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Simulating the impact of medium and large diversions on the hydrodynamics in the lower Mississippi River Delta

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ABSTRACT: The Mississippi River, which forms one of the world's largest watersheds, is also one of the world's most engineered river systems. Due to the presence of control structures and levees, necessary for flood protection and maintenance of navigation routes to a number of economically important ports, the lower Mississippi River Delta has become hydrodynamically isolated from the River. This has resulted in the deprivation of the sediments and nutrients vital for wetland maintenance and regeneration. The Delta is also being impacted by large subsidence rates resulting in relative sea level rise of up to 1 cm/year; higher than many other delta systems throughout the world. One of the solutions being proposed to reverse or slowdown wetland loss are medium- and large-scale river and sediment diversions. Properly located and designed diversions would recreate the historical delivery of river water and sediments into the coastal wetlands. A calibrated and validated two-dimensional hydrodynamic model of the lower River (from New Orleans down to the Gulf of Mexico) has been developed that includes all of the lower River passes and many of the dynamic forcings from the Gulf. Steady state solutions for water surface elevations at gage locations match well with observational data and the distribution of river flow among the different sections of river channel and passes capture the behavior of the limited field data available. In this paper, the influence of two diversions on the navigation and sediment transport behavior of the system is investigated. The first, West Bay (River Mile 4.7) was built in 2003; the second is a proposed diversion further upriver (River Mile ~30) around the Empire Area. Numerical modeling results are shown demonstrating the impacts on river stages, flow distribution through the passes and other uncontrolled sections of the lower River. River passes. The impact of proposed Empire diversion is more significant than the West Bay Diversion.

Keywords: Hydrodynamics, Simulation, Shallow Water, Lower Mississippi River, Diversion

1 INTRODUCTION

1.1 *Lower Mississippi River Delta (LMRD)*

The Mississippi River system drains approximately 3,224,600 km^2 representing about 41% of the 48 contiguous United States and two Canadian provinces (Knox, 2007). The Mississippi River ranks seventh worldwide in both annual sediment and water discharge with an annual average flow rate of 14,000 m^3/s and a freshwater discharge onto the continental shelf of 580 km^3 per year. The river discharge into the Gulf of Mexico is distinctly seasonal, with highest flows occurring between March and May and lowest flows occurring during August and October (USACE, 2004).

1.2 *Land Loss Problem in LMRD and Diversions*

In natural systems, large, fine-grained deltas subside due to sediment compaction, faulting, and other effects. Subsidence is counteracted by overbank sediment deposition and avulsion into low areas. The result is a delta in which subsidence and sedimentation balance over time (Kim *et al.*, 2009). This balance in the natural Lower Mississippi River Delta has been disturbed over the last century due to first levee construction. Since the mid 1800s, the lower Mississippi river has been canalized and shortened by 230 kilometers and 2,700 kilometers of levees were built along the river (Wiener *et al.*, 1998). Also, the construction of many storage dams and reservoirs on rivers in the watersheds of the upper tributaries has greatly reduced the sediment load of the Mississippi River. The sediment totals have decreased to between 150-200 million tons annually, which is almost half of the estimated load from the period of 1850 to 1963 (CREST, 2006). Hydrologically isolation of the river by the levees, decline of river-borne suspended sediments, natural causes such as sea level rise and geological subsidence, anthropogenic factors such as dredged canals and associated spoil banks are all causing an average loss of approximately 88 km^2 per year of Louisiana coastal wetlands (Mossa, 1995). In addition, these factors are all contributing to a relative sea level rise in some areas as high as 1 cm/year (USACE, 2004).

One proposed method of reestablishing the historical flow and sediment patterns is the use of river diversions (Mossa, 1995). Freshwater diversion projects are designed to create, nourish, and maintain emergent wetlands within a project area over a selected project life by enhancing the natural process of delta growth and, if available, through the beneficial placement of material dredged during construction and maintenance. It is predicted that these diversions will result in tidal flats that are intermittently flooded and suitable for marsh development (DeLaune et al., 2003 and USACE, 2004).

