Impacts of Channel Dredging on Storm Surge, Tidal Flows and Salinity in Corpus Christi Bay

Prepared for: Port of Corpus Christi Authority

Prepared by: Mukesh Subedee and James C. Gibeaut, PhD

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TEXAS A&M UNIVERSITY CORPUS CHRISTI | HARTE RESEARCH INSTITUTE FOR GULF OF MEXICO STUDIES

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1. Introduction

The Port of Corpus Christi Authority (PCCA) is permitted to and has started to deepen the Corpus Christi Ship Channel (CCSC) to a depth of -54 feet (MLLW) from the existing depth of -47 feet (MLLW) as well as to widen it in select reaches. PCCA has also initiated permitting of a project to deepen the outer reach of the ship channel (from the Gulf of Mexico to the ferry landing at Harbor Island) from the currently authorized depth of -54 feet (MLLW) to approximately -75 feet (MLLW) within the footprint of the -54' channel.

These ship channel improvements would allow larger ships access to the port that will generate a positive return on investment by reducing delays and congestion and increasing the efficiency and safety of port operations. This project assesses the impacts of the ongoing and proposed channel improvement projects on

1. Storm surge water levels and inundation duration patterns,
2. Tidal hydraulics, and
3. Salinity

in the Corpus Christi bay system by creating and applying site-specific hydrodynamic models. Numerical models are used to simulate bay hydrodynamics with existing channel configurations and compared to new simulations where the channel configurations are altered in the model.

Past studies have assessed the impact of earlier planned CCSC improvements on tide, salinity, and current. A detailed environmental impact and feasibility study of a proposed channel improvement project to widen and deepen the CCSC from -45 feet to a depth of -52 feet with 2 feet of advanced maintenance and extend the La Quinta Channel (LQC) was conducted by the U. S. Army Corps of Engineers and documented in *Corpus Christi Ship Channel, Texas, Channel Improvement Project, Final Feasibility Report and Final Environmental Impact Statement* (USACE, 2003). The study used a 2-dimensional finite element hydrodynamic and salinity model to evaluate impacts to tide, salinity and current due to increased channel depth and width. Similarly, AECOM recently conducted a study for PCCA to estimate the impacts of the proposed channel deepening projects on tides and associated current patterns within Corpus Christi Bay (PCCA, 2019). For that study, a 2-dimensional hydrodynamic model was developed to simulate the tides in the bay with and without planned projects.

1.1 Study Area

The Corpus Christi Bay System, located in the semi-arid Texas Coastal Bend, includes three of the seven estuaries in Texas: Corpus Christi, Aransas, and Upper Laguna Madre (Figure 1). Corpus Christi Bay is connected to Oso Bay and upper Laguna Madre to the southwest, Nueces Bay to the northwest and Redfish Bay to the northeast. Redfish Bay further connects to Aransas Bay to the northeast which is then connected to Copano Bay to the west. Corpus Christi Bay was designated by the Environmental Protection Agency as an estuary of national significance with over 234 species of fish (GulfBase 2010). It is also a natural harbor to the nation's largest port by revenue tonnage and leading energy export port (PCCA 2020).

Corpus Christi Bay is relatively flat and shallow with an average water depth between 3 and 4 m; it is connected to the Gulf of Mexico through two inlets (Islam *et al*., 2014): (1) Aransas Pass through which the ship channel is dredged and (2) Packery Channel, which is a water exchange and recreational boat channel. The hydrodynamic conditions of the bay are strongly influenced by meteorological factors, particularly wind. The mean astronomical tidal range of the bay is 0.3 m, and the impact of meteorological forcing is often greater than the astronomical range (Islam *et al*., 2014). Winds are mainly from the southeast that dominate more than 50% of the time, although winter cold front passages bring strong winds from the north. Freshwater inflow to Corpus Christi Bay is very low and the only sources include the Nueces River and Oso Bay, from Oso Creek. Other sources of freshwater inflows into the bay system are Mission River, Copano Creek and Aransas River.

The CCSC runs through Corpus Christi Bay from the Gulf of Mexico at Aransas Pass to the Corpus Christi Inner Harbor. The majority of the 29.4 nautical mile (nm) long ship channel is currently being deepened from 47 to 54 feet deep. The LQC branches from the CCSC at La Quinta Junction and extends for 5.9 nm to the north along Ingleside (Figure 1) (PCCA 2020). PCCA operates and manages the CCSC and LQC. The 12 feet deep and 125 feet wide Intra Coastal Waterway (ICW) also passes through the Corpus Christi Bay.

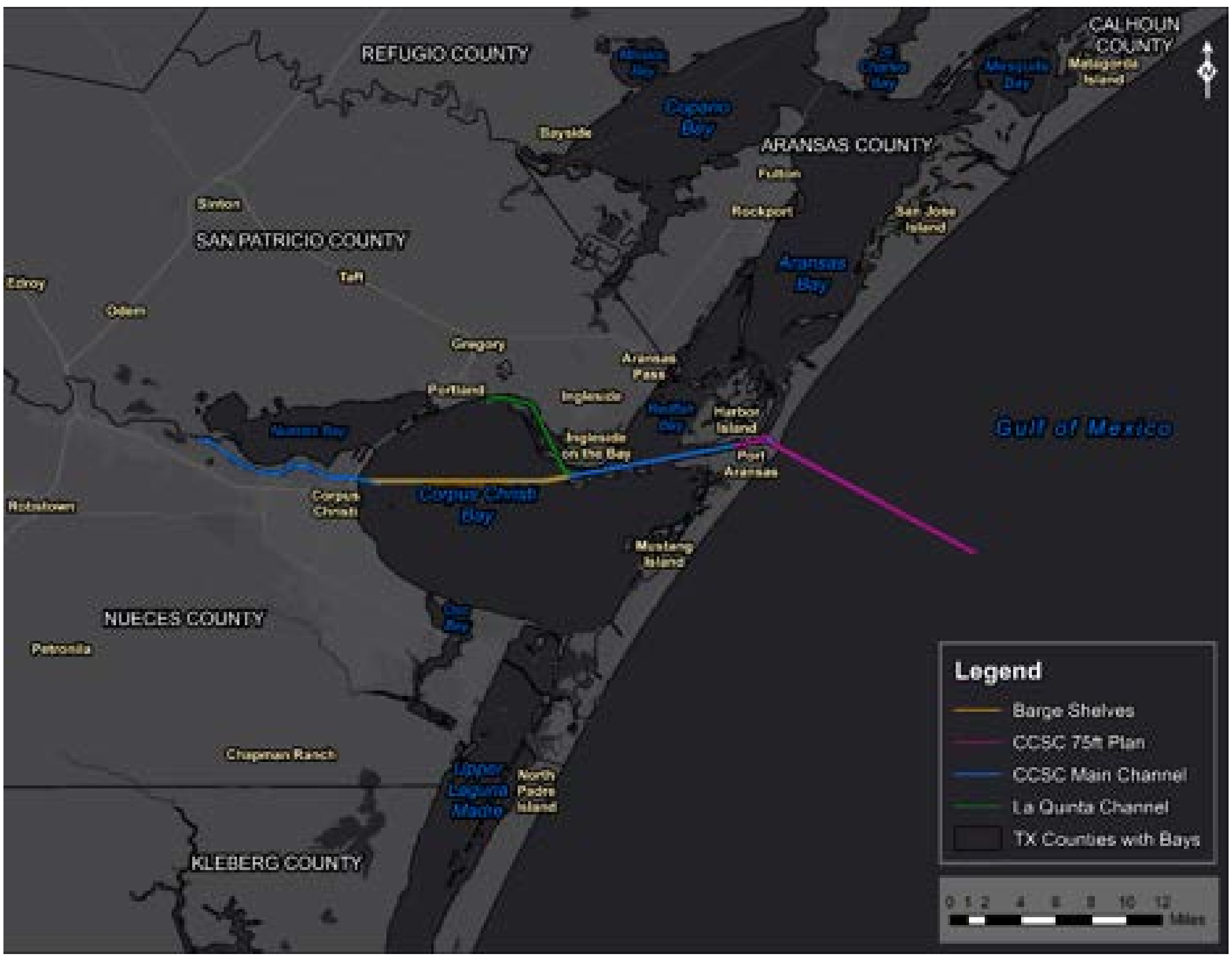

Figure 1. Study area map showing Corpus Christi Bay and adjacent bays. The major shipping channels managed by PCCA are also shown.

1.2 Modeling Scenarios

PCCA has started widening portions of the CCSC to 530 feet and deepening it to -54 feet (MLLW) from the Gulf of Mexico through the Inner Harbor. PCCA is also building additional barge shelves to allow for two-way vessel and barge traffic. PCCA has also started the permitting process to deepen the outer reach of the ship channel from the Gulf of Mexico to Harbor Island to -75 feet (MLLW) from the currently authorized depth of -54 feet. This study, therefore, uses three channel configuration scenarios to assess impacts on storm surge, tide, and salinity in Corpus Christi Bay as following:

1. **Existing Scenario (ES)**: The ES configuration represents the previously existing channel conditions based on the bathymetric survey conducted by the USACE in 2019-2020. This scenario has a nominal channel depth of -47 feet (MLLW) with 2 feet of allowable overdepth. The ES configuration is represented in the model grid by updating the CCSC and LQC footprints with the USACE survey bathymetric condition. The ES configuration also represents the current bathymetric condition of the bay. It is used for the model calibration and validation and for comparison with the ongoing and proposed channel improvement scenarios.

2. **Ongoing Project Scenario (OPS)**: The OPS configuration represents the currently ongoing channel improvement project scenario that will be completed soon. This scenario has a depth of -54 feet with -2 ft. advance maintenance and -2 ft. allowable overdepth, resulting in a total depth of -58 ft. (MLLW) for the CCSC. The barge shelves along the CCSC have a depth of -14 ft. with -2 ft. advance maintenance and -2 ft. allowable overdepth, resulting in a total depth of -18 ft. (MLLW). The LQC has a depth of -47 ft. with -2 ft. advance maintenance and -2 ft. allowable overdepth, resulting in a total depth of -51 ft. (MLLW). The OPS configuration is represented in the model by updating the ES bathymetry with -58 ft. (MLLW) along the CCSC, -18 ft. (MLLW) along the barge shelves and -51 ft. (MLLW) along the LQC. This scenario reflects the selected plan documented in *Corpus Christi Ship Channel, Texas, Channel Improvement Project, Final Feasibility Report and Final Environmental Impact Statement* (USACE, 2003).

3. **Future Project Scenario (FPS)**: The FPS configuration represents the proposed future channel deepening project to deepen the CCSC from the Gulf of Mexico to Harbor Island to -75 ft. (MLLW) from very recently constructed depth of -54 feet (MLLW). This increased deepening would allow Very Large Crude Carriers (VLLCs) to be fully loaded at the docks on Harbor Island. The FPS configuration is represented in the model by updating the OPS grid with -75 ft. (MLLW) along the CCSC from the Gulf of Mexico to Harbor Island. Figure 2 shows the footprint of the channel scenarios.

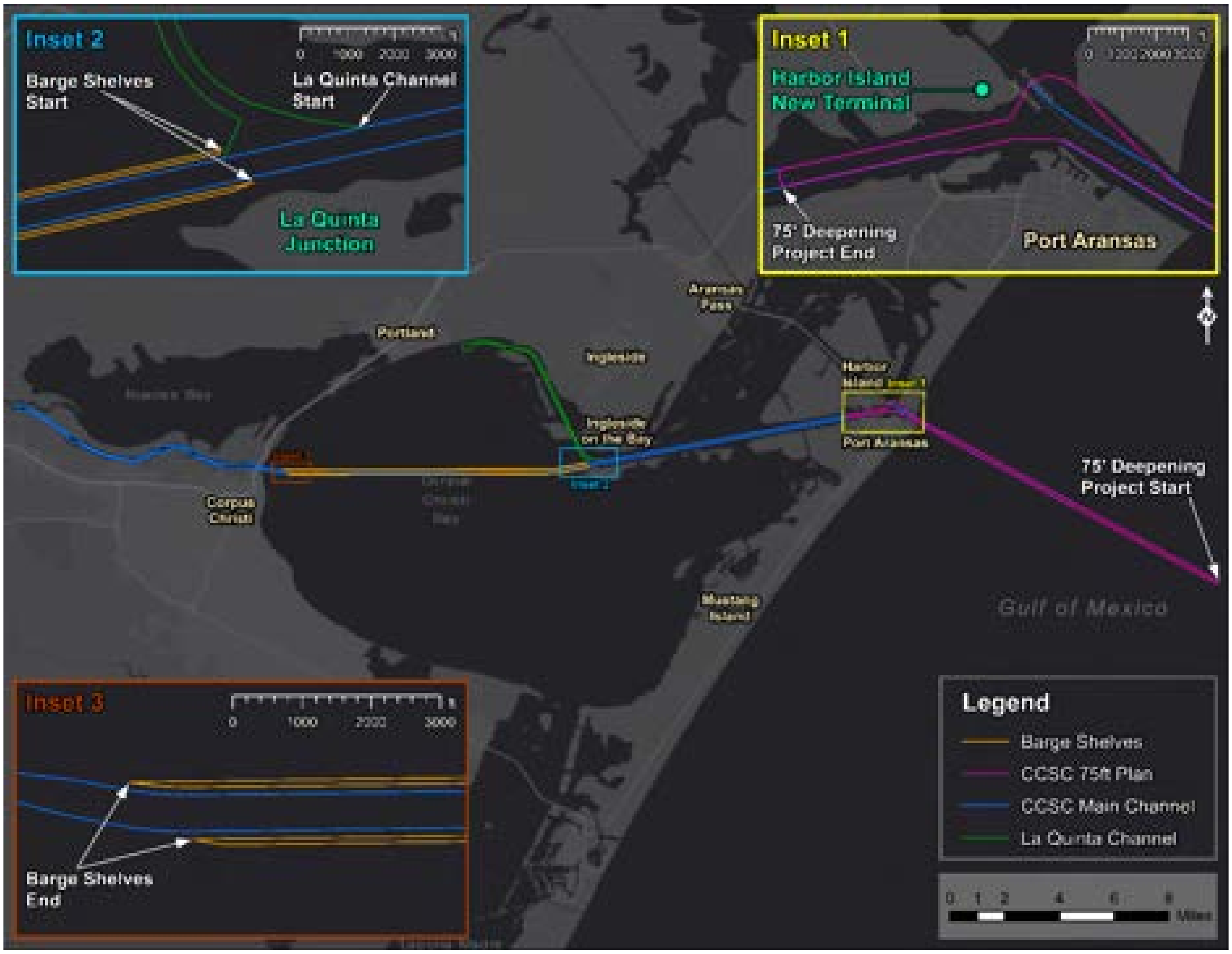

Figure 2. Map of channel footprints. Inset 1 shows the channel configuration where the proposed -75 ft. (MLLW) channel ends in front of the Harbor Island in Port Aransas. Inset 2 shows the La Quinta Junction where the CCSC and LQC intersect and the east end of the barge shelves. Inset 3 shows the CCSC footprint at the west end of the barge shelves.

2. Storm Surge Modeling

To assess how hurricane storm surge may change in the bay with modified channels, the coupled Advanced CIRculation (ADCIRC) and Simulating Waves in the Nearshore (SWAN) model are used (Booij *et al*., 1999 (SWAN); Luettich *et al*., 1992 (ADCIRC)). The coupled SWAN+ADCIRC model is used to simulate storm surge conditions with the existing channel dimensions (ES), ongoing dredging project conditions (OPS) and the planned future conditions (FPS). ADCIRC is a hydrodynamic circulation numerical model that simulates water levels and currents over a highly flexible, irregularly spaced mesh. It has been extensively used by the FEMA, USACE, USFWS, NOAA and many academic institutions for multiple applications in various geographical locations and is well-documented. It has also been validated using observations from several hurricanes in the Gulf of Mexico (Bunya *et al.*, 2010; Dietrich *et al.*, 2010; Hope *et al.*, 2013).

The SWAN and ADCIRC models are tightly coupled as an integrated wave and circulation model that operates on the same unstructured finite element mesh allowing for interaction of waves and circulation. The coupled SWAN+ADCIRC model solves the shallow-water equations on the nodes of a computational mesh and requires a variety of inputs including topography, bathymetry, bottom friction, astronomical tides, and meteorological forcing. The nodes communicate with each other via linear triangular finite elements. The unstructured finite element mesh can have varying resolution with element sizes ranging from kilometers in the open ocean to as fine as meters in the nearshore and in other critical areas like levees and channels. This coupled SWAN+ ADCIRC model provides the time and spatially varying water surface elevation, currents, wave height, wave direction and wave period.

2.1 Model Setup

For this study, the coupled SWAN+ADCIRC model uses the computational mesh developed for the Coastal Texas Flood Insurance Study (FIS) conducted by the USACE and FEMA (USACE, 2011). The mesh is referred to as TX2008_R35H and was obtained from the Computational Hydraulics Group at The University of Texas at Austin. The computational mesh domain includes the western North Atlantic Ocean, Caribbean Sea and Gulf of Mexico, and the element size varies from multiple kilometers in the open ocean to resolutions as fine as 15 m in the channels and rivers (Figure 3 and Figure 4). The maximum element size is approximately 200 m along the nearshore wave transformation zones and 5 km in the deep Gulf of Mexico. The TX2008_R35H has 3,352,598 nodes and 6,675,517 elements, and more than ninety percent of the computational nodes of the mesh reside on the Texas coast. The mesh is used and validated for simulating Hurricane Ike waves and storm surge and is also used for the 2019 Texas Coastal Resiliency Master Plan (TCRMP) (GLO, 2019; Subedee *et al*., 2018).

The topographic data along the Texas coast in the SWAN+ADCIRC mesh is recently updated with the seamless high resolution, 3-m, lidar-based topographic Digital Elevation Model (DEM) constructed by the Harte Research Institute for Gulf of Mexico Studies (HRI) for the Texas Coastal Resiliency Master Plan (TCRMP) study. The bathymetry in the computational mesh was obtained from multiple sources (USACE, 2011) and is not changed except along the CCSC and LQC with the most recently available bathymetric channel survey data. Because the vertical datum of the bathymetry in the ADCIRC model is NAVD88, the channel bathymetry, which is relative to Mean Lower Low Tide (MLLW) is also adjusted to NAVD88. In addition, SWAN+ADCIRC modeling requires an input of frictional roughness in the mesh that is characterized by the land cover type over which wind blows and wave and surge propagate. The frictional roughness, represented by the Manning's *n* coefficients, is assigned to each land cover class derived from the Coastal Change Analysis Program (C-CAP) land cover data and National Wetland Inventory (NWI) data. For more details on Manning's *n* values used, how the vertical datum shift from local MLLW to NAVD88 is accounted for in the model, and other model parameters, see the technical report of 2019 TCRMP (GLO, 2019).

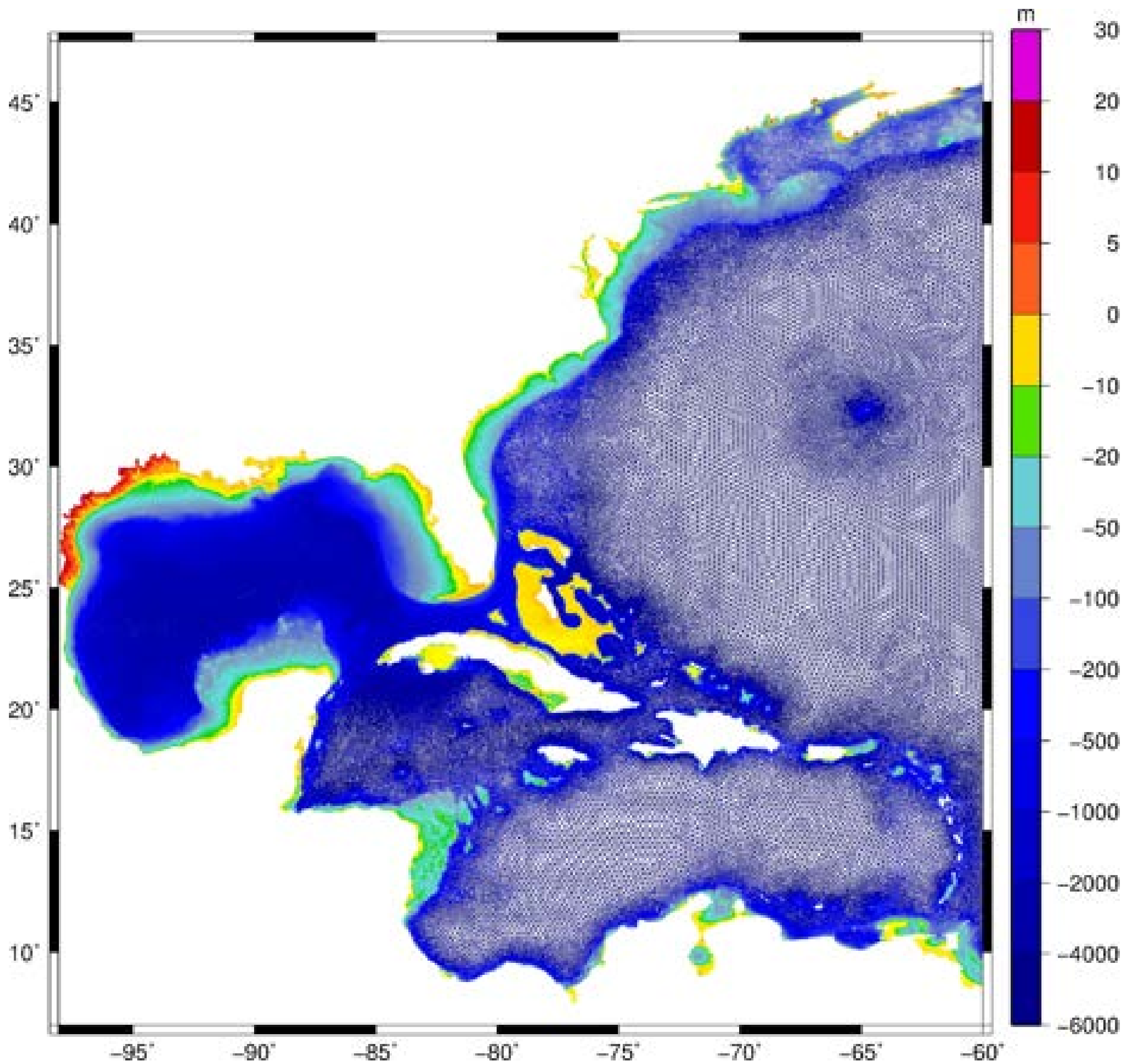

Figure 3. ADCIRC mesh with topographic and bathymetric values in meters. The larger triangular elements in the deep ocean can be seen in the mesh.

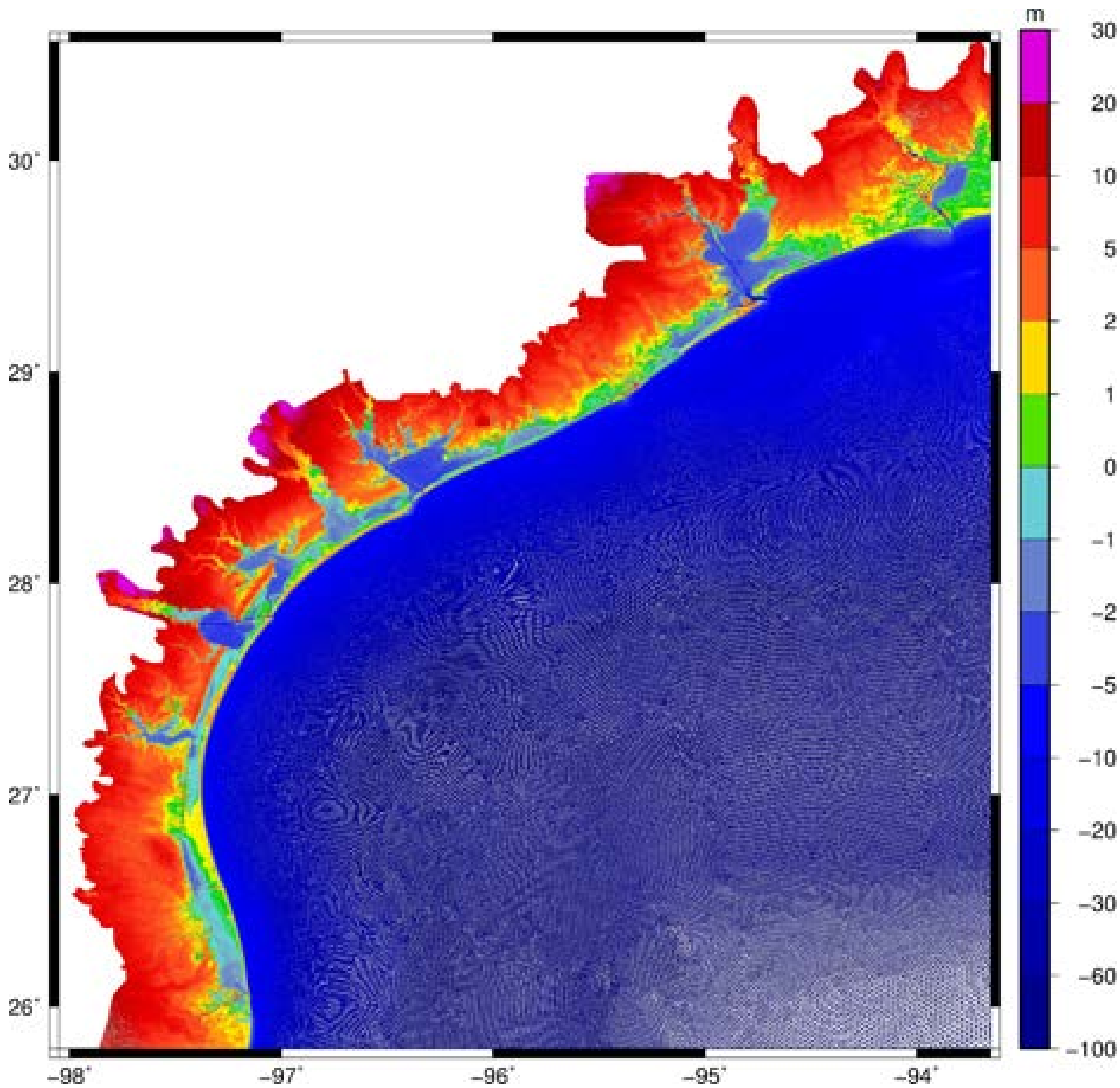

Figure 4. ADCIRC mesh with topographic and bathymetric values in meters along the Texas coast

The SWAN+ ADCIRC model is forced using meteorological wind and pressure fields of two selected hypothetical Category 4 hurricane events (Storm 319 and Storm 414) making landfall at or near Corpus Christi Bay (Figure 5). Storm 414 is a fast-moving storm with a large wind field but has slightly lower wind speed in comparison to Storm 319. Storm 319 makes landfall on North Padre Island near Bob Hall Pier and Storm 414 makes landfall 7 miles south of Storm 319 in the Padre Island National Seashore. Table 1 summarizes the storm characteristics for both selected storms. The same two hurricane events are simulated for each of the three channel depth scenarios (ES, OPS, FPS) to assess the difference in surge for the different channel configurations. Storm 319 is simulated for a total of 7 days (168 hours) and the landfall occurs 132 hours into the simulation, whereas Storm 414 is simulated for 4 days (96 hours) and the landfall occurs 84 hours into the simulation. All the models are run using the High-

Performance Cluster system (HPC) in the Texas Advanced Computing Center (TACC) at The University of Texas at Austin. Each simulation required approximately 15 hours to complete in over 1,200 computing cores.

