2-D Adaptive Hydraulics (AdH) Modeling at the Crossing of the Gulf Intercoastal Waterway (GIWW) and the Brazos River

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Abstract

The Gulf Intracoastal Waterway (GIWW), a portion of the U.S. Intracoastal Waterway located along the Gulf of Mexico, is a high-traffic inland channel which is crucial to the U.S. economy. The Brazos River is the largest river crossing the GIWW west of the Mississippi River. The crossing is about 7000 feet upstream from the gulf near Freeport, TX. Approximately 45 million tons of commercial cargo crosses the Brazos River annually, with an estimated product value of $4.5 billion.

Tidal and fluvial flows into the GIWW are controlled by sector gates on both sides of the Brazos River, constructed by USACE in 1943 as part of the Brazos River Floodgates project. The gates control sediment movement into the GIWW for low flows as well as flood flows. Contrary to what the name suggests, the gates do not serve to reduce the threat of flooding. The location of the gates (near the Brazos River crossing flows) and the high velocities at the gates (caused by tidal fluctuations and high river flows) result in navigation challenges. Approximately 65 vessel allisions occur annually. Those allisions and the associate navigation delays result in an annual economic loss of approximately $10.8 million. In 2019, a Final Integrated Feasibility Report-Environmental Impact Statement (FIFR-EIS) was conducted to investigate navigational delays and safety. The report recommended that the west gates be removed, the east gates be widened and set back, and the GIWW channel be realigned to increase safety and long-term navigational efficiency.

The paper will first address the 2-D AdH hydrodynamic model validation effort (which involved getting the model to reproduce USGS stage and velocity data in the project area) and the associated ship simulation efforts conducted at the U.S. Army Engineer Research and Development Center (ERDC) Ship/Tow Simulator in Vicksburg, MS. Regarding model validation, the needed attention to geometry, specifically the connections to off-channel storage, will be highlighted. Regarding the ship simulation efforts, the paper will cover 1) the discussions resulting in the scopes of work, 2) the efforts needed to provide the hydraulic and other input, and 3) a summary of the in-person simulation efforts and results.

Secondly, the paper will address the 2-D AdH sediment transport validation efforts and the subsequent simulations involving with-project conditions. The sources of input data (including already-existing data documented in the FIFR-EIS and bed and settling velocity data collected by ERDC) will be discussed as well as the qualitative to semi-quantitative results of sensitivity testing completed within the constraints of the project budget and schedule. The paper will conclude with the results of the modeling effort and the proposed path forward.

Introduction

The project location is shown in Figure 1. Features near the project are shown in Figure 2.

Figure 1. General Project Location

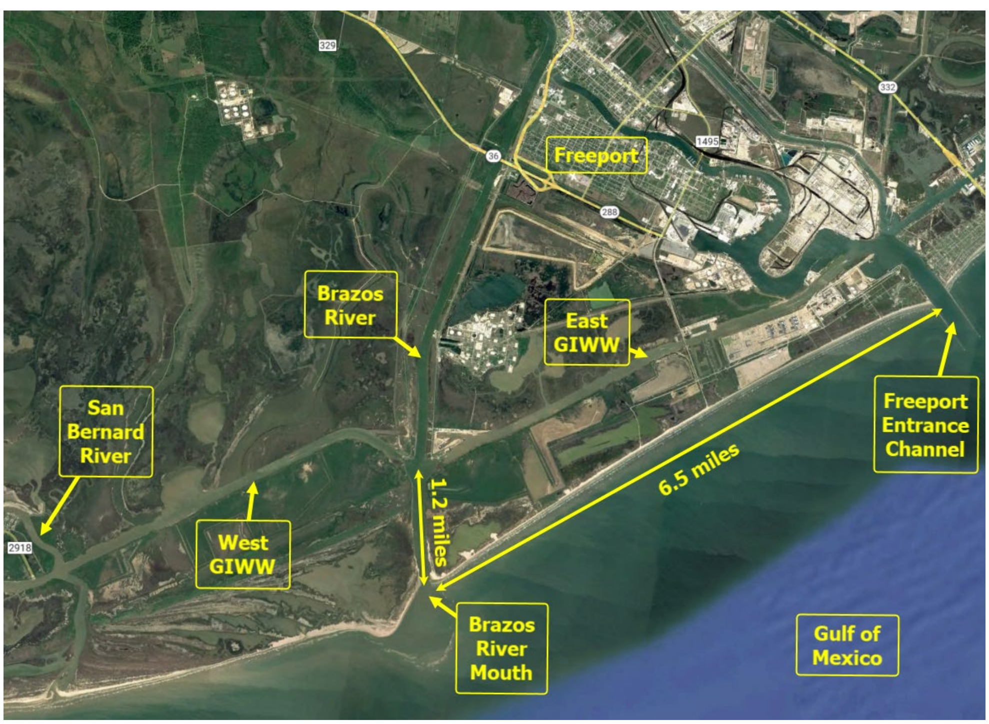

Figure 2. Features near Project Location

Features at the project site are shown in Figure 3.

