ATTACHMENT 2
HYDROLOGY AND HYDRAULICS REPORT

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Final Hydrology and Hydraulics Report

Freeport Harbor Channel Improvement Project
General Revaluation Report

HDR Project Number: 10026391

Brazoria County, TX
May 1, 2017

PRELIMINARY

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ENGINEER: BRETT L. GEESEY, P.E.

LICENSE NUMBER: 106642

FIRM NAME: HDR ENGINEERING, INC.

Executive Summary

A hydrology and hydraulics (H&H) analysis on sedimentation, relative sea level rise, wave climate, wave overtopping, and hydrodynamic climate was performed in support of Port Freeport's efforts on the General Reevaluation Report (GRR) for the Freeport Harbor Channel Improvement Project (FHCIP). As part of the GRR, three preliminary alternatives have been proposed to improve navigation within the "Dow Thumb" portion of the harbor. Alternative 1 consists of widening at Dow Thumb to 375 feet, a Bend Easing, and a Turning Notch all at 46 feet-MLLW depth. Alternative 2 consists of widening at Dow Thumb to 400 feet, a Bend Easing, and a Turning Notch all at 46 feet-MLLW depth. Alternative 3 consists of widening at Dow Thumb to 425 feet, a Bend Easing, and a Turning Notch all at 46 feet-MLLW depth. All H&H analyses were conducted assuming the channel's present configuration hereinafter referred to as the "No Action Alternative" and a proposed layout to improve navigation hereinafter referred to as "Alternative 2".

During the sedimentation analysis, historical maintenance dredging records from U.S. Army Corps of Engineers Galveston District were analyzed and time averaged leading to an estimate of average annual shoaling rate for the No Action Alternative. Increase factors were calculated for all reaches of Alternative 2 and were applied to the computed average leading to an estimate of average annual shoaling rate for Alternative 2. It was concluded from the sedimentation analysis, that annual shoaling rate will increase approximately 12% if Alternative 2 is implemented.

Relative Sea Level Rise (RSLR) was calculated as the sum of average global sea level rise, vertical land movement, and regional ocean basin trends utilizing various risk scenarios. RSLR results were presented to Port Freeport as well as USACE Galveston District. Based on discussion with USACE and for the purpose of consistency with previous projects, a 50-year RSLR of 1.18 feet based on USACE Intermediate Curve was suggested for this project.

The channel's wave climate was modeled in STWAVE under the No Action Alternative and Alternative 2 assuming an extreme storm event consisting of 100-year wind speed and 100-year still water level. Wave modeling was repeated with Relative Sea Level Rise added to investigate possible effects of Relative Sea Level Rise. It was concluded that, due to partial increase in particular fetch lengths, particularly at Dow and Stauffer plants, Alternative 2 will produce wave heights that are less than 0.1 feet greater compared to those of the No Action Alternative. Relative Sea Level Rise also appeared to cause increase of wave heights by less than 0.1 feet all over the domain.

Using the wave characteristics obtained from the wave analysis, the Levees and floodwalls protecting Dow and Stauffer plants were analyzed for overtopping. Due to minor increase of wave heights imposed by Alternative 2, it was concluded that Alternative 2 would have minimal effect on the overtopping of levees and seawalls protecting those plants. When overtopping analysis was repeated with RSLR added, despite minimal wave height increases, calculated overtopping discharges appeared substantially greater than those with no RSLR due to increase of base water surface elevation. Therefore, it is recommended that effects of RSLR to be considered in future evaluation of levees and floodwalls

The channel's non-storm hydrodynamic conditions were modeled in CMS-FLOW under No Action Alternative and Alternative 2. The hydrodynamic modeling was repeated with Relative Sea Level

Rise added to investigate the effects of Relative Sea Level Rise. The analysis suggested that implementation of Alternative 2 will have minimal effect on the channel's hydrodynamics.

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Acronyms

ASCE	American Society of Civil Engineers
CMS	Coastal Modeling System
ERDC	USACE Engineer Research & Development Center
FEMA	Federal Emergency Management Agency
FHCIP	Freeport Harbor Channel Improvement Project
FIS	Flood Insurance Study
GIWW	Gulf Intracoastal Waterway
GRR	General Reevaluation Report
HSDRRS	Hurricane and Storm Damage Risk Reduction System
LIDAR	Light Imaging, Detection, and Ranging
MIKE21 SW	MIKE 21 Spectral Wave Model
NAD83	North American Datum of 1983
NASA	National Aeronautics and Space Administration
NAVD88	North American Vertical Datum of 1988
NOAA	National Oceanic and Atmospheric Administration
RSLR	Relative Sea Level Rise
SMS	Surface Water Modeling System
STWAVE	Steady State Wave Model
USACE	U.S. Army Corps of Engineers
USCG	United States Coast Guard
USGS	United States Geological Survey
WSEL	Water Surface Elevation

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1 Introduction

1.1 Purpose

A General Reevaluation Report (GRR) for the Freeport Harbor Channel Improvement Project (FHCIP) is currently being performed to assess potential alternatives to improve navigation within the “Dow Thumb” portion of the harbor. The purpose of this report is to document the overall Hydrology and Hydraulics (H&H) analyses performed as part of the Freeport Harbor Channel Improvement Project General Revaluation Report (FHCIP GRR). The H&H analysis included five major tasks include:

- Sedimentation Analysis: Review of historical maintenance dredging records, calculation of average annual shoaling rate, and calculation of likely future shoaling rates.
- Relative Sea Level Rise Analysis: Calculation of 50-year RSLR rates considering average global sea level rise, vertical land movement, and regional basin trends based on various USACE and NOAA risk scenarios.
- Wave Analysis: Numerical modeling of wave climate in Freeport Harbor Channel under extreme metocean events and determination of likely changes to the wave climate subsequent to RSLR and channel modifications.
- Wave Overtopping Analysis: Calculation of wave overtopping discharge over levees and floodwalls under extreme metocean events and determination of likely changes subsequent to RSLR and channel modification.
- Hydrodynamic Analysis: Numerical modeling of hydrodynamics of Freeport Harbor Channel and determination of likely changes to the flow regime subsequent to channel modifications

A technical memorandum was developed for each task for review by the project team. This document compiles the memorandums previously developed and provides a review of the overall H&H analysis. Additionally the U.S. Army Corps of Engineers (USACE) Engineer Research & Development Center (ERDC) is performing risk base wave and surge analysis and risk and uncertainty analysis for FHCIP-GRR.

1.2 Project Location

Freeport Harbor Channel is located in Brazoria County, TX serving as an inland shipping channel to several industrial entities. The channel is considered a Federal Navigation Channel and is under the authority of U.S. Army Corps of Engineers (USACE) Galveston District. Figure 1 presents an aerial map of the project vicinity.

Figure 1 – Aerial map of Freeport Harbor Channel

1.3 Background

Prior to 1929, the Brazos River discharged into the Gulf of Mexico through the current location of Freeport Harbor. Being one of the few rivers in Texas directly discharging to the Gulf, the Lower Brazos River attracted several industries to establish navigation facilities along its banks. However, riverine sediments were deposited in the channel, requiring frequent dredging to maintain navigable water depths. To help reduce shoaling, in 1929, the USACE diverted the river to discharge into the Gulf at a new location approximately 6.5 miles southwest of the old Brazos River delta. The Gulf Intracostal Waterway (GIWW) currently connects the Freeport Harbor Channel to the Brazos River. Figure 2 presents the Brazos River Diversion and Freeport Harbor Channel.

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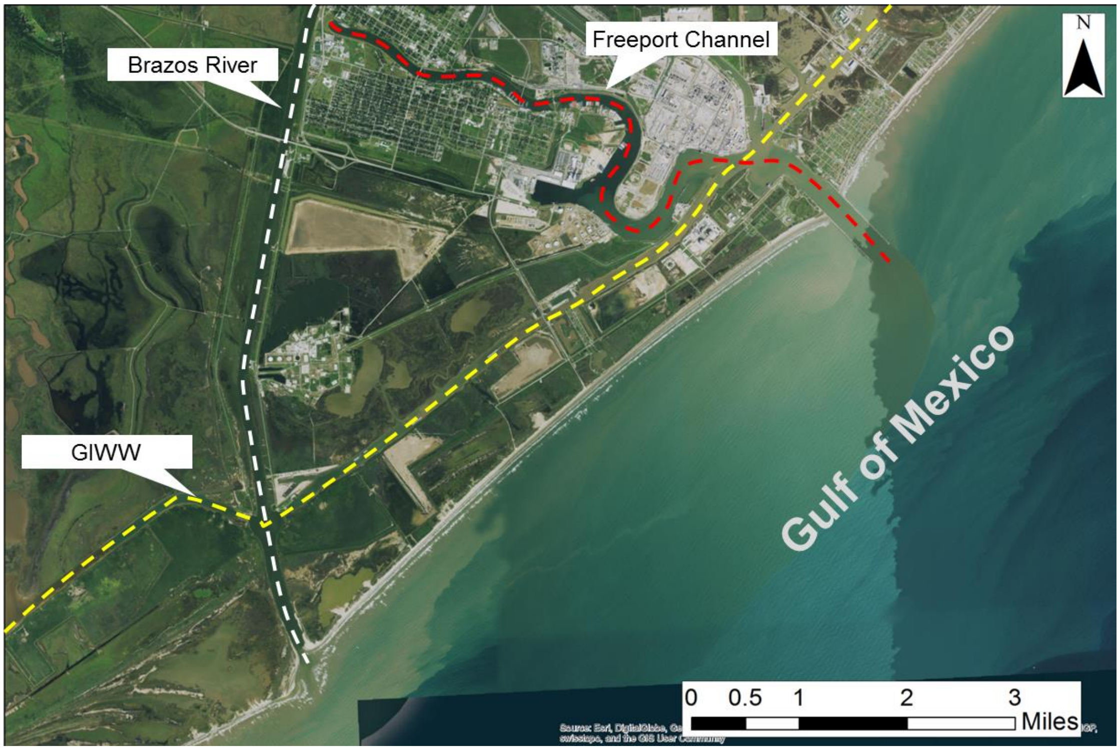

Figure 2 – Brazos River Diversion, Freeport Harbor Channel, and GIWW

1.4 Proposed Alternatives

As part of the FHCIP GRR, four alternatives are being considered in an effort to improve navigation specifically within the “Dow Thumb” portion of the channel. The alternatives are:

- **No Action Alternative:** consists of no modification to the Freeport Harbor Channel;
- **Alternative 1:** consists of widening at Dow Thumb to 375 feet, a Bend Easing, and a Turning Notch all at 46 feet-MLLW depth;
- **Alternative 2:** consist of widening at Dow Thumb to 400 feet, a Bend Easing, and a Turning Notch all at 46 feet-MLLW depth; and
- **Alternative 3:** consist of widening at Dow Thumb to 425 feet, a Bend Easing, and a Turning Notch all at 46 feet-MLLW depth.

The USACE Galveston district has tentatively selected Alternative 2 for further analyses. Features of the alternatives 1, 2, and 3 are presented in Figure 3.

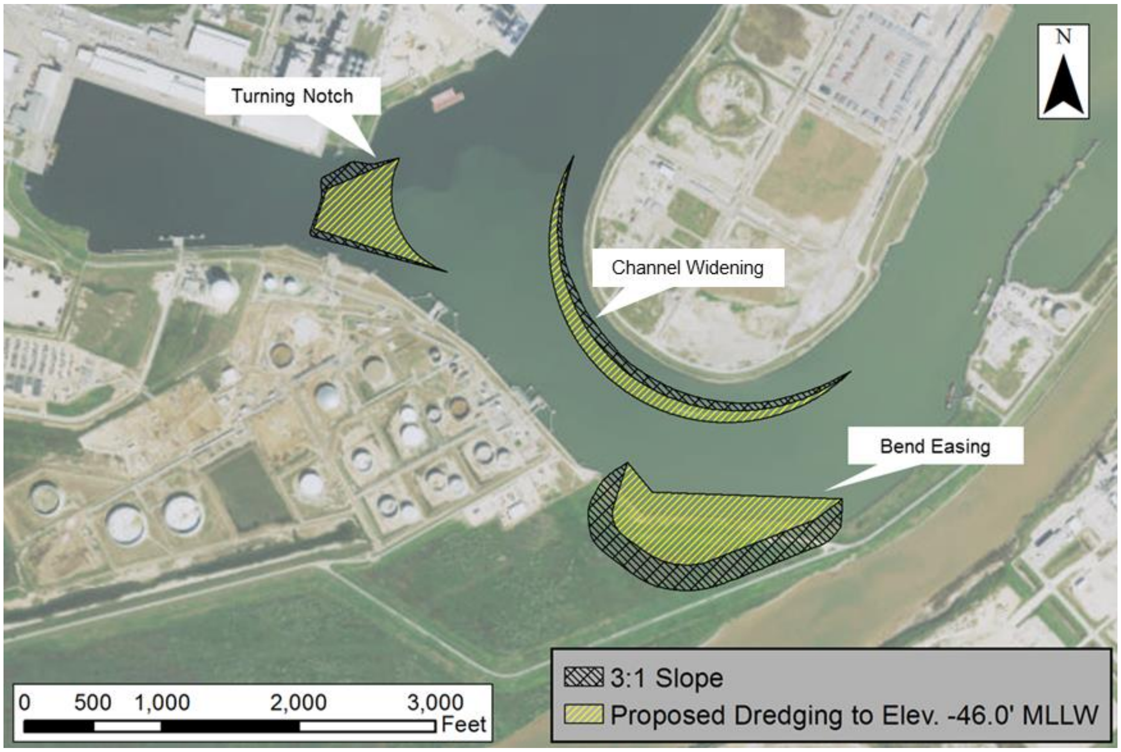

Figure 3 – Features of Alternatives 1-3

2 Sedimentation Analysis

The Sedimentation Analysis compares annual maintenance dredging requirement at Freeport Harbor Channel for the No Action Alternative to that of Alternative 2. Maintenance dredging records obtained from USACE Galveston District were analyzed and average annual shoaling rate at Freeport Harbor Channel (i.e. stations 71+52 to 184+20) was calculated providing maintenance shoaling rate of the No Action Alternative. An increase factor was then calculated by reach and multiplied by the calculated annual shoaling rate to estimate the likely annual maintenance shoaling rate for Alternative 2.

2.1 Historical Sedimentation

Since the diversion of the Brazos River in 1929, the Freeport Harbor Channel became free from upstream flow and has experienced decreased sedimentation. Average annual dredging requirements are estimated to be approximately 1.6 million cubic yards, including the entrance bar channel, jetty channel, and inner harbor channel (USACE, 2012b). Dredging requirements for the harbor channel (i.e. stations 71+52 to 184+20) since 1992 are shown in Figure 4.

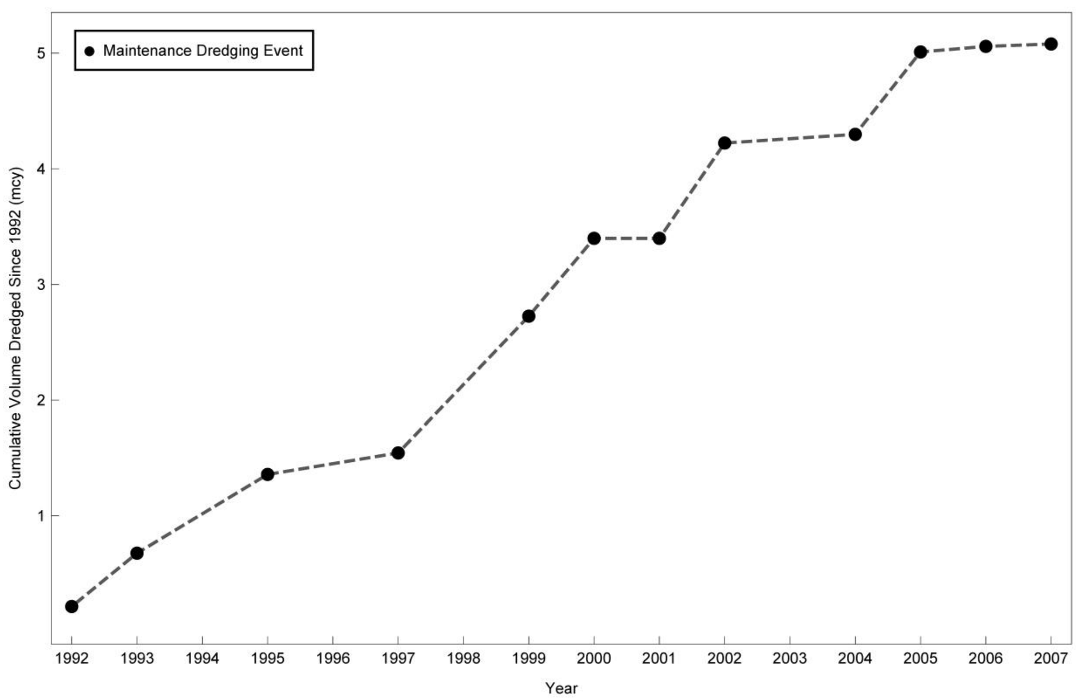

Figure 4 – Cumulative maintenance dredging volume since 1992

2.2 Analysis of Aerial Photography

Historical aerial photographs from Google Earth were reviewed to assist in identifying sources of sediment supply. Despite diversion of the river in 1929, sediment plumes visible in the aerial photographs suggest that suspended sediment from the Brazos River continues to be a significant source of sediment supply in Freeport Harbor. While the river discharges into the Gulf approximately 6.5 miles southwest of the harbor entrance, it still connects to the harbor through the GIWW. This connection can deliver sediment from the river during the river's peak discharge periods. As an example, Figure 5 (Google Inc., 2016) shows transport of sediment from Brazos River to Freeport Harbor Channel in December 2004. While forces from tides and waves can also transport sediment from the Gulf of Mexico into Freeport Harbor, riverine sediment from the Brazos River appears to be a significant source.

Figure 5 – Flow of suspended sediment from Brazos River to Freeport Harbor Channel, Dec 2004

Source: Google Earth, Image by NASA

2.3 Review of Previous Sedimentation Studies

As part of the previous FHCIP Feasibility Report (USACE, 2012b), USACE estimated that the overall annual dredging volume in the inner harbor channel (i.e. stations 71+52 to 184+20) will increase from approximately 281,000 cubic yards to 348,000 cubic yards. This increased shoaling rate was based on a 10 feet increase in depth plus channel widening up to 1,350 feet within the reach from Brazosport to Brazos Turning Basin (i.e. stations 78+52 to 115+52) (USACE, 2012b). It should be noted that this value was calculated for a different proposed modification and does not represent Alternative 2.

2.4 Analysis of Dredging Records

The current analysis utilized the same methodology used in the 2012 Feasibility Report to estimate the increase in annual dredging for Alternative 2. To help illustrate this method, Figure 6 shows a rectangular channel cross section per unit length.

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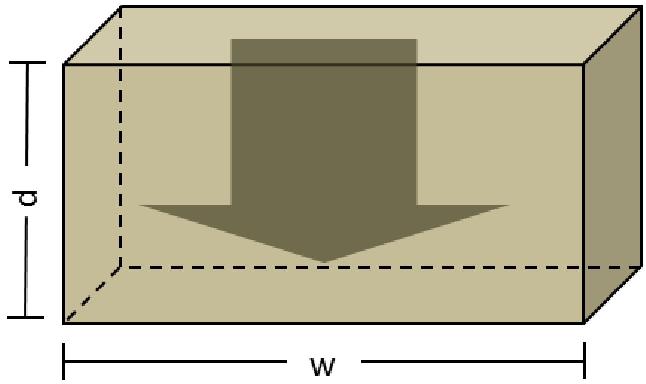

Figure 6 – Illustration of sedimentation at unit length of a rectangular channel

Given the dimensions, assuming sufficient settling time and homogeneous spatial distribution of suspended sediment, the volume of settled sediment per unit length of the channel can be calculated by:

$$v_s = w \times d \times c$$

In which:

v_s Sediment deposit volume per unit length

w Channel width

d Water depth

c Suspended sediment concentration

Assuming the channel width is increased, the area factor can be written as:

$$F_a = \frac{w'}{w}$$

In which:

F_a Area factor

w' New channel width

Therefore, assuming unchanged sediment concentration, the sediment deposit volume per unit length in the new channel, v'_s, can be calculated as:

$$v'_s = F_a \times v_s$$

Dredging records from USACE Galveston District[1] were analyzed; then, area factors were calculated for each reach based on Alternative 2. The analysis suggested the annual dredging volume at the inner harbor channel (i.e. stations 71+52 to 184+20) will increase from approximately 281,000 cubic yards per year to 315,000 cubic yards per year for Alternative 2. Table 1 contains a summary of the calculations performed to estimate the projected annual dredging requirement. A table of dredging records is provided in Appendix A.

[1] Dredging records were provided to HDR by Rob Thomas, P.E., Chief, Project Management Branch, on December 3, 2015.

Table 1 – Estimated annual dredging rates, No Action Alternative vs. Alternative 2

				No Action Alternative			Alternative 2			
	Stations									
Name	From	To	Length (ft)	Width (ft)	Dredging (cy/yr)	Rate (cy/yr/ft)	Width (ft)	Area Factor	Dredging (cy/yr)	Rate (cy/yr/ft)
LTB Reach	+71+52	+78+52	700	400	17,394	24.85	400	1.00	17,394	24.85
CH to Brazosport & Brazos turning basin	+78+52	+115+52	3,700	1100	91,942	24.85	1100	1.00	91,942	24.85
CH to UP TB	+115+52	+132+66	1,714	400	43,884	25.60	400	1.00	43,884	25.60
CH to UP TB to Bend Easing	+132+66	+147+38	1,472	400	36,578	24.85	400	1.00	36,578	24.85
Bend Easing	+147+38	+160+00	1,262	530	31,361	24.85	950	1.79	56,213	44.54
Dow Thumb	+160+00	+166+00	600	370	14,910	24.85	470	1.27	18,940	31.57
Dow Thumb	+166+00	+175+00	900	430	22,365	24.85	530	1.23	27,566	30.63
Dow Thumb to Upper TB	+175+00	+184+20	920	400	22,862	24.85	400	1.00	22,862	24.85
Total Freeport Harbor Channel	+71+52	+184+20	11,268	--	281,296	24.96	--	--	315,378	27.99

2.5 Sedimentation Analysis Conclusion

Based on a review of historical dredging data, Alternative 2 is estimated to increase the annual dredging rate in the inner harbor channel (i.e., stations 71+52 to 184.20) from approximately 281,000 cy/yr to 315,000 cy/yr. This represents an increase of approximately 12%.

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3 Relative Sea Level Rise Analysis

Analysis of Relative Sea Level Rise (RSLR) at Freeport Harbor utilized various National Oceanic and Atmospheric Administration (NOAA) and USACE risk scenarios and potential impacts to the proposed project alternatives. At the end, one of the risk scenarios was selected and utilized in this study based on discussions with USACE Galveston District.

The overall estimated relative sea level rise (RSLR) can be calculated as the combination of average global sea level change, vertical land movement, and regional basin (e.g. western Gulf of Mexico) trends. The relative contribution of each element to the future global Sea Level Rise (SLR) is not well established (Paris *et al*., 2012). While an average global Sea Level Rise of 1.7 mm/yr is calculated based on past measurements, the overall RSLR in a particular location includes other factors such as vertical land movement and regional basin trends (Paris *et al*., 2012).

Vertical land movement can occur through subsidence or uplift. Subsidence is the sinking or lowering of the land surface caused by natural compaction of loose soil; compression of soil due to groundwater, oil, or gas extraction; and oxidation of organic soil (Pavelko *et al*., 2006). Land uplift can result from tectonic activities or post-glacial rebound.

Mean sea level at a certain region can rise faster or slower than the average annual mean sea level rise. For instance, satellite image analysis suggests that since 1992, mean sea level within the Gulf of Mexico has risen substantially faster than the global average (Paris *et al*., 2012). This phenomenon is herein referred to as regional basin trend.

It is important to note that predictions of the global mean sea level in a given year in the future are generally defined as a range due to associated uncertainties in future rates. While a mean global sea level rise value of 1.7 mm/year is calculated based on previous observations (1992-2012), the value is anticipated to accelerate in the future. This requires development of various scenarios in which sea level rise is assumed to accelerate at various rates.

As a response to U.S. Global Change Research Act, NOAA has defined four global Sea Level Rise scenarios (*Lowest*, *Intermediate Low*, *Intermediate High* and *Highest)*, each taken depending on the risk tolerance of the project. The *Lowest* scenario assumes a constant linear sea level rise of 1.7 mm/yr; other scenarios add an acceleration term. The acceleration amount increases as scenarios become more conservative and risk tolerance decreases. Figure 7 shows estimated sea level rise values for each scenario through year 2100.

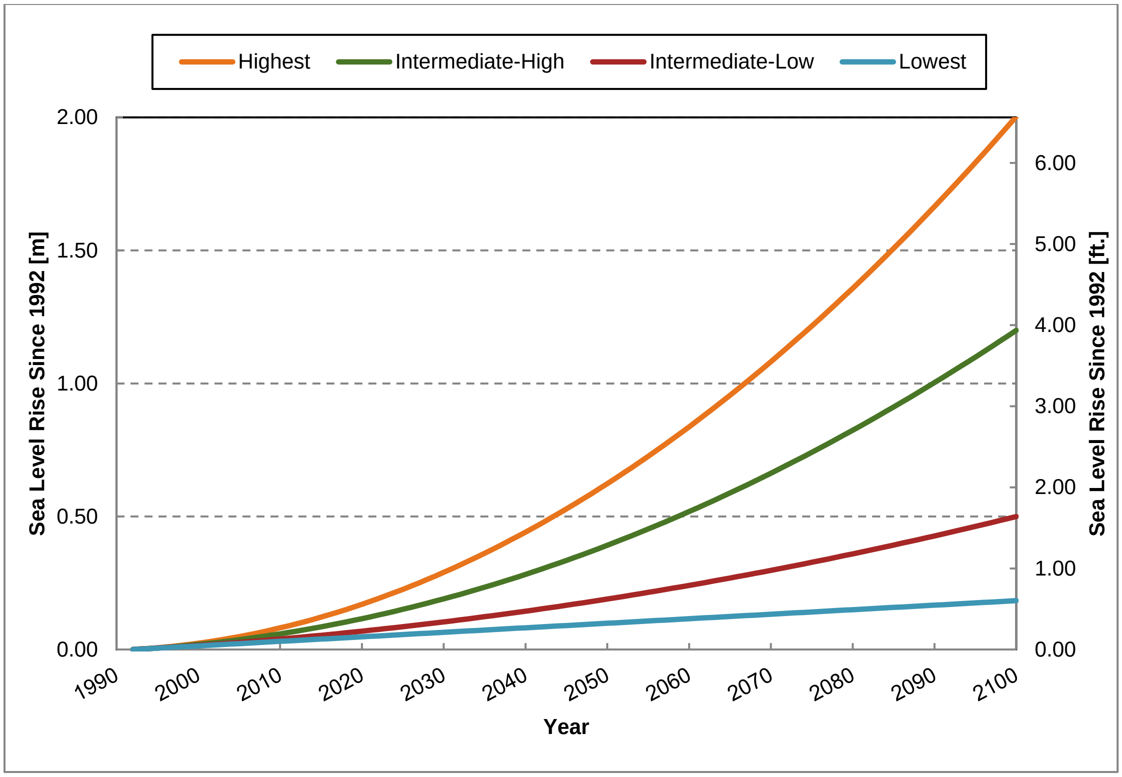

Figure 7 – Average global sea level rise for each NOAA Scenario since 1992

Source: Paris *et al*., 2012

NOAA (Paris *et al*., 2012) suggests applying the highest sea level rise scenario to projects with the least amount of risk tolerance. These projects include but are not limited to: national defense structures, power plants, airports, and other strategic structures. A less conservative scenario applies to projects determined to have a higher risk tolerance.

The USACE (2015) has developed three scenarios for future sea level rise acceleration. The USACE scenarios include *Low Curve*, *Intermediate Curve*, and *High Curve*. USACE has also developed an online tool located at http://www.corpsclimate.us/ccaceslcurves.cfm that calculates RSLR at a given location for a particular epoch.

3.1 RSLR Based on NOAA Scenarios

3.1.1 Global Mean Sea Level Rise

For the purpose of this assessment, construction of the FHCIP is assumed to start in 2020. The project will be assessed for 50 years of sea level rise providing a target year of 2070. Figure 8 presents a plot of global sea level rise for the selected epoch.

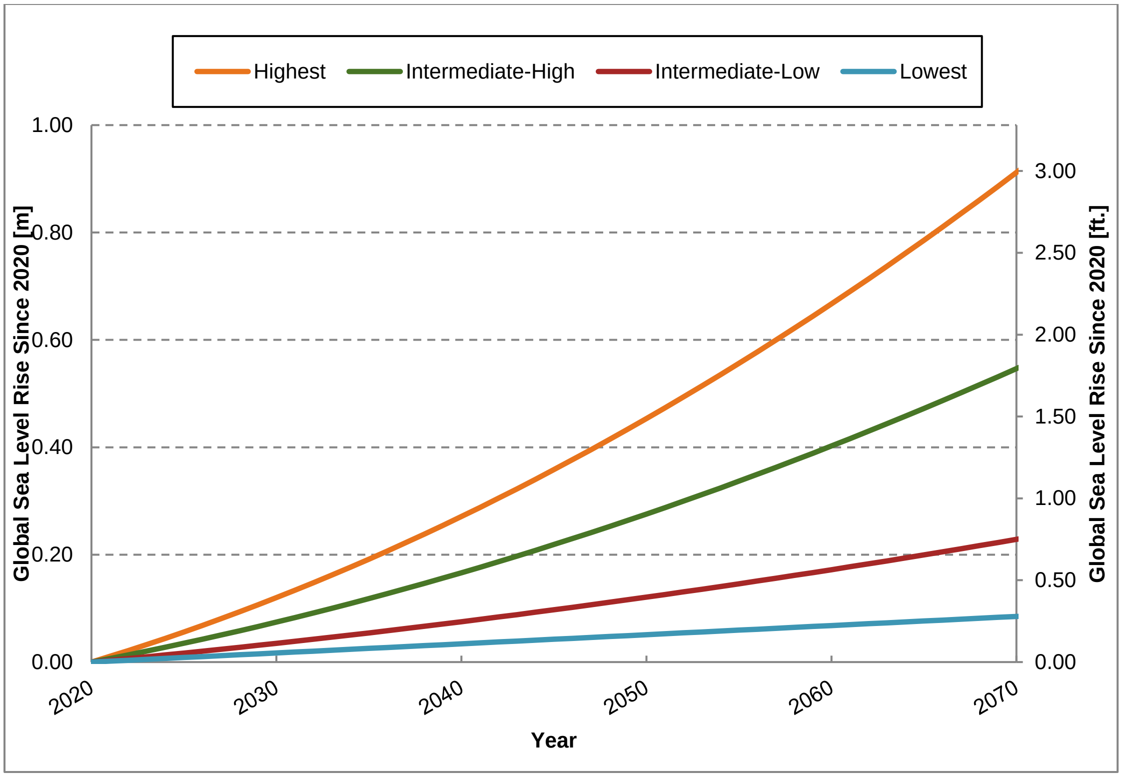

Figure 8 – Average global sea level rise between 2020 and 2070

3.1.2 Vertical Land Movement

Coastal areas along the Gulf of Mexico, particularly Texas and Louisiana, have experienced higher rates of RSLR than the global trend. This is mainly a result of land subsidence (Parris *et al*. 2012). Calculated vertical land movement values along U.S. coasts are provided in Zervas *et al*. (2013), who report average vertical land movement at Port Freeport (NOAA Station 8772440) of approximately -3.65 mm/yr, with a 95% confidence interval of 0.41 mm. This land subsidence value was added to the global mean sea level rise for each scenario.

Table 2 – Estimated Land Subsidence

Bathymetry Survey Year*	Target Year	Annual Subsidence	Total Subsidence
2020	2070	3.65 mm/yr (0.14 in/yr)	182.5 mm (0.6 ft)

*Note: For the purpose of the land subsidence calculations, it was assumed that available bathymetric data were representative of 2020 conditions.

3.1.3 Regional Basin Trends

In addition to experiencing comparatively high rates of RSLR, the Gulf of Mexico's mean sea level has been rising faster than the global trend over the past 60 years (Parris *et al*., 2012). While satellite records show that mean sea level in the Gulf of Mexico has increased 3.3 ± 0.4 mm/yr since 1992, some offshore areas have experienced sea level rise rates of as fast as 5.8 mm/yr. According to Parris *et al*., higher rates of sea level rise in the Gulf can be the effect of multi-decadal variability or large basin oceanographic effects given that the Gulf of Mexico is a large, shallow and semi-enclosed basin. Figure 9 shows average rise in mean sea level within the Northern Gulf of Mexico based on satellite records from 1993 to 2011.

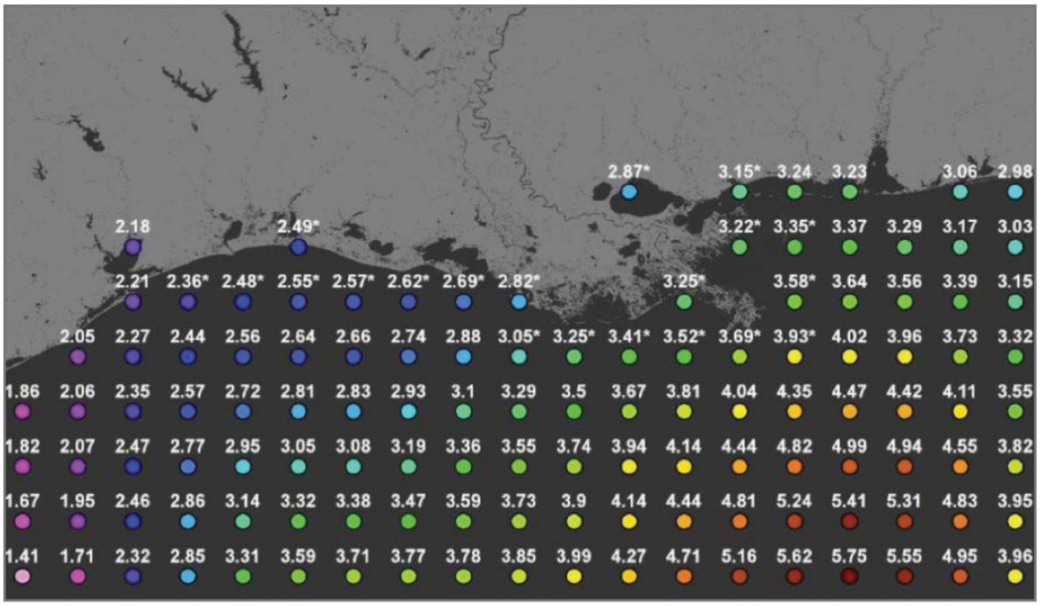

Figure 9 – Average MSL rise in Northern Gulf Region

Source: Brady Couvillion, USGS, Lafayette, LA published in Paris *et al*., (2012)

As shown in Figure 9, satellite records suggest that the mean sea level near Port Freeport has increased at a rate of approximately 2.05 mm/yr which is slightly (+0.35 mm/yr) greater than the average global sea level rise rate of 1.7 mm/yr. This study will include the additional 0.35 mm/yr in sea level rise.

3.1.4 Total Relative Sea Level Rise

Total RSLR is calculated as sum of Average Global Sea Level Rise, Vertical Land Movement, and Regional Basin Trend. Table 3 provides a summary of the total RSLR.

Table 3 – Estimated RSLR at Freeport, TX using NOAA scenarios

Contributing Variables	Scenarios of Sea Level Change (from 2020 to 2070)			
	Lowest Scenario	Intermediate-Low Scenario	Intermediate-High Scenario	Highest Scenario
Global Mean Sea Level Rise* [ft.]	0.3	0.8	1.8	3.0
Vertical Land Movement** [ft.]	0.6	0.6	0.6	0.6
Regional Basin Trend*** [ft.]	0.06	0.06	0.06	0.06
Total Relative Sea Level Change, ft	**0.96**	**1.46**	**2.46**	**3.66**

* Calculated from 2020 to 2070 (i.e., a 50-year projection).
** Subsidence rate based on Zervas et al. (2013). Calculated from 2020 to 2070. Assuming survey data to be conducted in 2020
*** Assuming a value of 0.35 mm/yr based on Paris *et al*. (2012)

3.2 RSLR Based on USACE Curves

The USACE provides an interactive RSLR calculator on the US Army Corps of Engineers *CorpsClimate*[2] portal. The calculator provides a range of RSLR estimates based on user inputs (e.g. location, epoch, etc.) and estimates from both NOAA and USACE risk scenarios. Table 4 provides a summary of the total relative sea level change based on the USACE calculator.

Table 4 – Estimated RSLR at Freeport, TX using USACE scenarios

Scenarios of Sea Level Change (from 2020 to 2070)		
Low Curve	**Intermediate Curve**	**High Curve**
0.71 ft	1.18 ft	2.68 ft

3.3 Potential Impacts on the No Action Alternative

An increase in relative sea level, in turn increasing water depth, has the potential to impact wave climate, hydrodynamic climate, resiliency and sedimentation. For instance, under the same wind speed and direction, wind-induced waves will generally be larger if water depth is increased.