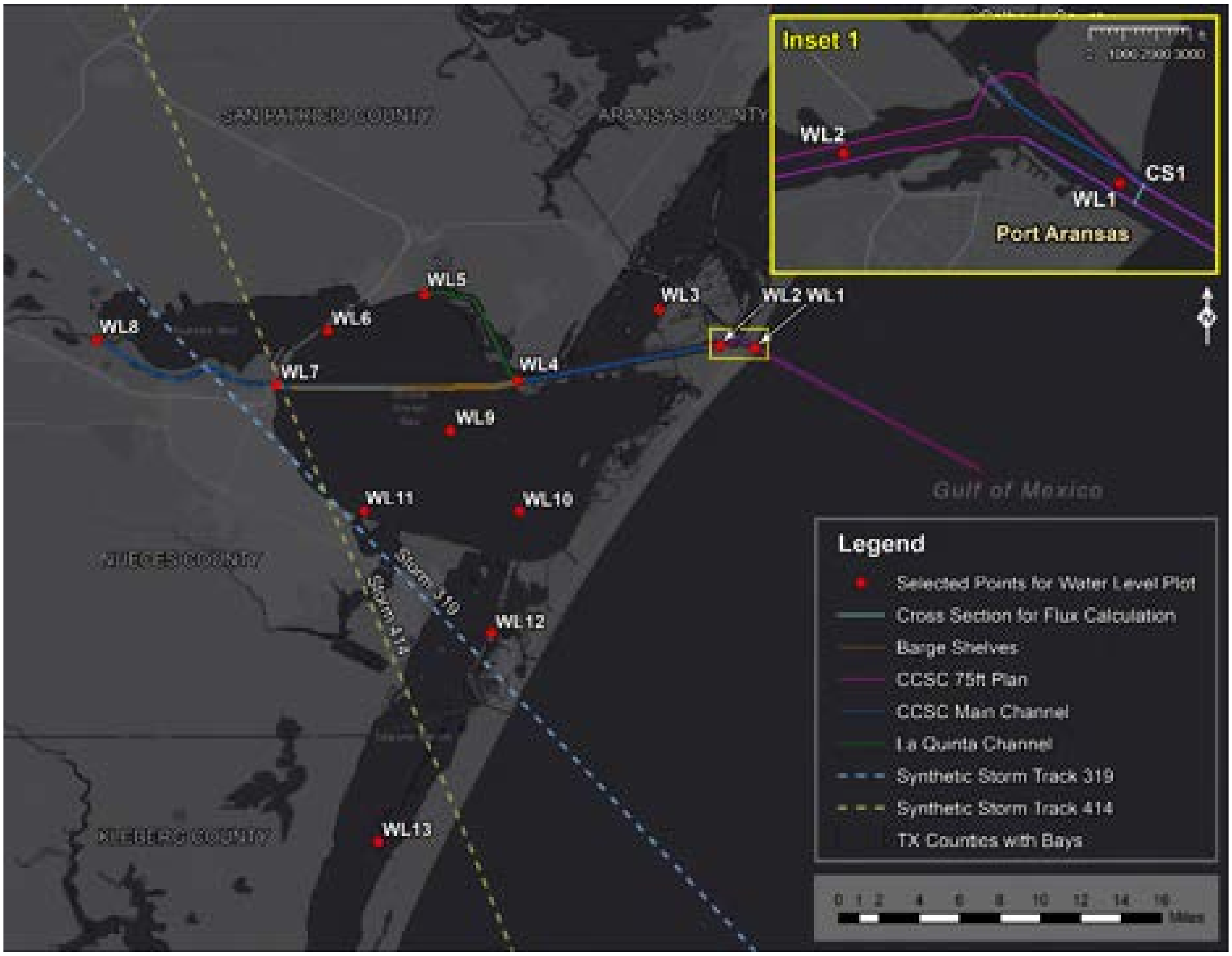

Figure 5. Study area map showing hurricane tracks, different channel footprints, and the selected points for plotting water level time series. The inset map shows two points for water level plots (WL1 and WL2) and the cross section (CS1) used for a velocity plot.

Table 1. Characteristics of simulated storms.

Storm	Landfall Location	Central Pressure (mb)	Radius of Max. Wind (mile)	Max. Wind Speed (mph)	Forward Speed (mph)
Storm 414	Padre Island National Seashore	910.2	23.28	134	27.27
Storm 319	Near Bob Hall Pier	905.2	11.98	143	10.47

2.2 Modeling Results and Discussion

The SWAMN+ADCIRC model computes the elevation of the water surface at every mesh node and time step during a storm simulation. The MAXELE, also known as maximum envelope of water (MEOW), is the maximum storm surge elevation at each node during a storm event and provides information about the maximum inundation patterns. Figures 6, 7, and 8 show the MAXELE in ES, OPS and FPS channel configurations due to Storm 319, and Figures 9, 10, and 11 show the same for Storm 414. The dashed line in these maps is the storm track. The higher storm surge impact is observed on the right side (east) of the storm tracks in both Storm 319 and 414, which is due to the counterclockwise direction of circulating winds during the hurricane as well as the stronger winds passing on the right side of the storm tracks. There is an extensive buildup of surge with MAXELE of 9-13 feet in front of Mustang Island due to Storm 319 (Figures 6, 7 and 8) whereas a much higher buildup of water with MAXELE of 16-20 feet is seen in front of North Padre Island and Mustang Island due to Storm 414 (Figure 9, 10, and 11). The fast-moving nature and large wind field of Storm 414 produces much higher storm surge in comparison to Storm 319 resulting in the complete inundation of the barrier islands with 10-16 feet of water and more inland penetration of the surge.

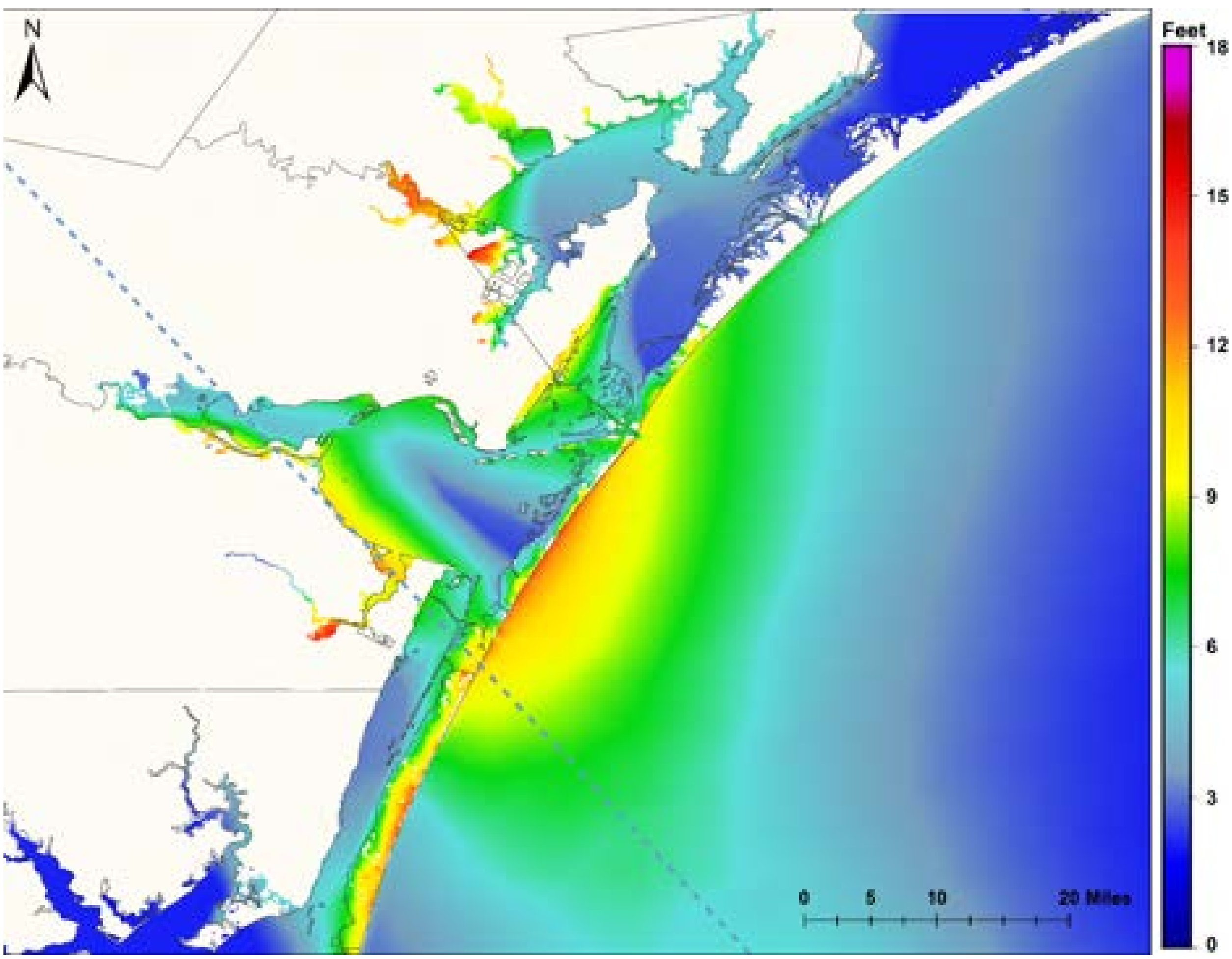

Figure 6. Maximum water surface elevation (MAXELE) in feet (NAVD88) for the ES channel configuration due to Storm 319 (storm track shown with dashed line).

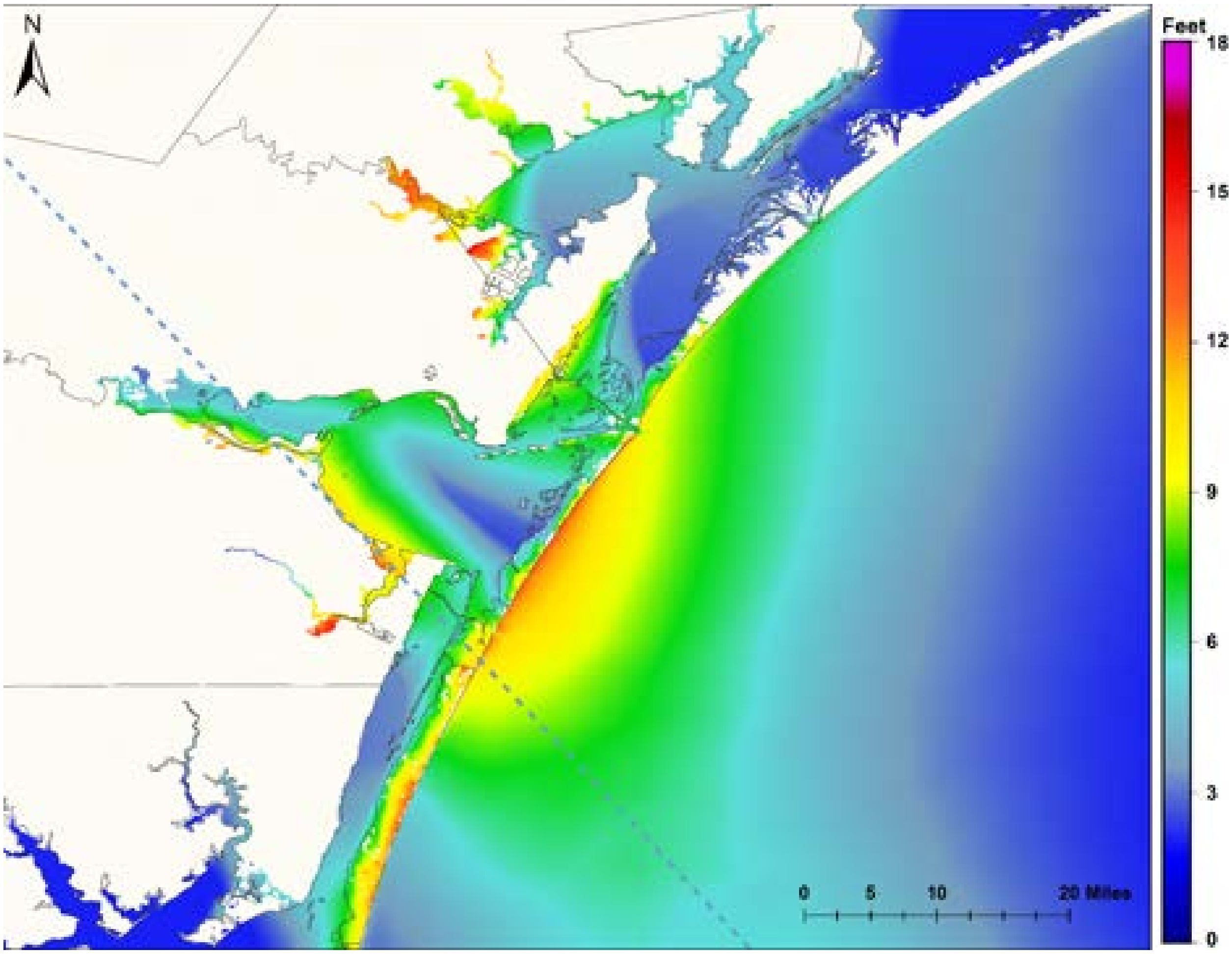

Figure 7. Maximum water surface elevation (MAXELE) in feet (NAVD88) for the OPS channel configuration due to Storm 319 (storm track shown with dashed line).

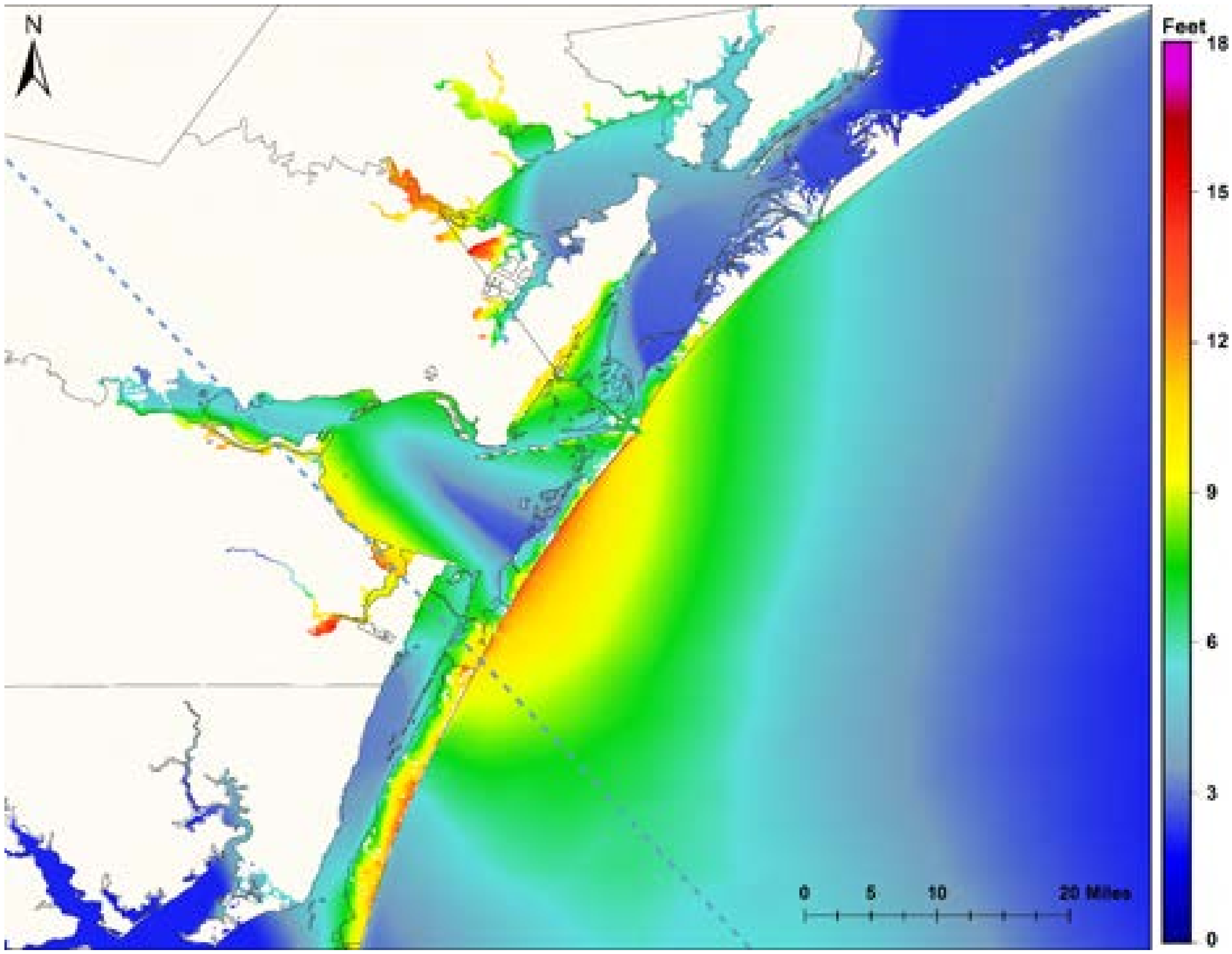

Figure 8. Maximum water surface elevation (MAXELE) in feet (NAVD88) for the FPS channel configuration due to Storm 319 (storm track shown with dashed line).

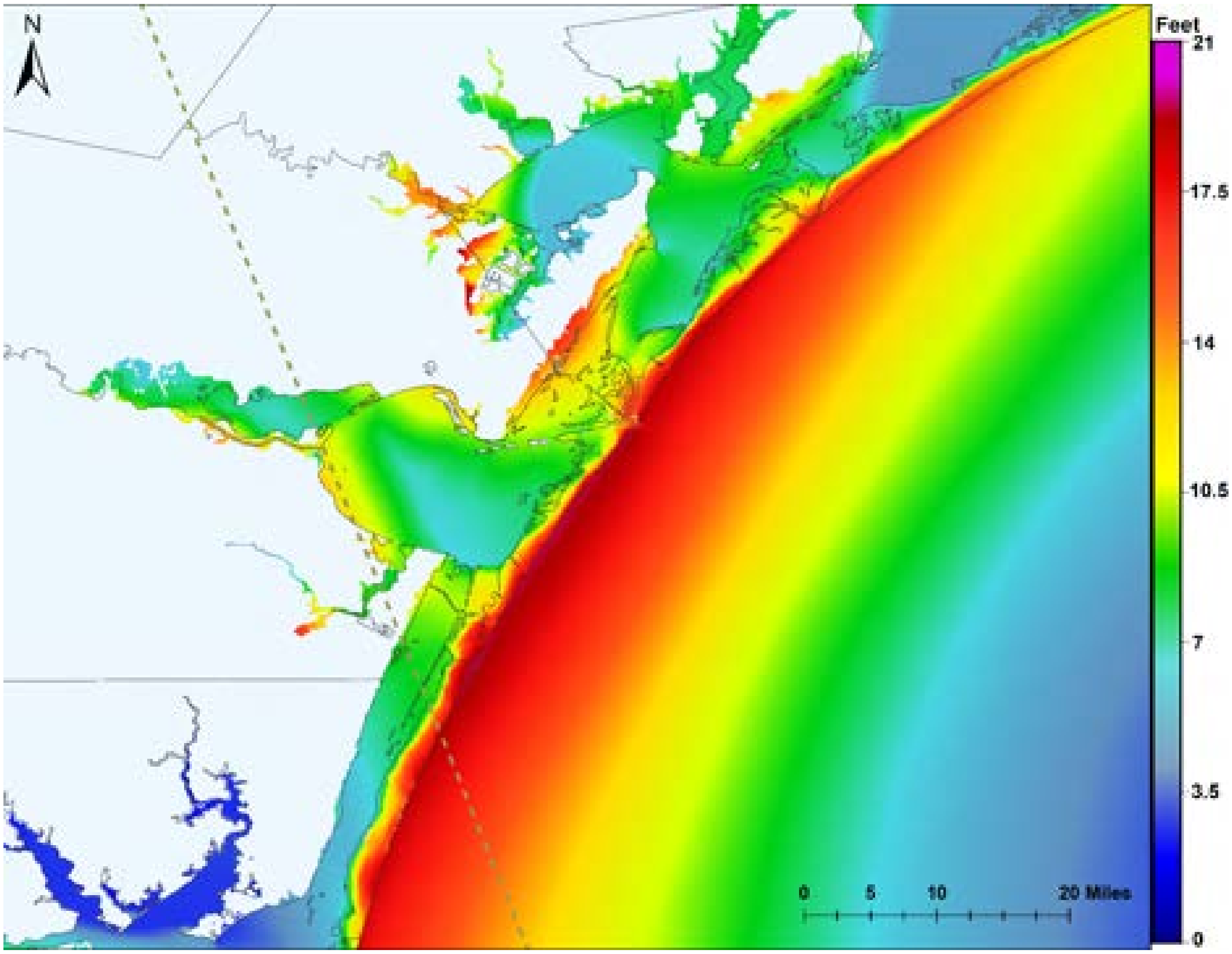

Figure 9. Maximum water surface elevation (MAXELE) in feet (NAVD88) for the ES channel configuration due to Storm 414 (storm track shown with dashed line).

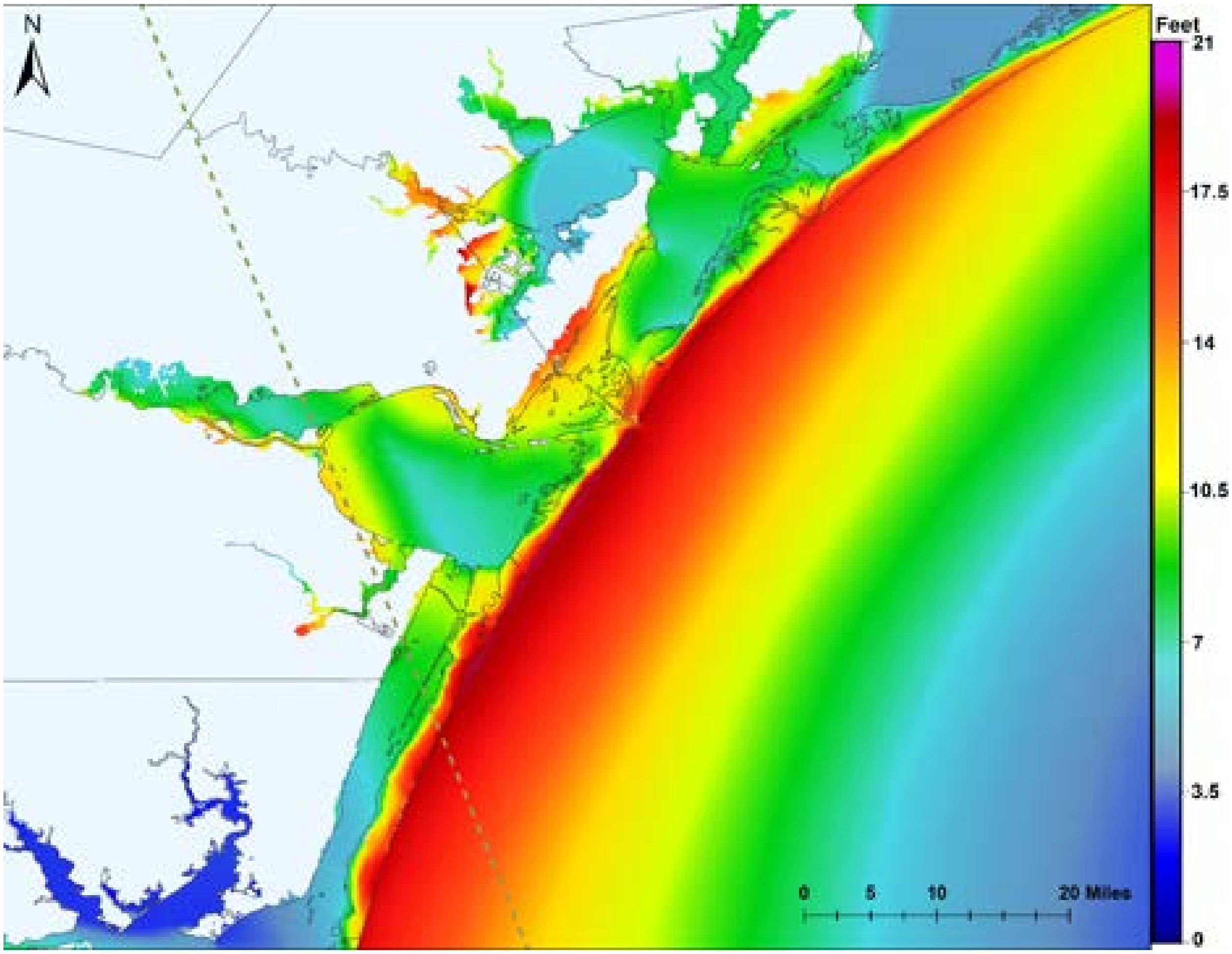

Figure 10. Maximum water surface elevation (MAXELE) in feet (NAVD88) for the OPS channel configuration due to Storm 414 (storm track shown with dashed line).

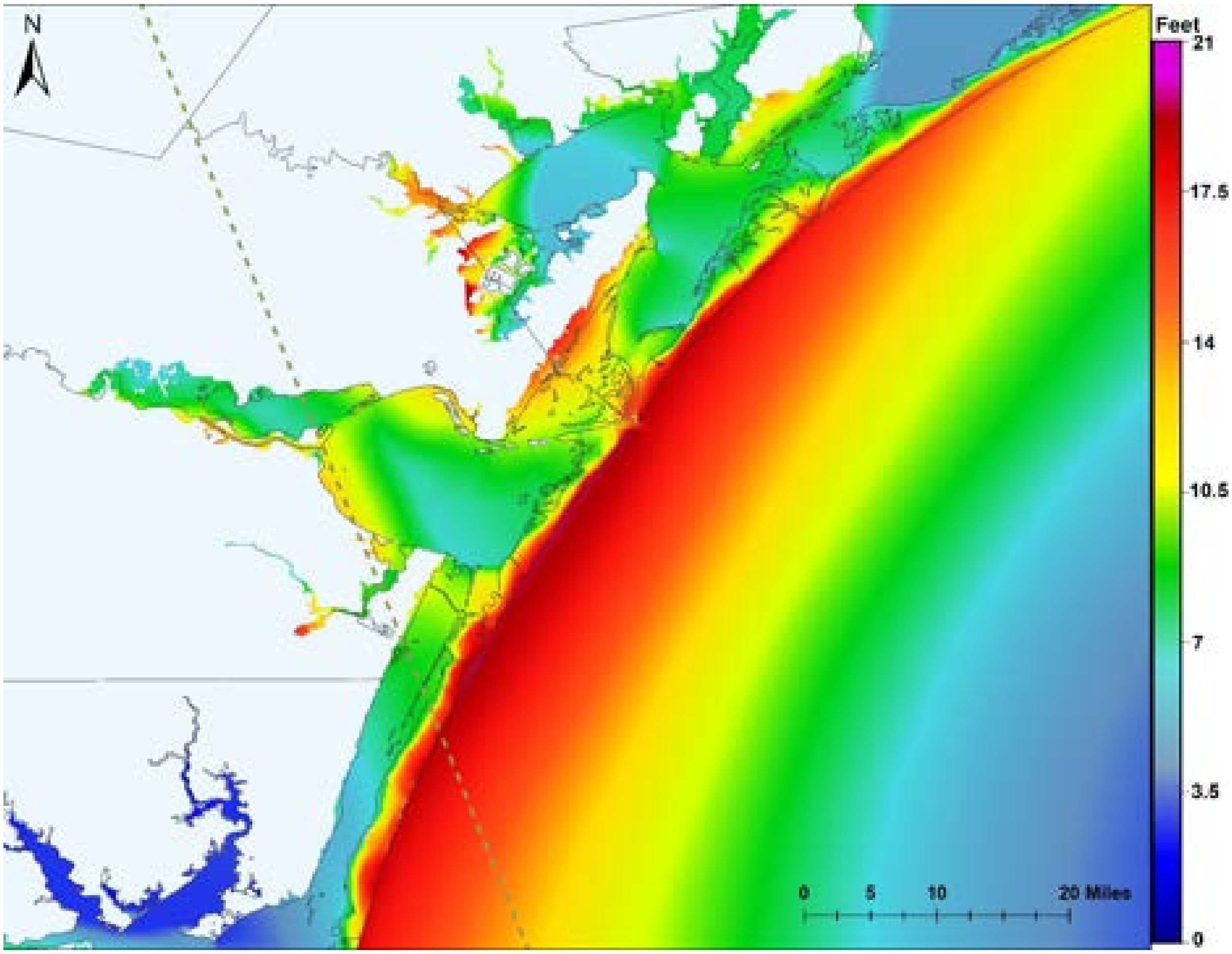

Figure 11. Maximum water surface elevation (MAXELE) in feet (NAVD88) for the FPS channel configuration due to Storm 414 (storm track shown with dashed line).

