Appendix H

Vessel Wake Analysis

Note: The Section 508 amendment of the Rehabilitation Act of 1973 requires that the information in Federal documents be accessible to individuals with disabilities. The USACE has made every effort to ensure that the information in this appendix is accessible. However, this appendix is not fully compliant with Section 508, and readers with disabilities are encouraged to contact Mr. Jayson Hudson at the USACE at (409) 766-3108 or at SWG201900067@usace.army.mil if they would like access to the information.

Port of Corpus Christi Authority Channel Deepening Project

Vessel Wake Analysis

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Port of Corpus Christi Authority Channel Deepening Project

Vessel Wake Analysis

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Revision	Date	Status	Comments	Prepared	Reviewed	Approved
A	01/25/2022	Draft	For Client Review	SG	LW	LW

Executive Summary

Freese & Nichols, Inc. (FNI) has engaged W.F. Baird & Associates Ltd. to provide coastal engineering and modeling services for the proposed Corpus Christi Channel Deepening project. The project will comprise deepening of the Outer and Approach Channels to 77 ft, and the Jetty Channel and seaward-most portion of the Corpus Christi Ship Channel to 75 ft. The channel will be used by vessels including laden VLCC's at a maximum draft of 68 ft departing from the planned Axis and Harbor Island terminals. A vessel wake analysis as described in this report was part of these studies developed for the purposes of assessing project adequacy for the Environmental Impact Statement. The study included an analysis of vessel transits and modeling of vessel transits and the resulting bed and shoreline change under channel scenarios with and without the channel deepening project.

Vessel induced wakes consist of both a primary and secondary wave and the magnitude of each (both absolute and relative) are a function of the vessel characteristics, speed through water and channel geometry. Being a constrained deep dredged channel with vessels traveling at relatively low speeds, the primary wave is dominant along the Corpus Christi channel for large tanker vessels. The constrained channel increases the primary drawdown wave, while typical vessel speeds result in relatively small secondary waves that reduce in magnitude as they propagate away from the vessel. As a result, the primary wave is the predominant driver for bed and shoreline change.

An estimate of annualized bed and shoreline change as a result of vessel wakes was made with a comparison of the following:

- Suezmax results compare the Future Without Project (FWOP) channel scenario against the FWP channel scenario with no change in traffic numbers.
- VLCC results compare the Future With Project (FWP) channel scenario with 2022 traffic projections against the FWP channel scenario with 2023 traffic projections (5% increase in VLCCs)

A comparison of the FWOP and FWP channel scenarios for both the Suezmax and VLCC indicate that there would be very limited change in bed morphology as a result of the channel deepening project. In general, the bed morphology results suggest a scouring pattern on the channel shoulders with sedimentation along top of channel bank and no sedimentation within the channel bed width for all scenarios. Some localized changes are observed for the FWP channel scenario; however, these are not considered significant.

Consistent with the bed change results, shoreline change modeling indicates that changes in vessel wakes as a result of the channel deepening project will have minimal impact on the future evolution of natural shorelines along the length of the Corpus Christi Shipping channel. A general recession trend is observed in the analysis of historical shoreline positions and the annual shoreline change modeling, however no discernable increase in the recessional trend as a result of the project could be identified.

In addition, both the vessel wake bed change and shoreline change modeling indicate that any change in vessel hydrodynamics due to the future project condition will not contribute to an increase in sedimentation within federal navigation channels.

Table of Contents

Tables

Figures

1. Introduction

1.1 Project Background

W.F. Baird & Associates Ltd. (Baird) was engaged by Freese & Nichols, Inc. (FNI) to provide coastal engineering and modeling services for the Corpus Christi Ship Channel Deepening Project (CDP). The project is the proposed deepening of the Offshore Channel to a nominal depth of 77 ft (Segments 1 and 2 in Figure 1.1), and the Entrance Channel and seaward-most portion of the Corpus Christi Ship Channel to 75 ft (Segments 3 to 6 in Figure 1.1). The channel will service the planned Harbor Island and Axis terminals with laden vessels, including very large crude carriers (VLCC's), departing from these terminals.

DREDGING PLAN

SCALE: 1" = 8000'

SEGMENT	STATIONING (@ CHANNEL CL)		*DEPTH (FT BELOW MLLW)	DESCRIPTION	PLAN VIEW LEGEND
	FROM	TO			
1	STA -620+00	STA -330+00	-77.0	*Outer Channel*	
2	STA -330+00	STA -72+50	-77.0	*Approach Channel*	
3	STA -72+50	STA -20+00	-75.0	*Jetties to Harbor Island Transition Flare*	
4	STA -20+00	STA 20+82.07	-75.0	*Harbor Island Transition Flare*	
5	STA 20+82.07	STA 38+16.43	-75.0	*Harbor Island Junction*	
6	STA 38+16.43	STA 110+00	-75.0	*Corpus Christi Channel*	

* DESIGN DEPTH SHOWN. DOES NOT INCLUDE 2.0 FT ADVANCED MAINTENANCE DREDGING OR 2.0 FT ALLOWABLE OVER DREDGE.

Corpus Christi Ship Channel Deepening Project
Individual Permit Application SWG-2019-00067

Preferred Channel Alternative

County: Aransas and Nueces — State: Texas
Application By: Port of Corpus Christi Authority — Date: April 2020

Figure 1.1: Dredging plan for the Corpus Christi Ship Channel Deepening Project

Baird's services include the following tasks:

- Vessel wake analysis
- Dynamic Underkeel Clearance (UKC) study
- Propeller scour study
- Tidal and hydrodynamic modeling

- Storm surge analysis
- Sediment transport modeling

The vessel wake analyses are addressed in this Report.

1.2 Study Objectives

The objectives of the vessel wake analyses are to assess model vessel generated hydrodynamics, including primary drawdown/surge wave and secondary bow and stern waves, for proposed project vessel traffic following the channel deepening. Further, the potential impacts from the vessel generated hydrodynamics on adjacent shorelines and any contribution to sedimentation within federal navigation channels are to be considered.

1.3 Vessel Wake Definitions

Two main types of waves are generated by moving vessels:

- Primary (or drawdown) wave; and,
- Secondary waves caused by discontinuities in the hull profile (bow and stern waves).

These two main types of waves are schematically presented in Figure 1.2.

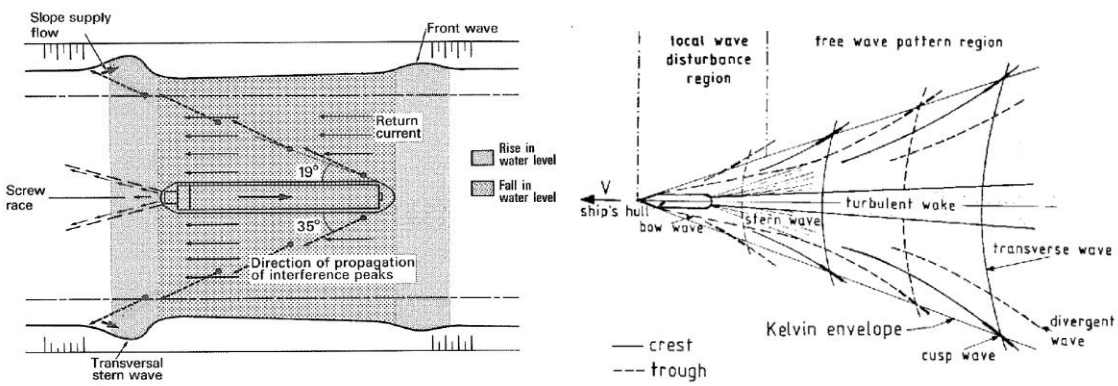


Figure 1.2: Schematics of the Primary (left, from PIANC, 1987) and Secondary (right, from CRISP, 2001) Waves Induced by Ship Motion

As the ship travels through the water, water flows past the vessel hull in the opposite direction of travel, known as the return current. This return flow causes the water level along the vessel's length to fall in order to maintain the total head (energy) constant and as a result the water level around the vessel is lowered. This water level depression is referred to as the primary or drawdown wave. In front of the vessel the water surface is elevated by the approaching vessel, known as the front waves, while in the transition between the water level depression and normal water level at the stern of the vessel is known as the transversal stern wave. When a vessel is in deep, open water the primary waves is of relatively small magnitude, however a vessel traveling at speed within a confined channel can generate a large drawdown wave. Further, this primary wave can interact with the channel slopes to shoal and propagate away from the vessel, as is observed at the Port of Corpus Christi.

Secondary waves are generated by surface oscillations at the bow and stern of the moving vessel that propagate away from the vessel as free surface waves. The free wave pattern spreads out from the vessel with decreasing wave amplitudes due to dispersion and diffraction and consists of symmetrical sets of diverging waves that move obliquely out from the sailing line and a single set of transverse waves that move in the direction of the sailing line. Two sets of diverging waves are generated (bow and stern).

The dominance of either the primary or secondary waves (in terms of magnitude) is highly dependent on the vessel (including draft), speed through water and waterway characteristics, however through the Corpus Christ channel primary waves are understood to be the dominant of the two and as a result produce the largest waves at the shoreline. This is due to the confined nature of the channel and large displacement of the tankers that amplify the primary wave, while typical vessel speeds for Suezmax and VLCCs are such that the secondary waves are lower magnitude and dissipate quickly as they propagate away from the vessel. Figure 1.3 presents examples along the Corpus Christi channel of tanker generated primary waves breaking at the shoreline. Figure 1.4 presents secondary wave patterns from a tanker in the Corpus Christi channel, indicating how the shorter period wakes dissipate relatively quickly away from the vessel.