Similar to the waves, the hydrodynamics can be affected by RSLR in a given channel. CMS-FLOW, the model later utilized in the hydrodynamic study (Section 6) of this report, defines the friction coefficient as below (USACE, 2012a):

$$C_b = g \times n^2 \times h^{-\frac{1}{3}}$$

In which,

C_b friction coefficient, dimensionless

n manning's n coefficient, $s/m^{1/3}$ or $s/ft^{1/3}$

[2] http://www.corpsclimate.us/ccaceslcurves.cfm

h water depth, *m or ft.*

g acceleration due to gravity, m/s^2 or ft/s^2

For a given roughness, an increase in water depth will result smaller friction coefficient. This leads to increased hydraulic conveyance in the channel and can cause higher sediment and saltwater influx.

Furthermore, water depth increases create a potential for increased loading on levees and seawalls from processes such as wave overtopping and storm flooding. The potential impacts of RSLR on wave overtopping are assessed in Section 5 of this report.

3.4 Potential Impacts on Project Alternatives

Similar to the No Action Alternative, RSLR affects the flow climate and wave climate of other Alternatives, mostly by providing greater water depths. Sections 4 through 6 of this project include wave modeling, overtopping analysis, and hydrodynamic modeling of the No Action Alternative and Alternative 2 under present and future sea levels. The impact of RSLR on project alternatives is investigated in those Sections.

3.5 RSLR Analysis Conclusion

Total RSLR at Port Freeport is slightly greater that the average global sea level rise primarily due to land subsidence and regional oceanographic behavior of the Gulf of Mexico. Based on NOAA scenarios, the relative sea level rise is estimated to be between 0.96 feet and 3.66 feet for the period of 2020-2070. Similarly, USACE scenarios predict a relative sea level rise of between 0.71 feet and 2.68 feet for the same period. Following coordination with USACE Galveston District[3], and to maintain consistency with previous USACE studies in the region, a 50-year RSLR value of 1.18 feet was selected for this H&H analysis based on the USACE Intermediate curve.

[3] Discussions on selection of RSLR amount were provided by Michael Kauffman, U.S. Army Corps of Engineers Galveston District Michael.G.Kauffman@usace.army.mil

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4 Wave Analysis

The wave analysis utilized numerical modeling to compare extreme wave climate of the No Action Alternative to that of Alternative 2. Wave climate for each Alternative is modeled assuming an extreme storm event consisting of 100-year wind speed and 100-year water level using the STeady State spectral WAVE model (STWAVE), a software developed by the U.S. Army Corps of Engineers (USACE, 2011b). Modeling of each alternative was repeated with an increased still water level based on 50 years of RSLR. Because the construction of Alternative 2 requires partial removal of a wave barrier on the south side of the channel, this section also provides an evaluation of removing the wave barrier. The impacts are measured by determining with and without conditions of wave height, and period, plus estimates of overtopping of the Hurricane Protection Flood Levee later provided in Section 0.

4.1 History of the Freeport Harbor Wave Barrier

A hurricane protection system was proposed and constructed in the late 1960s including the south Freeport Harbor wave barrier. The wave barrier is a 9,500-feet long earthen levee (see Figure 10) having a minimum crest elevation of 16 feet and side slope of 6H: 1V. The intent of the wave barrier was to limit wave attack on the flood protection structures leeward of the barrier, and to preclude direct access of storm surges to the navigation channel thereby lessening water levels leeward of the barrier (USACE, 1967). Figure 10 shows the location of the wave barrier. The wave barrier appears to have been designed assuming no protection from the land mass occupied by the town of Quintana. Since these earlier studies, several changes have occurred to the barrier island in the form of development and placement of dredged materials from Freeport Harbor Channel and the GIWW, making for a much greater elevation on the island. As confirmed through numerical modeling performed as part of the current investigation, the increased land elevations at Quintana greatly reduce the wave impacts on the wave barrier, with emergent land expected to remain even during the design storm. With this increased protection, the wave analyses only had to look at locally generated waves, and not those that could be generated in the Gulf.

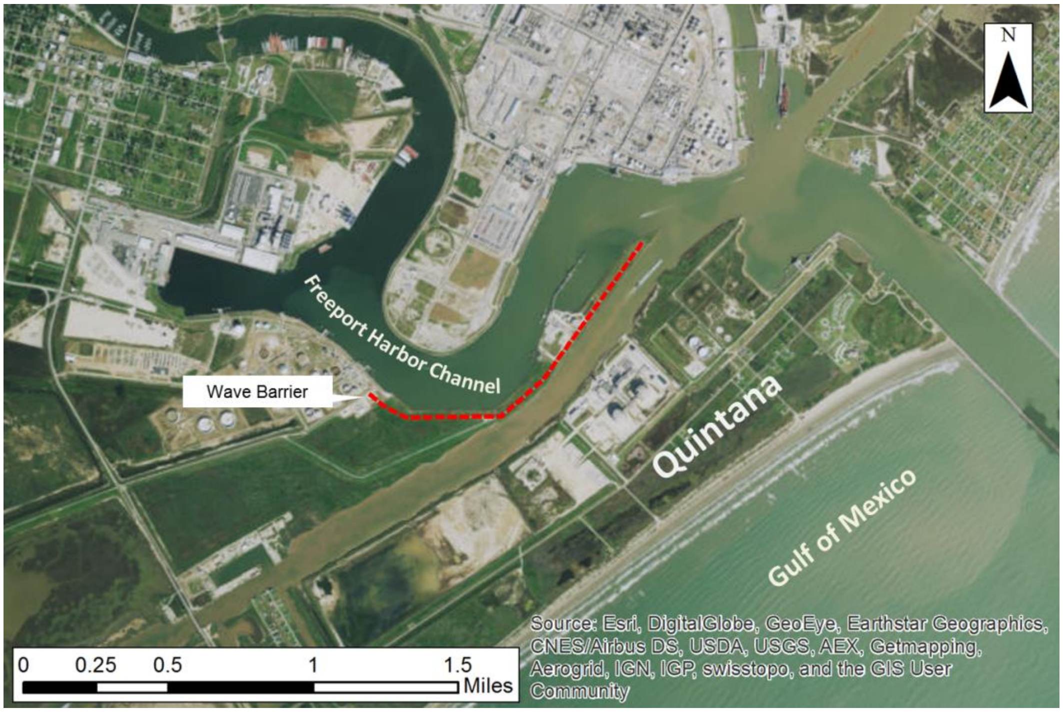

Figure 10 – Map of the Wave Barrier footprint

4.2 Metocean Conditions

Bathymetry, Water Surface Elevation (WSEL), and wind conditions were the primary metocean inputs for the STWAVE simulations. RSLR is also considered in the simulations for future conditions. Detailed information regarding the metocean input parameters is provided below.

4.2.1 Bathymetry and Topography

Bathymetry was obtained from an existing STWAVE model with 25-meter spacing provided by USACE[4]. To include accurate resolution of the flood protection features adjacent to the ship channel, the bathymetry was supplemented with LIDAR topography obtained from the United States Geological Survey (USGS, 2006). Figure 11 shows the bathymetry and topography used for the STWAVE model grid.

[4] Bathymetry from existing USACE model was provided to HDR by Chris Massey, Research Mathematician, ERDC-CHL-MS, Vicksburg, MS, on 8/24/2015.

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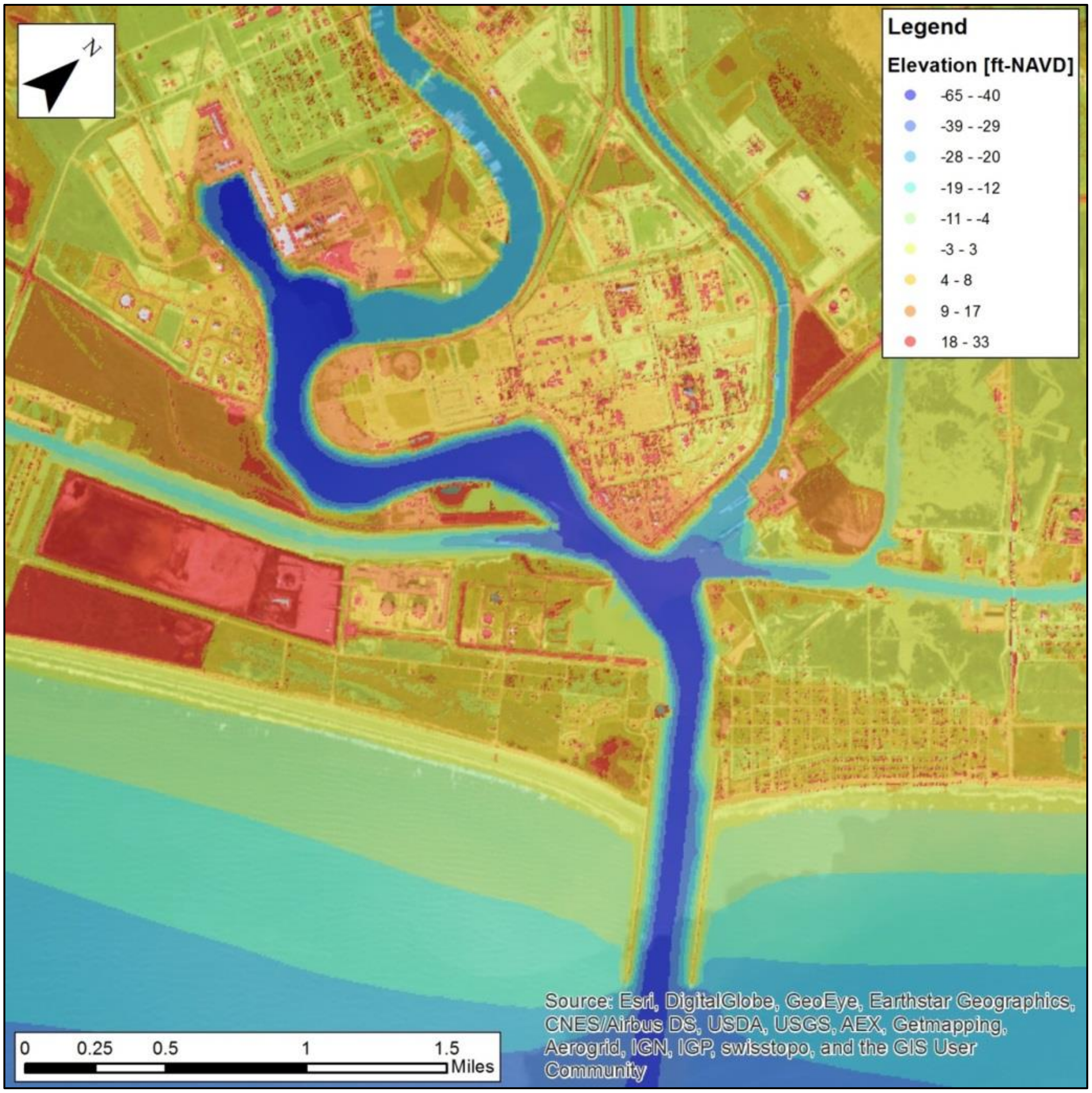

Figure 11 – Bathymetry and topography at Freeport Harbor (No Action Alternative)

4.2.2 Water Surface Elevation

A triangulated irregular network (TIN) database containing the Federal Emergency Management Agency's (FEMA's) 100-year still water elevations for Brazoria County was provided by Baker & Lawson[5]. The TIN was previously developed by FEMA in support of their most recent (still preliminary) Flood Insurance Study (FIS) and associated preliminary flood insurance rate maps. Based on this database the 100-year still water elevation at Port Freeport is approximately +13.2 feet NAVD. This elevation was applied as the 100-year still water elevation in the wave model.

[5] TIN for FEMA's 100-year still water elevation was provided to HDR by Mr. Herbert S. Smith, P.E., President, Baker & Lawson, Inc., Angleton, Texas on March 6, 2015.

4.2.3 Wind

The American Society of Civil Engineers (ASCE) has developed a 100-year wind speed map of the United States (ASCE, 2010). As shown in Figure 12, the 3-second 100-year wind speed near Port Freeport is approximately 127 mph. For wave generation modeling purposes, this wind speed was converted to 15-minute duration as 87 mph. The wave modeling was conducted by varying the wind direction in 22.5 deg increments from 0 deg to 337.5 deg clockwise from north.

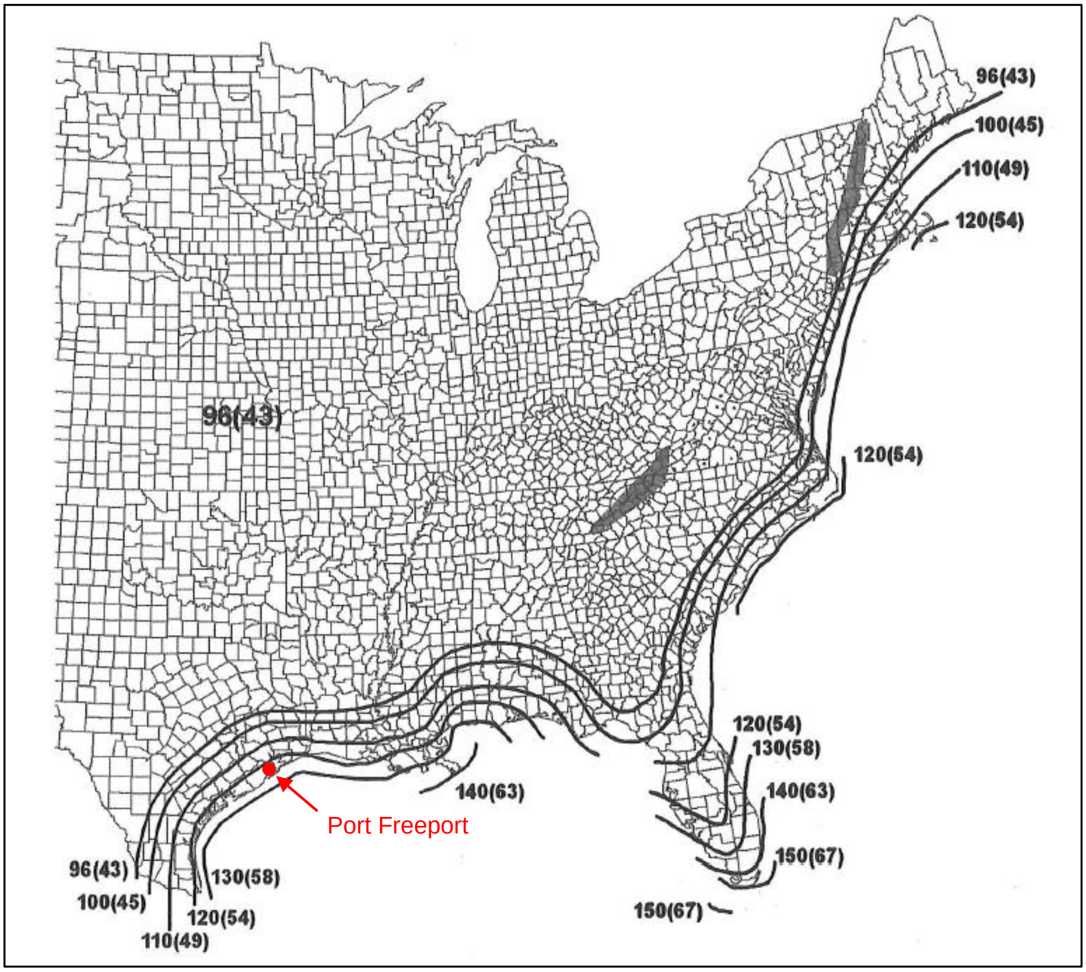

Figure 12 – ASCE 100-Year Wind Speed Map

Source: ACSE (2010)

4.2.4 Relative Sea Level Rise

Based on the results of Section 3 of this study, the model included a 50-year RSLR of 1.18 feet (i.e., a still water elevation of +14.4 feet NAVD) for simulation of future conditions.

4.2.5 Summary of Metocean Inputs

Two layouts, the No Action Alternative and Alternative 2, were simulated for present and future sea levels. A wind speed of 87 mph was applied to all directions (360° sweep in 22.5° increments). Table 5 contains summary of the modeled conditions.

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Table 5 – Summary of cases considered for STWAVE modeling

		Geometry Conditions	
		No Action Alternative	Alternative 2
Metocean Conditions	Current	100-year wind sweep, 100-year WSEL	100-year wind sweep, 100-year WSEL
	Future	100-year wind sweep, 100-year WSEL 50 years RSLR	100-year wind sweep, 100-year WSEL 50 years RSLR

4.3 Model Development

STWAVE was utilized to model waves under the conditions described earlier. STWAVE is a two-dimensional spectral model that solves for wave generation and propagation given user-specified bathymetry, water surface elevation and wind conditions. The Surface-water Modeling System (SMS) was used to setup, run, and plot the STWAVE simulations. SMS provides a graphical user interface for model pre-processing, processing and post-processing. Table 6 contains key details of the model setup. Figure 13 shows the extent of the STWAVE model domain.

Table 6 – General STWAVE Setup Details

Item	Details
X_0	964300.0 m
Y_0	4128375.0 m
Azimuth	142.0 deg
D_x[6] and D_y[7]	10 m
Number. of cells in x-direction	705
Number. of cells in y-direction	638
Surge	Spatially variable
Wind	Spatially constant

[6] Cell size in x-direction

[7] Cell size in y-direction

Figure 13 – Extents of STWAVE domain

It should be noted that the modeling simulations were conducted without bottom friction. Excluding roughness from wave models typically yields slightly larger waves and is common practice when calibration data is not available. This was deemed reasonable for the assessment of the relative change in wave height between the No Action Alternative and Alternative 2.

4.4 Wave Model Results

4.4.1 No Action Alternative

For the No Action Alternative, calculated significant wave heights (i.e. H_{m0}) generally did not exceed 4 feet within the area of interest. Peak wave periods (T_p) within the channel ranged from 2.5 to 3.5 seconds.

The maximum calculated H_{m0} at each cell (considering all wind directions) for the No Action Alternative is presented in Figure 14. Figure 15 contains plot of maximum H_{m0} along the channel centerline around Dow thumb (i.e. stations 132+67 to 186+91). Note that increases in the modeled wave heights under future sea level conditions were relatively small, generally less than about 0.1 feet. For reference, Figure 15 provides the location of channel stationing around Dow thumb.

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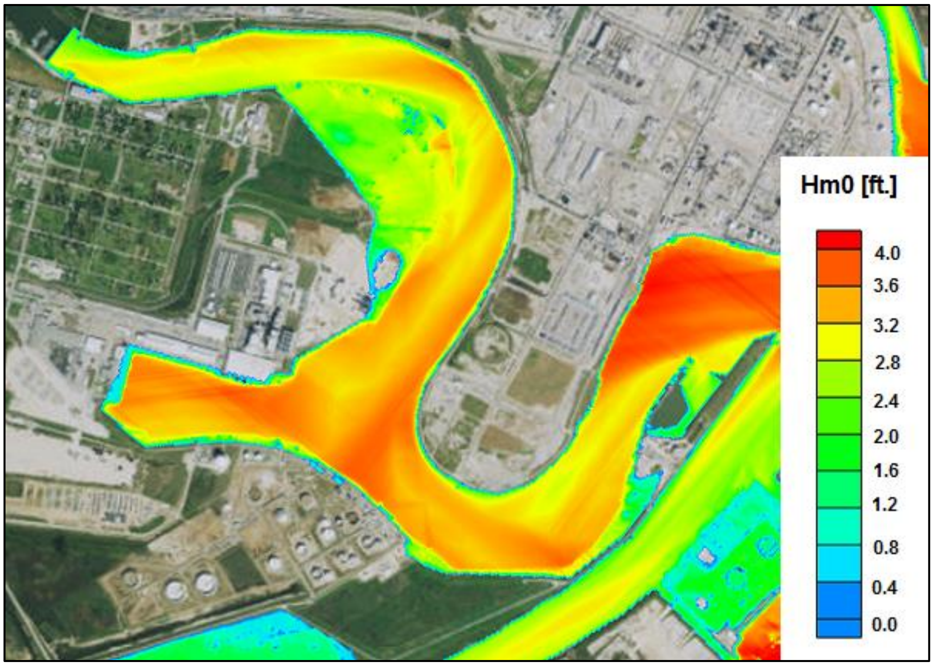

Figure 14 – Maximum of wave heights, No Action Alternative

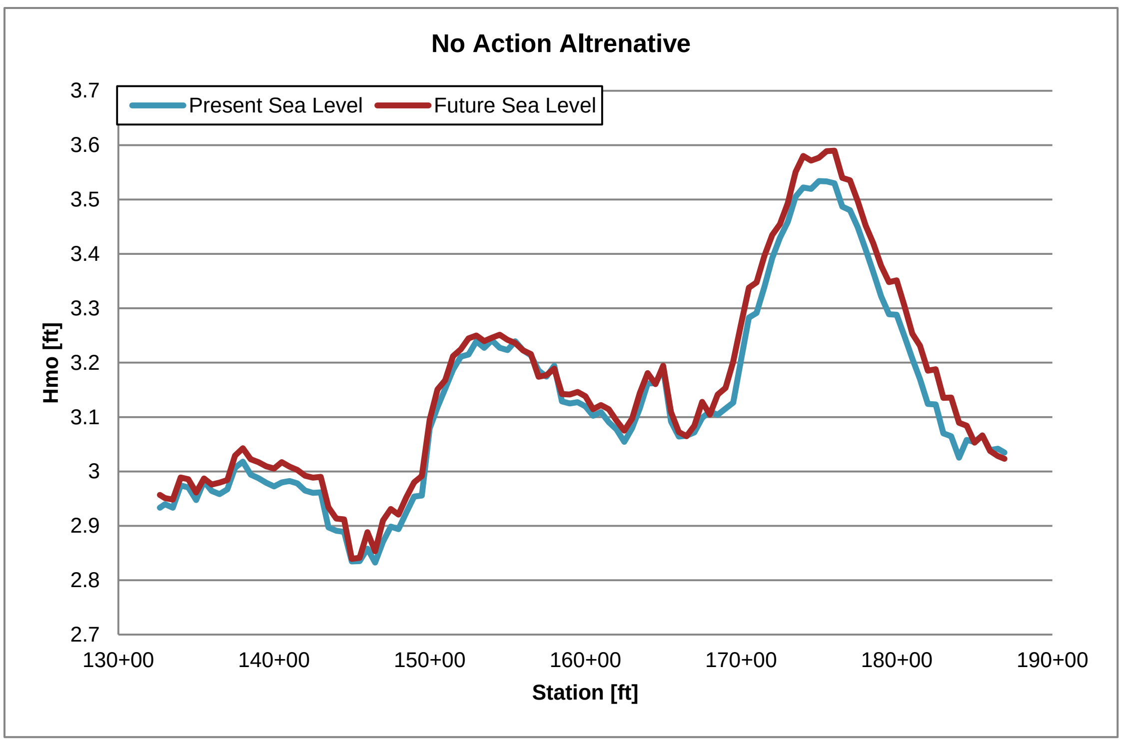

Figure 15 – H_{m0} sensitivity to RSLR: No Action Alternative

Figure 16 – Plot of channel centerline around Dow Thumb

4.4.2 Analysis of Alternative 2

Analysis of Alternative 2 indicates a potential for larger waves in various locations, especially southern Dow thumb, due to slight increase in the fetch from the Bend Easing. The potential increases are direction specific comparison of the maximum H_{m0} for the No Action Alternative and Alternative 2 along channel centerline is plotted in Figure 17 and Figure 18.. Visualized results of the wave model are provided in Appendix B.

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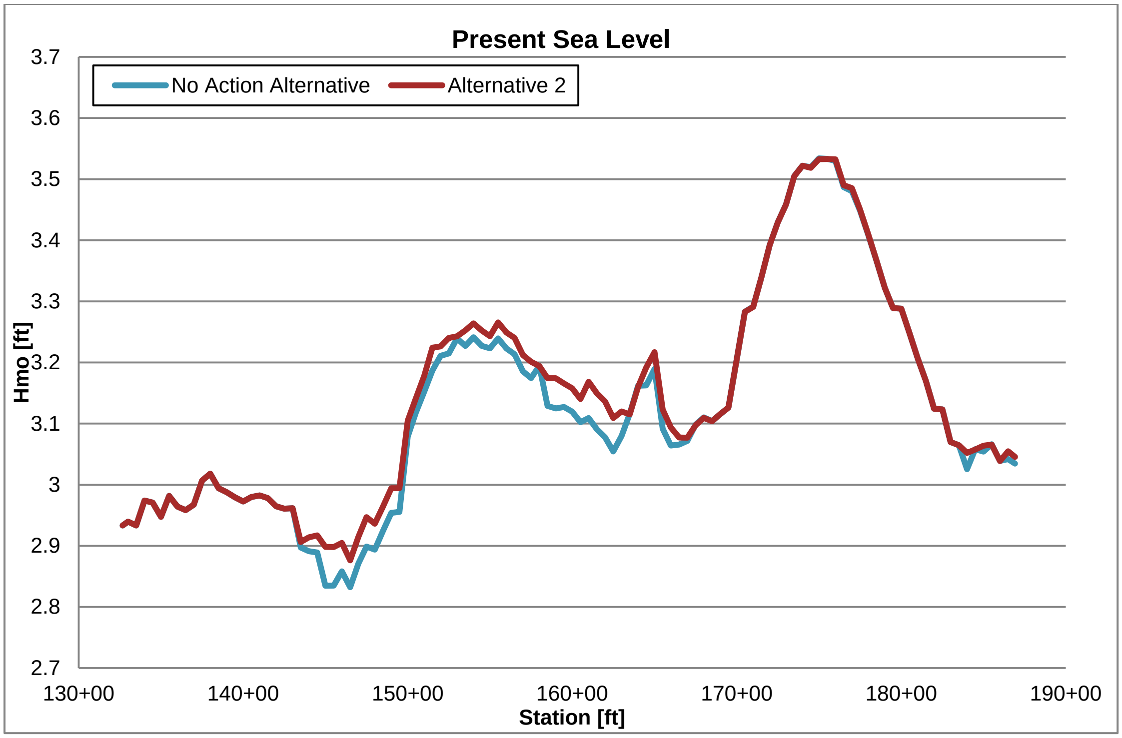


Figure 17 – Maximum simulated H_{m0} along Freeport Channel centerline, the No Action Alternative vs Alternative 2

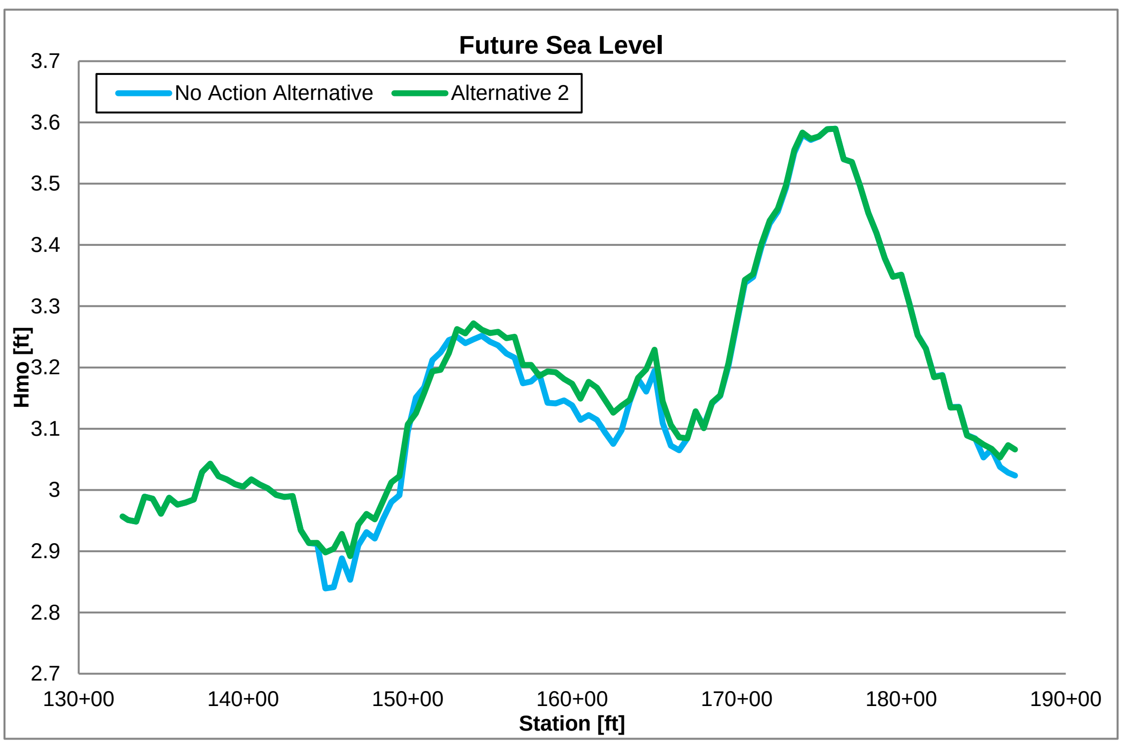


Figure 18 – Maximum simulated H_{m0} along Freeport Channel centerline, the No Action Alternative vs Alternative 2

4.4.3 Comparison of Model Results to Previous Studies

Based on previous experience modeling waves at Freeport Harbor and in other smaller-scale, limited-fetch basins, wave heights modeled using STWAVE appear to be over predicted. In particular, the relatively rapid rate of wave growth from the upwind boundary appears unrealistic for this basin configuration and wind condition. However, because the primary purpose of the model is to perform relative comparisons of waves for the various channel widening alternatives, conservative representation of the wave heights was judged to be acceptable. For the current assessment, STWAVE was preferred by USACE as the wave modeling software to be consistent with their larger scale modeling efforts. If detailed design is performed for any shoreline or flood protection improvements, an alternative wave modeling approach should be considered, if needed, to reduce design conservatism.

4.5 Wave Analysis Conclusion

Both sea level rise and implementation of Alternative 2 appear to slightly increase wave heights. While RSLR generally leads to a wave height increase over the entire domain, Alternative 2 only led to increase at Eastern Dow plant and Southern Stauffer Plant. Figure 19 presents the change in wave heights between the No Action Alternative and Alternative 2 for present sea level. It should be noted that a large increase is shown in the area of the bend easing because no waves exist with the No Action Alternative. Wave height increases as a result of Alternative 2 were modeled to be less than 0.1 ft. This study indicates that the increase in wave height based on Alternative 2 is driven by the increase in fetch length created by the Bend Easing feature.

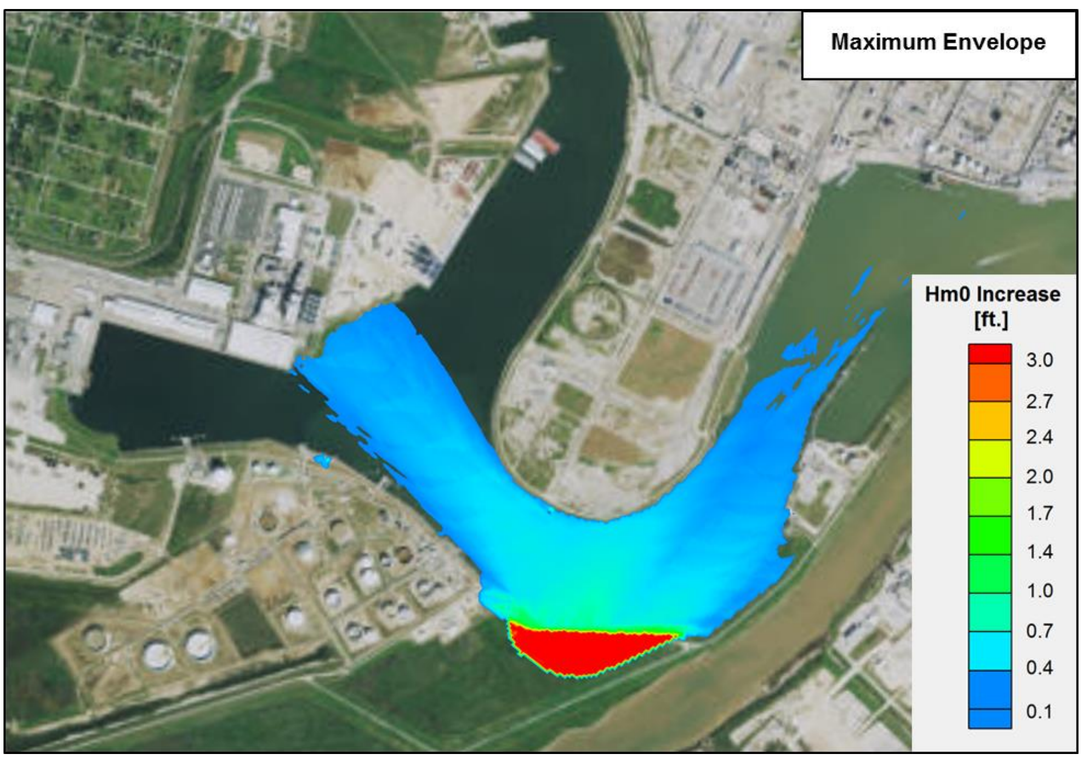


Figure 19 – Change in wave height Alternative 2 vs. No Action Alternative (Present Sea Level)

5 Wave Overtopping Analysis

The wave overtopping analysis includes an assessment of levees and floodwalls potentially affected by Alternative 2, for wave overtopping and resilience. The assessment includes an evaluation of the No Action Alternative and Alternative 2 assuming present and future sea levels. Figure 20 presents a map of Freeport Hurricane Flood Protection System.

5.1 Methodology

Overtopping discharge from wind-induced waves varies significantly depending on wave conditions (height, period, and direction) and water level. In the case of a tropical storm or hurricane, a small fraction of waves typically causes the majority of the overtopping. The overtopping discharge from a single wave can be over 100 times the overtopping discharge averaged over the storm peak (*USACE,* 2011a). Table 7 shows critical values for average overtopping discharge as published by in the USACE Coastal Engineering Manual (USACE, 2011a).

Based on lessons learned from Hurricane Katrina in 2005 as well as Dutch design guidelines, the USACE New Orleans District has published more conservative thresholds for average overtopping discharge over earthen levees (USACE, 2012c). The wave overtopping thresholds published in the Hurricane and Storm Damage Risk Reduction System Design Guidelines (HSDRRS) are shown in Table 8.

The following methodology was followed to assess the existing levees and flood protection structures around Freeport Harbor Channel for wave overtopping:

1. Statistical values for a 100-year wind speed and 100-year still water elevation were determined.
2. RSLR values were estimated and used to define future sea levels (Section 3).
3. Wave climate was modeled assuming the No Action Alternative and Alternative 2 with present and future sea levels (Section 4).
4. Potential areas vulnerable to wave overtopping were determined based on fetch increase as a result of Alternative 2, and observation points were setup in the mode along such areas.
5. Wave climate (height, period, and direction) at observation points were extracted from the wave model.
6. Average overtopping discharge was calculated at each location for both layouts and both sea levels.