Figures 12 and 13 show the impacts of the deepening of the ship channel on the MAXELE due to Storm 319 and Storm 414, respectively. In each figure, the MAXELE of ES is subtracted from the MAXELE of OPS (top map) and FPS (bottom map). The warmer colors in both figures show increased water levels due to the deepening of the channel in the OPS and FPS channel configurations. The increased depth of the ship channel allows more water to enter the bays, thus increasing the water level in the bays as well as slightly increasing the inundation extent. The MAXELE of the OPS channel configuration is higher by 0.75-2 inch in Corpus Christi Bay compared to the MAXELE of the ES configuration in both storms. There is a decrease in the MAXELE of the OPS configuration by 1-3 inch in Redfish Bay and Aransas Bay compared to the MAXELE of ES for both storms (see top maps in Figures 12 and 13).

The 75-feet deep ship channel in the FPS configuration increases the water level up to 3 inch in Corpus Christi Bay due to Storm 319 and up to 3.5 inch due to Storm 414 (see bottom maps in Figures 12 and 13). Furthermore, the MAXELE of the FPS configuration increases by 3-4 inch in Nueces Bay compared to the ES configuration during Storm 414. The widespread decrease in MAXELE modeled in the OPS configuration in Redfish Bay and Aransas Bay is not seen in the FPS configuration (see bottom maps in Figures 12 and 13). A hotspot of increased MAXELE by 4-12 inch occurs in front of Harbor Island in the

FPS configuration for both storms. This localized increase occurs where the 75-feet deep FPS channel configuration ends just inside Aransas Pass. There is no change in the MAXELE in the offshore regions for both storms and channel configurations.

To quantify the amount and locations of the additional amount of storm surge flooding caused by channel deepening, the OPS and FPS inundated areas were overlain on ES inundated areas for both storms. It is found that 319 acres and 492 acres of additional land area is inundated due to the OPS and FPS configurations respectively in comparison to the ES for Storm 414. For Storm 319, an additional land area of 220 acres and 447 acres is flooded due to the OPS and FPS configurations respectively in comparison to the ES configuration. These additional flooded areas are scattered in small areas throughout the study area.

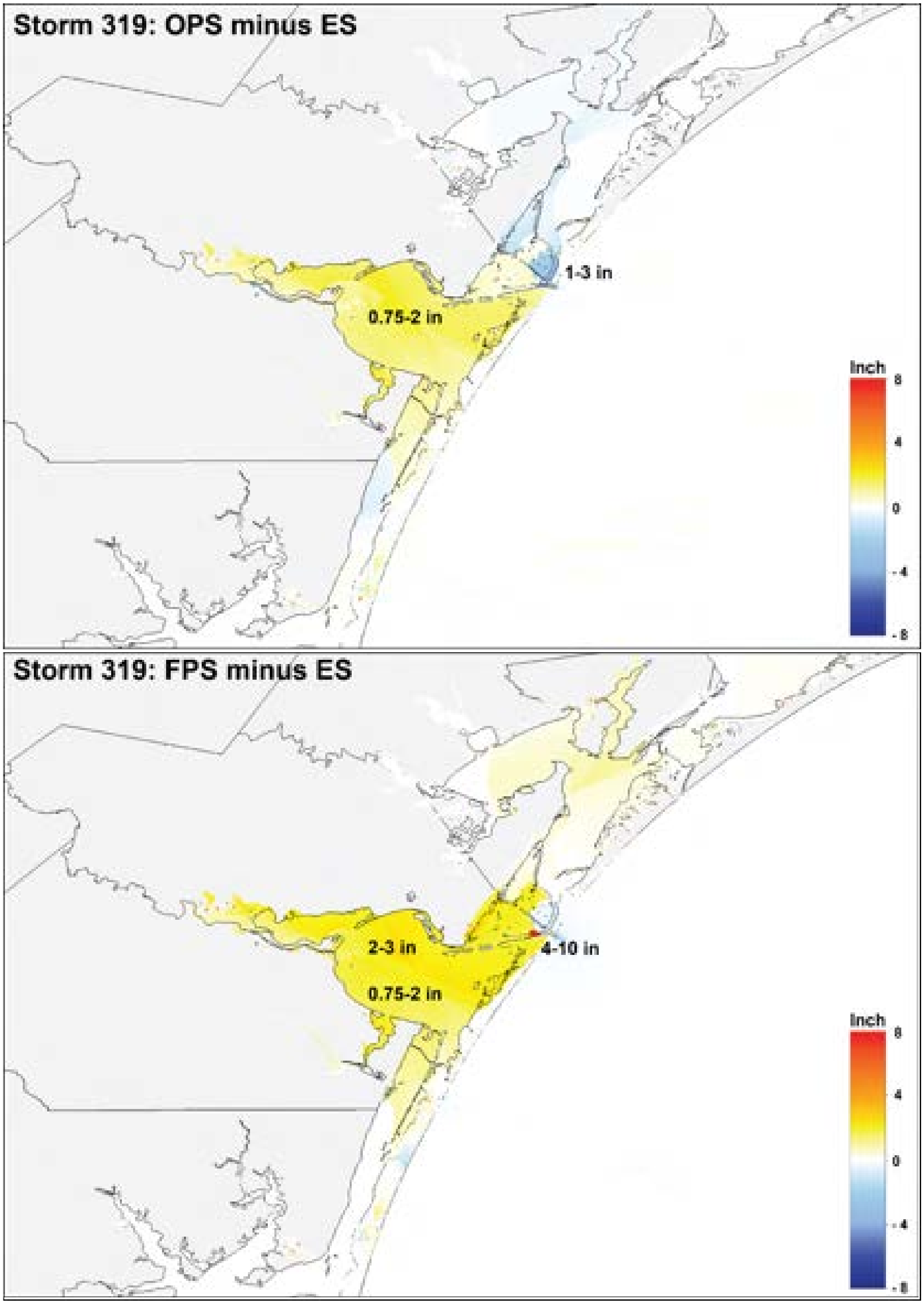

Figure 12. Difference in MAXELE of OPS and ES (top) and FPS and ES (bottom) due to Storm 319. Warmer colors indicate higher water level due to the increase in the channel depth in the OPS and FPS channel configurations.

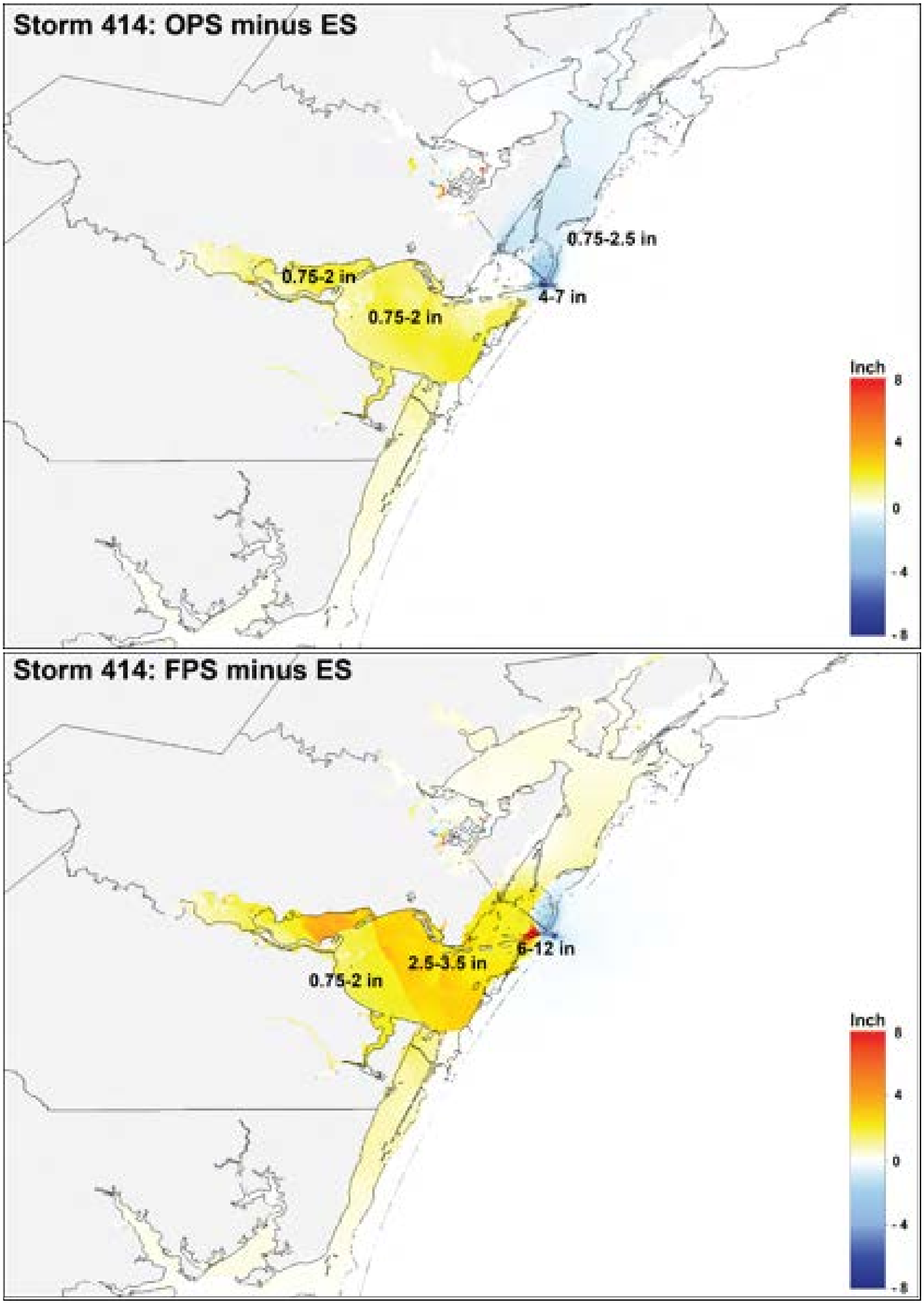

Figure 13. Difference in MAXELE of OPS and ES (top) and FPS and ES (bottom) due to Storm 414. Warmer colors indicate higher water level due to the increase in the channel depth in the OPS and FPS channel configurations.

Figure 14 shows the time series of the flow rate through cross-section CS1, which is in the mouth of CCSC in Aransas Pass (inset map in Figure 5), during Storms 319 and 414 for three channel scenarios. The peak flow rate of Storm 319 is higher than Storm 414. The peak flow rate for the OPS channel configuration is the highest in Storm 319 whereas the peak flow rate for the FPS configuration is the highest in Storm 414.

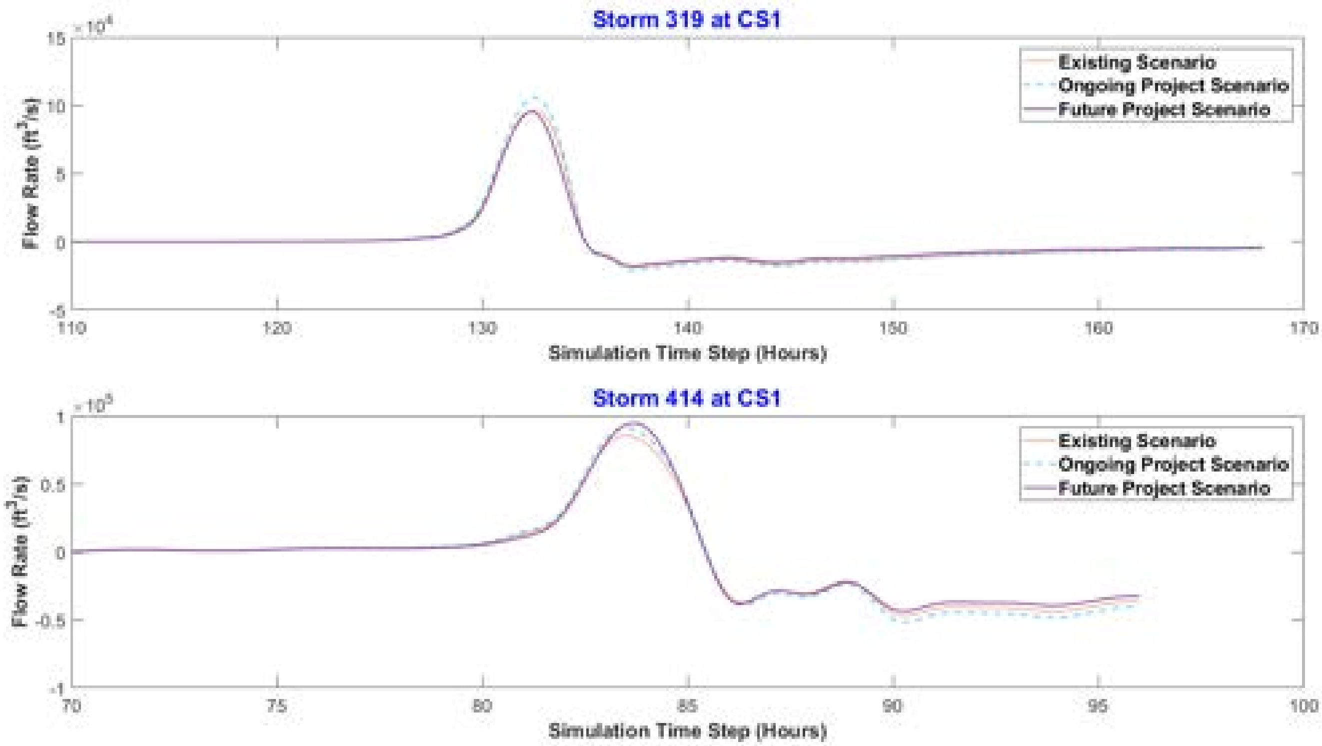

Figure 14. Flow rate time series at the CS1 cross-section (see Figure 5 for location) in the mouth of CCSC for three channel configurations during to Storm 319 (top) and Storm 414 (bottom). The positive values in the graph represent the flood flow (flowing into the bay) and the negative values represent the return flow (flowing out of the bay).

Figure 15, 16, and 17 show the time series of the water surface elevations (storm surge hydrographs) at selected observation points shown in Figure 5 for all three channel scenarios due to Storms 319 and 414. These hydrographs show water level changes over time during the hurricane event under different channel configurations. For example, comparing the hydrographs at WL1 and WL2, it can be seen how differently the water level changes over time at the mouth of CCSC and along the CCSC, which are a mile apart. The ES has the highest peak water level for both Storm 319 and 414 at WL1 (Figure 15) whereas the FPS has the highest peak water level for both storms at WL2 (Figure 16). The peak water level at WL2 for the FPS configuration is 9.4 inch higher than ES and 10.2 inch higher than OPS for Storm 319 whereas it is 9.8 inch higher than ES and 13 inches higher than OPS for Storm 414. The peak velocity at WL1 is 13.71 ft/s in ES, 14.3 ft/s in OPS and 13.75 ft/s in FPS configuration for Storm 319, and 14.11 ft/s in ES, 14.63 ft/s in OPS and 15.12 ft/s in FPS configuration for Storm 414. Figure 17 shows the storm surge hydrographs in the middle of Corpus Christi Bay (WL9) where the FPS has the highest peak water level for both storms. The peak water level in the FPS configuration is 1.7 inch higher than ES and 1.2 inch higher than OPS at WL9 for Storm 319, and FPS is 2.4 inch higher than ES and OPS is 1.2 inch higher than ES at WL9 for Storm 414. These values are similar to what are seen in the MAXELE difference maps shown in Figure 12 and 13.

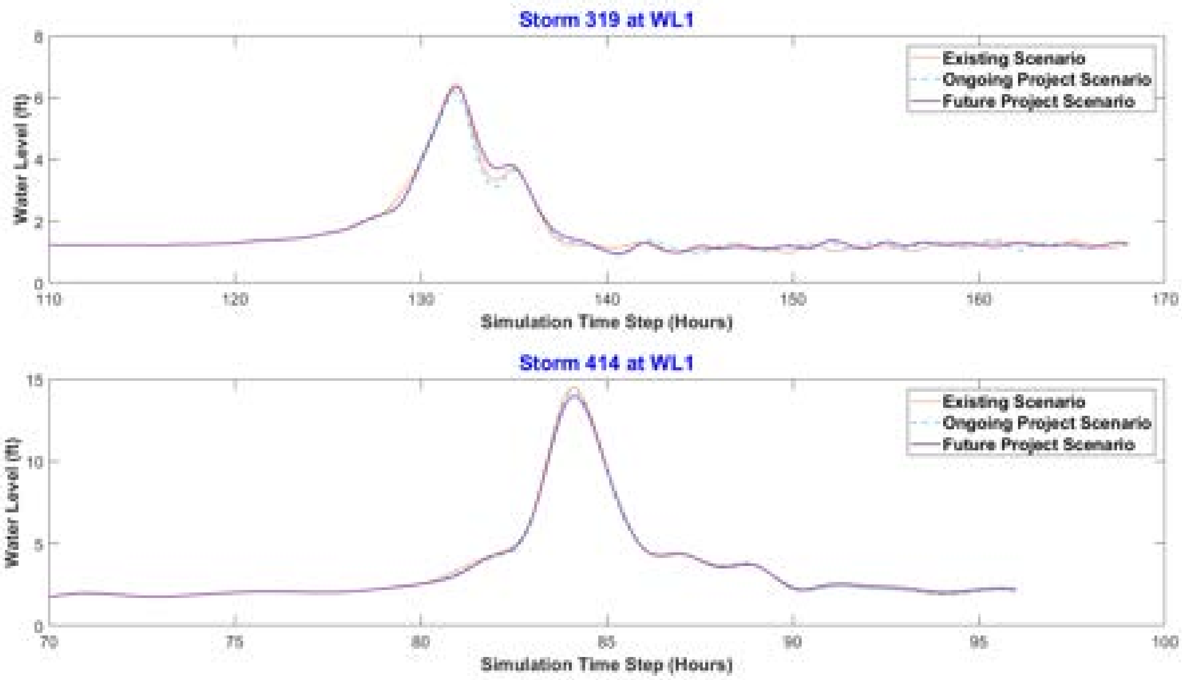

Figure 15. Water level time series in the mouth of CCSC (WL1) for Storm 319 and Storm 414.

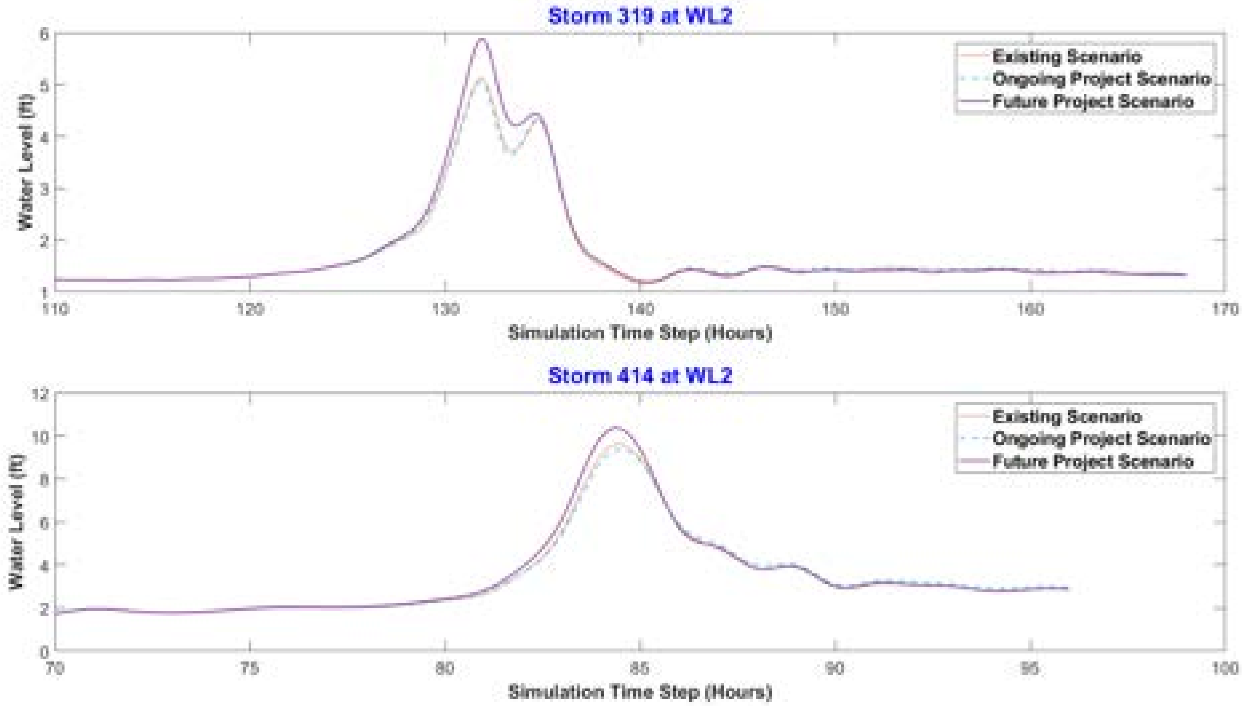

Figure 16. Water level time series adjacent to Harbor Island (WL2) for Storm 319 and Storm 414.

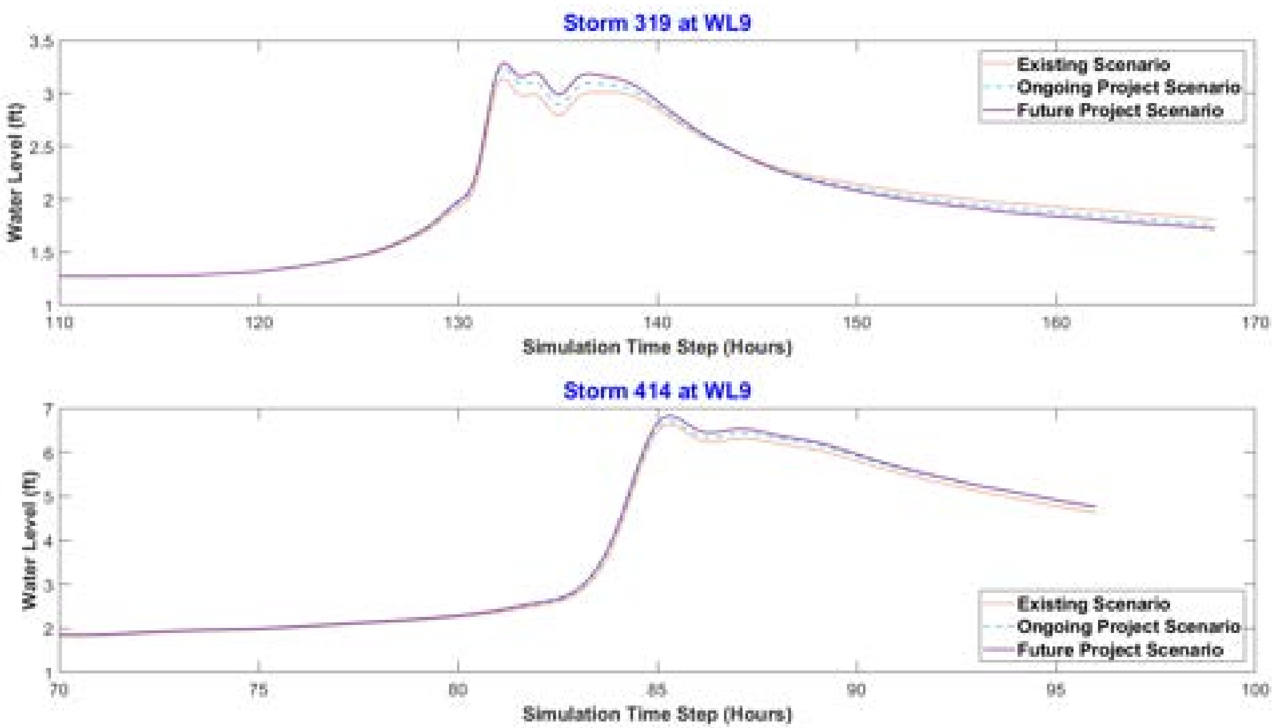

Figure 17. Water level time series in the middle of Corpus Christi Bay (WL9) for Storm 319 and Storm 414.

2.3 Summary of Storm Surge Modeling

Hydrodynamic storm surge modeling using SWAN+ADCIRC was conducted to evaluate coastal storm surge impacts in and around Corpus Christi Bay due to PCCA's proposed ship channel deepening projects. Since the model was recently calibrated and validated with Hurricane Ike for the Texas Coastal Resiliency Master Plan, no validation simulation was repeated. Two synthetic Category 4 storms forced the model to simulate storm surge conditions with the existing channel dimensions (ES), ongoing dredging project conditions (OPS), and the planned future conditions (FPS). Modeling outputs show storm surge water level elevations for each storm. The analysis of model output consists of generating difference grids showing the comparison of water level elevations between OPS and ES, and FPS and ES conditions. The flow rate through the cross-section in the mouth of CCSC is also calculated and compared among three channel scenarios. Furthermore, storm surge hydrographs are plotted that show how water level changes over time during the storm event under different channel scenarios. The key findings of the analysis are the following:

- Compared to the ES channel configuration, OPS and FPS channel configurations allow more water to enter the bays, thus increasing storm surge water levels as well as slightly increasing the inundation extent.
- Additional inundation covers 220 acres to 492 acers scattered in small areas throughout the bay system mostly in natural or low-hazard areas, however, parking lots and roads may also be impacted.
- The maximum elevation of the storm surge (MAXELE) for the OPS channel configuration is higher by 0.75-2 inch in Corpus Christi Bay compared to the MAXELE of the ES configuration for both storms.
- The FPS configuration increases MAXELE up to 3 inch in Corpus Christi Bay during Storm 319 and up to 3.5 inch during Storm 414 compared to the ES configuration.
- A hotspot of increased MAXELE by 4-12 inches occurs adjacent to Harbor Island in the FPS configuration during both storms.

3. Tidal Hydraulics Modeling

The model chosen for tide analysis is Delft3D-Flexible Mesh (Delft3D-FM) modeling suite which is the successor of the structured Delft3D 4 Suite developed by Deltares (Deltares, 2019). The modeling suite includes the widely used hydrodynamic model Delft3D and its newly developed unstructured engine called D-Flow Flexible Mesh (D-Flow FM) to compute the evolution of estuarine flows, salinity, and temperature dynamics. Delft3D-FM has an advantage over Delft3D due to its capability to have variable resolutions in one model domain. This capability helps prevent overly high resolution in less relevant areas, which reduces computational time. Therefore, the D-Flow FM model is chosen for this project because of its unstructured grid framework to create a single model domain of Corpus Christ Bay and adjacent bays highly complex geometry and to run long-term simulations at relatively low computational cost. D-Flow FM can simulate the hydrodynamics in the model area by solving the unsteady flow equations in either 2D or 3D. In this project, D-Flow FM Version 1.5.1.41875 is used. The tidal hydraulics simulations are performed with a 2D model.