Figure 1.3: Examples of Tanker Generated Primary Waves Breaking along the Shoreline of Corpus Christi Channel

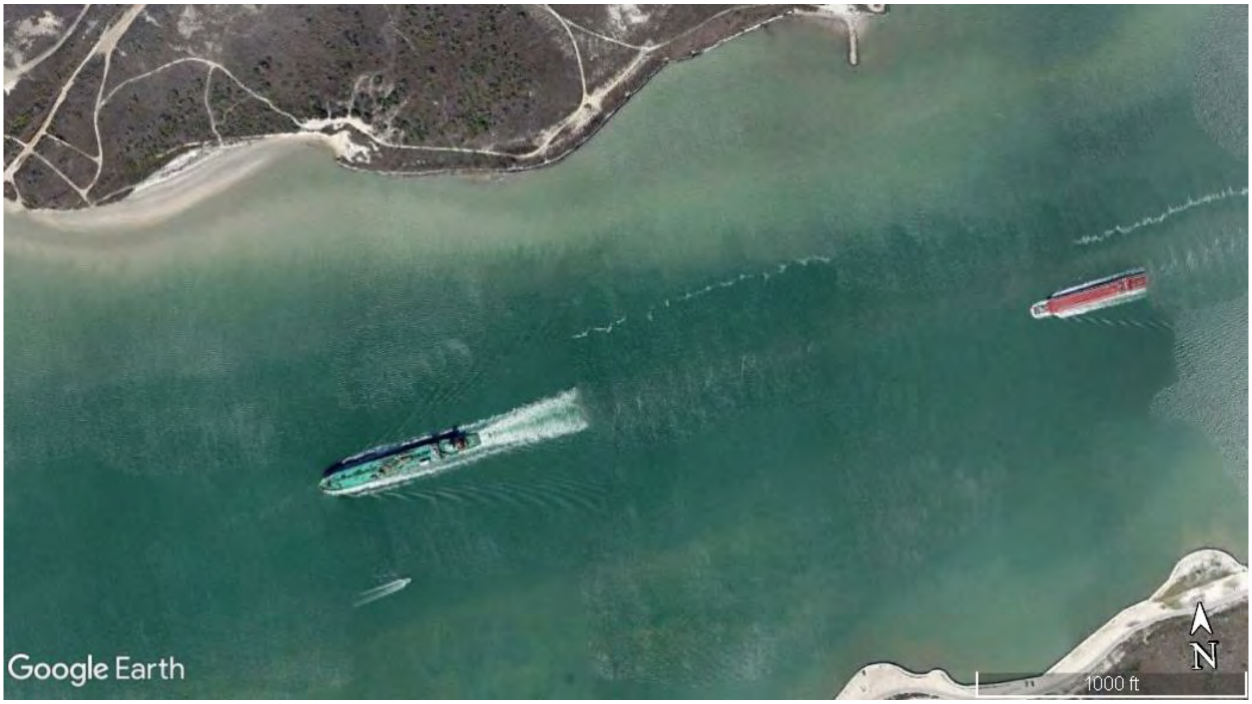


Figure 1.4: Example of Tanker Generated Secondary Waves in the Corpus Christi Channel

1.4 Report Outline

This report provides a brief description of the overall study methodology, model results and outcomes. The numerical models that are used to quantify the vessel generated hydrodynamics and shoreline response are summarized in Section 2. Input data to the vessel wake analyses are considered in Sections 3, including channel dimensions, vessel dimensions and vessel speeds. The vessel wake results are provided in Section 4 focusing on the vessel induced hydrodynamics. Sections 5 and 6 consider the associated bed change and shoreline responses by comparing the pre and post project scenarios. Conclusions are provided in Section 7.

2. Numerical Model Descriptions

Two numerical models were applied in these analyses. Vessel hydrodynamics, including the primary and secondary waves around the moving vessels, have been simulated in FUNWAVE with the results applied as boundary conditions to a series of XBEACH profile models to quantify the shoreline impacts to the change in vessel traffic.

2.1 FUNWAVE

FUNWAVE–TVD is the Total Variation Diminishing (TVD) version of the fully nonlinear Boussinesq wave model (FUNWAVE) developed by Shi et al. (2012). The central module of FUNWAVE solves the Boussinesq equations and also takes care basic functions such as wavemaker, wave breaking, sponge layers, boundary conditions and model input and output. More recently a ship-wake generation model has been implemented (Shi et al., 2018), that applies a moving vessel as either a pressure or slender source term in the model. While the FUNWAVE model allows various options to describe the shape of the vessel, Baird implemented an additional pressure source term that reads in a detailed vessel hull shape, such that the shape of the bow and stern for specific vessels are more accurately described in the simulation. Figure 2.1 presents an example of a VLCC hull shape as described in the model by Baird's updated source term.

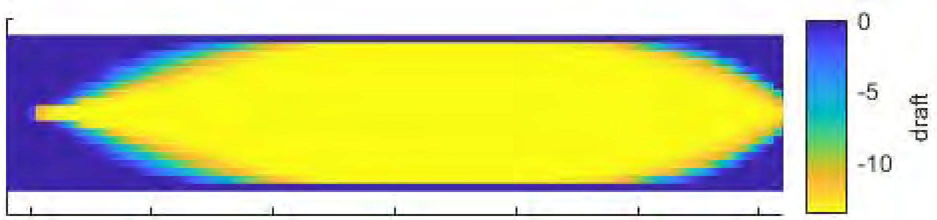


Figure 2.1: Example of a pressure field describing a VLCC hull shape in the FUNWAVE model

One notable limitation in the Boussinesq equations is the propagation of short period waves in deep water. For the specific case of large tankers at Port of Corpus Christ, modeling the channel and vessel at actual depth (i.e., >50ft) means that the short period secondary waves generated by the moving vessel cannot propagate away from the vessel due to the depth limitation of the Boussinesq equations.

To this end, a decoupled modeling approach has been adopted for this study, whereby the primary and secondary waves are modeled in separate simulations and the results combined into a post-processed result. The primary wave simulations are modeled at full depth, which is critical in quantifying the primary drawdown magnitude that is dependent on the relative depth of the vessel in the water column and the geometry of the channel. To ensure model stability for deep draft vessels with low underkeel clearance the 'Deep Draft Module' in FUNWAVE was activated for the primary wave simulations. The secondary wave simulations are modeled with a maximum depth of 15ft, and vessel draft that is proportional to the actual draft to water depth. This capping of the water depth to 15ft allows the short period secondary waves generated by the vessel (with periods less than 4s) to propagate in the model and produce the wake field.

FUNWAVE has a sediment transport module, that includes a suspended sediment advection/diffusion and bedload model, which was used to model sediment transport and bed morphology changes that occur during ship movements. The sediment transport model was applied in the primary wave simulations only.

The FUNWAVE model extent is presented in Figure 2.2. The model extent covers the full length of channel from the MODA terminal at Ingleside to past the Harbor Island terminals at 5m resolution for the primary wave simulations and 1m resolution for the secondary wave simulations. This extent covers the channel margin and unarmored shorelines that may be affected by a change in vessel traffic as a result of channel deepening project.

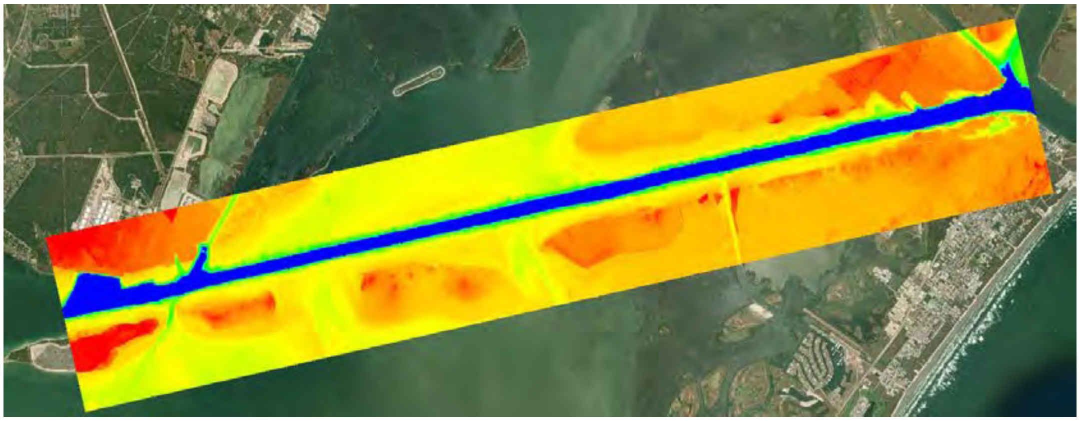


Figure 2.2: Extent of the FUNWAVE domain with color scale based on model depths for the existing channel condition

2.2 XBEACH Model

Shoreline changes as a result of ship generated hydrodynamics has been assessed using the XBEACH model (Roelvink et. al., 2009). The XBEACH model has been run in profile mode (2DV) and can accommodate the non-linear wave profile time series from the FUNWAVE simulations as boundary conditions and is well suited to describe the shoreline evolution as a result of run-up and drawdown at the shoreline from vessel wake.

XBEACH profiles were setup for 9 shoreline profiles along the channel length where ship hydrodynamic effects are observed as being most significant, informed by the vessel wake modeling and located at natural shoreline areas deemed most at risk due to the proximity to the channel deepening. Figure 2.3 presents the locations of the profile models.

Figure 2.3: Location of the XBEACH profile models (red) along the Port of Corpus Christi Channel

3. Physical Data Overview

The following section summarizes the relevant data and assumptions adopted in the vessel wake analyses. To confirm and validate the data and assumptions, Baird facilitated a workshop in May 2021 with pilots from the Port of Corpus Christi to discuss the vessel transits and maneuvers that are undertaken for both inbound and outbound vessel movements within the port. This ensured that the adopted data for vessel transits and tug operations for these studies were consistent with actual operations at the port.

3.1 Channel Dimensions

The length of channel assessed for the vessel wake analysis covers channel areas that are to be modified by the channel deepening project. It is noted that the USACE is currently embarking on a channel maintenance project along the full length of the Corpus Christi channel that will deepen the navigable depth to 54 feet. The channel deepening project will further deepen the channel to at least 75 feet from the Harbor Island Terminals, through the Jetty Channel to offshore (see Figure 1.1). Figure 3.1 provides a typical section of the channel deepening project at the eastern end of the Corpus Christi channel. The stated bed level that is assumed in the modeling and analysis is the authorized bed level. The channel will be dredged deeper to accommodate sedimentation that is expected to occur up to the guaranteed bed level before subsequent maintenance dredging occurs (i.e., advanced maintenance dredging).

