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TIDAL ASYMMETRY ANALYSIS OF THE GRAND BAY, MS ESTUARINE SYSTEM AND ITS EFFECTS ON SEDIMENT TRANSPORT

Davina Passeri[1], Matthew V. Bilskie[2], Scott C. Hagen[3]

ABSTRACT

A tidal asymmetry analysis of the diurnal Grand Bay, MS estuarine system was performed to investigate the effect of asymmetry on sediment transport patterns within the estuary. A high resolution hydrodynamic model was used to simulate astronomic tides and extract harmonic tidal constituents and time series plots of water surface elevations and velocities for various locations throughout the estuary. During spring tidal cycles, time series plots show the duration of flood tides are longer than the duration of ebb tides, with peak velocities occurring on ebb tides, characterizing the system as ebb dominant. However, the ebb dominance briefly reverses during neap tidal cycles, when the system temporarily becomes flood dominant. The minimal decrease in the amplitudes of the dominant harmonic constituents and overtides as they propagate through the estuary shows that friction and non-linearities are not responsible for the apparent asymmetry. More likely, the asymmetry is a result of asymmetric oceanic forcing, as asymmetry also exists outside of the estuary.

Calculating the net bed sediment transport rate shows that bed sediments are transported out of the estuary as a result of the system being primarily ebb dominant. Water samples collected in the estuary also show total suspended solid concentrations appear slightly greater during ebb tides.

1. INTRODUCTION

Tidal asymmetry occurs when the offshore tide becomes distorted as it propagates into shallow estuaries. Asymmetry can be characterized by the duration of the flood/ebb tide and the corresponding velocity; if the duration of the flood tide is longer, leading to a strong peak ebb velocity, then the system will be ebb dominant. Likewise, if the duration of the ebb tide is longer, leading to a stronger peak flood velocity, then the system is flood dominant. A flood dominant system will have net sediment transport shoreward (into the estuary), where as an ebb dominant system will have net sediment transport seaward (out of the estuary) (Aubrey & Speer, 1985).

In semi-diurnal regions where the M2 tidal constituent is dominant, oceanic tides generate higher frequency overtides as they enter the estuary's shallow waters (Aubrey & Speer, 1985). These overtides are generated due to non-linear physical processes associated with friction and continuity

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(Speer & Aubrey, 1985). As the overtides grow non-linearly as they propagate through the estuary, the sinusoidal form of the tides becomes distorted (Friedrichs, 1988; Blanton, 2002). Asymmetry can thus be characterized mainly by the M2 constituent and its overtides M4 and M6 (Blanton, 2002). The most straight forward method for determining if asymmetry exists is to examine time series plots of water levels and velocities to determine if there is a lag in the flood or ebb tides, as well as when the peak velocities occur. Speer and Aubrey (1985) developed relationships to classify if an estuary is flood or ebb dominant by determining the relative M2-M4 phase as defined by 2M2-M4. Blanton (2002) adapted this concept to include the M6 overtide, yielding a relative phase calculated by 3M2-M6. The magnitude of asymmetry may also vary throughout the estuary, and can be measured using the ratio of the amplitudes of M4 to M2 (the M4/M2 ratio) (Aubrey and Speer, 1985).

Although tidal asymmetry is not unique to semi-diurnal systems, most studies have taken place in semi-diurnal regions rather than diurnal regions. In diurnal regions, asymmetry cannot be determined using the phase relationships because the M2 overtides are not the dominant cause of asymmetry, as M2 is not the dominant constituent (Ranasinghe, 2000). Often, asymmetry in diurnal regions is a result of an asymmetric oceanic tidal signal due to the interaction of different tidal amplitudes and phase angles. Ranasinghe (2000) examined tidal asymmetry in inlets located in a diurnal region and concluded that if the oceanic tidal forcing is flood dominant, then the channel will also be flood dominant.

This study aims to define the asymmetry of the Grand Bay, MS estuarine system through use of a high resolution hydrodynamic model capable of accurately simulating astronomic tides. Potential effects of how the asymmetry will affect net sediment transport will also be explored.

2. STUDY AREA

The Grand Bay National Estuarine Research Reserve is a federally protected area located in Jackson County, Mississippi (

Figure **1**). It encompasses about 18,000 acres of both tidal and non tidal wetland habitats. The estuary is located in the diurnal region of the Gulf of Mexico, where the O1 and K1 tidal constituents are dominant. M2 is the dominant semi-diurnal constituent. It is a tidally dominated system, although geologic data show the presence of a larger river delta in the area at one point in time. It is believed that the Pascagoula River once flowed through the reserve, emptying into Point Aux Chenes Bay. However, the river changed its course and now flows into the Mississippi Sound, diverting sediments away from the estuary and forcing the system into a retrograde (Peterson, 2007).