3.1 Model Setup

An important lesson learned from previous modeling efforts in the region is to accurately describe the highly interconnected hydrodynamics and ecological processes in one computational domain. Therefore, a model grid that resolves the channel geometry effectively and has the balanced grid resolution along different water bodies is preferred. As such, a major development of this project has been the creation of an unstructured model grid to analyze tidal hydraulics in the Corpus Christi Bay System.

The Delft3D-FM model configuration for this project is adopted from the ADCIRC model that is used to assess hurricane storm surge impact in and around the Corpus Christi Bay. The ADCIRC model grid is imported to Delft3D-FM, and the grid structure and resolution is updated for alignment along main flow directions and model efficiency. The set-up for this unstructured grid is refined and adjusted to optimize the orthogonality and the smoothness in multiple directions. The grid extends from Mesquite Bay in the northeast and Mission Bay in the northwest, to the Upper Laguna Madre in the south (Figure 18). The model domain spans the Corpus Christi Bay System, covering all the surrounding bays and delta, and extends 12 miles offshore from the shoreline. The model utilizes a combination of grid triangles, rectangles and pentagons for the natural depictions of irregular coastlines and for numerical efficiency. The horizontal resolution of the grid ranges from 150–225 feet in the channels to 2,000 feet in the offshore area. The grid has 168,347 nodes and 500,464 edges. Figure 18 shows the extent of the model grid along with the offshore and land boundaries.

The bathymetry of the ADCIRC model is used in the Delft3D-FM model which was obtained from multiple sources (USACE, 2011). However, the bathymetry of CCSC and LQC are updated based on the latest USACE survey data. Since the vertical datum of the bathymetry in the ADCIRC model is NAVD88, the channel bathymetry, which is relative to Mean Lower Low Water (MLLW), is adjusted to NAVD88.

The model has three offshore boundaries – the eastern boundary (WL1) is a uniform water level boundary with water level data provided by Bob Hall Pier (NOAA Station ID 8775870). The north and south boundaries (NM2 and NM1) are defined as Neumann Boundaries with uniform zero values to prevent potential water level gradients across the boundary. The bathymetry and boundary setup of the model are shown in Figure 19. Wind forcing is also included as model input using data from Bob Hall Pier and is applied as a uniform wind profile over the entire grid. The Manning's n bottom friction scheme is selected for this study because of the ability to generate lower drag coefficients than the Chezy formulation in deep waters.

Figure 18. Delft3D-FM model grid is shown in blue. The magenta color shows the offshore boundaries and the black colored polygons show the land boundaries. The orange diamonds show NOAA tide stations used for input to the model (Bob Hall Pier) and water level output validation (Packery Channel, Port Aransas, and USS Lexington).

Table 2 provides the model settings selected after a series of model test runs to find good agreement between the modeled and observed data. For the model initialization, initial water level is defined as the average measurements of water level at the boundary and is given as a uniform value over the entire grid. The model was migrated to the High-Performance Computing system (HPC) at Texas A&M University – Corpus Christi and is run on 150 cores. A typical 1-month water level simulation takes 3.5 – 4 hours using 150 computing cores.

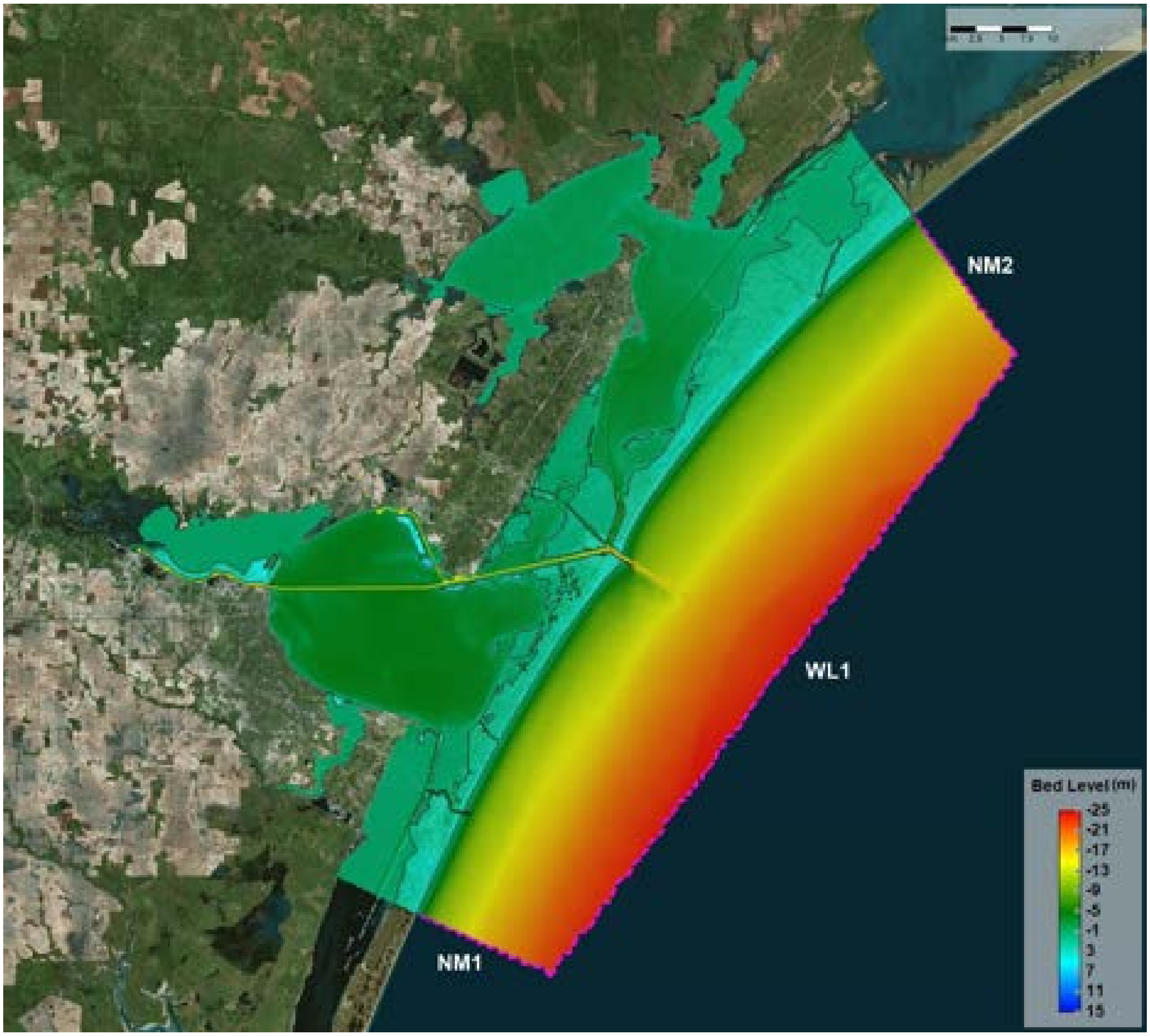

Figure 19. Bathymetry/topography (in meters) and boundaries of the model. The bathymetry shows the ES channel configuration. WL1 is the offshore water level boundary driven by Bob Hall Pier data, and NM1 and NM2 are the Neumann Boundaries with uniform zero values.

Table 2. Final settings used in the Delft3D model for the tidal analysis.

Parameters	Value
Maximum Courant number	0.5
Vertical layer type	Single
Manning's n	0.023
Viscosity: Horizontal, Vertical	0.01 m^2/s, 5×10^{-5} m^2/s
Diffusivity: Horizontal, Vertical	1 m^2/s, 5×10^{-5} m^2/s
Wind drag coefficient type Break points wind drag coefficient Break points wind speed	Smith & Banks (2 break points) 0.00063, 0.00242 0 m/s, 26 m/s

3.2 Model Validation

The Delft3D model is run at three time periods to capture different wind regimes and tide conditions. The wind forcing has a significant role in the water level in this area, therefore, three validation simulations are performed to capture the two opposing wind regimes: a) winds directed out of the southwest that dominate more than 50% of the time and b) strong winds directed out of the north associated with frontal passages. The time periods selected for the model validation are June 7th – July 7th, 2018 (30 days); Jan 1st – 15th, 2019 (15 days) and April 1st – 10th, 2019 (10 days).

For all three simulations, the model is driven by 6-minute verified water level data from Bob Hall Pier at the offshore boundary (WL1) and the output water level is compared with the Port Aransas, USS Lexington and Packery Channel tide stations (Figure 18). The model is also forced with the 6-minute wind velocity magnitude and direction time series using data from Bob Hall Pier.

Figure 20 shows the comparison of modeled and measured tidal water levels for a 1-month period in June/July 2018 at Port Aransas, USS Lexington and Packery Channel tide stations. Figure 21 shows the comparison of tidal water levels for a 15-day period in January 2019 at the same stations. Similarly, Figure 22 shows the comparison of tidal water levels for a 10-day period in April 2019 at the same tide stations. The model matches the timing of the measured tidal water levels at these three stations in all three simulation time periods with no detectable phase shift. The magnitude and timing of the measured and modeled tidal water levels at Port Aransas are similar in all three simulations. The model in general underestimates tidal amplitudes at USS Lexington throughout the simulations but captures the trend of water level fluctuations. The model performs quite well in the summer simulation in all three tide stations compared to the winter and spring simulations. Table 3 contains a summary of model validation statistics.

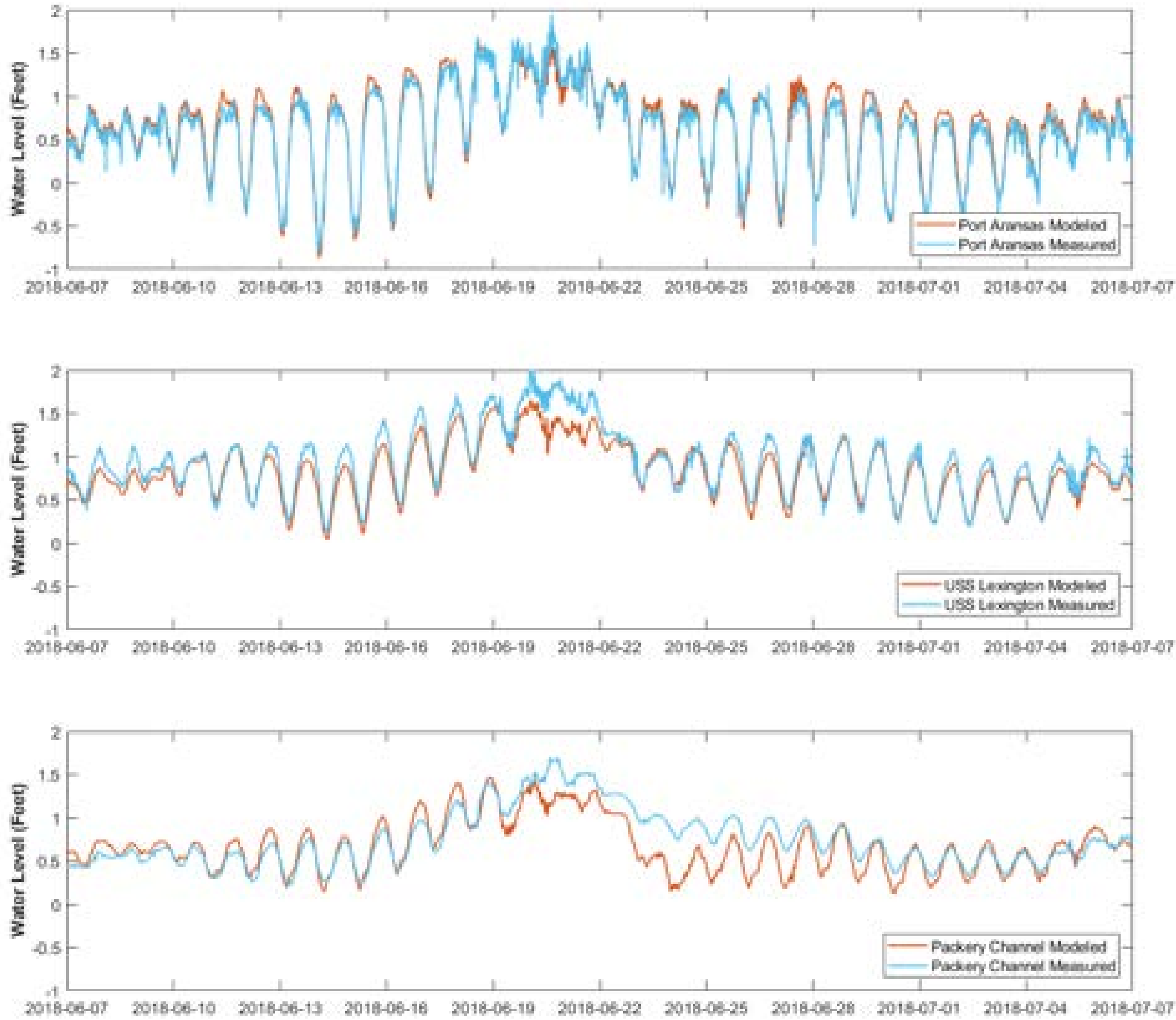

Figure 20. Observed (in blue) and modeled (in orange) water levels for Port Aransas, USS Lexington and Packery Channel tide stations over 1-month period between June 7th, 2018 and July 7th, 2018.

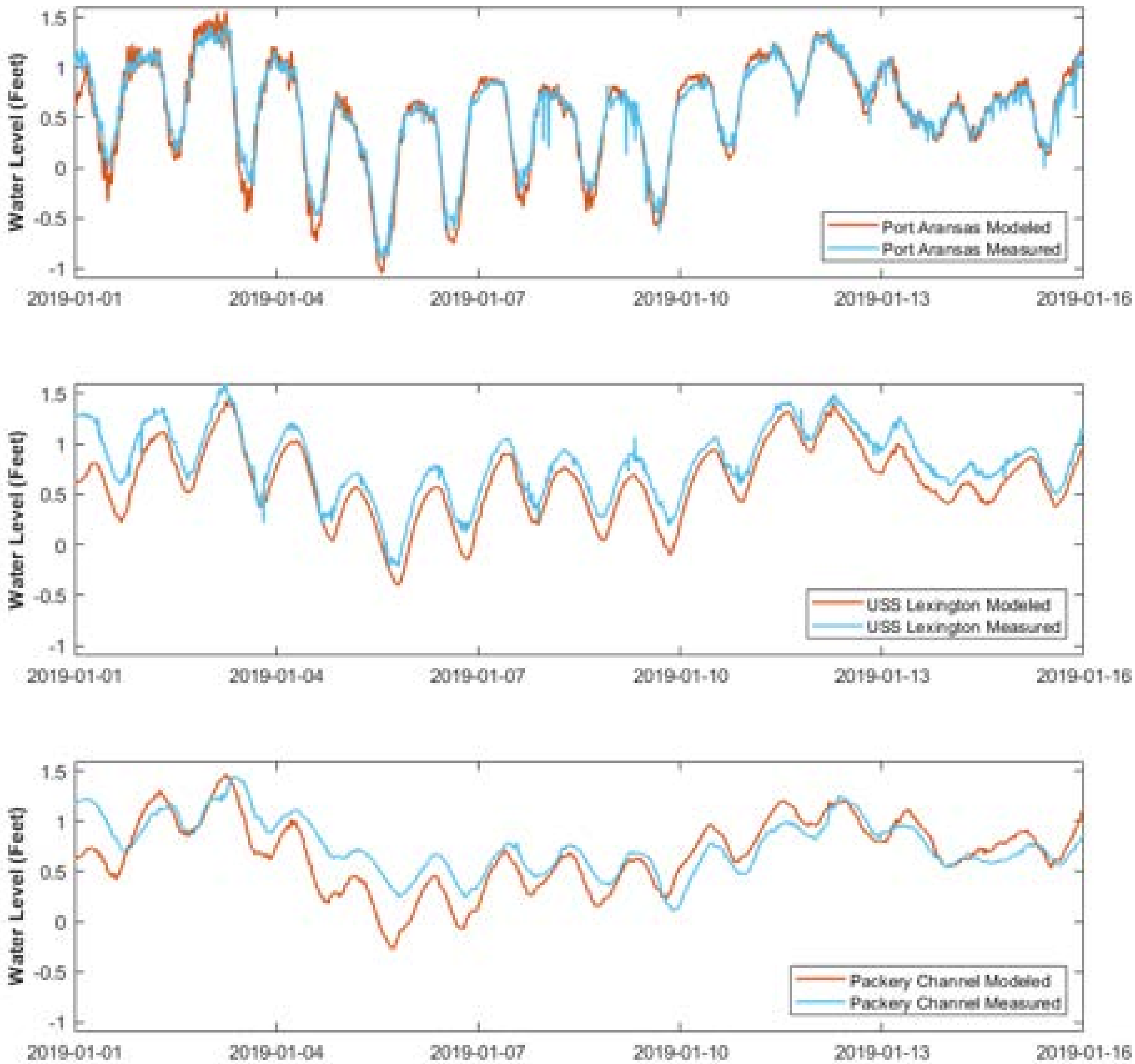

Figure 21. Observed (in blue) and modeled (in orange) water levels for three tide stations over 15-day period between January 1st, 2019 and January 16th, 2019.

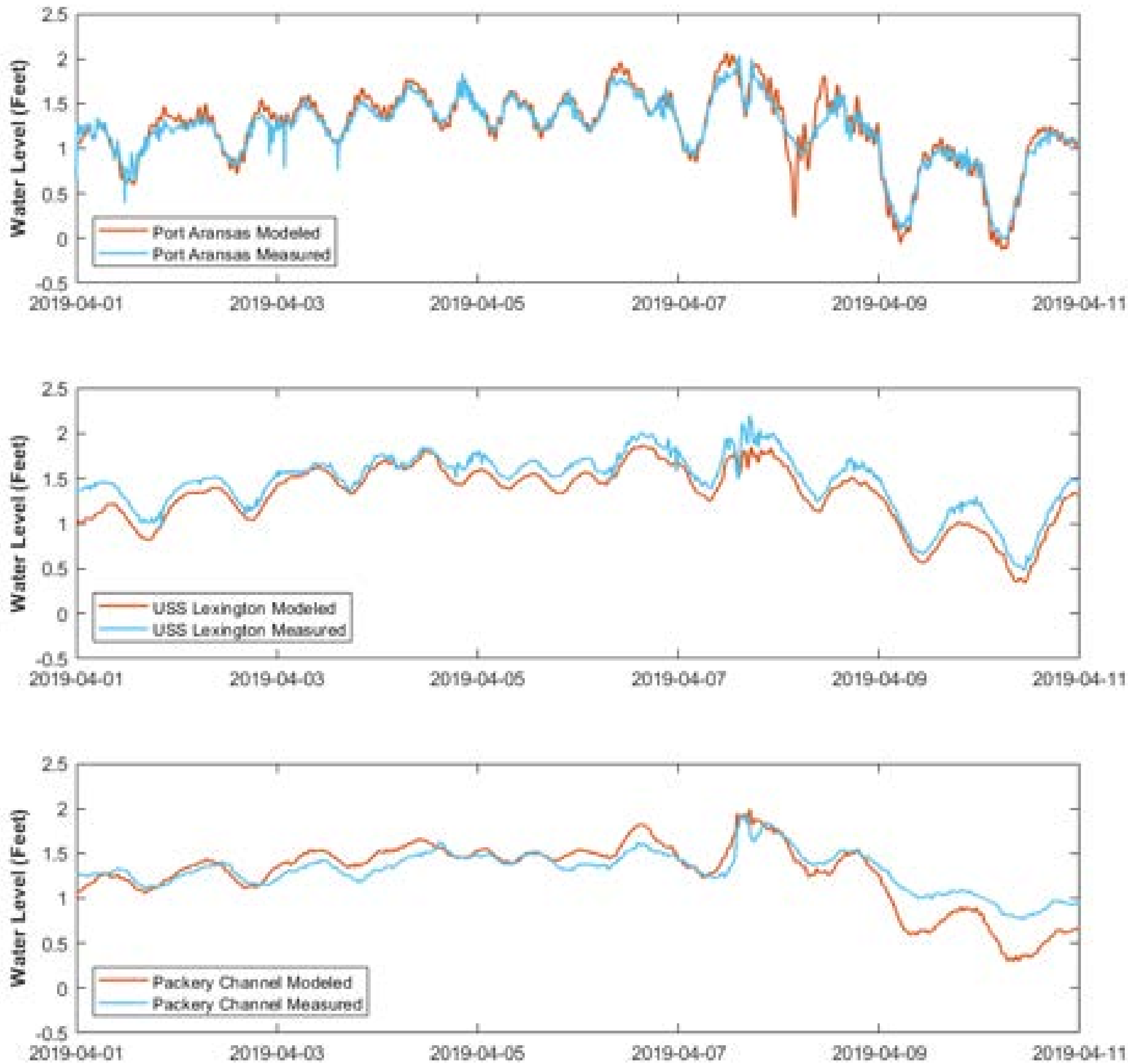

Figure 22. Observed (in blue) and modeled (in orange) water levels for three tide stations over 10-day period between April 1st, 2019 and April 11th, 2019.

Table 3. A summary of statistical metrics comparing observed and modeled water levels for three validation periods at three tide stations.

Simulation	Tide Station	Correlation Coefficient (R)	RMSE (ft)	Maximum Difference (ft)	Bias (ft)
Jun/July 2018 (1-month simulation)	Port Aransas	0.97	0.12	0.85	0.05
	USS Lexington	0.96	0.15	0.3	-0.1
	Packery Channel	0.92	0.21	0.25	-0.08
January 2019 (15-days simulation)	Port Aransas	0.96	0.12	0.6	-0.03
	USS Lexington	0.98	0.21	0.24	-0.19
	Packery Channel	0.93	0.23	0.38	-0.08
April 2019 (10-days simulation)	Port Aransas	0.98	0.12	0.53	0.03
	USS Lexington	0.97	0.16	0.13	-0.14
	Packery Channel	0.78	0.18	0.29	-0.03

3.3 Modeling Results and Discussion

The bathymetry of all the bays in the Delft3D-FM model is based on the ADCIRC model mesh used for the ES storm surge modeling, which has updated bathymetry condition along the CCSC and LQC with the USACE survey provided by the Port of Corpus Christi Authority (Figure 19). To represent the OPS channel configuration (Figure 23), the ES grid is altered to have a depth of 58 feet (MLLW) along the CCSC, 18 feet along the barge shelves, and 51 feet along the LQC. Similarly, to represent the FPS channel configuration (Figure 24), the OPS grid is altered to have a depth of 75 feet from the seaward opening of CCSC through Aransas Pass to Harbor Island.

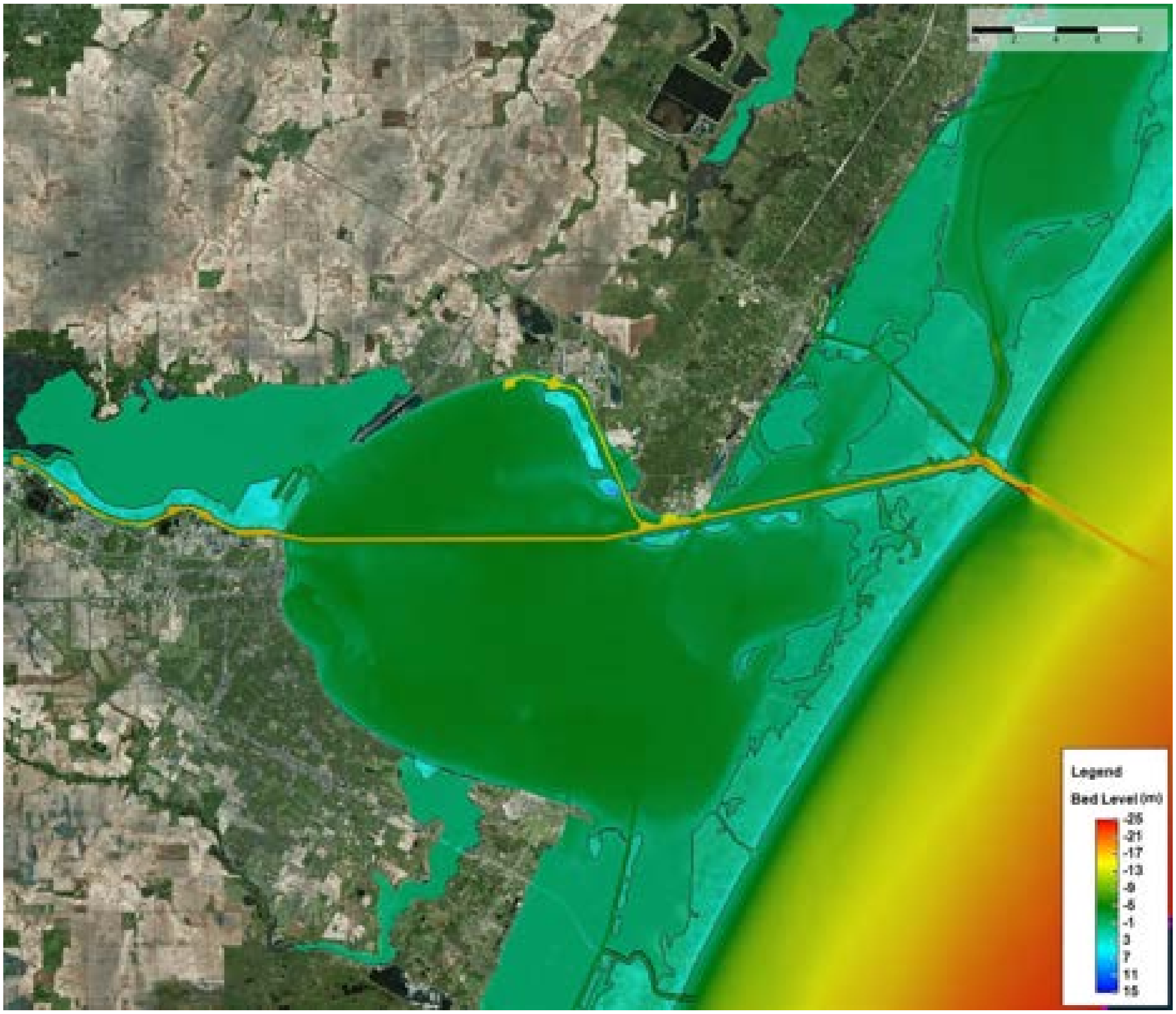

Figure 23. Bathymetry/topography (in meters NAVD88) for the OPS channel configuration. The negative values represent bathymetry and the positive values represent topography. The polygon outlines in black show the land boundaries.