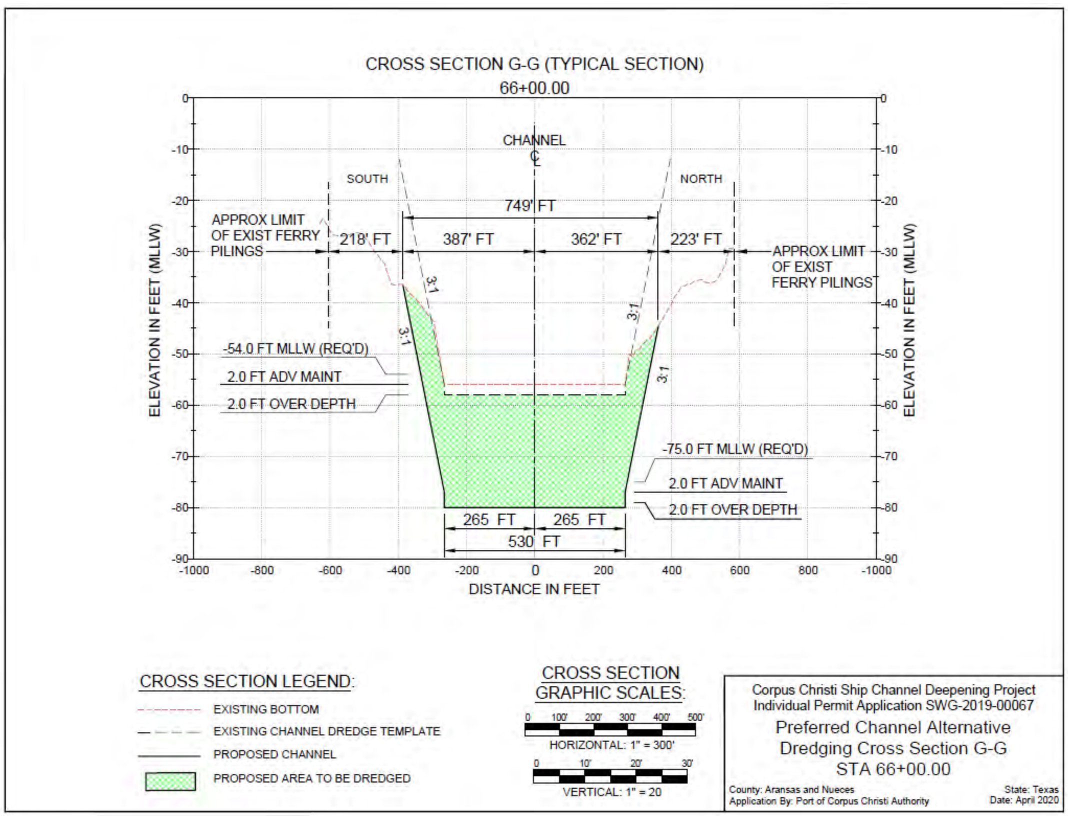


Figure 3.1: Design Section for the Corpus Christi Channel Deepening Project in the Corps Christi Channel (see Figure 1.1 for section location)

The vessel wake analysis has therefore been completed on two channel scenarios, as follows:

- Future Without Project (FWOP): An existing channel configuration following the maintenance dredging campaign with a navigable depth of 54 feet along the full length of the channel.
- Future With Project (FWP): A future channel configuration that includes the channel deepening project.

Figure 3.2 compares the plan bathymetry of the two channel scenarios.

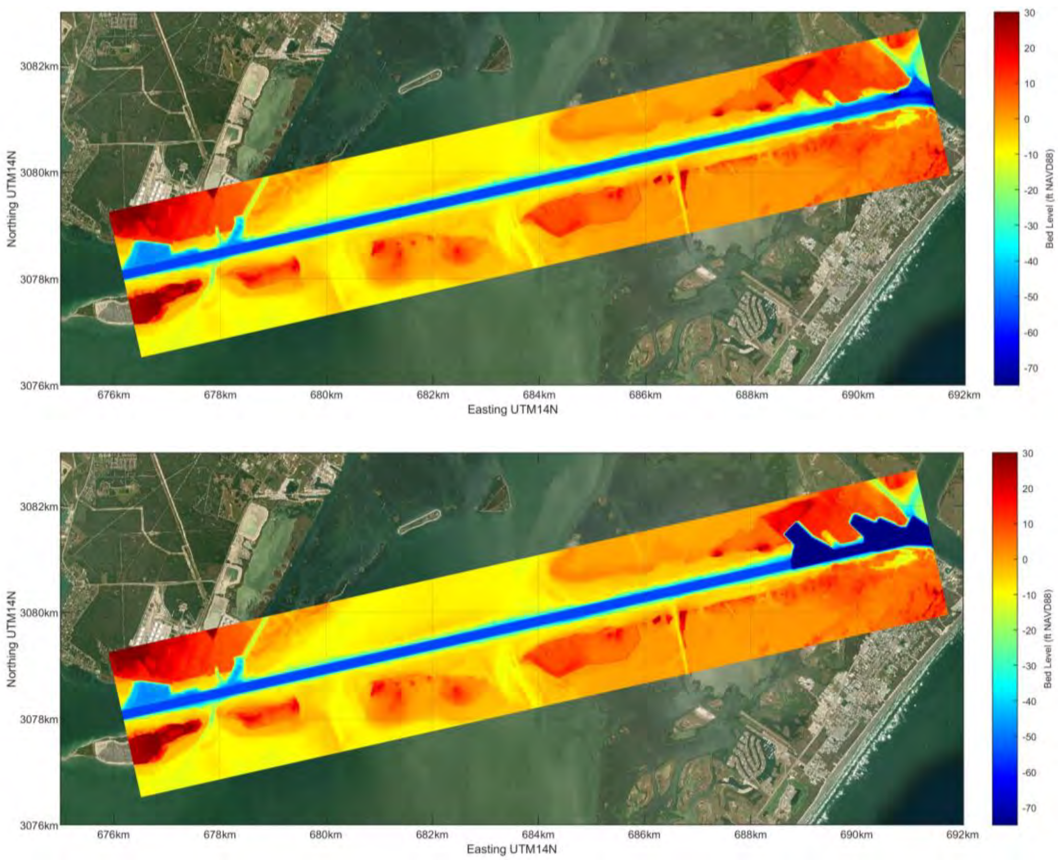


Figure 3.2: Channel Bathymetry from the FUNWAVE model for the Future Without Project (top) and Future With Project (bottom) Scenarios.

Bathymetric data for the vessel wake models was derived from the Cooperative Institute for Research in Environmental Sciences (CIRES), Continuously Updated Digital Elevation Model (CUDEM) - 1/9 Arc-Second Resolution Bathymetric-Topographic Tiles (v2020). Elevations were converted to the North American Vertical Datum of 1988 (NAVD 88) at Port Aransas. The horizontal coordinate system of Universal Transverse Mercator 14-North (UTM-14N) was used for all bathymetry data.

3.2 Vessel Dimensions

The design vessel for the channel deepening project is a 306k DWT VLCC laden to a draft of 68 ft. However, loading of the VLCC to the 68 ft draft will at times rely on a reverse lightering operation using a combination of Suezmax and VLCCs from the MODA terminal at Ingleside that will be limited in draft to 52ft due to the 54ft channel depth along the Corpus Christi channel. As such, two vessels were assessed in this vessel wake study with their dimensions summarized in Table 3.1.

Table 3.1: Vessel Dimensions

Dimension	Suezmax	VLCC
Length Over All (ft)	866.1	1089.2
Width (ft)	157.5	190.3
Ballast Draft (ft)	26.2	31.2
Laden Draft (ft) *	52.0	52.0

* Laden draft is depth restricted due to 54ft channel

3.3 Vessel Tracks and Speeds

Automatic Identification System (AIS) data of 50 large tanker inbound and outbound transits between the years 2019 and 2020 to/from the terminal at Ingleside were analyzed to quantify typical vessel tracks and speeds under existing operations. The inbound tracks with vessel speed (over ground) are shown in Figure 3.3. Vessel speed is generally maintained on an inbound transit around the channel bend before a slight reduction in speed past Port Aransas and then increasing speed down the length of the channel until again reducing for berthing at Ingleside. Departure tracks are presented in Figure 3.4, showing slower speeds along the channel and bend, with a more pronounced slow down past Port Aransas. It is noted that since these are historic data the maximum draft would be 45 ft for outbound transits.

The AIS track data was further analyzed at a point approximately halfway along the Corpus Christi channel to define lower, mean and maximum vessel speeds, as presented in Table 3.2. Vessel tracks that matched the lower, mean and maximum vessel speeds at the analyzed point were then selected as a basis for the FUNWAVE passing vessel analysis. That is, the vessel tracks and speed profiles applied in the modeling were based on actual measured track data.

Figure 3.3: Tracks and speed profiles of inbound transits to the Ingleside terminal from AIS data for VLCCs and Suezmaxs (2019 – 2020)

Figure 3.4: Tracks and speed profiles of outbound transits from the Ingleside terminal from AIS data for VLCCs and Suezmaxs (2019 – 2020)

Table 3.2: Vessel Speeds (kts) at Channel midpoint from analyzed AIS data for VLCC and Suezmax (2019-2020)

Direction of Travel	25th %tile	Mean	Maximum
Inbound	8.0	8.9	12.0
Outbound	7.5	8.1	10.5

3.4 Metocean Conditions

It is noted that the results from the modeling within this assessment are intended to provide an estimate of potential shoreline and channel bed level changes as a result of the project, and therefore will not quantify other processes (i.e., wind waves, storm surge etc.) which are not altered by the project but still contribute to the overall shoreline and sediment transport dynamics over short, medium and long time periods. As such, no wind, waves or currents have been applied in the FUNWAVE or XBEACH modeling.

Tides in the Corpus Christi channel have a tidal range of 1.04 ft, with a typical diurnal range of 0.9ft (MLW to MHW at Port Aransas, gauge 8775237). Given the relatively small tidal range, a fixed water level of Mean Sea Level (MSL), being +0.5ft relative to NAVD88, was applied to all modeling.

3.5 Sediment Data

A suite of sediment sampling data was obtained by Baird along the length of the Corpus Christi Channel. An example of the available data is presented in Figure 3.5. From the channel sedimentation study (also performed by Baird and documented in a separate report) it is noted that this section of the channel is not the main area for sedimentation, and therefore samples are more likely to represent the native sediment which appear to be approximately 50% sand, 25% silt and 25% clay.

Based on this assessment the following sediment parameters were specified in the FUNWAVE and XBEACH modeling, noting the bed was described by single sediment fraction with shear stress values representative of mixed beds:

- Medium Sediment Diameter, D_{50} = 0.12mm
- Dimensionless Sediment Size = 3
- Critical Shields parameter for suspended load, θ_{cr} = 0.091 (dimensionless)
- Critical Shields parameter for bedload, θ_{bcr} = 0.08 (dimensionless)
- Porosity of sediment, n = 0.37
- Settling velocity, wf = 0.02m/s

