basins, tidal action predominantly influences the daily flow regime in the area. The major tidal flow sources originate from Matanzas Inlet and periodically through barrier island breaches due to episodic dune overtopping from storm surges and waves.

To evaluate the feasibility of reducing the amount of shoaling at the area of interest, the Florida Inland Navigation District, the state agency involved with the construction and maintenance of dredged material disposal areas, funded a sedimentation study to (1) identify, quantify, and analyze the existing features, wave climate, hydrodynamics, and sediment characteristics of the Matanzas Inlet area, and (2) determine whether any alternatives exist that, if implemented, would reduce sediment inflow into the ICWW channel and other adjacent waterways. These alternatives could reduce the frequency and costs of dredging the ICWW channel near Maintenance Spoil Area St. Johns 1 (MSA SJ-1).

FIELD MEASUREMENTS

Semidiurnal tides with two highs and two lows per day and mixed tides during neap period characterize the astronomical tides in the study area. To provide the tide data for hydrodynamic model calibration and verification, the study installed pressure tide gauges in the ICWW near the S.R. 312 Bridge (T1) and near the Matanzas Inlet west of the S.R. A1A Bridge (T5) on July 10, 2007. The study also measured the flow velocity at three locations — in Matanzas River near Fort Matanzas (V1) and in the ICWW approximately 1.0 mile (1.6 kilometers) north (V2) and 0.5 mile (0.8 kilometer) south (V3) of MSA SJ-1. Figure 1 show the locations of the tide and velocity measurement stations. Applying an Acoustic Doppler Current Profiler (ADCP), the study measured neap and spring tidal velocities at the velocity stations on July 23 and July 30, 2007. The ADCP recorded the variation of horizontal flow speed and direction along the water depth at Stations V1 – V3 at intervals varying from 1 – 2 hours. Velocity measurements at each station consisted of 5-min recordings of current speed and direction at bins spaced approximately 1.6 feet (0.5 meter) along the water depth. The average speed and direction recorded during each measurement provided the depth-averaged flow data at each station.

Unfortunately, during the second velocity measurement on July 30, the study discovered the loss the T5 tide gauge. As a remedy, the study installed another tide gauge (T6) near the inlet on August 24, 2007 and conducted two additional ADCP velocity measurements on August 29 (spring tide) and September 4 (neap tide). These velocity measurements occurred at the same locations as the July 23 and July 30 velocity measurements. On August 24, the study also installed another tide gauge (T7) in the ICWW between MSA SJ-1 and the S.R. 206 Bridge to provide additional water level calibration data. Together with the two tide gauges installed on August 24, the tide gauge near S.R. 312 Bridge continued to record the tide level until their retrieval.



Figure 1: Locations of the tide level and flow velocity measurement stations

At the T1 gauge, tide range varied from 5.5 feet or 1.7 meters (S.R. 312) on August 29 – September 2, 2007. During this period, the tides at T6 (near Matanzas Inlet) and T7 (Off S.R. A1A) lagged the measured tide at T1 (S.R. 312) by an average of 0.5 and 0.25 hours. Figure 2 shows the time series of recorded depth-averaged flow velocity on September 4, 2007 at flow velocity stations V1, V2, and V3. The depth-averaged velocity represents the mean of all velocity measurements along the depth at each station at each measurement time. The figure also shows the standard deviation of approximately 150 velocity measurements for each vertical bin along the water depth. At Station V1, measurements show mostly northward flood flow with peak depth-averaged current speed of 3 feet per second (0.9 meter per second). Figure 2 also shows peak depth-averaged flood velocities of 1.9 feet per second (0.6 meter per second) at Station V2 and 2.4 feet per second (0.7 meter per second) at Station V3.

NUMERICAL MODELING

The MIKE21 Flexible Mesh (FM) two-dimensional hydrodynamic, sediment transport, and morphology (bed change) models simulate water surface elevation, flow velocity, bed and suspended sand transport, erosion, and deposition at the

area of interest. MIKE21 FM represents the portions of the Atlantic Ocean, Matanzas River, ICWW, and the ICWW's interconnected network of waterways as a two-dimensional waterway.