Figure 3. Features at Project Site

Flow currents at the crossing are influenced by the tidal cycle. USGS stage, velocity, and flow data during typical (low river flow, no storm surge) conditions are shown in Figure 4.

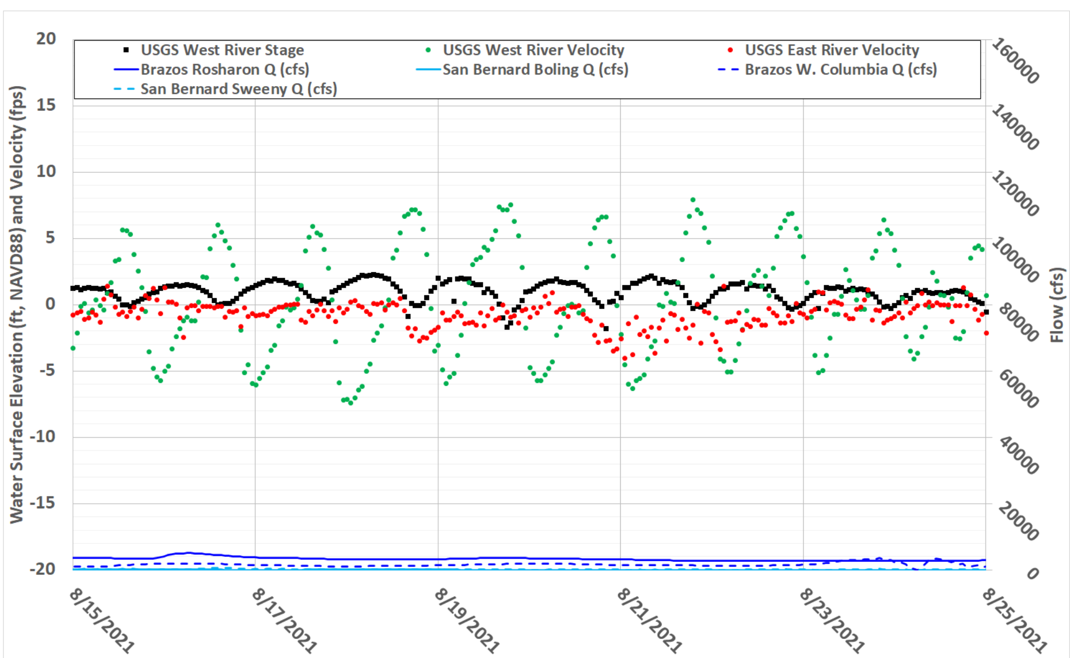

Figure 4. Site Stage and Velocity, Typical Low River Flow Conditions

Positive velocity indicates flow out of the GIWW channel towards the Brazos River channel. Positive velocity at the west gate indicates eastward flow. Positive velocity at the east gate indicates westward flow.

The tidal cycle has the greatest influence on velocities through the west gate. This is due to a good amount of tidal storage along the GIWW west of the Brazos River and to the Brazos River being the main path for supplying water to those tidal storage areas. Some tidal exchange of water does occur via the San Bernard River, but it is limited due to heavy sedimentation at its mouth. As seen in Figure 4, it is not uncommon for the velocity at the west gate to be 7 to 8 feet per second (fps or ft/sec) in either direction.

The tidal cycle has a smaller impact on velocities through the east gate. This is due to less tidal storage along the GIWW east of the Brazos River and to a strong hydraulic connection via the Freeport Entrance Channel. As with the west gate, flow can occur in either direction, but the higher velocities tend to be from the Brazos River into the GIWW channel, with a velocity of 4 fps not being too uncommon.

The high velocities at the gates and flow conditions that are almost always in transition due to the tidal cycle make navigation difficult.

USGS stage, velocity, and flow data during high river flow conditions are shown in Figure 5. When river flows are high, there's an increase in eastward flow at both gates (positive velocity at west gate and negative velocity at east gate), but especially through the east gate. It is important to keep in mind that the high river flows carry a lot of sediment. When the river flows subside, the west gate velocity (and therefore flow exchange) remains active (as discuss above and shown by Figure 4), but the east gate velocity (and therefore flow exchange) is reduced. Unless the river flow gets really high, navigation still occurs, but navigation restrictions are in effect.