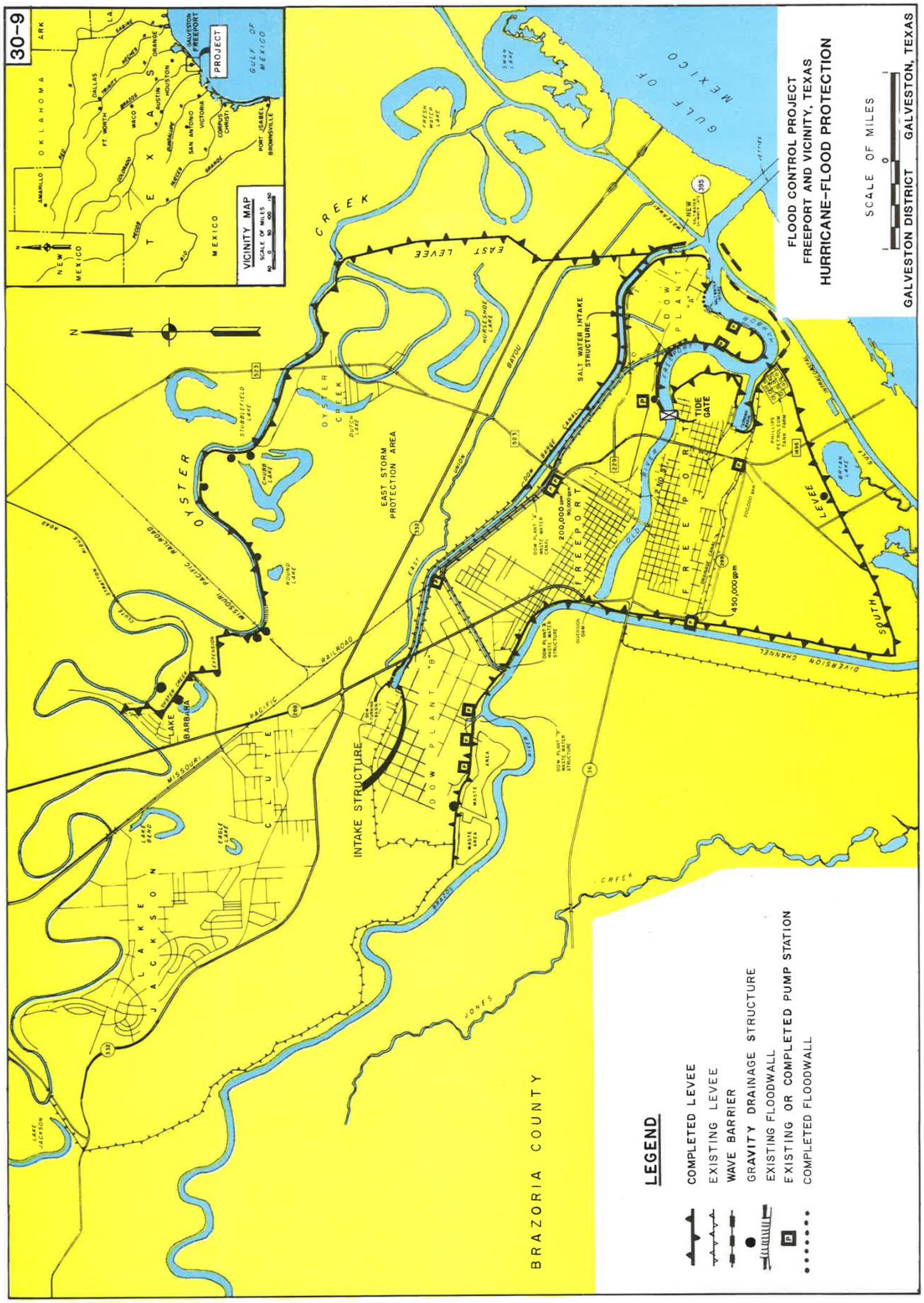
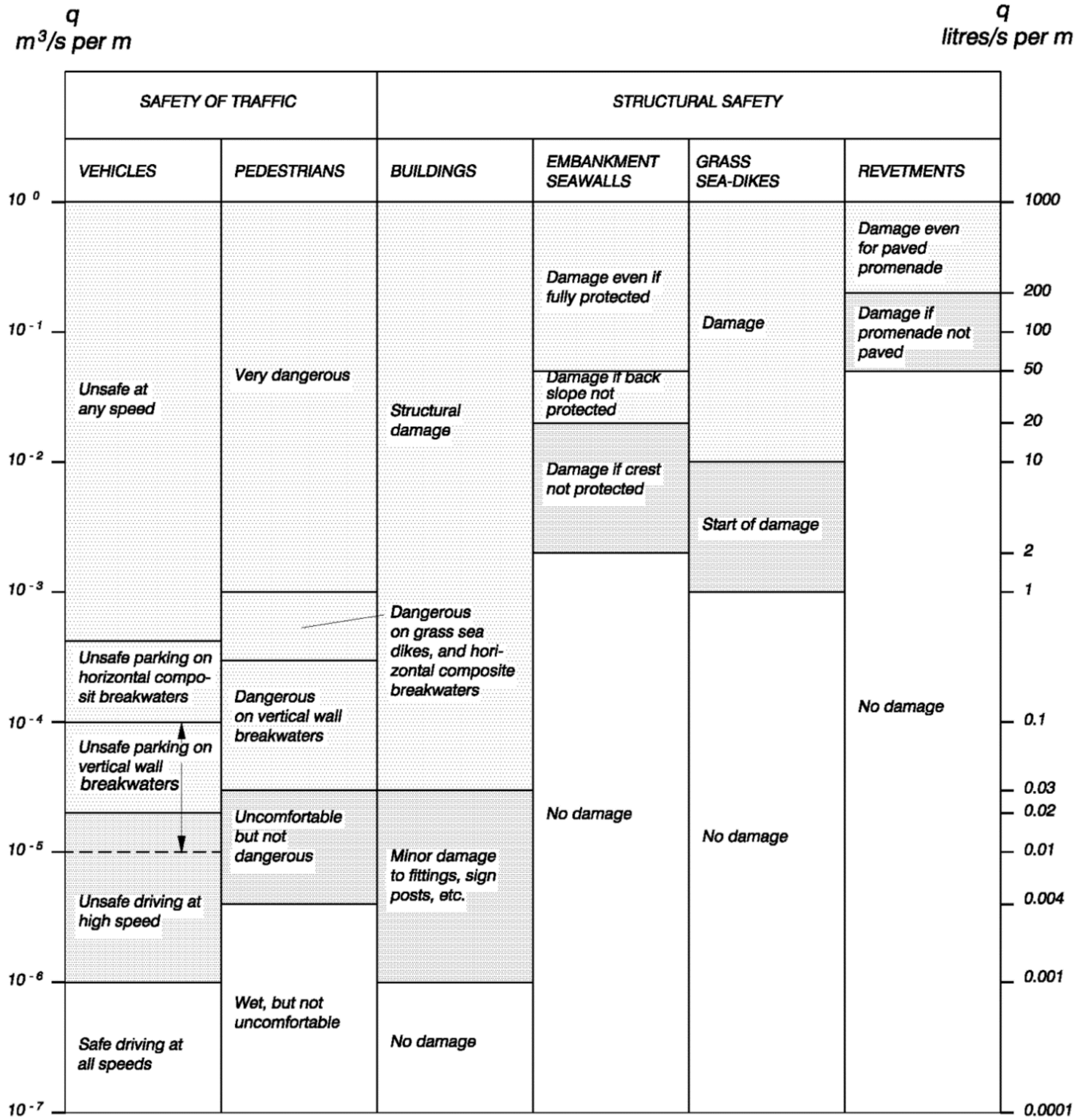


Figure 20 – Map of Freeport Hurricane Flood Protection

Table 7 – Critical values for average overtopping discharge



Source: USACE (2011a)

Table 8 – Threshold for average overtopping discharge over earthen levees

Cover Type	Threshold for average overtopping discharge	
	q (cfs/ft)	q (l/s/m)
Sandy soil with a poor grass cover	0.001	0.028
Clayey soil with a reasonably good grass cover	0.01	0.28
Clay covering and a grass cover for an armored inner slope	0.1	2.8

Source: USACE (2012c)

5.2 Present and Future Sea Levels

The 100-year design water level for present (2016) conditions was defined as +13.2 feet NAVD88 as explained in Section 4.2.2. A future design water level of +14.4 feet was calculated by adding RSLR to the present water level. A 50-year RSLR of 1.18 feet was determined based on the USACE Intermediate Curve for RSLR projections as explained in Section 3. Due to relatively short fetch, the wind setup was determined negligible.

5.3 Extreme Wave Climate

Local extreme wind-induced waves for the No Action Alternative and Alternative 2 for both present and future sea levels were modeled in STWAVE. Waves were modeled for wind directions varying 360 degrees in 22.5 degree increments. For additional information on the wave modeling refer to Section 4.

5.4 Development of Observation Points

Locations of potential wave overtopping were identified as locations where construction of a particular alternative (i.e. Alternative 2) would cause the wave fetch to increase. Based on the proposed alternatives, the southern extents of the Dow thumb and the southern extent of the Stauffer terminal were identified as potentially-impacted areas. Nine data extraction points, shown in Figure 21, were selected within those areas and levee/structure cross sections were extracted for each point using readily-available USGS LIDAR imagery from 2006. Note that a site-specific survey of the flood protection levee and other coastal structures was not performed for this effort. Table 9 provides additional detail regarding the location and structures along the areas of interest.

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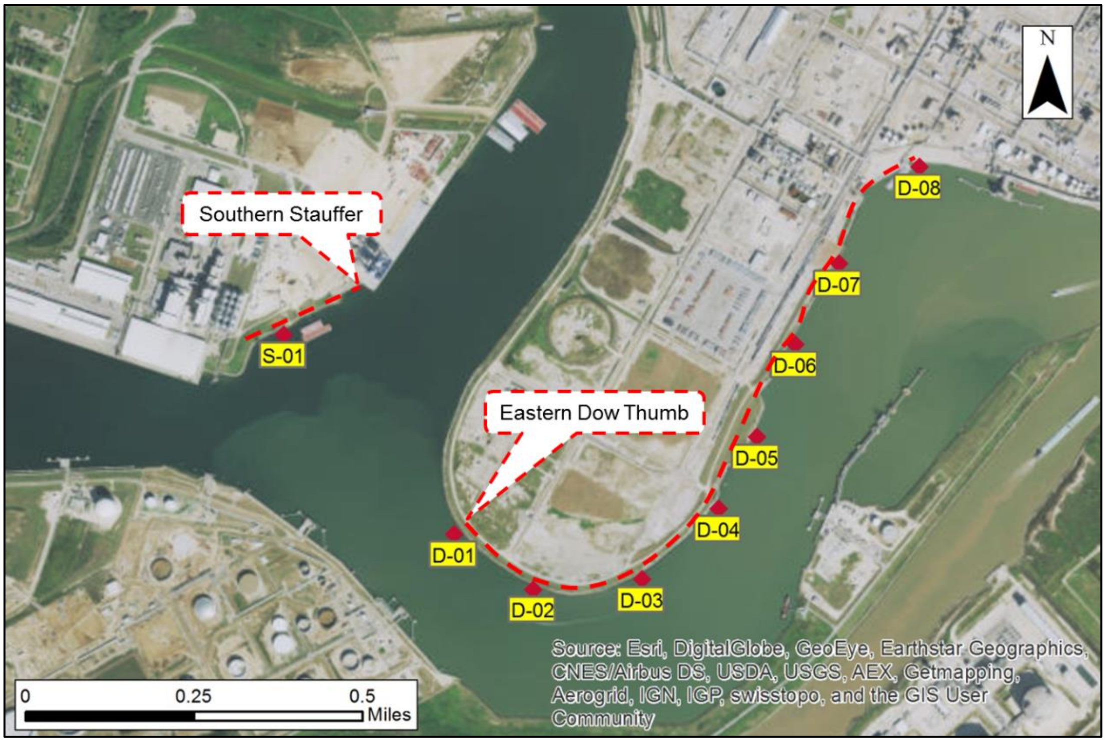

Figure 21 – Location of areas of interest and observation points.

Table 9 – Coordinates for observation points

Name	Location	Northing [US Survey ft]	Easting [US Survey ft]	Protection Structure
D-01*	Dow Chemical	13542647	3142213	Levee with Bermed Slope
D-02*	Dow Chemical	13542248	3142851	Levee with Bermed Slope
D-03*	Dow Chemical	13542370	3143696	Levee with Bermed Slope
D-04*	Dow Chemical	13542953	3144270	Levee with Bermed Slope
D-05†	Dow Chemical	13543528	3144538	Floodwall
D-06*	Dow Chemical	13544266	3144802	Levee with Bermed Slope
D-07†	Dow Chemical	13544917	3145110	Floodwall
D-08†	Dow Chemical	13545703	3145701	Floodwall
S-01‡	Stauffer Chemical	13544137	3140802	Levee with Uniform Slope

* Later referred to as "*Levee system protecting Dow Plant*"
† Later referred to as "*Levee system protecting Stauffer Plant*"
‡ Later referred to as "*Floodwall system protecting Dow Plant*"

Review of the available LIDAR data indicated that five of the locations, D-01, D-02, D-03, D-04 and D-06, representing the levee system adjacent to the Dow facility, were all bermed slopes with similar geometry. Three locations, D-05, D-07, and D-08, representing a floodwall system adjacent to the Dow facility, consisted of floodwall structures with a crest elevation of approximately +16 feet NAVD. One location, S-01, representing the levee adjacent to the Stauffer facility, was a uniformly-sloped (i.e., no berm) levee. All ground cover at the levees was considered to be "sandy soil with a poor grass cover" when evaluating the overtopping thresholds listed in Table 2. Figure 22 and Figure 23 show representative cross sections of levees based on the LIDAR data.

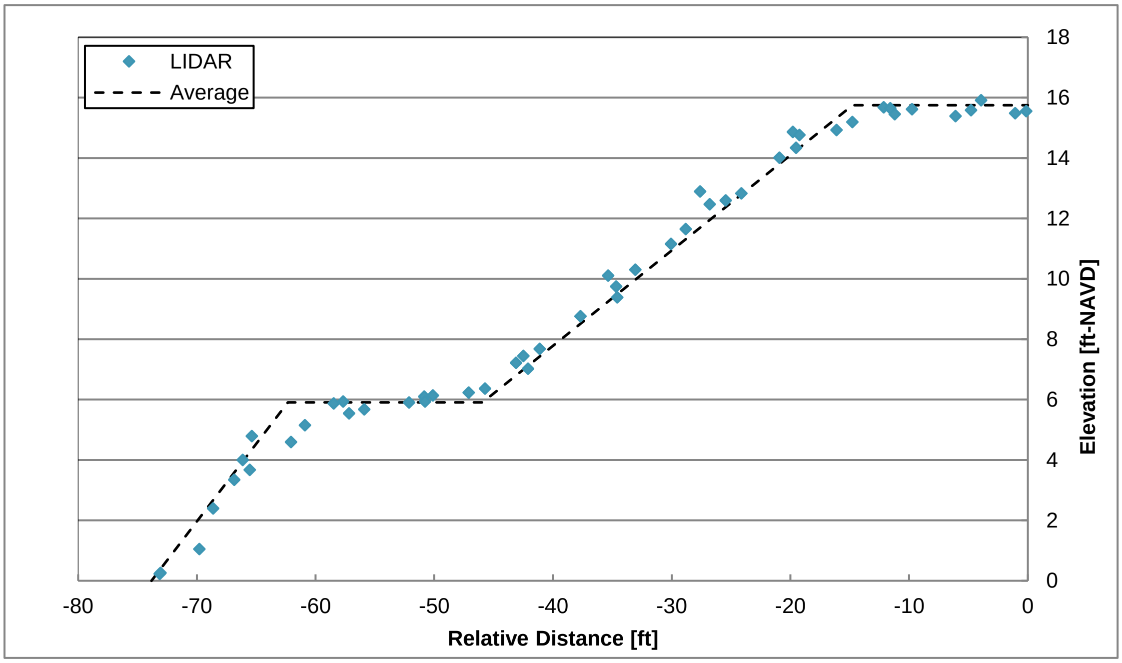

Figure 22 – Representative cross-section for levee system protecting Dow plant

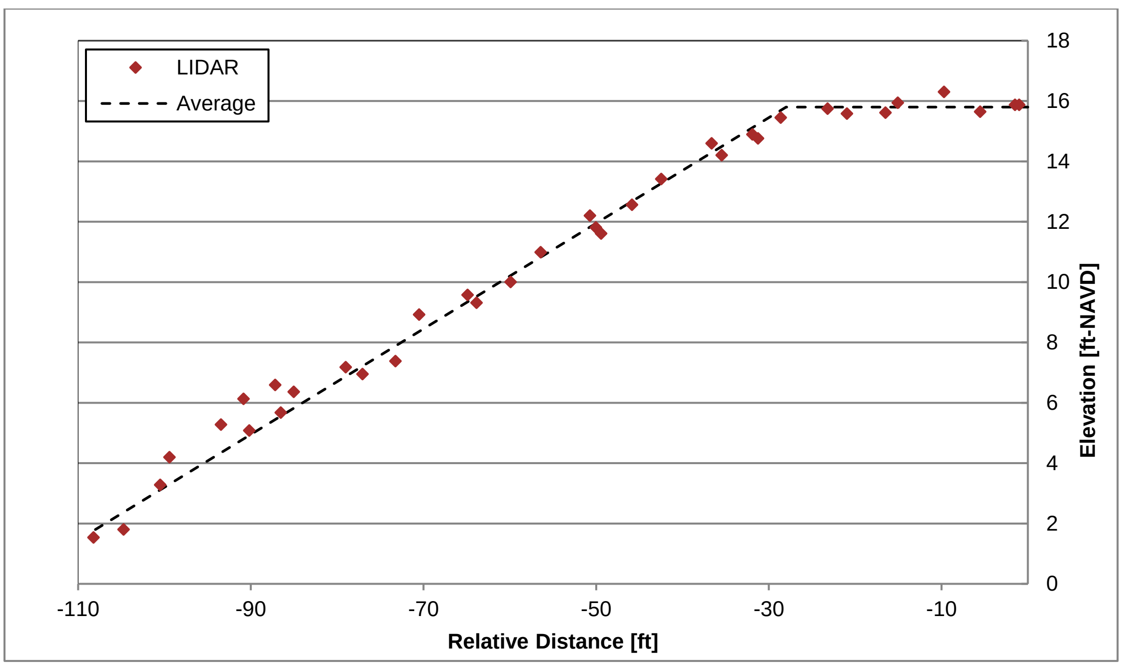

Figure 23 – Representative cross-section for levee system at Stauffer plant (S-01)

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5.5 Wave Climate at Observation Points

Wave heights and periods at each observation point were extracted from the wave model. The wave modeling task included a full wind sweep in 22.5 degree increments, allowing wave calculations for 16 wind directions. The maximum H_{m0} and corresponding wind direction varied based on the location. Table 10 and Table 11 present the maximum H_{m0} (maximum of H_{m0} for all wind directions) and associated Tp calculated for each point based on the No Action Alternative and Alternative 2, respectively.

As shown in Table 11, wave conditions for Alternative 2 are equal to the wave heights for the No Action Alternative shown in Table 10, except for two locations, D-02 and D-03. Both of these locations have a wave height increase of only 0.1 feet.

It should be noted that the STWAVE results appear to be conservative compared to previous modeling studies at Freeport Harbor. However, the intent of this task is relative comparison of cases rather than quantifying the actual rate of overtopping. Additional wave analysis is recommended if less conservative wave overtopping values are required (e.g., for comparison against overtopping thresholds listed in Table 7 and Table 8).

Table 10 – Extreme incident wave climate by location for the No Action Alternative

	Present Sea Level			Future Sea Level		
Observation Point	Maximum H_{m0} [ft]	Maximum Tp [s]	Wind Direction	Maximum H_{m0} [ft]	Maximum Tp [s]	Wind Direction
D-01	3.1	2.9	W	3.2	3.0	W
D-02	2.3	2.8	S	2.4	3.1	S
D-03	2.5	2.9	E	2.6	2.9	E
D-04	2.8	2.9	ENE	2.8	3.0	ENE
D-05	3.1	3.1	ENE	3.1	3.1	ENE
D-06	3.2	3.1	E	3.3	3.1	E
D-07	2.7	3.5	E	2.8	3.4	E
D-08	3.1	2.9	S	3.1	3.1	S
S-01	3.1	2.9	SSE	3.1	3.1	SSE

Note: Wind directions represent controlling condition for generation of largest waves.

Table 11 – Extreme incident wave climate by location for Alternative 2

	Present Sea Level			Future Sea Level		
Observation Point	Maximum H_{m0} [ft]	Maximum Tp [s]	Wind Direction**	Maximum H_{m0} [ft]	Maximum Tp [s]	Wind Direction**
D-01	3.1	2.9	W	3.2	3.0	W
D-02	2.5*	2.8	S	2.6*	3.1	S
D-03	2.6*	2.9*	S*	2.6	2.9	S*
D-04	2.8	2.9	ENE	2.8	3.0	ENE
D-05	3.1	3.1	ENE	3.1	3.1	ENE
D-06	3.2	3.1	E	3.3	3.1	E
D-07	2.7	3.5	E	2.8	3.4	E
D-08	3.1	2.9	S	3.1	3.1	S
S-01	3.1	2.9	SSE	3.1	3.1	SSE

* Indicates change compared to the No Action Alternative
** Wind directions represent controlling condition for generation of largest waves. For some locations the controlling wind direction varied between the No Action Alternative (Table 10) and Alternative 2 (Table 11).

5.6 Overtopping Assessment – No Action Alternative

Analysis of the No Action Alternative included calculation of average overtopping discharge at each observation point for the wave conditions presented in Table 10. Average overtopping discharge was calculated using applicable methods with corresponding H_{m0}, Tp, WSEL and the structure geometry of each location. While there are various methods outlined in the Coastal Engineering Manual (USACE, 2011a) for calculation of wave overtopping, methods are applicable on case-specific bases such as type of structure, freeboard, and incident wave conditions. Table 12 contains a summary of utilized overtopping formulations and their applicability. Calculated average overtopping discharge at each location for the No Action Alternative is provided in Table 13.

Table 12 – Utilized formulae for calculation of average overtopping discharge

Author	Structure	Overtopping model	Non-dimensional discharge, *Q*	Non-dimensional Freeboard, *R*	Applicability Range
Owen (1980, 1982)	Impermeable smooth, rough, straight and bermed slopes.	$Q = a\exp(-b\,R)$	$\frac{q}{g\,H_s\,T_{om}}$	$\frac{R_C}{H_S}\left(\frac{S_{om}}{2\pi}\right)^{0.5}\frac{1}{\gamma}$	$0.05 < R < 0.3$
Allsop et al. (1995)	Vertical wall with or without perforated front	$Q = a\exp(-b\,R)$	$\frac{q}{\sqrt{g\,H_s^3}}$	$\frac{R_C}{H_S}\frac{1}{\gamma}$	$R < 0.91$
Franco et al. (1994)	Vertical wall with or without perforated front	$Q = a\exp(-b\,R)$	$\frac{q}{\sqrt{g\,H_s^3}}$	$\frac{R_C}{H_S}\frac{1}{\gamma}$	$R > 0.91$

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Table 13 – Average overtopping discharge by method and location, No Action Alternative

		Present Sea Level			Future Sea Level		
Observation Point	Structure Type*	Applicable Method	q [cfs/ft]	q [l/s/m]	Applicable Method	q [cfs/ft]	q [l/s/m]
D-01	L	Owen (1980, 1982)	0.00004	0.004	Owen (1980, 1982)	0.011	0.983
D-02	L	Owen (1980, 1982)	0.000002	0.000	Owen (1980, 1982)	0.004	0.384
D-03	L	Owen (1980, 1982)	0.00001	0.001	Owen (1980, 1982)	0.004	0.326
D-04	L	Owen (1980, 1982)	0.00002	0.002	Owen (1980, 1982)	0.006	0.575
D-05	F	Allsop et al. (1995)	0.15	14.222	Allsop et al. (1995)	0.441	40.976
D-06	L	Owen (1980, 1982)	0.0001	0.01	Owen (1980, 1982)	0.015	1.378
D-07	F	Franco et al. (1994)	0.08	7.680	Allsop et al. (1995)	0.331	30.747
D-08	F	Allsop et al. (1995)	0.15	14.222	Allsop et al. (1995)	0.441	40.976
S-01	L	Owen (1980, 1982)	0.00005	0.005	Owen (1980, 1982)	0.014	1.296

* "L" = Levee, "F" = Floodwall

5.7 Overtopping Assessment – Alternative 2

It is important to note that although the geometry of Freeport Harbor Channel is proposed to change for Alternative 2, for the purposes of this assessment, all levees and flood protection structures are assumed to remain in their current configurations and geometries. Thus, any changes in overtopping rates determined herein are due to change in wave conditions and base water elevation.

As previously mentioned, wave conditions for Alternative 2 slightly increased at two observation points (D-02 and D-03). Therefore, average overtopping discharge for Alternative 2 was expected to increase at those points. Table 14 presents calculated average overtopping discharges for Alternative 2.

Table 14 – Average overtopping discharge by method and location, Alternative 2

		Present Sea Level			Future Sea Level		
Observation Point	**Structure Type****	**Applicable Method**	**q [cfs/ft]**	**q [l/s/m]**	**Applicable Method**	**q [cfs/ft]**	**q [l/s/m]**
D-01	L	Owen (1980, 1982)	0.00004	0.004	Owen (1980, 1982)	0.011	0.983
D-02	L	Owen (1980, 1982)	0.00001*	0.001*	Owen (1980, 1982)	0.006*	0.537*
D-03	L	Owen (1980, 1982)	0.00001	0.001	Owen (1980, 1982)	0.004	0.326
D-04	L	Owen (1980, 1982)	0.00002	0.002	Owen (1980, 1982)	0.006	0.575
D-05	F	Allsop et al. (1995)	0.15	14.222	Allsop et al. (1995)	0.441	40.976
D-06	L	Owen (1980, 1982)	0.0001	0.010	Owen (1980, 1982)	0.015	1.378
D-07	F	Franco et al. (1994)	0.08	7.680	Allsop et al. (1995)	0.331	30.747
D-08	F	Allsop et al. (1995)	0.15	14.222	Allsop et al. (1995)	0.441	40.976
S-01	L	Owen (1980, 1982)	0.00005	0.005	Owen (1980, 1982)	0.014	1.296

* Indicates increase compared to the No Action Alternative
** “L” = Levee, “F” = Floodwall

5.8 Wave Overtopping Analysis Conclusion

Table 15 shows the increases that RSLR could cause to wave overtopping for both the No Action Alternative and Alternative 2. Although RSLR is unlikely to cause a significant increase in wave heights, by increasing the base WSEL and decreasing freeboard, RSLR may cause the average overtopping discharges to increase by up to 0.3 cfs/feet in some locations.

Table 16 compares the average overtopping discharges between the No Action Alternative and Alternative 2. Increasing the channel width as proposed for Alternative 2 would result in slight increases to average overtopping discharges in two locations (i.e. D-02 and D-03); however, the increases are relatively minor and were judged to be insignificant from the standpoint of increasing the vulnerability to potential flooding.

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Table 15 – Sensitivity of overtopping to Relative Sea Level Rise

		No Action Alternative			Alternative 2		
		q [cfs/ft]			q [cfs/ft]		
Observation Point	Structure Type*	Present Sea Level	Future Sea Level	Difference	Present Sea Level	Future Sea Level	Difference
D-01	L	0.00004	0.011	0.011	0.00004	0.011	0.011
D-02	L	0.000002	0.004	0.004	0.00001	0.006	0.006
D-03	L	0.000009	0.004	0.004	0.00001	0.004	0.003
D-04	L	0.00002	0.006	0.006	0.00002	0.006	0.006
D-05	F	0.15	0.441	0.29	0.15	0.441	0.288
D-06	L	0.0001	0.015	0.015	0.0001	0.015	0.015
D-07	F	0.08	0.331	0.248	0.08	0.331	0.248
D-08	F	0.15	0.441	0.288	0.15	0.441	0.290
D-09	L	0.00005	0.014	0.014	0.00005	0.014	0.014

* “L” = Levee, “F” = Floodwall

Table 16 – Sensitivity of overtopping to channel configuration

		Present Sea Level			Future Sea Level		
		q [cfs/ft]			q [cfs/ft]		
Observation Point	Structure Type*	No Action Alternative	Alternative 2	Difference	No Action Alternative	Alternative 2	Difference
D-01	L	0.00004	0.00004	0	0.011	0.011	0
D-02	L	0.000002	0.00001	0.000008	0.004	0.006	0.002
D-03	L	0.000009	0.00001	0.000001	0.004	0.004	0
D-04	L	0.000020	0.00002	0	0.006	0.006	0
D-05	F	0.15	0.15	0	0.441	0.441	0
D-06	L	0.0001	0.0001	0	0.015	0.015	0
D-07	F	0.08	0.08	0	0.331	0.331	0
D-08	F	0.15	0.15	0	0.441	0.441	0
D-09	L	0.000049	0.00005	0	0.014	0.014	0

* “L” = Levee, “F” = Floodwall

6 Hydrodynamic Analysis

The hydrodynamic analysis includes an evaluation of the No Action Alternative and Alternative 2 comparing current velocities and water surface elevations for typical non-storm conditions. Numerical modeling of hydrodynamics in Freeport Harbor Channel was performed for the No Action Alternative and Alternative 2 with present and future sea levels to consider the potential effects of Relative Sea Level Rise (RSLR).

The flow module of the Coastal Modeling System, known as CMS-Flow, was utilized as the modeling software to accomplish this task. Developed by the U.S. Army Corps of Engineers, CMS-Flow is a 2D hydrodynamic model that solves for continuity, momentum and transport equations (USACE, 2012a). The program discretizes the domain on a structured Cartesian grid system with the ability to run in parallel computation environments.

6.1 Methodology

The following methodology was applied to accomplish the hydrodynamic analysis:

1. A hydrodynamic numerical model was developed for Freeport Harbor Channel.
2. Hydrodynamic simulations were performed for the No Action Alternative for the period from 6/16/2013 to 6/30/2013. The model was calibrated to achieve the desired accuracy.
3. The model was then modified to represent Alternative 2. The new layout was simulated for the same time period.
4. Both layouts (the No Action Alternative and Alternative 2) were simulated for the same period with RSLR added to reflect future sea level conditions.
5. Model outputs were compared to determine flow changes associated with Alternative 2 and investigate possible effects of RSLR.

6.2 Relative Sea Level Rise

Based on the results of Section 3 of this study, a 50-year RSLR of 1.18 feet was applied in the model for simulation of future conditions.

6.3 Bathymetry and Topography

Bathymetry within the domain was obtained from an existing USACE STWAVE model with 25-meter spacing provided by USACE[8]. It should be noted that due to simulation of regular non-storm hydrodynamics, land flooding is not expected to occur. Therefore, cells covering land were excluded from the simulations. For more information on bathymetry, refer to Section 4.2.1.

[8] Bathymetry from existing USACE model was provided to HDR Inc. by Chris Massey, Research Mathematician, ERDC-CHL-MS, Vicksburg, MS, on 8/24/2015.

6.4 Grid Generation

SMS was utilized to setup, run, and plot the CMS-Flow simulations. The model grid was developed with a cell size of 10 meters providing over 226,000 cells. Figure 24 shows the CMS-Flow grid.

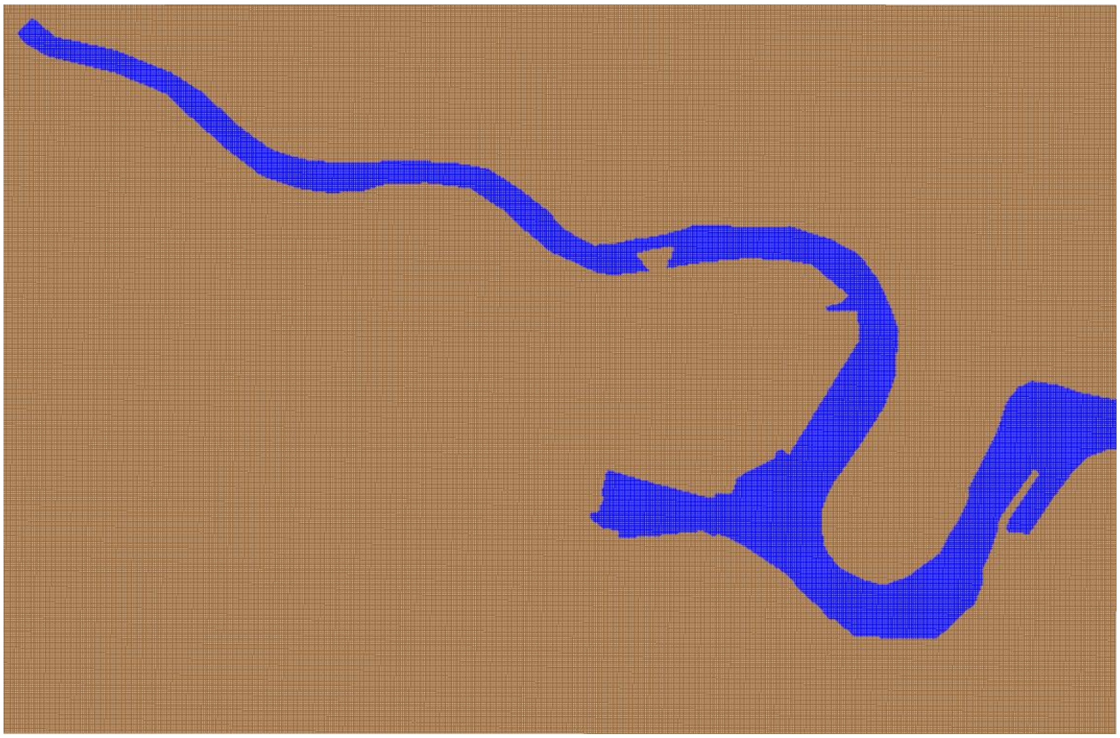

Figure 24 – CMS-Flow No Action Alternative grid

Note: Due to small cell size, cell surfaces are not visible

6.5 Boundary Conditions

Time series of either water level or discharge can be used as open boundary conditions in CMS-Flow. Water level measurements from NOAA Station 8772447 were utilized as input for the model. Figure 25 presents the location of the station relative the project location. As seen in Figure 25, the selected station is not precisely located at the open boundary. However, its measurements were considered representative of those at the open boundary based on its close proximity. When running simulations under future sea level, the water levels at the open boundary were increased by the amount of calculated RSLR as discussed in Section 2.

As an example of water levels typically experienced near the project site, a plot of water levels during year 2013 is presented in Figure 26. Although daily water levels typically remain within -2.0 to +2.0 feet NAVD, seasonal water levels (excluding tropical storms and hurricanes) exceed this range, with mean water levels typically trending higher in the fall and spring and lower in the winter and summer.

Figure 25 – Location of NOAA water level gauge used for open boundary

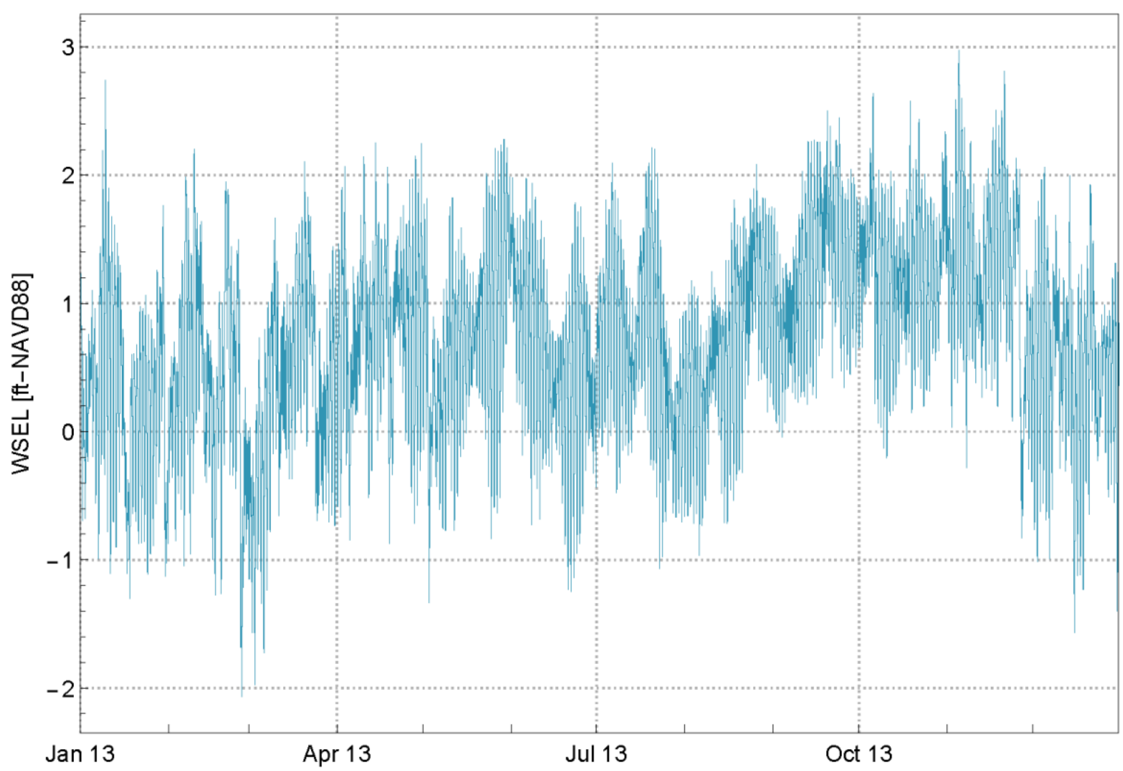

Figure 26 – Water level plot of NOAA Station 8772447 during calendar year 2013

Due to disconnection of Freeport Harbor Channel from the Brazos River, the upstream boundary was modeled as being closed. The model domain was extended all the way upstream to cover the entire channel length and capture the related storage effects.

Due to unavailability of hydrodynamic measurements in the Gulf Intracoastal Waterway (GIWW), the model's open boundary was placed inland of the GIWW, thereby eliminating the need to include the GIWW in the model. This simplification may affect accuracy of the flow patterns close to the boundary near the GIWW. However, water levels are expected to be relatively accurate at the boundary given the close distance of the boundary from the NOAA tide station (refer to Figure 25) selected for model forcing. Furthermore, because this task is focused on relative comparisons between the No Action Alternative and proposed improvements within the inner harbor, precise representation of flow patterns at the intersection between Freeport Channel and the GIWW is not required.

6.6 Roughness

CMS-Flow offers various input options for defining roughness to represent bottom friction. The most common method to express roughness in hydrodynamic modeling is through application of Manning's n coefficient. A Manning's n of 0.02 was determined appropriate for this case (Phillips et al., 2006). CMS-Flow can incorporate spatially variable roughness coefficients. However, it was assumed that the bed material is uniform. Thus, a Manning's coefficient of 0.02 was applied as spatially constant over the whole domain.

6.7 Wind Conditions

Due to the relatively small model domain, it was assumed that the local wind setup is already captured in water level measurements applied for model forcing at the open boundary. As a result, wind forcing was not included in the hydrodynamic model.

6.8 Development of Observation Points

To compare results of each modeling scenario, five observation points were established within the model domain. Model output including WSEL and current magnitude were compared to determine differences caused by RSLR as well as layout change to Alternative 2. Table 17 contains coordinates of the established observation points. Figure 27 presents a map of the points.