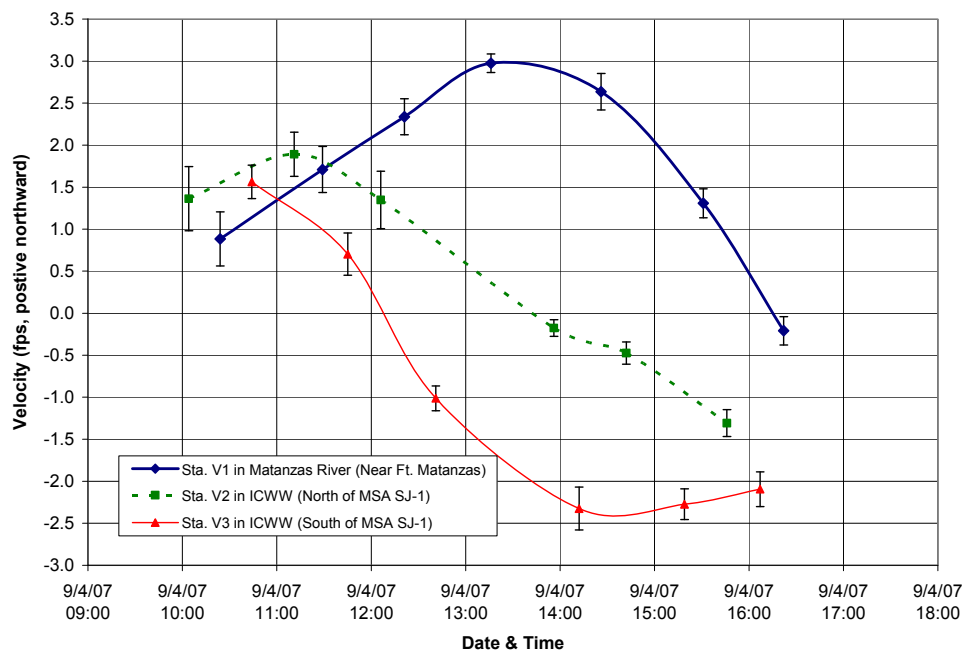
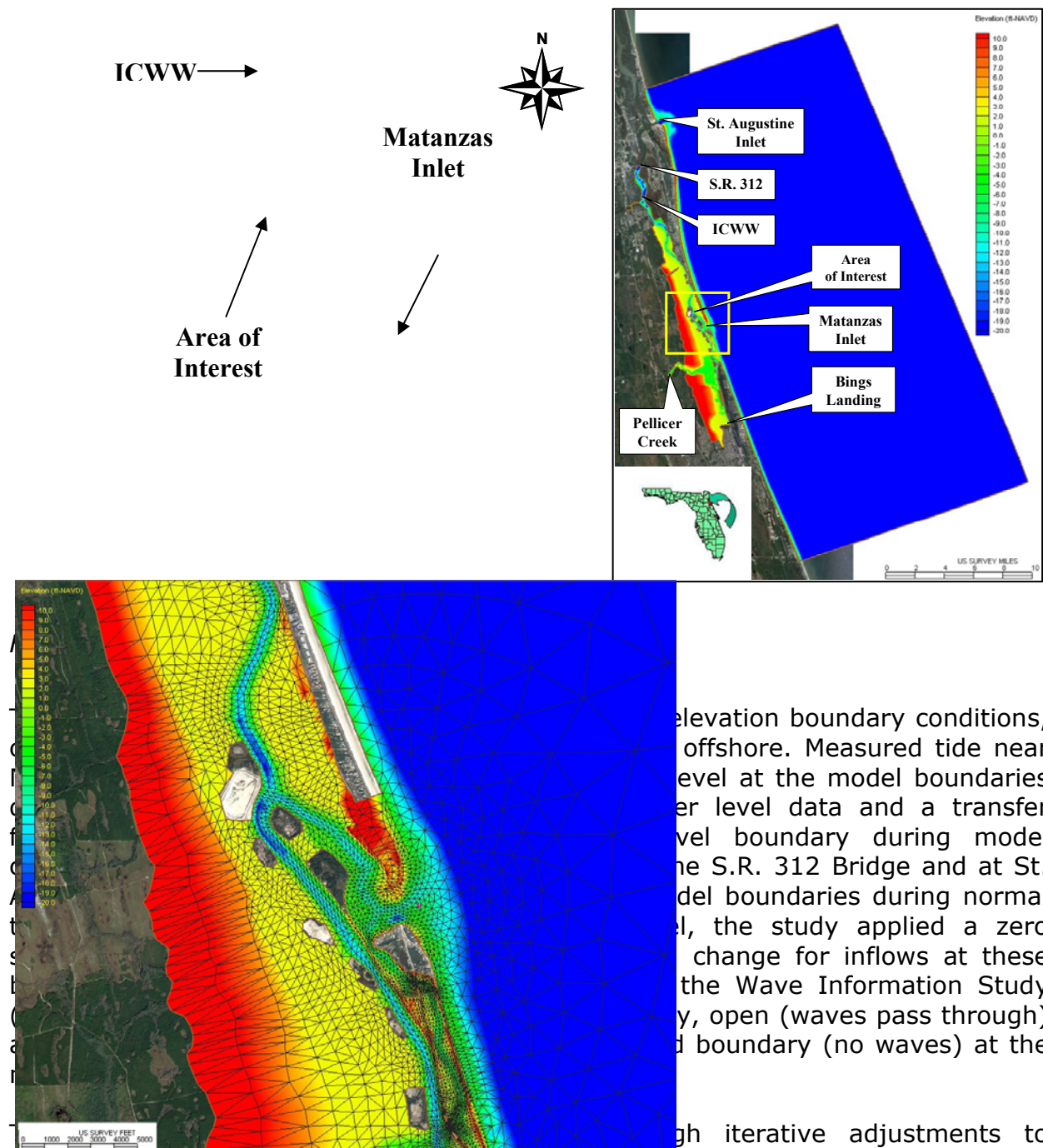