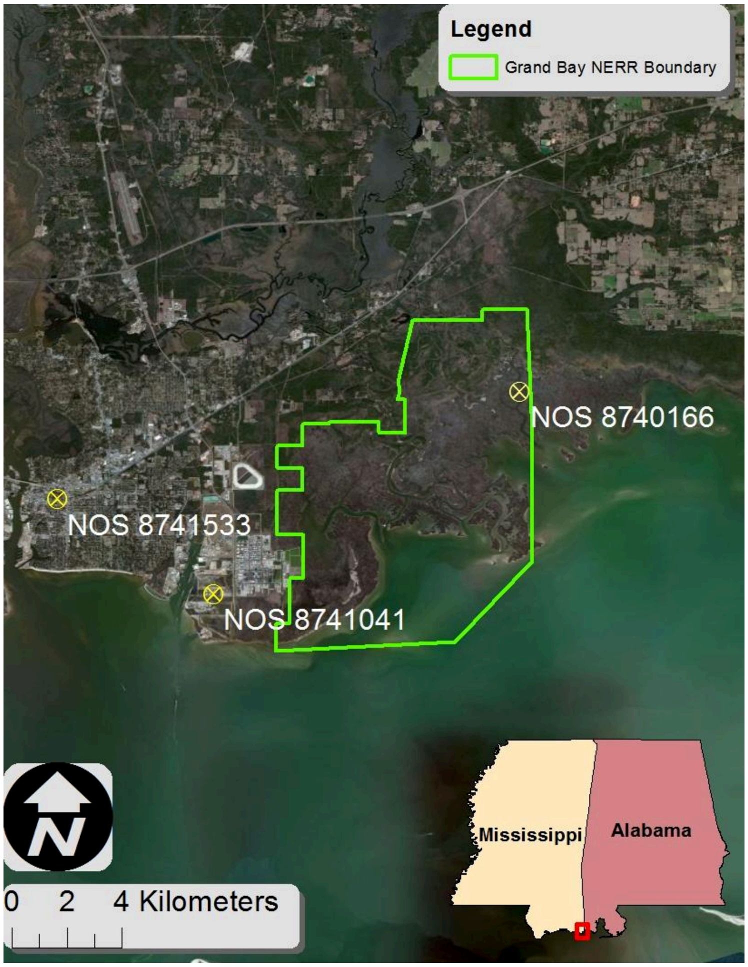
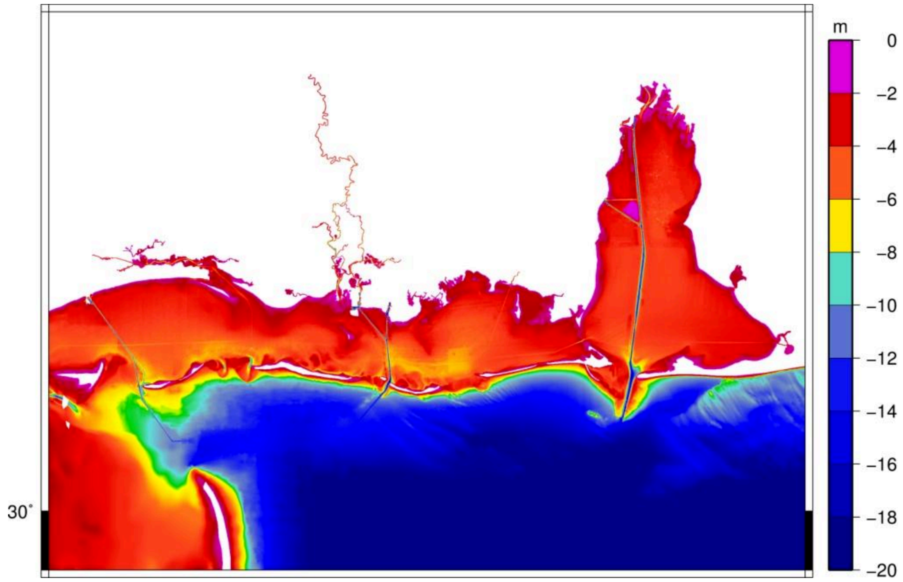


Figure 1 Study area of Grand Bay, MS (outlined) and locations of NOS tidal gauges

3. METHODS

3.1 Hydrodynamic Model

A high resolution ADCIRC (ADvanced CIRCulation) finite element mesh was used in this study to simulate astronomic tides. ADCIRC-2DDI is the two-dimensional, depth-integrated, code which solves the fully non-linear shallow water equations in the form of the Generalized Wave Continuity Equation (GWCE) for water surface elevation and currents in spherical coordinates (Kolar *et al.*, 1994; Luettich & Westerink, 2006; Westerink *et al.*, 2008). The finite element mesh describes the Western North Atlantic Tidal model (WNAT) domain west of the 60 degree west meridian, including the Caribbean Sea and the Gulf of Mexico (Figure **2**) (Hagen *et al.*, 2006; Dietrich *et al.*, 2011). Bathymetric depths were taken from previous finite element meshes of the WNAT domain, including the SL15 and SL16 (overland areas removed) (Bunya *et al.*, 2010; Dietrich *et al.*, 2011). High-resolution was incorporated for nearshore areas West of Mobile Bay, including Mississippi Sound, Grand Bay, Biloxi Bay, Bay St. Louis, and the Pascagoula River. Mesh resolution spans ~30 to 60 meters in the Pascagoula River and ~50 to 200 meters in Mississippi Sound and Grand Bay.



Model bathymetry for nearshore Mississippi and the Pascagoula River was obtained from National Ocean Service (NOS) hydrographic surveys (http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html), US Army Corps of Engineers (USACE) hydrographic channel surveys (http://navigation.sam.usace.army.mil/surveys/index.asp), NOAA's Estuarine Bathymetry (http://estuarinebathymetry.noaa.gov/), and NOAA nautical charts. Since all bathymetric data were referenced to different vertical datums, each dataset was converted to the NAVD88 datum using the VDatum software (http://vdatum.noaa.gov/).