Table 17 – Coordinates of hydrodynamic observation points

Point ID	Easting (US survey ft) Texas South Central	Northing (US survey ft) Texas South Central
OB1	3145820	13545156
OB2	3144967	13543581
OB3	3143290	13541744
OB4	3141391	13543453
OB5	3142572	13545255

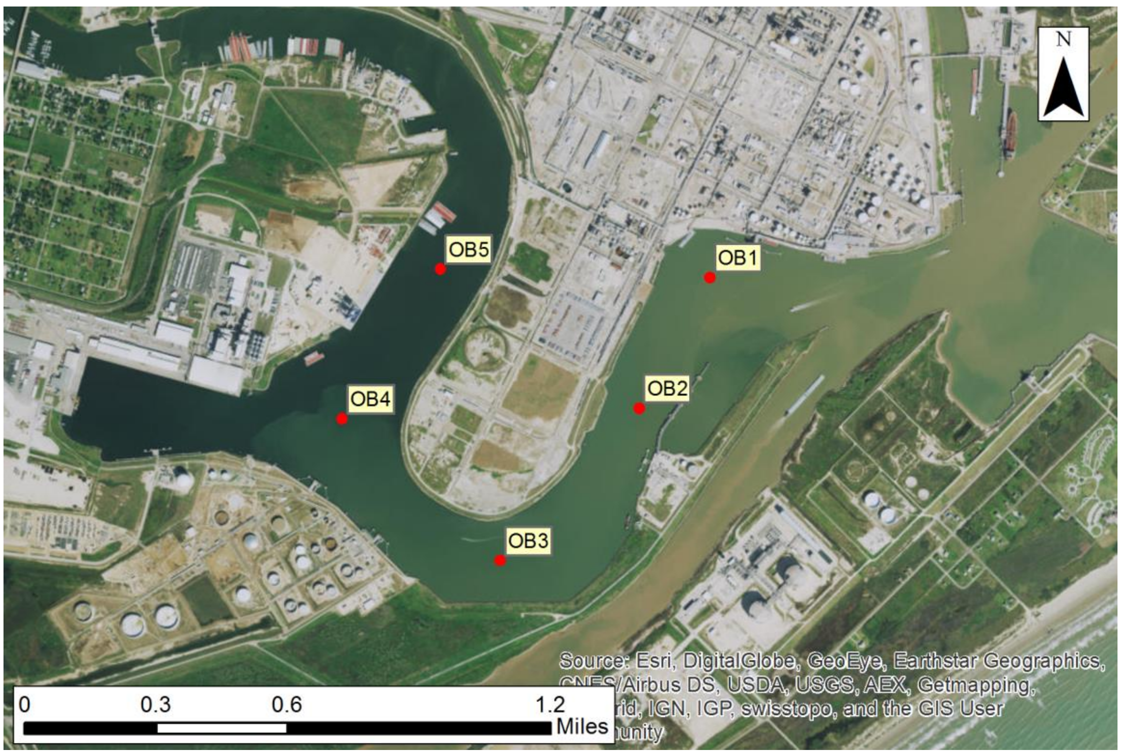

Figure 27 – Map of hydrodynamic observation points

6.9 Modeling of the No Action Alternative

Hydrodynamics for the No Action Alternative were simulated for the period from 6/16/2013 through 6/30/2013. To examine the accuracy of model output, modeled WSEL was compared to measured WSEL at USGS Station 08079120 (see Figure 28 for location). Note, the elevations reported by USGS correlated to MLLW values reported at the NOAA site and were adjusted based on the conversion provided by USACE (0 feet NAVD = +0.65 feet MLLW)[9]. A plot of measured versus modeled water levels around the USGS stations is presented in Figure 29.

[9] Based on correspondence, USGS agreed that the station datum appears to be equivalent to MLWW. Correspondence from USGS was received from Jeffery East, Surface Water Specialist, 19241 David Memorial Drive, Suite 180, Conroe, TX 77385 on May 24th, 2016.

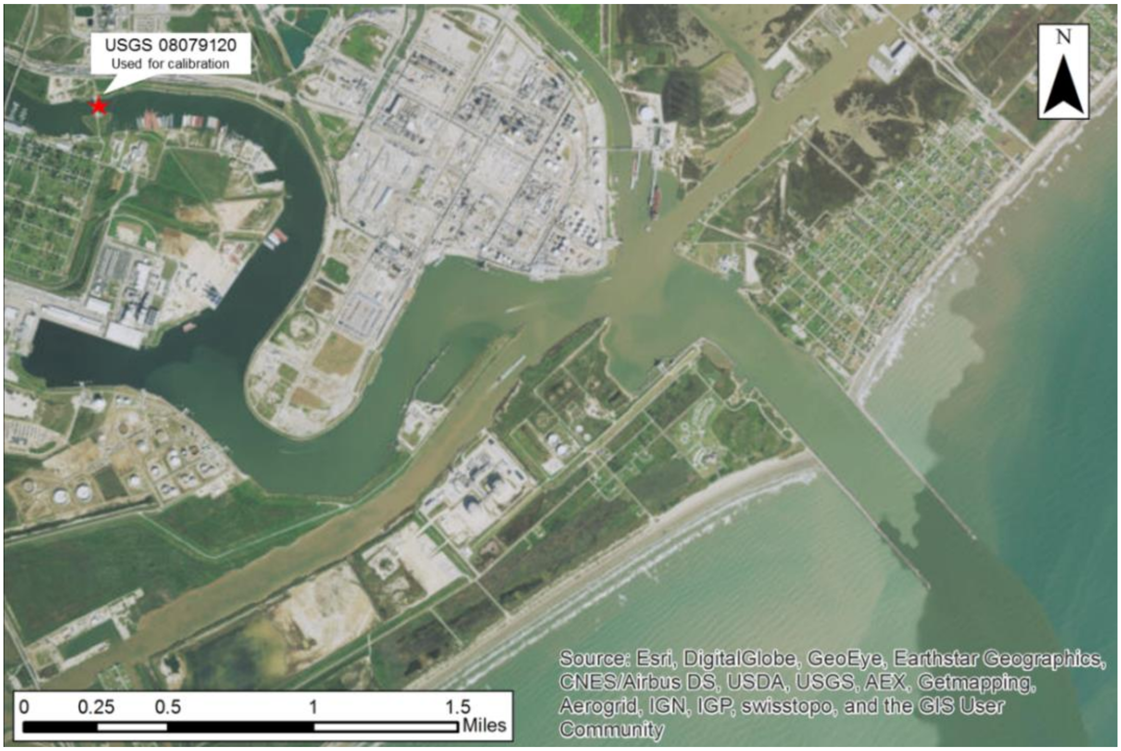

Figure 28 – Location of USGS water level gauge used for calibration

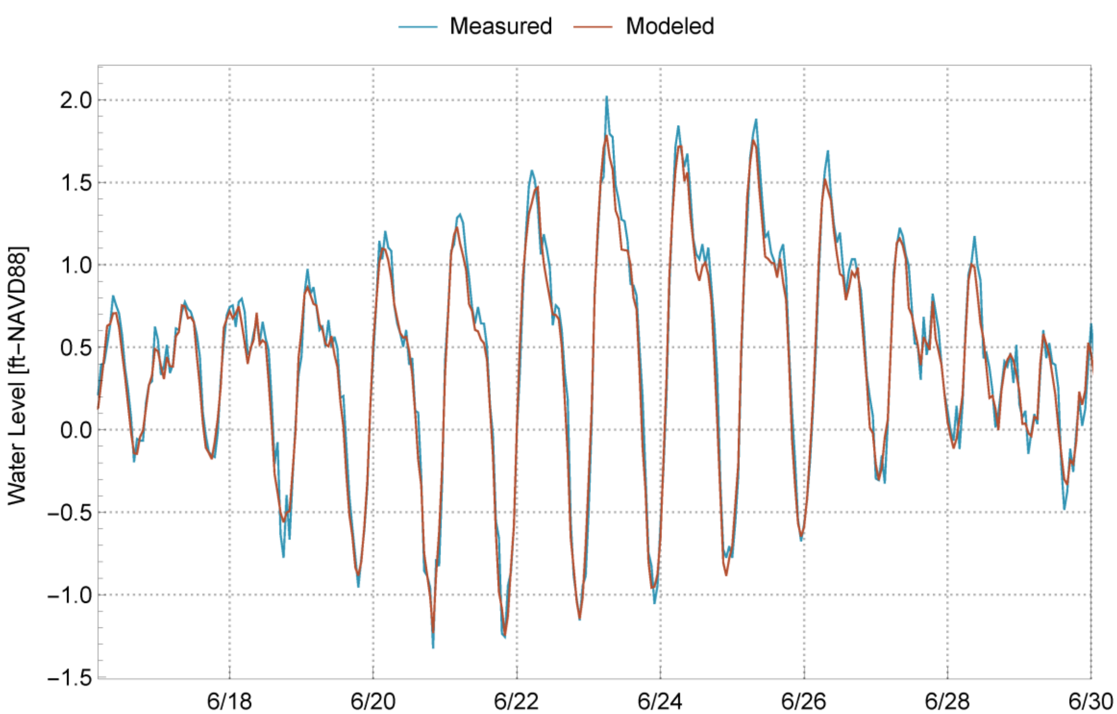

Figure 29 – Measured vs. modeled water level time series for USGS Station 08079120

As shown in Figure 29, the model output appears to be in acceptable agreement with measurements. Phase differences are not apparent and daily water level ranges appear to be well represented (i.e., generally within 0.1 feet of measured values).

After the model results were verified against USGS measurements, the simulation was conducted with RSLR added at the open boundary to represent potential impacts from future sea level increase.

6.10 Modeling of Alternative 2

The layout of Alternative 2 was implemented into the model's bathymetry, and simulations with present and future sea levels were performed for the same periods as applied for the No Action Alternative model.

6.11 Comparison of Model Results

Water level time series results at each observation point during the simulation period were compared. The comparison revealed that water levels remained relatively unchanged with Alternative 2. As an example, Table 18 compares modeled water levels at point OB3.

Table 18 – Comparison of modeled water levels at point OB3

		Water Levels (ft)		
	Sea Level	No Action Alternative	Alternative 2	Difference
Maximum	Present	1.79	1.79	0.00
	Future	2.97	2.97	0.00
75th Percentile	Present	0.79	0.79	0.00
	Future	1.97	1.97	0.00
Median	Present	0.44	0.44	0.00
	Future	1.62	1.62	0.00
25th Percentile	Present	-0.02	-0.02	0.00
	Future	1.14	1.14	0.00
Minimum	Present	-1.25	-1.25	0.00
	Future	-0.07	-0.07	0.00

Additionally, maximum current magnitudes at all observation points are compared in Table 19. As seen in Table 19, changes in currents were negligible, with a maximum change of only 0.019 fps (0.23 in/sec).

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Table 19 – Maximum velocity magnitude at observation points

		Maximum Current Magnitude, (ft/sec)		
	Sea Level	No Action Alternative	Alternative 2	Difference
OB1	Present	0.075	0.079	-0.004
	Future	0.070	0.074	-0.004
OB2	Present	0.172	0.178	-0.006
	Future	0.168	0.173	-0.006
OB3	Present	0.107	0.088	0.019
	Future	0.103	0.085	0.018
OB4	Present	0.045	0.045	0.000
	Future	0.043	0.043	0.000
OB5	Present	0.125	0.125	0.000
	Future	0.117	0.117	0.000

Finally, velocity vectors over the domain were reviewed for possible development of eddies resulting from Alternative 2. As shown in Figure 30, the model suggested formation of an eddy in the Bend Easing feature during falling tides; however, due to the small magnitude of the currents (i.e. less than 0.5 in/s), the eddy is unlikely to be problematic from a navigation or sedimentation standpoint.

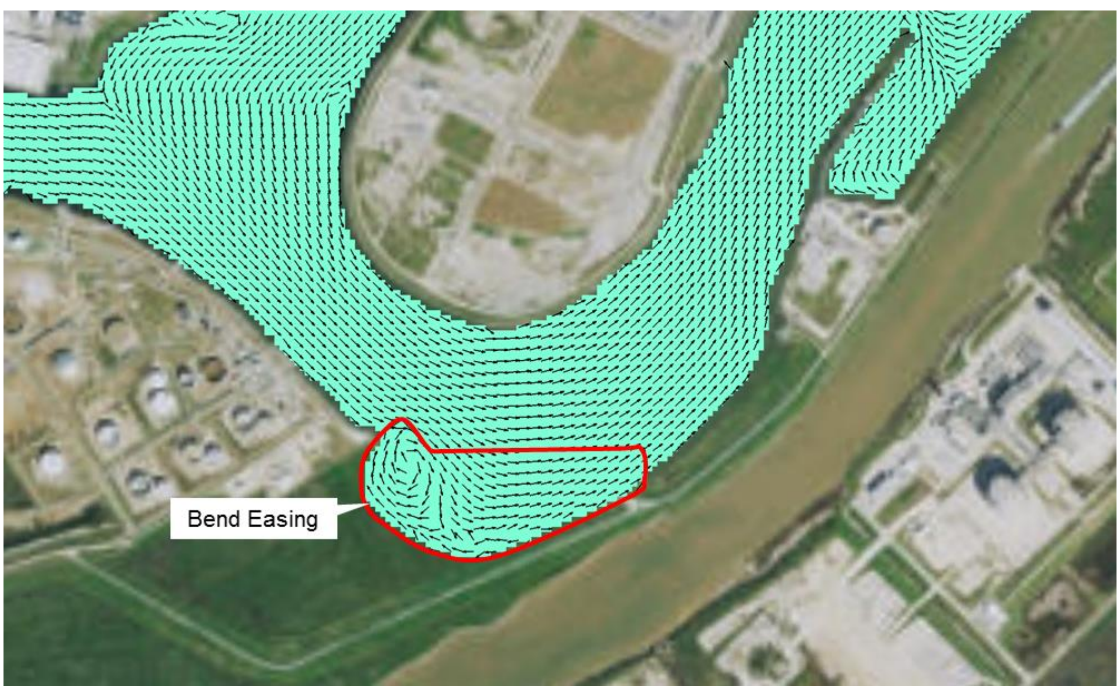

Figure 30 – Observed eddy at the Bend Easing (Alternative 2)

6.12 Hydrodynamic Analysis Conclusion

Based on the results of this assessment, there appear to be minimal changes in the hydrodynamics (water level and current velocity) within Freeport Harbor Channel based on a comparison of the No Action Alternative and Alternative 2. Based on analysis of Alternative 2, there was no change in the water level and there was slight variation of the current velocity (less than 0.019 fps). The potential impacts of the changes were considered with respect to navigation and sedimentation. Consideration was also given to potential impacts of RSLR.

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Appendix A. Summary of Maintenance Dredging Records

Table 20 – Summary of maintenance dredging records

Contact Number	Year	From Station	To Station	Total Volume (cy)	Volume within Sta. 71+52 to 184+20 (cy)
W912HY07C0028	2007	59+62	78+63	55,259	20,668
W912HY06C0012	2006	59+62	78+63	128,655	48,119
W912HY05C0015	2005	78+63	96+00	183,219	183,219
W912HY05C0015	2005	120+00	156+00	211,824	211,824
W912HY05C0015	2005	96+00	120+00	317,807	317,807
W912HY04C0015	2004	59+62	78+63	200,879	75,131
DACW6402C0017	2002	72+52.58	126+85.03	630,749	630,749
DACW6402C0017	2002	126+85.03	184+07	192,419	192,419
DACW6401C0023	2001	59+62.49	71+52.58	92,614	45
DACW6400C0023	2000	71+52	95+67	515,348	515,348
DACW6400C0023	2000	71+52	95+67	157,939	157,939
DACW6498C0026	1999	130+00	184+07	316,159	316,159
DACW6498C0026	1999	95+67	130+00	542,625	542,625
DACW6498C0026	1999	71+52	95+67	323,067	323,067
DACW6497C0043	1997	7152.58	8266.48	185,663	185,663
DACW6497C0008	1997	20+00	71+52.58	466,440	53
DACW6495C0040	1995	59+62.49	172+00	762,120	681,448
DACW6493C0014	1993	82+66.48	106+73.77	252,316	252,316
DACW6493C0014	1993	106+73.77	128+00	208,953	208,953
DACW6492C0044	1992	60+00	82+66.48	438,085	215,416
		Total Cumulative Dredged Volume, *mcy*			4,921,029

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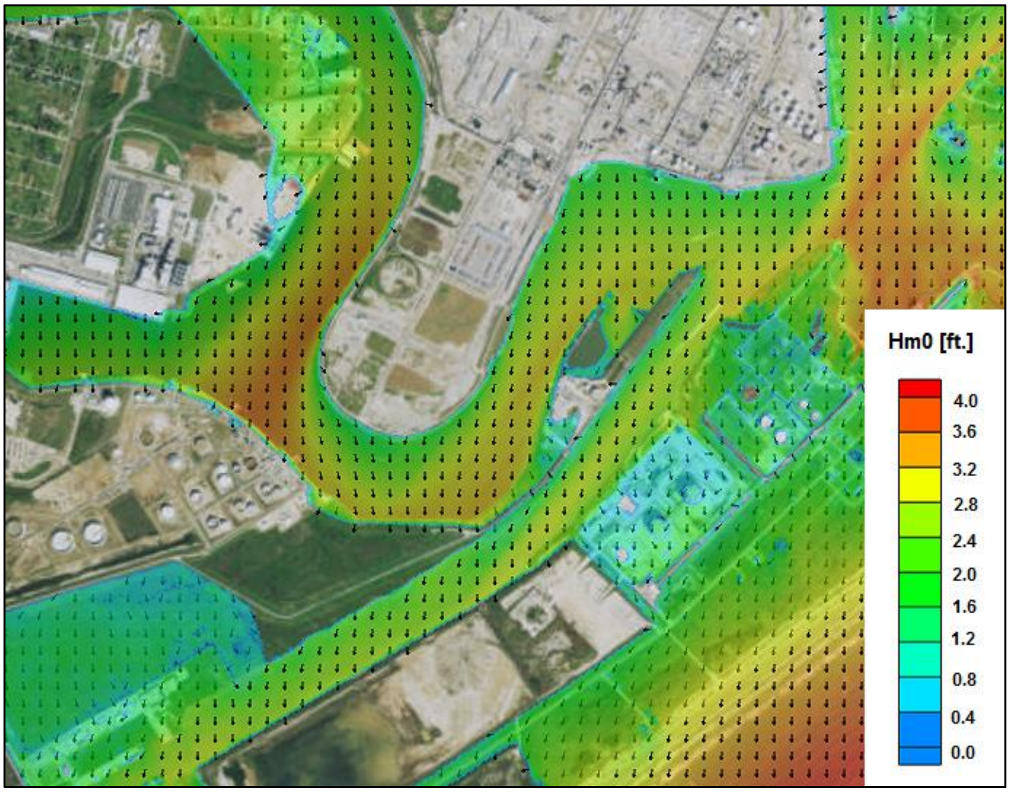
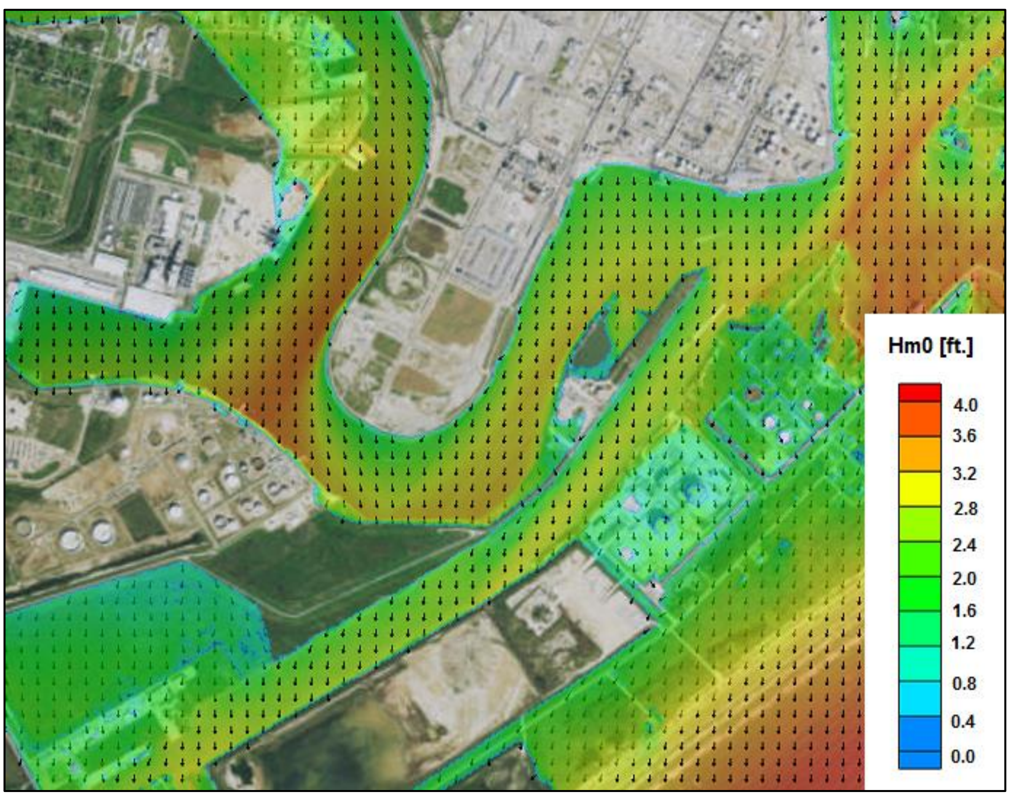
Appendix B. Wave Model Results

No Action Alternative, Wind Direction: N



Wave Model Result: No Action Alternative, N Winds, Present Sea Level



Wave Model Result: No Action Alternative, N Winds, Future Sea Level

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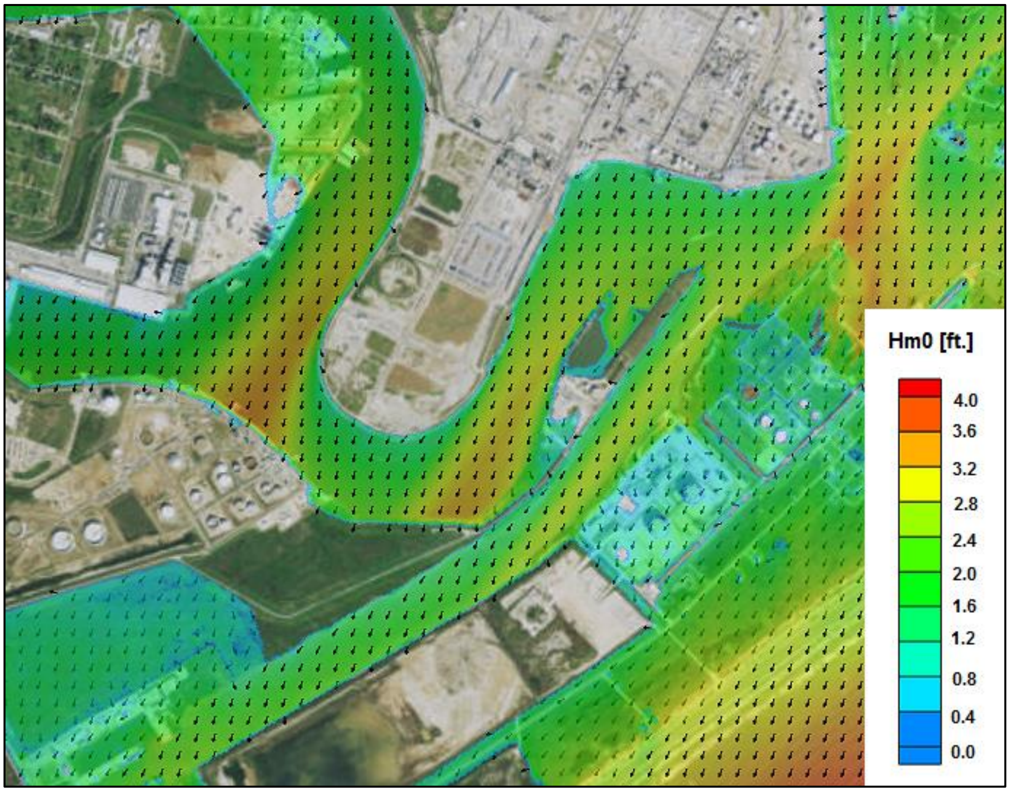
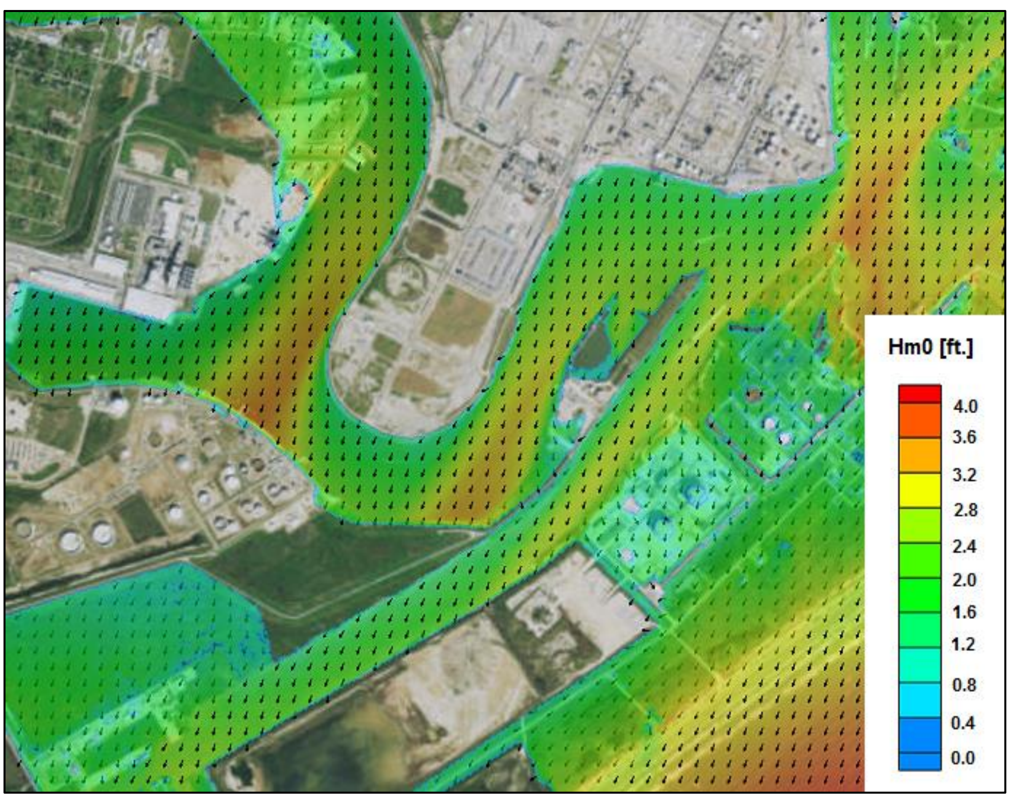
No Action Alternative, Wind Direction: NNE

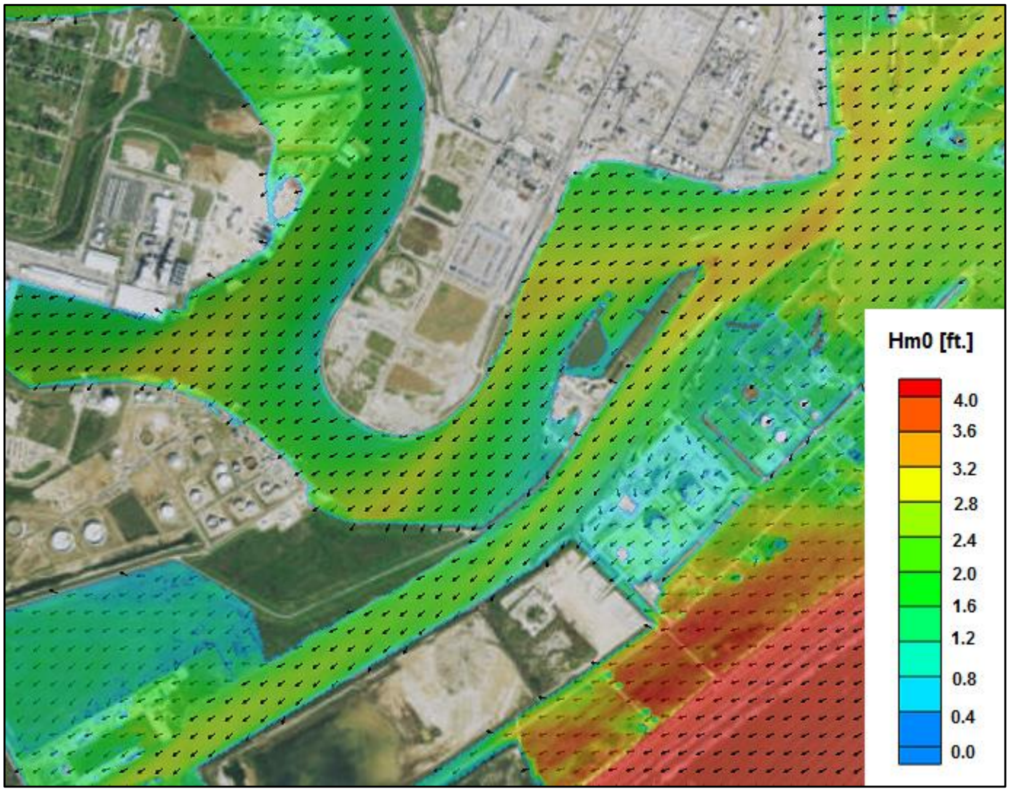


Wave Model Result: No Action Alternative, NNE Winds, Present Sea Level

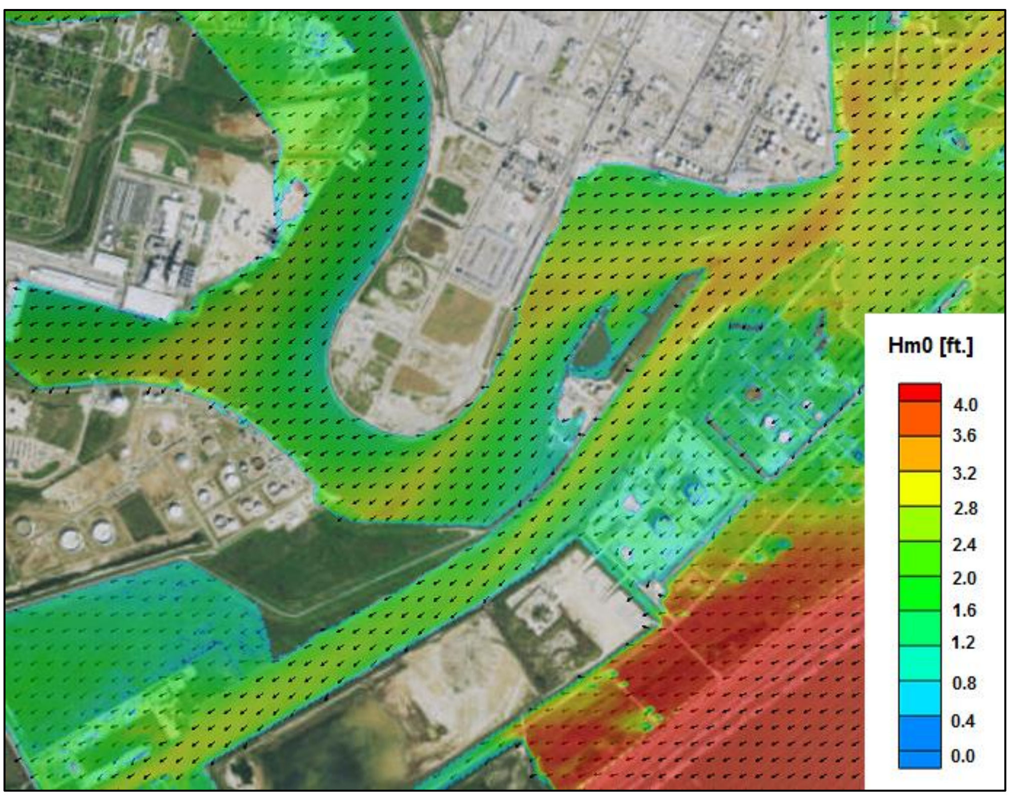


Wave Model Result: No Action Alternative, NNE Winds, Future Sea Level

No Action Alternative, Wind Direction: NE



Wave Model Result: No Action Alternative, NE Winds, Present Sea Level



Wave Model Result: No Action Alternative, NE Winds, Future Sea Level

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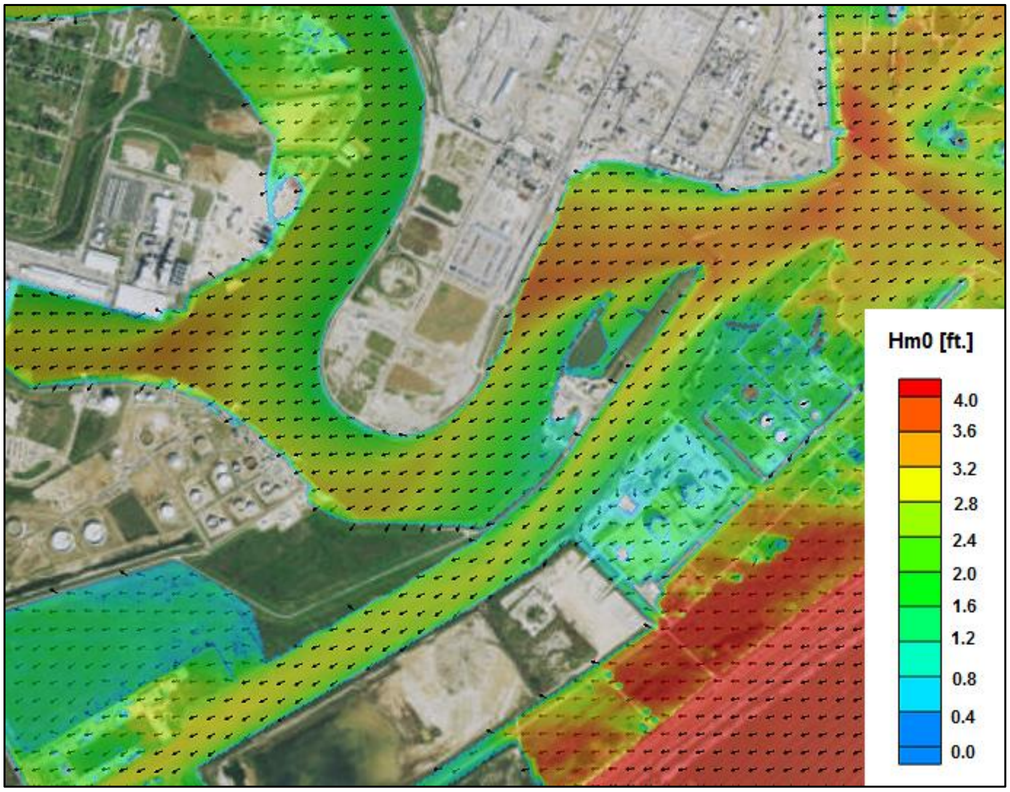
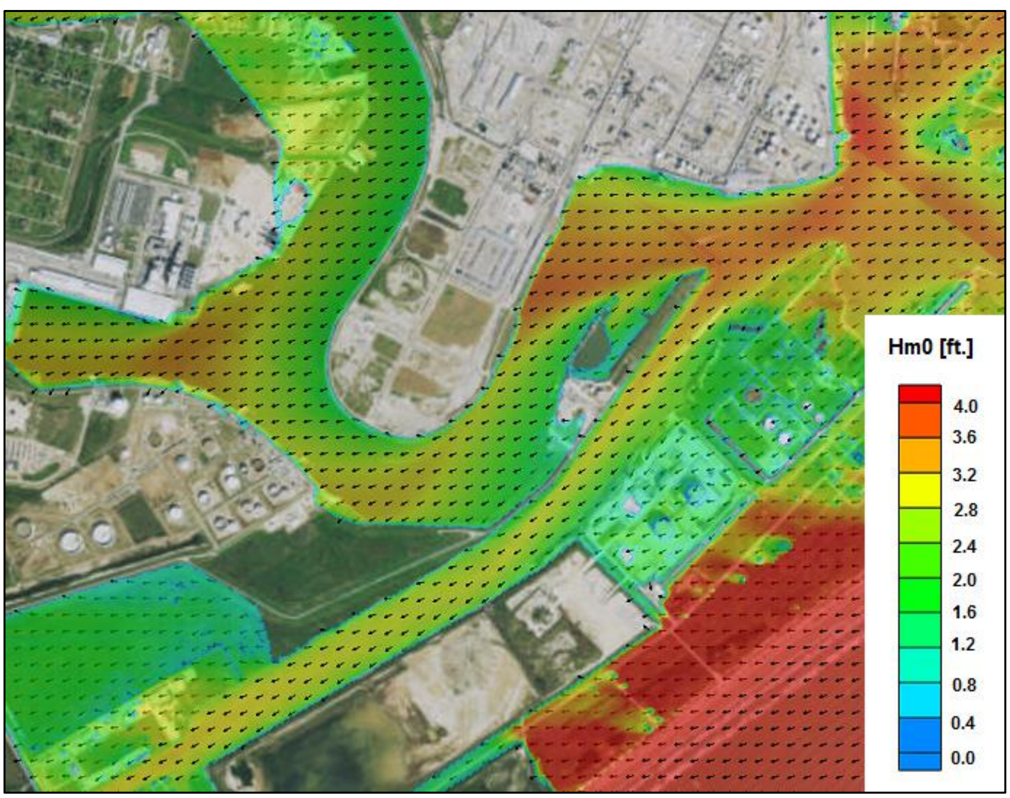
No Action Alternative, Wind Direction: ENE

