Extreme water level conditions for Fourchon Junction under different climate scenarios and their impact on deck elevation design

Restricted

SR.20.00492

April 2020

Restricted **SR.20.00492**

Extreme water level conditions for Fourchon Junction under different climate scenarios and their impact on deck elevation design

by

O.E. Sequeiros (GSNL-PTP/I/PN)
S. Jaramillo (GSUSI-PTP/D/GC)

Document History

Date	Issue	Reason for Change
14-Feb-2020	A	First issue for review
28-Apr-2020	0	Second issue for approval

Reviewers		
Name	**Ref. indicator**	**Role**
D. Dauterive	SPLC-DPE/4	Senior Project Manager
S. Fan	GSUSI-PTP/D/GC	Metocean Specialist
J. Newlin	SIEP-PTP/D/GC	Civil Marine TL

Executive summary

Port Fourchon Junction is located within Chevron's Fourchon Terminal, just south of Port Fourchon and is operated by Shell Pipeline Company LP. This manifold metering station is a critical junction for the Mars Corridor oil, as oil production from Mars (MC-807), Ursa (MC-809), Titan (MC-941), Who Dat (MC-547), Medusa (MC-582), and Olympus (MC-807B) flow through this station via a 24" pipeline.

Port Fourchon is at the edge of the Mississippi delta facing the sea, one of the world's most vulnerable low-elevation coastal zones. It is highly exposed to storm surge and wave-induced inundation under hurricanes which regularly visit the Gulf of Mexico. In addition, it experiences one of the largest rates of subsidence in the world, which combined with sea level rise, will increase the site vulnerability in the coming decades.

This study assesses present and future scenarios of subsidence and sea level rise under extreme metocean conditions induced by hurricanes and their impact on Port Fourchon Junction. Local effects such as the differential settlement of the barrier beach have been also considered.

Based on the importance of Port Fourchon Junction facilities and the design criteria outlined by relevant Recommended Practice and Guidance documents, it is proposed that for the design of the upgraded elevated facilities a 1000-year return period is adopted for all parameters (survival conditions). In the event that some circumstances allow or require milder than survival conditions, values corresponding to the 100-year return period (extreme conditions) are also provided as reference. For the selected future scenario critical design parameters are shown in the table below.

Recommended design parameters for the upgrade of Port Fourchon Junction

Scenario (see Table 3-1)	RP (years)	Elevation of deck underside m NAVD88 (ft NAVD88)	Flow velocity m/s (ft/s)	Hs m (ft)	Hmax m (ft)	Gust speed (3-sec) m/s (mph)
4	100	Not applicable	2.0 (6.6)	0.61 (2.0)	0.94 (3.1)	80 (179)
	1000	**6.1 (20.1)**	**2.6 (8.5)**	**0.90 (3.0)**	**1.52 (5.0)**	**87 (195)**

Glossary

Deep water: Water too deep for waves to be affected by the seabed friction (typically taken as half the wavelength)

Shallow waters: Waters shallow enough to affect wave propagation by refraction, shoaling and eventually wave breaking

HAT: Highest Astronomical Tide

LAT: Lowest Astronomical Tide

Hs: Significant wave height

Hmax = Maximum individual wave height

MHHW: Mean Higher-High Water

MHW: Mean High Water

MTL: Mean Tide Level

MSL: Mean Sea Level

MLLW: Mean Lower-Low Water (= NAVD88)

NAVD88: vertical datum (= MLLW)

RSLR: Relative Sea Level Rise (accounts for Sea Level Rise proper as well as Subsidence)

SLR: Sea Level Rise (eustatic: global change in the amount of water stored in the oceans, or a change in the geometry of the ocean basins)

Surge tide (or Storm tide): It is the water level rise during a storm due to the combination of storm surge and the astronomical tide.

Notation and Acronyms

ADCIRC: Advanced 3D Circulation Model for Shelves, Coasts, and Estuaries, http://adcirc.org/
AoI: Area of Interest
CPRA: Coastal Protection Restoration Authority (State of Louisiana)
DHI: Danish Hydraulic Institute
FEMA: Federal Emergency Management Agency
GoM: Gulf of Mexico
IPCC: Intergovernmental Panel on Climate Change
MBES: MultiBeam Echo Sounder
NOAA: National Oceanic and Atmospheric Administration
SBES: SingleBeam Echo Sounder
SWAN: Simulating Waves Nearshore Model
USGS: United States Geological Survey
WIG: Water Institute of the Gulf

Table of contents

1. Background

The Mississippi delta is one of the world's most vulnerable low-elevation coastal zones. Port Fourchon, located in coastal Louisiana, is highly exposed to inundation under hurricanes which regularly visit the Gulf of Mexico. Another important factor is the delta's high rate of subsidence, which combined with sea level rise, will increase the area vulnerability in the coming decades.

1.1. Port Fourchon vulnerability to inundation under hurricanes

In the Port Fourchon area the historical record indicates a frequency of approximately 1.2 storms per year. Inundation is the result of the combined action of storm surge, tides, waves and the presence of freshwater input, such as rivers.

1.1.1. Storm surge and tide

Storm tide is the water level rise during a storm due to the combination of storm surge and the astronomical tide. As the arrival of a storm within the tidal cycle is unknown, a certain high tide is assumed for design conditions. Since storm tide is the combination of surge and tide, it does require a reference level. In this study the reference level is the vertical datum NAVD88.
Storm surge is caused primarily by the strong winds in a hurricane or tropical storm. The low pressure of the storm has minimal contribution. The wind circulation around the eye of a hurricane blows on the ocean surface and produces a vertical circulation in the ocean. In deep water, there is nothing to disturb this circulation and there is very little indication of storm surge (Figure 1-1 left). Once the hurricane reaches shallower waters near the coast, the vertical circulation in the ocean becomes disrupted by the ocean bottom. The water can no longer go down, so it has nowhere else to go but up and inland (Figure 1-1 right).

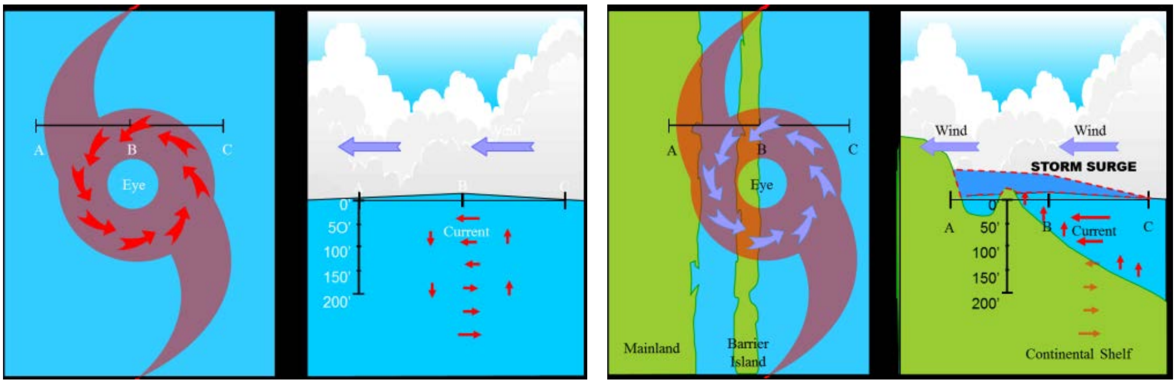

Figure 1-1: Hurricane effects in deep waters (left) and in shallow waters and coastal areas (right). Source NOAA.

The storm surge at a given location correlates only loosely with the intensity of the hurricane measured by wind speeds, such as the Saffir-Simpson wind scale. The reason being that there are many factors affecting storm surge and some of them may outweigh wind speed depending on the location and the storm features.

- Storm Intensity: All other variables being equal, stronger winds will produce a higher surge.
- Storm size: A larger storm will produce higher surge. There are two reasons for this. First, the winds in a larger storm are pushing on a larger area of the ocean. Second, the strong winds in a larger storm will tend to affect an area longer than a smaller storm.
- Storm Forward Speed: On the open coast, a faster storm will produce a higher surge. However, a higher surge is produced in bays, sounds, and other enclosed bodies of water with a slower storm.

- Angle of Approach to Coast: The angle at which a storm approaches a coastline can affect how much surge is generated. A storm that moves onshore perpendicular to the coast is more likely to produce a higher storm surge than a storm that moves parallel to the coast or moves inland at an oblique angle.
- Central Pressure: Lower pressure will produce a higher surge. However, the central pressure is a minimal contributor compared to the other factors.
- Shape of the Coastline: Storm surge will be higher when a hurricane makes landfall on a concave coastline (curved inward, such as the coastline between Port Fourchon and the Mississippi West Bay) as opposed to a convex coastline (curved outward, such as the Outer Banks of North Carolina).
- Width and Slope of the Ocean Bottom: Higher storm surge occurs with wide, gently sloping continental shelves, while lower storm surge occurs with narrow, steeply sloping shelves. Areas along the Gulf Coast, especially Mississippi and Louisiana (including Port Fourchon, Figure 1-2), are particularly vulnerable to storm surge because the ocean floor gradually deepens offshore. Conversely, areas such as the east coast of Florida have a steeper shelf, and storm surge is not as high.
- Local Features: Storm surge is highly dependent on local features and barriers that will affect the flow of water. A good example is the coast of North Carolina, which has the complexities of such features as barrier islands, inlets, sounds, bays, and rivers. While Port Fourchon does not have such natural features, it has been protected in recent years by a man-made barrier beach and a series of breakwaters (more in section 1.3 and 2.1). These features play a significant role in protecting Port Fourchon and add a level of complexity in the flow physics that require special modeling tools (more on section 3.3).

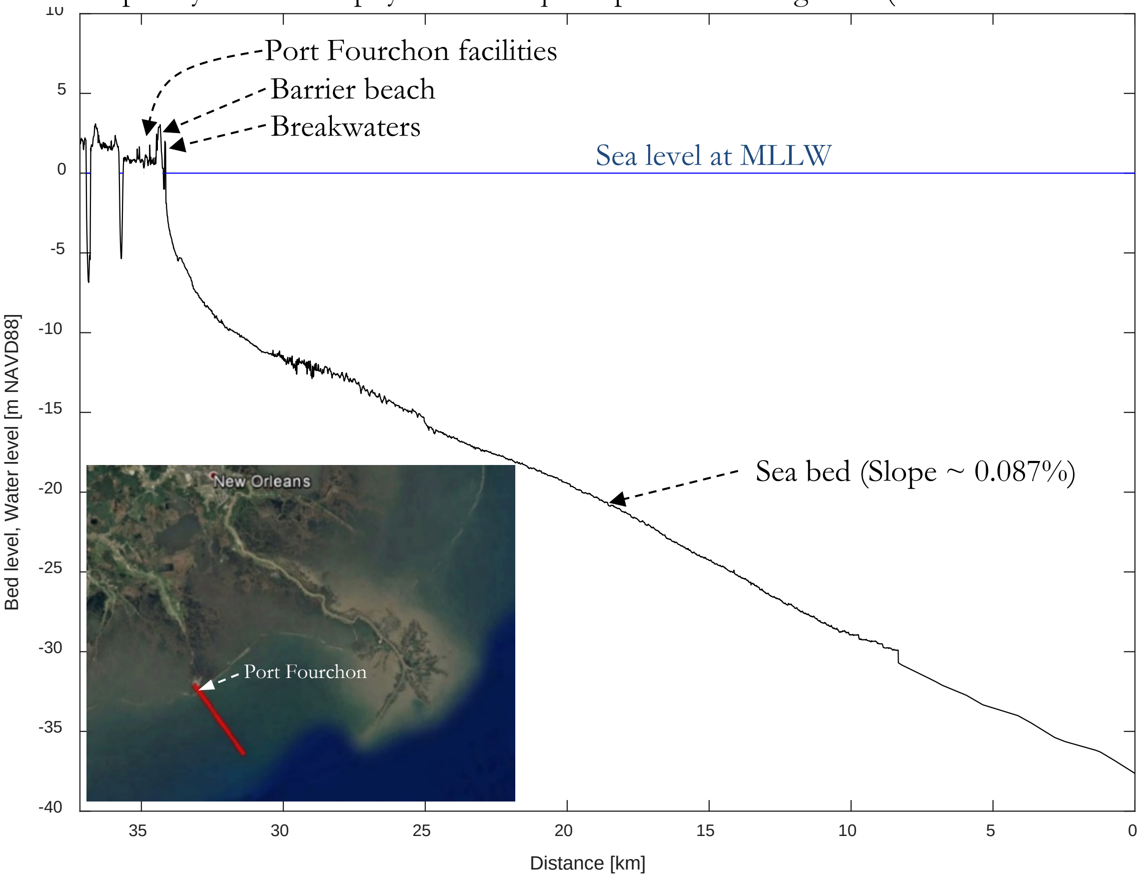

Figure 1-2: Wide and gentle sloping continental shelf offshore Port Fourchon. Seabed (black line). Sea level at zero vertical datum (NAVD88 = MLLW, blue line). Note that vertical and horizontal scales are not the same. Inset: Red line indicates cross section upon which the seabed in the main figure is projected.

1.1.2. Waves

Breaking waves contribute to the water level rise through wave runup and wave setup. Wave runup occurs when a wave breaks and the water is propelled onto the beach. Wave setup occurs when waves continually break onshore and the water from the runup piles up along the coast because it can't get back out to sea. The water level therefore rises as a hurricane approaches, especially since the waves become larger and more water is pushed onshore.

The contribution of waves to inundation levels in Port Fourchon has been carefully assessed in this study.

1.1.3. Rivers

Heavy rainfall ahead of a hurricane can cause river levels to rise well inland from the coast. Once all this water flows downriver and reaches the coast, local water levels especially near deltas and in bays will rise. The Bayou Lafourche is such a fresh water input relatively close to Port Fourchon. However, given its relative small size, the location of Port Fourchon facilities practically by the sea, and the time lag usually observed between ocean and hydrographic peaks, it has not been considered.

1.2. Subsidence and sea level rise

Coastal subsidence causes sea-level rise, shoreline erosion, wetland loss, and makes the area more vulnerable to inundation. The Mississippi delta experiences one of the largest rates of relative sea level rise (RSLR = subsidence + sea level rise) in the world. The majority of it comes from subsidence due to compaction of Holocene strata [8, 9, 10, 11]. The causes of subsidence in coastal Louisiana, attributed to factors as diverse as shallow compaction and deep crustal processes, remain controversial. Relative contributions of geologic, sedimentary, and anthropogenic processes to subsidence are vigorously debated, as well as methods to mitigate them [12]. Hydrocarbon production may be a contributing local factor in some places [13, 14] while groundwater extraction may be the cause in others [15, 16]. Current estimates of subsidence rates vary by several orders of magnitude. Millennial-scale compaction rates primarily associated with peat can reach 5 mm per year. However, locally and on timescales of decades to centuries, rates are likely to be 10 mm or more per year. In Port Fourchon and nearby Grand Isle RSLR ranges between 9.1 and 11.8 mm/year [17, 18, 19, 20, 21]. As sea level rise in the Gulf of Mexico has occurred at a rate of 1.8–2.2 mm/yr during the 20th century [22], subsidence is the major contributor to RSLR.