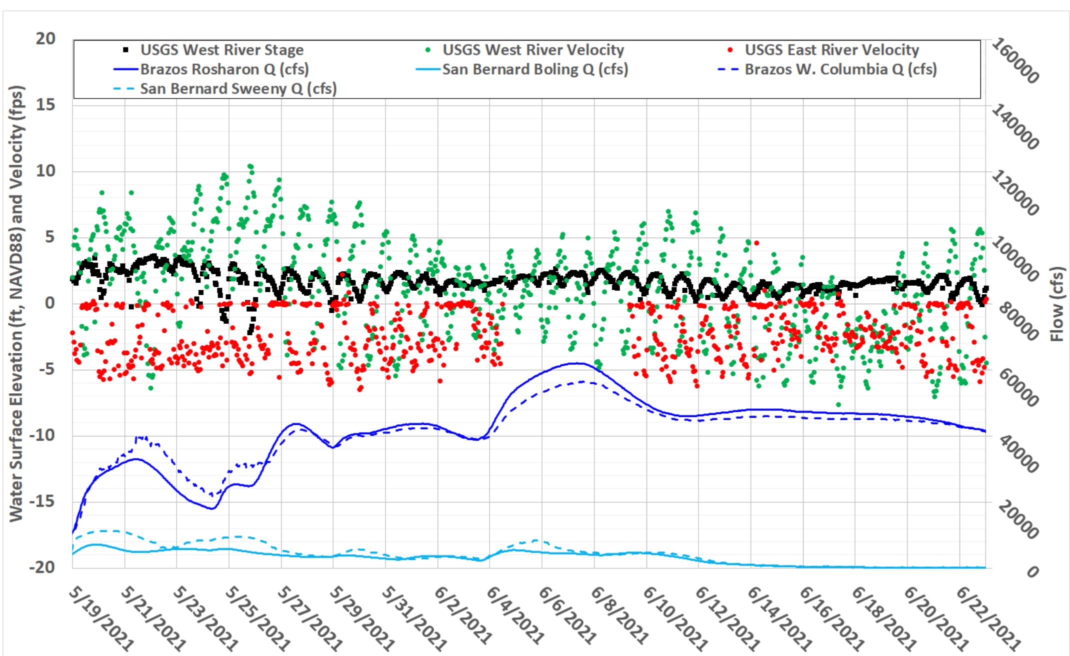

Figure 5. Site Stage and Velocity, High River Flow Conditions

USGS stage, velocity, and flow data during extreme river flow conditions are shown in Figure 6. The period shown is immediately after Hurricane Harvey. The river flows were record highs. The Brazos River flow at West Columbia and the San Bernard River flow at Sweeny (which are shorter-record gages downstream of the gages at Rosharon and Boling) show how flow breakouts, floodplain storage, and additional contributing areas alter the shape of the hydrograph for extreme flood events.

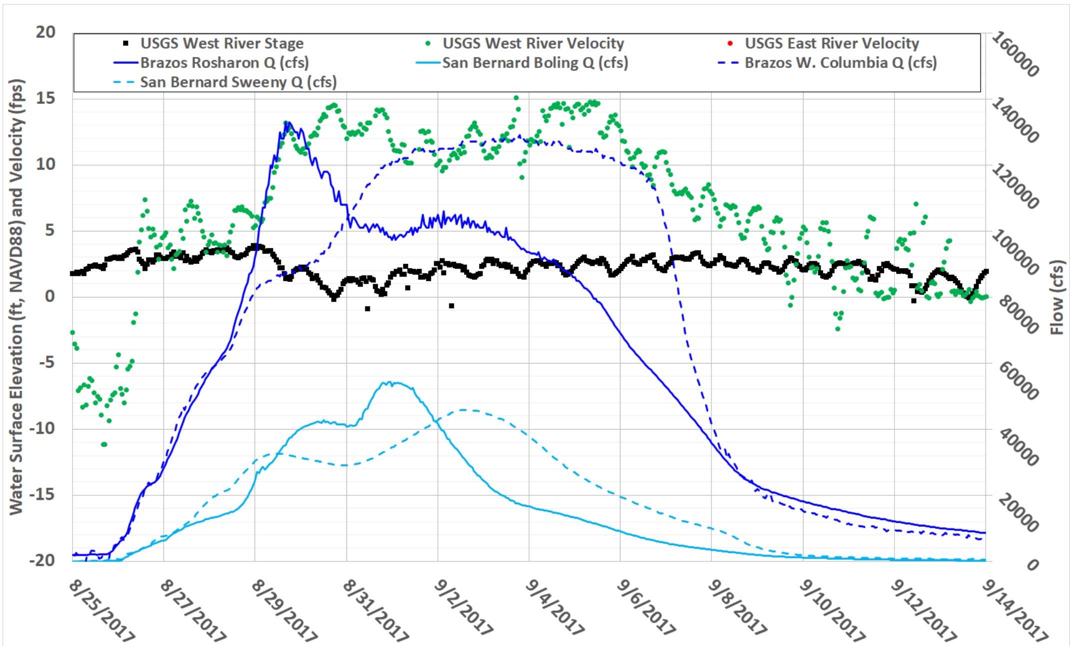

Figure 6. Velocities at the Existing Gates, Extreme River Flow Conditions

Unfortunately, velocity data at the east gate is absent since the velocity sensor failed just prior to this flood event, but it is known that the east gate was closed around 0600 hours on 01 Sep 2017 (after it was safe to get back to the gates after Hurricane Harvey) to prevent Brazos River flow and sediment from entering the GIWW channel. The west gate was left open since the flow was eastward through the west gate, which means Brazos River flow and sediment was not entering the GIWW channel west of the west gate. As will be shown when the modeling is discussed, the eastward flow through the east gate (seen for high river flows in Figure 5) becomes even more pronounced with extreme river flows. Navigation ceases due to high Brazos River velocities when the Brazos River flow exceeds 70,000 to 80,000 cfs (based on anecdotal evidence and model results).