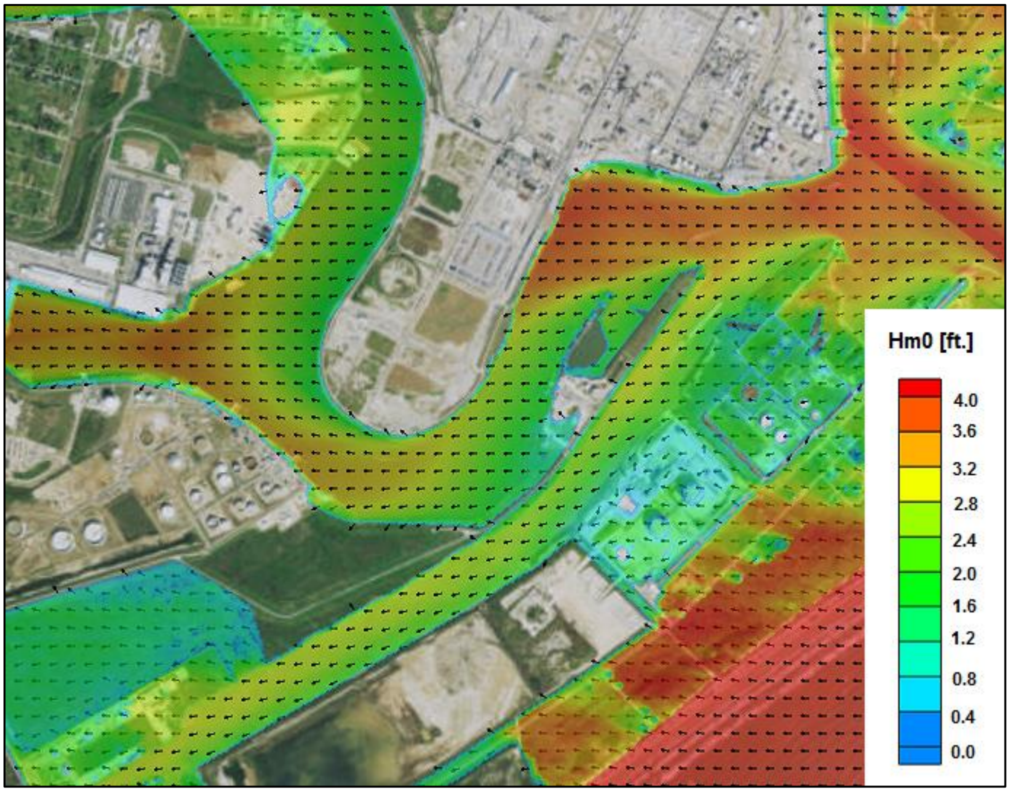


Wave Model Result: No Action Alternative, ENE Winds, Present Sea Level

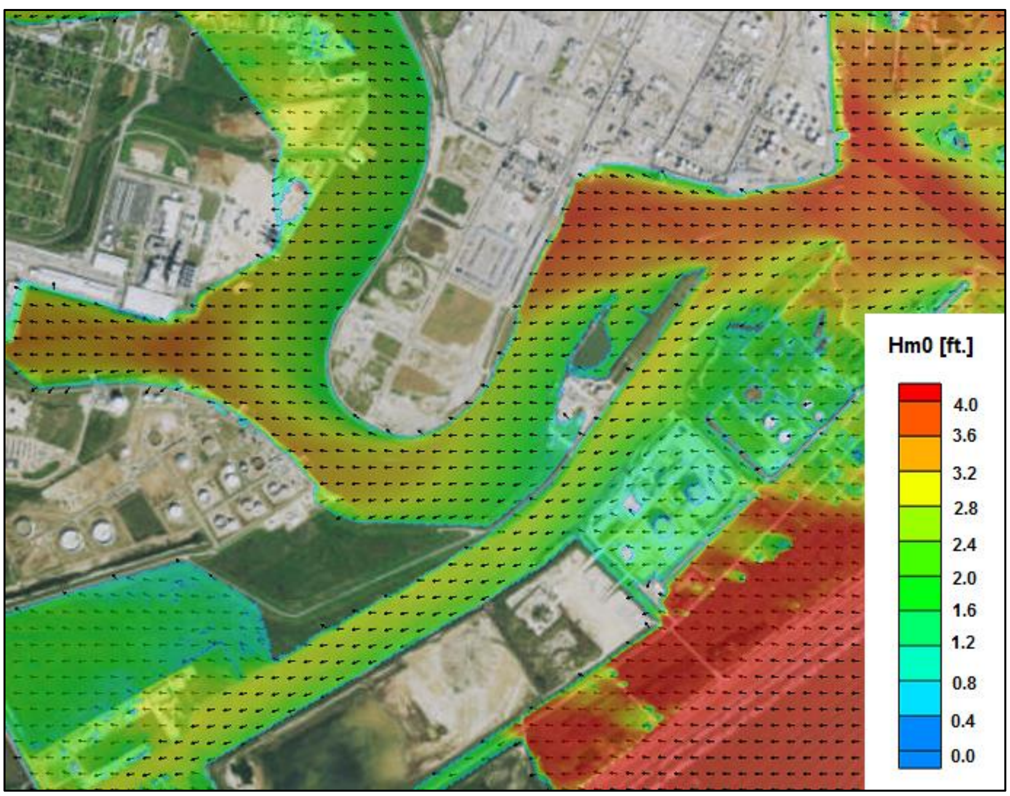


Wave Model Result: No Action Alternative, ENE Winds, Future Sea Level

No Action Alternative, Wind Direction: E



Wave Model Result: No Action Alternative, E Winds, Present Sea Level



Wave Model Result: No Action Alternative, E Winds, Future Sea Level

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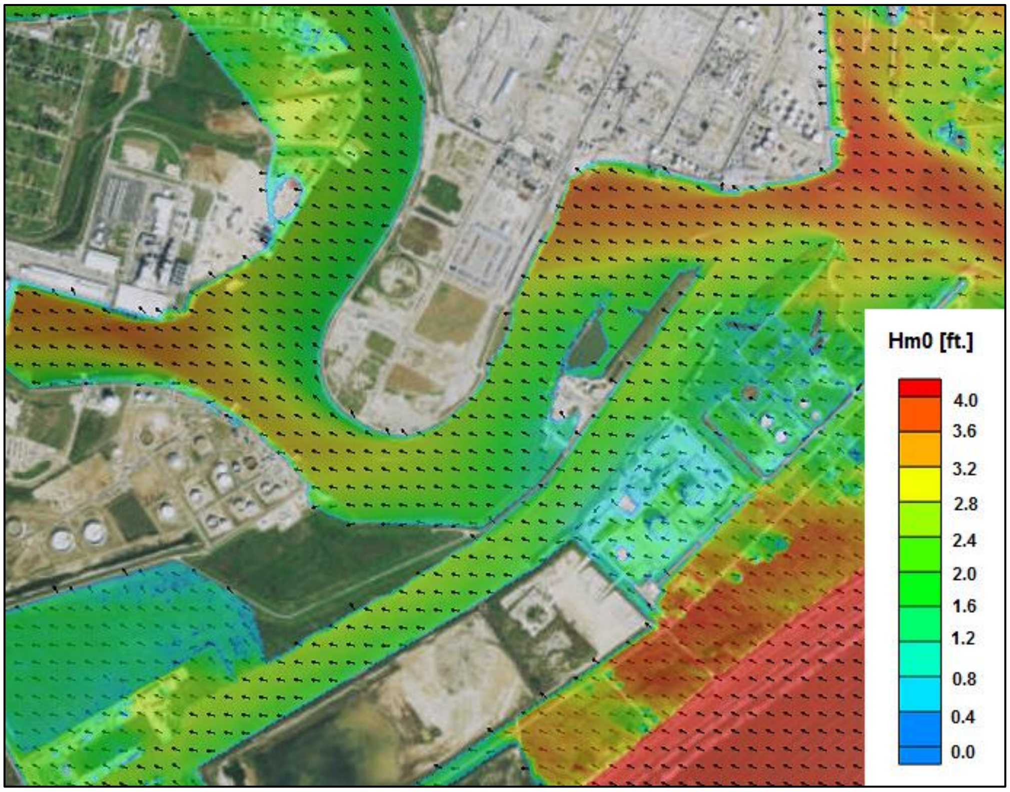
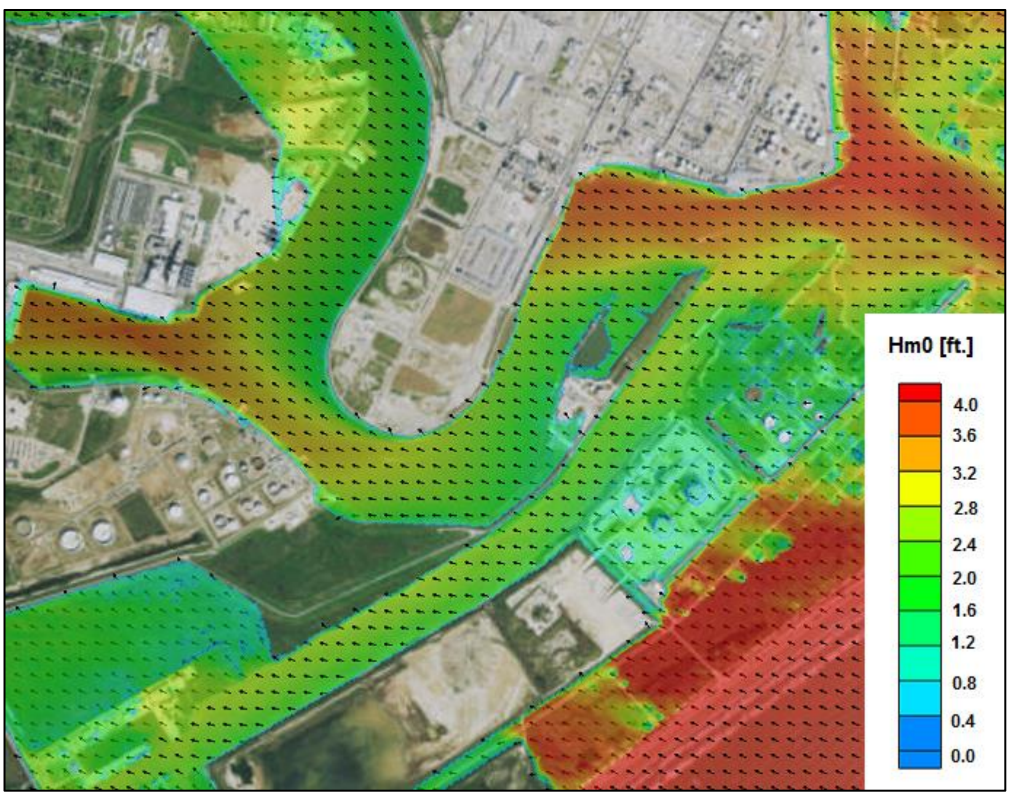
No Action Alternative, Wind Direction: ESE

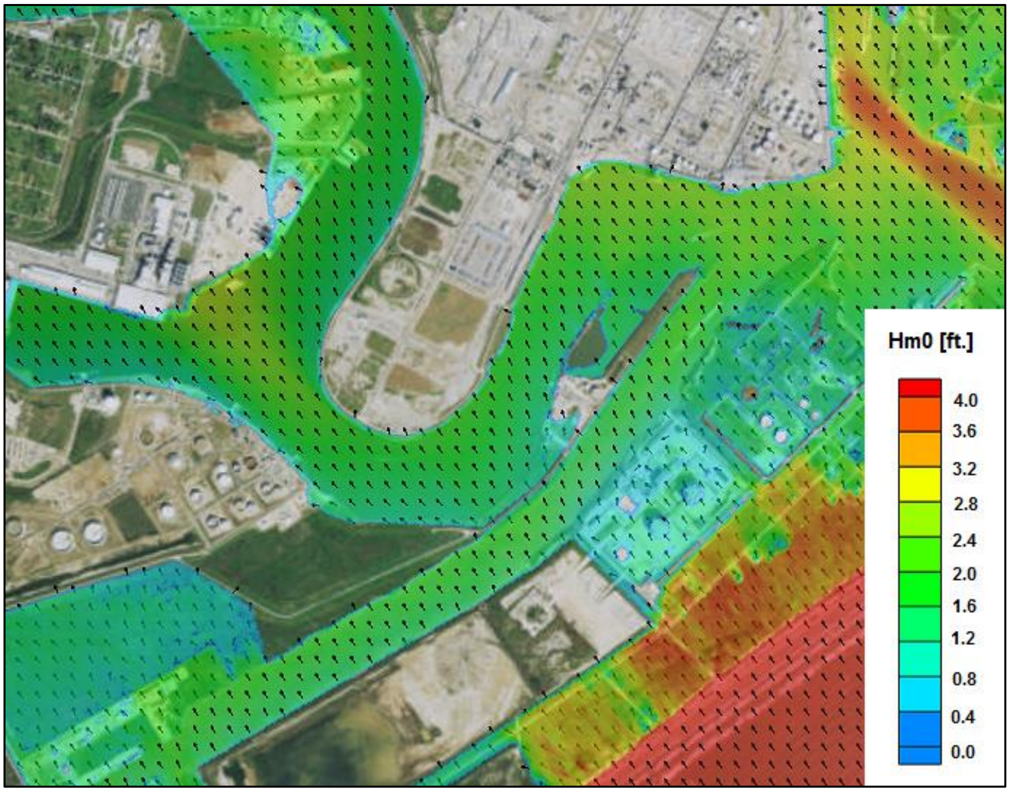


Wave Model Result: No Action Alternative, ESE Winds, Present Sea Level

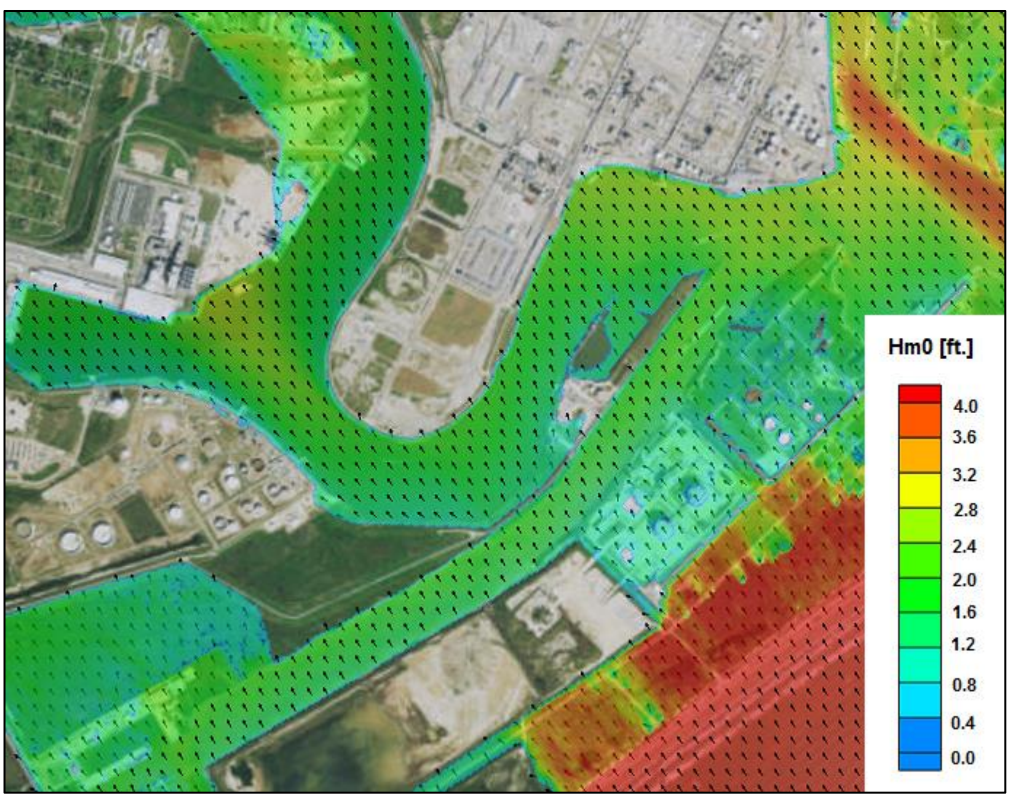


Wave Model Result: No Action Alternative, ESE Winds, Future Sea Level

No Action Alternative, Wind Direction: SE



Wave Model Result: No Action Alternative, SE Winds, Present Sea Level



Wave Model Result: No Action Alternative, SE Winds, Future Sea Level

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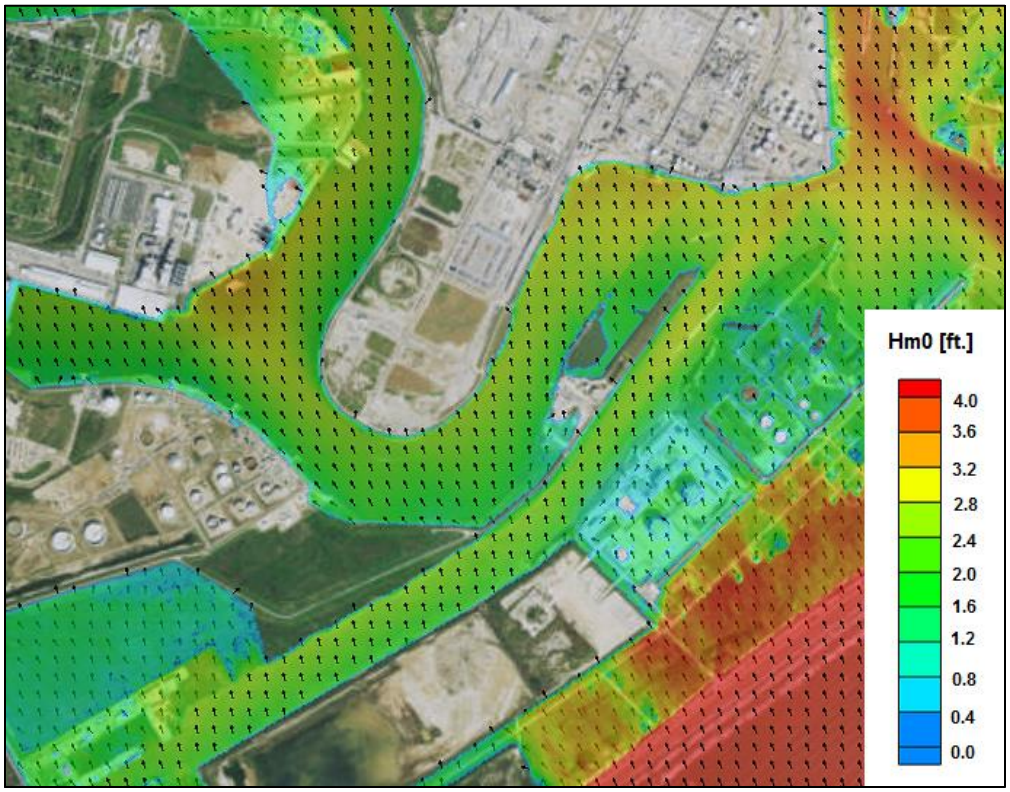
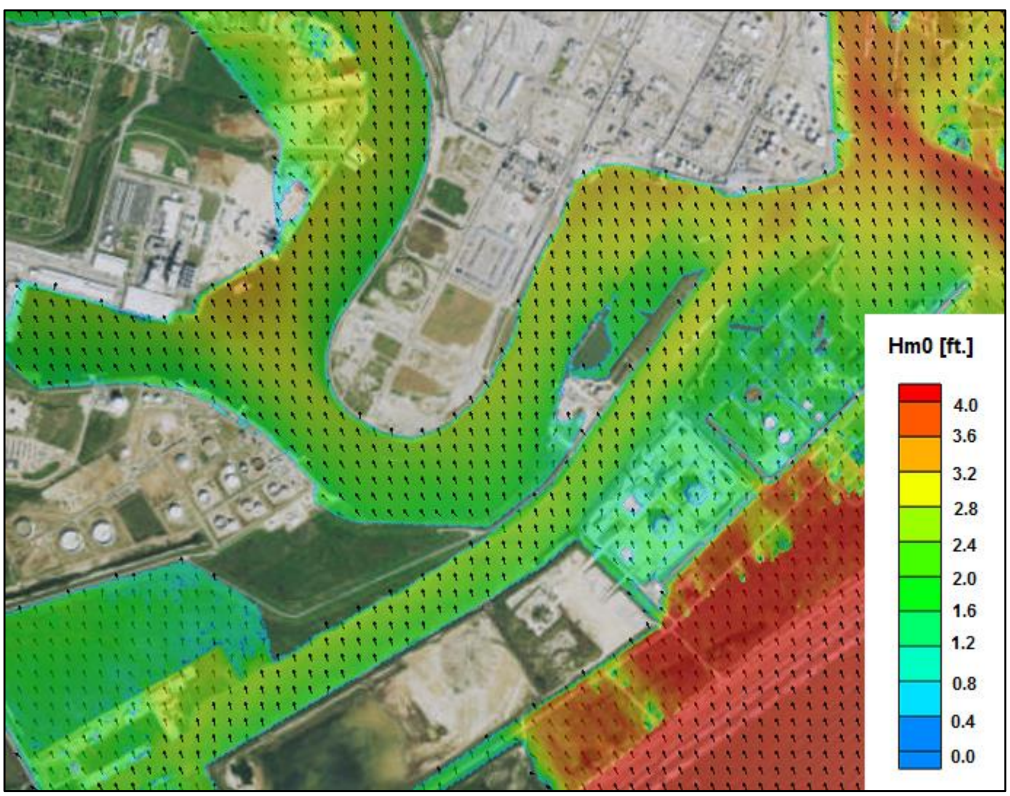
No Action Alternative, Wind Direction: SSE °