Figure 2: Measured flow velocity (September 4, 2007)

The HD (hydrodynamic), SW (wave), and ST (sediment transport and morphology) models in MIKE21 FM link dynamically: (1) the SW module computes and feeds back wave radiation stresses to the HD module to affect the HD module flow computation; (2) the HD model flow computes the tide- and wave-generated flow velocities that drive sediment transport; (3) the ST model sediment movement results in either erosion or deposition that changes bed elevations or shoreline location; and (4) bed or shoreline changes affect the subsequent SW and HD model computations (i.e., ST model feedbacks bed level changes to the SW and HD models).

To apply the MIKE21 FM model to the study area, the study developed a finite volume grid to map the channel network into the model's input format. The grid divides the model domain into triangles. The size of the triangles usually varies from large sizes in regions far from the study area to very fine sizes at the study area. The MIKE21 FM mesh stretches north-south from the S.R. 312 Bridge to Bings Landing approximately 20.3 river miles (32.7 kilometers) along the ICWW. In addition to this stretch of the ICWW, the mesh includes portions of Matanzas River north and south arms (3.6 miles or 5.8 kilometers), Pellicer Creek (4.7 miles or 7.6 kilometers), Matanzas Inlet (0.7 mile or 1.1 kilometers), Atlantic Ocean (9.1 miles or 14.6 kilometers), and other waterways connected to the ICWW. Spanning the ICWW 2.0 miles (3.2 kilometers) south of downtown St. Augustine, the S.R. 312 Bridge serves as the model's upstream boundary while the offshore Atlantic Ocean

boundary serves as the downstream boundary. The area of interest (adjacent to SMA SJ-1) is located approximately 12.2 river miles (19.6 kilometers) and 7.6 river miles (12.2 kilometers) from the upstream and downstream boundaries. Figure 3 shows the riverbed elevation in feet referenced to the North American Vertical Datum 1988 (ft-NAVD). The left portion of Figure 3, a detailed image of the area within the yellow box in the right portion, shows the model mesh near the area of interest.



Through iterative adjustments to hydrodynamic model parameters until data and model results agreed. For this

study, hydraulic calibration data consisted of the measured tide at Stations T6 and T7 and measured flow velocity at Stations V1 – V3 from August 24 – September 24, 2007. After model calibration, the study then applied the calibrated model parameters for model verification and simulation of normal tide conditions. The model verification data consisted of measured flow velocity at Stations V1 – V3 on July 23 and July 30, 2007.