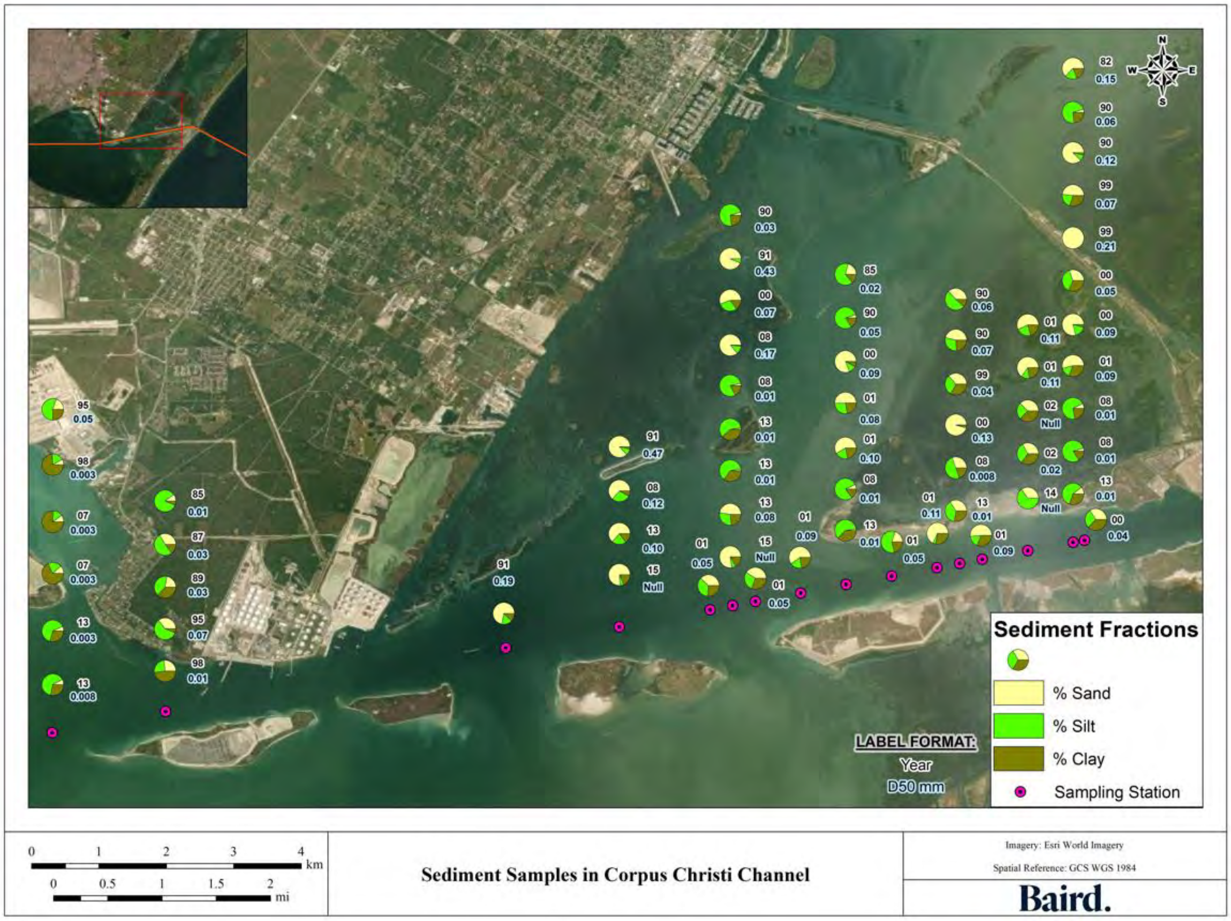


Figure 3.5: Example summary of available sediment sampling data in the Corpus Christi Channel

3.6 Pilot Workshop (May 2021)

To confirm the vessel and tug maneuvering on typical inbound and outbound transits and validate the analyses of vessel speeds, Baird facilitated a workshop with pilots from the Port of Corpus Christi. The pilots provided invaluable insight into vessel maneuvering and the navigation hazards that are dealt with at the port. At the conclusion of that meeting the pilots endorsed the assumptions made by Baird. One notable clarification from the pilots was the vessel speeds that would likely be achieved with a partially laden (to 52 ft) VLCC and Suezmax on an outbound transit, the maximum value from the AIS data was considered unrealistic for these design vessels with a 52ft draft. As such, Baird capped the outbound speed of the Suezmax and VLCC to the mean value (8.1kts) for the vessel wake analyses.

4. Vessel Wake Modeling

As noted previously, vessel wakes have been quantified using the FUNWAVE model system. Due to inherent limitations of the Boussinesq equations in propagating short period waves in deep water, a decoupled modeling approach has been adopted for this study, whereby the primary and secondary waves are modeled in separate simulations and the results combined into a post-processed result (see Section 2.1 for discussion). The following section provides a summary of the results for primary and secondary waves, including a benchmarking of the FUNWAVE model outputs.

4.1 Benchmarking of FUNWAVE Model Results

No water level data, of sufficient temporal resolution, for passing vessel effects was available to this study that would allow a direct validation of vessel wakes from the FUNWAVE model outputs. To this end, a benchmarking exercise was completed where the FUNWAVE model results were compared to commonly applied empirical and numerical models for vessel wakes. The intention of this exercise was to provide assurance as to the accuracy of the FUNWAVE model results. Additionally, the results were reviewed by local pilots and mariners to qualitatively validate the results.

Primary (drawdown) wave results from FUNWAVE were compared against results from the PASSCAT (potential flow) model and empirical relationships of Schiereck (2001) and Almstrom & Larson (2020). The results are summarized in Table 4.1, with a comparison in the water level surface around the vessel visually compared in Figure 4.1 from the FUNWAVE and PASSCAT model. Good agreement of the FUNWAVE model was found against approaches that define the confined channel in their estimate (i.e., PASSCAT, Almstrom & Larson, 2020).

Table 4.1: Comparison of Primary Wave Estimates using alternate empirical and numerical methods (in feet below SWL at 165ft from vessel hull)

Method	Vessel Speed	
	8 knots	12 knots
Schiereck (2001)	0.98	2.62
Almstrom & Larson (2020) ^	1.92	4.87
PASSCAT	1.41	3.77
FUNWAVE	1.31	3.94

^ derived from passenger vessels

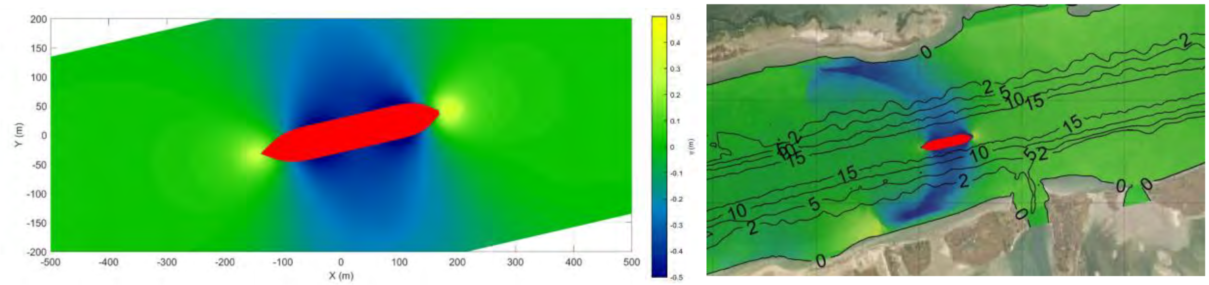


Figure 4.1: Visual Comparison of the Primary Wave Field around a VLCC vessel at a speed of 8 knots in the Corpus Christi Channel using the PASSCAT (left) and FUNWAVE (right) models

Secondary wave results from the FUNWAVE model were compared against the MICHLET potential flow solver (Cyberiad, 2015) and empirical relationships of Sireli (2002) and PIANC (1987), for a flatbed idealized case. Reasonable agreement was achieved when adopting a depth limited FUNWAVE model setup (as described in Section 2.1), as summarized in Table 4.2. A visual comparison of the FUNWAVE and MICHLET results are presented in Figure 4.2. It is noted that at speeds of 8-9 knots, the primary wave estimates (Table 4.1) are notable larger than the secondary waves (Table 4.2).

Table 4.2: Comparison of Secondary Wave Estimates using alternate empirical methods (in feet below SWL at 165ft from vessel hull)

Method	Vessel Speed		Wave Period
	8 knots	12 knots	
Sireli (2001)	0.16	1.05	2-4 sec
PIANC (1987)	0.20	1.31	3-4 sec
MICHLET	0.26	2.76	3-4 sec
FUNWAVE ^	0.15	1.02	3-4 sec

^ depth-limited model setup

In addition to the benchmarking exercise, FUNWAVE model results specific to the Corpus Christi channel were presented and discussed with Captain Jay Rivera (Riben Marine), a former pilot at the Port of Corpus Christi, to provide a sense check and anecdotal validation of the model outputs. Captain Rivera’s review noted the realistic nature of the primary wave, in terms of both drawdown magnitude next to the vessel and the shoaling, propagation, breaking and reflections along the shorelines adjacent to the channel.

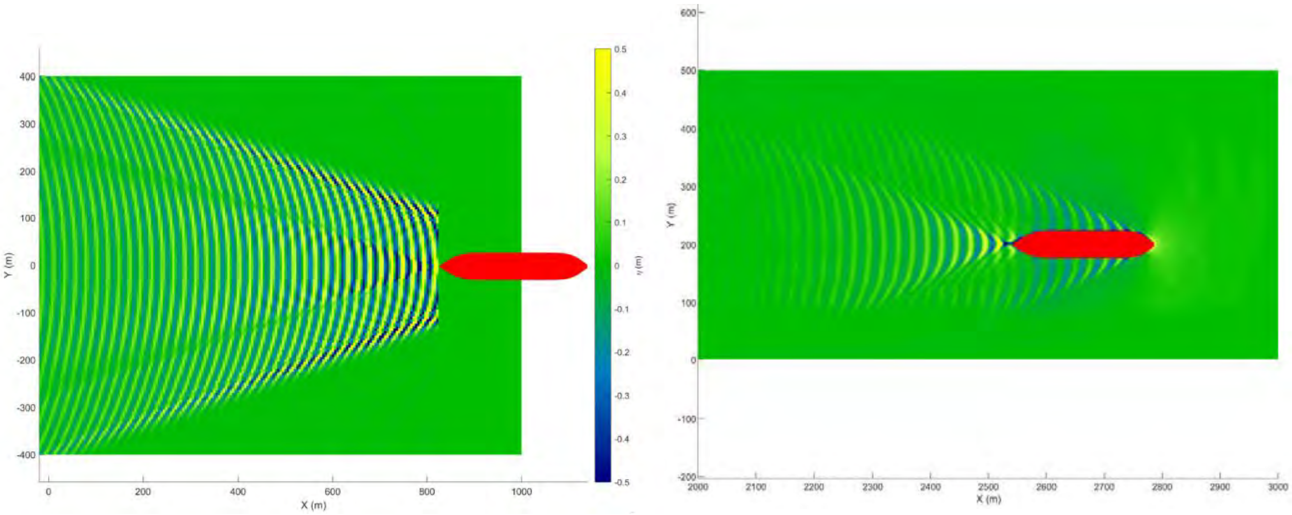


Figure 4.2: Visual Comparison of the Secondary Wave generated from a VLCC vessel at a speed of 12 knots over an idealized flatbed using the MICHLET solver (left) and FUNWAVE model (right)

4.2 Model Scenarios

A suite of model scenarios was completed in FUNWAVE, each describing a single vessel transit of the Corpus Christi channel. Table 4.3 provides a summary of the model scenarios, noting that each were run for a Suezmax and VLCC vessel for both the FWOP and FWP channel conditions. In total 40 simulations were completed.

Table 4.3: Summary of FUNWAVE model scenarios. Each scenario was modeled for Suezmax and VLCC Vessels for the FWOP and FWP channel conditions.