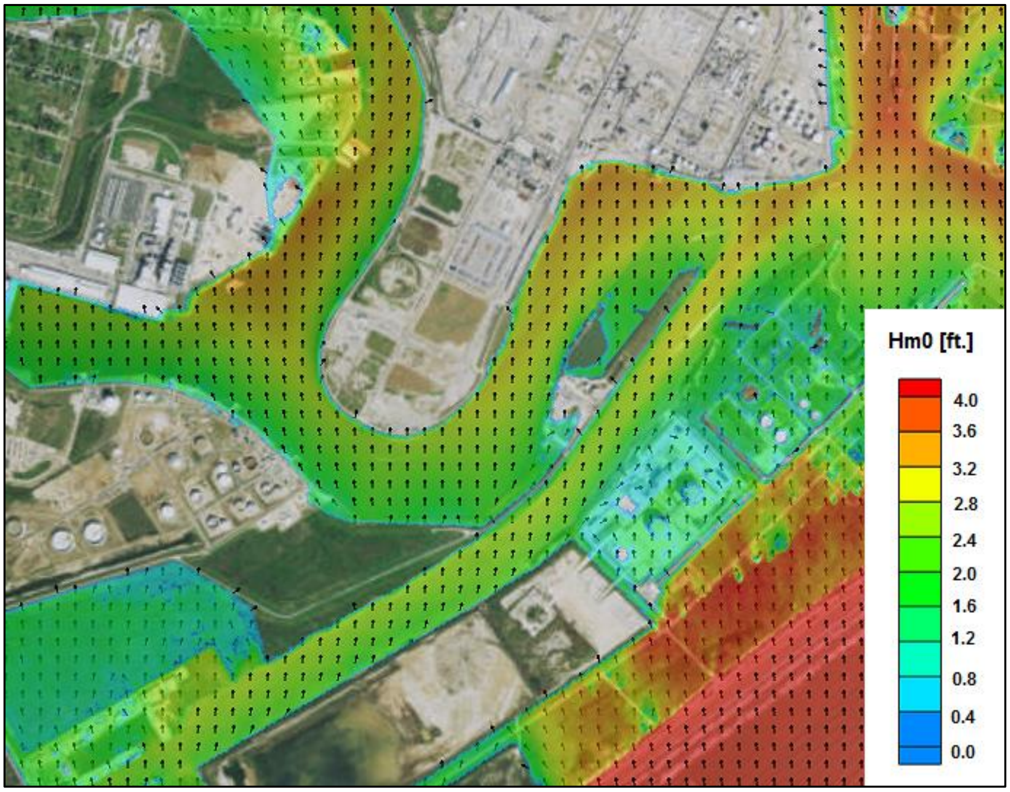


Wave Model Result: No Action Alternative, SSE Winds, Present Sea Level

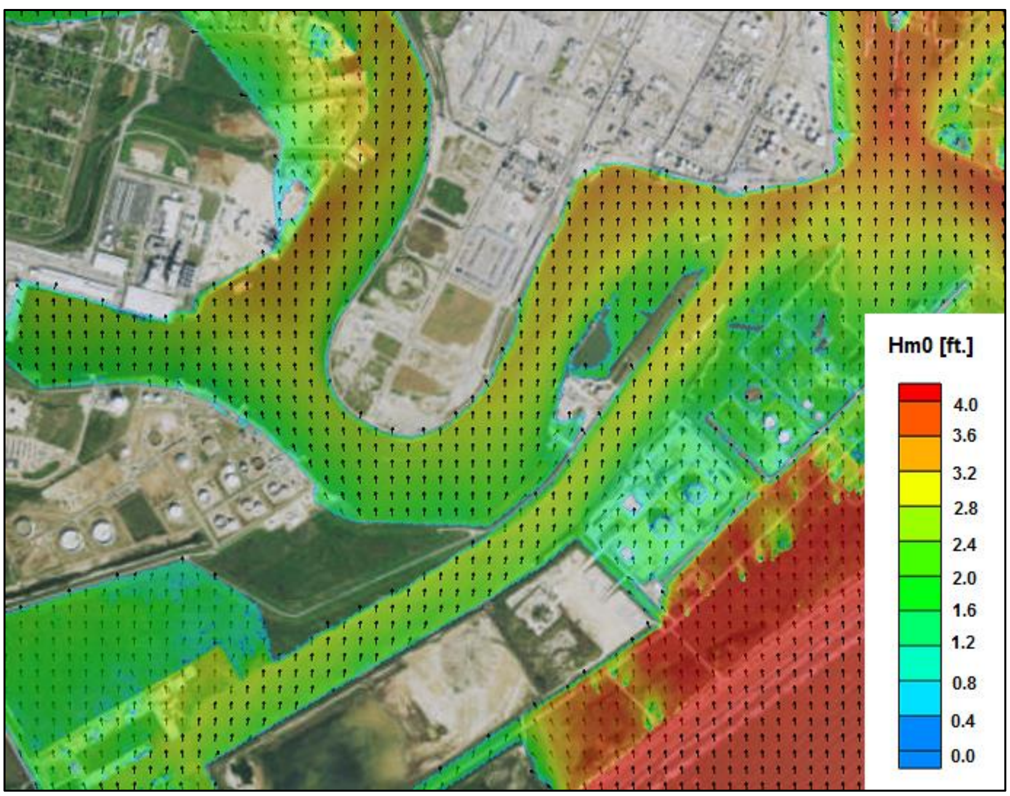


Wave Model Result: No Action Alternative, SSE Winds, Future Sea Level

No Action Alternative, Wind Direction: S

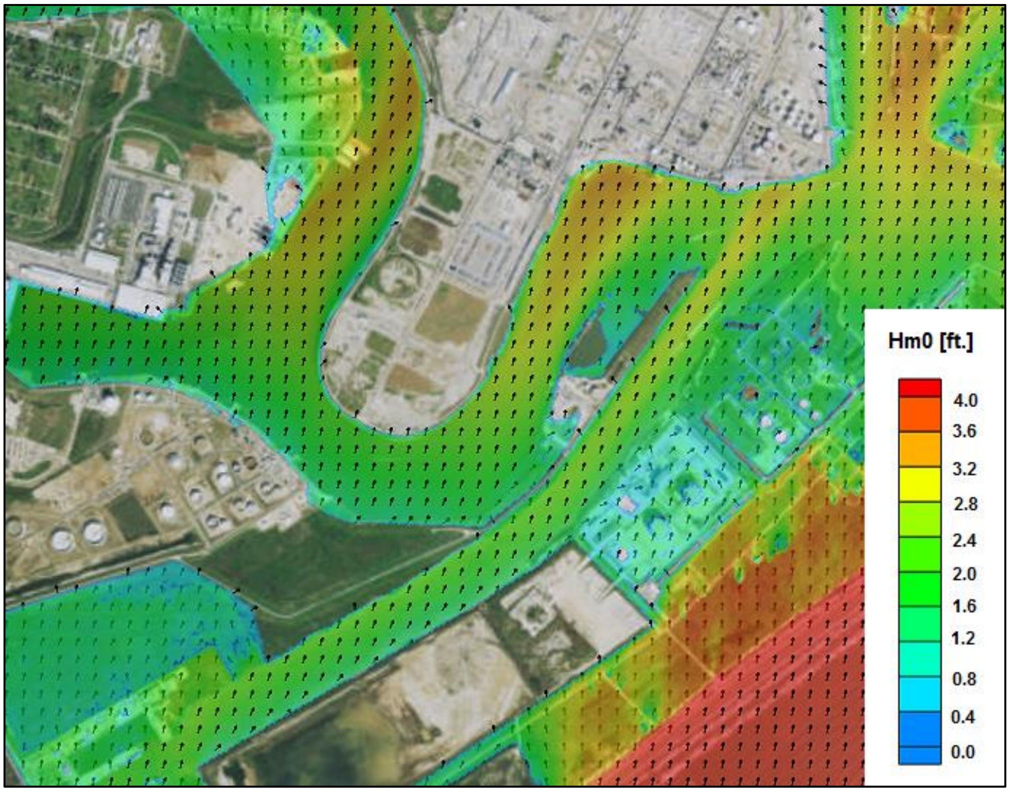


Wave Model Result: No Action Alternative, S Winds, Present Sea Level

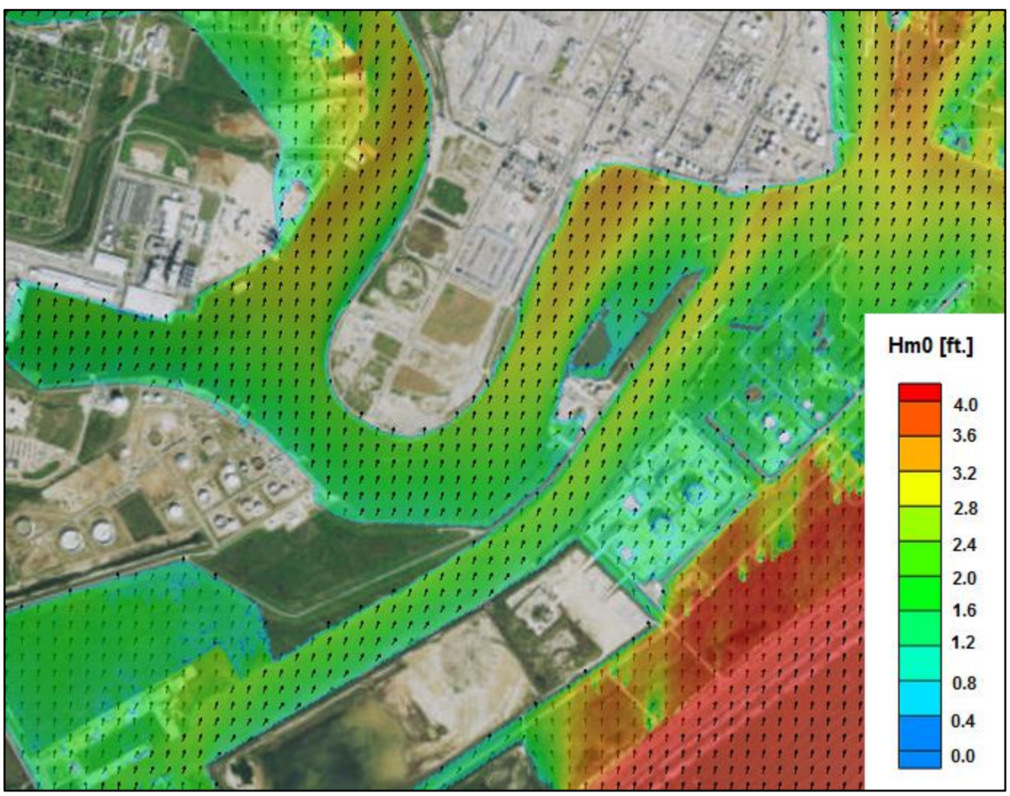


Wave Model Result: No Action Alternative, S Winds, Future Sea Level

No Action Alternative, Wind Direction: SSW

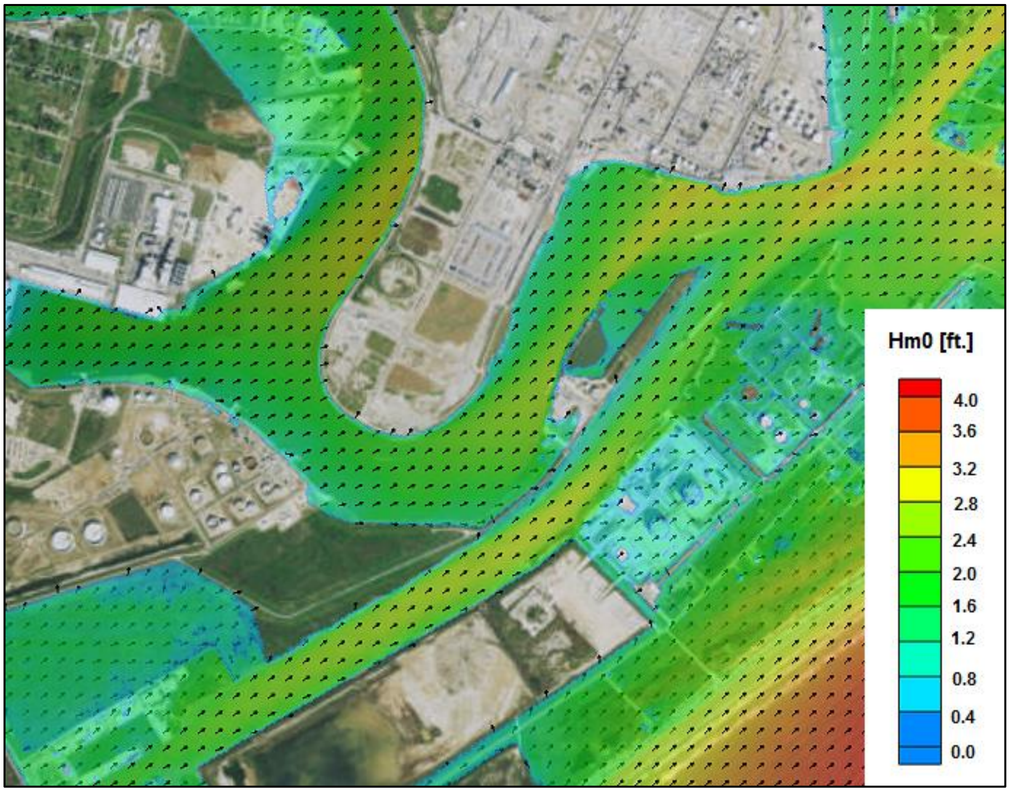


Wave Model Result: No Action Alternative, SSW Winds, Present Sea Level

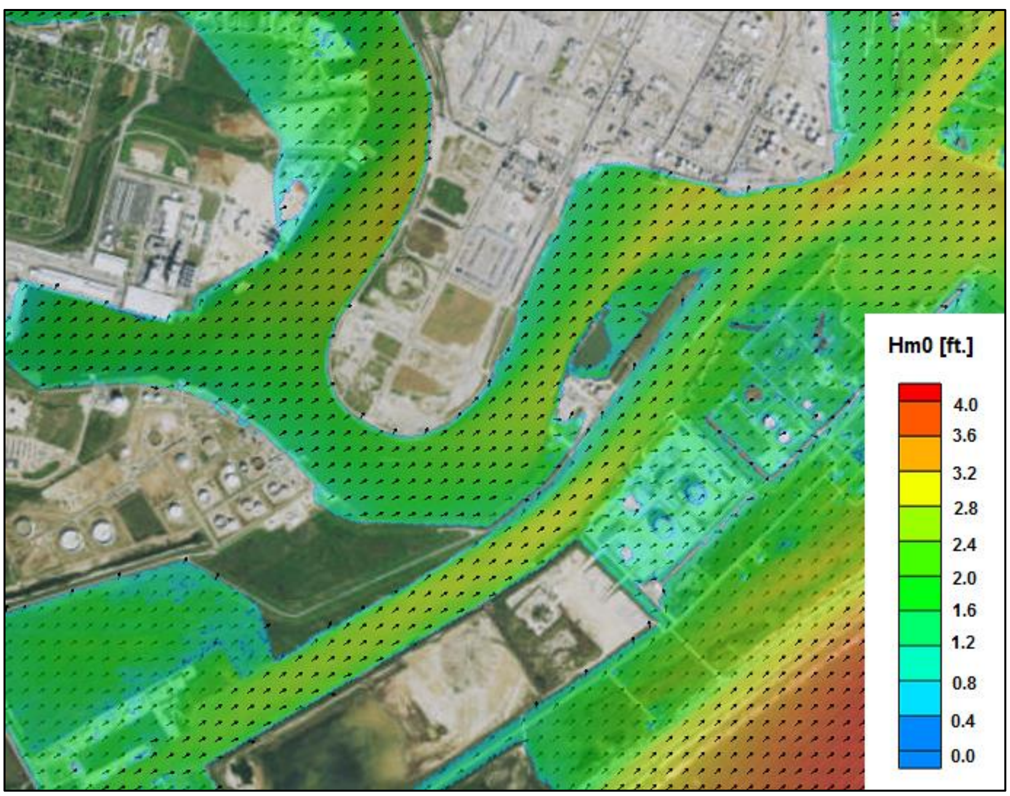


Wave Model Result: No Action Alternative, SSW Winds, Future Sea Level

No Action Alternative, Wind Direction: SW

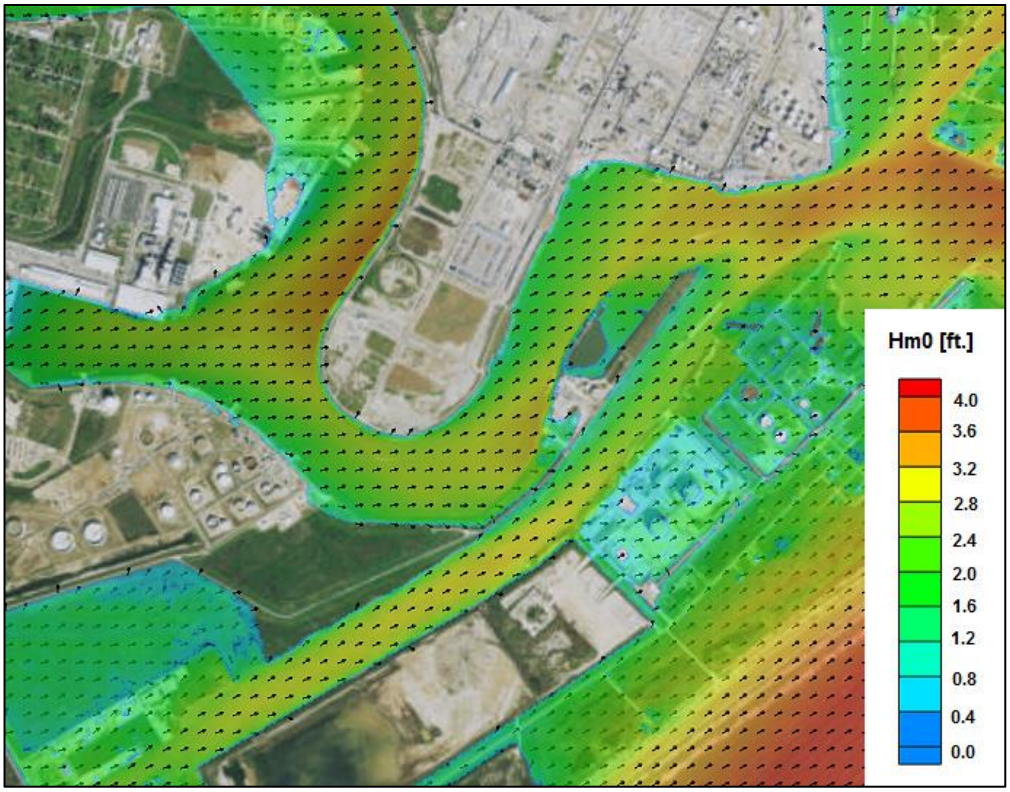


Wave Model Result: No Action Alternative, SW Winds, Present Sea Level

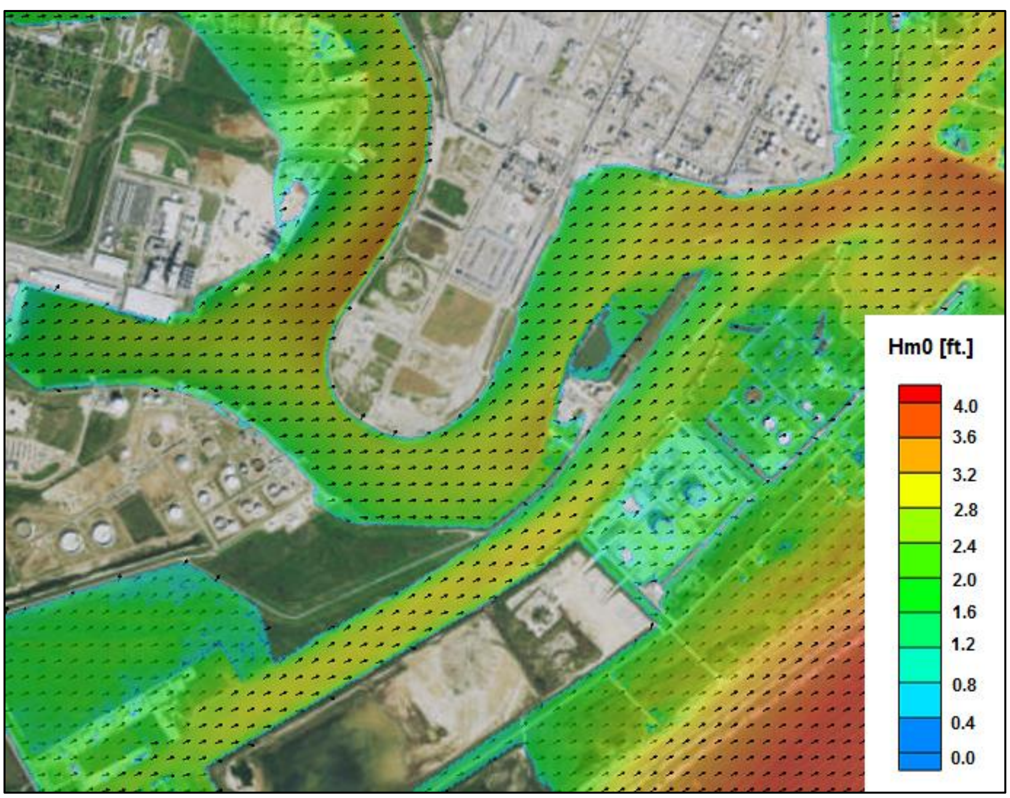


Wave Model Result: No Action Alternative, SW Winds, Future Sea Level

No Action Alternative, Wind Direction: WSW

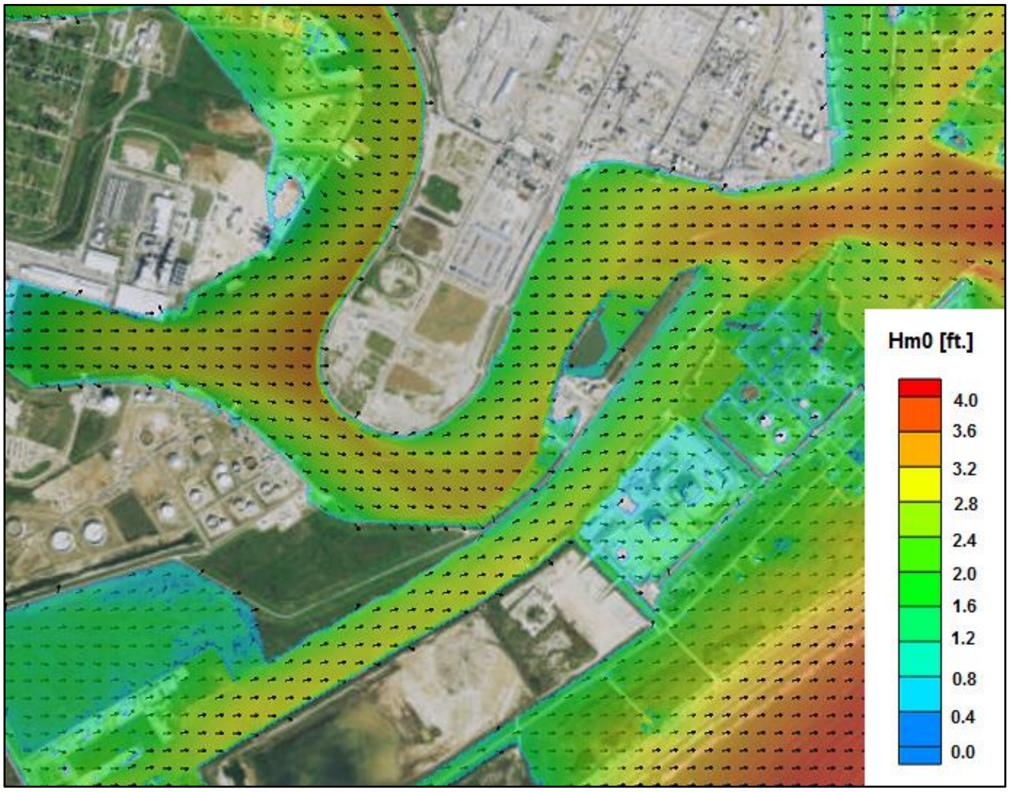


Wave Model Result: No Action Alternative, WSW Winds, Present Sea Level

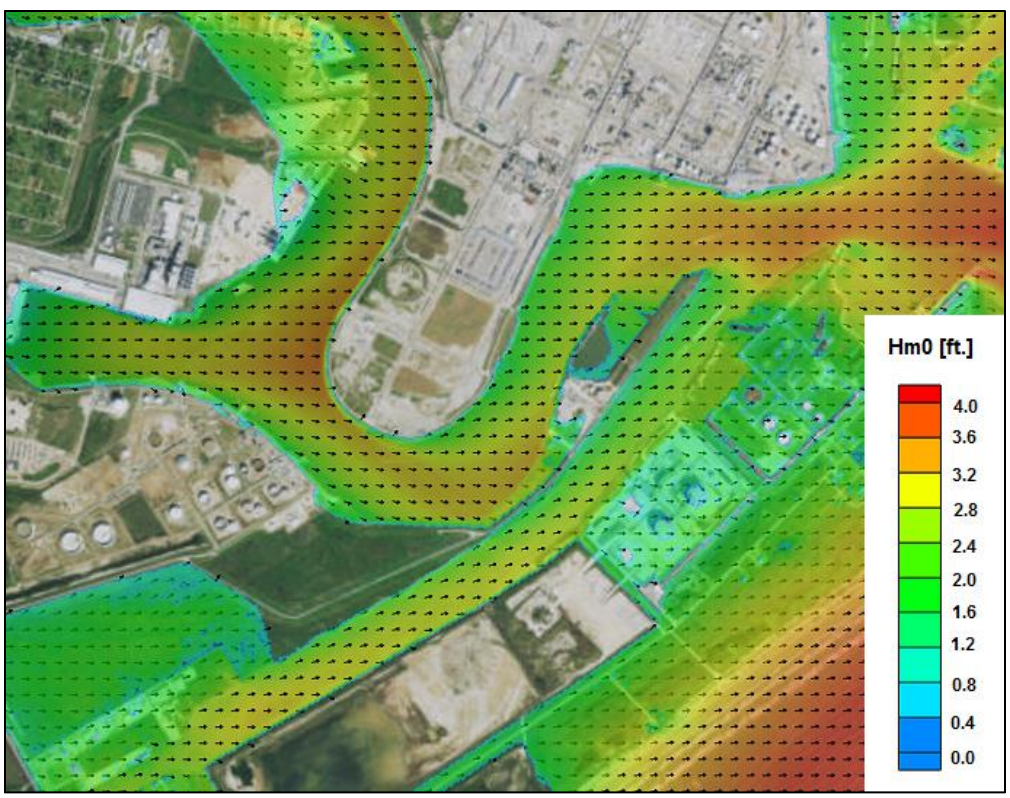


Wave Model Result: No Action Alternative, WSW Winds, Future Sea Level

No Action Alternative, Wind Direction: W

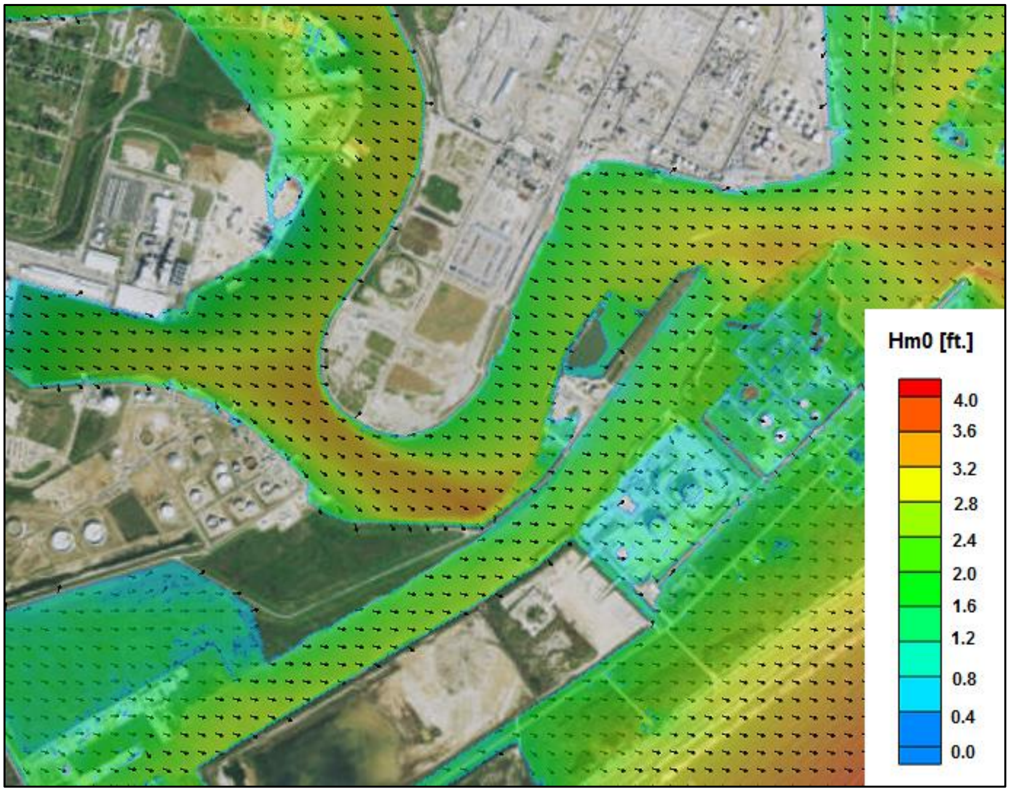


Wave Model Result: No Action Alternative, W Winds, Present Sea Level

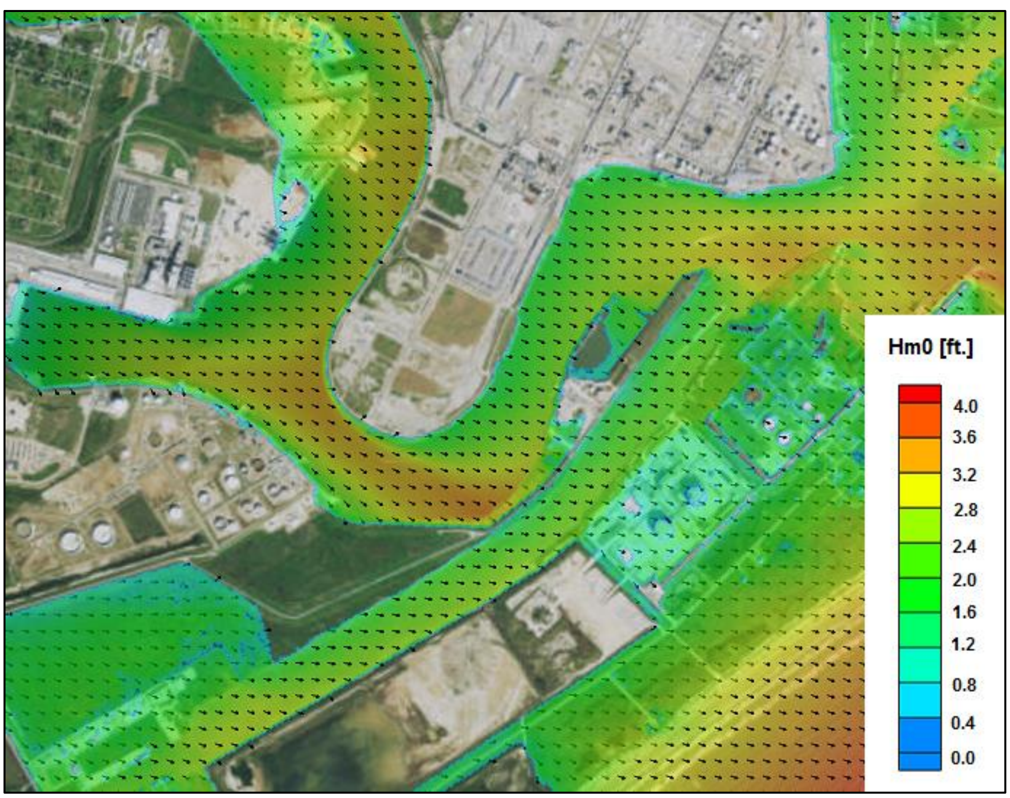


Wave Model Result: No Action Alternative, W Winds, Future Sea Level

No Action Alternative, Wind Direction: WNW

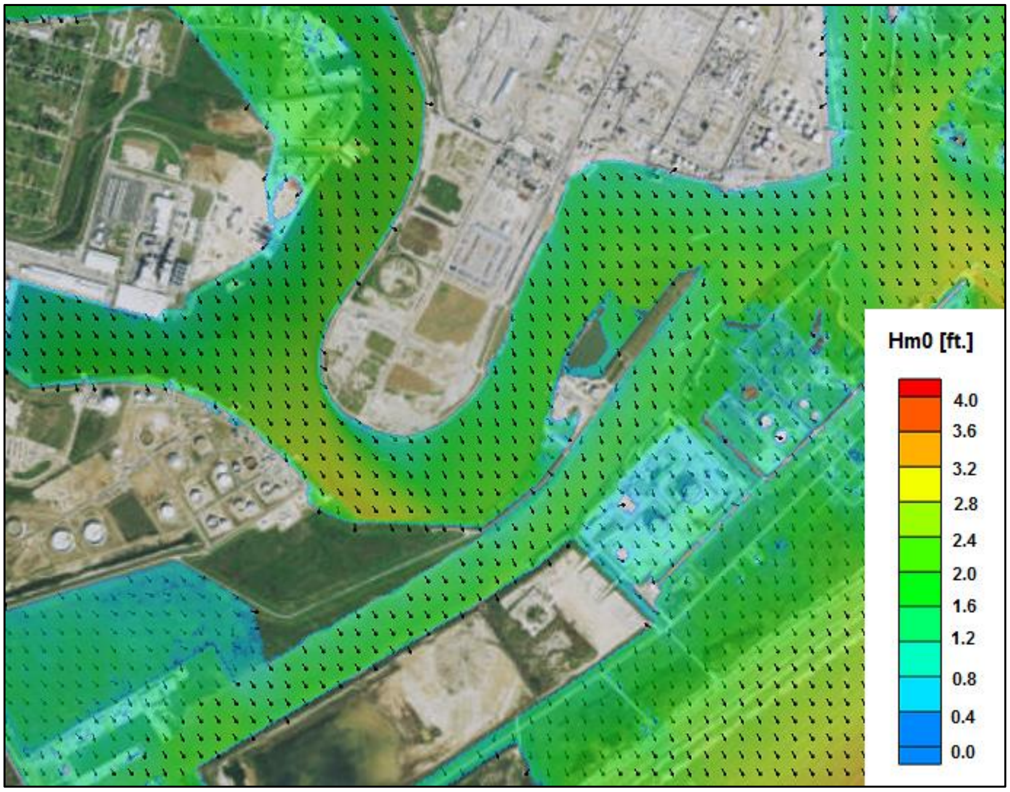


Wave Model Result: No Action Alternative, WNW Winds, Present Sea Level

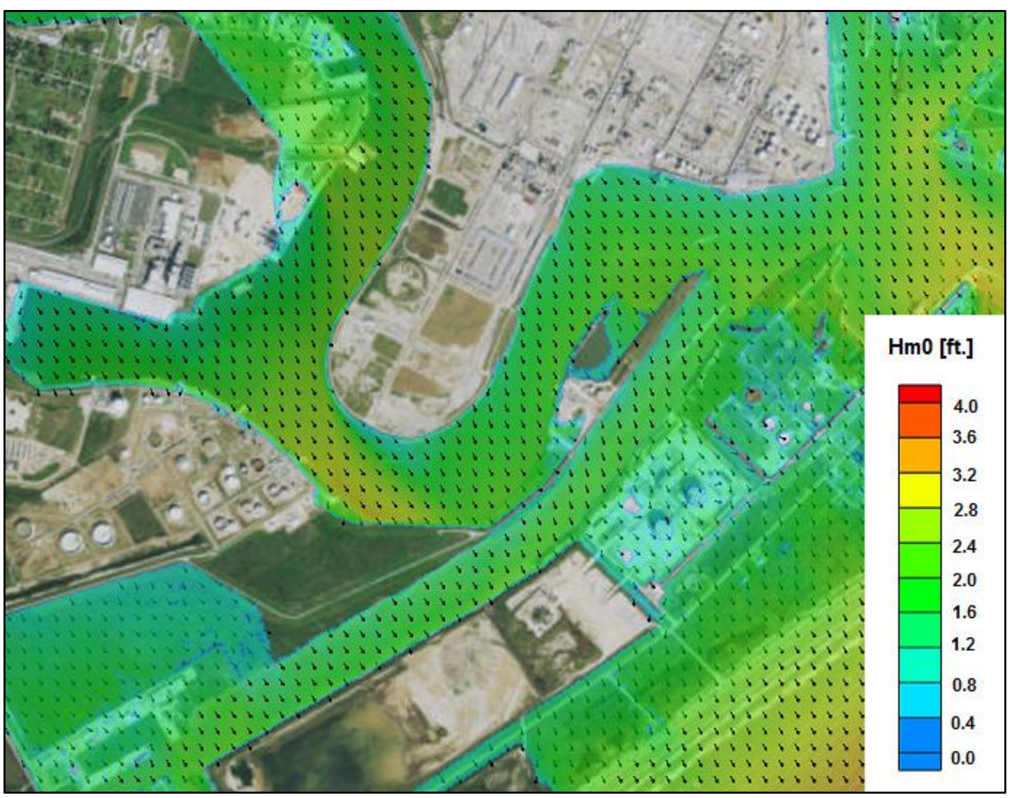


Wave Model Result: No Action Alternative, WNW Winds, Future Sea Level

No Action Alternative, Wind Direction: NW

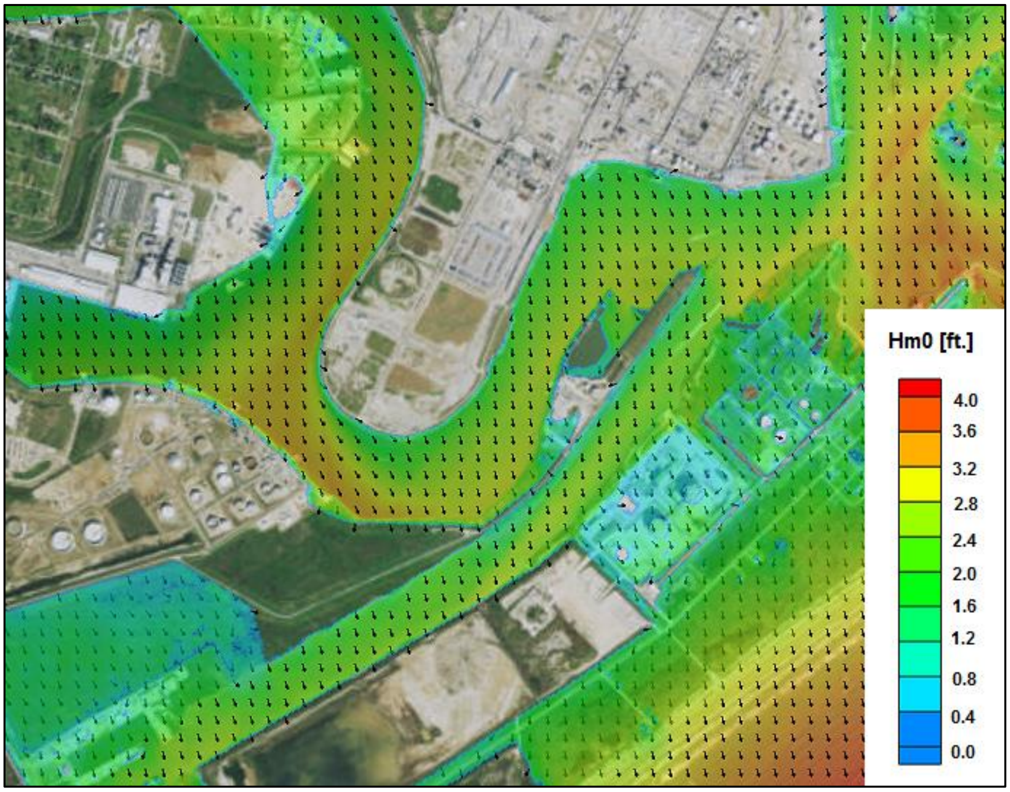


Wave Model Result: No Action Alternative, NW Winds, Present Sea Level

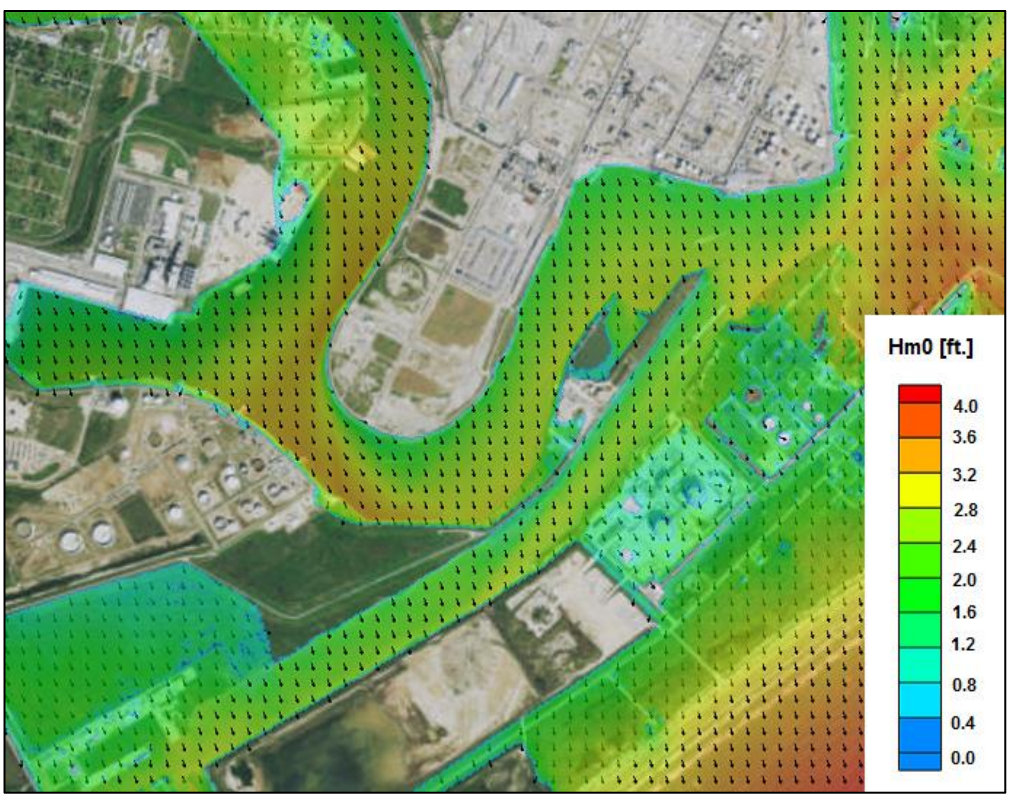


Wave Model Result: No Action Alternative, NW Winds, Future Sea Level

No Action Alternative, Wind Direction: NNW