Calibration occurred through iterative adjustments of friction (Manning's n) until model water surface elevations matched the data reasonably well. The study assigned a Manning's n of 0.025 for the ICWW and Matanzas River, Manning's n of 0.030 to 0.070 for its tributaries and marsh areas, and Manning's n of 0.025 for the offshore area. Figure 4 shows a comparison of the measured and model-simulated water surface elevations at Stations T6 and T7. The figures show excellent agreement between data and model-simulated water elevations during all phases of the tidal cycle. The model-simulated water surface elevation deviates from the more than a month long data set an average of -0.20 foot (0.06 meter) at Station T6 (or 5% of the published mean tidal range at Fort Matanzas) and 0.12 foot (0.04 meter) at Station T7 (or 3% of the averaged published mean tidal ranges at Anastasia Island and Fort Matanzas).

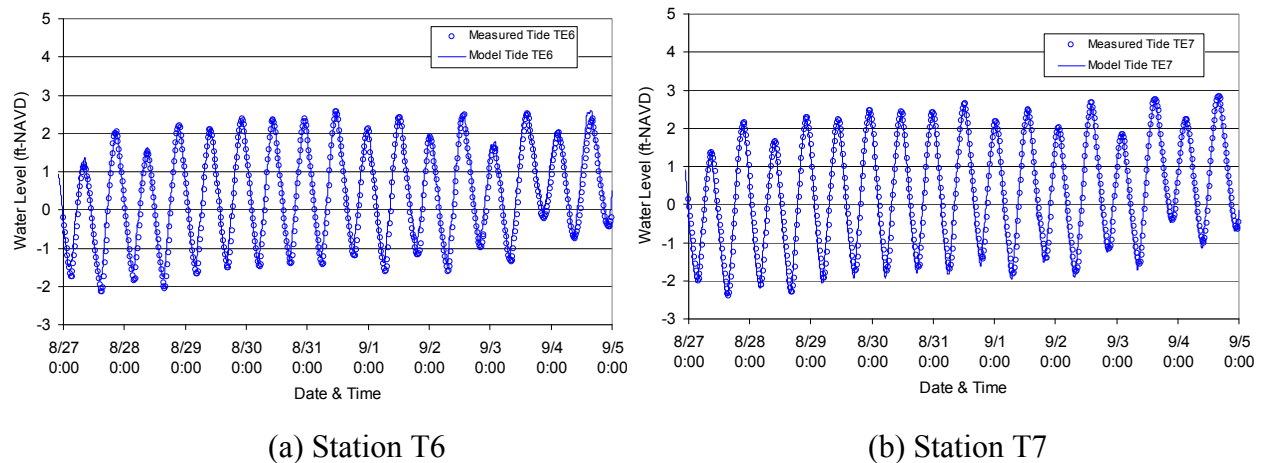


Figure 4: Comparison of measured and model-simulated water surface elevations near Matanzas Inlet (Station T6) and off S.R. A1A (Station T7) during calibration period

Figure 5 show a comparison of the measured and simulated currents at Station V1. The top graphs show the comparison of model-simulated current speed and measured depth-averaged current speed and its corresponding standard deviation. Currents measured at Station V1 ranges 0.0 – 3.0 feet per second (fps) or 0.0 – 0.9 meter per second. Model simulation of current speed at Station V1 compares very well with measurements. The model simulated current speed compared well with data in 11 out of 13 measurements. The maximum discrepancy from measurements was approximately 0.7 foot per second (0.2 meter per second). The bottom graphs show a comparison of the model-simulated and measured depth-averaged current direction. Notably, the directions shown on the bottom graphs

refer to the heading direction relative to north. As examples, headings of 90° and 180° indicate east and south current directions. As shown in the bottom graphs in Figures 5, the model accurately simulated flow direction — an indication that the model simulates well the tidal phase in the model domain. Model simulated velocity at Stations V2 and V3 generally compared well with the measured velocity.