Model Setup and Validation

AdH is a two-dimensional (2-D) shallow water flow model. Computed velocities are depth-averaged values. The final AdH model extents and boundary condition locations are shown in Figure 7. The model started with a larger domain to the west and east along the GIWW channel, but it was reduced in size after demonstrating that stage and velocity results were not significantly different with a larger domain. Also, as indicated in Figure 7, boundary conditions were not applied at the west and east extents of the model domain along the GIWW channel. Similar to testing the model domain, testing was done (by applying reasonable flow hydrographs at the west and east GIWW channel extents) to determine model results near the project site are not significantly impacted by not allowing flow at these boundaries.

The inflow locations correspond to USGS gage 08116850 (Brazos Rv nr West Columbia, TX) and USGS gage 08117705 (San Bernard Rv nr Sweeny, TX). As noted above when discussing Figure 6, breakouts and related floodplain storage occur upstream of these gages and the longer-record upstream gages for very high river flows, especially along the Brazos River. To avoid having to understand and properly model those breakouts, the downstream gages were used as the upstream inflow locations. High ground along the Brazos River downstream of the inflow location prevents breakout flow all the way to the GIWW channel. High ground along the San Bernard River downstream of the inflow location prevents breakout flow to within about 3 to 4 miles to the GIWW channel.

The gulf stage boundary was assigned stage data from NOAA gage 8772471 (Freeport Harbor).

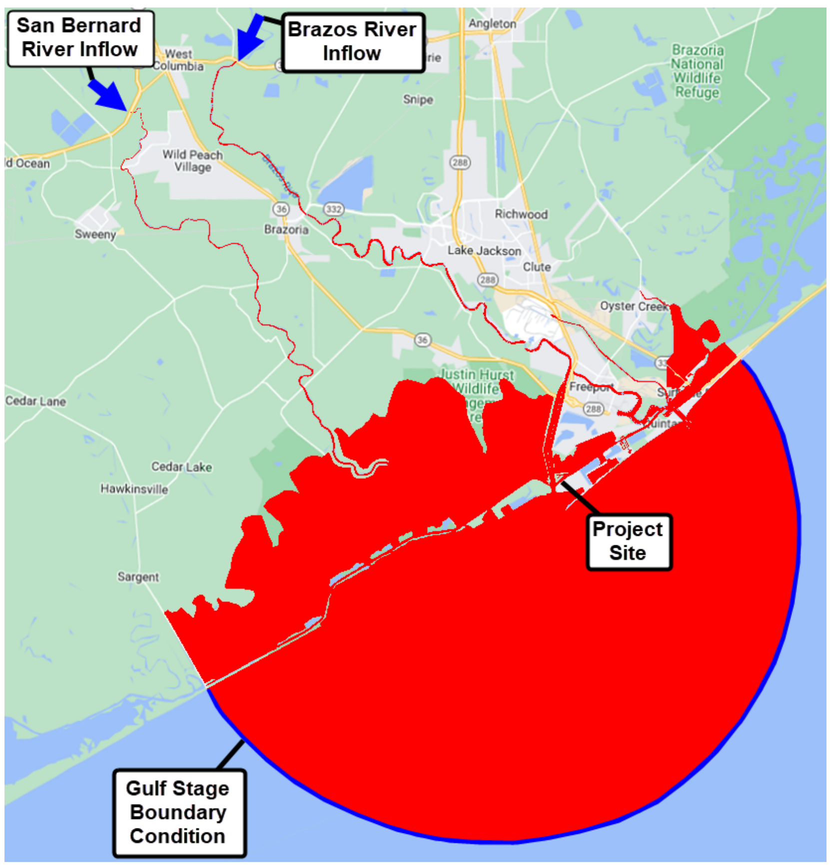

Figure 7. AdH Model Domain and Boundary Condition Locations

Validation, Hydrodynamics Only

Developing a model that reasonably reproduces measured stage and velocity data for low to moderate river flows required attention to geometric detail, especially near the gates and how floodplain storge is connected (and not connected) to the GIWW channel. An example of the type of detail needed is shown in Figure 8.