Along the Mississippi River above Head of Passes (River Mile -0.6) a number of freshwater diversion projects have been proposed by the Coastal Wetlands Planning, Protection and Restoration Act (CWPPRA) located at various potentially favorable reaches, most of these are located at former crevasse sites. One of those projects, West Bay Sediment Diversion opened in November 2003, and is located on the right descending bank of the Mississippi River in Plaquemines Parish, LA, at River Mile 4.7 above Head of Passes. Another potential diversion site is located at Empire around River Mile 30. In addition to West Bay, two diversion structures in the LMRD that have been built are the Caernarvon Freshwater Diversion into Breton Sound opened in 1991and the Davis Pond Freshwater Diversion into the Barataria estuary opened in 2002. Both of those diversions have much less capacity than West Bay and the ones proposed by CWPPRA.

Freshwater and sediment diversions are very complicated systems involving many design components and large amounts of data uncertainty (Willson *et al*., 2007). Numerical models can be used as tools to help weight the costs of constructing and managing a diversion against the potential benefits it will provide. Also, the construction and efficient operation of river diversions will require an understanding of the impact of the diversion on the hydraulics and sediment transport in the river in the receiving wetlands. Proper design and management of the diversion structures will optimize the capturing of the appropriate water discharge and transport of sediment and nutrients within the diversion channel.

Another effect of freshwater diversions that should be investigated is their impact on navigation. The Mississippi river and its ports belong to one of the most important economic gateways in the United States. Therefore it is of great importance to keep the river navigable. The U.S. Army Corps of Engineers maintains, with dredging, a minimal water depth of 13.7 meters. In addition, a major concern to the shipping industry is the effect of large-scale diversions on the river hydrodynamics and the ability to maintain vessel control.

This study focuses on the use of a two-dimensional hydrodynamic model to capture the hydrodynamics of the LMRD (main river reach and passes) under existing conditions. After calibration and validation, the model is used to study the influence of two river diversion structures. Hydrodynamic simulations for West Bay and a hypothetical diversion near Empire will be assessed to investigate their flow capacity and impact on the river hydraulics.

2 NUMERICAL MODELING

2.1 *ADH Modeling System*

The Advanced Hydraulics (ADH) Modeling System developed and supported by the Coastal and Hydraulics Lab of Engineer Research and Development Center (ERDC) of US Army Corps of Engineers (USACE) is a finite element software package that can handle saturated and unsaturated groundwater flow, overland flow, three dimensional Navier-Stokes flow and two or three dimensional shallow water problems. The 2D shallow-water equations used for this application are a result of the vertical integration of the equations of mass and momentum conservation for incompressible flow under the hydrostatic pressure assumption. ADH is equipped with a friction algorithm that automatically adjusts the friction for variations in water depth.

ADH is an implicit code and therefore, the time step size is not stability limited for the linear problem (i.e., not limited to the stability conditions imposed by the Courant–Friedrichs–Lewy (CFL) number). As a result the model can take larger time steps; hence, reducing the turnaround time on time-critical simulations. However, nonlinear instability will occur if the time step is too large. Additionally if the time step size is excessively large, simulation accuracy will suffer. To select the most appropriate time step, ADH utilizes a Pseudo-Transient Continuation with a limit on the maximum time step length (Tate, McAlpin, & Savant, 2009).

The major strength of ADH is its ability to dynamically refine the domain mesh in areas where more resolution is needed at certain times due to changes in the flow conditions. This process is done by normalizing the results so that an error quantity is determined for each element. If this error exceeds the tolerance set by the user, then the element is refined. ADH is also able to unrefine previously refined areas when the added resolution is no longer needed however, the adaption would not make the mesh coarser than the initial one (Berger and Tate, 2009).

The wetting drying capabilities of ADH within the marsh areas as the water level changes is ideal for shallow marsh environment. This tool is being developed at CHL and has been used to model sediment transport in sections of the Mississippi River, tidal conditions in southern California, and vessel traffic in the Houston Ship Channel (Gambucci, 2009).