1.3. Man-made sheltering structures

In order to shelter Port Fourchon facilities from flooding and inundation from the sea, a barrier beach and a series of breakwaters have been constructed (Figure 1-3, detailed bathymetry in section 2.1). These man-made features are effective in protecting Port Fourchon, but the effectiveness depends on their continuous maintenance. In addition, they modify flow and waves in such a complex way that numerical modelling can be successfully carried out only if the fundamental fluid physics are properly recalled in high resolution space and time domains.

The barrier beach and the breakwaters seem to have been emplaced after 1989 and before 1998. The barrier beach seems to have been subject to some degree of restoration in 2012-2014 [23].

Figure 1-3: Port Fourchon junction facilities in 1989, 1998 and 2015. Note the appearance of breakwaters between 1989 and 1998. Source Google Earth.

2. Data sources

2.1. Bathymetry and topography

High resolution single beam bathymetry (Table 2-1) and LiDAR topography from different sources (NOAA, CPRA, USGS) were compiled by the Danish Hydraulic Institute (DHI). Additionally, a coarse resolution topo-bathy layer was retrieved covering all of southern Louisiana. This dataset is an amalgamation of a large number of sources and only serves as data on land and in the Timbalier Bay region, where no modern sounding-based bathymetry was available. This dataset is referred to as the "Coastal Digital Elevation Model". Vertically, it was referenced to MHW, but for use in this project was off-set by 40 cm to better correspond to the MLLW reference used by the detailed surveys.

A coastal LiDAR dataset has been included to increase the level of detail near the breakwaters at the channel entrance and at the facility to the east of it. The LiDAR data is referenced to NAVD88, which coincides with MLLW. Additional LiDAR data from 2001 was available along the coastline but was not considered due to being deemed obsolete for this study[1].

The two breakwaters at the entrance to Port Fourchon were digitized from a Sentinel-2 optical satellite image, in an effort to assure proper representation in the resulting dataset. Within the digitized area, elevations were taken from the coarse topo-bathy layer. The breakwaters in front of the facility east of the channel entrance have been added to the dataset through inclusion of the LiDAR dataset as well as manually added points. The elevations of the breakwaters were based on available engineering drawings. Water depths between the breakwaters and beach were estimated based on the general coastal transects.

The final combined dataset has a 10 m horizontal resolution and vertical datum NAVD88, which coincides with MLLW (Figure 2-1, Figure 2-2). Further details are found in Appendix 1 (Technical note on bathymetry – Port Fourchon).

The Water Institute of the Gulf (WIG) also provided two coarser resolution datasets for present and future conditions. The latter is projected 50 years in the future based on present rates of subsidence and described in the Louisiana's 2012 Coastal Master Plan [1].

Table 2-1 data is roughly a decade old, hence when estimating future subsidence starting from present conditions this difference has to be considered.

Table 2-1 Available NOAA bathymetries (UTM 15N, vertical NAVD88=MLLW)

Registry #	Project #	Year	Spatial Resolution
H11785	OPR-K977-SA-08	2008-2009	1m point spacing 45m line spacing
H11804 & H11805	OPR-K977-FU-08	2008-2009	5m point spacing 50m line spacing
H12425	OPR-K339-KR-12	2012	2m point spacing 50m line spacing
H11537	OPR-K362-KR-06	2006-2007	5m point spacing 90m line spacing
H11457	OPR-K362-KR-05	2006-2007	5m point spacing 90m line spacing

---

[1] Yates, Xan, Nayegandhi, Amar, Brock, J.C., Sallenger, A.H., Klipp, E.S., and Wright, C.W., 2009, ATM coastal topography–Louisiana, 2001: UTM Zone 15 (part 1 of 2): U.S. Geological Survey Data Series 464, 1 DVD. https://pubs.usgs.gov/ds/464/

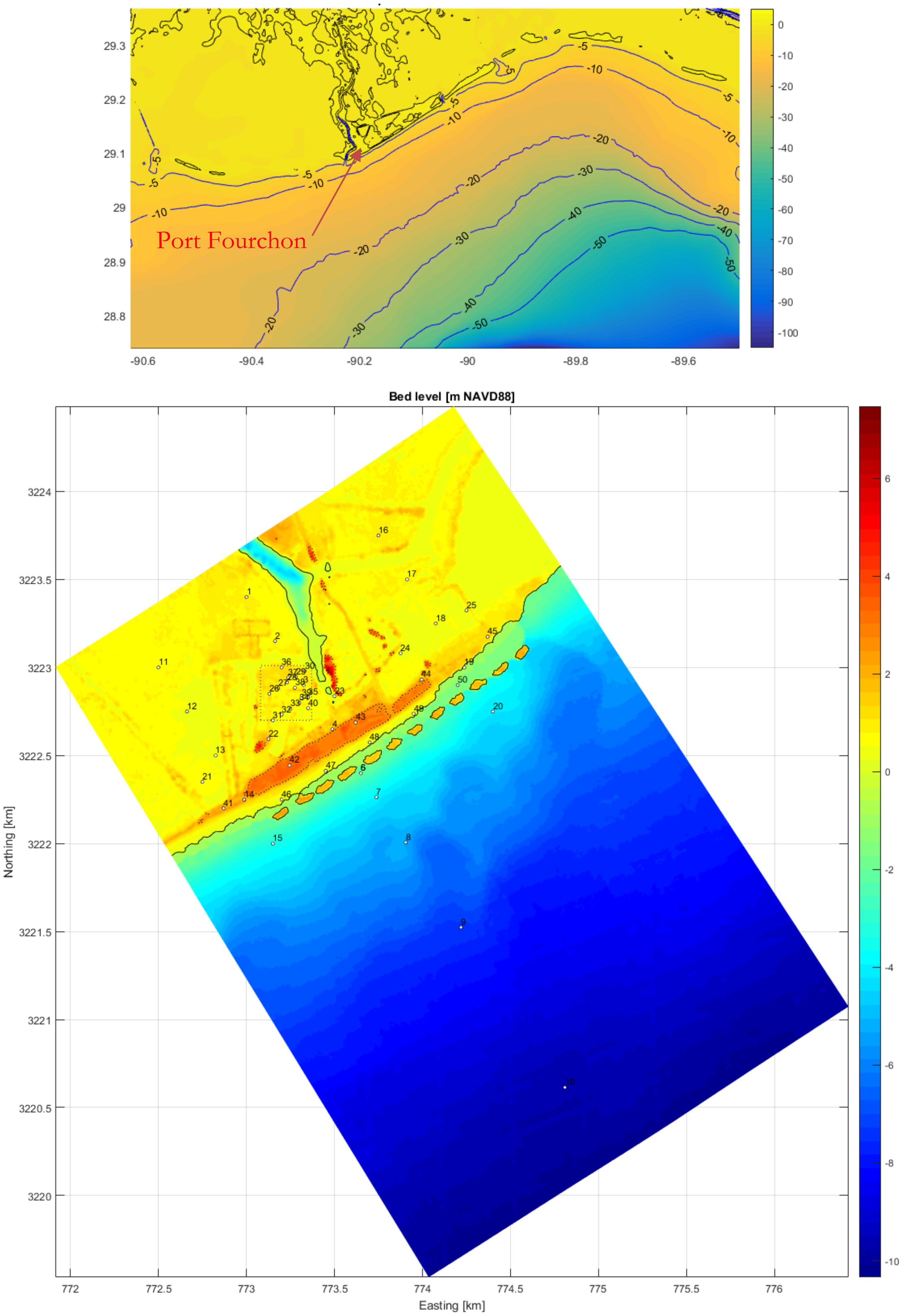

Figure 2-1: Combined bathymetry and topography. Top: regional. Bottom: Port Fourchon AoI. Vertical datum is m NAVD88, which is equal to MLLW. Port Fourchon facilities are roughly encompassed by the dotted rectangle behind the barrier beach and the breakwaters. Numbered markers indicate selected nodes for model output timeseries.

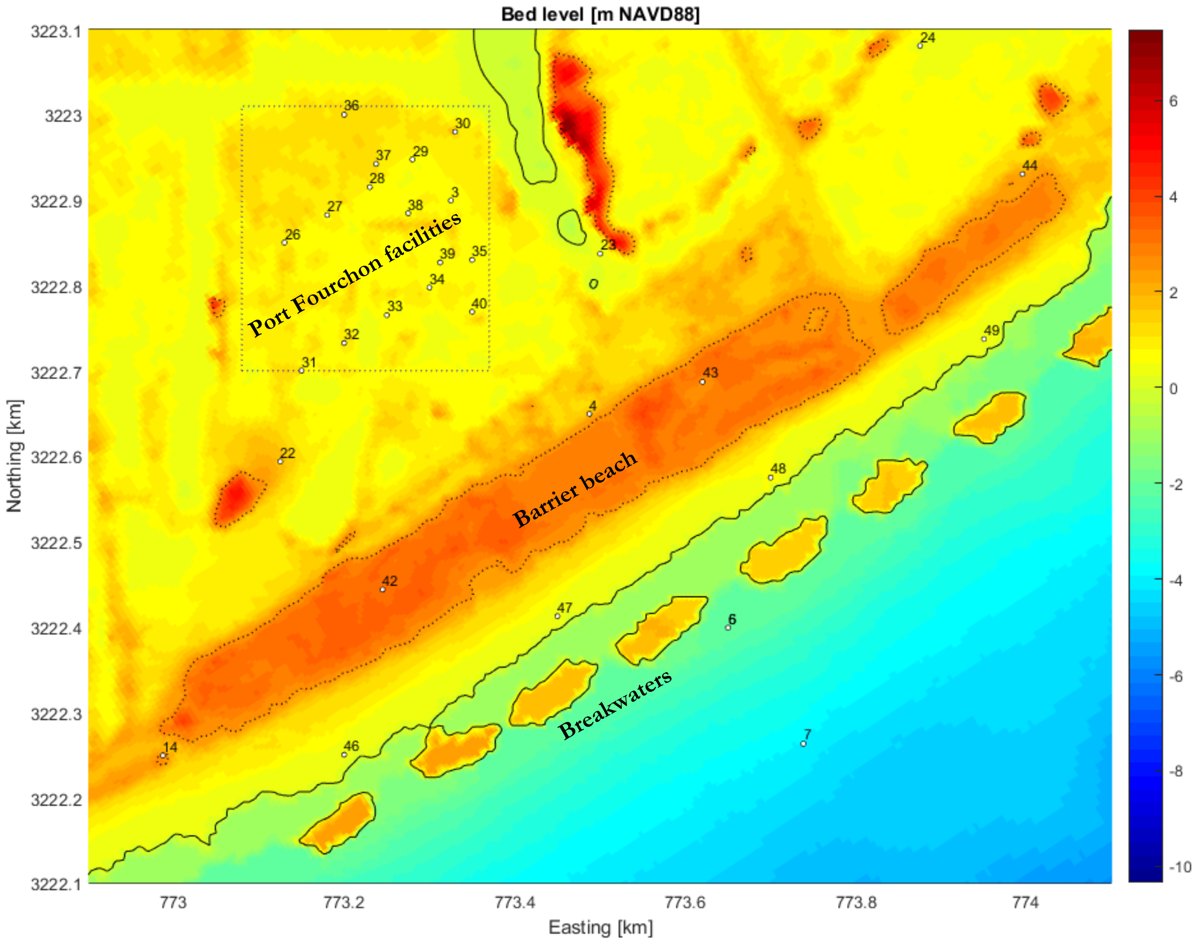

Figure 2-2: Bathymetry and topography. Zoom to Port Fourchon junction area of interest.

2.2. Metocean sources

2.2.1. WIG and FEMA

Present and future metocean conditions at selected nodes (Figure 2-3) in the form of synthetic storms based on a coupled SWAN- ADCIRC model carried out by The Water Institute of the Gulf (WIG) for the Louisiana Master Plan [1]. The future metocean conditions account for a sea level rise of 0.45 m and the landscape evolution that occurs during that time. The following parameters are extracted for 446 synthetic tropical storms.

1. Maximum water surface elevation (meters navd88 2004.65)
2. Time series water surface elevation (meters navd88 2004.65)
3. Maximum current speed (m/s)
4. Time series current velocity (vector) (m/s)
5. Maximum significant wave height (meters)
6. Time series significant wave height (meters)
7. Maximum wave direction (i.e. direction of wave in 5) (deg)
8. Time series wave direction (i.e. direction of wave in 6) (deg)
9. Maximum wave mean period, TM01 (i.e. mean period of wave in 5) (seconds)

10. Time series mean wave period, TM01 (i.e. mean period of wave in 6) (seconds)
11. Maximum wave peak period, TPS (i.e. peak period of wave in 5) (seconds)
12. Time series peak wave period, TPS (i.e. peak period of wave in 6) (seconds)
13. Time series atmospheric pressure (mH20)
14. Time series wind vector (m/s)
15. Time series wind speed (m/s).

While wind speed time series are provided every 15 minutes, the averaging period is 30 minutes. Wave and current time series are provided and averaged every 20 minutes.

ADCIRC is a flow circulation model for shelves, coasts, and estuaries [5]. ADCIRC uses the provided wind data, multiplied by 1.09 to convert from 30-minute to 10-minute wind fields. It contains no adjustment to the boundary layer and the winds should be considered full marine exposure wind fields.

The water surface elevation is the surge tide. It includes the storm surge and the astronomical tide. In the Gulf of Mexico, the tide range is small enough for probabilities of different storms happening at different points in the tide cycle, and thus, it is more efficiently handled statistically than within the simulations directly. Storm peaks in FEMA/WIG dataset account for tide even though this is not directly modeled, and therefore peak surge elevations do not need to be corrected for tides.

In addition to the timeseries the WIG provided extreme values derived by the Federal Emergency Management Agency (FEMA) IDS2 study [2] based on a different set of simulations but utilizing identical wind conditions as those by the WIG.