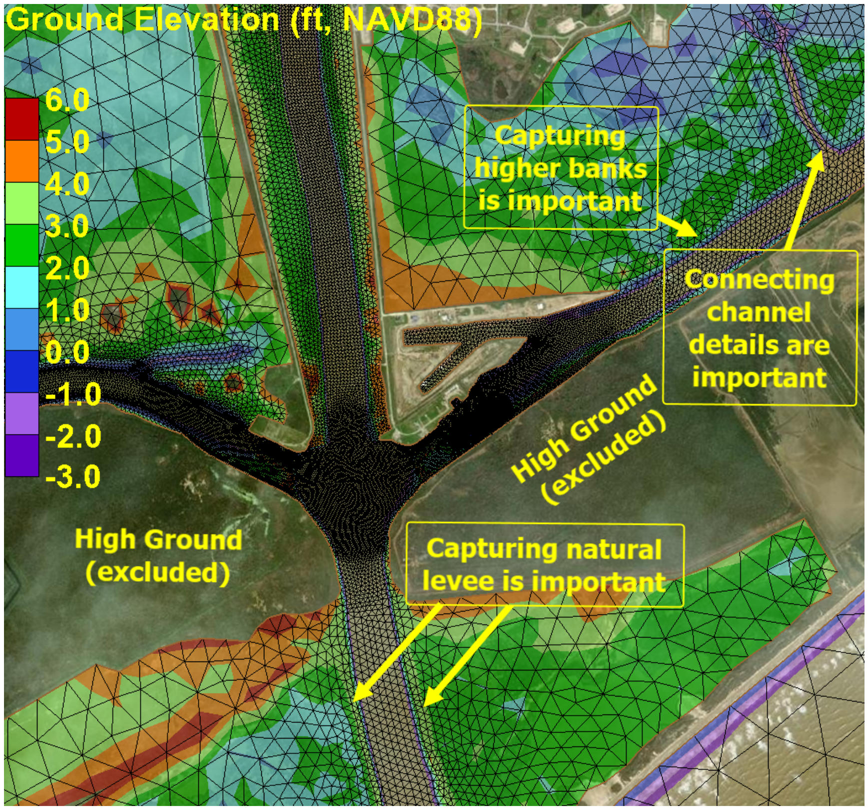

Figure 8. Geometric Detail Needed for Model Validation

While time consuming, developing a computational mesh that has sufficient detail to properly control the movement of flow but doesn't have more detail than needed is important such that model run times, file sizes, and the time post-process results don't become excessively large.

Besides getting the geometry correct, the Manning's n values were adjusted (within reasonable bounds) to get good agreement between the modeled stage and velocity results and the measured stage and velocity data.

An example period of the how the model compares to measured data during low flow conditions is shown in Figure 9. Stages and west gate velocities compare very well. Within the period shown, there are some differences between measured and modeled east gate velocities, but overall, the results look good.

Figure 10 shows modeled vs. measured results for moderate to high flow conditions (this figure needs some work - need to make more readable and show results of west gate and east gate together). As with the low river flows, the model does a good job reproducing measured data.

When first running the extreme river flow period that followed Hurricane Harvey, the model results did not compare all that well to the available measured data for very high flows and on the falling limb of the hydrograph. This is shown in Figure 11 (figure I have is a bit old and has a few issues; needs to be updated). The reason why the model wasn't doing a good job was sediment transport.