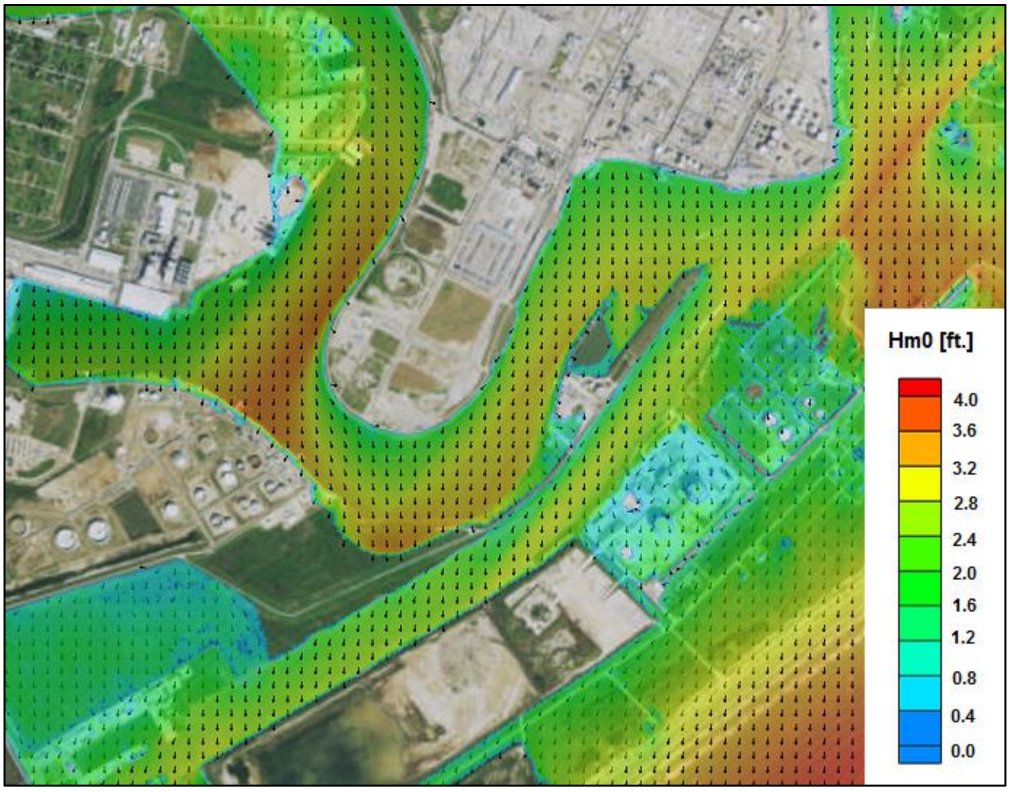


Wave Model Result: No Action Alternative, NNW Winds, Present Sea Level

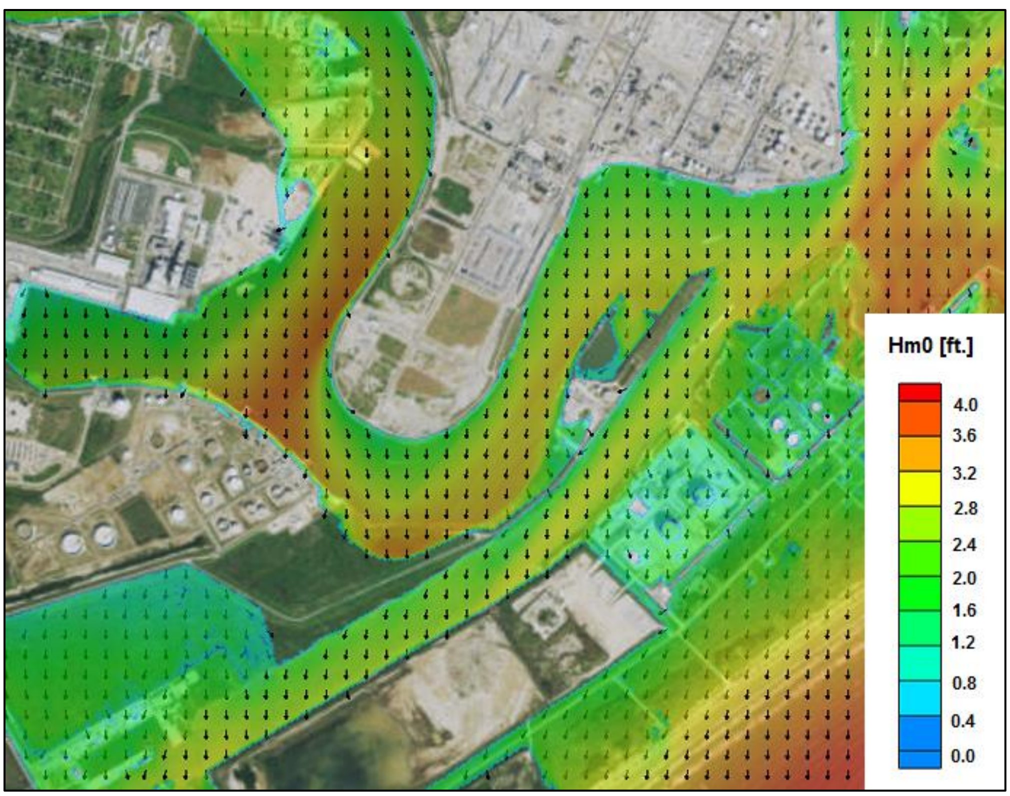


Wave Model Result: No Action Alternative, NNW Winds, Future Sea Level

Alternative 2, Wind Direction: N

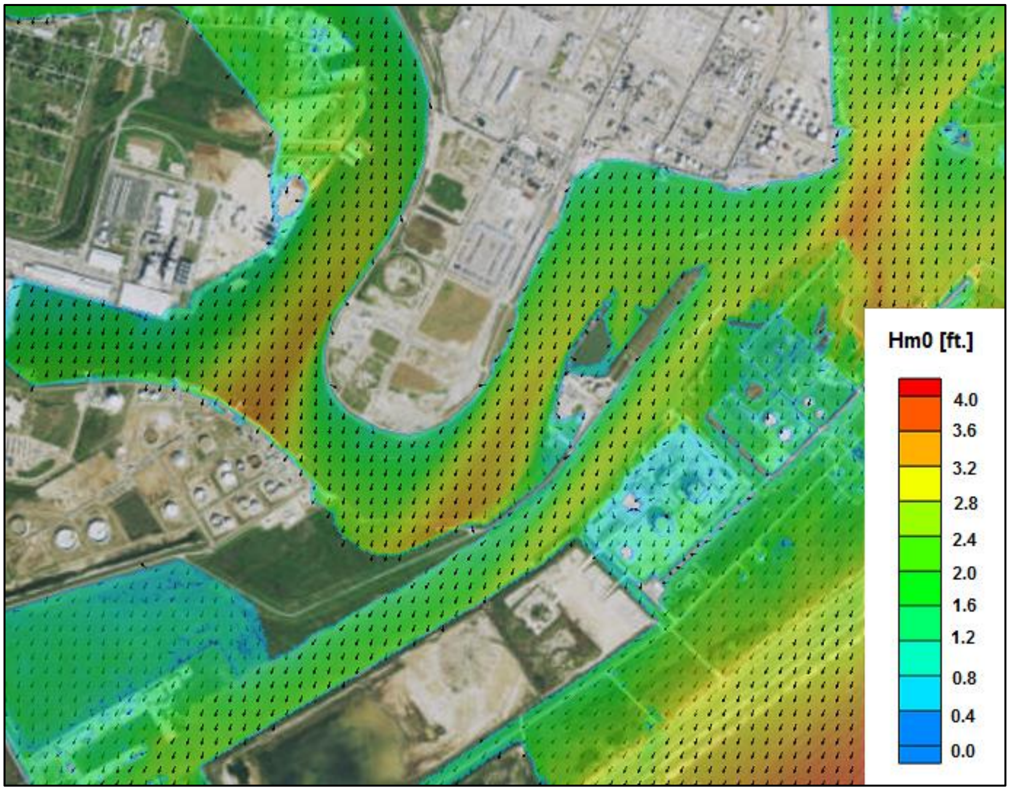


Wave Model Result: Alternative2, N Winds, Present Sea Level

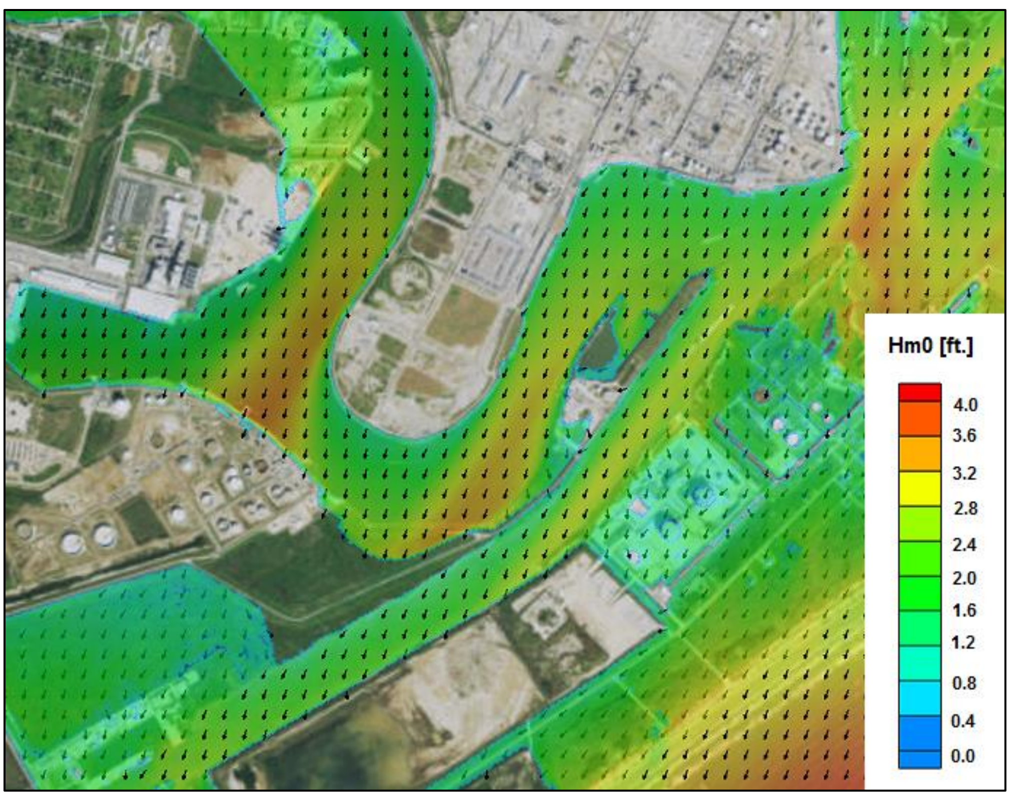


Wave Model Result: Alternative2, N Winds, Future Sea Level

Alternative 2, Wind Direction: NNE

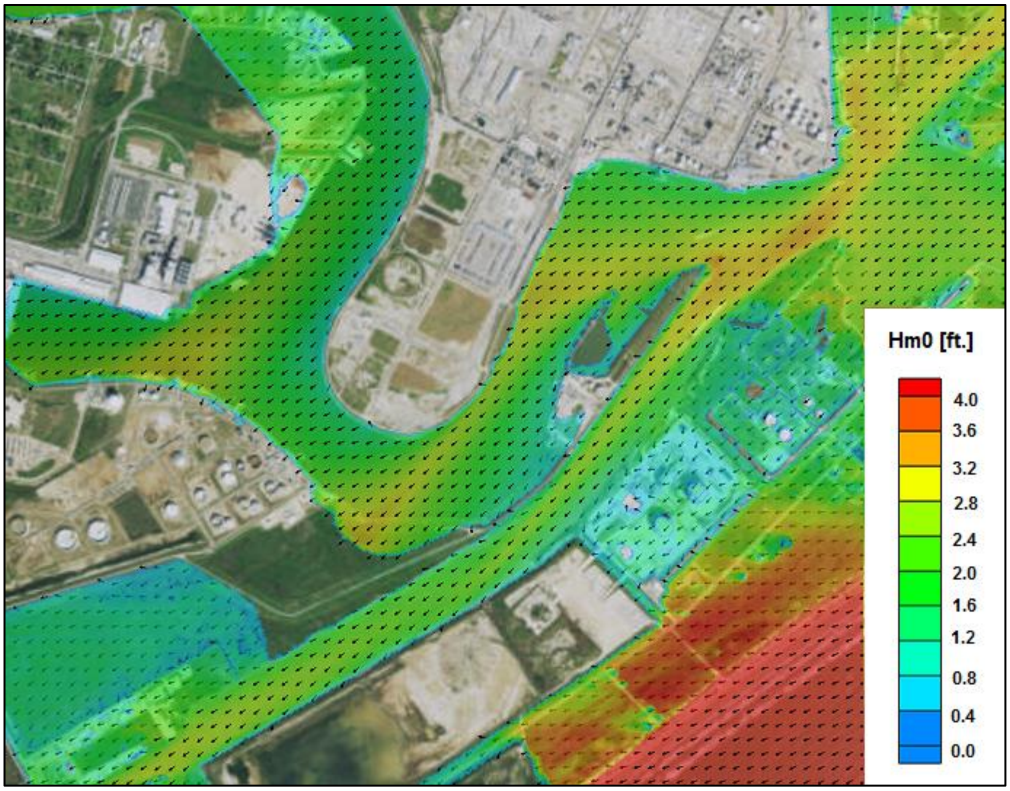


Wave Model Result: Alternative2, NNE Winds, Present Sea Level

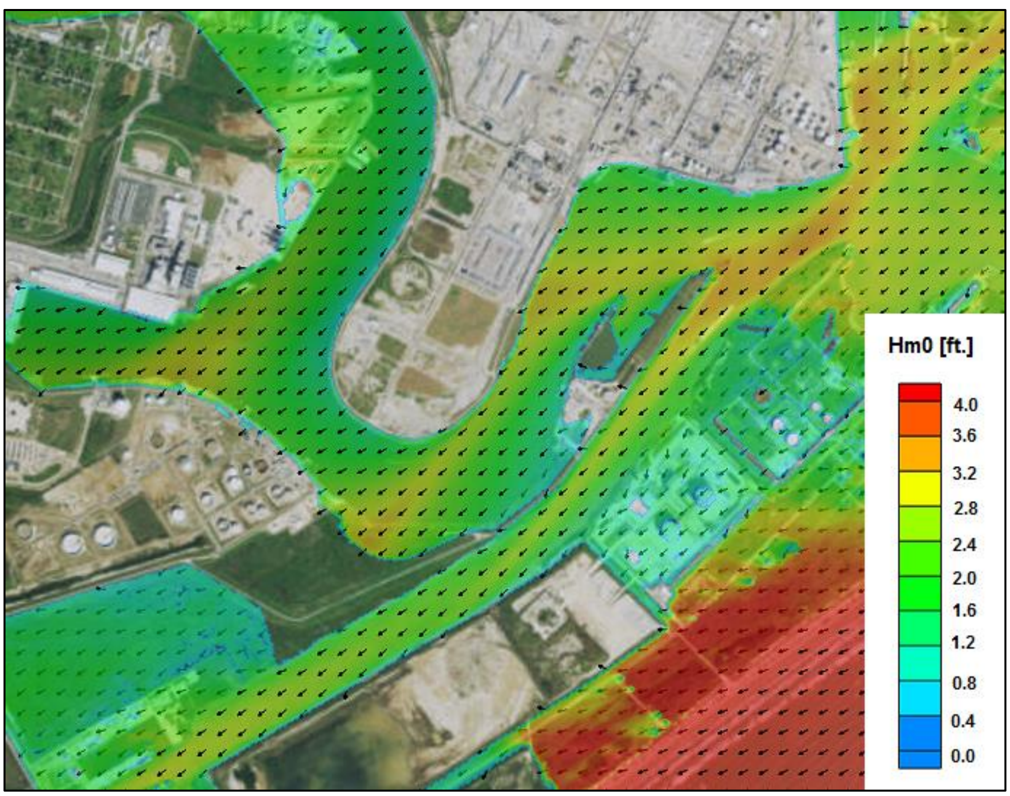


Wave Model Result: Alternative2, NNE Winds, Future Sea Level

Alternative 2, Wind Direction: NE



Wave Model Result: Alternative2, NE Winds, Present Sea Level



Wave Model Result: Alternative2, NE Winds, Future Sea Level

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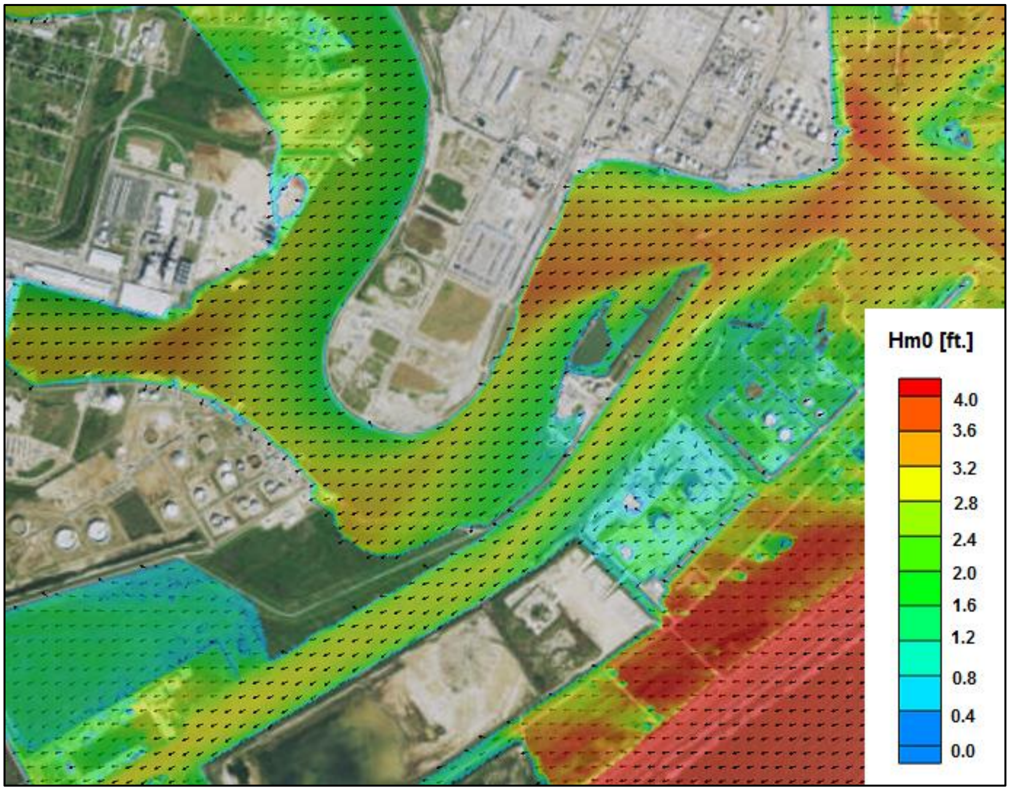
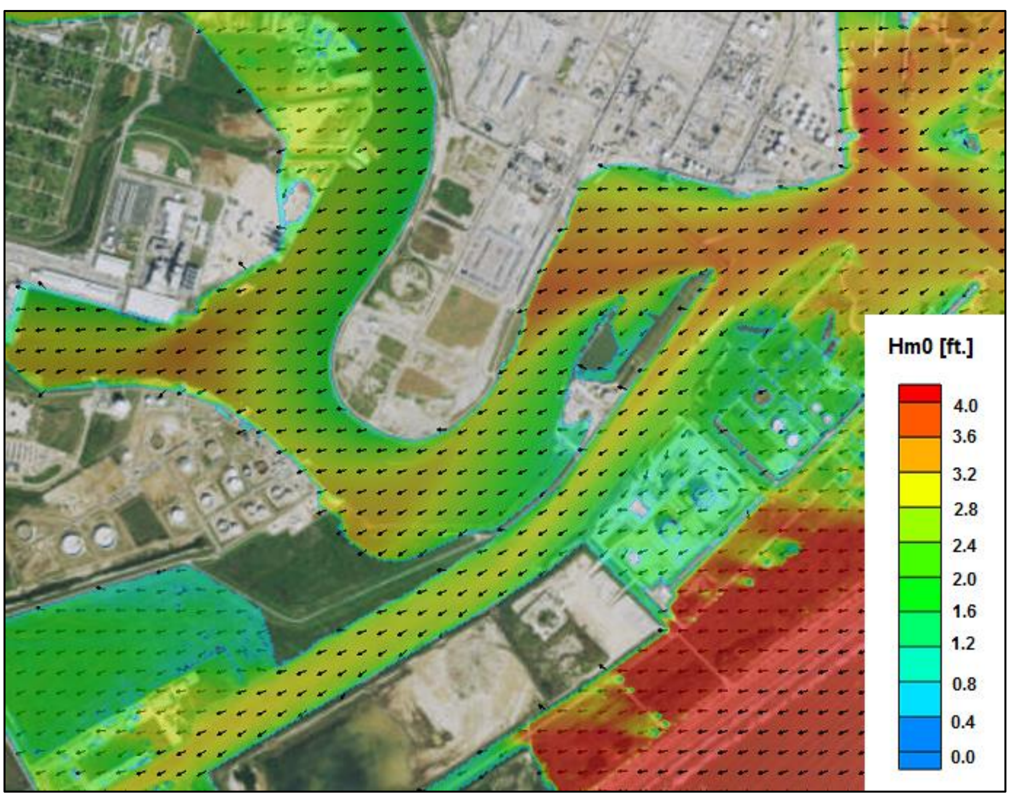
Alternative 2, Wind Direction: ENE

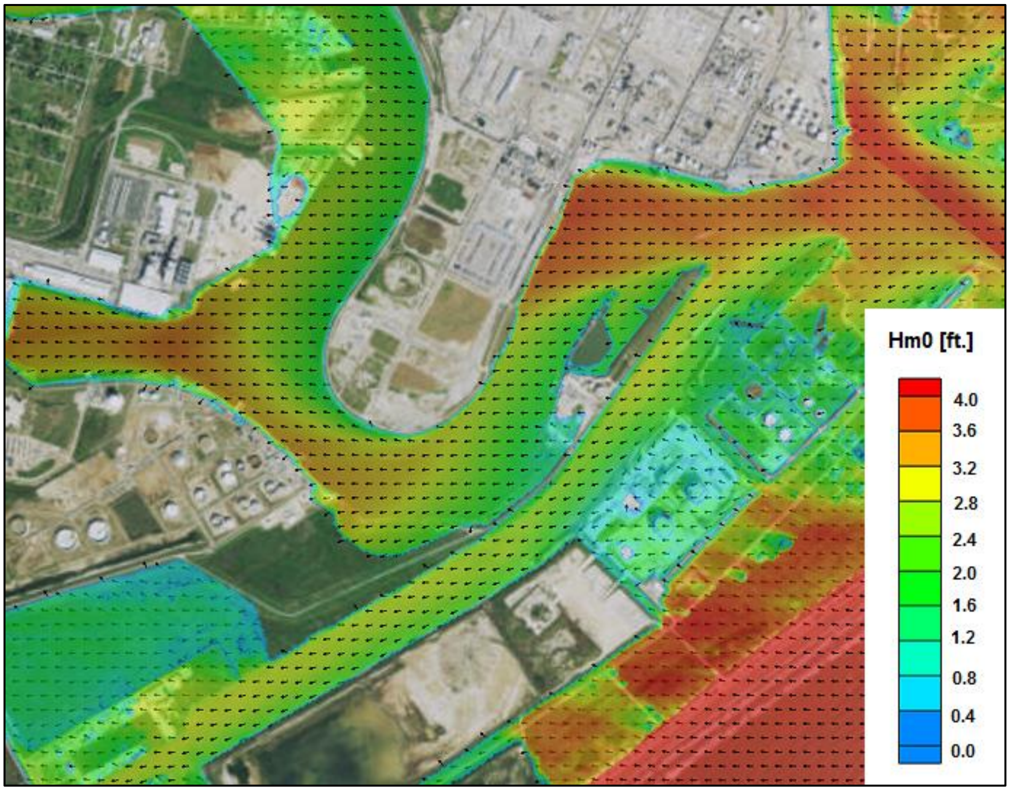


Wave Model Result: Alternative2, ENE Winds, Present Sea Level

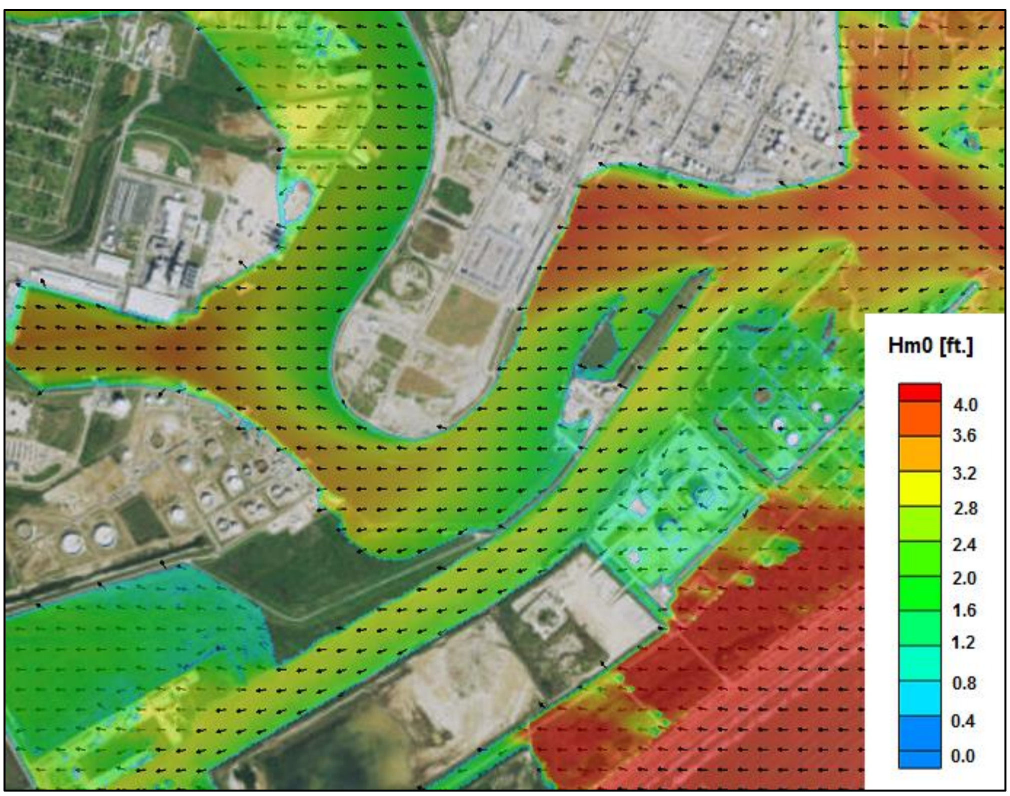


Wave Model Result: Alternative2, ENE Winds, Future Sea Level

Alternative 2, Wind Direction: E



Wave Model Result: Alternative2, E Winds, Present Sea Level



Wave Model Result: Alternative2, E Winds, Future Sea Level

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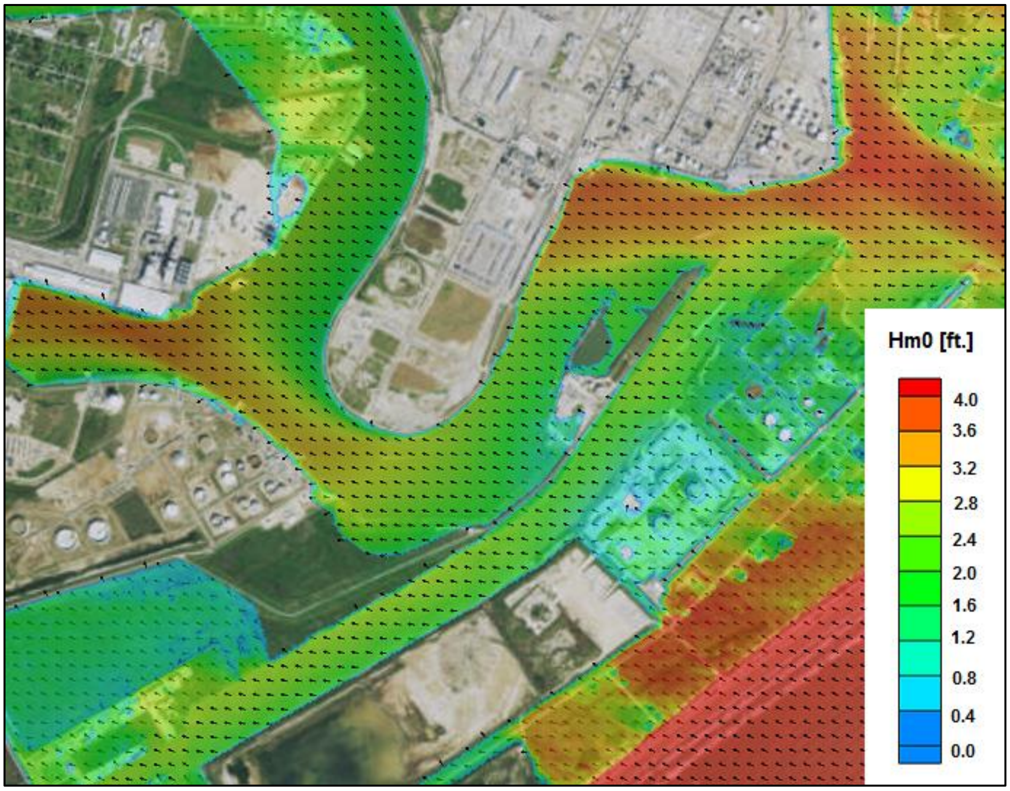
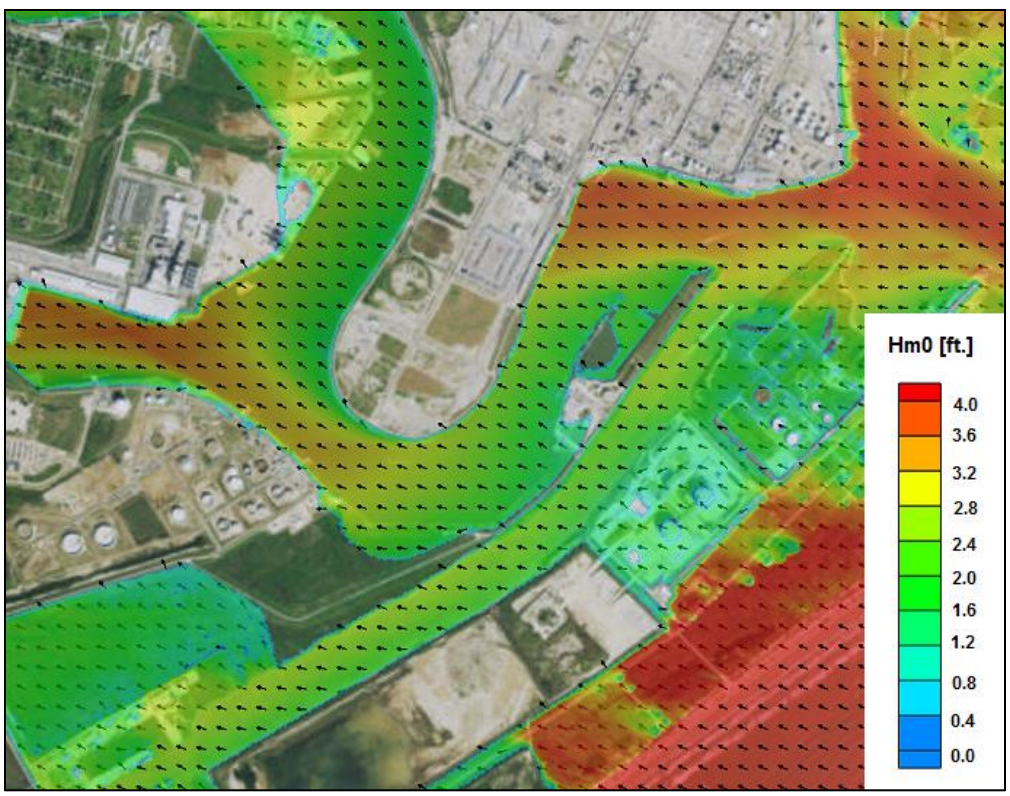
Alternative 2, Wind Direction: ESE

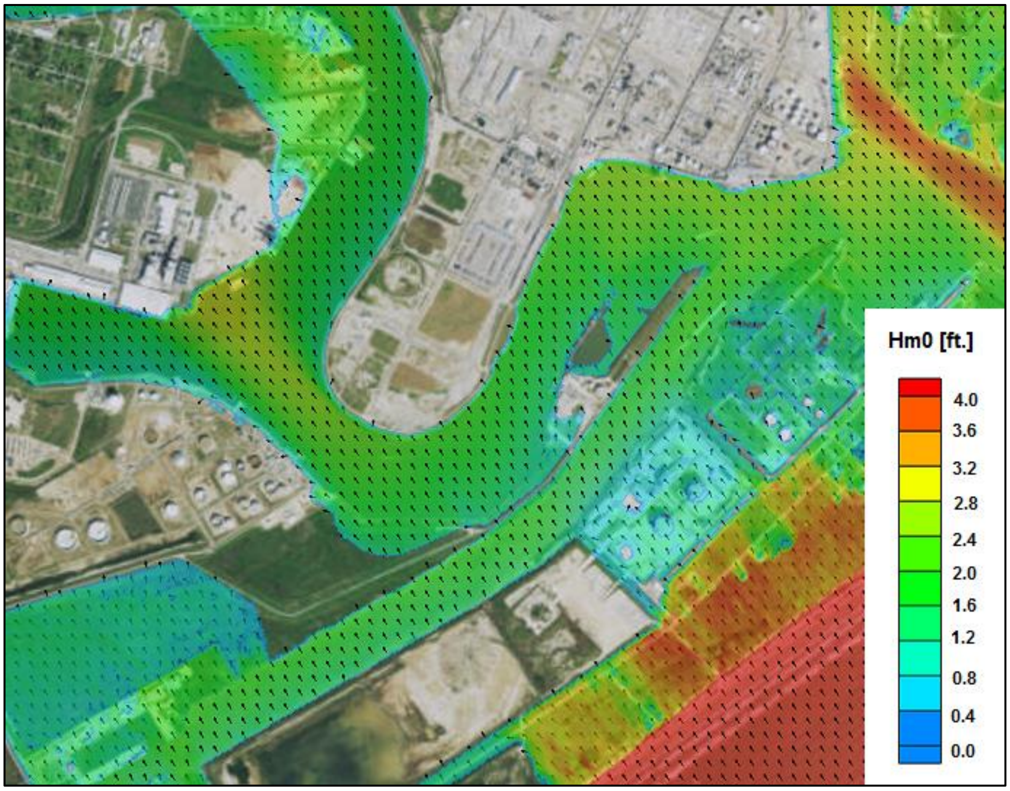


Wave Model Result: Alternative2, ESE Winds, Present Sea Level

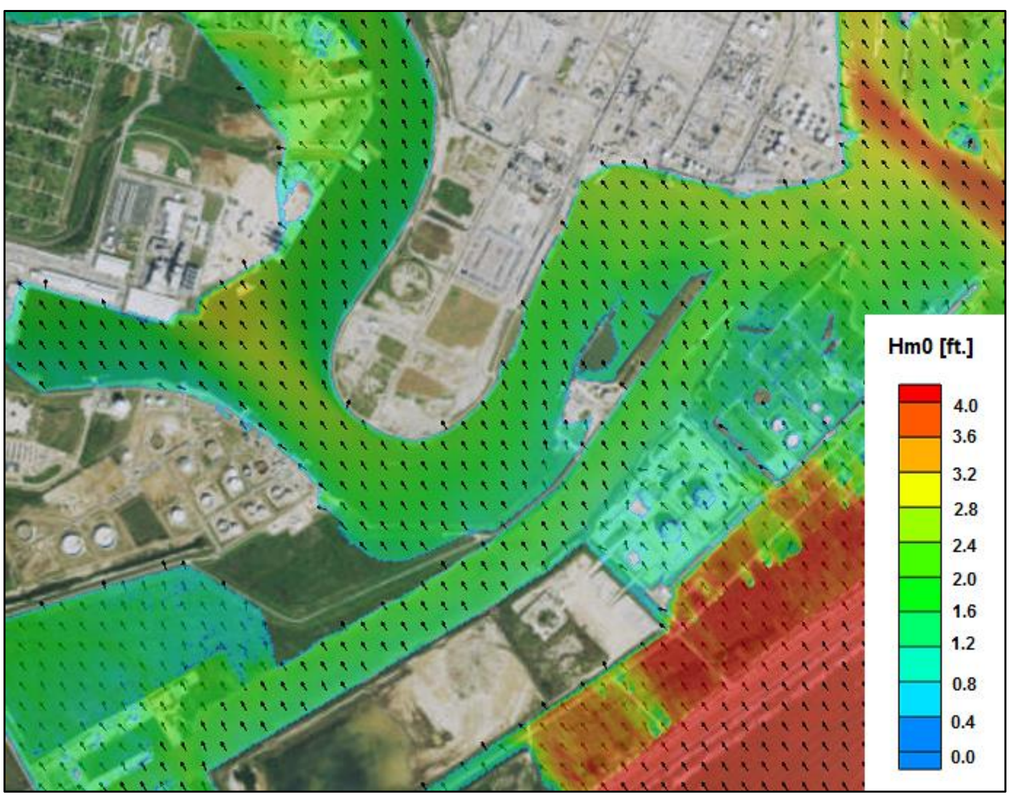


Wave Model Result: Alternative2, ESE Winds, Future Sea Level

Alternative 2, Wind Direction: SE



Wave Model Result: Alternative2, SE Winds, Present Sea Level



Wave Model Result: Alternative2, SE Winds, Future Sea Level

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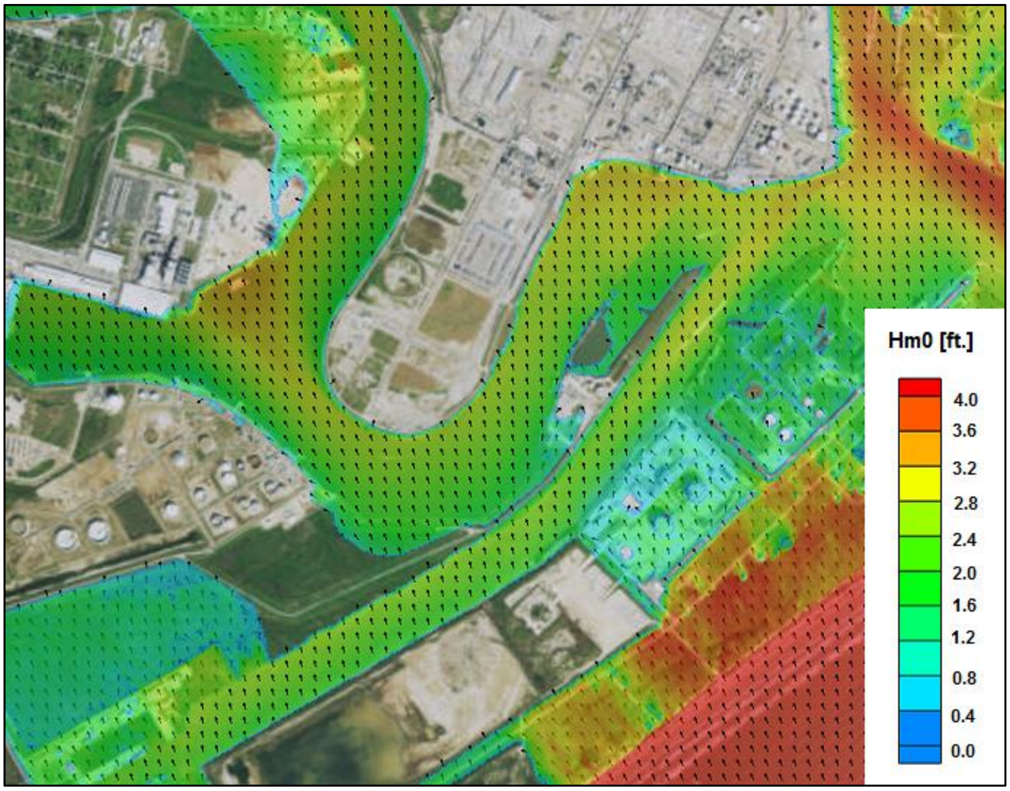
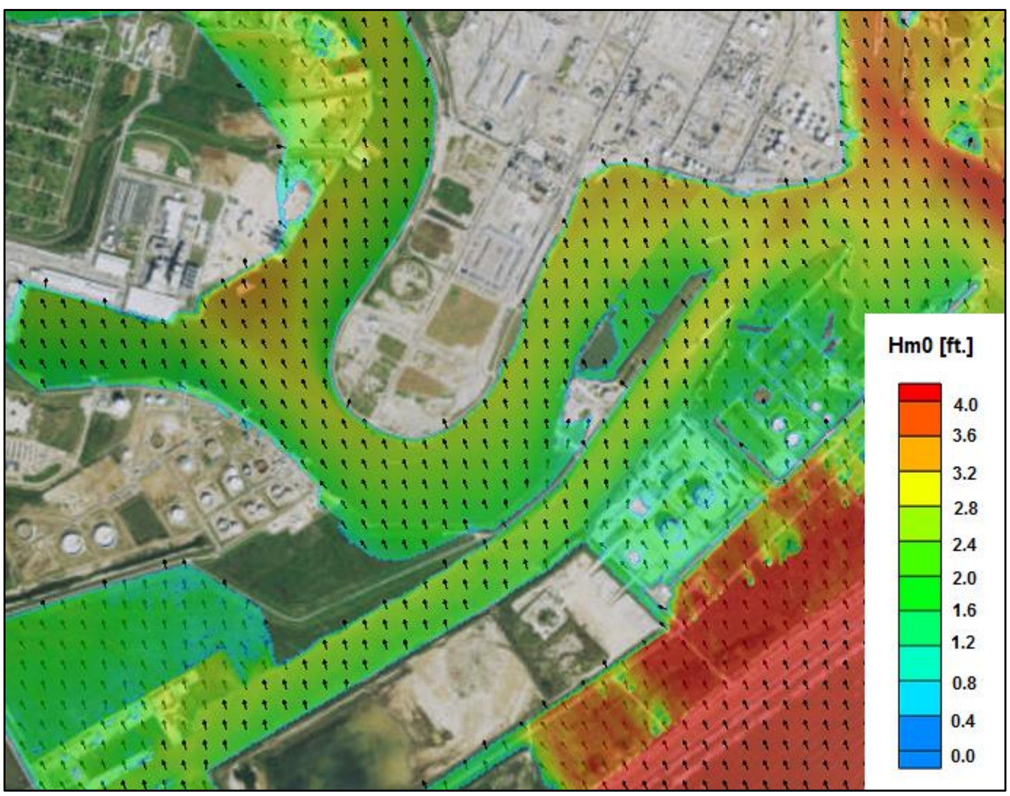
Alternative 2, Wind Direction: SSE