Vessel Wake Type	Sediment Transport / Morphology	Direction of Travel	25th %tile	Mean	Maximum
Primary	Yes	Inbound	Y	Y	Y
		Outbound	Y	Y	Y
Secondary	No	Inbound	-	Y	Y
		Outbound	-	Y	Y

Example of spatial outputs from the FUNWAVE modeling for primary and secondary wave scenarios is presented are follows:

- Figure 4.3: Suezmax Primary Wave, Mean Speed Profile, for Inbound and Outbound.
- Figure 4.4: Suezmax Secondary Wave, Mean Speed Profile, for Inbound and Outbound.
- Figure 4.5: VLCC Primary Wave Mean Speed Profile, for Inbound and Outbound.
- Figure 4.6: VLCC Secondary Wave Mean Speed Profile, for Inbound and Outbound.

It is noted that there is a primary wave response around the vessel, albeit small, in the secondary wave simulations, which was filtered out of the timeseries results in post-processing prior to application to the XBEACH profile models.

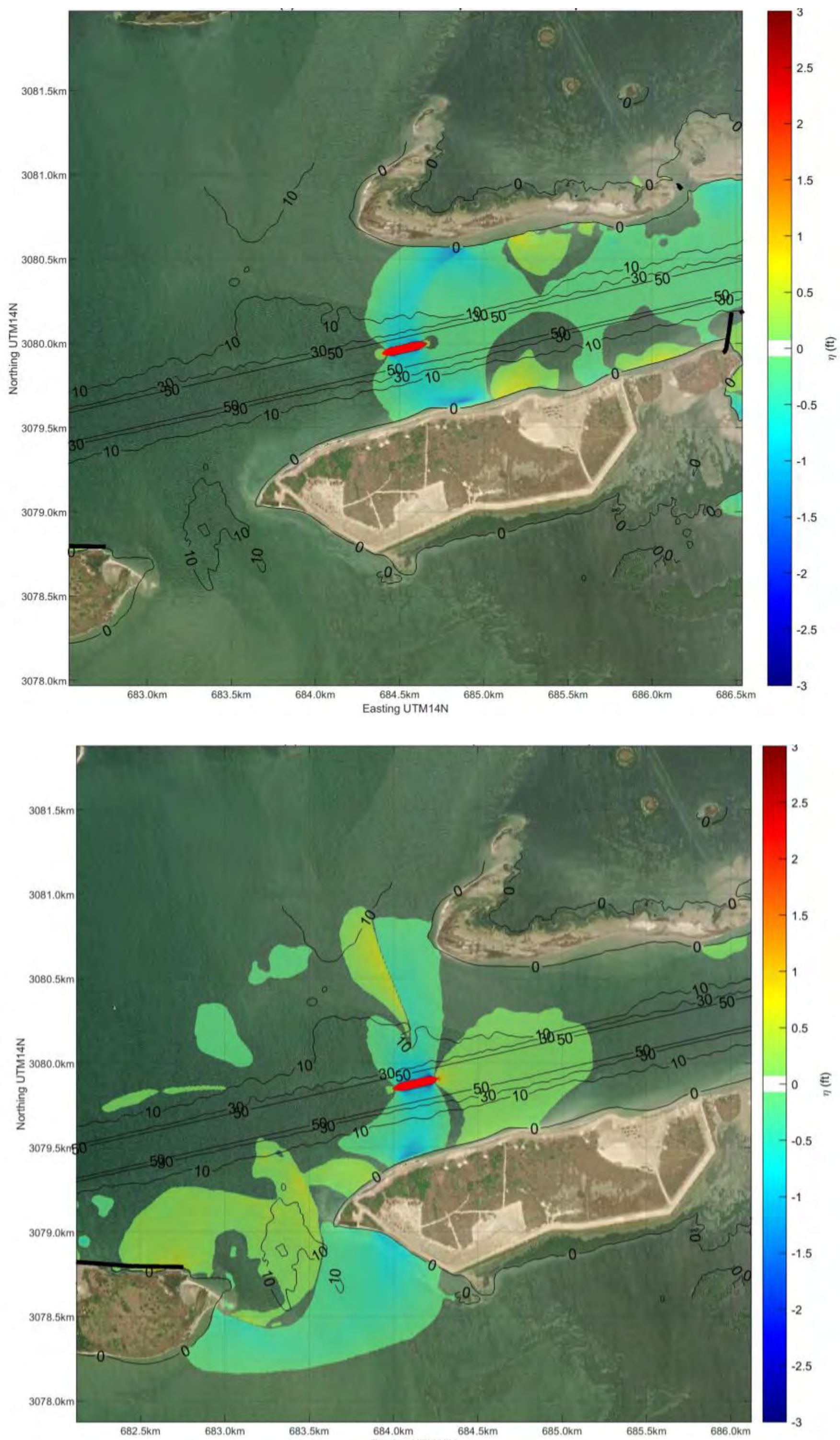


Figure 4.3: Example Primary Wave Field for an Inbound (left) and Outbound (right) Suezmax Vessel (Mean Speed) Scenario (Water Level Surface in ft relative to SWL)

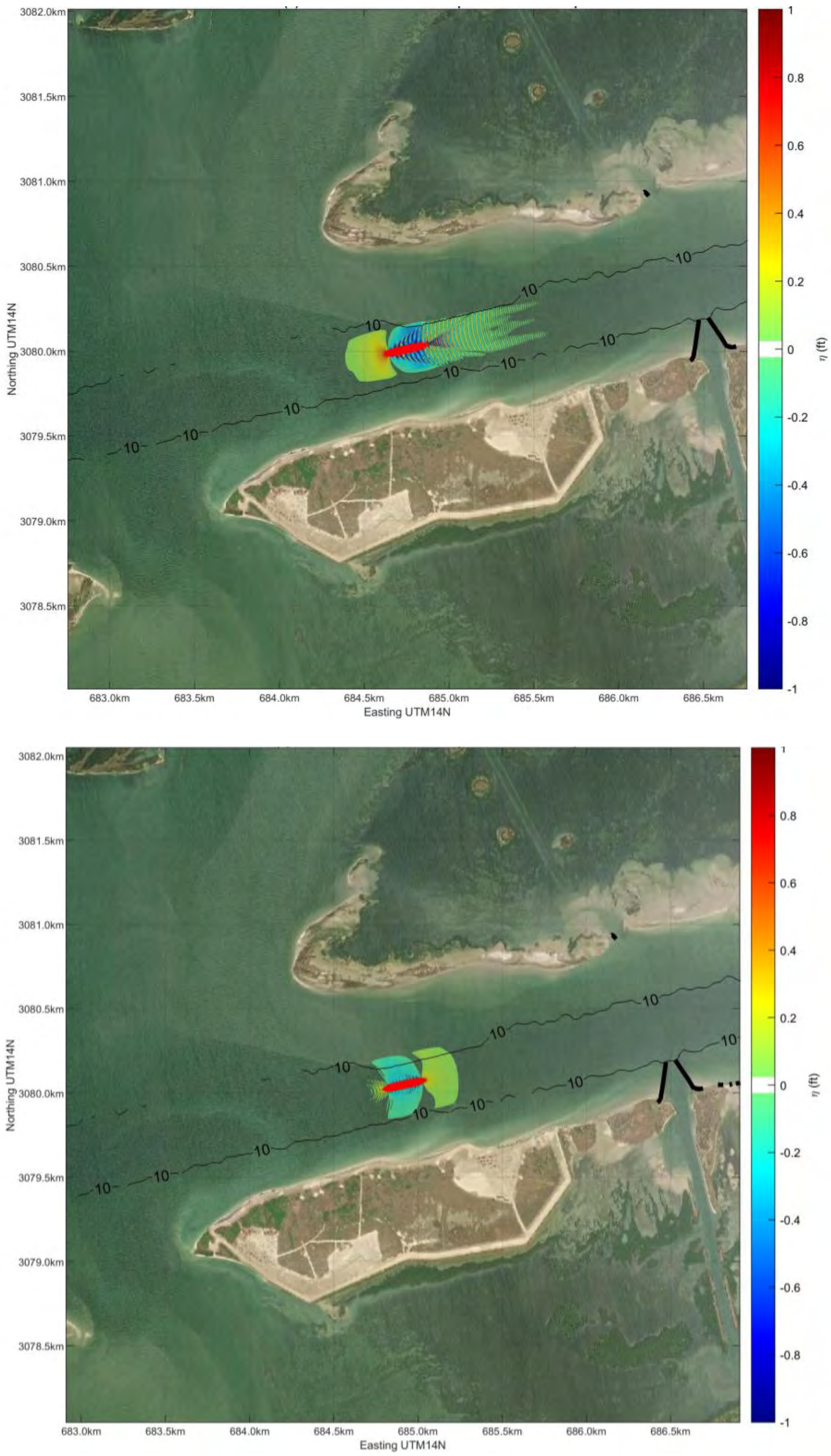
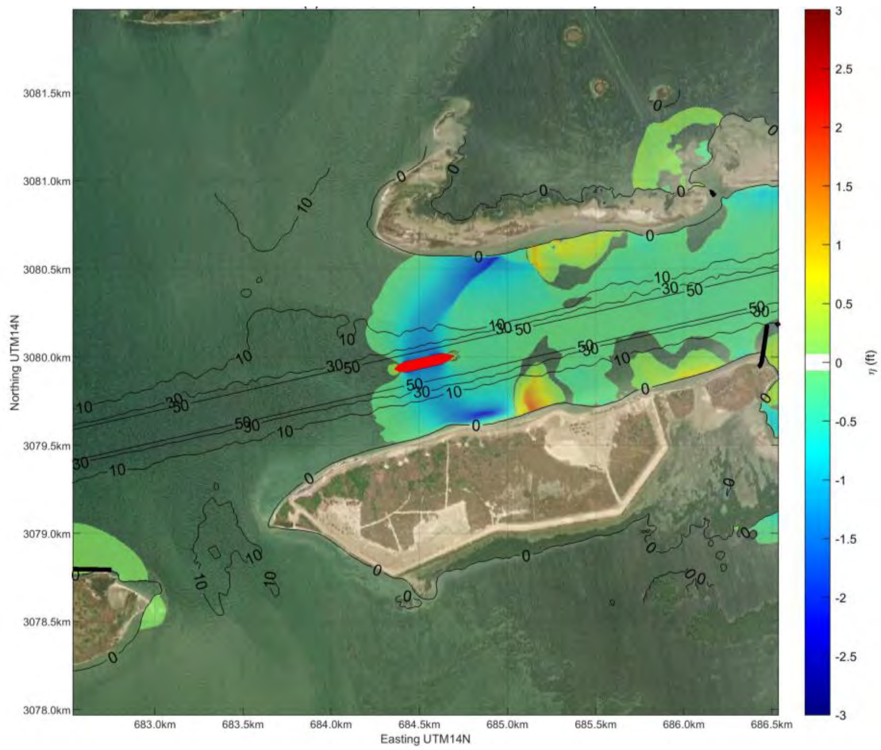