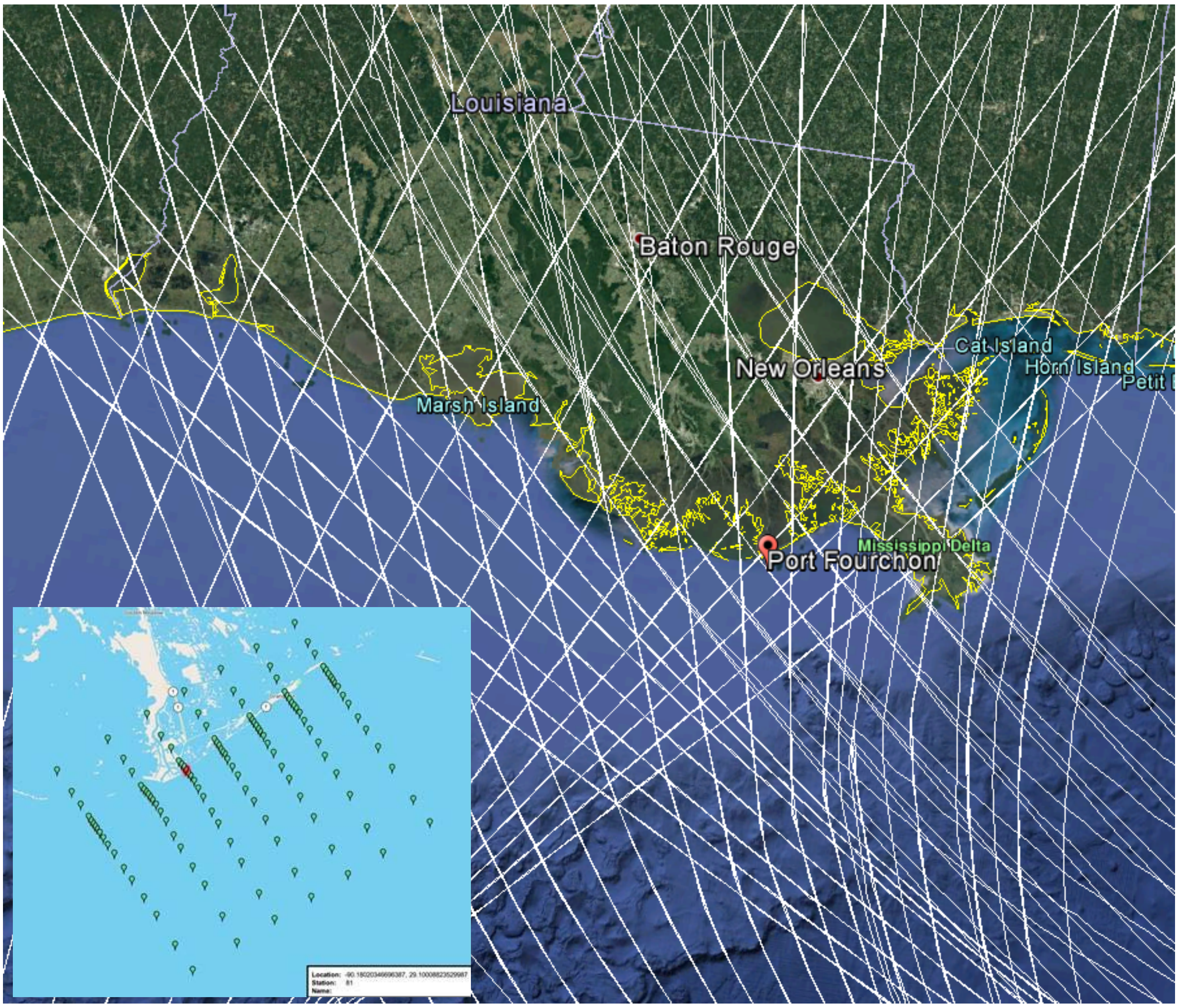

Figure 2-3: Tracks of the 446 synthetic hurricanes in the database relevant to Port Fourchon. Inset: Selected nodes around Port Fourchon where timeseries were extracted

2.2.2. NOAA water elevation

Water elevation at NOAA Grand Isle station 8761724/8761720 and Port Fourchon Belle Pass 8762075 were downloaded from NOAA's Tides and Currents site [3] (Table 2-2, Figure 2-4).

Table 2-2 NOAA water elevation stations relevant for Port Fourchon

Location	Station	Parameter	Latitude	Longitude	Interval	Duration
Port Fourchon Belle Pass	8762075	Water elevation	29° 6.8' N	90° 11.9' W	1 hr	2003-2019
Grand Isle	8761724 (8761720)	Water elevation	29° 15.8' N	89° 57.4' W	1 hr	1979-2019 (1947 -1980)

Figure 2-4: Location of Port Fourchon Belle Pass and Grand Isle NOAA stations.

2.2.3. Oceanweather

A few Oceanweather GOMOS2017 and GOMOS08_Shallow hindcasts nodes relevant to Port Fourchon were available but were not considered fit for purpose for this study. Upon evaluating them it was found that they significantly overestimated wave heights in shallow waters.

Nevertheless, being an historical dataset, the average rate of storms per year (~1.2) was taken from GOMOS2017. This rate is needed to convert the synthetic WIG dataset into a timeseries.

3. Methods

3.1. Scenarios

The aim of the study is to assess present and future scenarios that cover a spectrum of uncertainties in terms of:

- Metocean conditions
- Subsidence
- Sea level rise
- Differential settlement of barrier beach

On that regards the scenarios considered are shown in Table 3-1.

Table 3-1 Scenarios assessed in this study.

Scenario number	Scenario key features
1	Present time - Grand Isle surge
2	Present time - FEMA surge
3	Future time - FEMA surge - Grand Isle RSLR
4	Future time - FEMA surge - Port Fourchon RSLR
5	Future time - FEMA surge - Port Fourchon Subsidence and IPCC SLR
6	Future time - FEMA surge - Port Fourchon RSLR and differential settlement of barrier beach

Extreme metocean conditions, including waves and surge, depend on whether they are assessed in present or future time. In the case of the latter more severe extremes are expected because sea level rise and subsidence are expected to result in larger extreme waves at a given location and wave breaking closer to shore.

The first scenario is the most representative of present conditions and reliable for short return periods because it is based on recorded surge data. Its primary purpose is to reality-check the model.

For the remining scenarios, whether present or future time, the surge is based on FEMA extremes. FEMA extreme are based on synthetic simulations that cover a wide spectrum of hurricane paths and strengths that are lacking in the observed local hurricane history. Hence FEMA extreme surge are larger than those derived from Grand Isle records.

For Relative Sea Level Rise (RSLR) two main cases are considered based on observed records at Grand Isle and at Port Fourchon (Scenarios 3 and 4). RSLR accounts for both subsidence and eustatic sea level rise (SLR). While the observed SLR is the same at both locations, the subsidence at Port Fourchon is larger than at Grand Isle.

Scenario 5 takes the subsidence from Port Fourchon and the SLR from the IPCC 5th Assessment Report RCP4.5 scenario.

Scenario 6 takes Port Fourchon RSLR and adds a differential settlement on the barrier beach based on recent observations projected to the end of the asset lifespan. This scenario assumes that no maintenance will be done on the barrier beach.

3.2. Return period assessment

Low return period (< 10 yr) are mostly studied to assess the validity of the model against observed sea level data at Grand Isle and Port Fourchon.

High return periods (> 50 yr) under future scenarios are studied for design conditions.

Present time scenarios are thus assessed for 1, 10, 50, 100 and 500 years return periods. While future time scenarios are assessed for 50, 100, 500 and 1000 years return periods.

3.3. XBeach setup

XBeach is public domain model developed by several entities led by Deltares and funded by the United States Army Corps of Engineers, The Netherlands Rijkswaterstaat, and the European Union among others [6].

It is a non-hydrostatic, wave-resolving model that resolves 2D horizontal coupled equations for wave propagation, flow, sediment transport and bottom changes, given varying (spectral) wave and flow boundary conditions.

Among other features it handles diffraction, reflection, wave breaking in shallow waters, flow over dykes and breakwaters. This is precisely the type of wave and flow conditions expected at Fourchon, which is sheltered from the sea by a large barrier beach and a series of breakwaters.

As XBeach is a computationally intensive software and the aim of the study is to assess extreme scenarios only, the conditions to be modelled represent the peak of hurricanes.

Each simulation is run for 45 min, of which the last 30 min are considered the effective real time, and the first 15 min are model warm up.

Boundary conditions for selected return periods are derived from the extreme value analysis of the FEMA/WIG hurricane database.

3.4. XBeach domain

As XBeach is a computationally expensive model due to the high resolution required by the spatial grid and the short time step, the model domain should be carefully assessed. In addition, the optimum solution of the non-hydrostatic phase-resolving wave equations impose some pre-requisites on where the offshore boundary should be set.

The offshore boundary should be set sufficiently deep so the waves entering the domain are not breaking at said boundary. Wave breaking is resolved internally by the model by steepening of the wave front. The rule of thumb being that the ratio of wave height to water depth (H/d) at the offshore boundary should be $H/d < 1/3$ for optimum conditions, and never larger than 1/2. Because of the gentle sloping seabed offshore Port Fourchon, and the fact that the study targets peak hurricane conditions, this results in a rather large across-shore domain size.

There is also a requirement on the relative wave number at the offshore boundary. The relative wave number (kd) is defined by the wave number times the water depth. When XBeach is run in the default one-layer depth-average mode it requires $kd < 1$ for the offshore boundary to be sufficiently shallow and the non-hydrostatic nonlinear shallow water equations to be properly solved. This condition can be relaxed to $kd < 5$ if the two-layer grid is enabled in XBeach, but at the expense of some additional computational time [7].

As these two requirements oppose each other, the result is a limited range where the offshore boundary can be set.

Regarding domain along-shore size, it depends on the local topography and bathymetry. In the case of Port Fourchon the outstanding features are the breakwaters and the beach barrier. The domain along-shore size should be sufficiently large, so all the breakwaters and the core thicker part of the barrier beach are included (see Figure 3-1 and Figure 2-1). While the barrier beach fades eastwards of the asset, it still stands west of it for a longer distance, albeit thinner than at the central core. This creates an along-shore asymmetry that will inform wave and flow propagation when significant inundation and wave-overtopping happen and needs to be accounted in the model.

The onshore boundary should be sufficiently inland to capture key topographic features such as dykes, roads, channels, and terrain irregularities that affect flow and wave propagation. In particular the Rappelet Road that runs east of the asset provides some degree of sheltering as it is elevated from the surrounding terrain forming a dyke-like feature.

Figure 3-1: Satellite image of Port Fourchon circa January 2015. Source Google Earth.

3.5. Simulation matrix

Table 3-2 summarizes all relevant XBeach simulations run in this study.

Table 3-2 XBeach simulation matrix

Run	Name	Time	RP [yr]	Surge	RSLR (= Subsidence + SLR) *	Diff. Settlement ǂ
1	XB01_c_100y_SurgeFEMA	present	100	FEMA	n.a.	n.a.
2	XB02_c_100y_SurgeGI	present	100	Grand Isle	n.a.	n.a.
3	XB03_c_500y_SurgeFEMA	present	500	FEMA	n.a.	n.a.
4	XB04_c_500y_SurgeGI	present	500	Grand Isle	n.a.	n.a.
5	XB05_c_50y_SurgeFEMA	present	50	FEMA	n.a.	n.a.
6	XB06_c_50y_SurgeGI	present	50	Grand Isle	n.a.	n.a.
7	XB08_c_1y_SurgeFEMA	present	1	FEMA	n.a.	n.a.
8	XB08_c_1y_SurgeGI	present	1	FEMA	n.a.	n.a.
9	XB09_c_10y_SurgeFEMA	present	10	FEMA	n.a.	n.a.
10	XB09_c_10y_SurgeGI	present	10	FEMA	n.a.	n.a.
11	XB01_f_100y_SurgeFEMA_RSLRGI	future	100	FEMA	Grand isle	n.a.
12	XB03_f_500y_SurgeFEMA_RSLRGI	future	500	FEMA	Grand Isle	n.a.
13	XB05_f_50y_SurgeFEMA_RSLRGI	future	50	FEMA	Grand Isle	n.a.
14	XB10_f_1000y_SurgeFEMA_RSLRGI	future	1000	FEMA	Grand Isle	n.a.
15	XB01_f_100y_SurgeFEMA_RSLRPF	future	100	FEMA	Port Fourchon	n.a.
16	XB03_f_500y_SurgeFEMA_RSLRPF	future	500	FEMA	Port Fourchon	n.a.
17	XB05_f_50y_SurgeFEMA_RSLRPF	future	50	FEMA	Port Fourchon	n.a.
18	XB10_f_1000y_SurgeFEMA_RSLRPF	future	1000	FEMA	Port Fourchon	n.a.
19	XB01_f_100y_SurgeFEMA_RSLRPFIPCC	future	100	FEMA	P.F. subsidence + IPCC RCP4.5 SLR	n.a.
20	XB03_f_500y_SurgeFEMA_RSLRPFIPCC	future	500	FEMA	P.F. subsidence + IPCC RCP4.5 SLR	n.a.
21	XB05_f_50y_SurgeFEMA_RSLRPFIPCC	future	50	FEMA	P.F. subsidence + IPCC RCP4.5 SLR	n.a.
22	XB10_f_1000y_SurgeFEMA_RSLRPFIPCC	future	1000	FEMA	P.F. subsidence + IPCC RCP4.5 SLR	n.a.
23	XB01_f_100y_SurgeFEMA_RSLRPF_DS	future	100	FEMA	Port Fourchon	Barrier beach
24	XB03_f_500y_SurgeFEMA_RSLRPF_DS	future	500	FEMA	Port Fourchon	Barrier beach
25	XB05_f_50y_SurgeFEMA_RSLRPF_DS	future	50	FEMA	Port Fourchon	Barrier beach
26	XB10_f_1000y_SurgeFEMA_RSLRPF_DS	future	1000	FEMA	Port Fourchon	Barrier beach

* Grand Isle Relative Sea Level Rise = 9.1 mm/yr = 0.455 m / 50 yr
Port Fourchon Relative Sea Level Rise = 11.8 mm/yr = 0.59 m / 50 yr
Port Fourchon subsidence (0.49 m / 50 yr) + IPCC AR5 RCP4.5 SLR (0.26 m / 50 yr) = 0.75 m /50 yr

ǂ Differential Settlement of barrier beach = 0.55 m / 50 yr. Barrier beach top capped at 2.95 m NAVD88 (down from the present 3.50 m NAVD88)

In addition, XBeach 1D simulations were run starting from deeper waters (38 m water depth) to confirm that the boundary conditions for the 2D simulations at the model offshore boundary (11 m water depth) were consistent with FEMA/WIG extremes.

3.6. XBeach parameters

XBeach version v1.23.5527 was used in this study and run in non-hydrostatic mode. A typical set up file is shown in Appendix 2.

4. Extreme values

4.1. Synchronicity and directionality of metocean parameters

All metocean dataset available for the area of interest (Figure 4-1) point to a strong correlation between the most critical parameters for inundation, wind, waves and surge.

In the Gulf of Mexico extreme values are defined by hurricanes. While the GoM is large body of water and during the early stages of hurricanes waves might be dominated by swell, at the hurricanes peak it is windsea that prevails. Wind speed and wave height have a strong correlation (Figure 4-2) and, in this study, extreme winds and waves are assumed to by synchronous. Waves and surge also correlate very well and for the sake of this study are taken as synchronous (Figure 4-3).

Due to a wide continental slope (> 50 km, Figure 1-2) with a mild slope (~0.087%) wave refract far offshore. But the time the enter the model domain (~3 km from the coast) they directionality is mostly form the SE quadrant (Figure 4-4). Wind directionality is more spread but still the SE quadrant contains the prevalent directions. For this reason, and for the purpose of modeling, wave and wind directions are considered to be the same and with an angle of attack perpendicular to the coast. This is a conservative assumption that enhances the hurricane inundation potential (see section 1.1.1), but it is also realistic because the isobaths are mostly parallel to the coast in the entire domain and further offshore making the waves propagate perpendicular to the coast, and directions of waves and winds are often aligned at peak conditions for the most severe hurricanes.