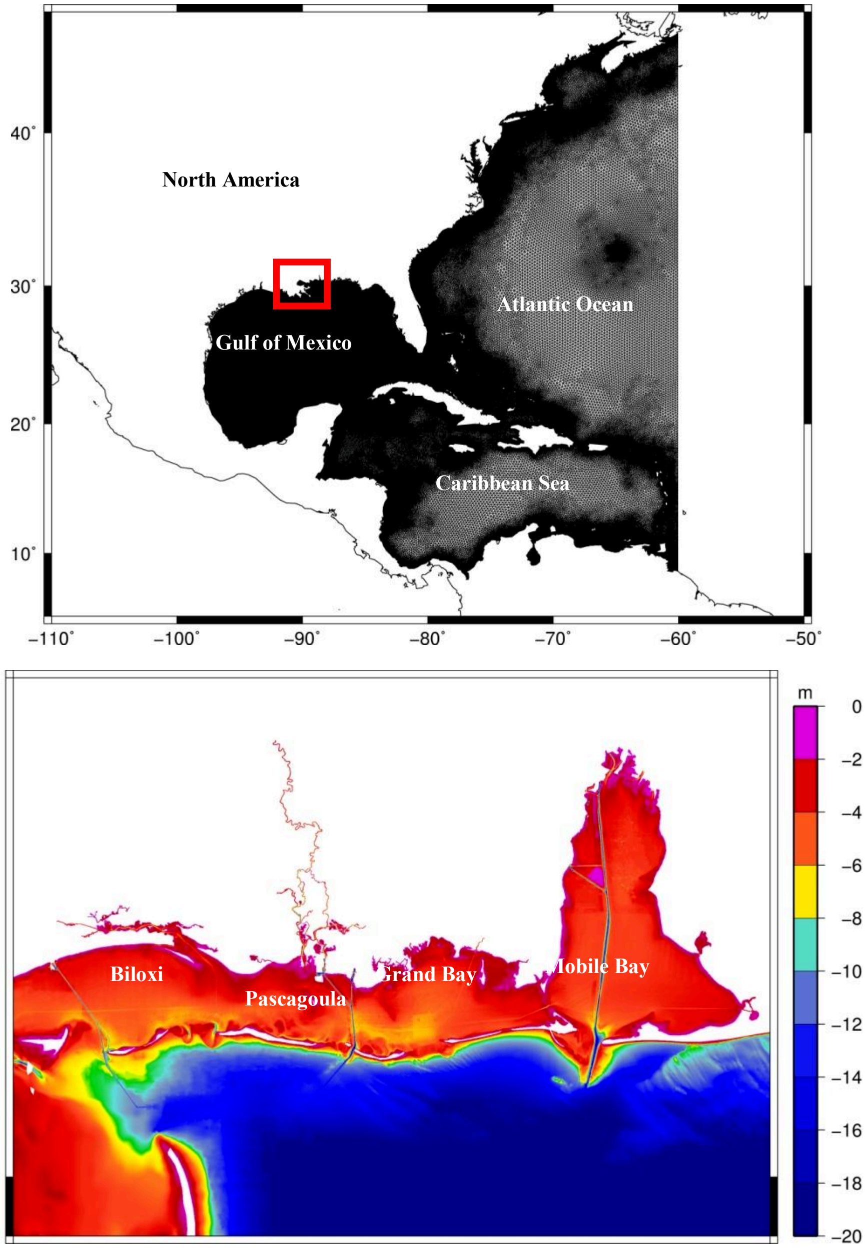


Figure 2 (Above) Extent of finite element mesh with study area outlined, (Below) Model bathymetry

3.2 Astronomic Tidal Simulation

Astronomic tides were simulated for 45 days, beginning from a cold start with a 10-day hyperbolic tangent ramp function. Seven harmonic constituents (K1, O1, M2, S2, N2, K2, and Q1) forced water surface elevations along the open ocean boundary (60^{o} west meridian). Water surface elevations, depth integrated velocities, and amplitudes and phases of elevation harmonic constituents were output at 23 stations throughout the estuary (Figure 3).

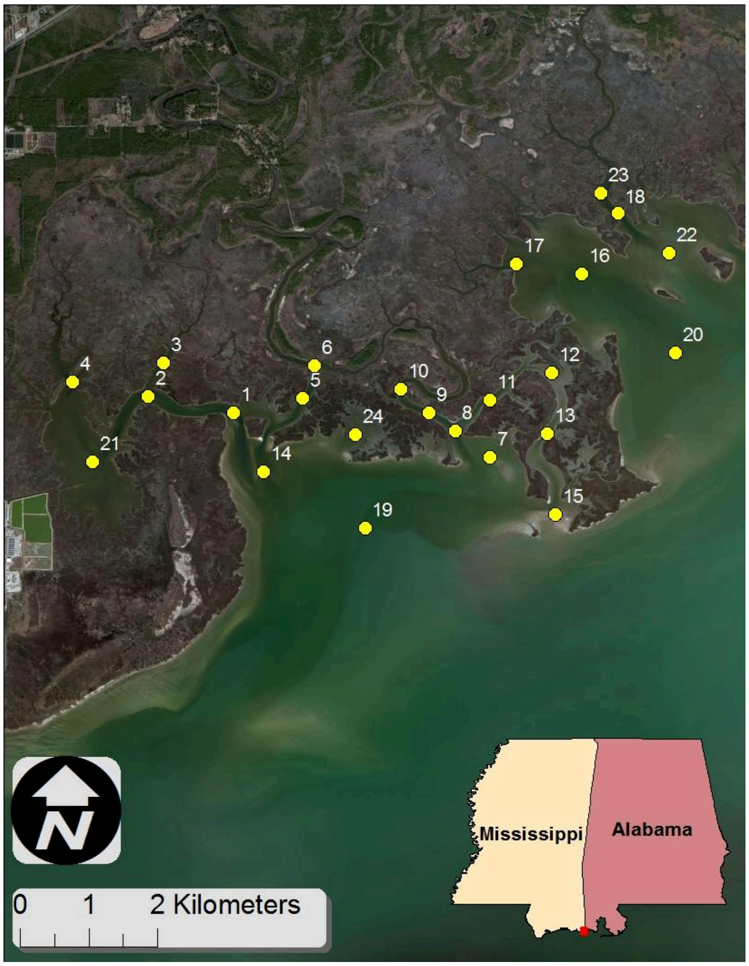
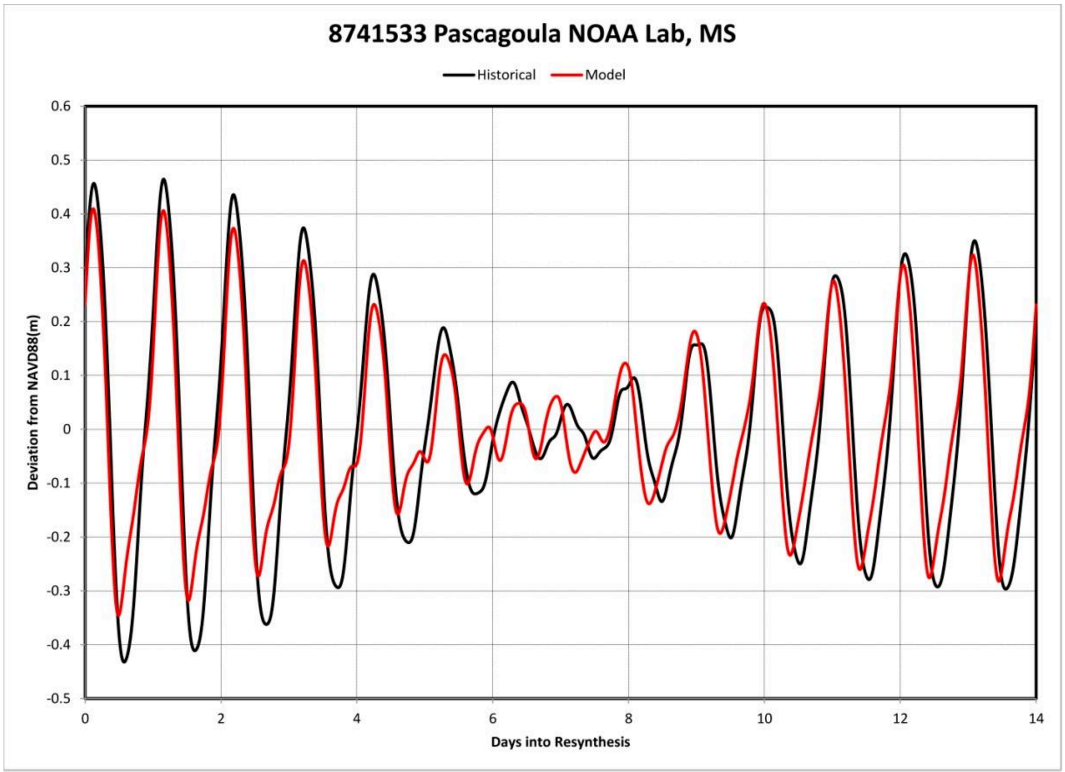