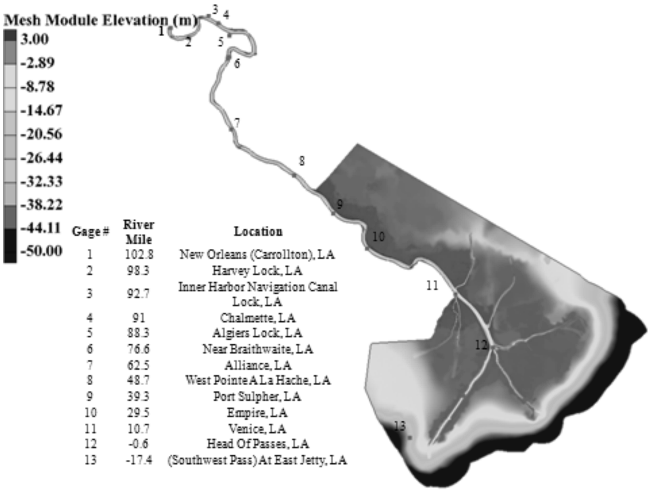
Another major benefit of ADH is its portability, i.e. the ability to run on any number of processors and machines ranging from a standard PC to high-end supercomputers on both Windows and UNIX based systems. The ADH code has been parallelized using a Single Processor Multiple Data (SPMD) approach. The domain is decomposed using the METIS graph partitioning libraries. The communication between processors is explicitly defined using Message Passing Interface (MPI) calls (Hallberg, 2006).

2.2 *Mesh Generation and Model Domain*

An unstructured finite element mesh was developed. Elevation data for the finite element mesh came from five different sources. One source of topography data is LIDAR measurements made in 2002 of land elevations; these are acquired from "Atlas: The Louisiana Statewide GIS" (ATLAS, 2009) in the form of edited XYZ ASCII files. Another set of LIDAR data was acquired from National Oceanic and Atmospheric Administration's National Ocean Service (NOAA, 2009). Although the NOAA set of data comes from more recent measurements (i.e., 2005), it did not cover most of the land sections in this study area. The 2004 Mississippi River hydrographic survey book (USACE, 2007) and routine hydrographic surveys (USACE, 2009a) performed by New Orleans District to monitor local river and waterway navigation conditions were used for the river bathymetry. Other elevation data, not available from the above data sources, are obtained from a high resolution coastal mesh previously developed at the University of Notre Dame under contract to the USACE for use in surge probability evaluation, hurricane protection planning, and coastal restoration planning (Westerink et al., 2006).

A reach of the Lower Mississippi River from Carrollton (New Orleans) at River Mile (RM) 103 down to the Gulf of Mexico as deep as 80 m was selected as a study area. The developed mesh (see Figure 1 for model domain and elevation contours) contains 214,515 nodes and 424,207 elements. The total area of the mesh is 3.97×10^7 m^2 with node spacing as low as 40 m.

The hydrodynamic model is calibrated and validated by using the gage readings taken by USACE (2009b) at 13 river locations (Figure 1). Note that River Mile 0 is located at the Head of Passes near Gage 12. Continuous discharge data is available at Tarbert Landing (RM 306.3). Because there are no significant additions or losses of water between this station and the study area, 2 days lagged flow data at Tarbert Landing was used to obtain stage hydrographs at gages for the water years between 1987 and 2009 after excluding extreme values and non-physical outliers. Mean and standard deviation river stage values at each gage corresponding to 708 m^3/s (25,000 cfs) discharge intervals are calculated to represent the observation data for comparison with model results.