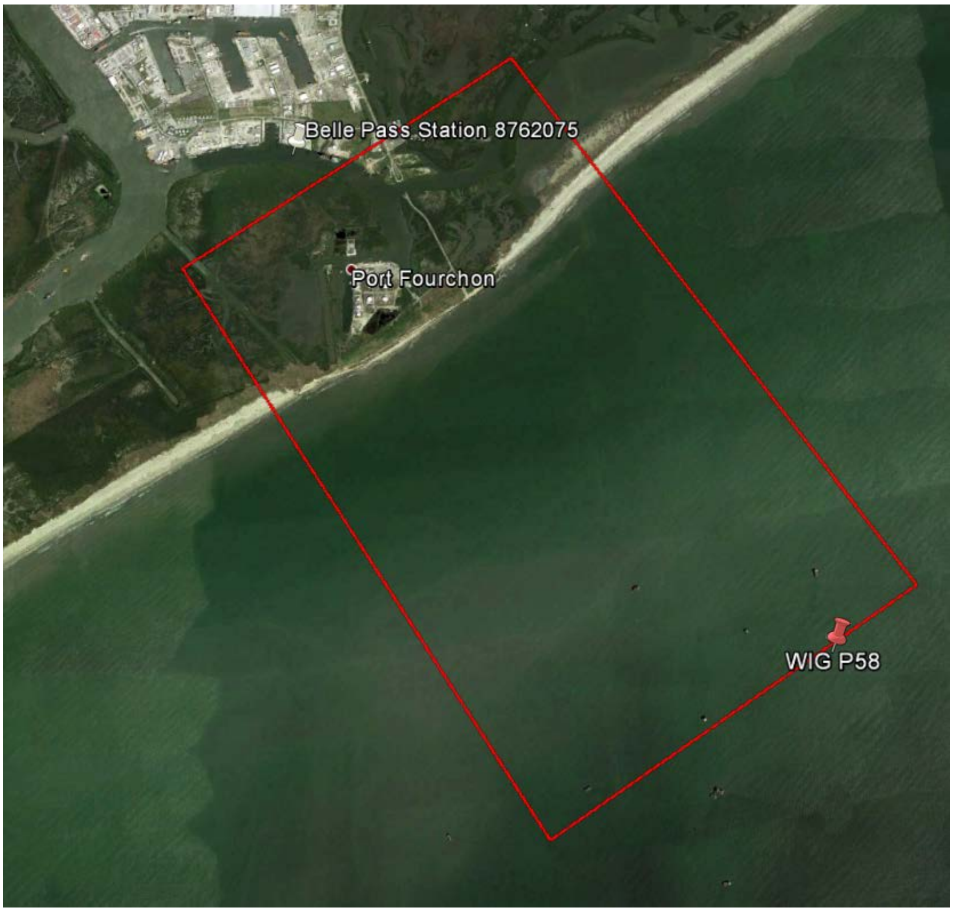

Figure 4-1: Port Fourchon and surroundings. Model domain indicated by red polygon (~4.5 km x 3km). Offshore boundary conditions based on WIG P58 (29.08115 N, 90.16401 W). Fourchon Belle Pass NOAA station indicated by white marker. Google Earth.

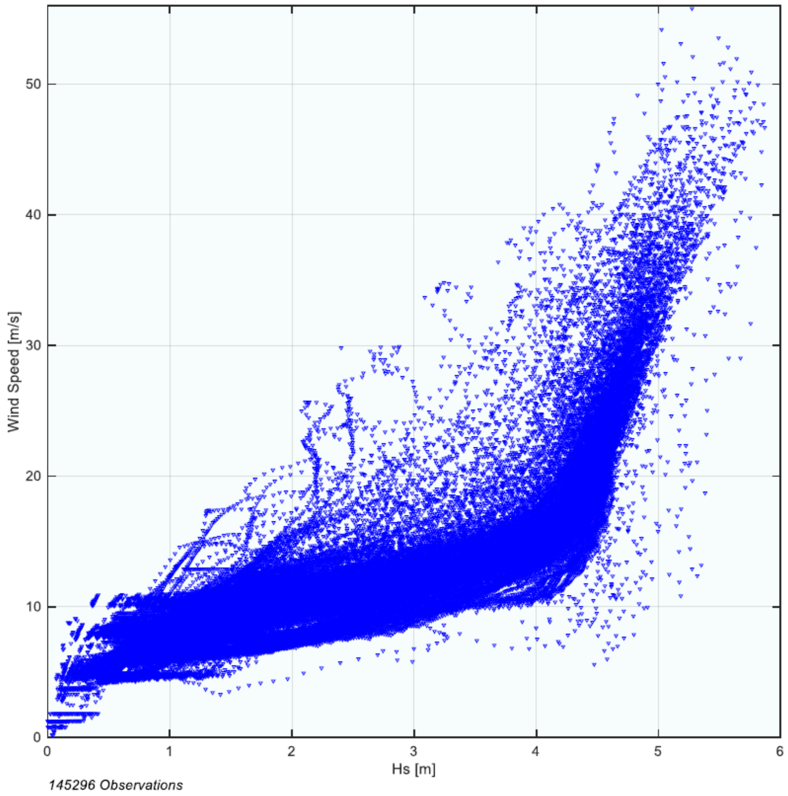

Figure 4-2: Scatter plot of Hs and wind speed at WIG node 58 (water depth ~ 11 m). The trend change for waves beyond ~4 m is thought to be caused by shallow water effects under hurricanes.

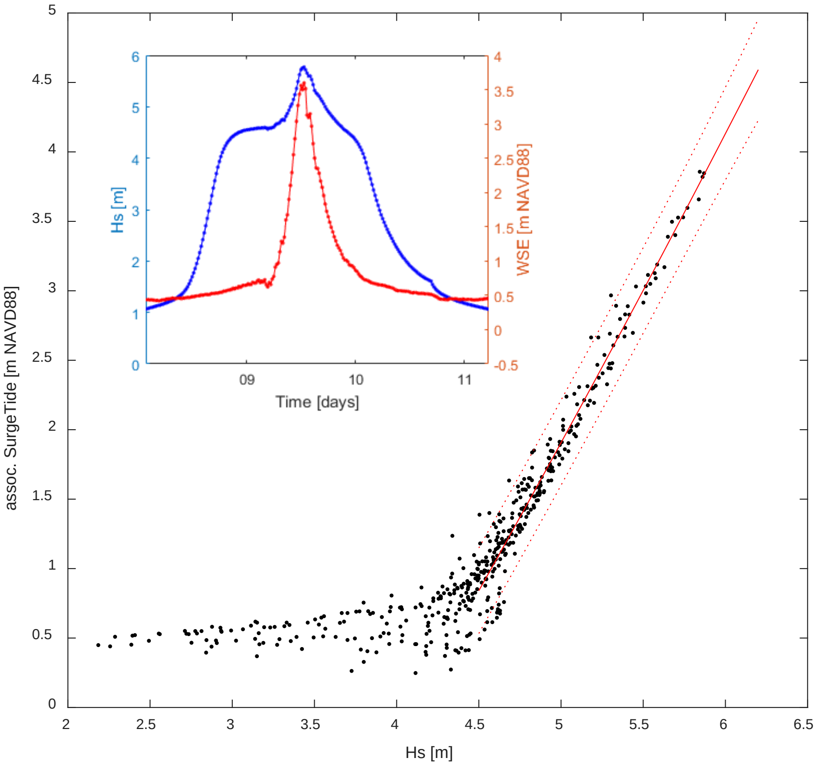

Figure 4-3: Peak Hs and associated surge tide at WIG node 58 (water depth ~ 11 m). The trend change for waves beyond ~4 m is thought to be caused by shallow water effects under hurricanes. Red line indicates best fit and red dotted lines indicate 5-95% confidence interval. Inset: time series of Hs (blue) and water level (red) for a typical hurricane.

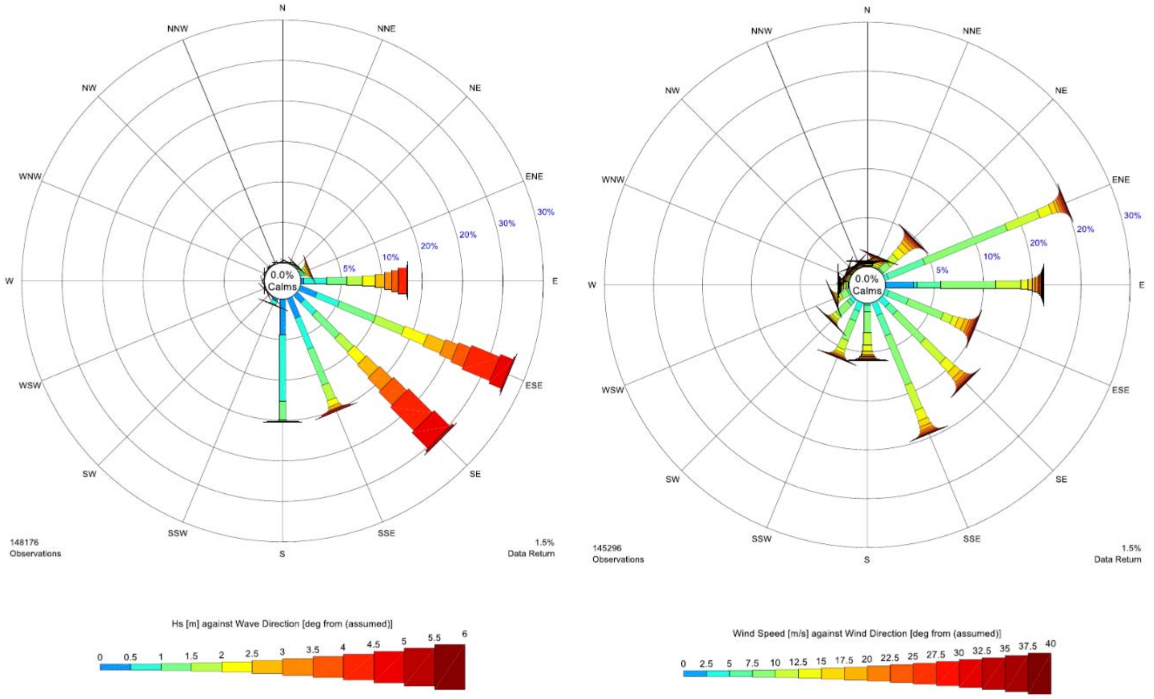

Figure 4-4: Wave roseplot (left) and wind roseplot (right) at WIG node 58 (water depth ~ 11 m).

4.2. Effects of atmospheric pressure

Storm surge is generated by the combined effects of surface winds and the decreased atmospheric pressure, causing a local rise in sea level (the *inverted barometer effect*).

The increase in static water level due to atmospheric pressure alone is estimated as [32]:

$$\eta = \frac{\Delta p}{\rho_w g}$$

For a strong tropical cyclone (i.e. cat. 5) Δp can be ~ 100 hPa = 10000 Pa. Hence η can be in the order of ~ 10000/1025/9.81 = 1 m. This represents a significant contribution that cannot be neglected.

Boundary conditions for the XBeach model come from the coupled SWAN- ADCIRC model provided by WIG, which does account for atmospheric pressure (section 2.2.1). In this way atmospheric pressure effects are included in the entire XBeach domain by forcing its boundary conditions with metocean data from a model that includes atmospheric pressure effects.

However, *within* the XBeach model itself atmospheric pressure effects have been not included. The main reason being the scale of horizontal pressure variations. states that the length scale for the horizontal pressure variations, representative of the influence of the atmospheric pressure effect, is L ~ 400 km [32, p. 80]. This is roughly two orders of magnitude larger than the XBeach domain, whose scale in this case is ~4 km. Spatial variations in atmospheric pressure are deemed too small to be accounted *within* XBeach domain.

In addition, the inverted barometric effect becomes relatively weaker in shallow waters. The ratio of surface stress to atmospheric pressure forcing is for strong hurricanes ~10 for 20 m water depth, but only 0.01 for 2000 m water depth [32, p. 80]. Which indicates that the atmospheric pressure effect decreases relative to the (wind) surface stress effect in shallower waters. At the boundary of the XBeach model (h~15 m) the surface stress effects are then more than one order of magnitude larger than the atmospheric pressure effect.

4.3. Subsidence and Sea Level Rise

Based on Grand Isle (Figure 4-5) and Port Fourchon NOAA stations Relative Sea Level Rise (RSLR) is on average 9.1 and 11.8 mm/year respectively [18, 20]. Grand Isle station records start in the late 1940s. Port Fourchon Belle Pass station has records starting in 2003.

Eustatic SLR in the Gulf of Mexico is about 2 mm/year [22]. This represents a 17-22% of the total RSLR in the surroundings of Port Fourchon and is similar to the low-end scenario in the Louisiana's 2012 Coastal Master Plan [1]. Local subsidence can then be estimated to range between 7.1 mm/year and 9.8 mm/year.

In contrast the IPCC First Assessment Report business-as-usual scenario, and Fifth Assessment Report RCP4.5 scenario, projected a SLR of 5.0-5.2 mm/yr [24, 25]. This represents a systematic overestimation since 1990 of more than 150% the observed SLR (Figure 4-6). The moderate scenario in the Louisiana's 2012 Coastal Master Plan has a similar value of SLR [1].

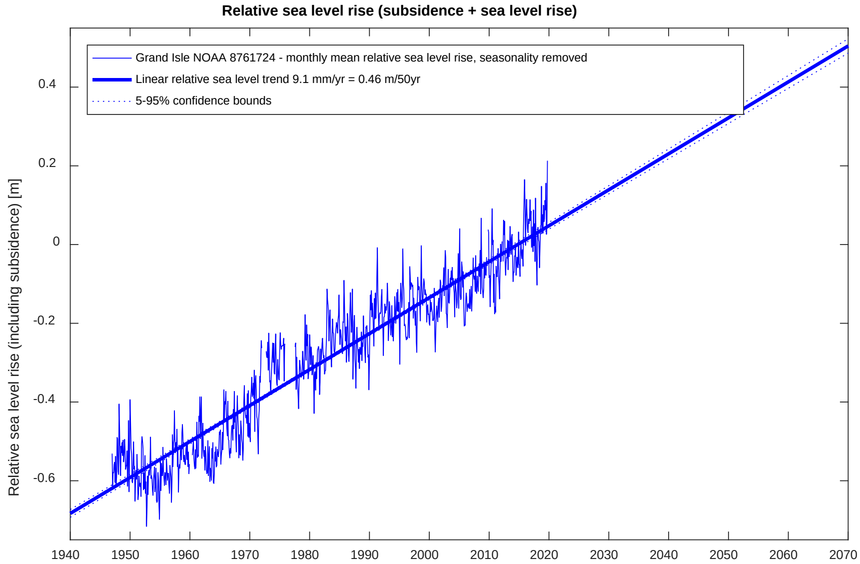

Figure 4-5: Relative Sea Level Rise (RSLR = Subsidence + SLR) recorded in Grand Isle.