Figure 3 Output locations for astronomic tidal simulation in Grand Bay estuary

3.3 Verification

The model's performance was assessed through a 14 day tidal resynthesis. A comparison of observed versus modeled tides at NOS tidal gauge stations 8741533 and 8741041 show good agreement in phase and amplitude. Overall, the model performs relatively well; however, this tidal model is still under development (

Figure **4**). The model represents the in-bank areas only and does not include the marsh floodplain, which, if included, may improve results of the astronomic tidal simulation in this region (Takahashi, 2008).



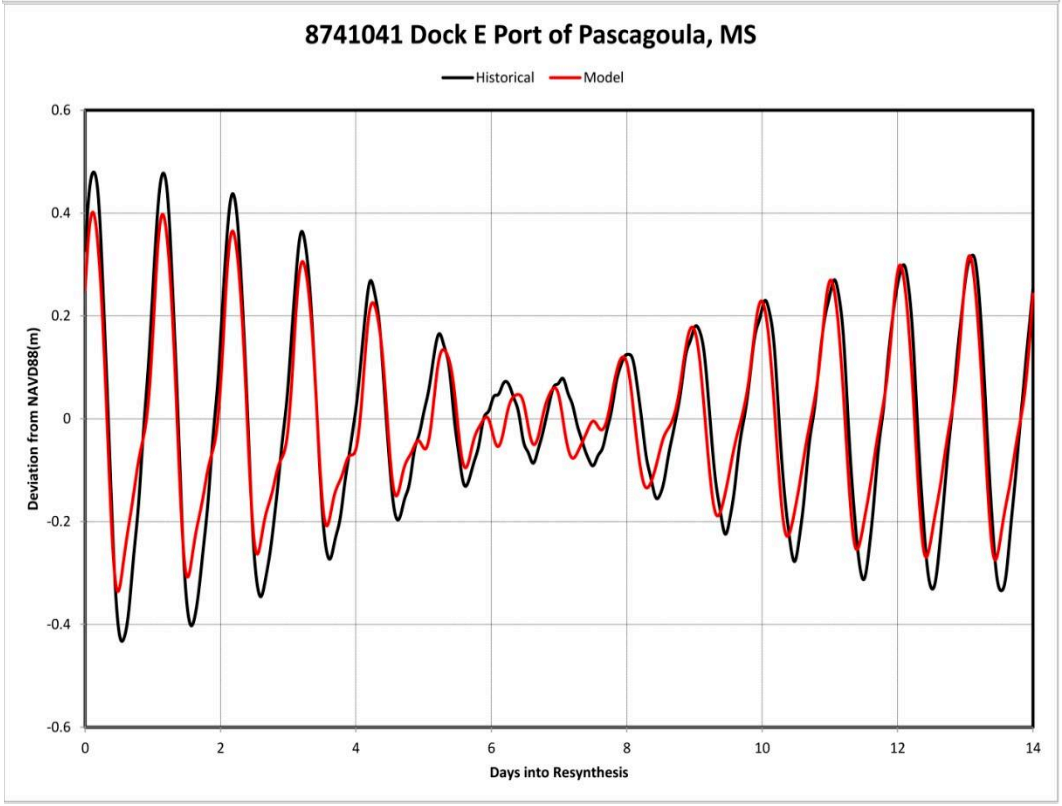


Figure 4 Modeled results compared with historical 14 day tidal resynethesis at NOS tidal gauge stations