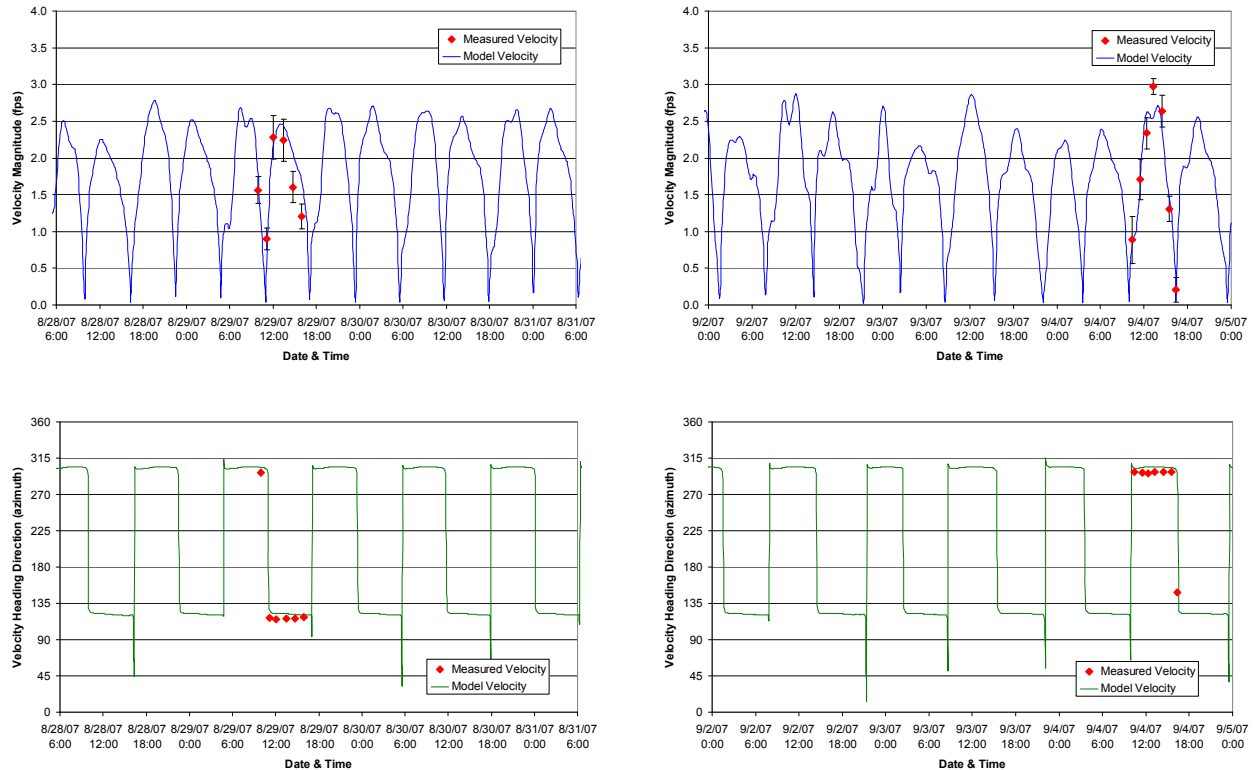


Figure 5: Comparison of measured and simulated flow velocity at Station V1 for calibration period

Model verification ensures that the calibrated parameters apply to simulations outside the calibration period. To verify model performance, the study applied the July 21 – 30, 2007 measured tides as boundary conditions on the calibrated model and compared the model's simulated velocity with the measured velocity at Stations V1 – V3. In general, the model computed velocity agrees well with the measurements.

The absence of available measured wave and sediment concentration data precluded calibration of the wave and sediment transport models. Therefore, the study verified wave model performance by testing the capability of the wave model to simulate the prescribed wave height, direction, and period at the offshore boundary and nearshore area. Results show the wave model simulates well wave propagation and simulates well the changing of wave directions.

The sediment transport model, integrated with the hydrodynamic and wave models, simulated longshore and cross-shore sediment transport. The model input data included sediment porosity of 0.40 and sediment size spatially varied in the model

domain. USACE core sample data from the ICWW and Taylor Engineering (1991) provided the present sediment transport model a mean sediment diameter of approximately 0.15 mm in the ICWW and Matanzas River. Mean sediment ranges (Florida Coastal Engineers, 1976) within the seaward limit of littoral activity (i.e., landward of the 35-foot or 10.7-meter depth contour) for active beaches in St. Johns County provided the present model with a nearshore sediment diameter of 0.11 mm. Mehta and Jones (1977) provided a beach median sediment grain diameter of 0.36 and 0.19 mm in the marsh areas.