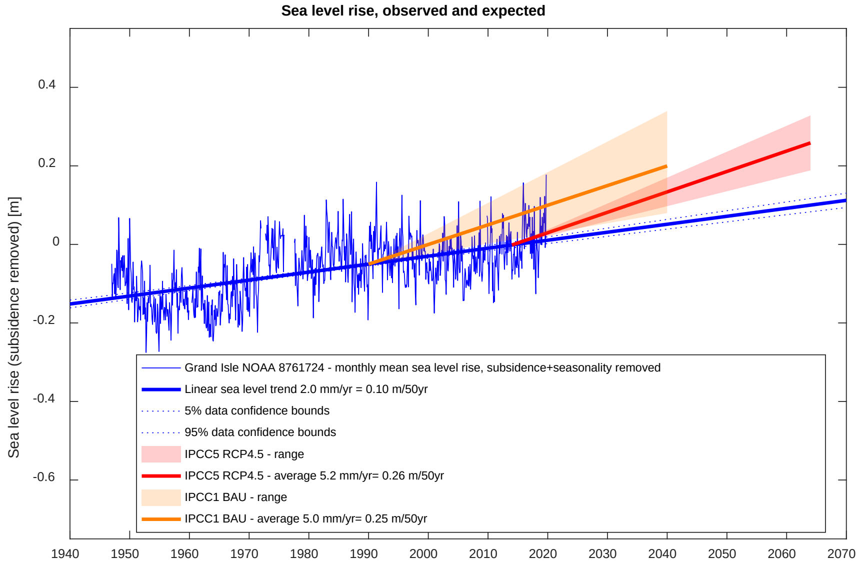

Figure 4-6: Sea Level Rise (SLR) recorded in Grand Isle. Trends predicted by IPCC FAR (1990) and AR5 (2013) Business-As-Usual and RCP4.5 scenarios are also shown.

4.4. Water levels and tides

The highest water levels recorded at Grand Isle NOAA station are shown in Table 4-1. Sea level rise trend has been accounted in computing these extremes. The 100-year return period is estimated by NOAA to be 1.93 m above MHHW (2.25 m above MLLW). At Port Fourchon station the highest water level was 1.40 m MLLW under hurricane Rita (09/24/2005).

Tidal levels based on Grand Isle and Port Fourchon NOAA water level stations are show in Table 4-2.

Table 4-1 Highest water levels recorded at Grand Isle. Source: NOAA Tides and currents.

Date	Hurricane	Water Level [m MLLW]
9/19/1947	Fort Lauderdale	1.27 m
9/24/1956	Flossy	1.29 m
9/9/1965	Betsy	2.17 m
9/7/1974	Carmen	1.14 m
10/27/1985	Juan	1.20 m
9/26/2002	Isidore	1.21 m
8/29/2005	Katrina	1.58 m
9/24/2005	Rita	1.27 m
9/1/2008	Gustav	1.48 m
9/12/2008	Ike	1.44 m
8/29/2012	Isaac	1.59 m

Table 4-2 Tidal levels at Grand Isle and Port Fourchon stations. Datum is MLLW (= NAVD88). Source: NOAA Tides and currents.

Level	Port Fourchon [m MLLW] station 8762075 (2003-present)	Grand Isle [m MLLW] station 8761724 (1979 - present)	Description
HAT	0.621	0.548	Highest Astronomical Tide
MHHW	0.368	0.323	Mean Higher-High Water
MHW	0.364	0.321	Mean High Water
MSL	0.192	0.163	Mean Sea Level
MTL	0.185	0.162	Mean Tide Level
MLLW = NAVD88	0.000	0.000	Mean Lower-Low Water
LAT	-0.332	-0.291	Lowest Astronomical Tide

4.5. Barrier beach differential settlement

Based on studies by Byrnes et al. 2015 [23] on Port Fourchon along Caminada Headland, differential settlement due to sediment consolidation is expected on the barrier beach (Figure 4-7). Based on a logarithmic best fit the barrier beach average differential settlement in 50 years' time is projected to a high-end average above 0.5 m (Figure 4-8). This is considered conservative because 25 years after the 2012-2014 restoration the differential settlement is expected to tend asymptotically to zero, rather than keep growing with a logarithmic trend [Jason Newlin: personal communication].

A differential settlement of 0.55 m in 50 years is assumed for modelling purposes. To mimic future conditions of the barrier beach, barring additional restorations, this is enforced by capping the barrier beach top at 2.95 m NAVD88, down from the present 3.5 m NAVD88 (Figure 4-9).

Figure 4-7: Station locations for sediment borings and anchor monuments for documenting subsurface sediment characteristics and monitoring elevation changes in response to beach restoration along Caminada Headland [23].

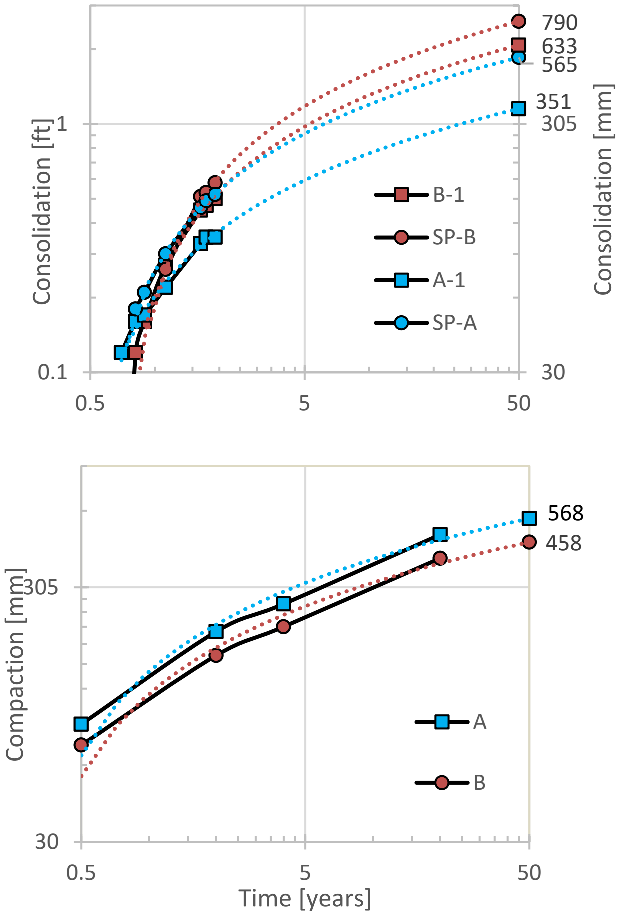

Figure 4-8: Barrier beach differential settlement as per consolidation (top) and compaction (bottom) rates at points A and B (Figure 4-7). Observations markers from Byrnes et al, 2015 [23] and projections (dotted lines, logarithmic best fit). SP stands for Settlement Plates, A-1 and B-1 indicate the shortest anchors 19.1 ft deep subject to the largest consolidation. Compaction is based on ongoing settlement and geotechnical properties.

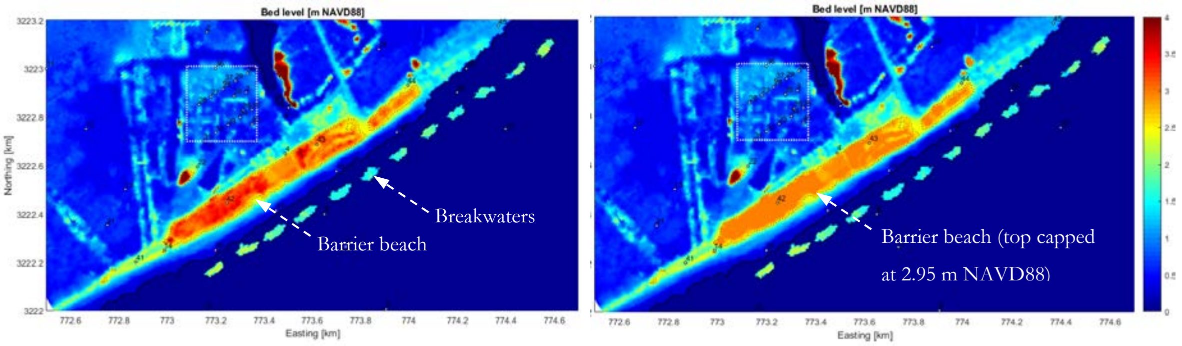

Figure 4-9: Barrier beach now (left) and projected in 50 years' time assuming no additional restoration by capping its top at 2.95 m NAVD88 (right). Scale is m NAVD88.

4.6. Extreme values for model boundaries

Table 4-3 summarizes the extreme values to force on XBeach boundaries for different return periods.

Table 4-3 Extreme values for XBeach model boundaries

RP	yr	1	10	50	100	500	1000	Time	Source Data
Wind Speed (WS) 30-min averaged	m/s	24.8	44.0	50.8	52.6	54.9	55.4	Present and Future	WIG P58
Hs	m	4.55	5.26	5.64	5.77	6.01	-	Present	WIG P58
Tp associated to Hs	s	12.0	13.7	15.4	15.4	15.4	-	Present	WIG P58
SurgeTide	m NAVD88	0.41	1.68	2.68	3.11	3.90	-	Present	FEMA P58
SurgeTide	m NAVD88	0.52	1.35	1.87	2.12	2.72	-	Present	Grand Isle station
RSLR 2070	m	-	-	0.46	0.46	0.46	0.46	Future	Grand Isle *
RSLR 2070	m	-	-	0.59	0.59	0.59	0.59	Future	Port Fourchon**
Hs	m	-	-	5.76	5.88	6.08	6.14	Future	WIG P58
Tp associated to Hs	s	-	-	15.4	15.5	15.6	15.6	Future	WIG P58
SurgeTide + RSLR 2070	m NAVD88	-	-	3.41	3.78	4.46	4.76	Future	FEMA/WIG P58 + Grand Isle RSLR
SurgeTide + RSLR 2070	m NAVD88	-	-	3.54	3.92	4.59	4.89	Future	FEMA/WIG P58 + Grand Isle RSLR
SurgeTide + RSLR IPCC RCP4.5	m NAVD88	-	-	3.70	4.08	4.75	5.05	Future	FEMA/WIG P58 + Port Fourchon subsidence + IPCC RCP4.5 SLR
Barrier beach differential settlement	m	-	-	0.55	0.55	0.55	0.55	Future	Port Fourchon barrier beach differential settlement ǂ

Notes: datum is NAVD88 2004.65

* Grand Isle Relative Sea Level Rise = 9.1 mm/yr = 0.455 m / 50 yr. [18]

** Port Fourchon Relative Sea Level Rise = 11.8 mm/yr = 0.59 m / 50 yr [20]

Port Fourchon subsidence (0.49 m / 50 yr) + IPCC AR5 RCP4.5 SLR (0.26 m / 50 yr) = 0.75 m /50 yr

ǂ Differential Settlement of barrier beach = 0.55 m / 50 yr. Barrier beach top capped at 2.95 m NAVD88 (down from the present 3.50 m NAVD88). Derived from [23].

4.7. Water level in present and future time

At present time Port Fourchon facilities are above water even under high tide. Figure 4-10 (top) shows Port Fourchon under Mean Higher-High Water (MHHW), which is 0.368 m NAVD88 (Table 4-2).

Accounting for observed rates of subsidence and eustatic sea level rise, Port Fourchon Relative Sea Level Rise (RSLR) will be 0.59 m in 50 years' time (Table 4-3). Under such circumstances Port Fourchon facilities will be mostly under water under MHHW which is equivalent to 0.96 m NAVD88 in present time (Figure 4-10, bottom). Even under mean sea level (MSL) which is 0.192 m NAVD88 Port Fourchon will be mostly flooded on permanent basis.

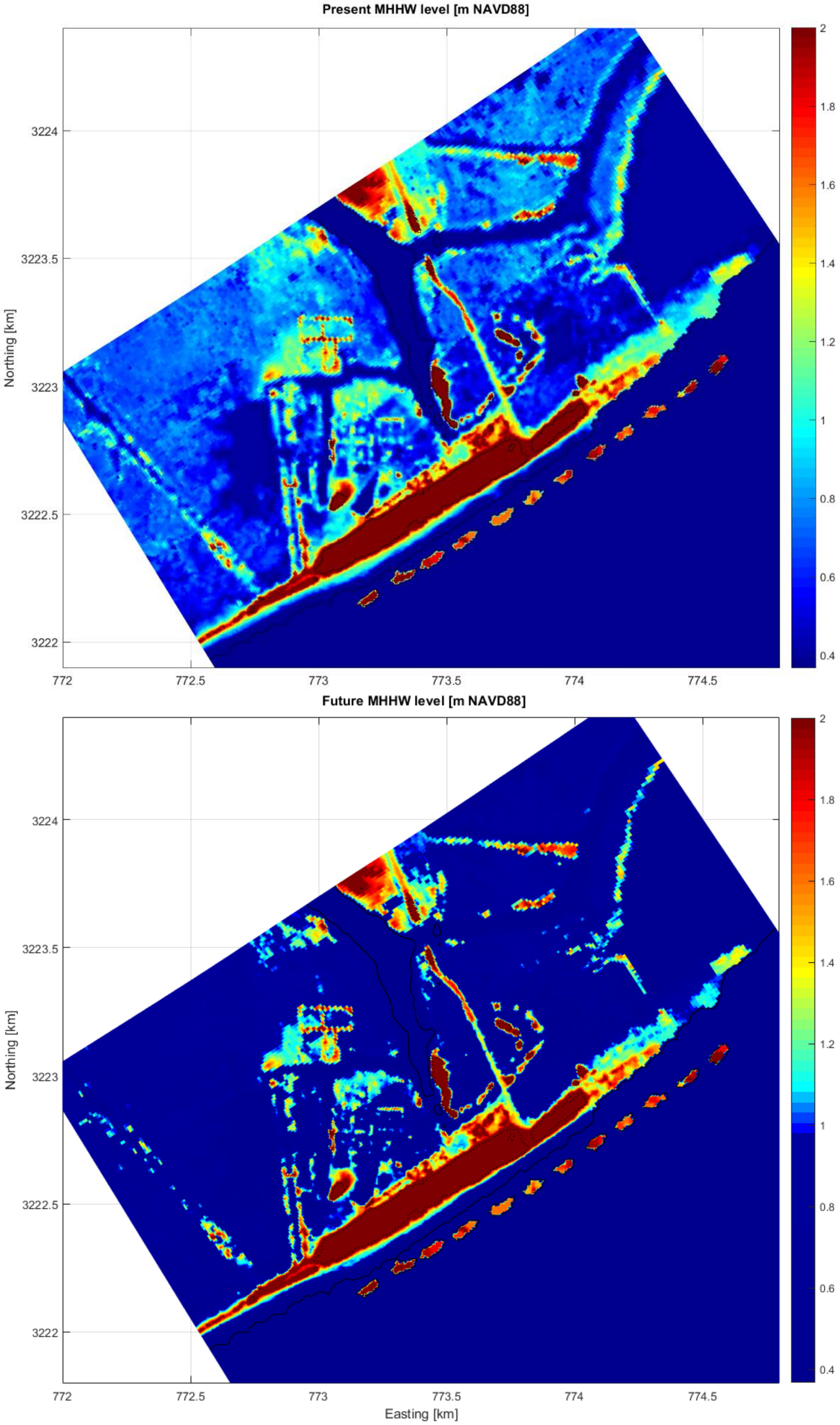

Figure 4-10: Port Fourchon under Mean Higher-High Water (MHHW=0.368 m NAVD88) at present time (top), and future time (bottom) assuming a Relative Sea Level Rise of 0.59 m in 50 years , equivalent to 0.96 m NAVD88 in present time

5. Results

All scenarios in Table 3-2 with the extreme conditions defined in Table 4-3 were run and assessed. In the next sections the key features for some characteristic scenarios are described before summarizing all meaningful results. The first two scenarios correspond to low return periods (1- and 10-year return periods) at present time. Their purpose is to assess the model predictions against actual data recorded at Grand Isle. The last two scenarios correspond to high return periods (100- and 1000-year return periods) at future time. Their purpose is to estimate design conditions. Appendix 3 has a video of one of the simulations run.