4. RESULTS AND DISCUSSION

4.1 Tidal Asymmetry

Examining time series plots of water surface elevations and depth integrated velocities show similar results at each station. During the spring tide cycle, the duration of the flood tide is longer than the duration of the ebb tide, with peak velocities occurring on ebb tides. This characterizes the system as ebb dominant. However, during the neap tide cycle, this ebb dominant asymmetry briefly reverses; the duration of flood tides become equal or greater than that of ebb tides, and peak velocities are slightly greater during flood tides. This flood dominance lasts for approximately one day, and then the system reverts back to ebb dominance (

Figure **5**). Similar behavior is exhibited at all of the output stations both outside and inside the estuary (

Figure **6**). Temporal variation within the spring and neap cycle is often observed in diurnal regions due to the fact that the O1 and K1 constituents are not exactly half of their dominant diurnal counterparts (M2, S2) (Sivakholundu, 2009). In this region, the O1 and K1 amplitudes are more than twice as large as the M2 amplitude, and five to six times as large as the S2 amplitude. Because this system is most frequently ebb dominant, it is expected that net sediment transport will be directed out of the system (seaward).

Harmonic analysis shows the dominant tidal constituents in the estuary are the diurnal O1 and K1 constituents, and the semi-diurnal constituent M2. The frictional nature of estuaries can be demonstrated by the significant decay of all semi-diurnal and diurnal constituents, with associated large phase lags (Aubrey and Speer, 1984), which in turn can cause asymmetry. The amplitudes of the O1, K1 and M2 constituents minimally decrease or remain about equal as they propagate through the tidal creeks. The largest difference from outside of the tidal creek to the inner most station of the tidal creek is on the order of 2 cm, or a 9% difference. The phases also slightly increase or remain equal with propagation; the largest increase is about 19°, although most phases remain relatively equal (

Table **1**). This indicates that friction is most likely not a driver in the estuary's asymmetry. The primary indicator of non-linearity in an estuary is the steady increase of the amplitude of the M4 or M6 overtides with distance into the estuary (Aubrey & Speer, 1984). The amplitudes of the M4 overtide either decrease with distance into the estuary, or remain the same (

Table **1**). The M6 amplitudes can be considered negligible, as their amplitudes are typically less than 0.1 cm. This indicates that non-linearities are absent in the estuary, and therefore are not a cause of the observed asymmetry. Because asymmetry is observed at stations inside and outside of the estuary, asymmetry in the oceanic forcing is most likely the source, as Ranasinghe (2000) also concluded.

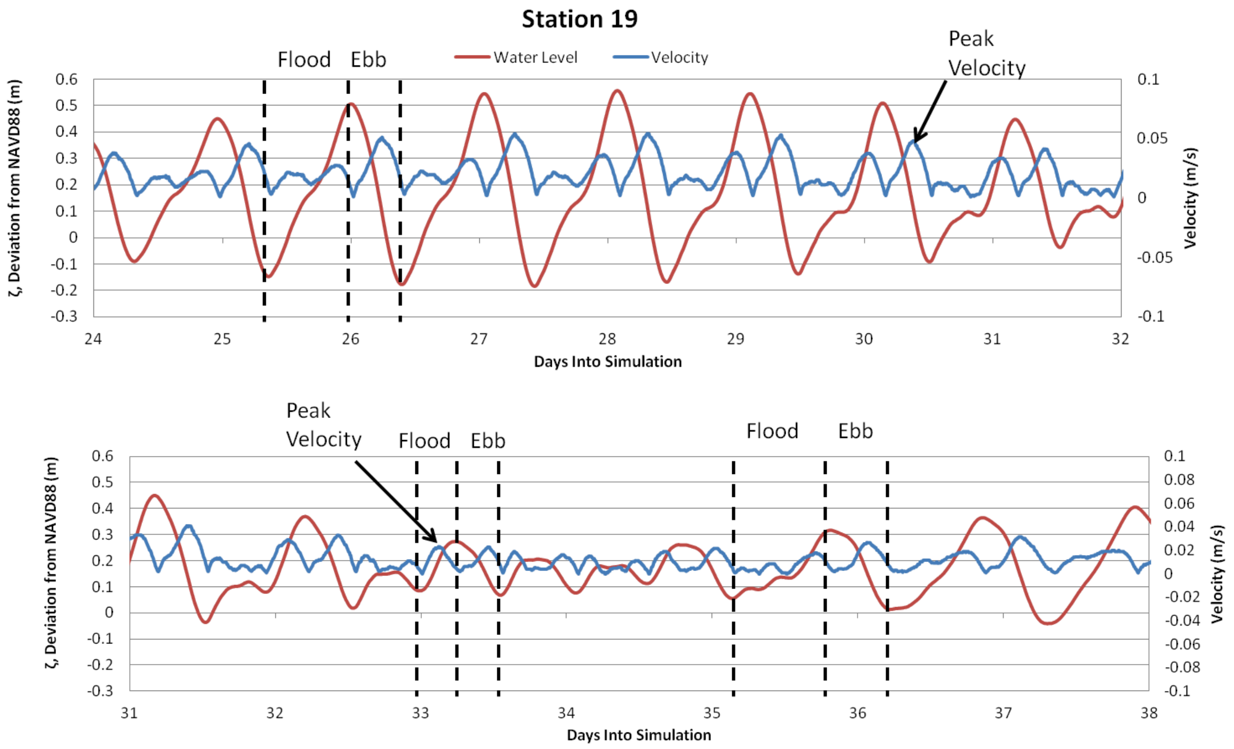


Figure 5 Time series water surface elevations and velocities at Station 19 (outside of the estuary)