Figure 4.4: Example Secondary Wave Field for an Inbound (left) and Outbound (right) Suezmax Vessel (Mean Speed) Scenario (Water Level Surface in ft relative to SWL)



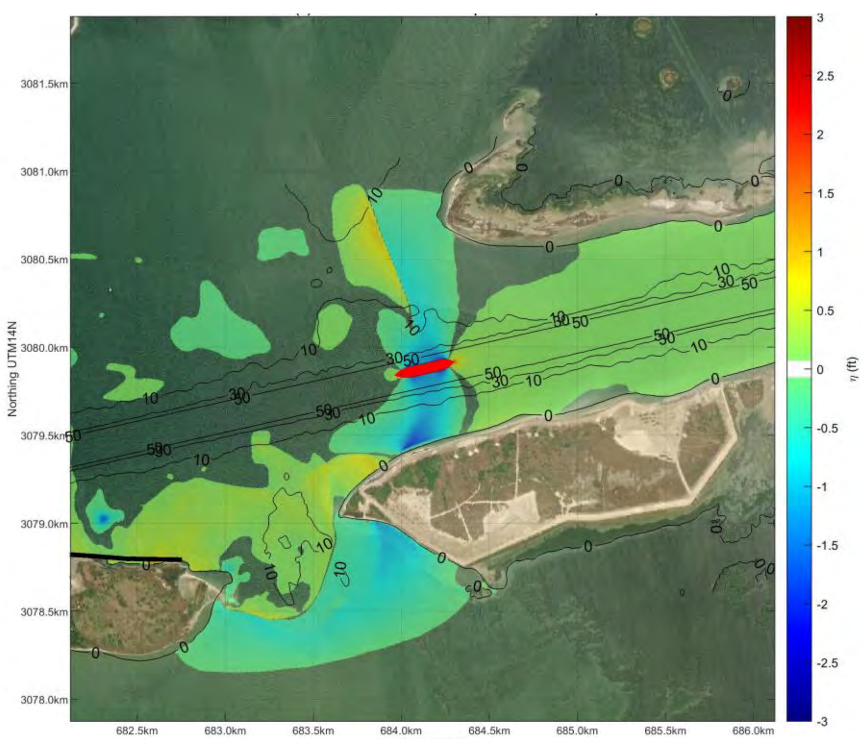


Figure 4.5: Example Primary Wave Field for an Inbound (left) and Outbound (right) VLCC Vessel (Mean Speed) Scenario (Water Level Surface in ft relative to SWL)

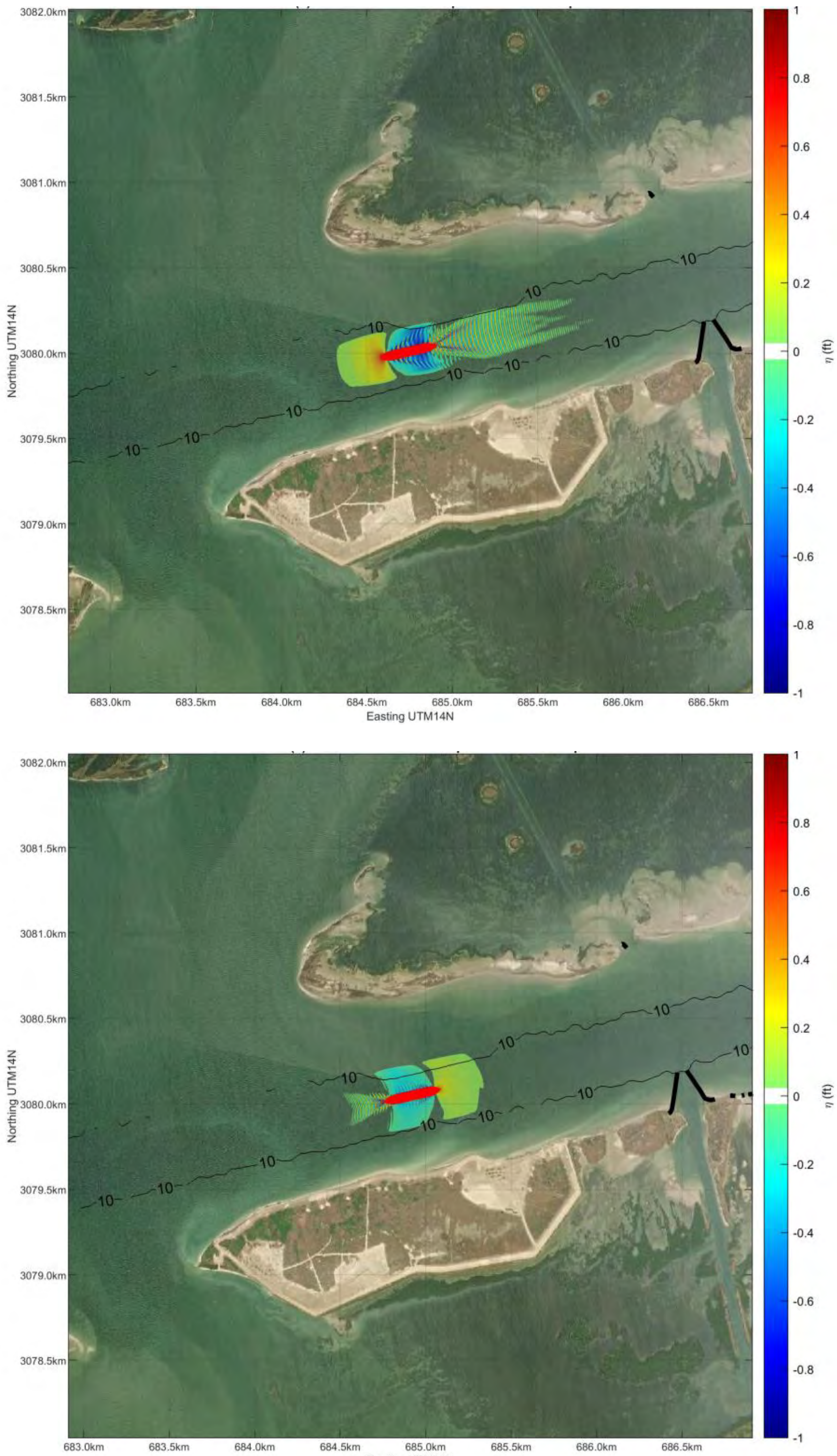


Figure 4.6: Example Secondary Wave Field for an Inbound (left) and Outbound (right) VLCC Vessel (Mean Speed) Scenario (Water Level Surface in ft relative to SWL)

5. Bed Change Analysis

To assess the impact to bed change as a result of the channel deepening project, comparison of bed change outputs from the FUNWAVE model were assess for FWOP and FWP scenarios. In addition, an assumption regarding a change in vessel traffic as a result of the project was needed. Such guidance was provided by USACE in consultation with the Port of Corpus Christi, indicating the projected vessel traffic for the year 2022 would form the basis for the FWOP scenario.

For 2022, the vessel traffic projection is as follows:

- 120 Aframax
- 95 Suezmax
- 110 VLCC

An annual growth rate of 5% to the VLCC vessel traffic is projected and the year 2023 is to be adopted for the FWP scenario. This would result in an increase in VLCC numbers to 116 per year.

5.1 Annualized Bed Change

The bed change results from the individual (single transit) primary wave simulations have been post-processed and combined based on the projected vessel traffic numbers to produce an annualized bed change outcome. The annualized results are a weighted average of the three vessel speed scenarios, with a higher weighting given to the mean speed scenario (min 20%, mean 60%, max 20%), inbound and outbound are then combined (as each vessel will make two transits of the channel; inbound and outbound) and then multiplied by the vessel count. Results are presented separately for VLCC and Suezmax. Aframax vessels have not been considered as part of this assessment, however the results would be consistent with the Suezmax vessels.

Annualized bed change results are presented in Figure 5.1 to Figure 5.4, noting:

- Suezmax results compare the FWOP channel scenario against the FWP channel scenario with no change in traffic numbers.
- VLCC results compare the FWOP channel scenario with 2022 traffic projections against the FWP channel scenario with 2023 traffic projections (5% increase in VLCCs)

A comparison of the FWOP and FWP channel scenarios for both the Suezmax and VLCC indicate that there would be very limited change in bed morphology as a result of the project. In general, the bed morphology results suggest a scouring pattern on the channel shoulders with sedimentation along top of channel bank. No sedimentation is observed within the channel width. While the annualized bed change results indicate very similar outcomes, notable differences include:

- Nearshore shallow area adjacent to Pelican Island (on the southern side of channel) shows greater deposition/erosion magnitudes for the FWP case. This outcome is considered a result of a marginal change in the characteristic of the primary wave for inbound vessels due to the channel deepening further to the east. The change is localized, and it is noted that the shoreline in this area is armored.
- Shallow areas around entranced to the new terminals at Harbor Island show localized areas of increased scour, which is a direct result of the terminal developments. This outcome should be considered as part of terminal design (i.e., armoring may be deemed necessary).

Overall, the annualized bed change results indicate that there would be minimal additional impact to seabed morphology as a result of the channel deepening project.