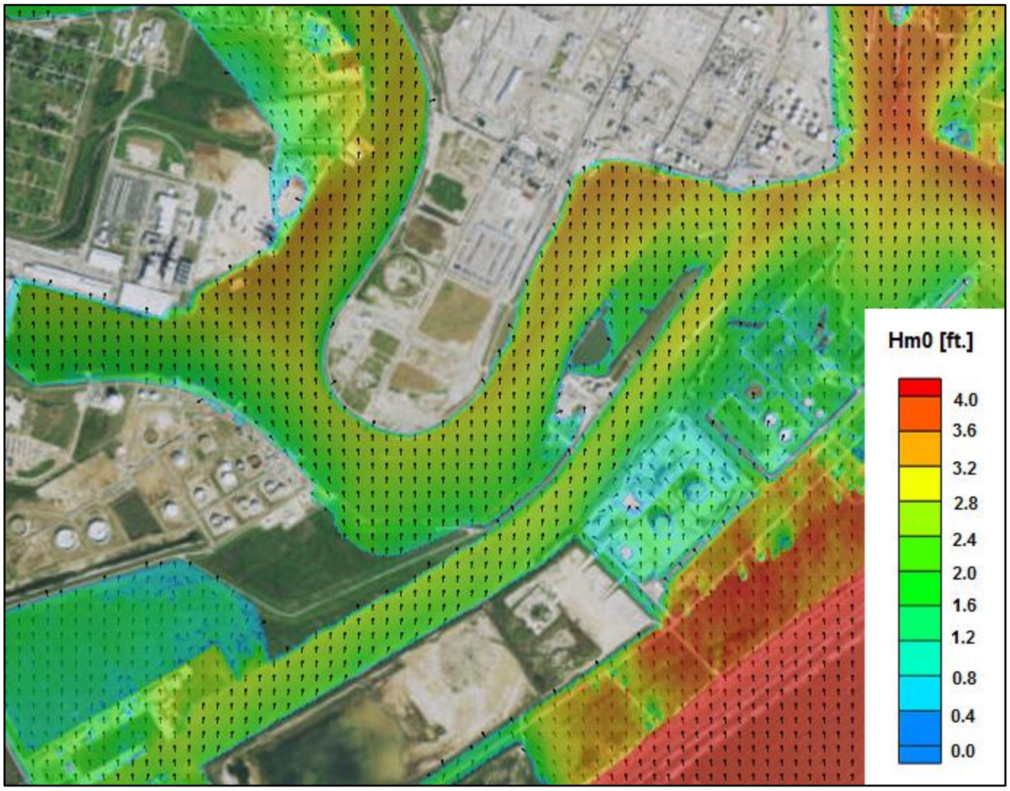


Wave Model Result: Alternative2, SSE Winds, Present Sea Level

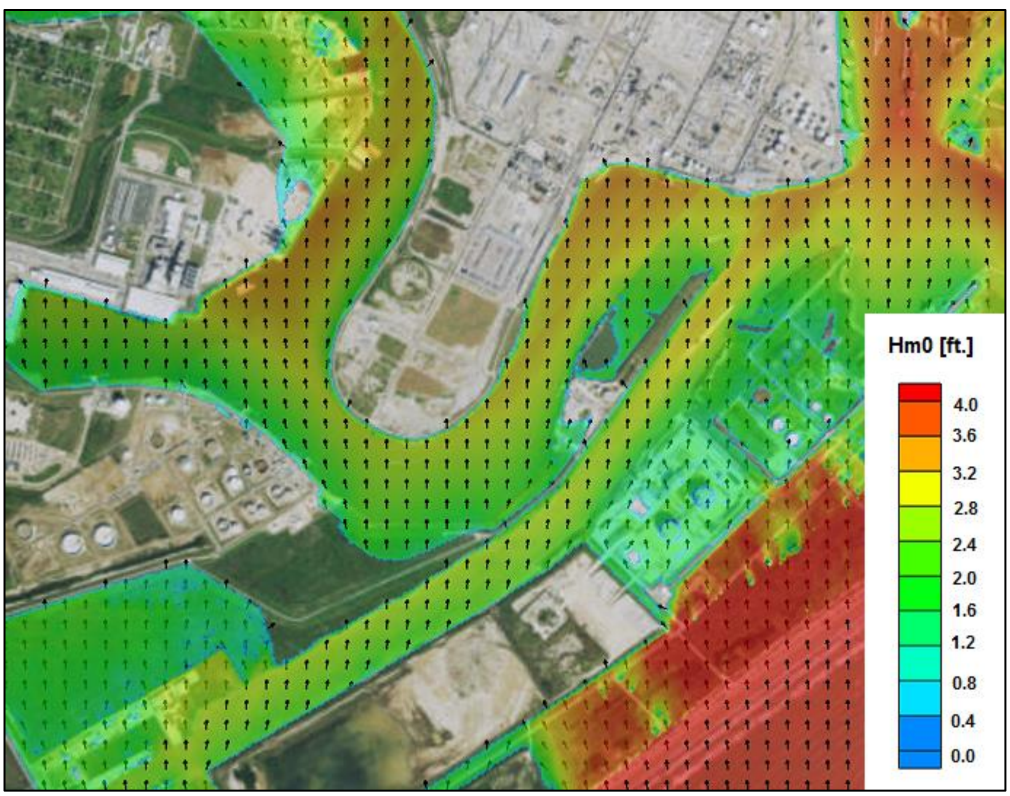


Wave Model Result: Alternative2, SSE Winds, Future Sea Level

Alternative 2, Wind Direction: S

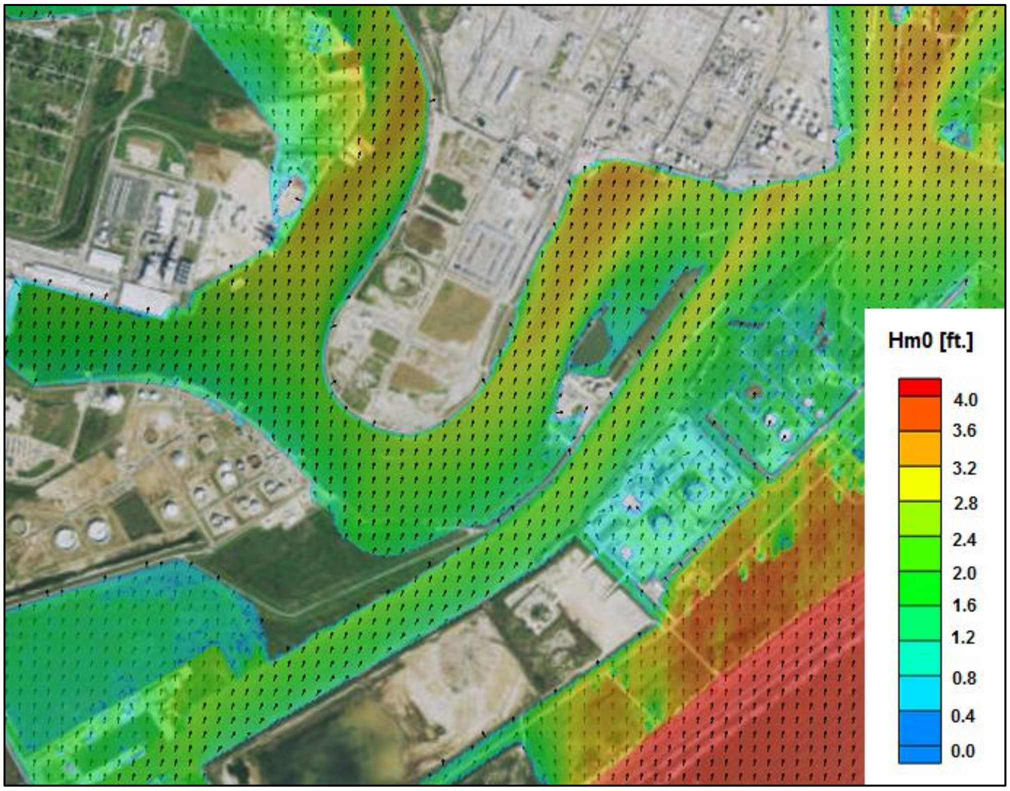


Wave Model Result: Alternative2, S Winds, Present Sea Level

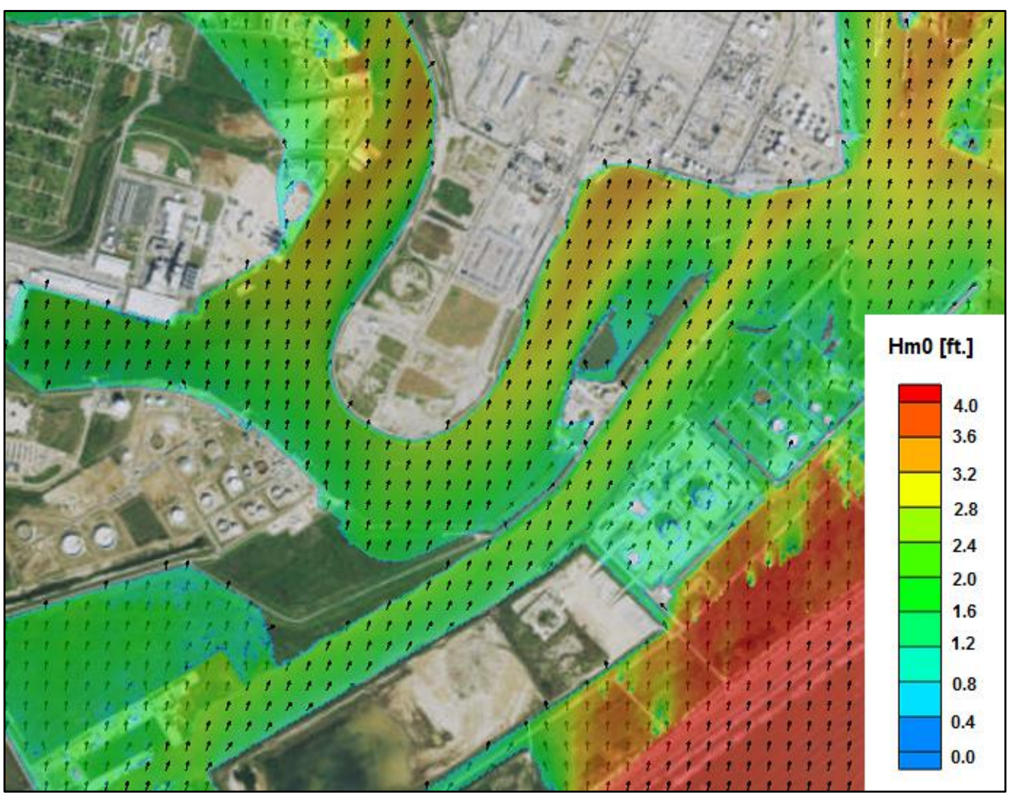


Wave Model Result: Alternative2, S Winds, Future Sea Level

Alternative 2, Wind Direction: SSW

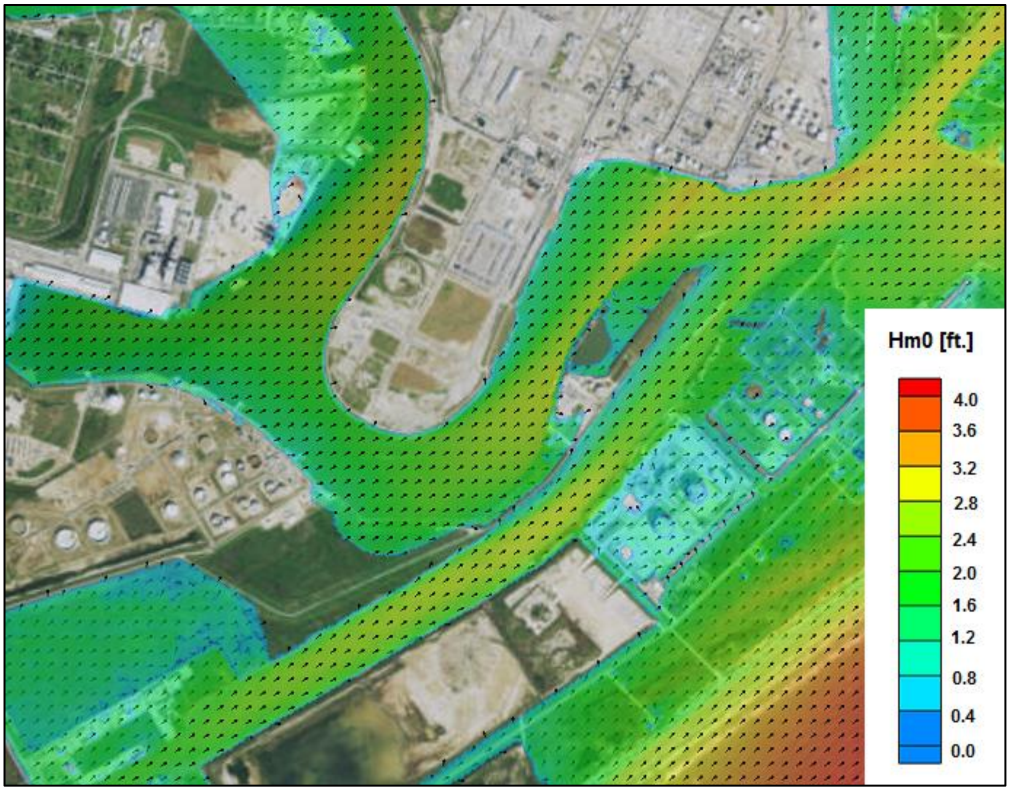


Wave Model Result: Alternative2, SSW Winds, Present Sea Level

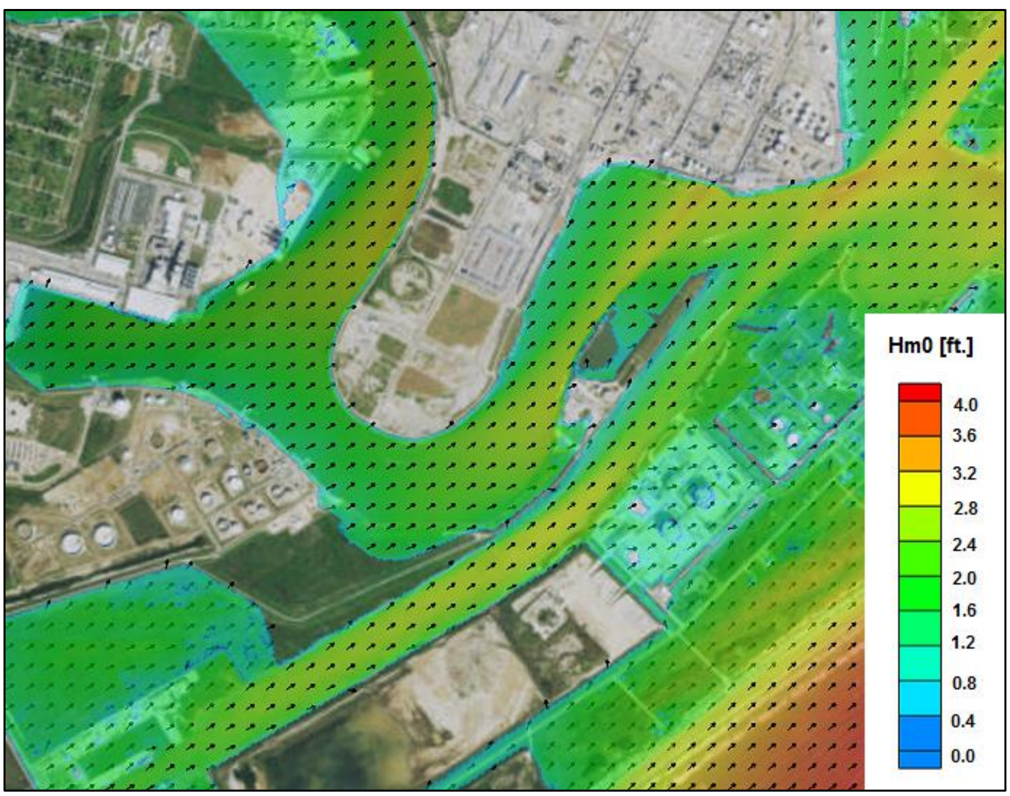


Wave Model Result: Alternative2, SSW Winds, Future Sea Level

Alternative 2, Wind Direction: SW



Wave Model Result: Alternative2, SW Winds, Present Sea Level



Wave Model Result: Alternative2, SW Winds, Future Sea Level

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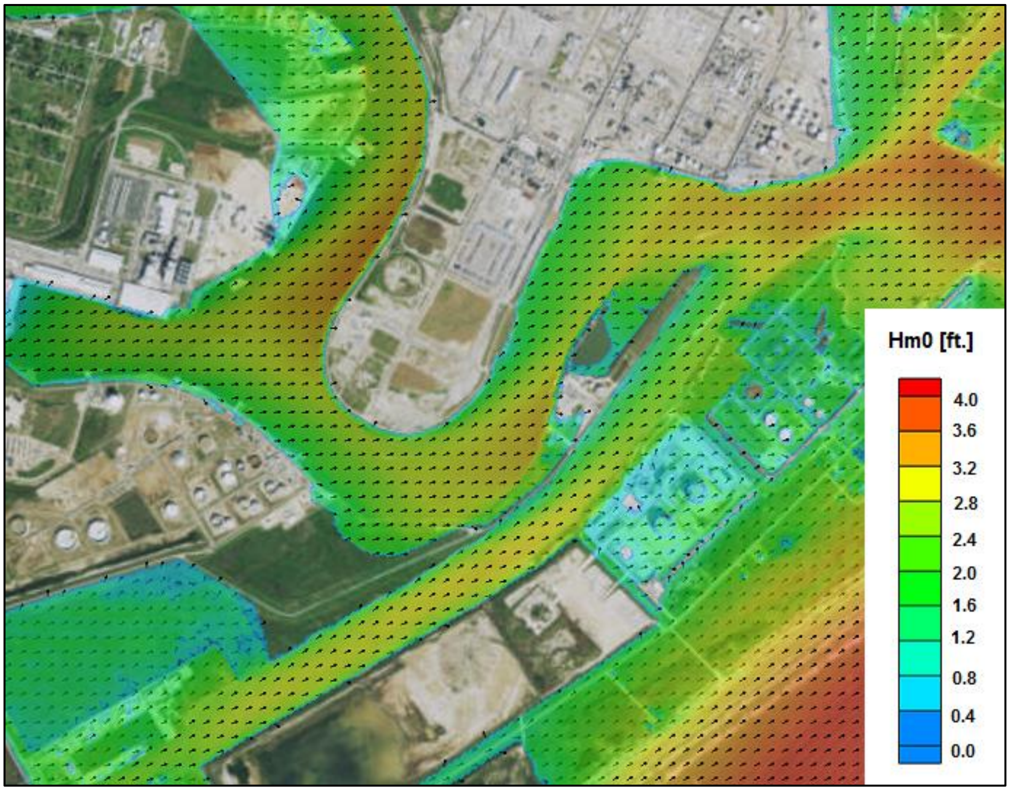
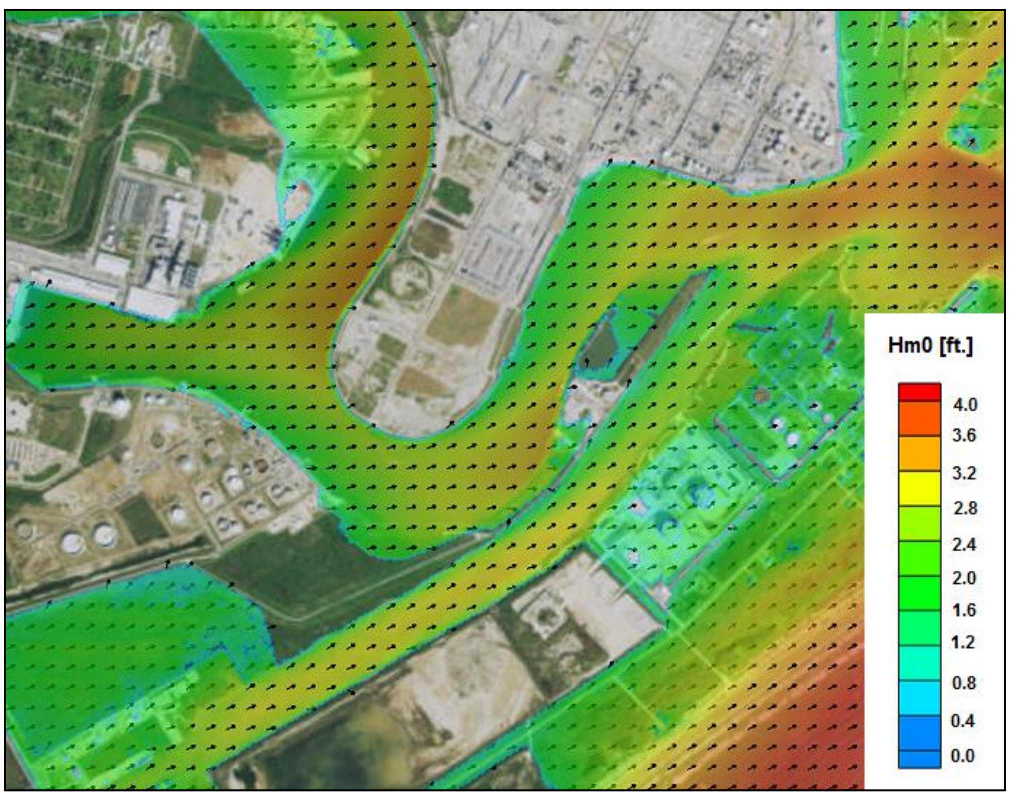
Alternative 2, Wind Direction: WSW

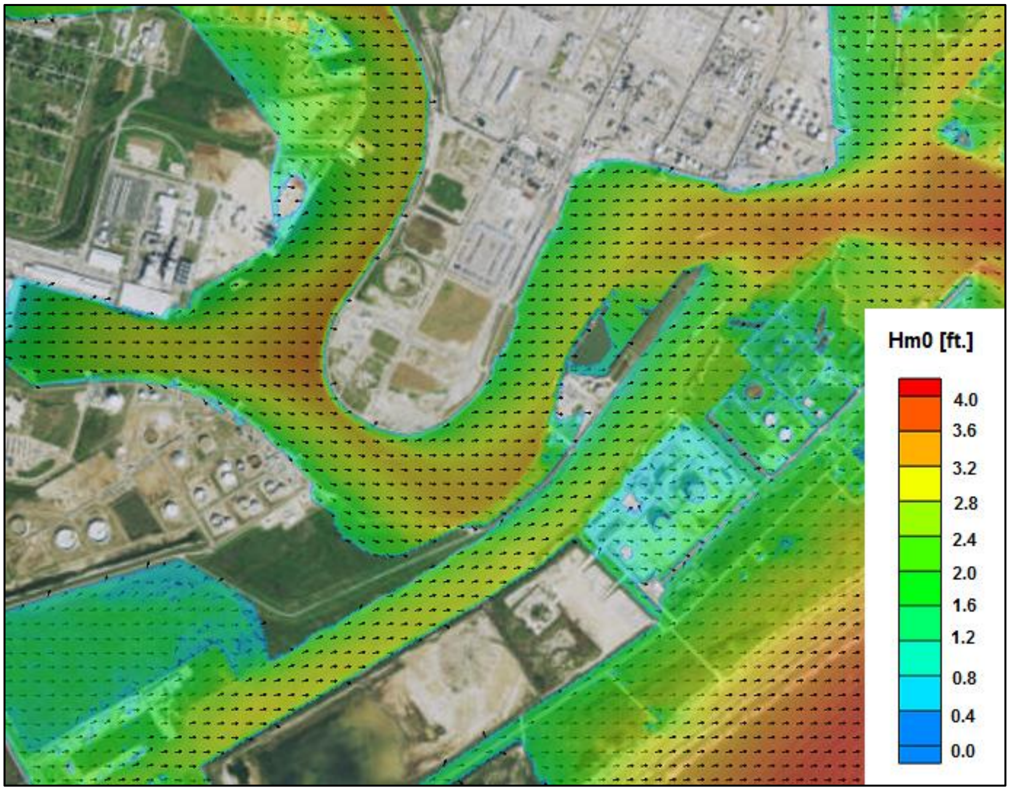


Wave Model Result: Alternative2, WSW Winds, Present Sea Level

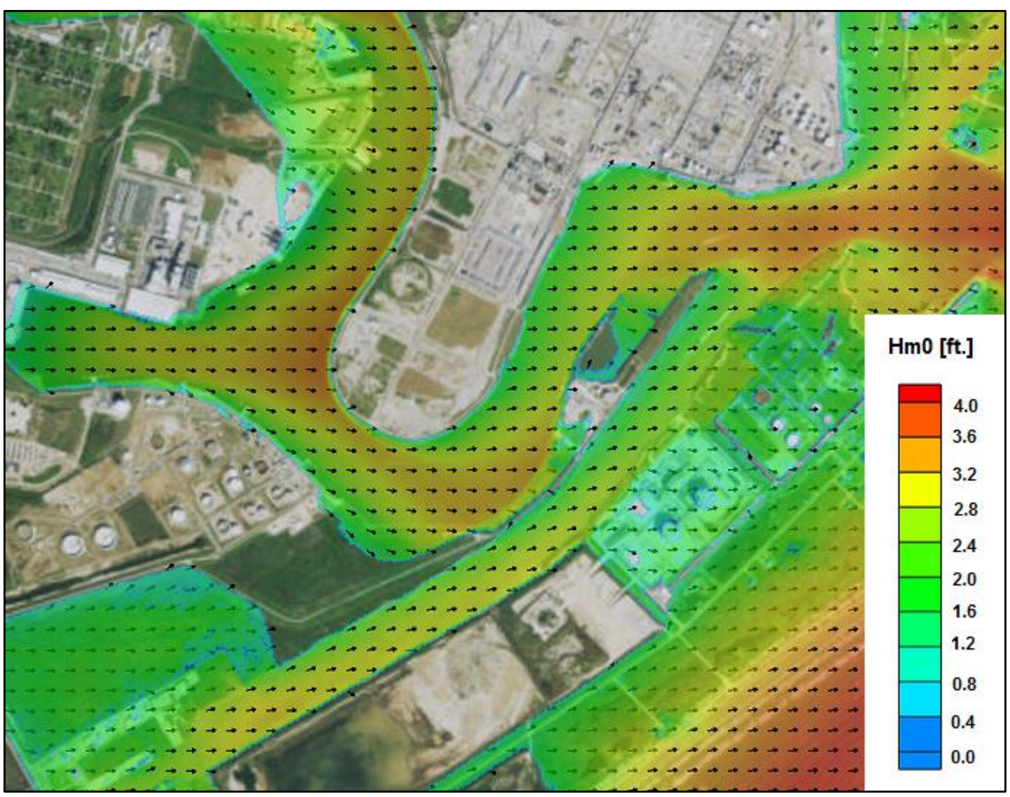


Wave Model Result: Alternative2, WSW Winds, Future Sea Level

Alternative 2, Wind Direction: W

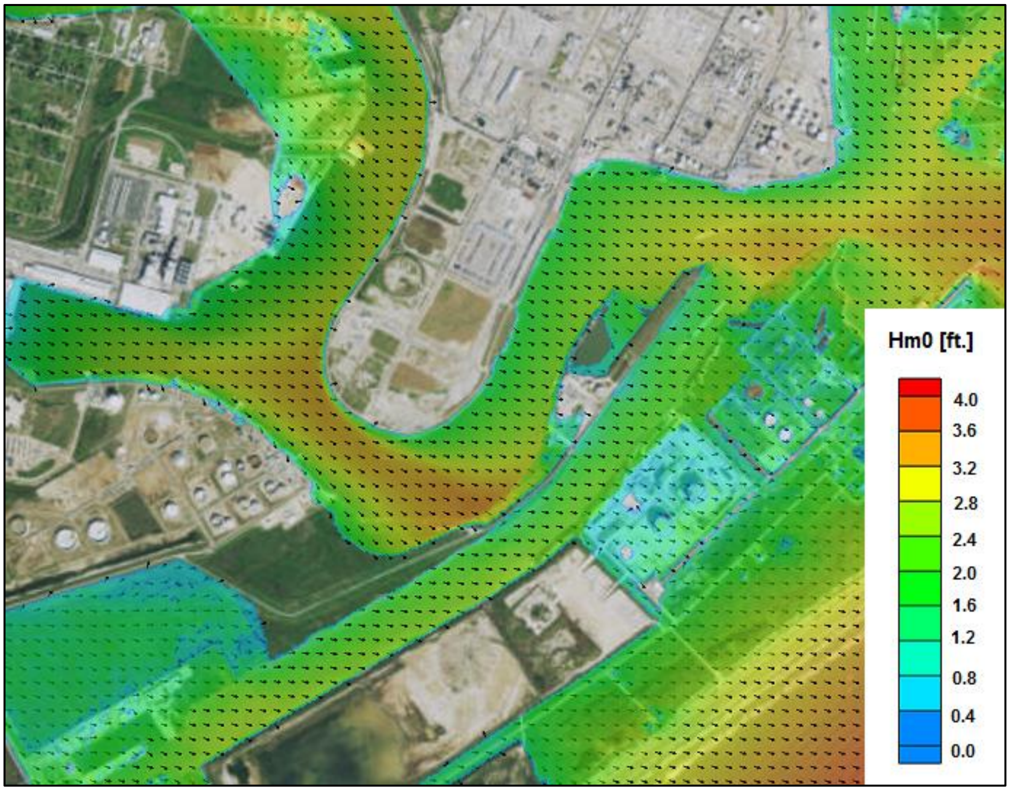


Wave Model Result: Alternative2, W Winds, Present Sea Level

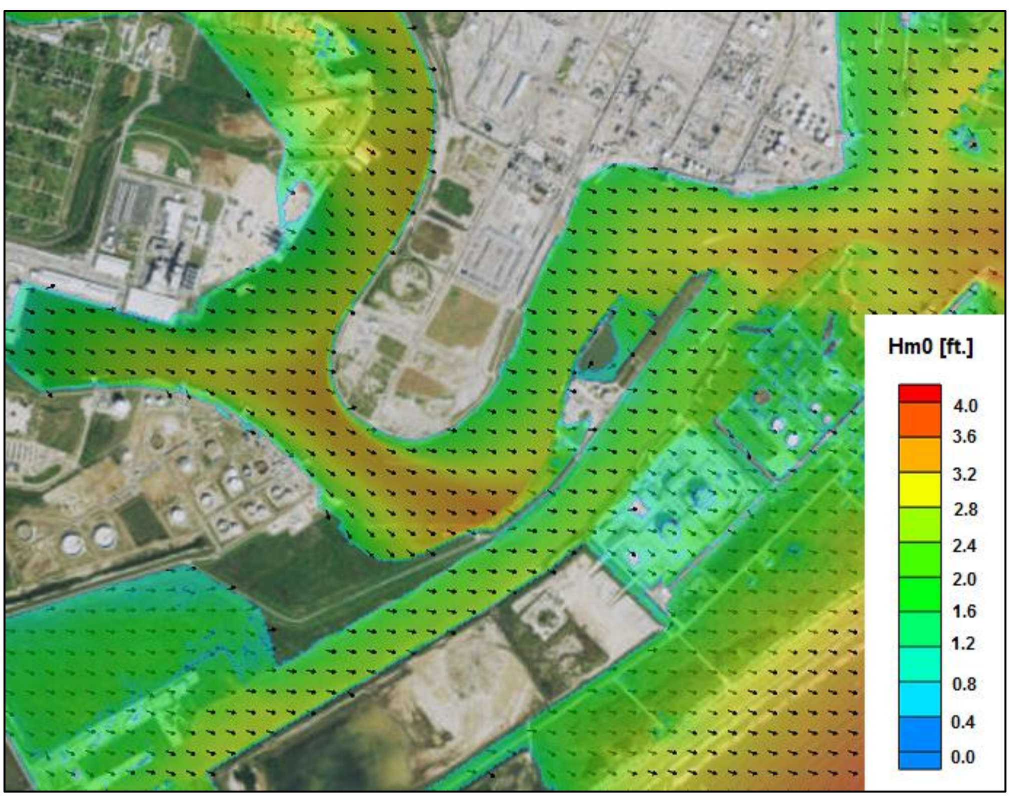


Wave Model Result: Alternative2, W Winds, Future Sea Level

Alternative 2, Wind Direction: WNW

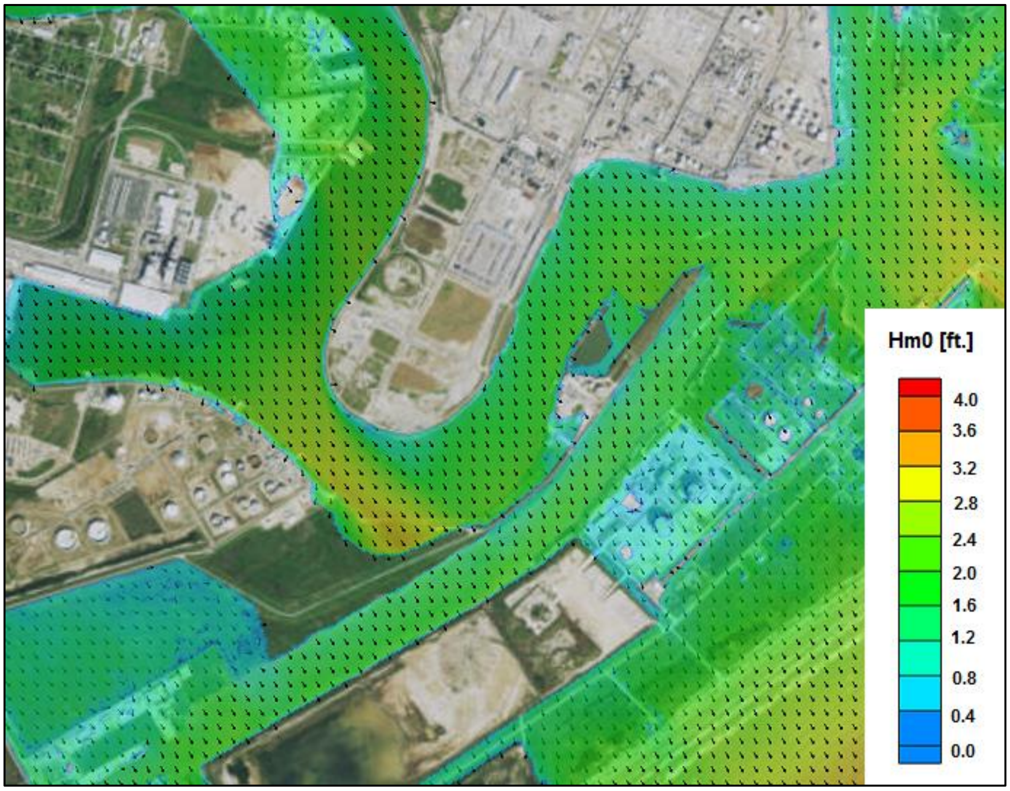


Wave Model Result: Alternative2, WNW Winds, Present Sea Level

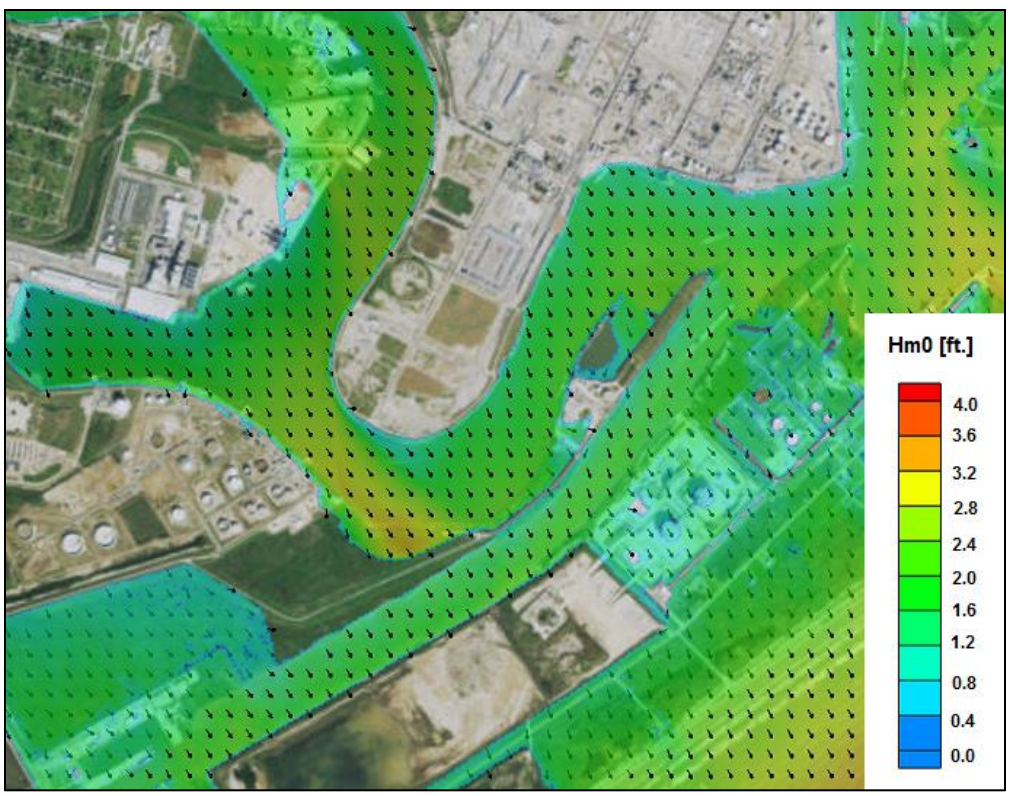


Wave Model Result: Alternative2, WNW Winds, Future Sea Level

Alternative 2, Wind Direction: NW



Wave Model Result: Alternative2, NW Winds, Present Sea Level



Wave Model Result: Alternative2, NW Winds, Future Sea Level

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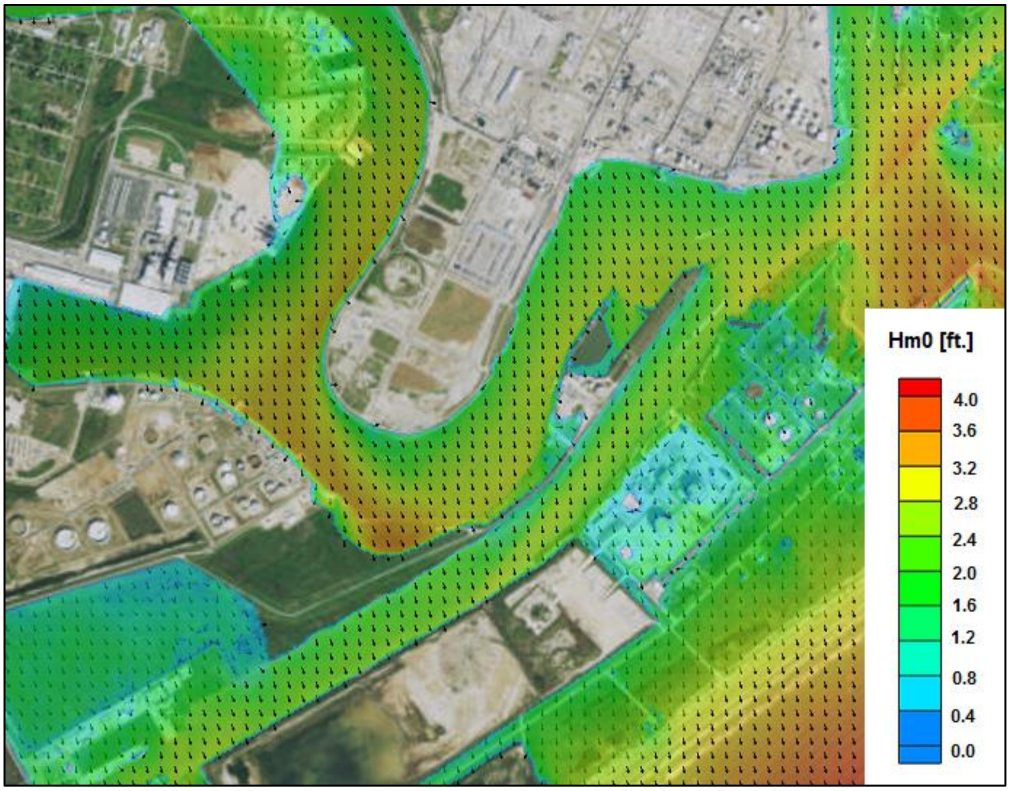
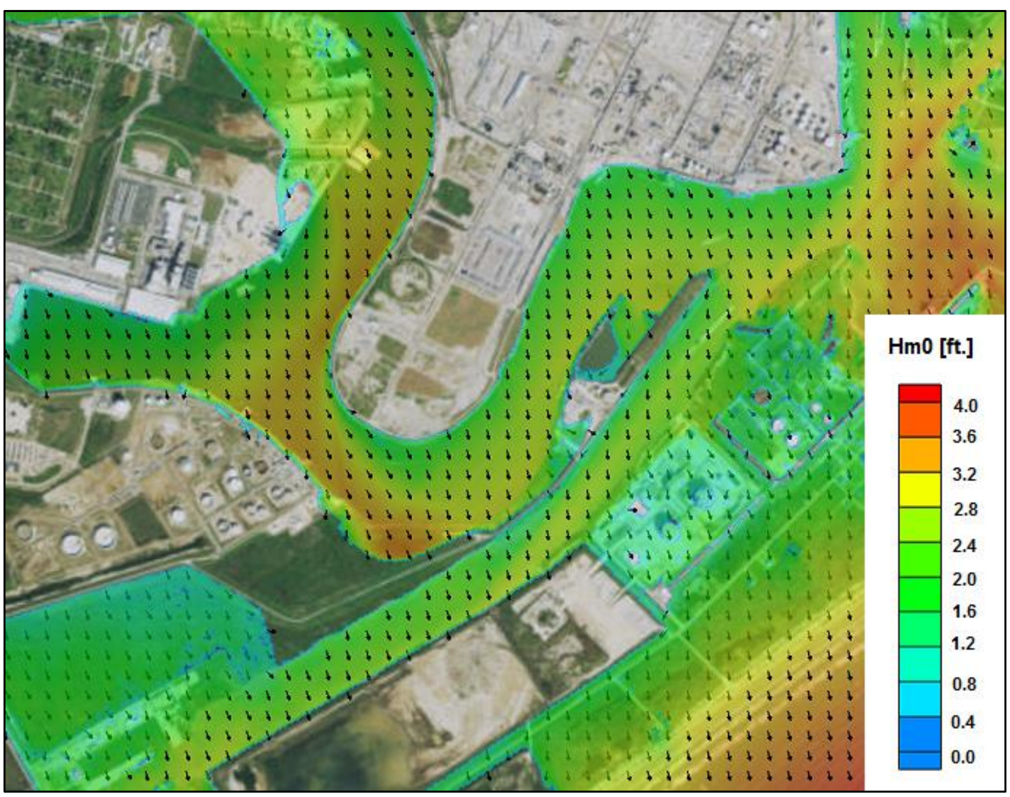
Alternative 2, Wind Direction: NNW



Wave Model Result: Alternative2, NNW Winds, Present Sea Level



Wave Model Result: Alternative2, NNW Winds, Future Sea Level