The spatial distribution of sediment mean diameters in the sediment transport model provided a sediment transport pattern consistent with inlet, beach, and ICWW hydraulics. In the ICWW, the abrupt decreases in sediment transport rate along the northern tip of Rattlesnake Island explain the historical depositional pattern in the area — sediments from Matanzas River deposit in the ICWW as the flood current swings south to the ICWW. The sediment transport model applies the sediment mass conservation equation to compute changes in bed elevation with the computed sediment transport. The model-computed sediment transport patterns prove consistent with historical observations in the area. These major patterns include (1) formation of the ebb shoal, (2) erosion at Summer Haven beach, and (3) shoaling in the ICWW from Cuts SJ 59 – 61. Because the sediment transport model simulated well the observed morphological changes in the study area, the study considers the sediment transport model and, in general, the integrated hydrodynamic, wave, and sediment transport models sufficient to (1) understand sediment transport forcing mechanisms in the study area, (2) identify potential alternatives to reduce ICWW shoaling, (3) evaluate the performance of alternatives to reduce ICWW shoaling, (4) understand the potential impact of the alternatives to flow and sediment transport, and (5) estimate potential morphological changes associated with modifications to the study area.

Like other state-of-the-art sediment transport models, the model does not usually provide very accurate magnitudes of erosion and deposition. Thus, the study fine-tuned the sediment transport model to reflect an annualized deposition of approximately 71,000 cubic yards (54,283 cubic meters) in Cuts SJ 59 – 61. Notably, Taylor Engineering (1991) provides estimates of approximately 65,000 – 71,000 cubic yards (49,696 – 54,283 cubic meters) per year of sediment deposition in the same area.

EVALUATION OF ALTERNATIVES TO REDUCE ICWW SHOALING

The study — in consultation with the Florida Inland Navigation District (FIND) — evaluated a no-action alternative and three proactive alternatives to reduce ICWW shoaling. The proactive alternatives included constructing a sediment trap or basin in the north arm of Matanzas River, constructing a spur dike off the northern tip of Rattlesnake Island, and extending the existing sediment trap in the ICWW. Evaluation criteria for these alternatives included, in order importance, the following: (1) a reduction in sediment deposition in Cuts SJ 59 – 61, (2) no undesirable effect on sediment transport patterns around the inlet and interior

waters, and (3) a net reduction in maintenance dredging costs. The present study also evaluated the no action alternative to provide baseline data to compare the relative effects of each proactive alternative.

To estimate long-term morphological changes in the study area requires simulation of sediment transport over several years. However, such long-term simulations require lengthy computational time that goes beyond the schedule of the present study. Alternatively, the study simulated two, one-month-long sediment transport scenarios and prorated the computed transport for a typical year (e.g., 1992). Based on previous estimates of local littoral transport, the net littoral transport equal to approximately 400,000 cubic yards (305,822 cubic meters) per year qualified as a typical year. Predicted inshore and offshore tides and hindcast offshore WIS Station 420 waves in a representative month (normal tide conditions) and another month (northeaster conditions) provided the boundary conditions for the two, one-month long simulations. The study prorated the volume that shoaled during these periods to estimate the annual shoaling rate in Cuts SJ 59 – 61. This methodology pivots on the assumption that the month-long normal tide period (April 1992) represents the area's estuarine tidal sediment transport.

Finding a representative month-long period required several model runs and volume computations to identify periods when model-computed shoaling in Cuts SJ 59 – 61 prorates to an annualized rate of approximately 71,000 cubic yards (54,283 cubic meters). This shoaling rate is consistent with the amount of littoral transport captured by Matanzas Inlet. To find a representative northeaster month, the study reviewed the WIS Station 420 wave record to select a month-long period when large waves originated from the northeast quadrant. WIS Station 420 data shows the select month-long period in November – December 1992 had two distinct northeaster events — the first (November 7 – 13) lasted 5.5 days and the second (November 16 – December 2) lasted 21 days. WIS Station 420 data reflect maximum wave heights of 10 feet (3 meters) and wave periods of 4.5 – 8.5 sec during both events. Averaging the shoaling rates from the two events yielded an estimated shoaling rate per northeaster event. Given that the meteorological data show that five northeasters per year affect the Matanzas Inlet area, multiplying the shoaling rate per northeaster event by five yielded an estimated shoal volume in Cuts SJ 59 – 61 from northeasters in a year. The sum of the shoaling attributed to northeasters and tides provides the annual shoaling volume (70,933 cubic yards or 54,232 cubic meters) in the area of interest.