5.1. 1-year return period present time

Under a 1-year return period storm in present (current) time the model predicts that Port Fourchon asset should not be inundated (Figure 5-1). Waves are damped by breakwaters and stopped by the barrier beach. The breakwaters are not overtopped by the waves.

5.2. 10-year return period present time

Under a 10-year return period storm in present time the model predicts that Port Fourchon asset should be mildly inundated (Figure 5-2). The barrier beach highest ground remains above water. However, the breakwaters are submerged under waves. Rappelet Road remains above water and offers sheltering from the east side. Figure 5-2 shows results run with surge level based on Grand Isle station. The same simulation run with FEMA surge level results in a very similar pattern, only with slightly more inundation on site.

5.3. 100-year return period future time

Under a 100-year return period storm in future time the model predicts that Port Fourchon asset will be completely inundated (Figure 5-3, top). Waves overtop the barrier beach. Both barrier beach and breakwaters are submerged. Rappelet Road is also under water. In spite of this, the asset still receives a fair degree of protection by the barrier beach, that clearly damps the waves making the highest water level on site (~4.5 m NAVD88) much lower than it otherwise be. Without the barrier beach water levels on the asset could easily be one meter higher (Figure 5-3, bottom).

5.4. 1000-year return period future time

Under a 1000-year return period storm in future time the model predicts that Port Fourchon asset will be completely inundated, an overall pattern similar to the 100-year return period scenario only more severe (Figure 5-4). Both barrier beach and breakwaters are submerged. Rappelet Road is also under water. Wave height and flow speed on site are not negligible, probably resulting in erosion and local scour, and impact design conditions. The sheltering effect of the barrier beach is still there, albeit diminished. One indication of it is that the direction of wave propagation onshore does not significantly change compared to offshore. This means that the barrier beach core is perceived as a lesser obstacle than in lower return period scenarios and there is little wave diffraction around its eastern and western edges. The highest water level on site (~5.95 m NAVD88) is still lower that it would otherwise be if the barrier beach were not in place.

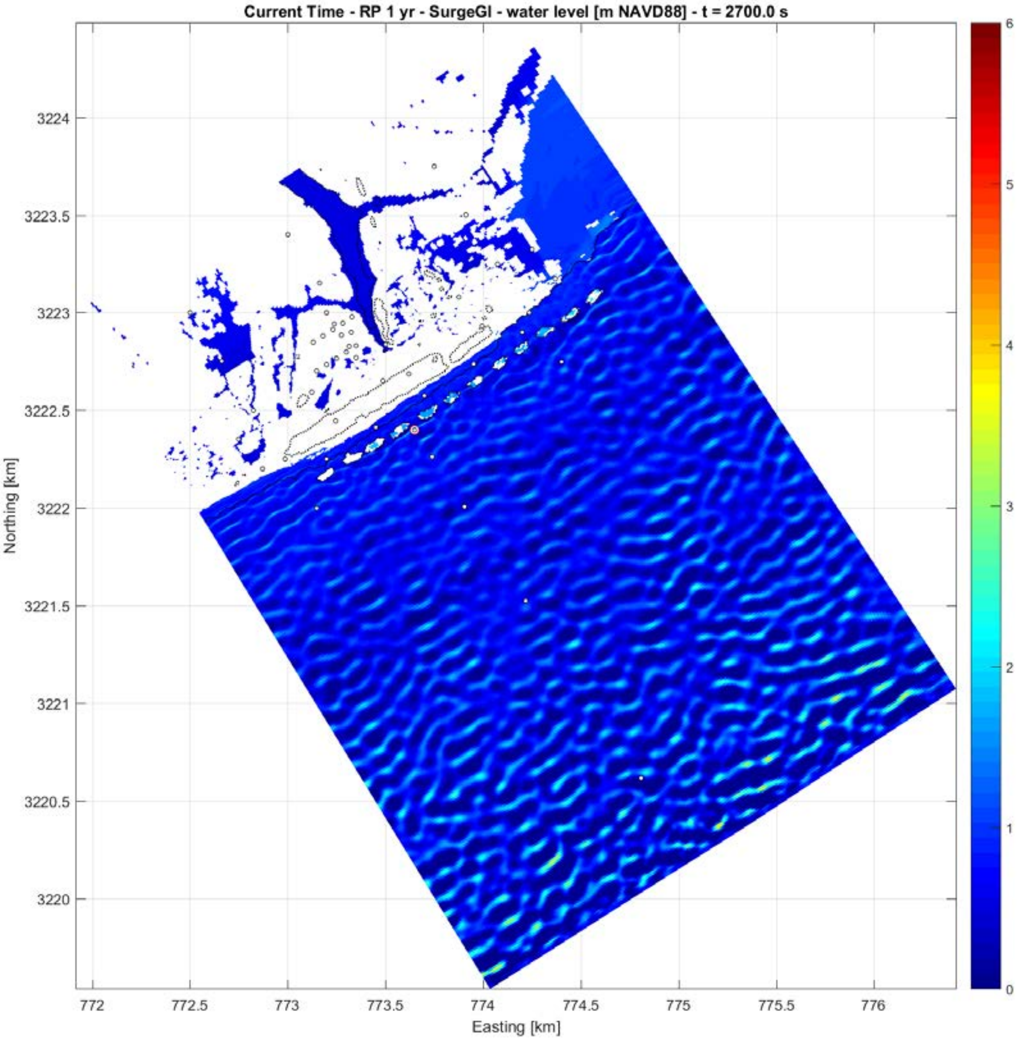

Figure 5-1: Instance of a 1-year return period simulation (present time)

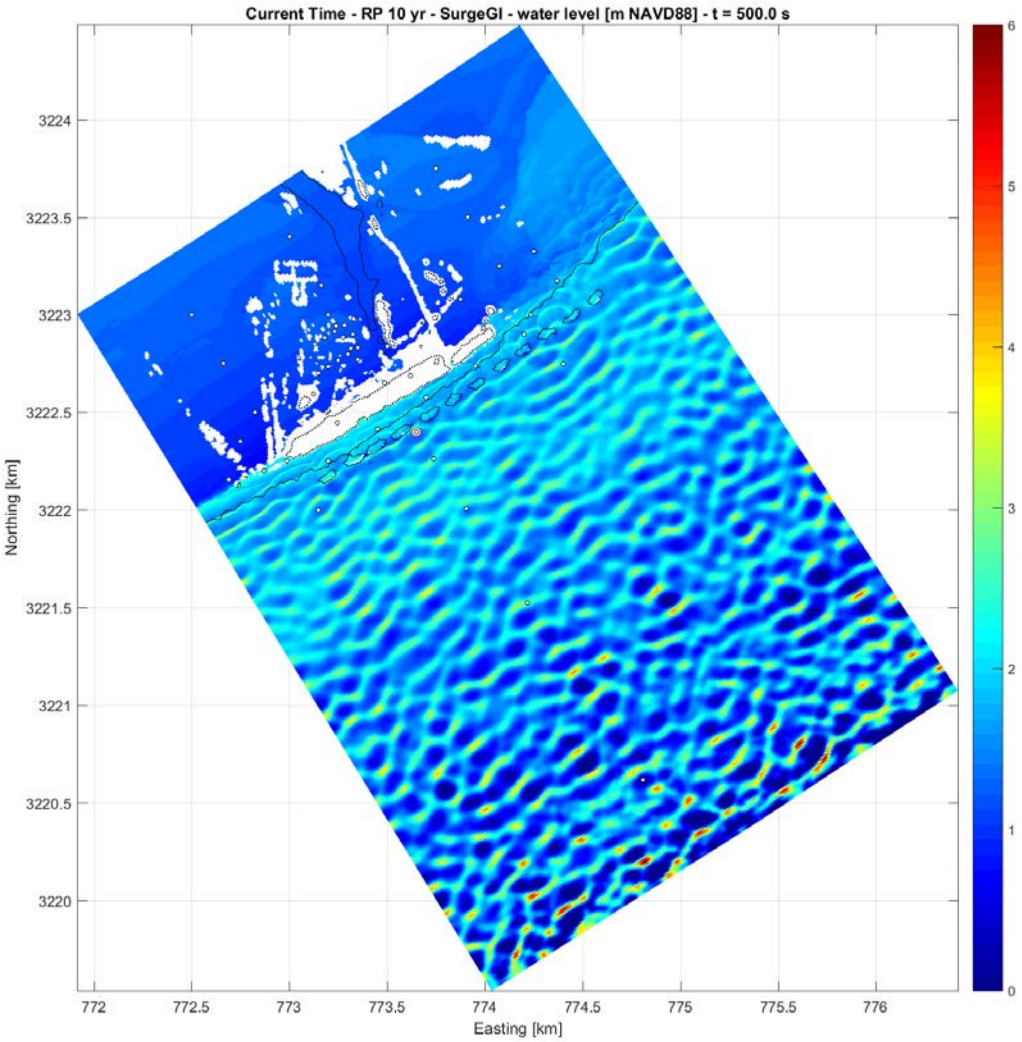

Figure 5-2: Instance of a 10-year return period simulation (present time)

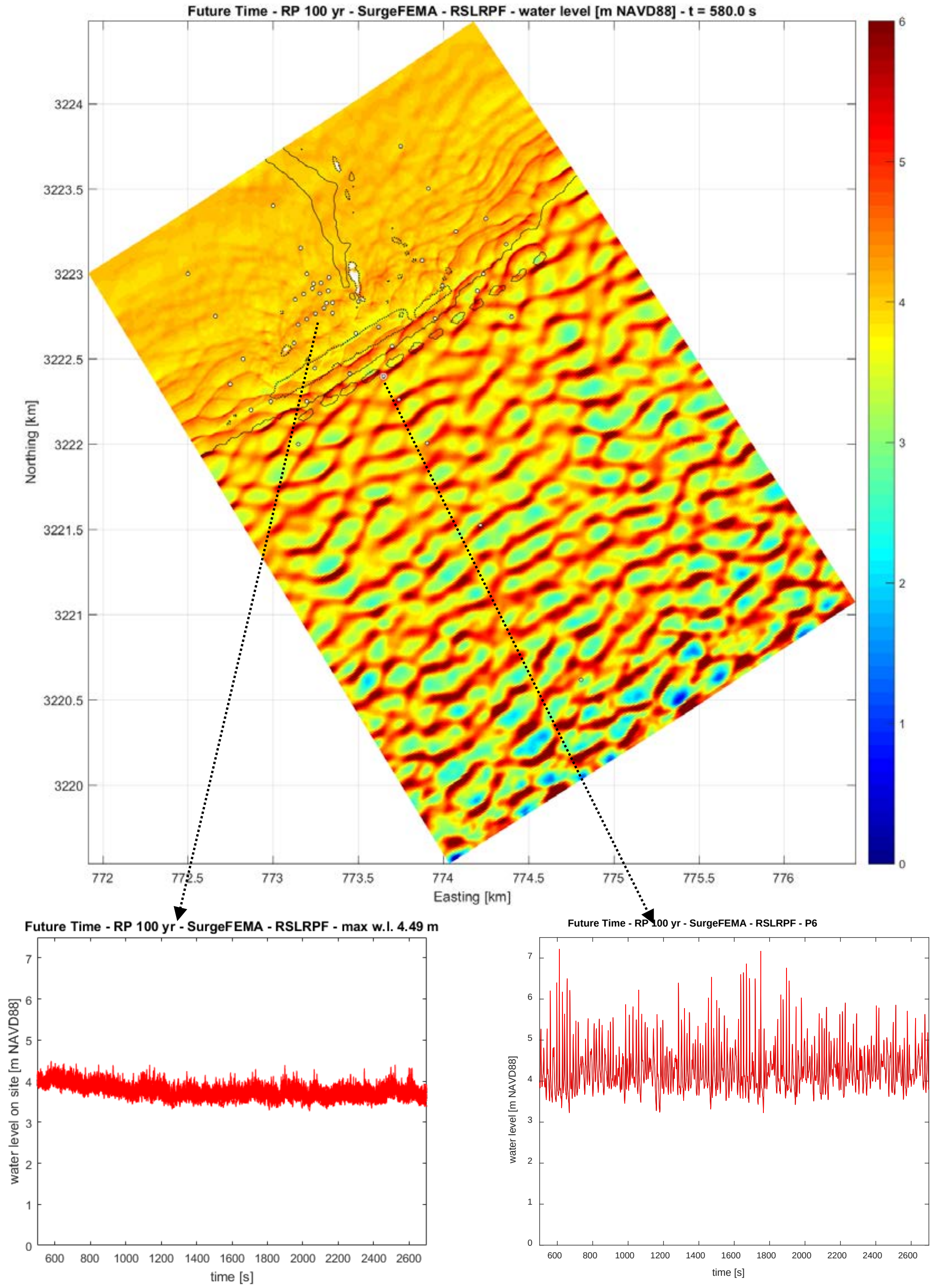

Figure 5-3: Top: Instance of a 100-year return period simulation (future time). Time series of water level at several locations on site (left) and one location just offshore the breakwaters (right).