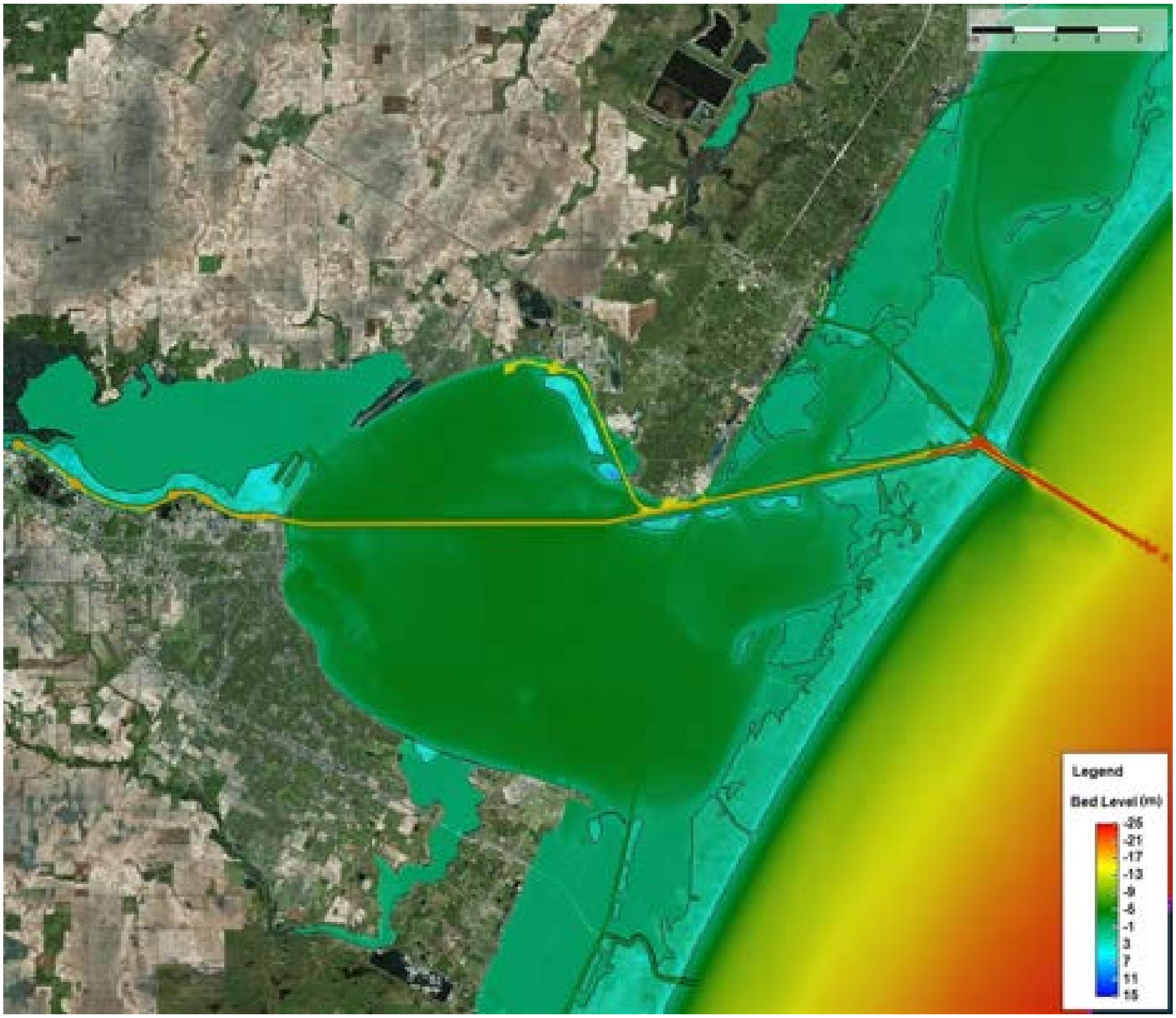

Figure 24. Bathymetry/topography (in meters NAVD88) for the FPS channel configuration. The negative values represent bathymetry and the positive values represent topography. The polygon outlines in black show the land boundaries.

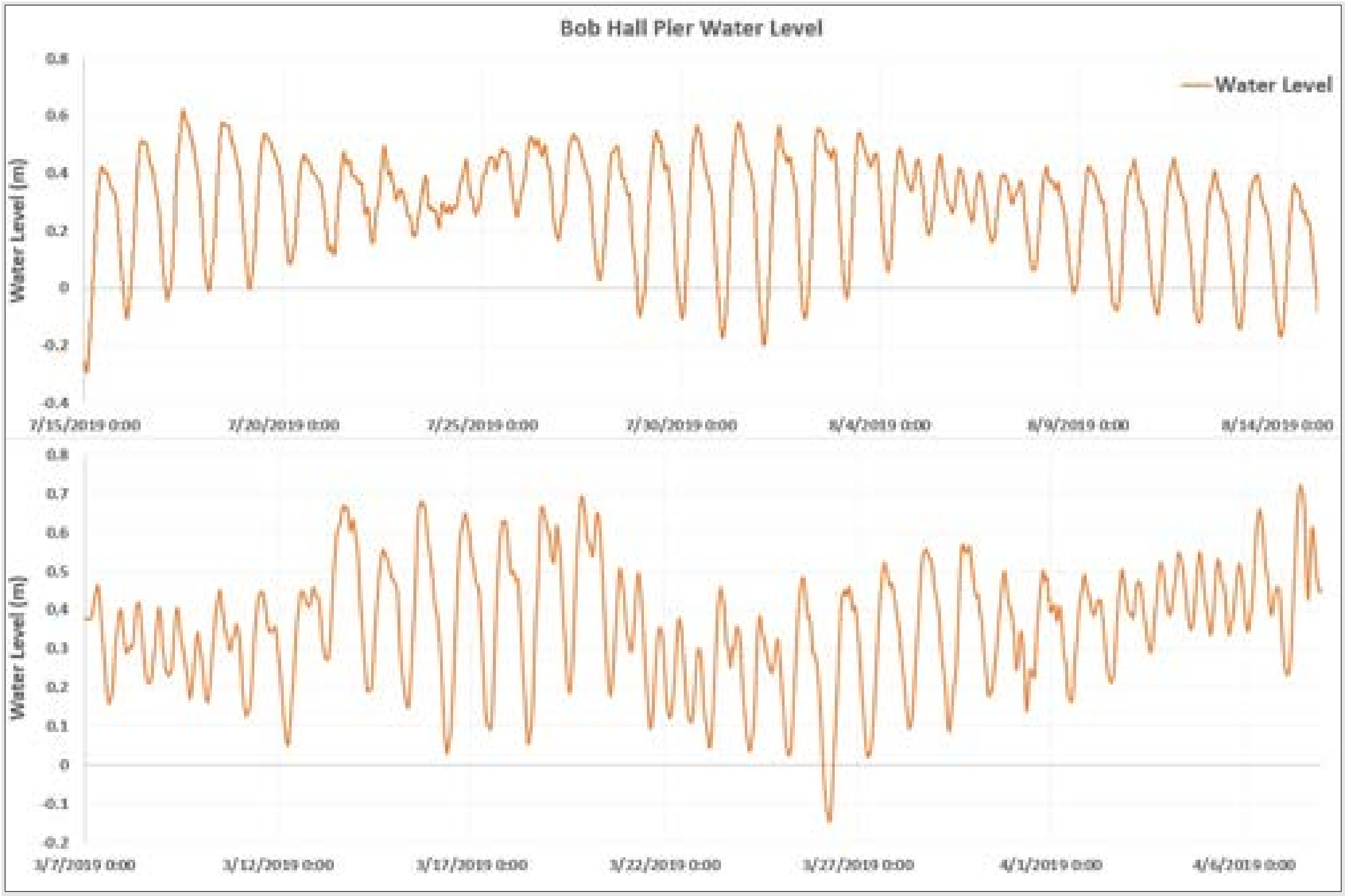

Figure 25. Time series plot of water level in July/August 2019 (top graph) and March/April 2019 (bottom graph) at Bob Hall Pier station. This is input water level for the spring and summer simulation.

To assess the impact of the channel depth, the model is run for 1-month periods in March/April 2019 and July/August 2019. These two periods are selected to cover varying environmental conditions such as times of high and low seasonal water levels and strong winds from various directions. Figure 25 and 26 show how different the water level and wind is during those two periods with the time series plot of water level and wind speed/direction at Bob Hall Pier station. The March/April simulation is from March 7th, 2019 to April 7th, 2019, and the July/August simulation is from July 15th, 2019 to August 15th, 2019. Both these models are driven by verified water level data from the Bob Hall Pier station at the offshore boundary and with a uniform wind profile over the entire grid, also from the Bob Hall Pier station.

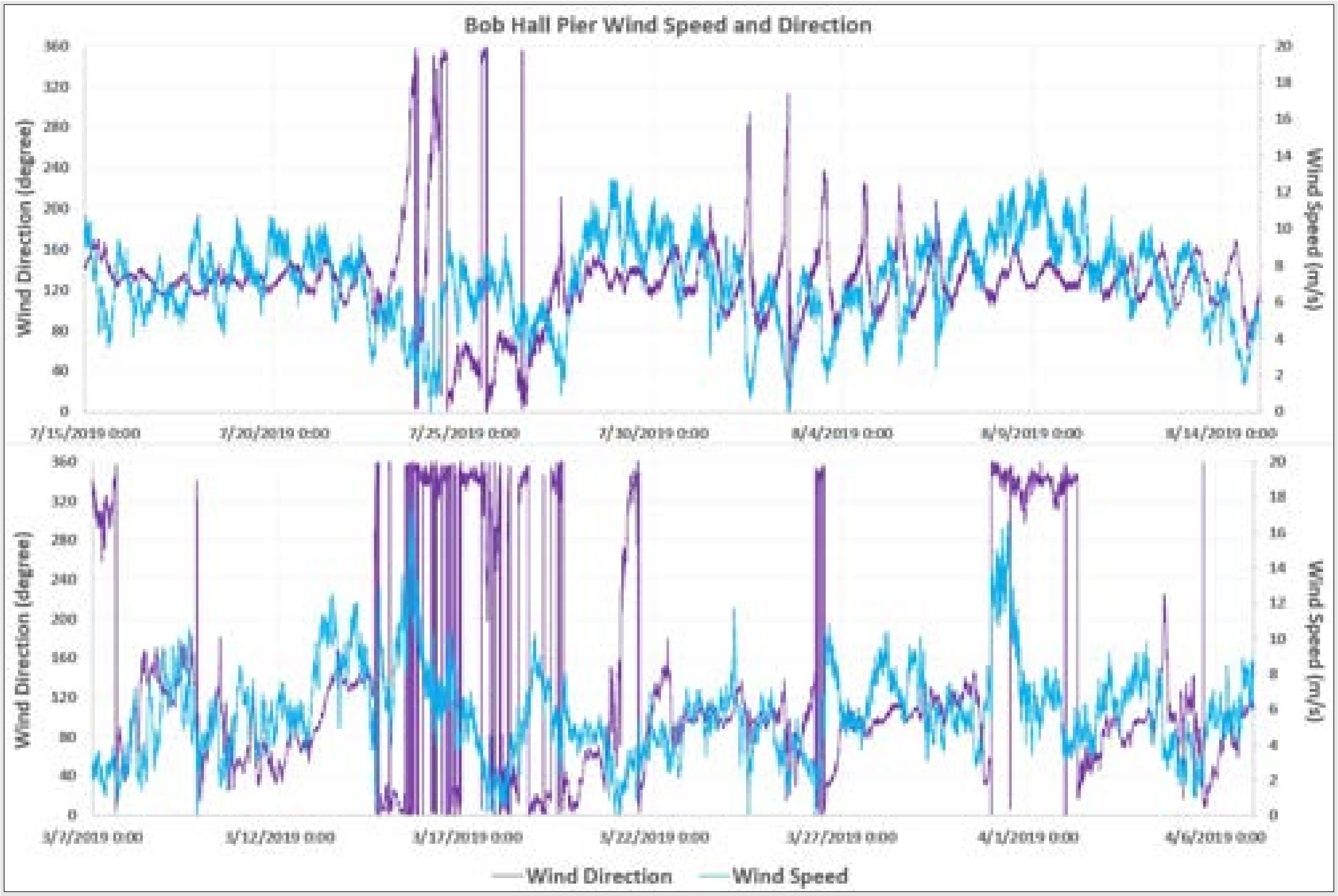

Figure 26. Time series plot of wind direction/speed in July/August 2019 (top graph) and March/April 2019 (bottom graph) at Bob Hall Pier station. This is input wind speed and direction for the spring and summer simulation.

To assess the impacts on the tidal range for each channel configuration, a total of 25 observation points throughout the bay system are selected (Figure 27). There are 7 points in Corpus Christi Bay, 3 points in Nueces Bay, 3 points in Redfish Bay, 5 points in Aransas/Mesquite Bay, 3 points in Copano Bay and 4 points in Upper Laguna Madre. Among those 25 points, the water level hydrographs of 6 points, one in each bay as shown with the white box in Figure 27, are plotted in Figure 28 - 33.

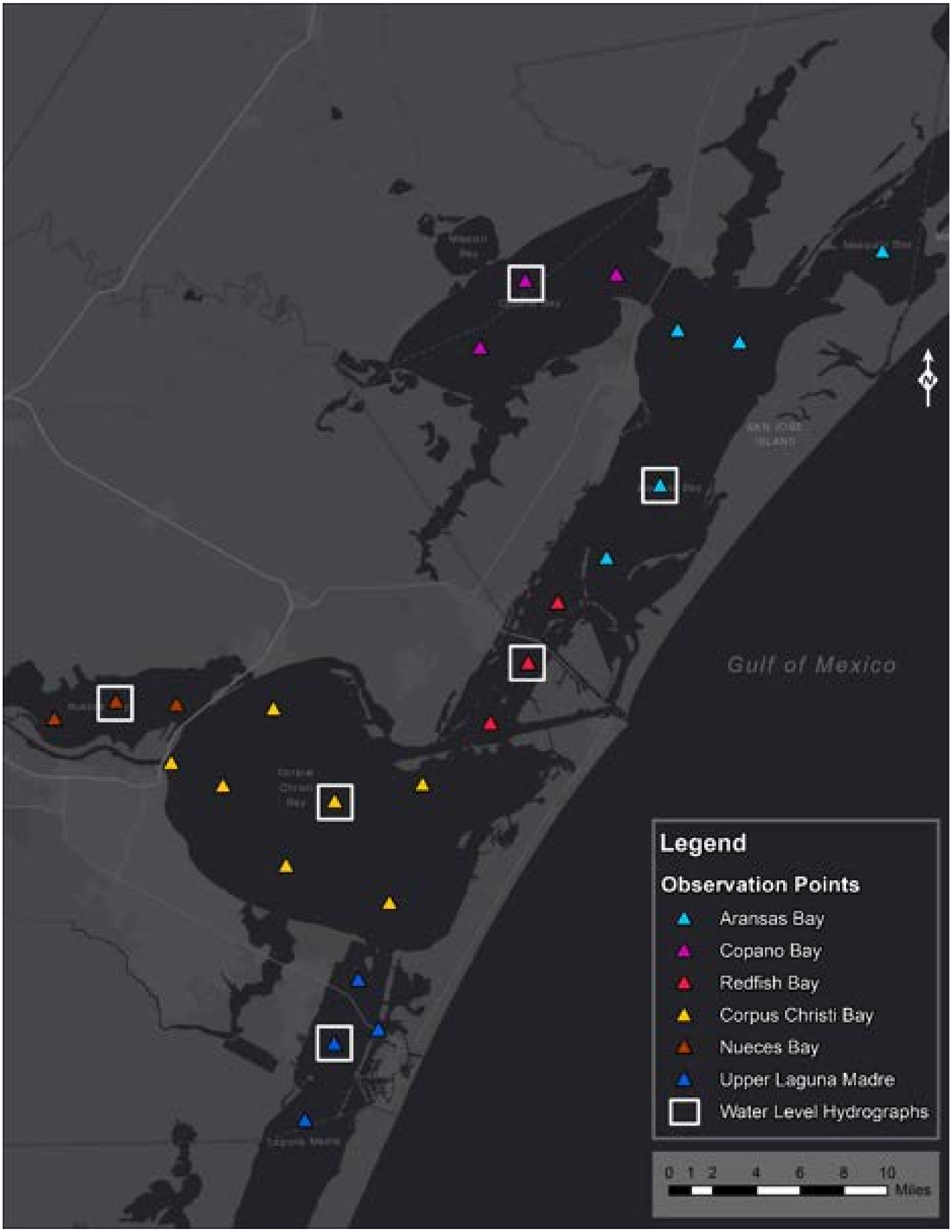

Figure 27. Locations of observation points throughout the bay system for the tidal range comparison. The water level hydrographs of the observation points in the white box are plotted.

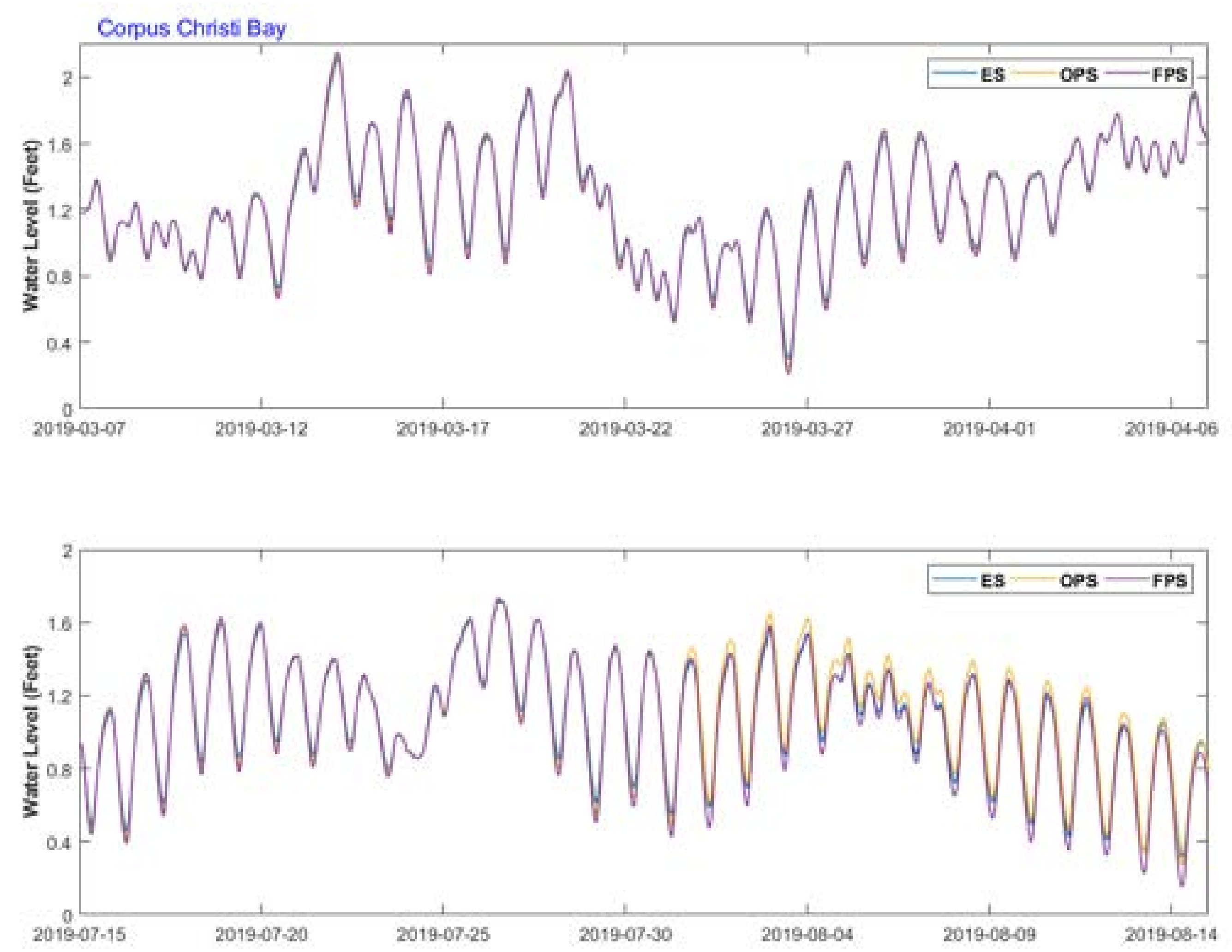

Figure 28. Tide comparison between ES, OPS and FPS at an observation point in the middle of Corpus Christi Bay shown with white box in Figure 27. The top graph is over a 1-month period in Mar/Apr 2019 and the bottom graph is over a 1-month period in Jul/Aug 2019.

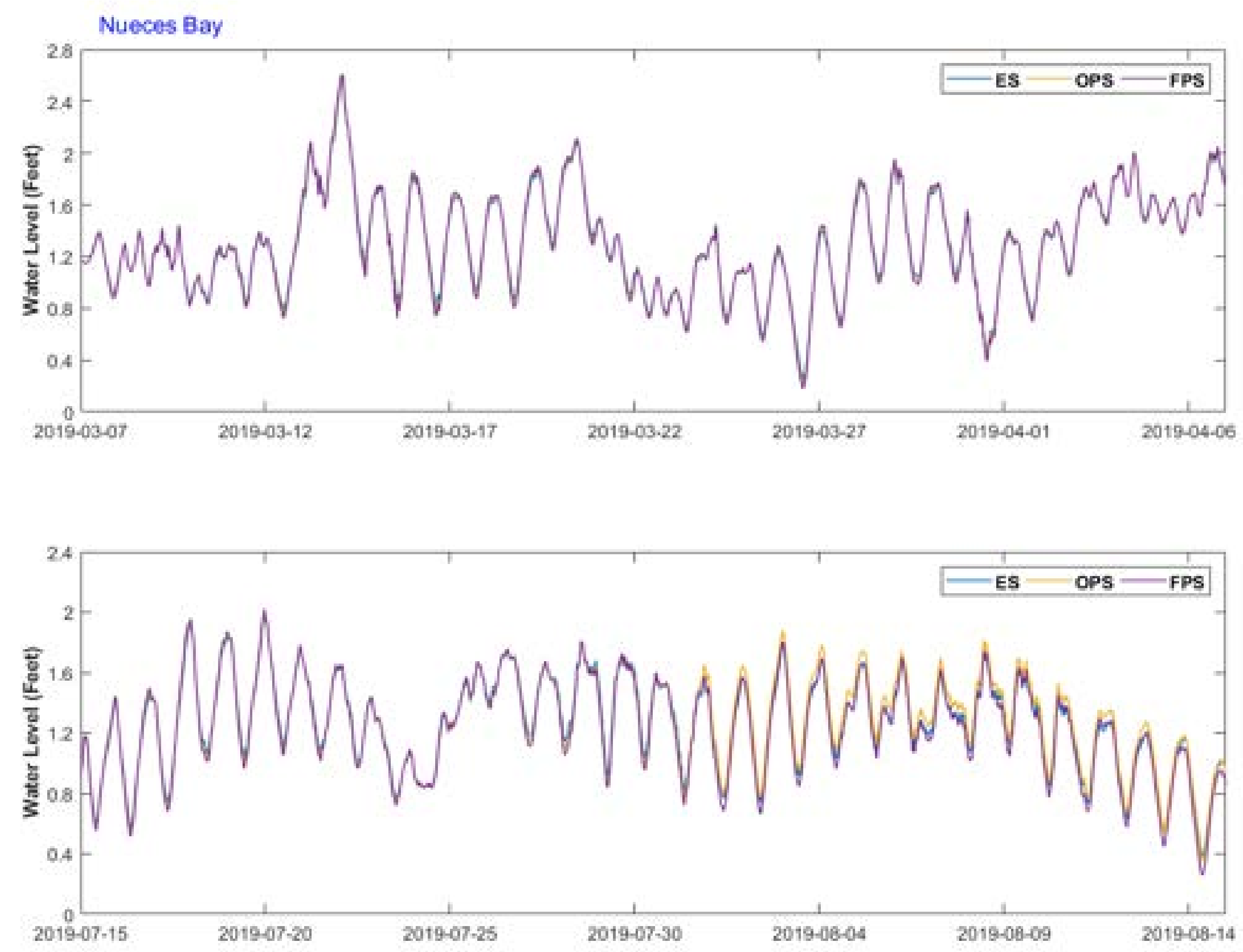

Figure 29. Tide comparison between ES, OPS and FPS at an observation point in the middle of Nueces Bay shown with white box in Figure 27. The top graph is over a 1-month period in Mar/Apr 2019 and the bottom graph is over a 1-month period in Jul/Aug 2019.

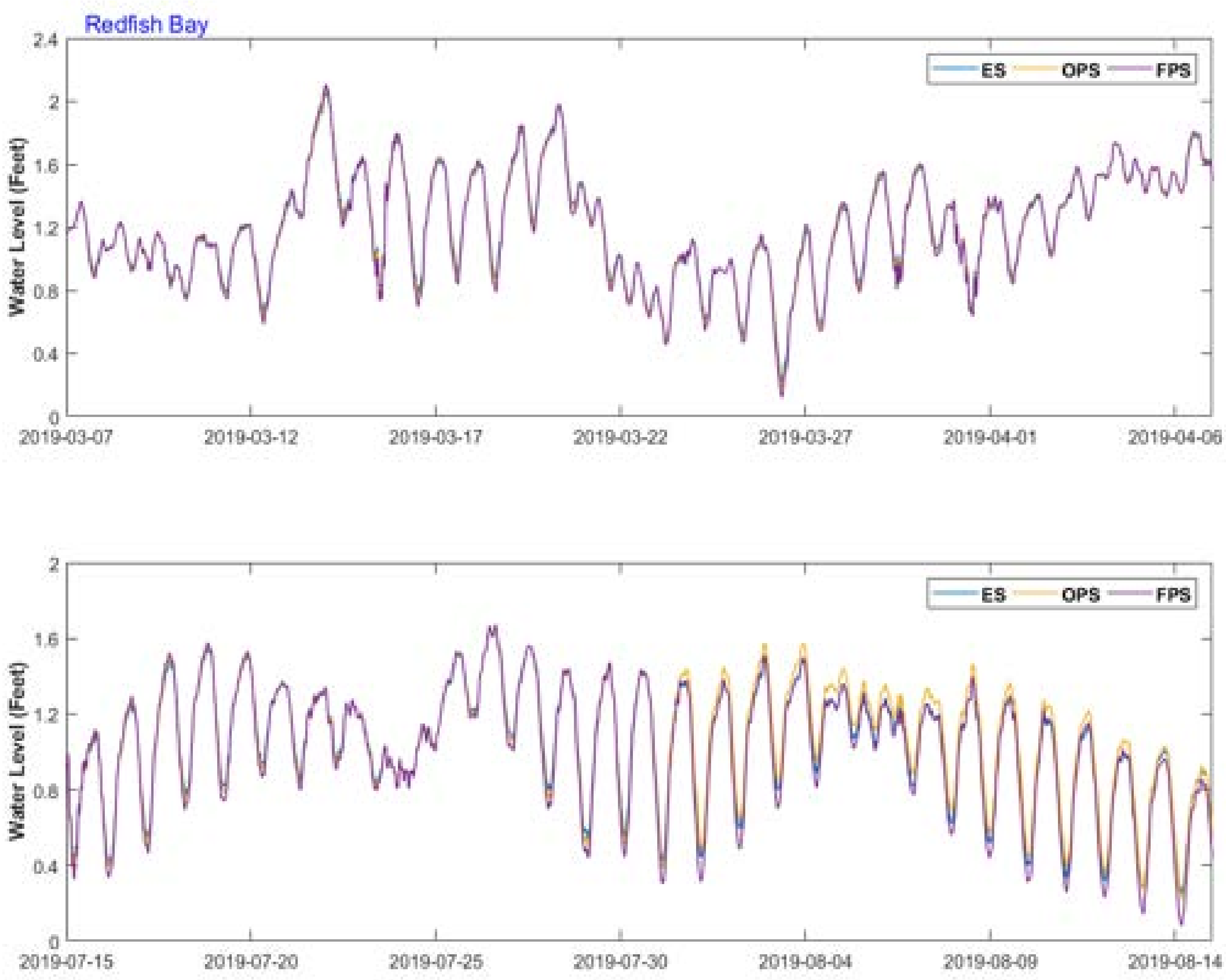

Figure 30. Tide comparison between ES, OPS and FPS at an observation point in the middle of Redfish Bay shown with white box in Figure 27. The top graph is over a 1-month period in Mar/Apr 2019 and the bottom graph is over a 1-month period in Jul/Aug 2019.