Model results show that constructing a spur dike off the northern tip of Rattlesnake Island or extending the existing sediment trap in the ICWW will not likely reduce shoaling in the area of interest. In addition, model results show that among potential sediment basins in the north arm of Matanzas River, basins located south of Fort Matanzas (i.e., basin does not extend north of Fort Matanzas) will likely also not reduce shoaling in ICWW SJ Cuts 59 – 61.

In assessing the performance of a sediment basin in Matanzas River north arm and north of Fort Matanzas, the study considered five sediment basins — each with a different location, length, and bed elevation — as likely to reduce shoaling in ICWW Cuts SJ 59 – 61 by 62% – 100%. Among these alternatives, a 1,190 feet (363 meters) long, 280 feet (85 meters) wide, 20 feet (6 meters) deep basin seems the most feasible based on estimated construction and maintenance cost. The basin would likely reduce ICWW Cuts SJ 59 – 61 shoaling by 82%. The basin would extend north to the confluence of Matanzas River north arm and the ICWW and south almost to Fort Matanzas. Based on a St. Johns River Water Management District (SJRWMD) 2001 bathymetric survey, depths in this area range 5 – 10 feet (1.5 – 3.0 meters). Thus, construction of this basin would require dredging by as much as 15 feet (4.6 meters) into the riverbed.

Model results indicate the basin would reduce dredging frequency in the ICWW from the current frequency of one dredging operation every three years to one dredging operation every four years. Each dredging operation would remove approximately 312,000 cubic yards (238,541 cubic meters) from the ICWW Cuts SJ 59 – 61 and from the basin at an equivalent uniform annual cost of \$1,261,000. In comparison, the study estimates a current equivalent uniform annual cost of \$1,229,000 to dredge ICWW Cuts SJ 59 – 61. Thus, the results of the cost analysis show this alternative could provide an additional cost of approximately \$32,000 per year.

The additional cost of \$32,000 per year translates to about 4,400 cubic yards (3,364 cubic meters) or a 0.4 foot (0.1 meter) dredge depth in the basin. A depth of 0.4 foot (0.1 meter) is likely within the error of the SJRWMD 2001 bathymetric data with the present day bathymetry of the area because the area's highly dynamic morphology can make the riverbed erode or accrete by more than 0.4 foot (0.1 meter)) in many locations. Thus, the additional cost associated with the alternative could increase or decrease with more accurate bathymetric data.

EFFECT OF BREACHING OF BEACH DUNE

During this study, a storm event in October 2008 created a 200-foot (61-meter) wide breach through the beach dunes in Summer Haven. The breach occurred 0.7 mile (1.1 kilometers) southeast of Matanzas Inlet. As shown in Figure 6, by January 2009, the breach grew twice its original width. Thus, to understand the potential impact of the breach at the area of interest, this study included the evaluation of the Summer Haven dune breach on the area's hydraulics. Model results show the tidal prisms in the area of interest will change by less than 3%. This small change could translate to approximately 5% more sediment transport in the area of interest. The breach will likely reduce the prism at the inlet by less than 7%. Summer Haven River experiences the strongest impact from the breach. Prisms at the S.R. A1A North Bridge will reduce by as much as 62% and the prism at the S.R. A1A South Bridge will increase by as much as 47%. The larger flood prisms in Summer Haven River will likely transport more sediments north and south of the breach. Consequently, shoaling rates near the north bridge will likely increase

without closure of the breach. This breach, however, will likely have a small effect on shoaling at the area of interest.



Figure 6: Breached dune in Summer Haven

CONCLUSIONS

The study considers the numerical model applied in this study sufficient to understand sediment transport forcing mechanisms in the study area; identify potential alternatives to reduce ICWW shoaling; evaluate the performance of alternatives to reduce ICWW shoaling; understand the potential impact of the alternatives to flow and sediment transport; and estimate potential morphological changes associated with modifications to the study area.

Based on model applications, a sediment deposition basin in Matanzas River north arm presents possible solutions to reduce dredging frequency at Cuts SJ 59 – 61. A final assessment would benefit from updated bathymetric information of the Matanzas River and Cuts SJ 59 – 61, and vibracore borings at the basin site and surrounding area. The Summer Haven dune breach that occurred in October 2008 will likely have a small effect on shoaling at the area of interest.

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