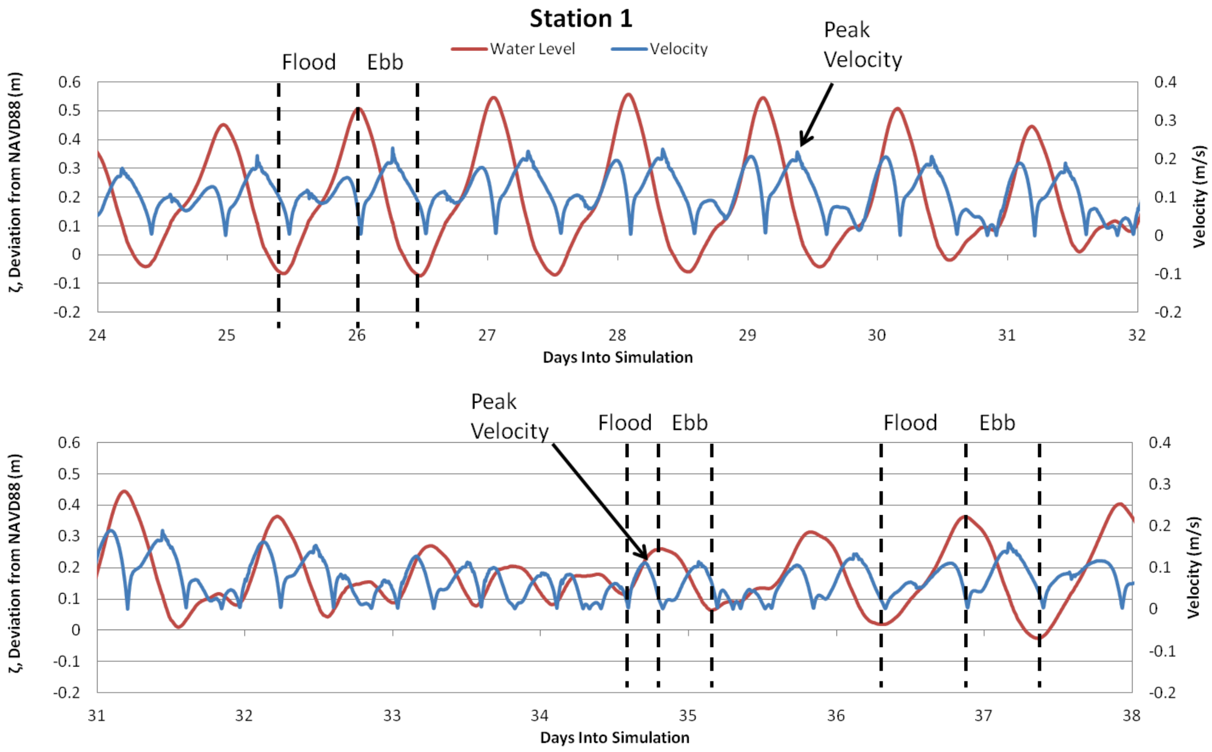


Figure 6 Time series water surface elevations and velocities at Station 1 (inside of the estuary)

Table 1 Dominant tidal constituents and overtides (amplitude in cm, phase in degrees)

	O1		K1		M2		M4		M6	
Station	**Amplitude**	**Phase**	**Amplitude**	**Phase**	**Amplitude**	**Phase**	**Amplitude**	**Phase**	**Amplitude**	**Phase**
1	13.09	34.83	14.04	35.31	5.30	115.69	0.47	70.76	0.07	220.49
2	12.81	43.28	13.62	43.30	4.54	125.08	0.37	128.57	0.14	235.19
3	12.81	43.56	13.62	43.59	4.53	125.57	0.37	128.46	0.13	235.96
4	12.78	49.03	13.53	49.11	4.30	133.77	0.51	154.05	0.19	250.66
5	13.87	28.64	14.63	30.24	6.40	117.99	0.75	80.90	0.06	172.22
6	13.88	28.74	14.63	30.34	6.41	118.17	0.76	81.28	0.06	173.43
7	14.09	25.43	14.83	27.32	6.79	114.81	0.80	67.64	0.08	168.03
8	14.09	25.76	14.84	27.64	6.79	115.45	0.81	68.93	0.08	174.44
9	13.45	26.78	14.20	28.35	6.60	111.50	0.72	64.06	0.11	182.33
10	14.02	26.01	14.88	28.13	6.77	115.12	0.85	65.96	0.04	173.76
11	14.09	26.11	14.84	27.99	6.81	116.10	0.86	70.81	0.06	178.33
12	10.19	36.72	11.10	33.95	6.33	87.41	0.57	21.19	0.22	215.77
13	10.18	36.43	11.09	33.63	6.34	87.04	0.57	17.98	0.23	213.92
14	14.08	25.54	14.82	27.44	6.78	115.08	0.79	68.55	0.08	171.40
15	14.09	25.55	14.83	27.45	6.79	115.10	0.81	68.26	0.09	170.38
16	14.19	26.30	14.96	28.15	6.92	116.87	0.92	73.24	0.13	172.96
17	14.19	26.33	14.96	28.18	6.91	116.95	0.93	73.37	0.14	172.90
18	14.19	26.39	14.96	28.24	6.92	116.99	0.93	73.55	0.13	173.89
19	14.07	25.38	14.82	27.29	6.77	114.78	0.79	67.44	0.08	167.76
20	14.17	26.13	14.94	28.00	6.91	116.54	0.90	72.33	0.13	173.44
21	12.77	48.86	13.52	48.93	4.29	133.40	0.50	153.45	0.19	250.09
22	14.19	26.28	14.96	28.12	6.91	116.78	0.92	73.20	0.13	172.89
23	14.19	26.40	14.96	28.25	6.92	117.01	0.93	73.59	0.13	173.98

4.2 Sediment Transport

To begin to understand how this asymmetry may affect sediment transport patterns, the bed sediment transport rate, q (g cm^{-1} s^{-1}), was calculated using the equation given by Gadd (1978):

$$\boldsymbol{q = \beta(u - u_{TH})^3} \tag{1}$$

where β is the empirical constant (4.48 x 10^{-5} g s^2 cm^{-4}); u is the tidal velocity; and u_{TH} is the threshold velocity for initiation of sediment transport. The threshold velocity is determined to be 20 cm/s through use of the Hjulstrom curve (Hjulstrom, 1935), assuming a median grain size (D_{50}) of 0.026 mm for the estuary (the median grain size found through field research in a similar Mississippi river delta estuary) (Marshak, 2011). The calculated values of q are negative for the entire simulated tidal cycle at every station, indicating net bed sediment transport is directed out of the system, as expected due to its ebb dominant nature (
Figure 7).