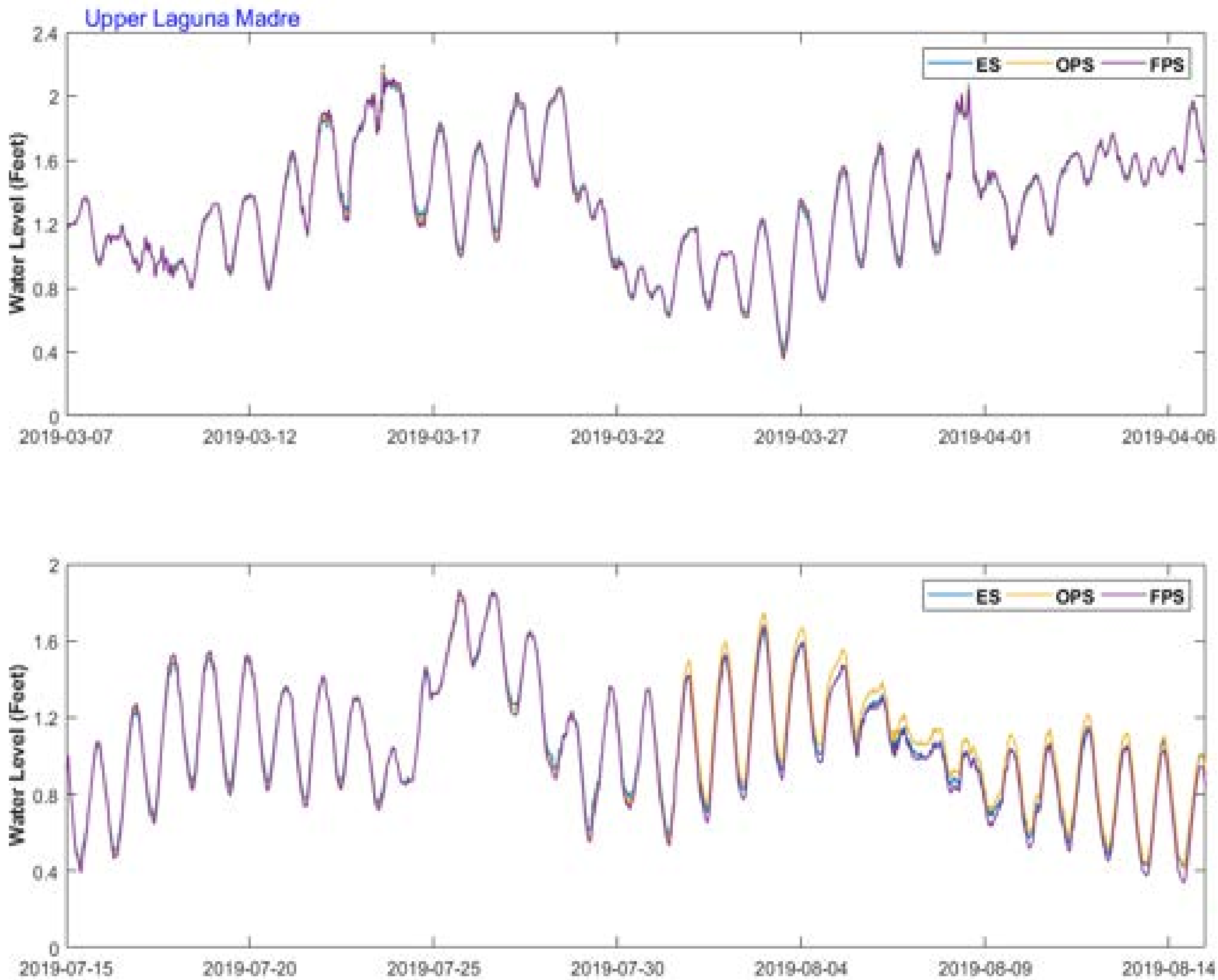

Figure 31. Tide comparison between ES, OPS and FPS at an observation point in the middle of Upper Laguna Madre shown with white box in Figure 27. The top graph is over a 1-month period in Mar/Apr 2019 and the bottom graph is over a 1-month period in Jul/Aug 2019.

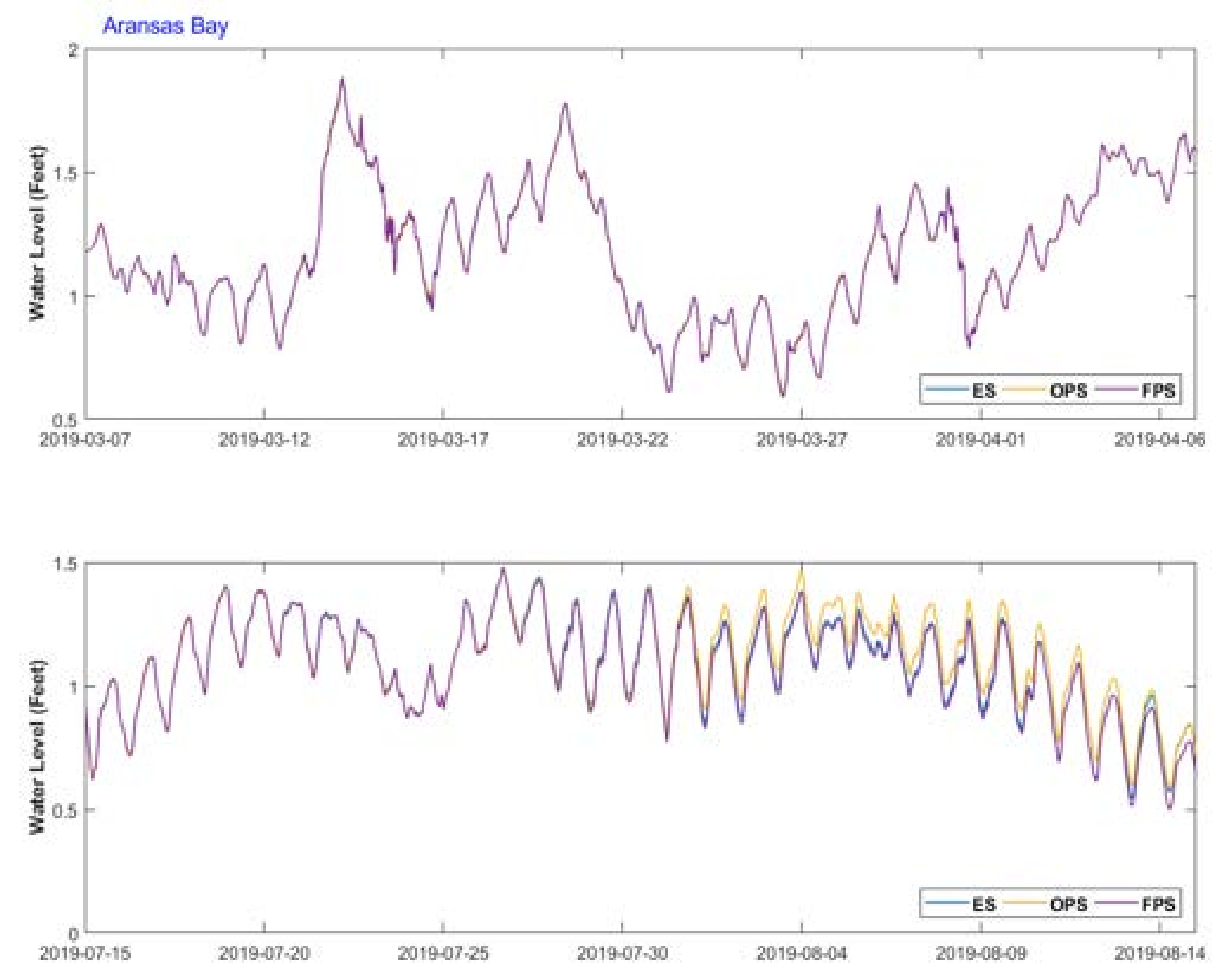

Figure 32. Tide comparison between ES, OPS and FPS at an observation point in the middle of Aransas Bay shown with white box in Figure 27. The top graph is over a 1-month period in Mar/Apr 2019 and the bottom graph is over a 1-month period in Jul/Aug 2019.

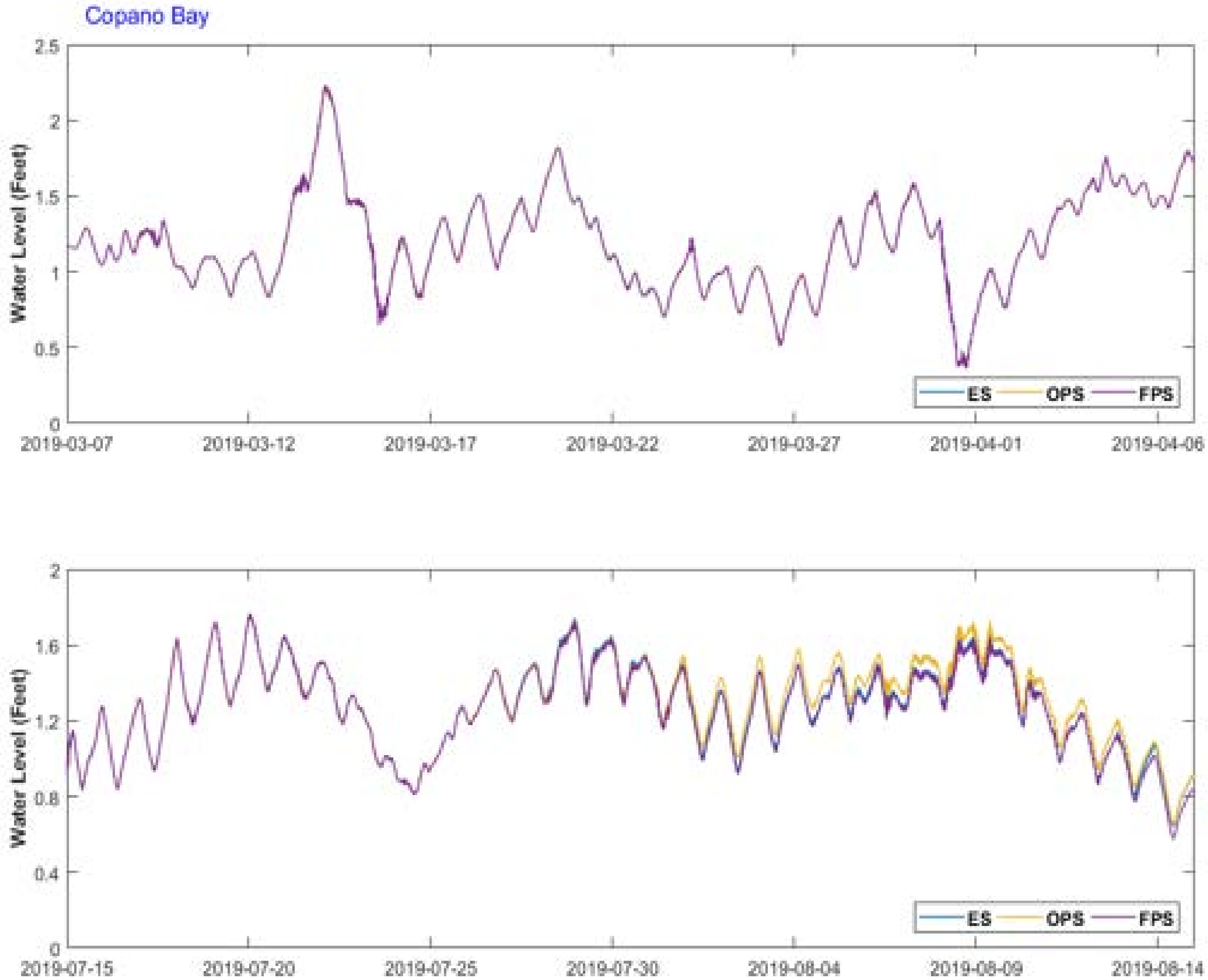

Figure 33. Tide comparison between ES, OPS and FPS at an observation point in the middle of Copano Bay shown with white box in Figure 27. The top graph is over a 1-month period in Mar/Apr 2019 and the bottom graph is over a 1-month period in Jul/Aug 2019.

The water level hydrographs in Figure 28 - 33, in general, show slight increases in the tide range for both the OPS and FPS channel configuration at all locations compared to the ES channel configuration. It is also apparent that for the OPS configuration the water level rose slightly in all the bays relative to the ES and FPS scenarios beginning in early August and for the rest of the summer (Jul/Aug 2019) simulation. Other model outputs including water velocity and discharge during the summer OPS simulation also show similar patterns.

The average of the diurnal tide range for all three scenarios and the percent change from ES to OPS and FPS in each bay are summarized in Table 4. The average diurnal tide range for a bay is calculated by taking the average of the diurnal tide ranges computed for the 1-month simulation at all the observation points in each bay. The top table shows the average diurnal tide range for three scenarios and the percent change in each bay for the 1-month tide simulation in spring (Mar/Apr) 2019, and the bottom table shows the same for the summer (Jul/Aug) 2019 simulation. For the spring and summer simulations in Corpus Christi, Nueces, and Redfish Bays and Upper Laguna Madre, there is an increase in diurnal tide ranges from ES to OPS conditions ranging from 4.45% to 7.48%, and for ES to FPS conditions increases range from 9.27% to 13.52%. Aransas and Copano Bays show smaller increases in diurnal tide range of 0.01% to 0.84% for ES to OPS conditions and 1.98% to 2.40% for ES to FPS conditions.

These modeled observations are consistent with channel deepening making the system less restrictive to Gulf of Mexico tides: a positive correlation between channel depth and the amplitude of diurnal tide range (i.e., the deepest channel conditions (FPS) causing the largest increases) and greater increases in bays closer to the CCSC and lesser in bays farther from the CCSC.

To assess the change in water level in each bay for each scenario, the mean of the daily higher high water level for each station’s time series is averaged with the other stations in a bay for both spring and summer simulation periods (Table 5). Mean higher high water level remains the same or increases slightly (0.03 ft maximum change) in both the OPS and FPS compared to the ES channel configuration for the spring simulation in all bays. For the summer simulation, water level is lowest for the ES channel configuration and highest for the OPS configuration, with a maximum change of 0.04 ft.

Table 4. The average diurnal tide range for ES, OPS and FPS scenarios, and percent change from ES to OPS and from ES to FPS in each bay. The top table is for a 1-month tide simulation in Mar/Apr 2019, and the bottom table is for a 1-month simulation in Jul/Aug 2019.

Simulation date: 3/7/2019 0:00 to 4/7/2019 0:00					
	ES Average Tide Range (ft)	**OPS Average Tide Range (ft)**	**FPS Average Tide Range (ft)**	**Percent Change from ES to OPS**	**Percent Change from ES to FPS**
Corpus Christi Bay	0.58	0.62	0.65	6.63%	12.21%
Nueces Bay	0.69	0.73	0.76	4.98%	9.27%
Redfish Bay	0.52	0.54	0.58	4.52%	11.17%
Aransas Bay	0.33	0.33	0.34	0.25%	2.40%
Copano Bay	0.40	0.40	0.41	0.21%	1.98%
Upper Laguna Madre	0.50	0.53	0.55	5.47%	9.96%
Simulation date: 7/15/2019 0:00 to 8/15/2019 0:00					
	ES Average Tide Range (ft)	**OPS Average Tide Range (ft)**	**FPS Average Tide Range (ft)**	**Percent Change from ES to OPS**	**Percent Change from ES to FPS**
Corpus Christi Bay	0.65	0.70	0.74	7.48%	13.52%
Nueces Bay	0.69	0.73	0.76	5.90%	10.09%
Redfish Bay	0.64	0.67	0.71	4.45%	11.90%
Aransas Bay	0.36	0.36	0.36	0.01%	2.31%
Copano Bay	0.35	0.35	0.35	0.84%	2.21%
Upper Laguna Madre	0.58	0.61	0.63	6.59%	9.84%

Table 5. The mean of daily higher high water levels for ES, OPS and FPS scenarios, and percent change from ES to OPS and from ES to FPS in each bay. The top table is for a 1-month tide simulation in Mar/Apr 2019, and the bottom table is for a 1-month simulation for Jul/Aug 2019. Elevations are in feet relative to NAVD88.

Simulation date: 3/7/2019 0:00 to 4/7/2019 0:00					
	ES Average of High Tide Water Level (ft) (NAVD88)	**OPS Average of High Tide Water Level (ft) (NAVD88)**	**FPS Average of High Tide Water Level (ft) (NAVD88)**	**Percent Change from ES to OPS**	**Percent Change from ES to FPS**
Corpus Christi Bay	1.54	1.56	1.57	0.84%	1.53%
Nueces Bay	1.65	1.67	1.68	0.70%	1.30%
Redfish Bay	1.46	1.47	1.48	0.53%	1.13%
Aransas Bay	1.31	1.31	1.31	-0.04%	0.22%
Copano Bay	1.40	1.40	1.40	-0.05%	0.18%
Upper Laguna Madre	1.55	1.56	1.56	0.62%	1.10%

Simulation date: 7/15/2019 0:00 to 8/15/2019 0:00					
	ES Average of High Tide Water Level (ft) (NAVD88)	**OPS Average of High Tide Water Level (ft) (NAVD88)**	**FPS Average of High Tide Water Level (ft) (NAVD88)**	**Percent Change from ES to OPS**	**Percent Change from ES to FPS**
Corpus Christi Bay	1.39	1.43	1.40	2.97%	0.79%
Nueces Bay	1.60	1.63	1.60	2.30%	0.30%
Redfish Bay	1.32	1.36	1.33	2.84%	0.38%
Aransas Bay	1.26	1.29	1.25	2.30%	-0.64%
Copano Bay	1.43	1.46	1.43	2.09%	-0.52%
Upper Laguna Madre	1.34	1.38	1.35	2.97%	0.73%

3.4 Summary of Tidal Hydraulics Modeling

The impacts on tidal hydraulics are assessed using a 2-dimensional implementation (2DH) of the Delft3D Flexible Mesh (Delft3D FM) modeling suite. The computational engine called D-Flow FM in the Delft3D-

FM modeling suite was selected to evaluate the change in tide range and water level in the Corpus Christi Bay System due to PCCA's proposed CCSC deepening projects. An unstructured model grid that covers the Corpus Christi Bay System was created and a robust hydrodynamic model developed that has been validated for water levels over wide-ranging tidal and wind conditions. Model calibration and validation efforts show that the model is able to accurately represent hydrodynamics throughout the bay system. To assess the impact of the channel depth, the model was run for two, 1-month periods with varying environmental conditions of high and low seasonal water levels and strong winds from various directions. Water level hydrographs show how water level changes over time under different channel scenarios for Corpus Christ and adjacent bays. Similarly, average diurnal tide ranges were calculated in each bay for ES, OPS and FPS scenarios.

The model output shows slight increases in the tide range for both the OPS and FPS channel configurations at all locations compared to the ES channel configuration. Water level rises slightly in all bays in the OPS configuration starting in late July during the summer (Jul/Aug 2019) simulation. The increase in the average tide range, in general, follows similar patterns in each bay in both spring and summer simulations. These results are consistent with the model results in the study *Corpus Christi Ship Channel, Texas, Channel Improvement Project, Final Feasibility Report and Final Environmental Impact Statement* (USACE, 2003) which showed that the average tidal range increases by 0.04 – 0.06 feet in Corpus Christi Bay and Nueces Bay for a 2-year simulation period in 1993 and 1994. Similarly, these results are also consistent with the findings of *Corpus Christi Ship Channel Deepening Project, Impacts to Tidal Flows in Corpus Christi Bay* (PCCA, 2019) for a 16-day simulation period in August 2018. These slight increases in tide range and water level are not expected to cause measurable impacts to natural or built environments. Relative sea level rise rate measured at the Rockport tide gauge is currently 0.02 feet/year and increasing (Sweet et al., 2017), hence it is expected that water level and tide range increases caused by channel deepening will be overwhelmed by increases from other causes in a few years. The key findings of the analysis are the following:

- The average tide range increases by approximately 5 – 8% from ES to OPS and by 9 – 14% from ES to FPS in Redfish, Corpus Christi, and Nueces Bays and Upper Laguna Madre, whereas the increase is less than 1% from ES to OPS and approximately 2% from ES to FPS in Aransas and Copano Bays.
- The mean high tide water level (mean of daily higher high water levels), increases slightly in both the OPS and FPS configurations compared to the ES channel configuration with a maximum change of 0.04 ft.

4. Salinity Modeling

Hydrodynamic transport in the estuaries can be well-described by two dimensions (2D) models as presented in section 2 of this report. However, salinity dynamics and transport in the estuaries are governed by three dimensional (3D) processes such as estuarine circulation and is a bit unrealistic to simulate in a 2D model. Therefore, it is recommended to model salinity dynamics with a 3D model so that the gravitational circulation and temperature dynamics can be simulated. Consequently, the same D-Flow FM model in the Delft3D-FM modeling suite that is used for the tide analysis is used for the salinity analysis. D-Flow FM can simulate the hydrodynamics in the model area by solving the unsteady flow equations in either 2D or 3D. The 3D simulation lets the thickness distribution of vertical layers discretize into multiple layers. The 3D model, however, increases computational demands and takes about 10 times longer to run than the 2D model.

4.1 Model Setup

The same Delft3D model that is calibrated for tidal water elevations explained in Section 3.1 is used for the salinity analysis. The same unstructured grid that spans the Corpus Christi Bay System and extends from Mesquite Bay in the northeast and Mission Bay in the northwest, to the Upper Laguna Madre in the south is used (Figure 18). The horizontal resolution of the grid ranges from 150–225 feet in the channels to 2,000 feet in the offshore area. The grid has 168,347 nodes and 500,464 edges.

The model forcing is shown in Figure 34. Salinity is implemented by simulating initial salinities and river discharges in addition to the tide. The model is driven by water levels from Bob Hall Pier and salinity from TABS Buoy D on the eastern boundary at the Gulf of Mexico, and freshwater inflows from Oso Creek, Nueces River and Mission River. There are two Neumann boundaries in the north and south with uniform zero values to prevent potential water level gradients across the boundary. A spatially varying surface salinity grid based on historical measurements is also used as initial salinity conditions. Wind forcing is also included in the model using 6-minute data from the Bob Hall Pier and is applied as a uniform wind profile over the entire grid. The same bathymetry used in the tidal analysis is used for the salinity modeling.

Since evaporation has been recognized as a major driving force affecting salinity structure (Geng *et al.*, 2016), the composite heat flux model is considered in the model by incorporating relative humidity, air temperature and cloud cover over the model domain. These data are obtained from the National Weather Service at Corpus Christi Naval Air Station (KNGP) with data gaps filled by the CBI TAMUCC Meteorological Station. The cloudiness in percentage is determined by assigning perfectly clear sky (CLR) as 0%, few clouds (FEW) as 25%, scattered clouds (SCT) as 50%, broken clouds (BKN) as 75% and overcast (OVC)/obscure sky (VV) as 100% cloud cover. All three datasets (relative humidity, air temperature and cloudiness) are input every 5-minuteutes in the model simulations.

The model was first set up to simulate in 2DH mode. However, it became clear that salinity modeling is unrealistic in 2DH mode and spatial variations were observed as river discharge was input to the model. Consequently, the σ layer approach in Delft3D is used which lets the thickness distribution of vertical layers discretize into multiple layers. Five σ layers are used, each covering 20% of the local water depth. For the model initialization, initial water level is defined as the average measurements of water level at the boundary and is given as a uniform value over the entire grid. Similarly, an initial water temperature of 29° C is used to start the model and was calculated by taking an average of water temperature during summer months in three stations located in Upper Laguna Madre (NPS Bird Island station), Nueces Bay (SALT03) and San Antonio Bay (GBRA) where data are available. Table 6 provides the summary of model settings selected after a series of model testing until good agreement between the modeled and observed data is observed. The model was migrated to the High-Performance Cluster system (HPC) at TAMUCC and run using 150 cores. A typical 1-month 3D salinity simulation takes 24 – 30 hours.

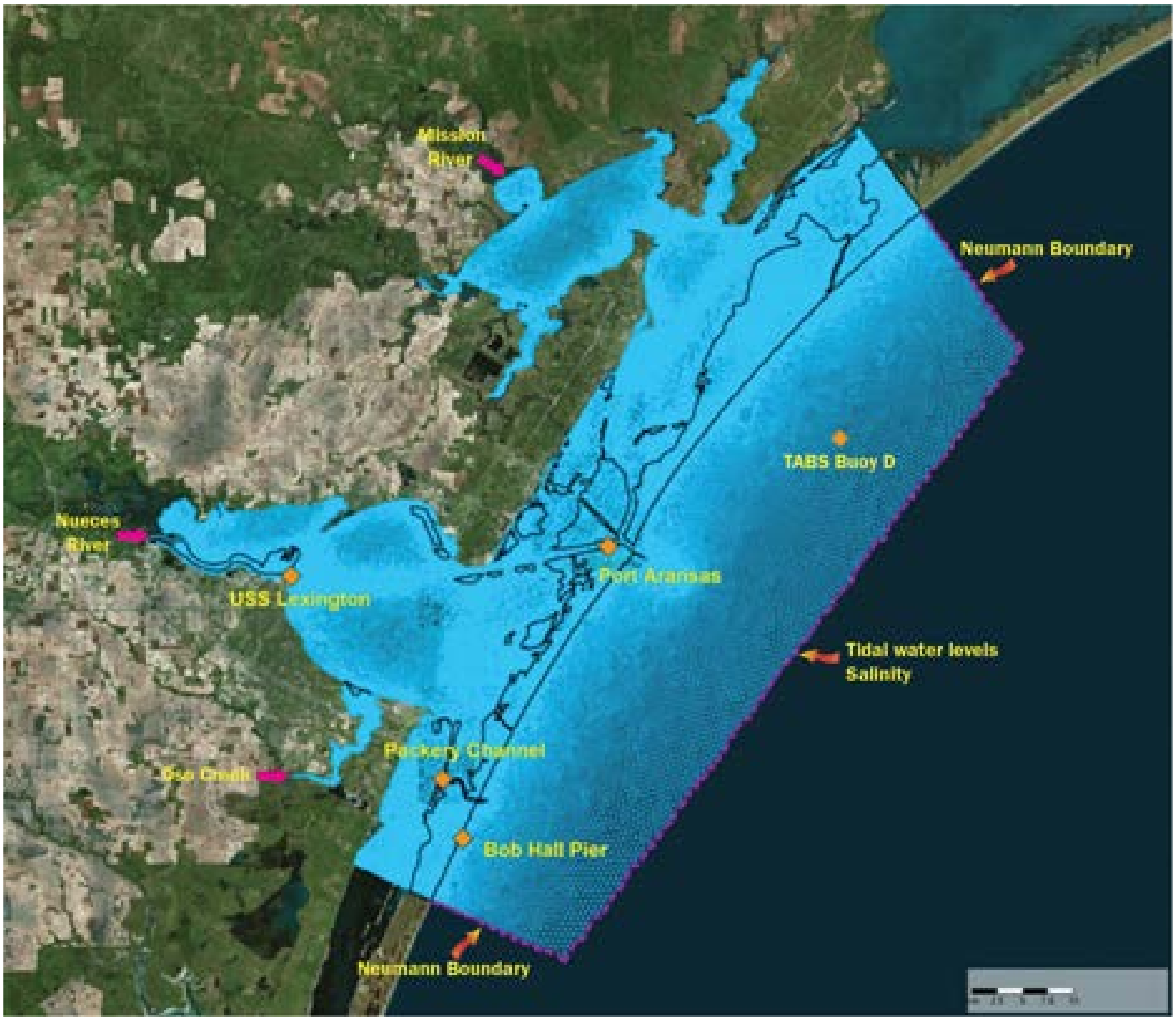

Figure 34. Delft3D-FM model grid is shown in blue. The magenta color shows the offshore boundaries, and the black colored polygons show the land boundaries. The model is driven with tidal water levels from Bob Hall Pier, surface salinity from Buoy D, and river flows from Oso Creek, Nueces River and Mission River (shown with pink arrows).