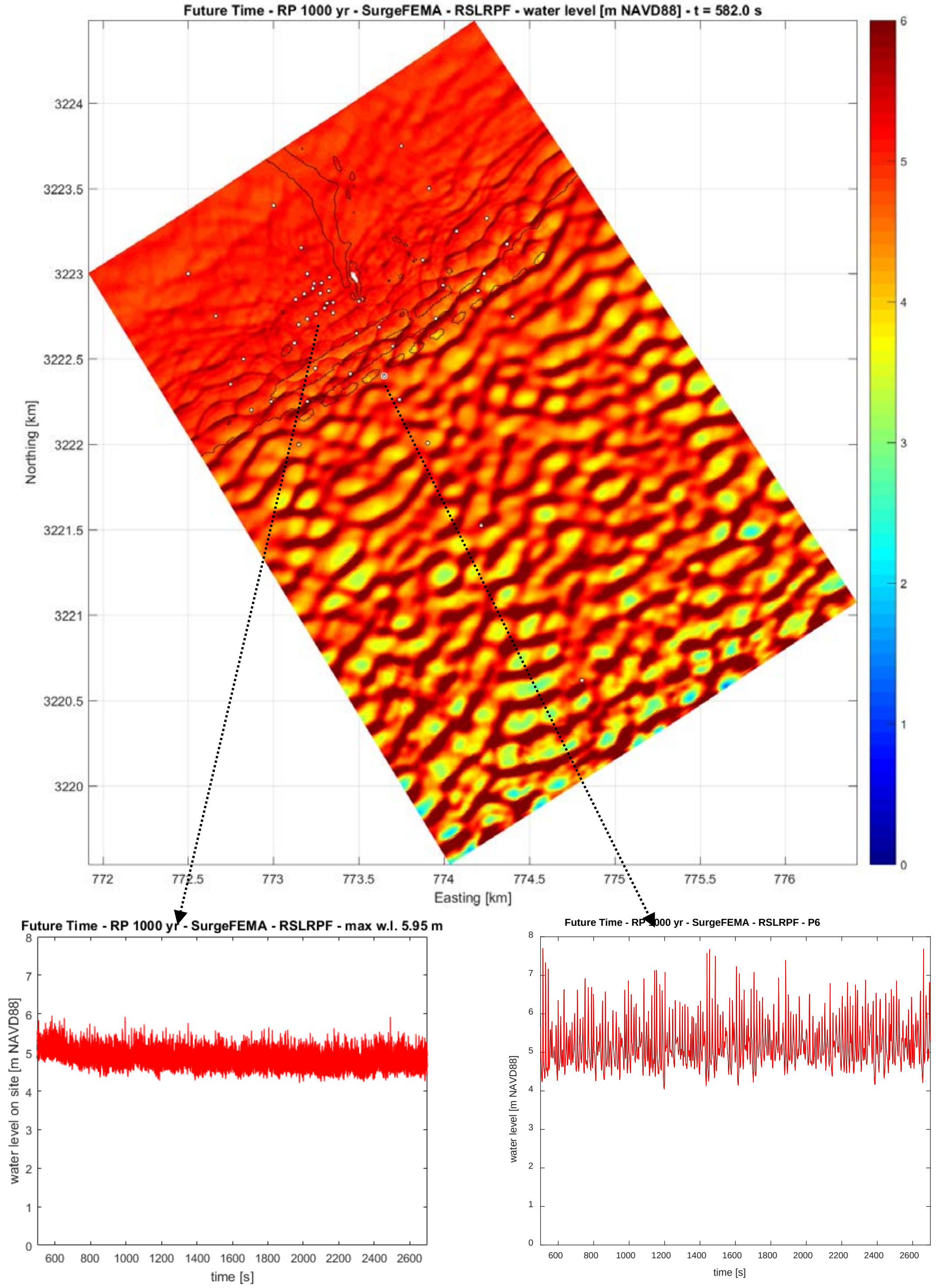

Figure 5-4: Top: Instance of a 1000-year return period simulation (future time). Time series of water level at several locations on site (left) and one location just offshore the breakwaters (right).

5.5. Summary of results

Table 5-1 to Table 5-4 and Figure 5-5 to Figure 5-7 summarize results of water elevation, depth-averaged flow velocity and wave height on site for all scenarios and return periods. These results account for the entire spatial variability in the Port Fourchon site.

Table 5-1 Max water elevation (wave crest) in meters above NAVD88 on site for all scenarios and all return periods

		RP [yr]					
		1	10	50	100	500	1000
Scenario (see Table 3-1)	1	Dry	1.27	1.90	2.13	2.89	-
	2	Dry	1.44	2.77	3.50	4.69	-
	3	-	-	3.96	4.60	5.50	5.88
	4	-	-	4.08	4.73	5.77	6.03
	5	-	-	4.49	5.19	6.00	6.21
	6	-	-	4.16	4.78	5.83	6.10

Table 5-2 Max depth-averaged flow velocity [m/s] on site for all scenarios and all return periods (average max + std).

		RP [yr]					
		1	10	50	100	500	1000
Scenario (see Table 3-1)	1	Dry	0.54	0.70	0.71	0.98	-
	2	Dry	0.63	0.85	1.23	1.97	-
	3	-	-	1.46	1.83	2.33	2.56
	4	-	-	1.62	1.95	2.44	2.59
	5	-	-	1.69	2.01	2.61	2.62
	6	-	-	1.68	1.92	2.35	2.57

Table 5-3 Max significant wave height Hs [m] on site for all scenarios and all return periods.

		RP [yr]					
		1	10	50	100	500	1000
Scenario (see Table 3-1)	1	Dry	0.02	0.07	0.10	0.23	
	2	Dry	0.03	0.20	0.34	0.58	
	3	-		0.41	0.55	0.82	0.87
	4	-		0.45	0.61	0.80	0.90
	5	-		0.53	0.65	0.88	0.94
	6	-		0.50	0.61	0.81	0.86

Table 5-4 Max individual wave height Hmax [m] on site for all scenarios and all return periods.

		RP [yr]					
		1	10	50	100	500	1000
Scenario (see Table 3-1)	1	Dry	0.04	0.07	0.12	0.43	-
	2	Dry	0.04	0.29	0.49	0.86	-
	3	-	-	0.59	1.00	1.55	1.45
	4	-	-	0.76	0.94	1.24	1.52
	5	-	-	0.93	1.07	1.39	1.57
	6	-	-	0.81	1.00	1.17	1.43

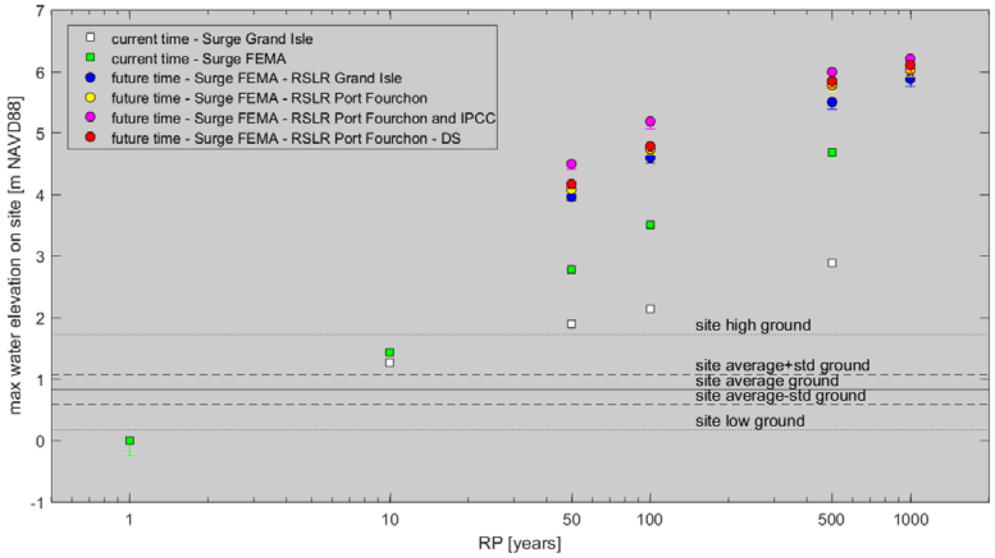

Figure 5-5: Max water elevation (wave crest) on site for all scenarios and all return periods.

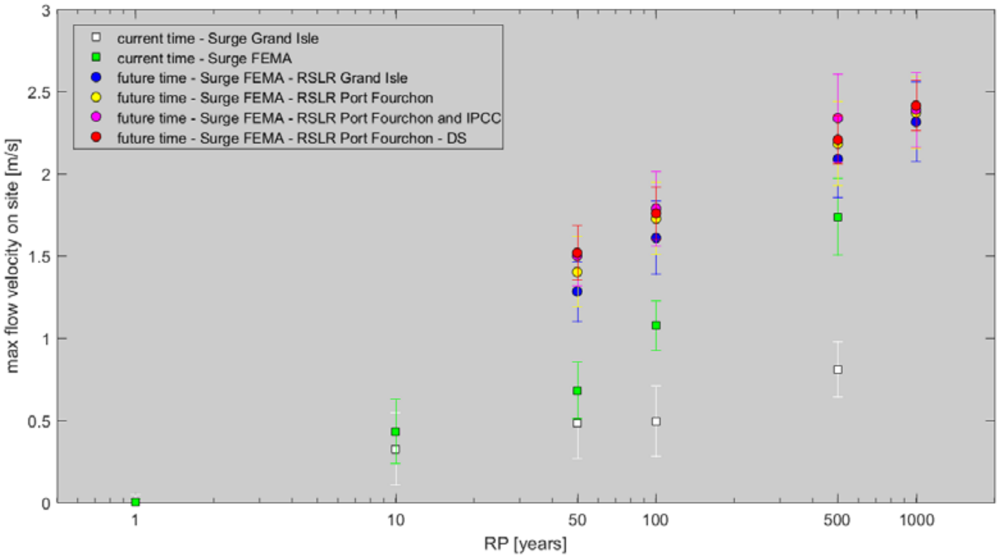

Figure 5-6: Max depth-averaged flow velocity on site for all scenarios and all return periods (marker is average max, errors bar are ± std).

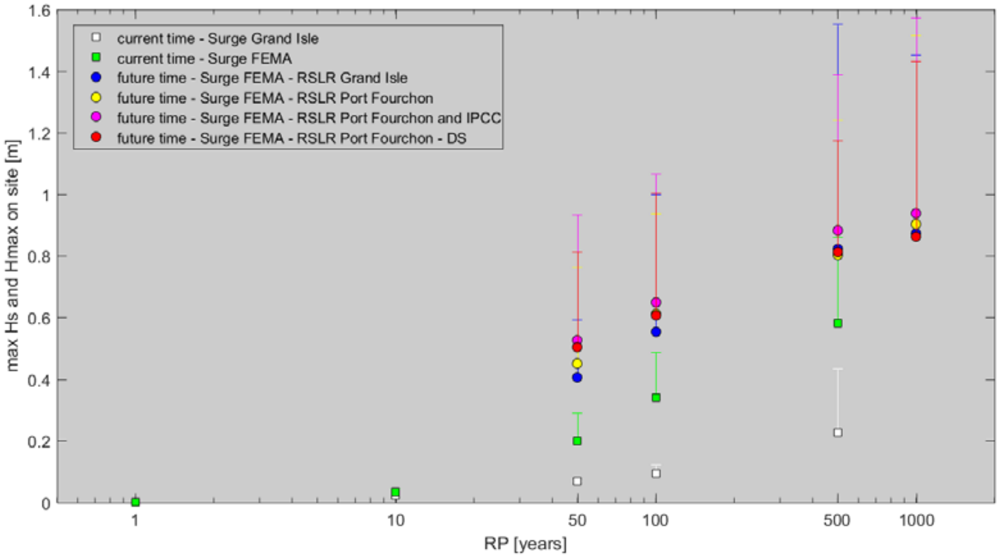

Figure 5-7: Max significant wave height (Hs - marker) and max wave height (Hmax – error bar) on site for all scenarios and all return periods.

6. Design considerations

As most of the natural terrain where Port Fourchon facilities rest is expected to be permanently under water by the end of the lifespan (Figure 4-10 bottom), design guidelines may well be taken from fixed offshore structures.

6.1. Return period

The current API RP-2A WSD-22nd Ed (Planning, Designing, and Constructing Fixed Offshore Platforms—Working Stress Design [26]), states in the section concerning deck clearance:

> *Large forces result when waves strike a platform's deck and equipment. To avoid this, the bottom of the lowest deck should be located at an elevation that will clear the calculated crest of the design wave with adequate allowance for safety. For new platforms in the Gulf of Mexico, the elevation for the underside of the deck shall not be lower than the 1000-year return period maximum crest elevation provided in API RP-2MET or site-specific data developed in accordance with the requirements of API RP-2MET. […]*

6.2. Air gap and green water

The same API document [26] asserts:

> *An air gap, the distance between the maximum crest elevation used for deck clearance and the bottom of steel on the lower deck* (see Figure 6-1)*, shall be provided for any known or predicted long term seafloor subsidence, both regional and that due to hydrocarbon extraction. An additional air gap should be allowed to account for structures that experience significant structural rotation or "set down."*

In addition, the API 2INT-MET Interim Guidance on Hurricane Conditions in the Gulf of Mexico [27] and the US Department of the Interior NTL 2007-G26 [28] suggest or state that the air gap should be 5' (1.5 m). While API 2INT-MET does not relate a return period to the air gap, the NTL 2007-G26 specifies that the 5' air gap should apply to a 100-year return period (extreme), while no air gap might be applied to a 1000-year return period (survival).

The current API RP-2TOP 1st Ed (Topsides Structure [29]) says in the section on deck elevation and green water

> *The probability of having the estimated wave crest elevation exceeded somewhere locally within the extent of the full platform deck area is higher than the probability of having it exceeded at just one point since the potential crest encounter area is larger than one point. When the entire deck area is considered, a local crest elevation occurring somewhere in the deck area may exceed the point-estimated crest height by as much as 15 % for the same probability level. This effect is described by Forristall in Reference [80]. As a result, the design wave crest elevation, above which the lowest deck should be set, equals [100-year wave crest elevation (including storm surge and tide) + 15 % + 1.5 m safety air gap]. For the Gulf of Mexico, it turns out that the 1000-year wave crest envelopes this latter elevation, and thus the 1000-year wave crest is used without any additional air gap applied.*

6.3. Wind criteria

Wind speed design criteria is relevant for an elevated structure wind loading. The ASCE/SEI 7-16 code [30] states that for buildings with risk category IV (which includes Port Fourchon type of facility) the basic wind speed is a 3-second gust of 85 m/s for Fourchon area (Fig 26.5-1D therein). According to the ASCE it roughly corresponds to a ~3000-year return period.

The more location-specific ATC Hazards by Location recommended by the ASCE 7-16 [31] suggests a gust wind speed of 87 m/s (194 mph) for Port Fourchon.

By means of the ISO wind equations translating these 3-sec gust speeds into 1-min averages speeds results in 72 and 73 m/s.

These wind speeds are slightly larger than the 1000-yr return period 3-sec gust and 1-min wind speeds derived from 30-min averaged WIG winds (Table 4-3) with a 95% confidence interval and equal to 71 and 84 m/s respectively.

All these winds speeds correspond to a category 5 hurricane according to the Saffir-Simpson scale.

6.4. Design criteria for Port Fourchon

Based on the above recommended practices and guidelines the robust criteria by API RP-2MET is adopted. The elevation for the underside of the deck endorsed for the upgrading of Port Fourchon facilities shall not be lower than the 1000-year return period maximum crest elevation (with no air gap).