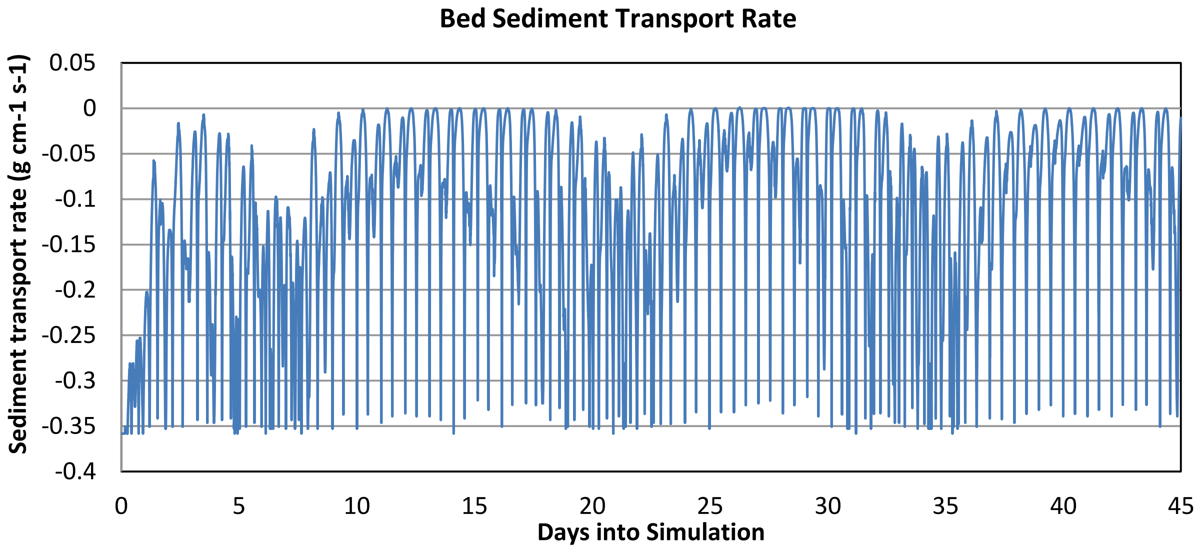


Figure 7 Calculated bed sediment transport rate at station 1 based on equation 1

To investigate potential effects on the suspended sediment transport, results were compared with water samples collected on a tri-hourly basis over a full 14-day tidal cycle at three locations in the Grand Bay estuary during the wet season in July 2012 (Figure 8). Each sample is a 5 ft, depth integrated water column that is analyzed for total suspended solids (TSS). TSS concentrations are plotted against observed water levels at NOS tide gauge 8740166 located in Grand Bay, MS (Figure 8). At all three locations, a base TSS concentration of about 50 mg/L and less appears to exist. At the GBOL1 location, TSS concentrations appear to be elevated during ebb tides, indicating that the concentration of sediment is higher when the tide is going out (

Figure 9). This may be explained by the ebb dominance of the system, in which the net sediment transport will be directed out of the estuary. During the evening of July 24th, at the beginning of the neap cycle, an elevated TSS concentration appears during a flood tide. This elevation could be related to the change in symmetry during the neap cycle, however further exploration should be made to determine if it is a result of atmospheric effects such as winds. At the GBOL2 location, there are only a few elevated TSS concentrations, but all were captured again during the ebb tide (

Figure 9). At the TSS200 location, all samples seem to yield sediment concentrations within the baseline, although the base concentrations during the ebb tides appear to be slightly elevated in comparison to the flood or slack tides (

Figure 9).