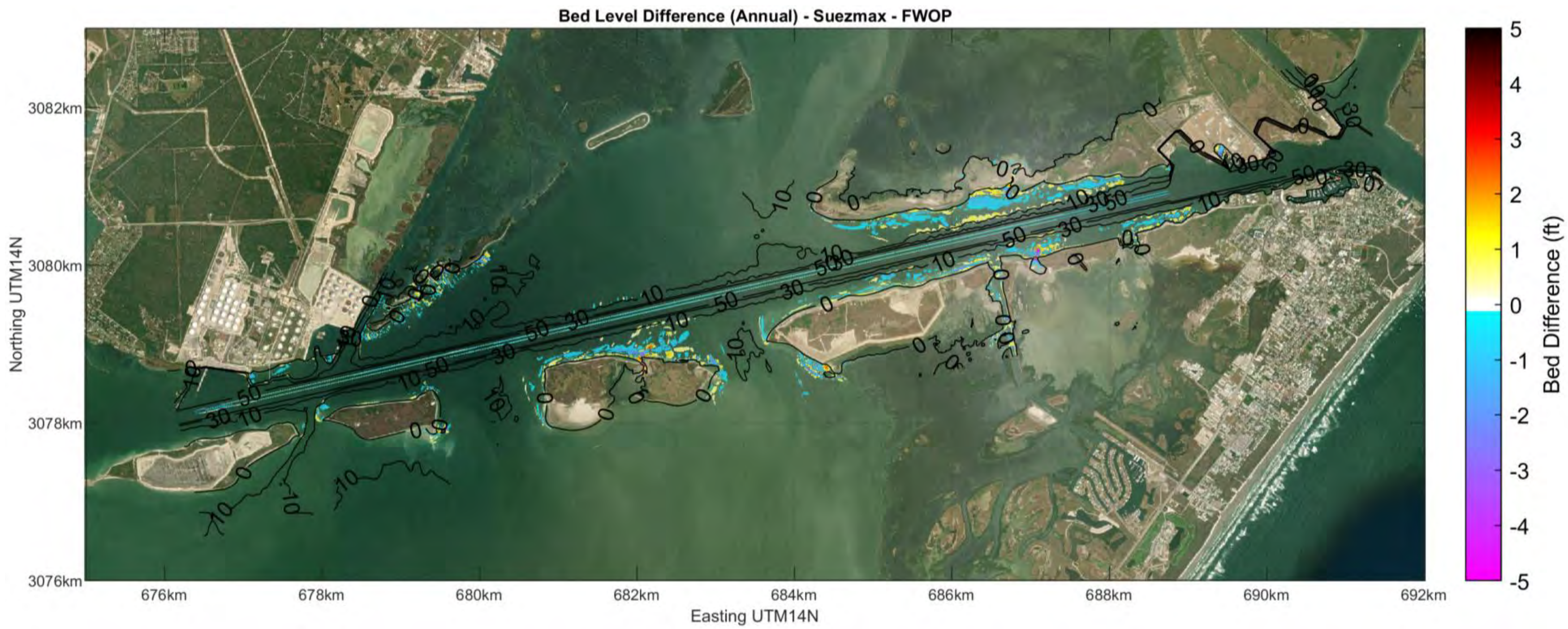


Figure 5.1: Annualized Bed Level Change under Future Without Project Channel Conditions for Suezmax vessel traffic

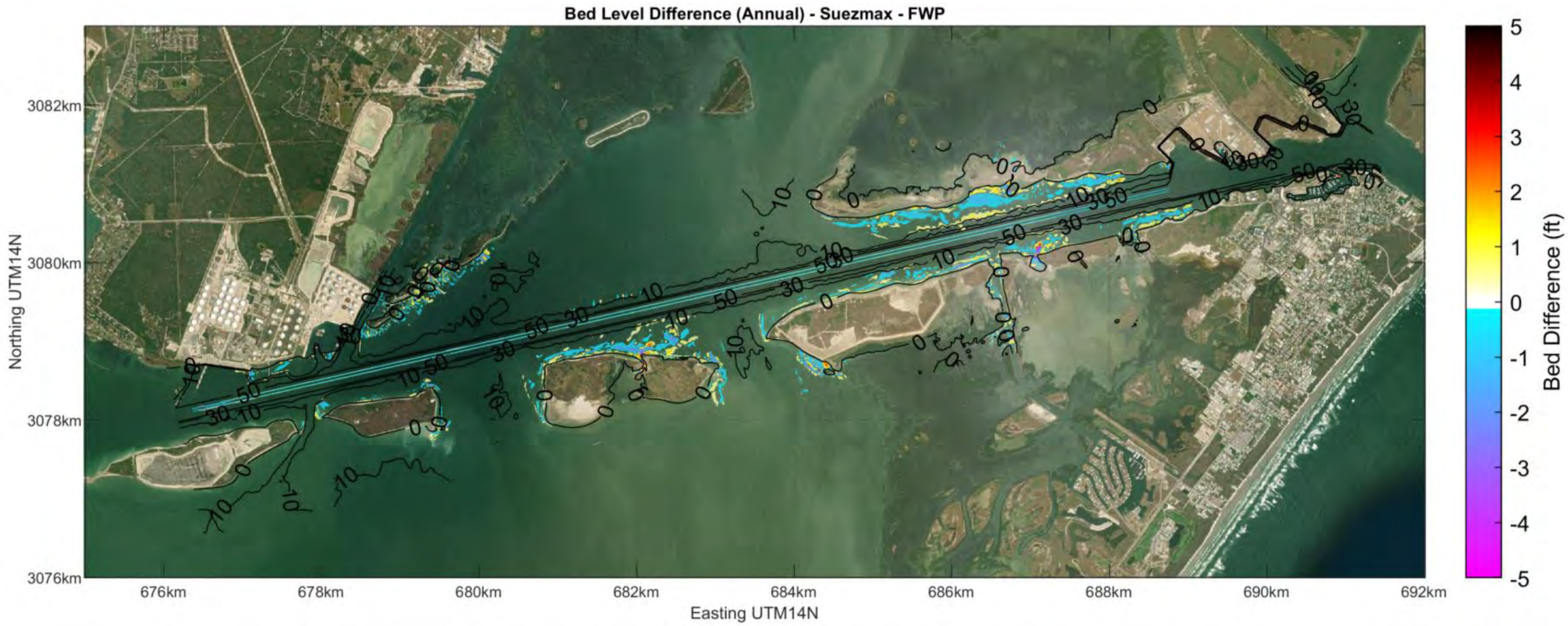


Figure 5.2: Annualized Bed Level Change under Future With Project Channel Conditions for Suezmax vessel traffic

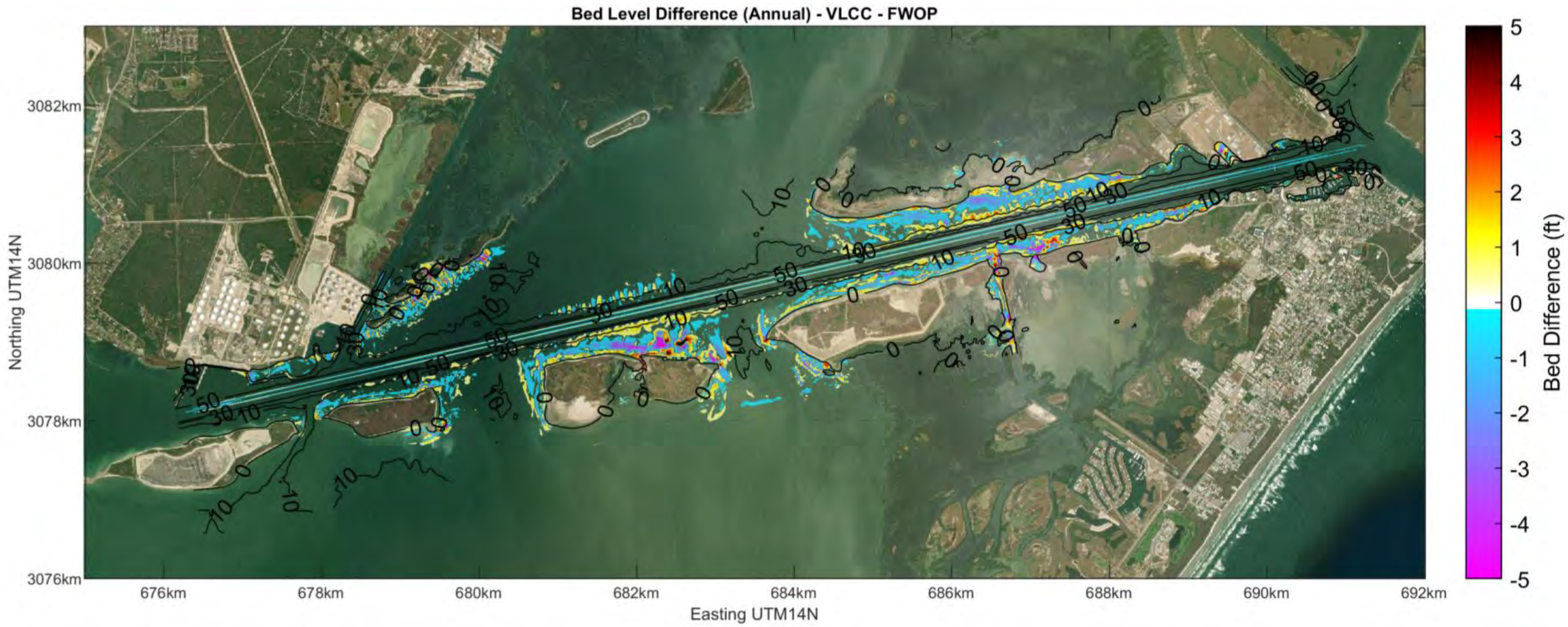


Figure 5.3: Annualized Bed Level Change under Future Without Project Channel Conditions for VLCC vessel traffic

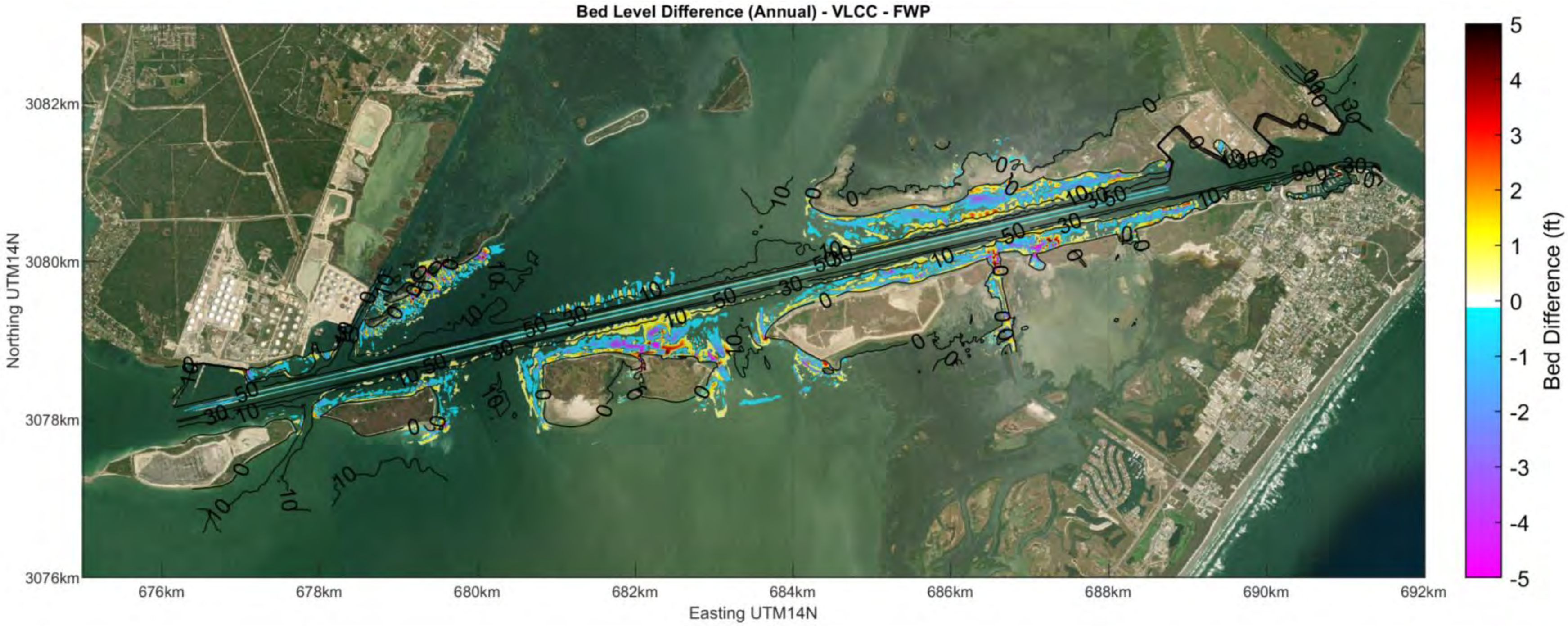


Figure 5.4: Annualized Bed Level Change under Future With Project Channel Conditions for VLCC vessel traffic

6. Shoreline Change Analysis

Shoreline changes as a result of ship generated hydrodynamics has been assessed using the XBEACH model along a series of shoreline profiles, located by identifying natural shoreline areas deemed most at risk from consideration of the vessel wake modeling outputs. Annualized shoreline change adopted the same assumptions regarding vessel traffic as done for the bed change analysis and compared the FWOP and FWP scenarios through synthesized yearlong simulations of vessel wakes. The results from the XBEACH modeling provide an estimate of potential shoreline changes as a result of the project but do not quantify other processes (i.e., wind waves, storm surge etc.), which are not altered by the project but still contribute to the overall shoreline dynamics over short, medium and long time periods.