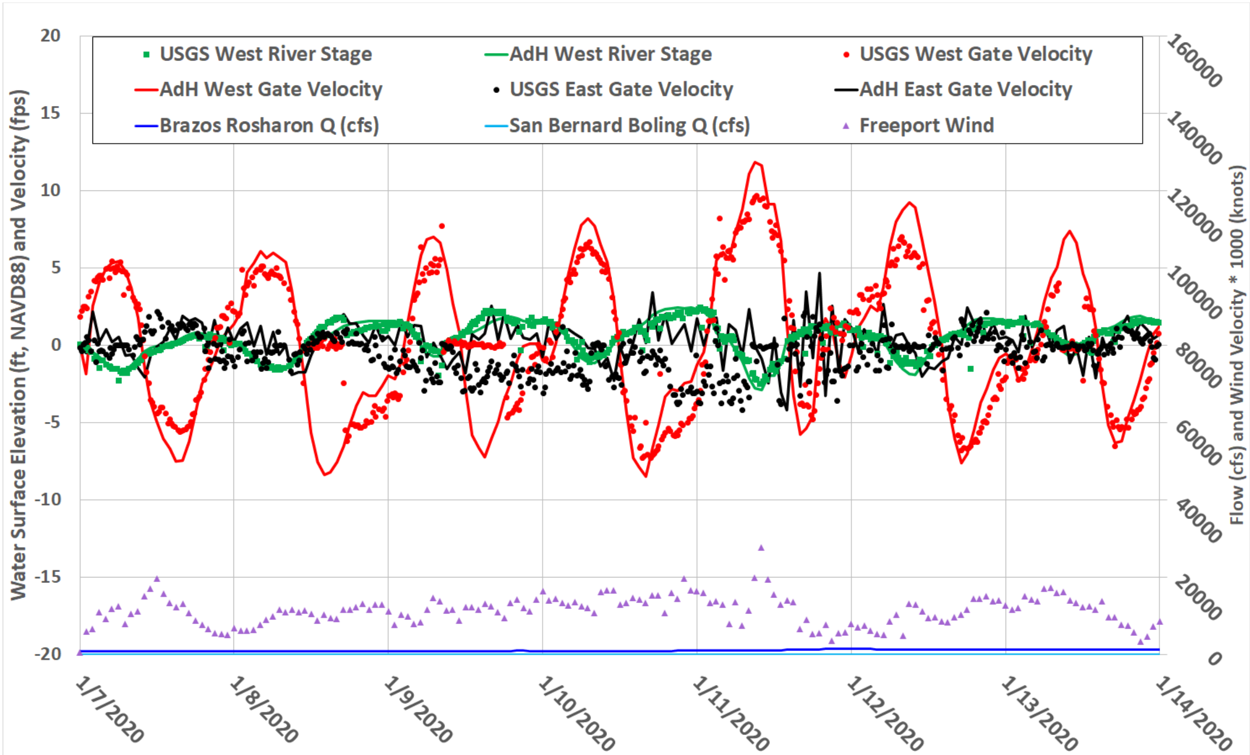

Figure 9. Validation of Hydrodynamics, Low River Flow

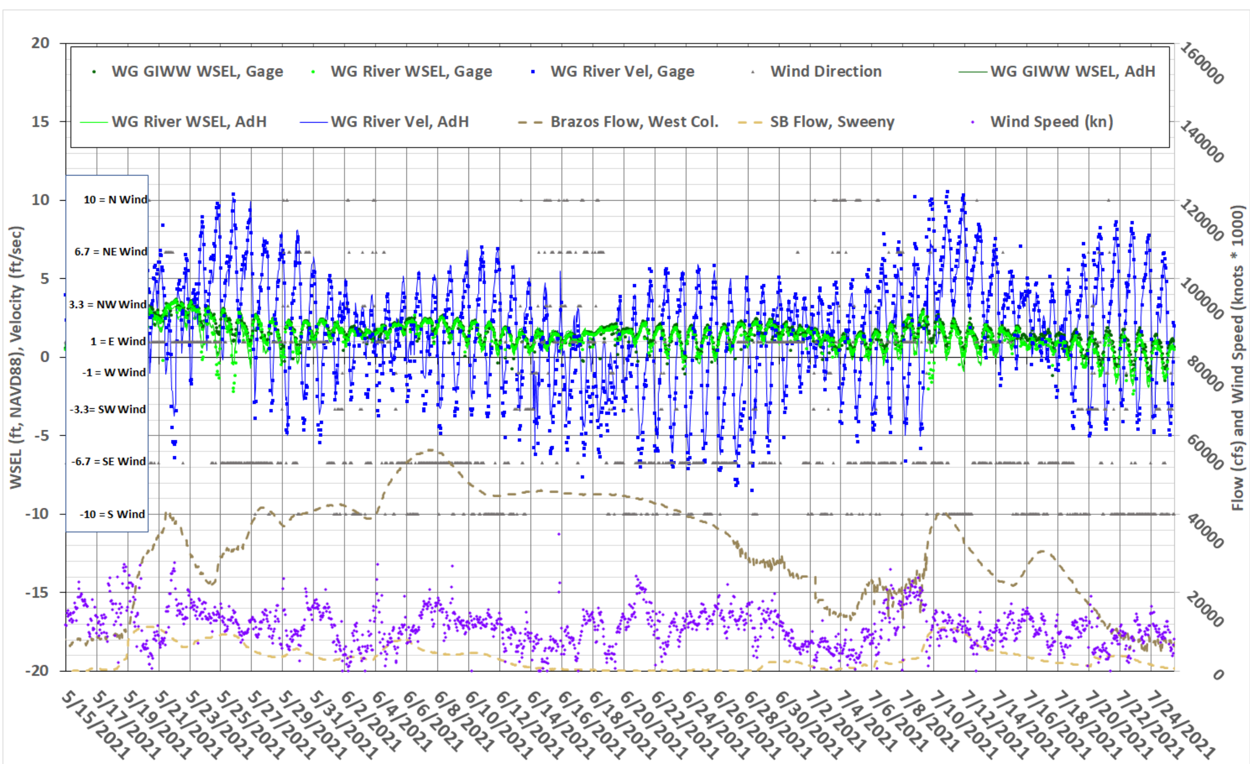

Figure 10. Validation of Hydrodynamics, Moderate to High River Flow

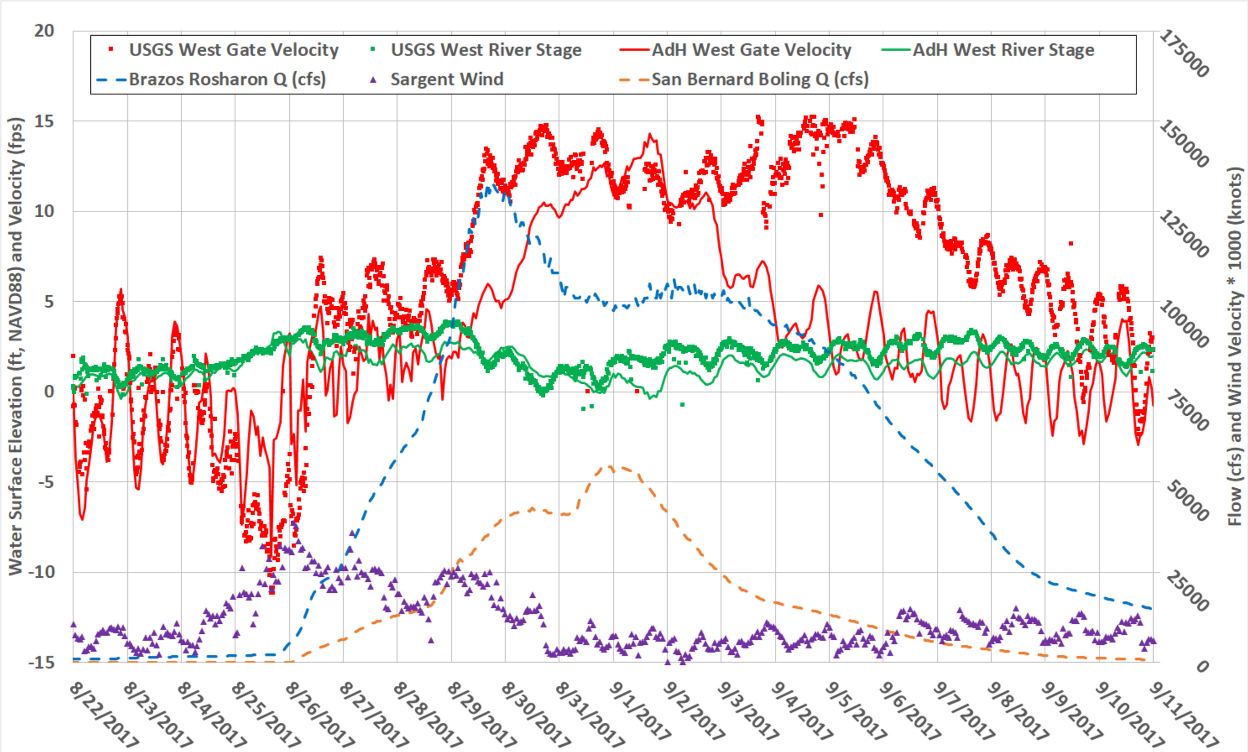

Figure 11. Validation of Hydrodynamics, High River Flow

Validation, Hydrodynamics and Sediment Transport

Scour is the reason why the model results shown in Figure 11 do not compare well to the available measured data. Immediately upon adding sediment to the model and running a simulation of period following Hurricane Harvey, it was obvious that scour of the Brazos River was critical in getting good results for an extreme flow event.

USACE ERDC collected grain size data in the summer of 2021 (not yet published). Based on the measured data and data available in the Hydraulic Appendix of the 2019 Final Integrated Feasibility Report – Environmental Impact Statement (FIFR-EIS) (USACE Galveston District 2019), four grain sizes were modeled. ERDC collected data such that porosity, the critical shear stress for erosion, the erosion rate constant, the critical shear for deposition, and the settling velocity could be estimated for the cohesive grain sizes. The erosion flux equation that requires these parameters is presented in the AdH Sediment Transport User Manual (USACE ERDC 2021). The grain sizes and the grain-size specific sediment transport parameters included in the sediment transport model are presented in Table 1.