Table 6. Final model settings used in the Delft3D model for salinity analysis

Parameters	Value
Vertical layer type	Sigma layer
Number of vertical layers	5
Maximum Courant number	0.5
Manning's n	0.023
Viscosity: Horizontal, Vertical	0.001 m^2/s, 5×10^{-5} m^2/s
Diffusivity: Horizontal, Vertical	1 m^2/s, 5×10^{-5} m^2/s
Wind drag coefficient type	Smith & Banks (2 break points)
Break points wind drag coefficient	0.00063, 0.00242
Break points wind speed	0 m/s, 26 m/s

4.2 Model Calibration/Validation

Model validation is performed by comparing model output to salinity data collected at monitoring stations at Indian Point Pier in Corpus Christi Bay and SALT01 in Nueces Bay (Figure 35). These are the only stations where salinity data, required for the model validation, was available in Corpus Christi Bay and Nueces Bay. A 38-day period in August – September 2018 (08/01/2018 – 09/07/2018) was used for model setup and validation. This period contains nearly complete data for all relevant stations, except for a 2.5-day gap at the Indian Point Pier salinity monitoring station. There were two high-water events in one of the rivers during this time period, but they were not flood stage events.

The bathymetry of the ADCIRC model is used in the Delft3D-FM model which was obtained from multiple sources (USACE, 2011). However, the bathymetry of CCSC and LQC are updated based on the USACE surveyed bathymetry. Because the vertical datum of the bathymetry in the ADCIRC model is NAVD88, the channel bathymetry, which is relative to Mean Lower Low Water (MLLW), is adjusted to NAVD88.

For the validation simulation, the model is driven by 6-minute verified water level data from Bob Hall Pier at the offshore boundary, 30-minute salinity from TABS Buoy D also at the offshore boundary, and 15-minute freshwater inflows from Oso Creek, Nueces River and Mission River. The model is also forced with the 6-minute wind velocity magnitude and direction time series using data from Bob Hall Pier. Along with the offshore salinity boundary using TABS Buoy D data, a spatially varying surface salinity grid based on historical measurements (median value) is used as the initial salinity condition. The composite heat flux model is considered in the model by incorporating relative humidity, air temperature, and cloud cover over the model domain. The details about the input data used in the salinity modeling are presented in Table 7.

The model did not perform satisfactorily for salinity even after calibrating the model to predict water level well. The spatially varying surface salinity grid used as the initial salinity condition in the model improved the salinity output. However, the model still predicts very little variation in salinity at both validation stations. Figure 36 shows a comparison of model output surface salinity to measured data at two selected salinity stations in Corpus Christi Bay and Nueces Bay. It can be seen from the graphs that the model has not effectively captured the salinity variation.

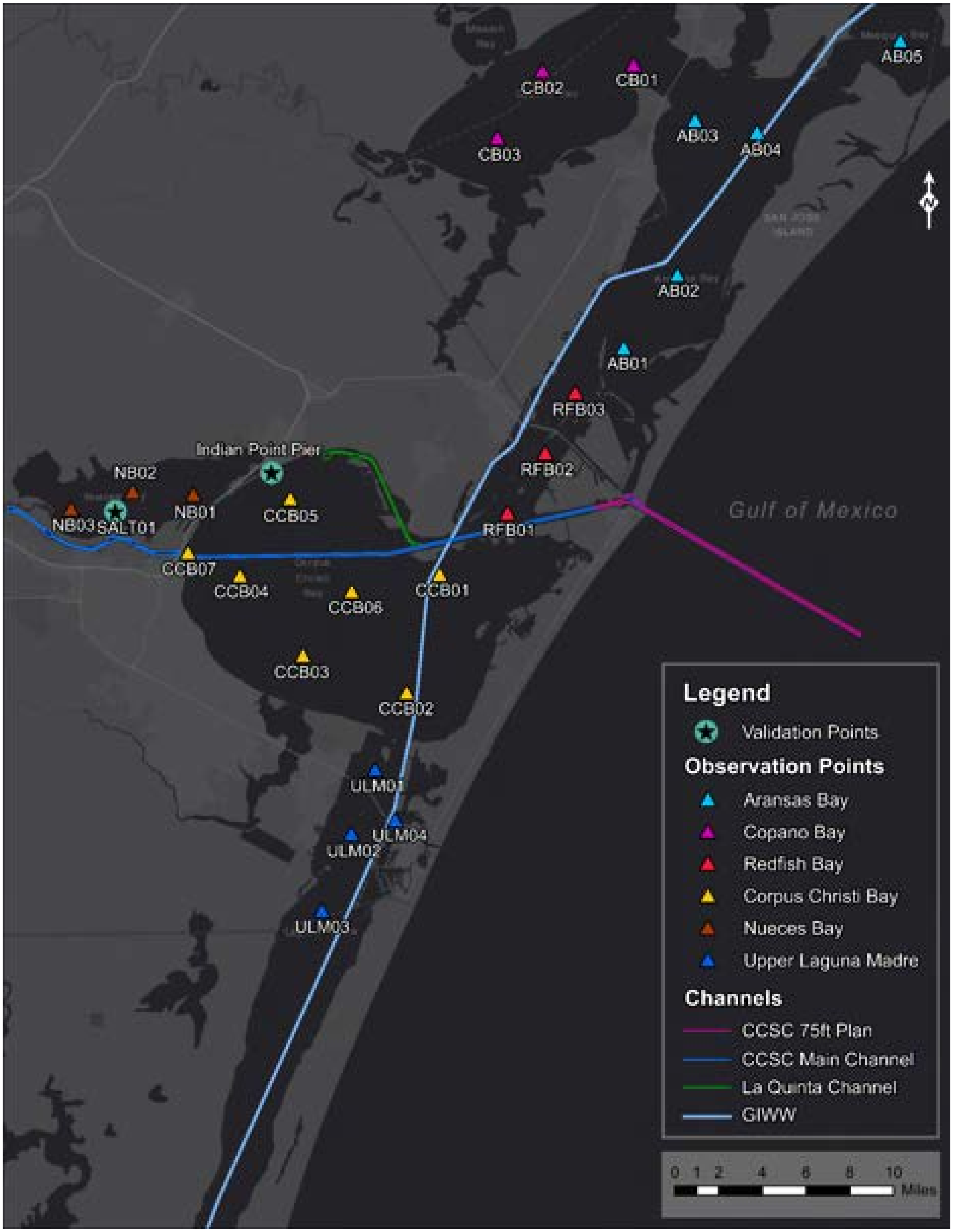

Figure 35. Validation points (Indian Point Pier and SALT01 in Nueces Bay) used for the surface salinity validation and model observation points used for three channel configurations comparison.

Table 7. Input data used in the salinity modeling.

Input data	Description	Station/Source
Water Level	Offshore boundary	NOAA – Bob Hall Pier
	Neumann boundary – at North and South end of study area	n/a
Salinity	Offshore boundary	Texas Automated Buoy System (TABS) Buoy D
	Spatially varying surface salinity	TPWD – median salinity value
River Discharge	Nueces River boundary	USGS – Nueces River at Calallen
	Oso Creek boundary	USGS – Oso Creek at Corpus Christi
	Mission River boundary	USGS – Mission River at Refugio
Wind	Uniform wind velocity magnitude and direction	NOAA – Bob Hall Pier
Relative Humidity	Uniform percentage relative humidity	NWS Corpus Christi Naval Air Station/Truax Field (KNGP) + Corpus Christi Meteorological TAMUCC (CBI)
Air Temperature	Uniform air temperature	KNGP + CBI
Cloud Cover	Uniform percentage cloud coverage	KNGP

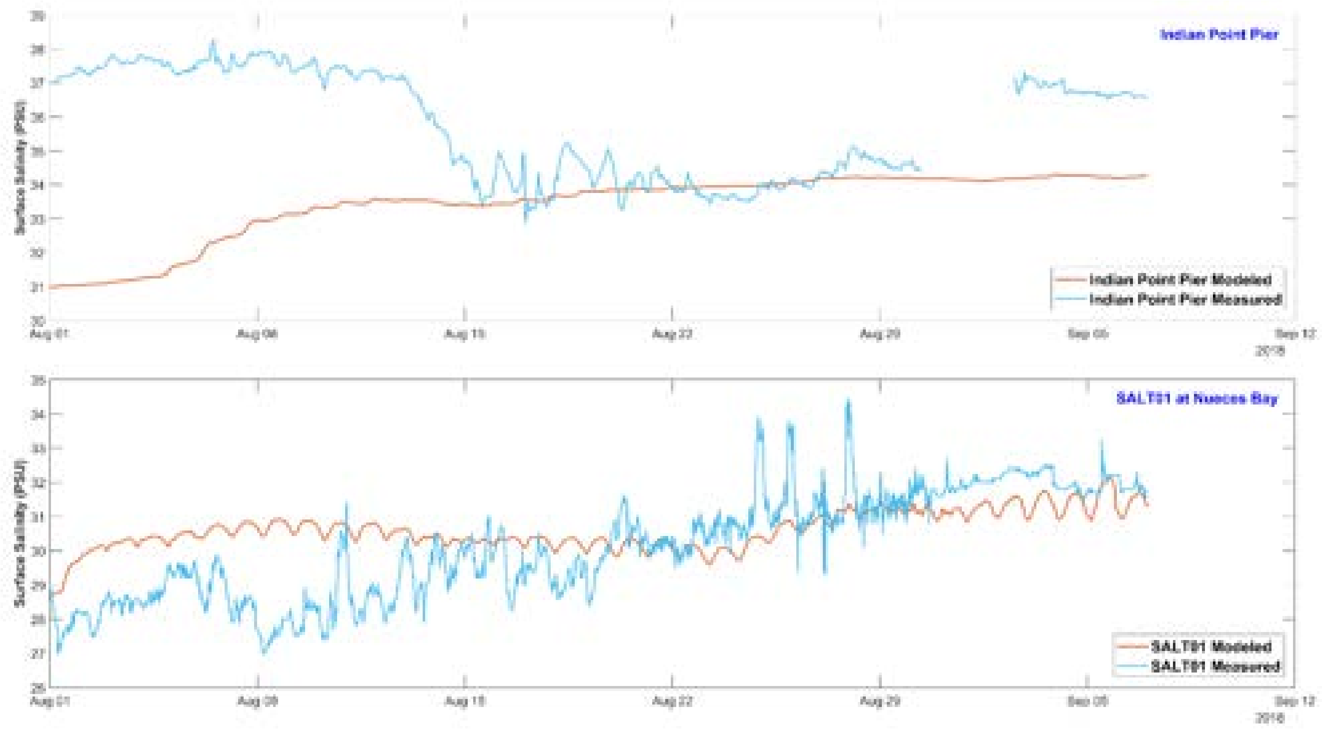

Figure 36. Surface salinity for a 38-day period in Aug/Sept 2018 (08/01/2018 – 09/07/2018) at Indian Point Pier and SALT01 salinity stations. No data are available between 08/30/2018 and 09/02/2018 at Indian Point Pier for the comparison.

The model correlation coefficient (R), root mean square error (RMSE), maximum difference and average error or bias for the salinity stations in Corpus Christi Bay and Nueces Bay are shown in Table 8. Although the model has not captured the salinity variation accurately, the model performs better in Nueces Bay compared to Corpus Christi Bay with RMSE of 1.38 PSU and correlation coefficient of 0.6 at the SALT01 salinity station. The negative bias for the Indian Pier Point salinity station in Corpus Christi Bay indicates that the model underpredicts salinity in comparison to the measured values. The model mostly underpredicts salinity in the first two weeks of August, but it does comparatively better during the middle of the simulation period (second half of August) for the Indian Pier Point station.

To test if the model was accounting for the correct amount of freshwater entering the system through the river boundaries, observational cross-sections were added close to those boundaries. The modeled discharge along the cross-sections matches the measured input discharge, which indicates that the correct amount of freshwater is entering the system. However, it is found that the model cannot properly simulate the transport and mixing of the freshwater in the bays. Therefore, the influence of two upticks in river discharge in Oso Creek and Nueces River during the validation period cannot be seen in the model output. Those upticks occurred on August 6-8 and August 11-13, which significantly decreased measured salinity value from 38 PSU to 33 PSU at the Indian Point Pier station (see top graph of Figure 36). Similarly, both these upticks in river discharge decreased measured salinity value by almost 3 PSU at the SALT01 station (see bottom graph of Figure 36). Table 8 and Figure 36 show better statistical metrics and more of the expected variation in the model output salinity at SALT01 station than at Indian Point Pier station. The higher freshwater inflow, proximity to the Nueces River boundary, and a relatively small bay may be the reason better results are obtained at the SALT01 salinity station compared to the Indian Pier Point station, which is quite far from all three river boundaries thus having minimum influence of river discharge.

Table 8. A summary of mean statistical metrics for model validation at two salinity stations – model correlation coefficient (R), root mean square error (RMSE), maximum difference and average error or bias of salinity.

Observation Point	Correlation Coefficient (R)	RMSE (PSU)	Max Difference (PSU)	Bias (PSU)
Indian Pier Point	-0.72	3.48	-6.70	-2.44
SALT01 (Nueces Bay)	0.60	1.38	3.51	0.49

4.3 Modeling Results and Discussion

To assess the impact of channel depth on salinity, the ES mesh, which has bathymetry based on the ADCIRC model in the bays and the latest USACE survey bathymetric data in the CCSC and LQC, was altered to have a depth of 58 feet (MLLW) along the CCSC, 18 feet (MLLW) along the barge shelves, and 51 feet (MLLW) along the LQC to represent the OPS channel configuration (Figure 23). The OPS grid is altered to have a depth of 75 feet (MLLW) along the mouth of CCSC through Aransas Pass to Harbor Island to represent the FPS channel configuration (Figure 24).

The model was run to simulate a 1-month period in July/August 2019 (07/15/2019 – 08/15/2019) with all three channel configurations. The model is driven by inputs from the same stations and sources as mentioned in Table 7, and model settings as in Table 6. Among the three river discharge boundaries in the model, Nueces River has the highest freshwater inflow in the system and Oso Creek has the lowest during this period.

A total of 22 observation points throughout the bay system are selected to assess the impacts on the salinity in each channel configuration (Figure 35). There are 7 points in Corpus Christi Bay, 3 points in Nueces Bay, 3 points in Redfish Bay, 5 points in Aransas/Mesquite Bay and 4 points in Upper Laguna Madre. The output salinity time series simulated for three channel configurations are plotted for each observation point. The salinity shown in these plots is bottom salinity values which are larger than or equal in magnitude to the surface salinity values due to the density differential of salt water. The following figures show the impacts on the bottom salinity for three channel scenarios (ES, OPS and FPS) at each observation point.

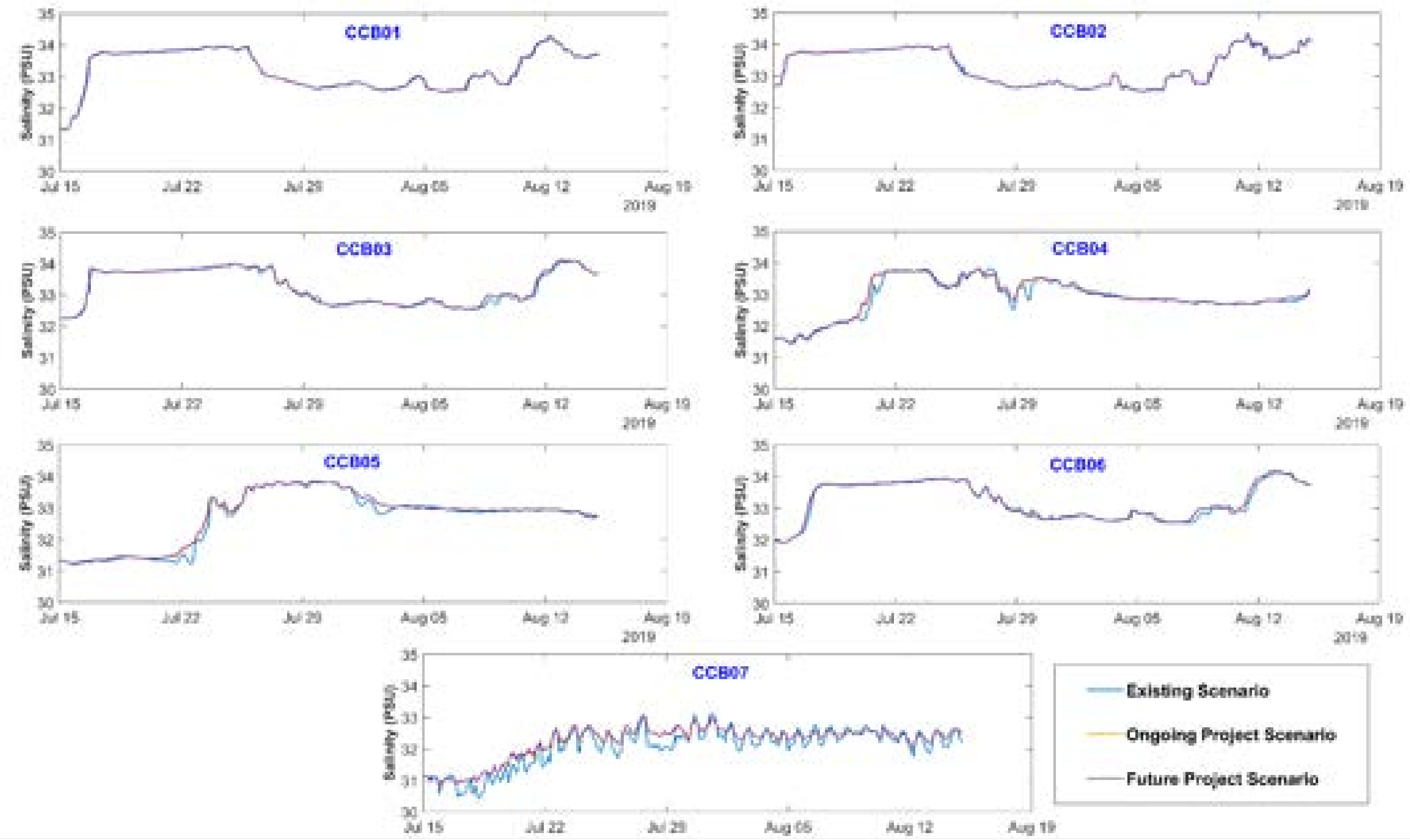

Figure 37. Salinity comparison between ES, OPS and FPS at 7 observation points in Corpus Christi Bay.

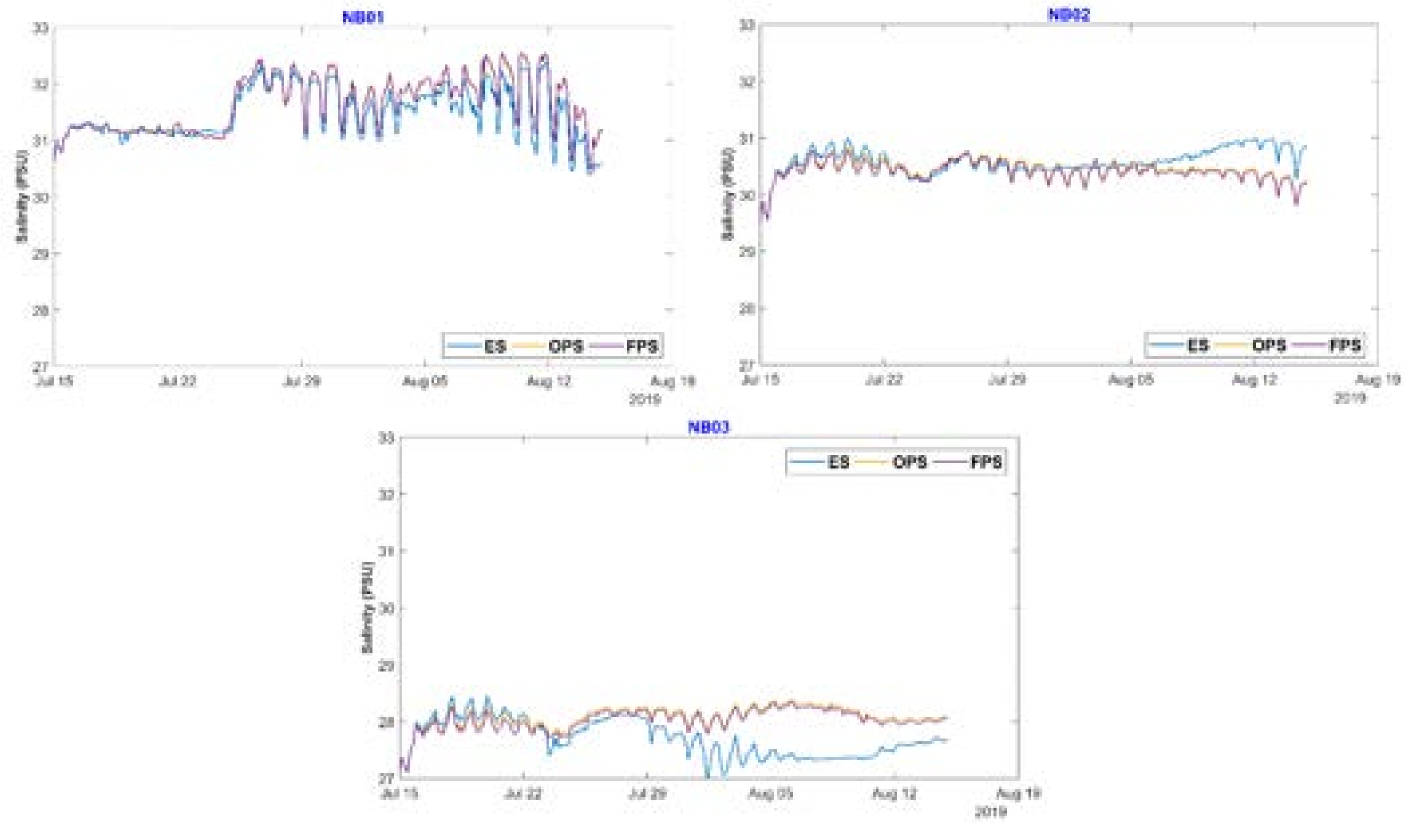

Figure 38. Salinity comparison between ES, OPS and FPS at 3 observation points in Nueces Bay.

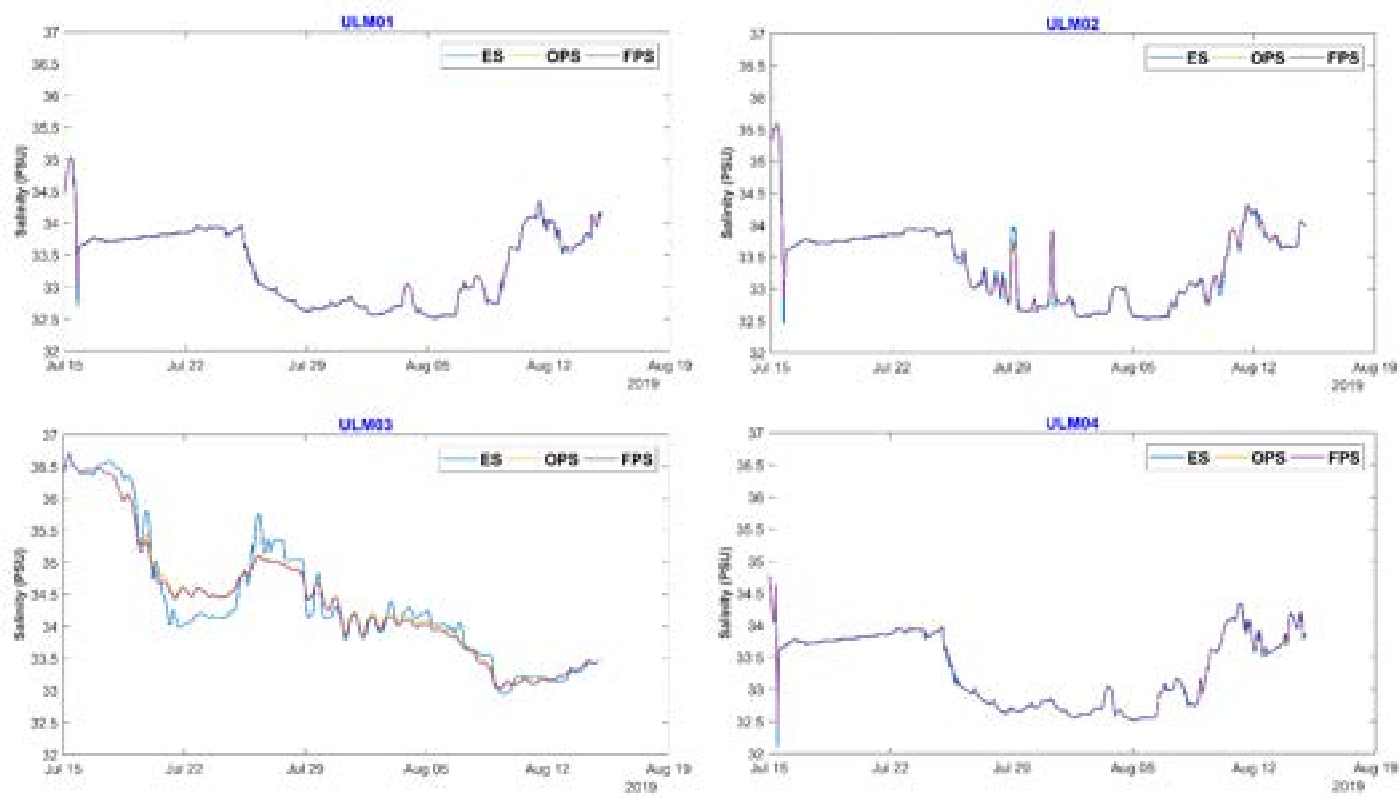

Figure 39. Salinity comparison between ES, OPS and FPS at 4 observation points in Upper Laguna Madre.