Gage #	River Mile	Location
1	102.8	New Orleans (Carrollton), LA
2	98.3	Harvey Lock, LA
3	92.7	Inner Harbor Navigation Canal Lock, LA
4	91	Chalmette, LA
5	88.3	Algiers Lock, LA
6	76.6	Near Braithwaite, LA
7	62.5	Alliance, LA
8	48.7	West Pointe A La Hache, LA
9	39.3	Port Sulpher, LA
10	29.5	Empire, LA
11	10.7	Venice, LA
12	-0.6	Head Of Passes, LA
13	-17.4	(Southwest Pass) At East Jetty, LA

Figure 1. Elevation contours and gage locations within the model domain

The mesh, used for the calibration and validation simulations, includes the West Bay Sediment Diversion, the largest constructed sediment diversion in Louisiana. The West Bay diversion was initially constructed using a hydraulic cutter head dredge with a pipeline transport system (Figure 2). After construction the diversion has grown over time expanding to 22.5 m deep and 150 m wide and having a capacity of 1400 m^3/sec. The model has been run with and without the diversion included (Figure 2) with different boundary conditions to investigate the effect of the diversion on the general river hydrodynamics.

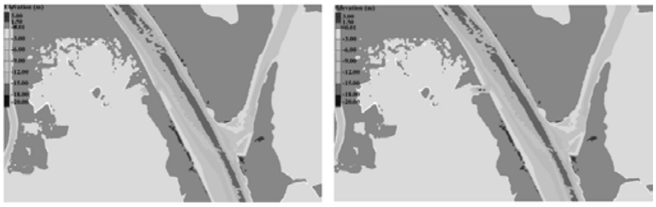


Figure 2. Elevation contours with and without West Bay Diversion

Another test case for investigating the impact of a diversion involved locating a hypothetical river diversion located further upriver near Empire (RM 30), Louisiana. A mesh for that area, previously developed by Dill (2007), is modified and combined with the current mesh (Figure 3). The diversion channel used at that area is 10 m deep and 245 m wide with a capacity over 2,830 m^3/sec (100,000 cfs).

Figure 3. Current Mesh with Hypothetical Empire Diversion

The number of nodes in this mesh is 228,907 and the number of elements is 452,908.

Running simulations with large meshes has become much easier in recent years, as computational resources have become more powerful and easier to utilize. In this study, Louisiana State University Center for Computation and Technology (CCT), The Louisiana Optical Network Initiative (LONI) and Coastal Environmental Modeling Laboratory (CEML) High Performance Computing resources are utilized extensively. Although these kind of complex models cannot simulate events at the decade-scale, having model times on the order of months can supply useful information on important river processes and management schemes. Utilization of High Performance Computing allows for one-day dynamic hydrodynamic simulations to be completed in less than one hour of CPU time.

Steady state solutions were obtained using constant inflow and tailwater boundary conditions. Three flow rates; 11,327 m^3/sec (400,000 cfs), 22,654 m^3/sec (800,000 cfs) and 28,317 m^3/sec (1,000,000 cfs) which represent low medium and high flow levels in the Lower Mississippi River Delta were applied for the inflow boundary conditions. Three tailwater conditions (0.00 m, 0.35 m and 0.70 m) were applied for each of the flow rates providing a total of nine simulations.

The tail water elevation boundary conditions were determined for nodes along the model open water boundary by calculating the low, mean and high water levels in Gulf of Mexico using ADCIRC Tidal Database (Mukai *et al.,* 2002) and T_Tide Harmonic Analysis Toolbox (Pawlowicz *et al.,* 2002). To look at potential impacts of future sea level rise, we will use the simulations made at 0.35 m tailwater to represent normal current day conditions and simulations made at 0.7 m tailwater as normal conditions at a future date. For reference, eustatic sea level rise occurred at a rate 1-2 mm/year in the twentieth century (USACE, 2004).

3 RESULTS AND DISCUSSION

Hydrodynamic action is the most important mechanism involved in transport processes in rivers and coastal waters. The hydrodynamic model developed here will form the foundation for: (a) sediment transport modeling to investigate the impact of diversions and relative sea level rise on sedimentation properties of the river and (b) a solute and oil transport modeling for the Mississippi River Delta (e.g., Danchuk and Willson, 2010); and (c) investigation of various strategies for managing the lower River and its resources.