AdH treats clay (≤ 3.9 µm) as fully cohesive and treats sand (≥ 63 µm) as fully non-cohesive. Silt (3.9 µm – 63 µm) is treated as cohesive but cohesiveness is based on the grain size (i.e. coarser silt is less cohesive than finer silt). When coarse and fine sediment classes are mixed in the sediment bed, the behavior is complex. A bed consisting of both non-cohesive and cohesive and cohesionless sediment classes may exhibit non-cohesive or cohesive or cohesionless behavior, depending on the fraction of silt and clay classes that are present in the mixture.

Table 1. Modeled Grain Size Information

Grain Size (µm)	Went-worth Size Class	Specific Gravity	Por-osity	Critical Shear for Erosion (Pa)	Erosion Rate Con-stant	Critical Shear for Deposition (Pa)	Settling Velocity (m/sec)
2.5	Coarse Clay	2.72	0.8	0.15	0.003	0.06	6.6E-05
8.0	Fine Silt	2.72	0.8	0.22	0.003	0.15	1.6E-04
30	Medium Silt	2.72	0.8	0.22	0.003	0.15	4.0E-04
125	Fine Sand	2.65	0.8	See note	See note	See note	See note

Note: Non-cohesive, calculated by AdH

Properties that vary spatially are typically assigned to material types defined within the model domain. The material types near the project site are shown in Figure 12.