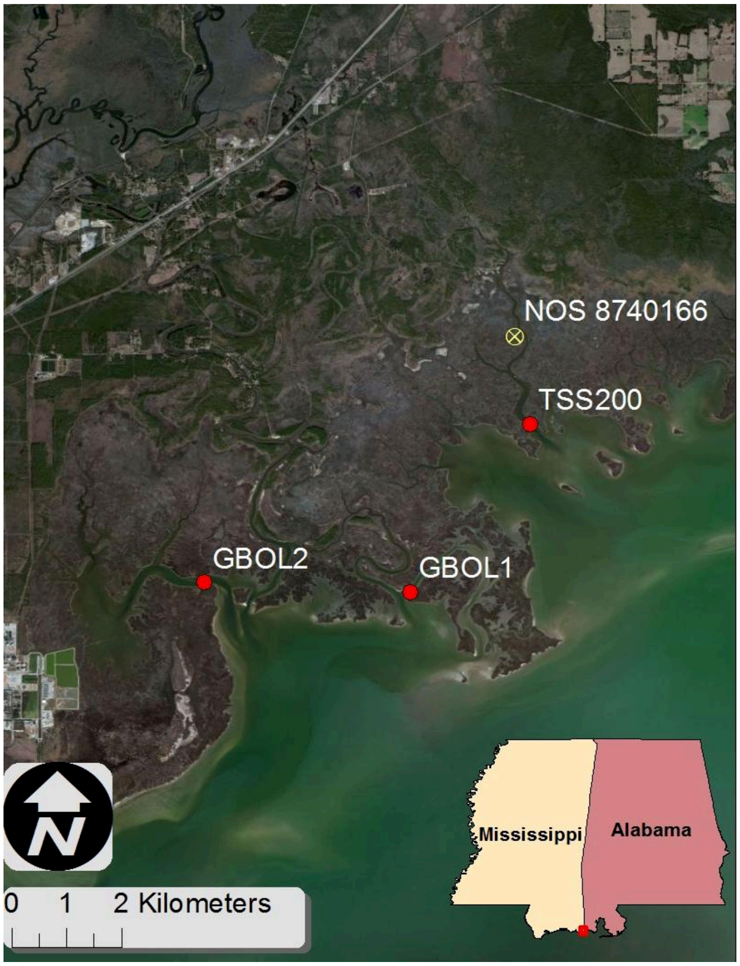


Figure 8 Locations of TSS samples and NOS gauge in Grand Bay, MS

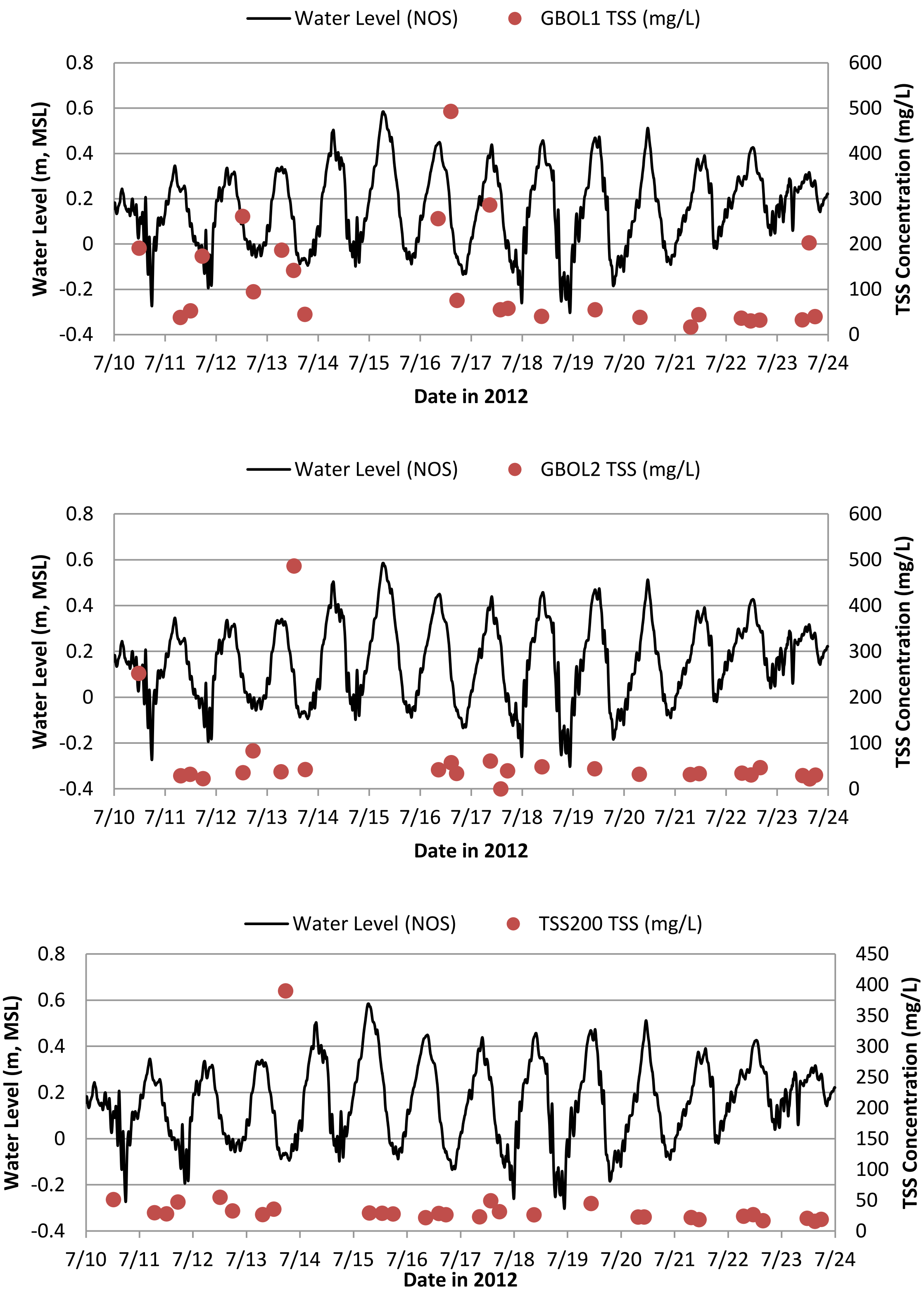


Figure 9 TSS concentrations compared with observed water levels during July 2012 at three locations in Grand Bay, MS

5. CONCLUSIONS

Time series water surface elevation and velocity plots indicate that the Grand Bay estuary is an ebb dominant system, although it may periodically switch to flood dominance during neap tidal cycles. The minimal decay in amplitude of the dominant O1, K1 and M2 constituents indicate that friction does not play a major role in causing the asymmetry. Likewise, because the amplitude of the M4 overtide either decreases or remains the same, non-linearities are appear to be generating the apparent asymmetry. The most likely driver of the estuary's asymmetry is asymmetry present in the oceanic tidal forcing.

Calculating the bed sediment transport rate confirms that ebb dominance causes net bed sediment transport out of the estuary. TSS concentrations determined from collected water samples taken within the Grand Bay estuary also indicate the presence of higher concentrations of sediment on ebb tides.

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