During model calibration, ADH's refinement indicator was used to identify the regions around the bendways and wetting/drying areas that required more resolution to decrease mass balance errors. The increased resolution resulted in some improvement in the detailed hydrodynamics, but did not change the overall hydrodynamics over the large areas. The adaptive capability will be more vital in the future modeling work, where the hydrodynamic model will be run simultaneously with other transport models (e.g., sediment, solute and oil), since the necessary refinement requirements will be less predictable ahead of time.

Overall, the simulated water surface elevations (WSEL) are in good agreement with the observations, particularly for the low and medium flow rates (Figure 4). Simulation results at the high flow are better for the section of the river from RM 50 (West Pointe A La Hache) down to Gulf of Mexico than the section between RM 110 and RM 65 (Carrollton to Alliance). Some preliminary simulations were made that include some dikelike structures in that reach to the existing mesh without changing the resolution in an effort to test their effect on the WSELs. Results did not show any significant improvement. A series of simulations were also run to test the required model resolution i.e. grid convergence, using the adaptive scheme of ADH. Analysis of the WSELs and velocity magnitudes indicated that there was no need for additional refinement for the current application of the model.

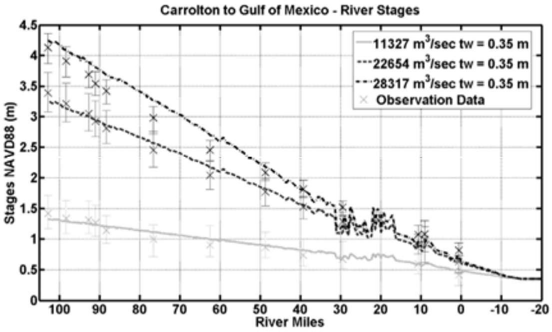


Figure 4. Simulated and Observed Water Surface Elevations; mean observed WSELs are given along with error bars which show +/- 1 standard deviation

After model calibration to river stage data, flow rates across a number of river and pass cross sections (Figure 5) were calculated and compared to flow data collected during a number of recent USACE field surveys conducted for West Bay Diversion Work Plan (ERDC, 2009) (Tables 1 and 2). Flow measurements from the field indicate that, at medium and high flow rates, the discharge at Venice (RM 10) is approximately 60-70% of the Tarbert Landing discharge. The simulated results show reasonable agreement with these estimates. The USACE data shows that approximately 45% of the total discharge is lost to the multiple cuts from Venice to below Cubit's Gap. One potential reason why the model underestimates this loss is that the elevation data around the receiving areas of lower River passes is higher than the current conditions. As a result of this underestimate, the model over estimates the flow through Southwest Pass. Closer inspection of the topography in the lower river shows that the land elevations are very close to the water surface elevations. Thus, even a 1 ft change in the topography can cause significant changes in flow distributions. The elevation data of the mesh will be updated for future studies as newer data become available..

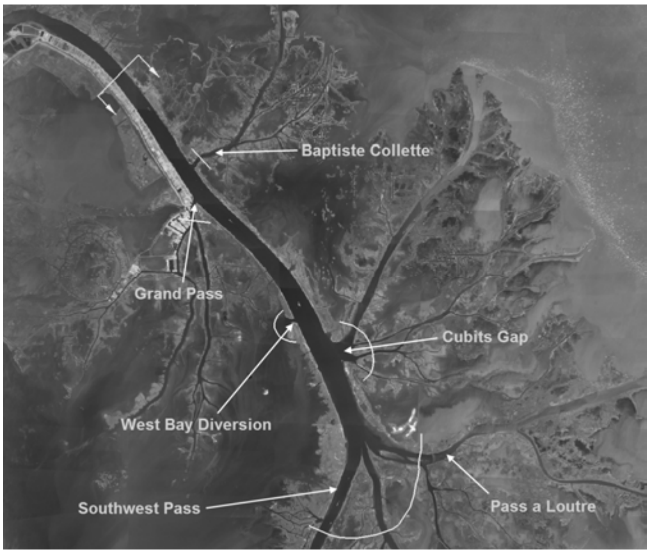


Figure 5. Locations of the cross sections use for flow comparisons

Table 1. Simulated and Observed (ERDC, 2009) Flow Fractions at Selected River Cross Sections