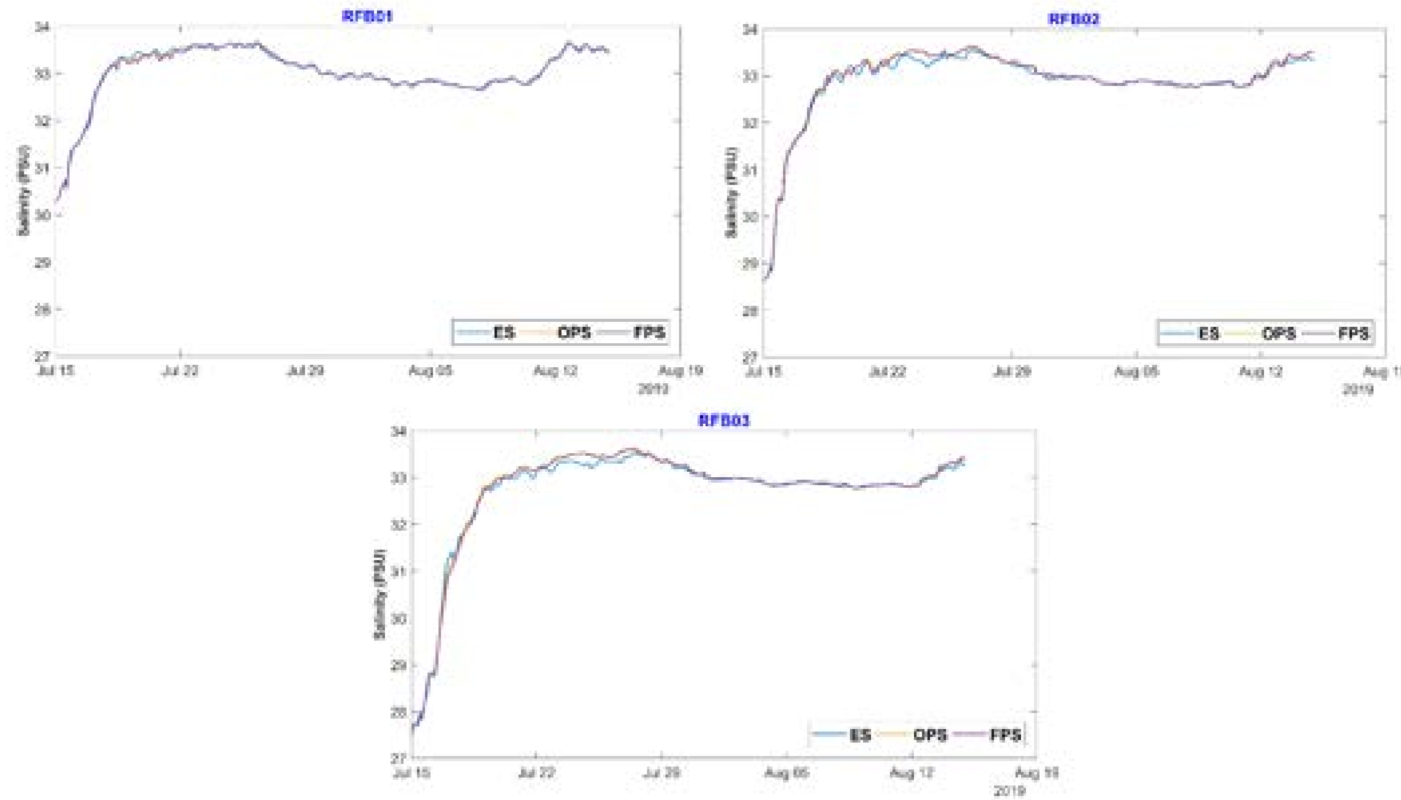

Figure 40. Salinity comparison between ES, OPS and FPS at 3 observation points in Redfish Bay.

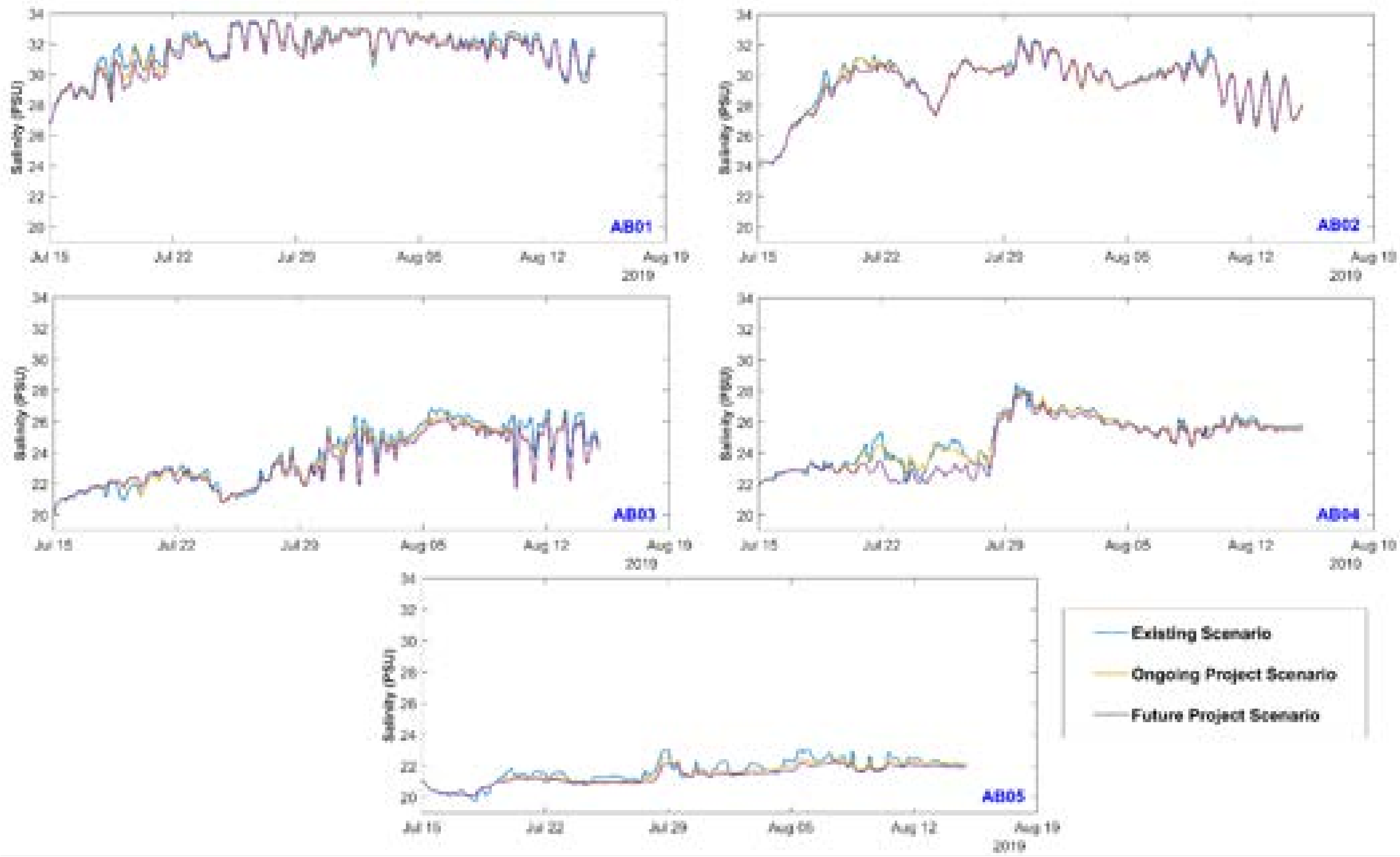

Figure 41. Salinity comparison between ES, OPS and FPS at 5 observation points in Aransas Bay.

The bottom salinity time series in Figure 37 - 41, in general, show very small changes in the salinity for both OPS and FPS channel configurations compared to the ES configuration at all locations. The higher variation in salinity due to the channel deepening projects (OPS and FPS configurations) is seen in the upstream (upper bay) locations of the CCSC. The salinity values are almost identical in all three channel configurations near the mouth of the CCSC (see stations CCB01 in Figure 37 and RFB01 in Figure 40). The values start to diverge in the stations located farther up the CCSC. Therefore, the most noticeable difference in the salinity due to the increased depth of the ship channel is seen in Nueces Bay (Figure 38). Table 9 shows the average salinity for all three scenarios at selected stations located near the entrance to the upstream locations. There is an increase in salinity between ES and OPS or FPS at all observation points and more of an increase at locations farther up the CCSC and in Nueces Bay as seen in Table 9. This pattern could be caused by seawater intrusion in the form of a wedge along the bottom of the deepened ship channel due to the higher density of seawater. This salinity wedge might have migrated a bit farther upstream due to the channel deepening.

Table 9. The average salinity at selected observation points for three channel configurations, and percent change from ES to OPS and from ES to FPS. See Figure 35 for station locations.

Simulation date: 7/15/2019 0:00 to 8/15/2019 0:00					
	ES Average Salinity (PSU)	**OPS Average Salinity (PSU)**	**FPS Average Salinity (PSU)**	**Percent Change from ES to OPS**	**Percent Change from ES to FPS**
RFB01	33.04	33.06	33.05	0.05%	0.04%
CCB01	33.06	33.08	33.08	0.05%	0.05%
CCB04	32.85	32.89	32.90	0.13%	0.14%
CCB07	32.25	32.44	32.44	0.58%	0.58%
NB01	31.40	31.68	31.68	0.92%	0.91%
NB03	27.66	28.09	28.04	1.55%	1.36%

The average of median salinity for all three scenarios and the percent change from ES to OPS and FPS in each bay are summarized in Table 10. The values in the table are calculated by taking the average of median bottom salinity during the 1-month period simulation at all the observation points in each bay. The increase from ES to OPS and FPS in all the bays is less than 1%, and the largest salinity change is 0.31 PSU in the OPS and FPS configurations. There is a 0.72% and 1.23% decrease in salinity in Aransas Bay in the OPS and FPS configurations, respectively.

Table 10. The average of the medians of salinity of each model observation points in a bay. ES, OPS and FPS scenarios, and percent change from ES to OPS and from ES to FPS for each bay.

Simulation date: 7/15/2019 0:00 to 8/15/2019 0:00					
	ES Average Salinity (PSU)	**OPS Average Salinity (PSU)**	**FPS Average Salinity (PSU)**	**Percent Change from ES to OPS**	**Percent Change from ES to FPS**
Corpus Christi Bay	32.94	32.99	32.99	0.17%	0.17%
Nueces Bay	29.87	30.08	30.05	0.72%	0.61%
Redfish Bay	32.99	33.01	33.01	0.08%	0.07%
Aransas Bay	26.58	26.40	26.27	-0.72%	-1.23%
Upper Laguna Madre	33.70	33.78	33.77	0.24%	0.21%

4.4 Summary of Salinity Modeling

The 3D implementation of a hydrodynamic model in the Delft3D-FM modeling suite, D-Flow FM, was applied to assess the impacts on salinity in the Corpus Christi Bay System due to PCCA's proposed CCSC deepening projects. The same unstructured grid developed for the tidal hydraulics modeling is used for this analysis. The model is forced with inputs including water level, offshore salinity, wind speed and direction, and the freshwater discharge of the Nueces River, Oso Creek, and Mission River. The composite heat flux model is applied in the model by incorporating relative humidity, air temperature and cloud cover over the model domain. To assess model performance, simulated model output is compared with measured salinity and water level at stations in Corpus Christi Bay and Nueces Bay for 2018. The model successfully represents water levels but does not perform well for salinity and predicts little variation in salinity in Corpus Christi Bay. The model performs relatively well in Nueces Bay compared to Corpus Christi Bay. Although the model validation is not completely satisfactory, we proceeded to model the bay systems with an emphasis on revealing changes caused by different channel configurations rather than predicting absolute salinity.

To assess the impact of channel depth on salinity, the model was run for a 1-month period in July/August 2019 with all three channel configurations. The salinity time-series at selected observation points under different channel configurations are plotted and median salinity values are calculated and compared in each bay for three channel scenarios. The model output shows small increases in salinity for both the OPS and FPS channel configurations compared to the ES channel configuration in all bays except Aransas Bay. There is a small salinity decrease in Aransas Bay in the OPS and FPS in comparison to the ES configuration. The model results indicate that the deeper channels will allow migration of higher salinity water from the CCSC entrance into the upper reaches of the bays hence greater increases in salinity are predicted farther up the ship channel and in Nueces Bay. These model outputs are similar to the salinity modeling results of a two-year simulation (1988 – 1989) during normal to dry periods reported in *Corpus Christi Ship Channel, Texas, Channel Improvement Project, Final Feasibility Report and Final Environmental Impact Statement* (USACE, 2003) which has shown an increase in monthly average salinity by 0.1 – 0.4 PPT in Corpus Christi Bay and by 0.1 PPT in Nueces Bay. The key findings of the analysis are the following:

- The variation in salinity between ES and OPS or FPS channel configurations is quite small for most locations – less than 1% increase in all bays except Aransas Bay where it decreases slightly.
- Higher increases in salinity due to the channel deepening projects (OPS and FPS configurations) is most prominent in the upper bay locations of the ship channel and in Nueces Bay.

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EXHIBIT A
Scope of Work

STUDY OF INFLUENCE OF CHANNEL IMPROVEMENT PROJECTS ON STORM SURGE, TIDE, AND SALINITY WITHIN THE CORPUS CHRISTI BAY SYSTEM

Major Tasks

1. Data Collection and Preparation

a. Hurricane Scenarios

This project will select from a suite of 660 available numerical storm scenarios recently commissioned by the USACE and Texas General Land Office (GLO) for use in the Coastal Texas Study. We will choose a single representative track of a category 4 storm that is most likely to cause a difference in surge for the different channel configurations. In the USACE's collection of synthetic storms, there are 6 storm tracks that pass through the area (Figure 1). Within these 6 tracks there are 45 storms with different characteristics, including 19 storms of category 3 or higher (Table 1). We have made a preliminary selection of storm TC_JPM0130, which is a category 4 storm along Track 1, to test the impact of channel deepening. We will finalize this selection after consultation with the PCCA following project start.

Table 1. Synthetic storm characteristics for storms with tracks crossing the Corpus Christi Bay region shown in Figure 1. Shaded row is storm TC_JPM0130 preliminarily chosen for modeling under this project.

Track ID	Storm Name	Category	Wind Speed - Landfall (mph)	Forward Speed (mph)	RMW - Landfall (miles)	Central Pressure - Landfall (mb)	Total Hours	Time Step (min)
Track 0	TC_JPM0057	Cat 5	159.28	27.73	20.3	900.3	132	5
	TC_JPM0058	Cat 4	146.16	11.16	13.24	910.2	252	15
	TC_JPM0059	Cat 3	120.52	5.87	29.26	921.3	312	15
	TC_JPM0060	Cat 3	116.81	8.86	15.584	933.7	282	15
	TC_JPM0061	Cat 3	113.63	18.87	5.52	947.7	162	5
Track 1	TC_JPM0130	Cat 4	141.01	13.92	18.45	905.2	222	15
	TC_JPM0132	Cat 3	114.54	6.10	21.77	927.3	312	15
Track 2	TC_JPM0228	Cat 4	143.35	5.29	17.92	900.3	312	15
	TC_JPM0230	Cat 3	126.93	22.21	24.68	921.3	132	5
	TC_JPM0229	Cat 3	120.42	10.01	23.96	910.2	282	15
Track 3	TC_JPM0319	Cat 4	143.23	10.47	11.98	905.2	252	15
	TC_JPM0321	Cat 3	127.86	15.31	12.82	927.3	222	5
	TC_JPM0320	Cat 3	122.50	18.30	28.48	915.6	192	5
Track 4	TC_JPM0414	Cat 4	134.45	27.27	23.28	910.2	132	5
	TC_JPM0415	Cat 3	113.68	16.46	12.15	921.3	192	5
	TC_JPM0413	Cat 3	112.34	9.55	20.85	900.3	282	15
	TC_JPM0500	Cat 4	133.97	6.79	18.07	905.2	312	15

Track 5	TC_JPM0501	Cat 4	133.28	25.09	24.14	915.6	132	5
	TC_JPM0503	Cat 3	124.22	17.03	9.23	940.4	192	5

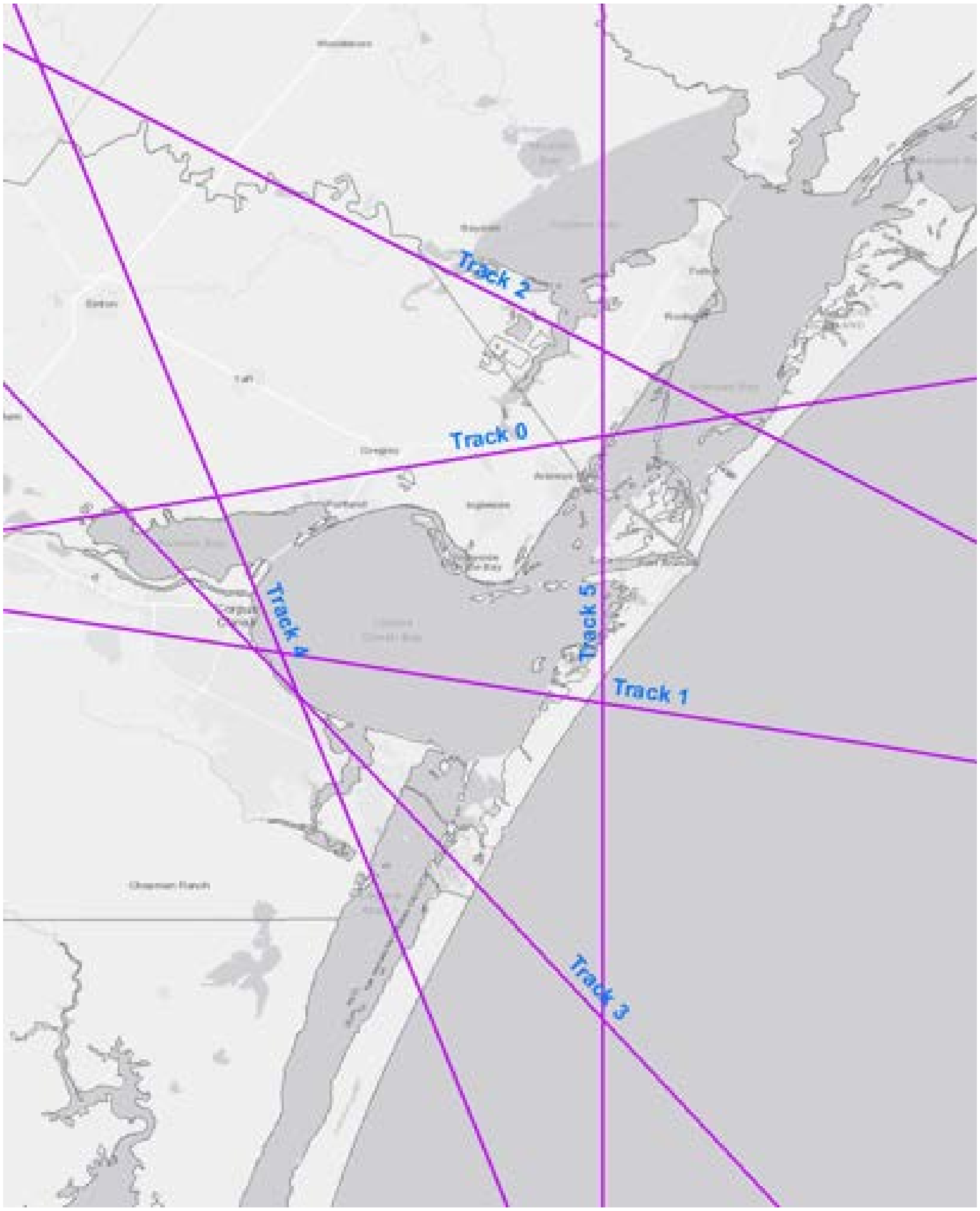

Figure 1. Synthetic hurricane tracks in the USACE's collection passing through the Corpus Christi Bay region

b. Delft3D Data Preparation

The Delft3D model will be calibrated and forced using wind, tide, salinity, current and discharge data from a variety of monitoring stations, as seen in Figure 2 and listed in Table 2. There are six NOAA stations in the study area that collect wind and water level data every 6 minutes that will be used for water level calibration or for forcing boundary conditions. Two stations, one on the outer end of the Aransas Pass jetties (8775241) and one at Bob Hall Pier (8775870) will be used for the offshore boundary condition. Two NOAA PORTS stations record current speed, direction, along channel velocity, and cross-channel current velocity every 6 minutes. Salinity data will be obtained from the Texas Water Development Board's (TWDB) monitoring stations as seen in Figure 2. These data are collected hourly. The bathymetry data in the ADCIRC mesh will be adapted for use in the Delft3D model.

Figure 2. Location of stations used to collect wind velocity, water level, salinity, and current data for Delft3d calibration

Table 2. The ID, name, data type, resolution, date established, and source of the stations used for Delft3D calibration

ID	Location	Data type	Resolution	Established	Source
8775244	Nueces Bay	Water level,	6 min	01/12/2010	NOAA
8775296	USS Lexington	Water level	6 min	01/08/2004	NOAA
8775237	Port Aransas	Water level	6 min	05/25/1990	NOAA
8775241	Aransas Pass	Water level, Wind	6 min	08/01/2016	NOAA
8775792	Packery Channel	Water level, Wind	6 min	11/30/1988	NOAA
8775870	Bob Hall Pier	Water level, Wind	6 min	05/09/1983	NOAA
INPT	Nueces Bay	Salinity	60 min	05/15/2017	TWDB
BIRD	Upper Laguna Madre	Salinity	60 min	05/12/1989	TWDB
Port Aransas, Channel View	Port Aransas Channel	Currents	6 min	n/a	NOAA
Oxy Oil and Gas CM	Corpus Christi Bay	Currents	6 min	n/a	NOAA

2. Model Setup and Mesh Development

a. ADCIRC

For this project, HRI will use ADCIRC, an open source hydrodynamic storm surge model, to evaluate coastal storm surge impacts in and around Corpus Christi Bay. HRI will use high performance computing resources at the Texas Advanced Computing Center (TACC) for the model runs. Each simulation will require approximately 15 hours to complete in over 1,200 computing cores. ADCIRC has already been installed in TACC, and we have used it for the GLO and USACE studies.

HRI will use the *TX2008_R35H* computational mesh that was used and validated for simulating recently completed storm surge analysis studies for the Texas Coastal Resiliency Master Plan and Coastal Texas Study. The mesh domain includes the western North Atlantic Ocean, Caribbean Sea and Gulf of Mexico, and the element sizes vary from 20 km in the deep Atlantic Ocean to 30 m in the channels and rivers. The maximum element size is 200 m along the nearshore wave transformation zones and 5 km in the deep Gulf of Mexico. The element size along the Corpus Christi Ship Channel is approximately 60 m. This mesh reflects the current topographic-bathymetric conditions for input to ADCIRC. Using digital plans provided by PCCA, HRI will modify this mesh to reflect the ongoing and planned channel configurations.

b. Delft3D

To evaluate tidal hydraulics and salinity impacts for this project, HRI will use the Delft3D FM modeling suite. This modeling suite includes the widely used hydrodynamic model Delft3D, and multiple computational engines including the D-Flow Flexible Mesh (D-Flow FM) engine which is selected for this project. D-Flow FM is capable of handling curvilinear grids as well as unstructured grids. HRI will use High Performance Computing (HPC) resources on our campus for D-FLOW FM model runs. Furthermore, we expect to maintain D-FLOW FM on our HPC for future needs.

During the last two months, HRI has worked on developing a structured mesh covering the model domain. The current version has a varying resolution of 28 m along the channel to 236 m offshore, and it will soon be tested on our HPC. The unstructured ADCIRC mesh described above can also be imported to Delft3D FM and updated to increase the resolution as needed. This project will explore both the structured and unstructured approach in the Delft3D model to create a robust hydrodynamic modeling system that can be used for future analyses as needs arise. The selected mesh will be modified using digital plans provided by PCCA to represent the ongoing and planned channel configurations.

3. Hydrodynamic Model Runs

a. ADCRIC

HRI proposes to run models for a single initial representative storm. This storm will be run three times with three channel configuration scenarios: Existing Scenario (ES); Ongoing Project Scenario (OPS); and Future Project Scenario (FPS). The ES will use the existing channel configurations (channel maintained to a depth of -47 ft. MLLW) with the current bathymetric condition of the bay. OPS will consider the full ship channel maintained to a depth of -54 ft. MLLW based on plans provided by the PCCA and with the current bathymetric condition of the rest of the bay. The FPS will consider the outer reach of the ship channel maintained to a depth of -75 ft. MLLW and the remainder of the channel maintained at -54 ft. MLLW, based on PCCA plans, with the current bathymetric condition for the rest of the bay.

b. Delft3D in 2D Mode

The same three channel configuration scenarios used for ADCIRC (EC, OPS and FPS) will be used for the 2D implementation of the Delft3D hydrodynamic model. Each model scenario will be run to cover model periods with varying environmental conditions such as periods of high and low seasonal water levels, strong winds from various directions, and high freshwater inflow.

In addition, model simulations for sea level conditions projected to occur in the year 2050 will be run. A moderate projection for Relative Sea Level Rise (RSLR) of 1.9 ft in 2050 will be used.

4. Model Results and Visualization

a. ADCIRC Results and Visualization

The modeling output will show storm surge water level elevations for each storm. Model output generated for three scenarios (EC, OPS and FPS) will be compared and visualized through the creation of difference grids. The difference grids will show the difference in water level elevations calculated among three scenarios. All model output and analysis products with metadata will be made available to the PCCA.

b. Delft3D Results and Visualization

The modeling outputs will be analyzed for spatio-temporal differences in tide range, tidal prism, and salinity between the three scenarios (ES, OPS and FPS) over the modeled time periods in and around Corpus Christi Bay. Results from the model will be visualized in maps, tables, graphs, and animations. All model output and analysis products with metadata will be made available to the PCCA.

5. Impact Analysis

Impacts to the natural and built environments resulting from the deepening of the channel will be analyzed by overlaying ADCIRC and Delft3D model results with other data related to environmental sensitivities, such as nearby critical infrastructure and wetland habitats. A comparison of the extent and depth of storm surge inundation and tidal dynamics will be made between the 3 channel scenarios and for conditions projected in 2050 after a 1.9 ft RSLR. Habitat and infrastructure vulnerabilities will be identified. Additionally, an elevation range-habitat type distribution will be determined for the present environment using high resolution topography and land cover data developed by HRI. Comparisons between current and new tide ranges and sea levels will be assessed to determine potential shifts in habitats. Additional modeling using the Sea Level Affecting Marshes Model (SLAMM) may be performed to assess how potential changes in sea level caused by channel deepening could affect the distribution of wetland habitats near the channel.

i

From: Pollack, Jeff <jpollack@pocca.com>
Sent: Monday, April 19, 2021 4:55 PM
To: Koesema, Dan <Dan@pocca.com>; MacDonald, Tony <tmacdonald@pocca.com>; Fudge, Natasha <Natasha@pocca.com>; Hale, Danielle <dhale@pocca.com>
Cc: Robertson, Clark <crobertson@pocca.com>; Strawbridge, Sean <sstrawbridge@pocca.com>; Garza, Sarah <Sarah@pocca.com>
Subject: FW: Final Report: lnterlocal Cooperation Contract
Importance: High

Dan/Tony/Natasha/Danielle,

Please find attached the final report and the contracted scope of work from modeling work performed by Dr. Gibeaut at TAMUCC. We undertook this work voluntarily, for our own purposes, to add color to some of the preliminary modeling performed in support of the CIP and -75' project, but it turns out (per the USACE) that these results may reduce the scope of additional modeling responsible as part of the EIS for the -75 project.

Jim et. al modeled changes in salinity, tidal hydraulics, and storm surge under different channel configurations and different storm scenarios. The findings herein, particularly related to storm surge, may help inform our basis of design for infrastructure in various locations (particularly Harbor Island).

Sarah and I would be happy to discuss further at any point.

Thanks,
Jeff

Jeffrey Pollack, AICP, ENV SP
Chief Strategy Officer
Port of Corpus Christi
p: (361) 885-6230 m: (361) 906-5440
w: portofcc.com e: jpollack@pocca.com

From: Gibeaut, James <James.Gibeaut@tamucc.edu>
Sent: Thursday, April 1, 2021 8:59 PM
To: Garza, Sarah <Sarah@pocca.com>; Pollack, Jeff <jpollack@pocca.com>
Cc: Subedee, Mukesh <mukesh.subedee@tamucc.edu>
Subject: Final Report: Interlocal Cooperation Contract

Mr. Pollack and Ms. Garza,
Please find enclosed our final report titled "Impacts of Channel Dredging on Storm Surge, Tidal Flows and Salinity in Corpus Christi Bay." Please contact me with any questions or requests. I attach both Word and pdf formats.

Regards,
Jim

James C. Gibeaut, Ph.D.
Endowed Chair for Geospatial Sciences
Director, Gulf of Mexico Research Initiative Information and Data Cooperative
Harte Research Institute for Gulf of Mexico Studies
Texas A&M University - Corpus Christi
6300 Ocean Drive, Unit 5869
Corpus Christi, Texas 78412-5869
Voice (361) 825-2060
Fax (361) 825-2050
james.gibeaut@tamucc.edu
www.hri.tamucc.edu