6.1 Shoreline Trends

A preliminary analysis of historical shoreline change was completed by mapping shoreline positions over a suite of available historical imagery, obtained from Google Earth. The shoreline mapping outcomes are presented in Figure 6.1 and identify a clear recessional trend.

Figure 6.1: Shoreline Position Mapping along a Section of the Corpus Christi Shipping Channel covering the period 1956 to 2020

6.2 Shoreline Modeling Approach

Shoreline changes was modeled using the XBEACH model system in profile mode (2DV). The XBEACH model can accept the non-linear wave profile time series from the FUNWAVE simulations as boundary conditions and is well suited to describe the shoreline evolution as a result of run-up and drawdown at the shoreline from vessel wake.

Depths along each profile were extracted from high resolution survey of the area and extended from land to the relative deep water in the channel. Sediment along the profiles were described by native sediments, as presented in Section 3.5. Figure 6.2 presents the locations and naming of the XBEACH profiles.

Figure 6.2: Location of the XBEACH profile models (red) along the Port of Corpus Christi Shipping Channel

Boundary conditions for the profile models were developed by combining water level timeseries from the FUNWAVE model results (for both primary and secondary wave simulations) in a continuous series, based on the projected vessel numbers. Initially the primary and secondary wave results were combined for each vessel/speed/channel scenario. Timeseries boundary conditions were then generated by randomly repeating the timeseries from the three vessel speed scenarios, with a higher occurrence given to the mean speed scenario (min 20%, mean 60%, max 20%). For each vessel transit, an inbound and outbound timeseries was included (as each vessel will make two transits of the channel: inbound and outbound). In this way, each profile model was run for an approximately 20-day period, being the equivalent of a year's worth of vessel wakes based on the projected vessel numbers.

6.3 Annual Shoreline Change Estimates

Annual shoreline change results are presented in Figure 6.3 for all eight profiles. In general, a flattening of the profiles is observed, with most change occurring in water depths less than 4ft, close to the shoreline. This outcome is consistent with the FUNWAVE bed change results. In addition, shoreline recession is predicted at all profiles as a result of vessel wakes, ranging from 3 ft (profile 2) to 6 ft (profile 8) at MSL. The recession trend in the modeled profiles is in keeping with the observed changes in shoreline position (see Figure 6.1).

Differences in the shoreline change estimates for the FWOP and FWP scenarios are negligible with no observable difference in the annual result. It is noted that the rate of shoreline and profile change slows over the course of the simulations and as such the additional 6 VLCC transits make very little difference to the final outcome for the FWP scenario. While this observation may point to a limitation in the model, the outcome is considered valid and reasonable and consistent with outcomes from the FUNWAVE bed change modeling.

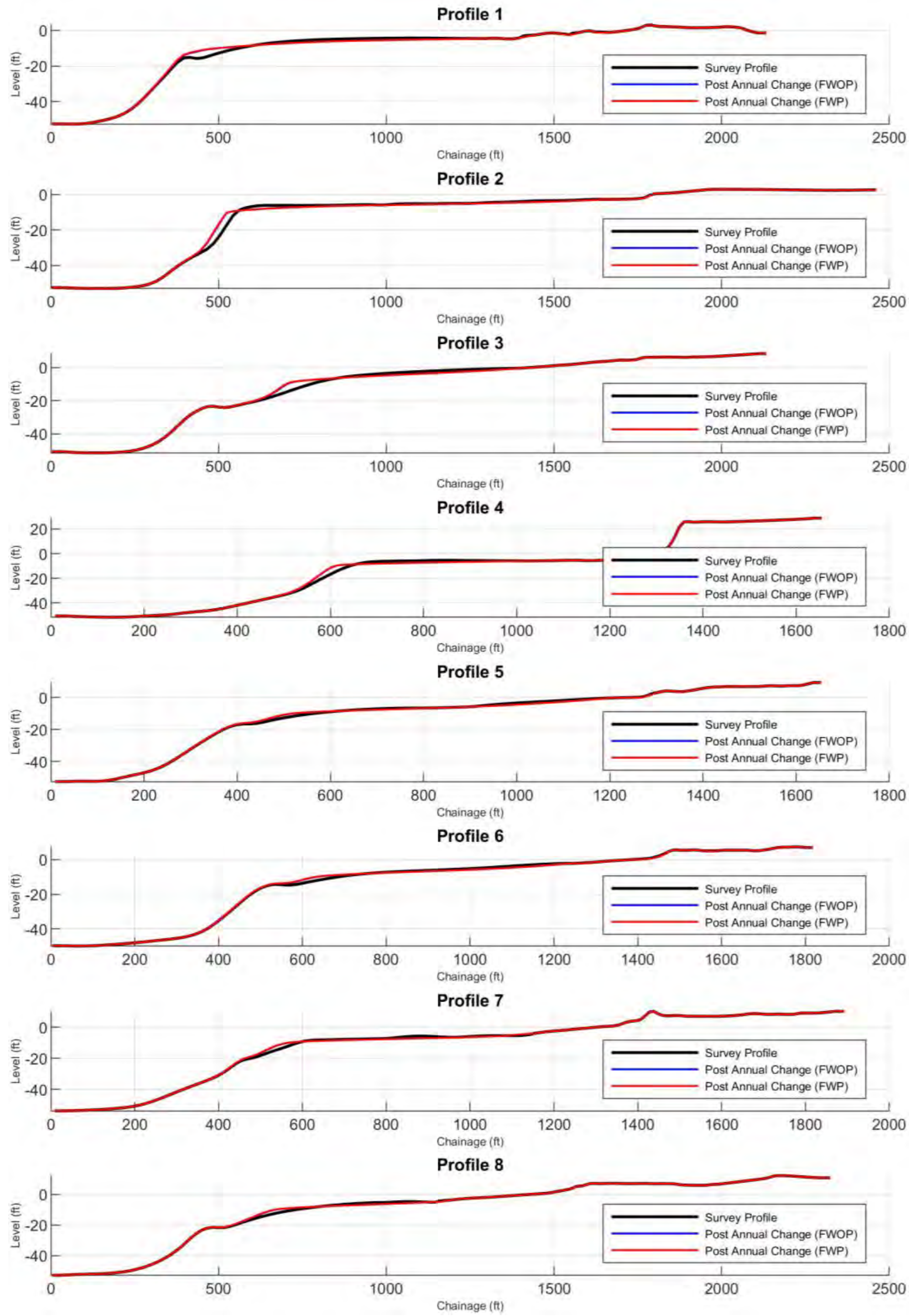


Figure 6.3: Annual Shoreline Change Results as a result of vessel wakes for the FWOP and FWP scenarios at Profile 1 (top) to Profile 8 (bottom).

7. Conclusions

Baird has conducted a vessel wake analysis as part of the modeling services for the Corpus Christi Channel Deepening project. The project will comprise deepening of the Outer and Approach Channels to 77 ft, and the Jetty Channel and seaward-most portion of the Corpus Christi Ship Channel to 75 ft. The channel will be used by laden VLCC's at a maximum draft of 68 ft departing from the planned Axis and Harbor Island terminals. In addition, growth in the reverse lightering operations between the MODA terminal at Ingleside and the Harbor Island terminals would be more VLCC vessel utilize the Corpus Christi Ship Channel.

The vessel wake study consisted of the following tasks:

- Assessment of vessel speeds in the channel.
- Modeling and assessment of vessel induced wakes for Suezmax and VLCC vessels.
- Modeling and assessment of bed morphology along the Corpus Christi Ship Channel as a result of vessel hydrodynamics.
- Modeling and assessment of shoreline response at selected locations along the Corpus Christi Ship Channel as a result of vessel hydrodynamics.

Vessel induced wakes consist of both a primary and secondary wave and the magnitude of each (both absolute and reliative) are a function of the vessel characteristics, speed through water and channel geometry. Being a constrained deep dredged channel with vessels traveling at relatively low speeds, the primary wave is dominant along the Corpus Christi channel for large tanker vessels. The constrained channel increases the primary drawdown wave, while typical vessel speeds result in relatively small secondary waves that reduce in magnitude as they propagate away from the vessel. As a result, the primary wave is the predominant driver for bed and shoreline change.

An estimate of annualized bed and shoreline change as a result of vessel wakes was made with a comparison of the following:

- Suezmax results compare the Future Without Project (FWOP) channel scenario against the FWP channel scenario with no change in traffic numbers.
- VLCC results compare the Future With Project (FWP) channel scenario with 2022 traffic projections against the FWP channel scenario with 2023 traffic projections (5% increase in VLCCs)

A comparison of the FWOP and FWP channel scenarios for both the Suezmax and VLCC indicate that there would be very limited change in bed morphology as a result of the channel deepening project. In general, the bed morphology results suggest a scouring pattern on the channel shoulders with sedimentation along top of channel bank and no sedimentation within the channel width for all scenarios. Some localized changes are observed for the FWP channel scenario; however, these are not considered significant.

Consistent with the bed change results, shoreline change modeling indicates that changes in vessel wakes as a result of the channel deepening project will have minimal impact on the future evolution of natural shorelines along the length of the Corpus Christi Shipping channel. A general recession trend is observed in analysis of historical shoreline positions and the annual shoreline change modeling, and no discernable increase in the recessional trend as a result of the project could be identified. Further, the project is not likely to contribute to an increase in sedimentation within federal navigation channels as a result of a change in vessel hydrodynamics.

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