Location	Tail Water	11,327 m^3/sec		28,317 m^3/sec	
		Model*	Obs.*	Model*	Obs.*
Venice	0.00 m	99%	75-100%	71%	~78 %
	0.35 m	96%		67%	
	0.70 m	86%		61%	
Above West Bay	0.00 m	80%	~70%	55%	~59 %
	0.35 m	77%		53%	
	0.70 m	67%		47%	
Head Of Passes	0.00 m	68%	~55%	46%	~45 %
	0.35 m	64%		43%	
	0.70 m	55%		38%	
SW Pass	0.00 m	48%	~32%	29%	-
	0.35 m	41%		27%	
	0.70 m	32%		22%	

* with respect to the flow rate at Tarbert Landing

After validation of the current model, the impact of West Bay Diversion and proposed Empire Diversion were analyzed by investigating the steady state solutions of the hydrodynamic model only. Simulations with West Bay Diversion open are used as baseline runs. During this process, we investigated the variation of river stages and velocity magnitudes along the river together with flow rates across a number of river and pass cross sections.

Table 2. Simulated and Observed (ERDC, 2009) Flow Fractions through Lower River Passes

Location	Tail Water	11,327 m^3/sec		28,317 m^3/sec	
		Model*	Obs.*	Model*	Obs.*
Bap. Col.	0.00 m	7%	9.2%	4.5%	8.2%
	0.35 m	7%		4.4%	
	0.70 m	6%		4%	
Grand Pass	0.00 m	9%	9.5%	6%	8.7%
	0.35 m	8%		6%	
	0.70 m	7%		5.4%	
West Bay Diversion	0.00 m	2%	4.5%	3%	4.3%
	0.35 m	3%		3%	
	0.70 m	4%		3%	
Cubit's Gap	0.00 m	7%	11%	5%	8.5%
	0.35 m	7%		4.6%	
	0.70 m	6%		4%	
South Pass	0.00 m	12.6%	12%	8.6%	9%
	0.35 m	12%		8.3%	
	0.70 m	10%		7.4%	

* with respect to the flow rate at Tarbert Landing

According to the steady state simulation results at low and high flowrates, there was not any significant difference in the river stages and velocity magnitudes along the river with and without the West Bay Diversion. Also, very little change is observed for the distribution of the flow rates (Tables 3 and 4). Since the simulated flow through West Bay Diversion channel is less than the field data, we would not expect much impact on the model results. Obviously, definitive conclusions for West Bay Project would not be possible without accurately simulating the flow through the West Bay Diversion.

Table 3. Flow Rates at Selected River Cross Sections with and without West Bay Diversion (WBD) with tail water elevation of 0.35 m

Location	11,327 m^3/sec		28,317 m^3/sec	
	With WBD	W/out WBD	With WBD	W/out WBD
Venice	10,927	10,900	19,078	18,920
Above WBD	8,726	8,640	14,922	14,645
HOP	7,279	7,346	12,303	12,642
SW Pass	4,684	4,792	7,506	7,745

Note: All units are in m^3/sec

Table 4. Flow Rates through Lower River Passes with and without West Bay Diversion (WBD) with tail water elevation of 0.35 m

Location	11,327 m^3/sec		28,317 m^3/sec	
	With WBD	W/out WBD	With WBD	W/out WBD
Bap. Col	809	819	1,243	1,250
Grand Pass	913	964	1,671	1,799
WBD	300	0	813	0
Cubit's Gap	798	812	1,303	1,330
South Pass	1,361	1,388	2,355	2,406