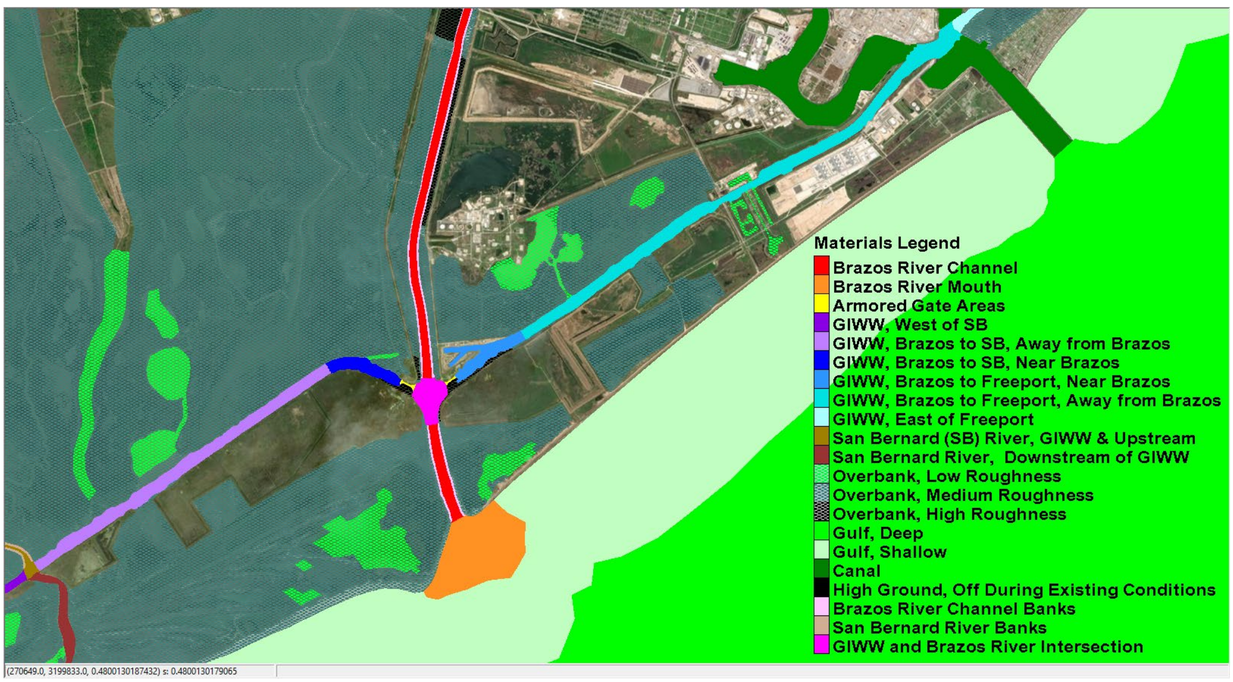

Figure 12. AdH Existing Condition Material Types

During the initial model validation effort involving hydrodynamics only, spatially varying bed roughness (via a Manning's n value) was assigned to the material types. With sediment transport the bed layer properties were assigned to the material types. The bed layer properties include porosity, critical shear stress for erosion, an erosion rate constant, an erosion rate exponent, and the percent of each grain size. The need for these bed layer properties is explained in the AdH Sediment Transport User Manual (USACE ERDC 2021).

In addition to collecting grain size data, USACE ERDC also collected bed layer data in the summer of 2021 (not yet published). ERDC's data and the bed layer grain size distribution information from the FIFR-EIS were considered in setting the bed layer properties. The bed roughness and bed layer properties used in the model are presented in Table 2. The percent of silt was divided equally between the two silt grain sizes modeled.

Table 2. Material Type Properties (upper 0.25-meter thick bed layer)

Material Type Name	Manning n	Porosity	τ_c [Pa]	A [kg m^{-2} s^{-1}]	Exponent n	Clay %	Silt 1 %	Silt 2 %	Sand %
Brazos River Channel	0.025	0.76	0.8	0.0019	1.17	32	31	31	6
Brazos River Channel Banks	0.025	0.76	0.8	0.0019	1.17	32	31	31	6
Brazos River Mouth	0.022	0.76	0.8	0.0019	1.17	32	31	31	6
San Bernard (SB) River, GIWW & Upstream	0.025	0.76	0.8	0.0019	1.17	32	31	31	6
San Bernard River, Downstream of GIWW	0.025	0.76	0.8	0.0019	1.17	32	31	31	6
San Bernard River Channel Banks	0.025	0.76	0.8	0.0019	1.17	32	31	31	6
GIWW, West of SB	0.024	0.60	0.226	0.0020	1.05	60	18	19	3
GIWW, Brazos to SB, Away from Brazos	0.024	0.60	0.226	0.0020	1.05	47	23	24	6
GIWW, Brazos to SB, Near Brazos	0.024	0.60	0.226	0.0020	1.05	29	27	28	16
GIWW, Brazos to Freeport, Near Freeport	0.024	0.60	0.226	0.0020	1.05	27	32	32	9
GIWW, Brazos to Freeport, Away from Brazos	0.024	0.60	0.226	0.0020	1.05	44	25	26	5
GIWW, East of Freeport	0.024	0.60	0.226	0.0020	1.05	47	25	25	3
GIWW and Brazos River Intersection	0.024	0.68	0.617	0.0028	1.28	21	36	36	7
Armored Gate Areas	0.030	Set as non-erodible							
Overbank, Low Roughness	0.024	Set as non-erodible							
Overbank, Medium	0.035	Set as non-erodible							
Overbank, High Roughness	0.050	Set as non-erodible							
Gulf, Deep	0.020	Set as non-erodible							
Gulf, Shallow	0.020	Set as non-erodible							
Canal	0.020	Set as non-erodible							
High Ground, Off During Existing Conditions	0.030	Set as non-erodible							

Sensitivity analyses were conducted during the modeling effort, but in the end the more complete grain size distribution information of the FIFR-EIS Hydraulic Engineering Appendix was used for the final AdH model runs.

The model validation effort with sediment transport proceeded with an effort to reproduce stage, velocity, and bed displacement results for two periods bounded by bed surveys that allowed the development of measured bed displacement results: 1) 09 Aug 2017 to 29 Sep 2017 (which includes the extreme flow event following Hurricane Harvey), and 2) 19 May 2021 to 25 Jul 2021 (which includes a long period of a moderate to high flow event).