Note: All units are in m^3/sec

The simulated flow through the Empire diversion channel (3,874 m^3/sec for high flow case; ~15% of the total flow) is much higher than through West Bay resulting in a more significant impact on the River hydrodynamics. Starting from a few miles upstream of the proposed Empire Diversion location down to River Mile 10 (~20 miles downstream of diversion location) there is a reduction in the velocity magnitudes of around 0.2 m/sec (Figure 6). As expected, the diversion reduces the fluxes through the river, however the impact on the river stages is not significant since the Lower Mississippi River Delta is a very large and complex system. The flow distribution through the passes downstream of Venice does not change very much. Of particular interest to navigation is the fraction of flow (40-50%) that passes through SW Pass, the primary navigation route from the Gulf of Mexico to the ports in the Mississippi River.

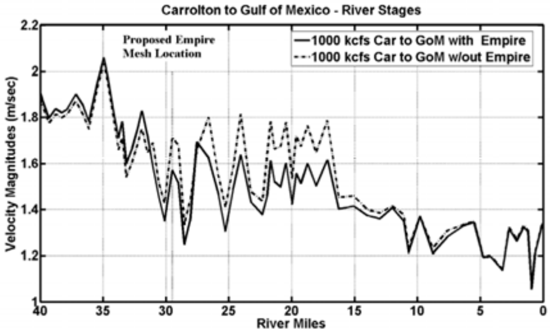


Figure 6. Simulated Velocity Magnitudes with 0.35 m tail water elevation.

The tail water boundary condition of 0.35 m is considered as mean sea level under current conditions and a tail water condition of 0.70 m is used to examine the potential impact of future sea level rise on the system. Model results show that at upstream locations, the tail water elevation has a more significant effect on the stages at low flow rates while there is little or no effect at the medium and high flow rate (Figure 7). The most significant impact of tail water elevations can be seen in the lower portion of the river (from Venice, RM 10, to Gulf of Mexico) where, under higher sea levels, flooding occurs at all flow rates in the regions that are close to the open water boundary. This flooding also results in an approximately 10% decrease in the flow through the West Bay diversion (Table 5). In contrast, the higher sea level results in an insignificant decrease in the Empire diversion, located farther upriver where the stages are unaffected at higher flowrates.

Table 5. Flow Rates through diversion channels with high flow rate (28,317 m^3/sec) (All units are in m^3/sec)

Location	Tail Water	
	0.35 m	0.70 m
Empire Diversion	3,874	3,828
West Bay Diversion	1,303	1,137

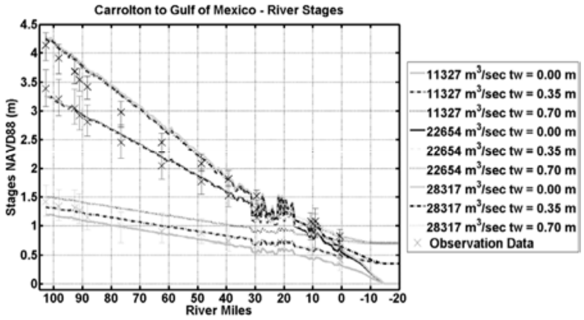


Figure 7. Simulated and Observed Water Surface Elevations; mean observed WSELs are given along with error bars which show +/- 1 standard deviation

4 CONCLUSION

A 2 dimensional hydrodynamic model was calibrated and validated in order to better understand the hydrodynamic processes in the Lower Mississippi River Delta. This model serves as a useful tool for studying the impact of diversions and sea level rise on the system as well as understanding the river discharge into adjacent bays and the Gulf of Mexico. This framework will also be useful for sediment and solute transport modeling. Under steady-state conditions, the model was shown to closely match existing river stage conditions and do a reasonable job of capturing the flow distributions. Future efforts are aimed at improving the elevation data to more accurately simulate the flow through the passes, validation of the model to unsteady events, and the addition of sediment transport. The numerical complexity of these simulations will require the inclusion of the adaptive mesh capabilities of ADH.

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