For wave height and flow velocity a 1000-year return period is recommended.

The recommended design wind speed is 87 m/s which is equivalent to a 1000-year return period gust speed derived from the WIG wind dataset.

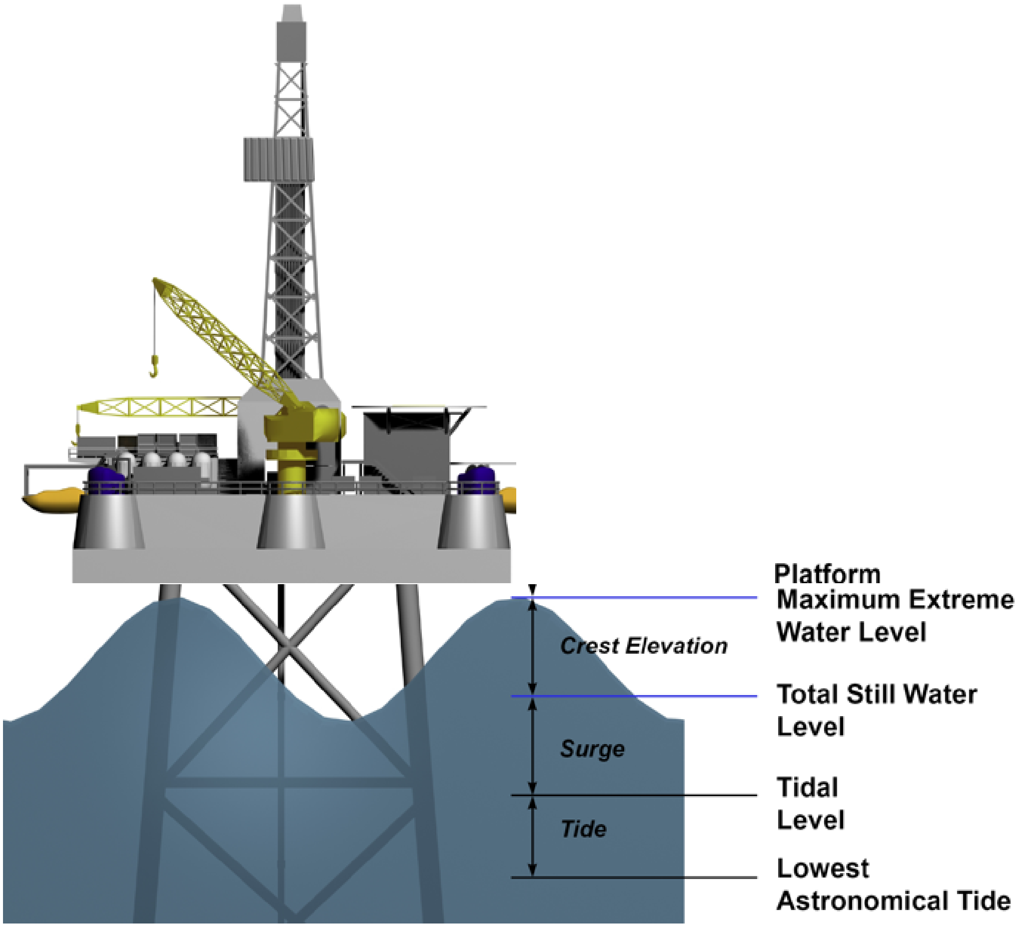

Figure 6-1: Design criteria for deck elevation of fixed offshore platforms for a return period of 1000 years Adapted from API Bulletin 2INT-DG. Note: according to API RP-2TOP the air gap is not needed for 1000-year return period design condition (survival).

7. Conclusions

- ✓ Port Fourchon site should be subject to flooding for 10-year return period conditions based on Grand Isle observations. For 5-6 years return period conditions some degree of milder partial flood should also be expected. This is well captured by the model.
- ✓ While the highest inundating level is mostly dependent on winds, waves and surge acting together, surge is the single most critical parameter that defines the asset's base inundation level.
- ✓ Design future conditions based on surge extreme from FEMA simulations are recommended over surge extremes derived from Grand Isle observations
- ✓ FEMA hindcast is conservative with respect of observed surge data at Grand Isle because it is based on a hypothetical hurricane dataset honed for high return periods. An additional but realistic conservative assumption has been made by forcing the winds and waves with the same direction and perpendicular to the coast.
- ✓ The barrier beach and the breakwaters play a key factor in sheltering site from waves and surge. Even when submerged under extreme high return period conditions they dissipate the waves ensuring that the maximum water level (wave crest elevation) on site is lower than would otherwise be without them. It is then important to maintain them fit for purpose during the entire lifespan of the asset.
- ✓ Both Grand Isle and Port Fourchon subsidence scenarios yield similar results.
- ✓ IPCC overestimate sea level rise trend, but its impact for high return periods design-scenarios is relatively marginal because subsidence still plays a larger role than eustatic sea level rise.

8. Recommendations

- ✓ Based on the importance of Port Fourchon Junction facilities, the design criteria outlined in section 6, and the higher subsidence level observed at Port Fourchon (compared to Grand Isle), it is recommended that a 1000-year return period and future scenario based on FEMA surge level and Port Fourchon RSLR is adopted for design (Scenario 4 in Table 3-1. Yellow dot in Figure 5-5, Figure 5-6, Figure 5-7). The subsidence associated to this scenario is 9.8 mm/year. The sea level rise associated to this scenario is 2 mm/year (straight blue line in Figure 4-6).
- ✓ This assumes that the barrier beach and the breakwaters will be kept fit for purpose, and restored whenever required, during the entire lifespan of the project
- ✓ The 1000-year design scenario results in wave elevation on site (including wave crest) during peak hurricane conditions of 6.03 m NAVD88.
- ✓ Design depth-averaged flow velocity on site is 2.6 m/s, design significant wave height is 0.90 m and design max wave height is 1.52 m. Design gust speed is 87 m/s.
- ✓ Table 8-1 summarized the recommended design parameters for the upgrade of Port Fourchon Junction. The recommended design return period is 1000 years for all parameters (survival conditions). In addition, the 100-year return period is also shown for some parameters (extreme conditions).

Table 8-1 Recommended design parameters for the upgrade of Port Fourchon Junction*

Scenario (see Table 3-1)	RP (years)	Elevation of deck underside m NAVD88 (ft NAVD88)	Flow velocity m/s (ft/s)	Hs m (ft)	Hmax m (ft)	Gust speed (3-sec) m/s (mph)
4	100	Not applicable	2.0 (6.6)	0.61 (2.0)	0.94 (3.1)	80 (179)
	1000	**6.1 (20.1)**	**2.6 (8.5)**	**0.90 (3.0)**	**1.52 (5.0)**	**87 (195)**

* Elevation of deck is rounded up to account for topographic uncertainty.

- ✓ The above design conditions shall be accounted for the elevation of Port Fourchon facilities, whether by a Waskey concrete structure (Figure 8-1) or a steel structure. Both should be designed to withstand the combined action of the waves and current. Soil erosion and localized scour around columns should be also accounted for if natural terrain is left exposed.
- ✓ It is uncertain how the beach barrier would survive a potential breach or erosion during hurricane peak states. This morphological scenario can be assessed in XBeach providing composition of material, type, and grain size are available.
- ✓ Given the results at Port Fourchon Junction, it is recommended that a similar study with a reduced scope is carried out for Fourchon Pump station, a facility located 6.1 km (3.8 miles) to the NE. Being located further inland, inundation levels are expected to be milder than at Fourchon Junction and might be a feasible alternative for the junction. This can be evaluated with XBeach as well for a reduced number of scenarios and return periods.

Figure 8-1: Example of a Waskey concrete deck.

Acknowledgments

The authors acknowledge and appreciate the advice provided by Zach Cobell, Mike Miner, Ioannis Georgiou and Soupy Dalyander from The Water Institute of the Gulf; Mead Allison from Tulane University; and Jason Newlin, Civil Marine TL in Houston.

References

1. Louisiana's 2012 Coastal Master Plan. Coastal Protection and Restoration Authority (CPRA). State of Louisiana. https://coastal.la.gov/our-plan/2012-coastal-masterplan/2012-coastal-master-plan-projects/
2. Flood Insurance Study: Southeastern Parishes, Louisiana, Intermediate Submission 2: Offshore Water Levels and Waves, FEMA, US Army Corps of Engineers, New Orleans District, July 24, 2008. https://coast.nd.edu/femaIDS2.html
3. NOAA Tides and Currents. https://tidesandcurrents.noaa.gov/
4. Louisiana's 2017 Coastal Master Plan. Coastal Protection and Restoration Authority (CPRA). State of Louisiana
5. ADCIRC: Advanced 3D Circulation Model for Shelves, Coasts, and Estuaries, http://adcirc.org/
6. XBeach user manual https://xbeach.readthedocs.io/en/latest/
7. De Ridder, M.P. 2018. Non-hydrostatic wave modelling of coral reefs with the addition of a porous in-canopy model. Master of Science. TU Delft and NUS Singapore.
8. Törnqvist, T. E., D. J. Wallace, J. E. A. Storms, J. Wallinga, R. L. van Dam, M. Blaauw, M. S. Derksen, C. J. W. Klerks, C. Meijneken, andE. M. A. Snijders (2008), Mississippi Delta subsidence primarily caused by compaction of Holocene strata, Nat. Geosci., 1(3), 173–176,doi:10.1038/ngeo129.
9. Meckel, T. A., Ten Brink, U. S. &Williams, S. J. Current subsidence rates due to compaction of Holocene sediments in southern Louisiana. Geophys. Res. Lett. 33, L11403 (2006).
10. Dokka, R. K., Sella, G. F. & Dixon, T. H. Tectonic control of subsidence and southward displacement of southeast Louisiana with respect to stable North America. Geophys. Res. Lett. 33, L23308 (2006).
11. Wolstencroft, M., Z. Shen, T. E. Törnqvist, G. A. Milne, and M. Kulp (2014), Understanding subsidence in the Mississippi Delta region due to sedi-ment, ice, and ocean loading: Insights from geophysical modeling, J. Geophys. Res. Solid Earth, 119, 3838 –3856,doi:10.1002/2013JB010928
12. Kim, W., Mohrig, D., Twilley, R., Paola, C., and Parker, G., 2009, Is it feasible to build new land in the Mississippi River Delta?: Eos, v. 90, p. 373–374, doi:10.1029/2009EO420001.
13. Morton, R. A., Bernier, J. C. & Barras, J. A. Evidence of regional subsidence and associated interior wetland loss induced by hydrocarbon production, Gulf Coast region, USA. Environ. Geol. 50, 261–274 (2006).
14. Chan, A.W. & Zoback, M. D. The role of hydrocarbon production on land subsidence and fault reactivation in the Louisiana coastal zone. J. Coast. Res. 23, 771–786 (2007).
15. Dokka, R. K. Modern-day tectonic subsidence in coastal Louisiana. Geology 34, 281–284 (2006).
16. Kolker, A. S., M. A. Allison, and S. Hameed (2011), An evaluation of subsidence rates and sea-level variability in the northern Gulf of Mexico, Geophys. Res. Lett.,38, L21404,doi:10.1029/2011GL049458
17. Byrnes M.R., Britsch L.D., Berlinghoff J.L., Johnson R. and Khalil S. 2019. Recent subsidence rates for Barataria Basin, Louisiana. Geo-Marine Letters https://doi.org/10.1007/s00367-019-00573-3
18. Byrnes M.R., Britsch L.D., Berlinghoff J.L. and Johnson R. 2018. Final Report: Determining Recent Subsidence Rates for Barataria Basin, Louisiana: Implications for Engineering and Design of Coastal Restoration Projects. Prepared for: Louisiana Coastal

Protection and Restoration Authority. Prepared by: Applied Coastal Research and Engineering In Cooperation with CDM Smith

19. Allison M., Carruthers T., Clark R., Di Leonardo D., Hemmerling S., Meselhe E., Moss L., Weathers D., White E. and Yuill, B. 2018. Partnership for Our Working Coast: Port Fourchon Phase 1 Technical Report. The Water Institute of the Gulf. Prepared for and funded by Shell, Chevron, Danos, and the Greater Lafourche Port Commission. Baton Rouge, LA.
20. Jankowski K.L., Tornqvist T.E. and Fernandes A.M. 2017. Vulnerability of Louisiana's coastal wetlands to present-day rates of relative sea-level rise. Nature Communications. doi: 10.1038/ncomms14792
21. Nienhuis, J.H., Tornqvist T.E., Jankowski K.L., Fernandes, A.M. and Keogh M.E., 2017. A New Subsidence Map for Coastal Louisiana. GSA Today, v. 27, The Geological Society of America. doi: 10.1130/GSATG337GW.1.
22. Ivins, E. R., Dokka, R. K. & Blom, R. G. Post-glacial sediment load and subsidence in coastal Louisiana. Geophys. Res. Lett. 34, L16303 (2007).
23. Byrnes M.R., Hedderman C., Hasen M., Roberts H., Khalil S., and Underwood, S.G. 2015. Differential sediment consolidation associated with barrier beach restoration: Caminada headland, south Louisiana. doi: 10.1142/9789814689977_0192
24. IPCC, 1990: Climate Change: The IPCC Scientific Assessment. Report of Working Group I of the Intergovernmental Panel on Climate Change [Houghton, G.J. Jenkins, J.J. Ephraums (eds.)]. Cambridge University Press, Cambridge, United Kingdom, 365 pp.
25. IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.
26. API Recommended Practice 2A-WSD Planning, Designing, and Constructing Fixed Offshore Platforms—Working Stress Design 22nd Ed., Nov 2014, 310 p.
27. API 2INT-MET: Interim Guidance on Hurricane Conditions in the Gulf of Mexico. May 2007.
28. United States Department of the Interior. Minerals. NTL No. 2007-G26. Design of New OCS Platforms and Related Structures for Hurricane Conditions
29. API RP-2TOP. Topsides Structure. ISO 19901-3:2010 (Modified), Petroleum and natural gas industries — Specific requirements for offshore structures — Part 3: Topsides structure. 1st Ed. Aug 2019.
30. ASCE/SEI 7-16. Minimum Design Loads and Associated Criteria for Buildings and Other Structures. American Society of Civil Engineers (ASCE) Reston, VA. 2017.
31. ATC Hazards by Location. https://hazards.atcouncil.org/ See Port Fourchon here.
32. Queensland Climate Change and Community Vulnerability to Tropical Cyclones. Ocean Hazards Assessment. Stage 1. Review of Technical Requirements. 2001. Australia. Bureau of Meteorology, Queensland. Dept. of Emergency Services, Queensland. Environmental Protection Agency, James Cook University, Queensland. Department of Natural Resources and Mines, Systems Engineering Australia. Source.

Appendix 1. DHI technical note on Port Fourchon Bathymetry

Technical note on
bathymetry - Port Fo

Appendix 2. Example of XBeach parameter set up file

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% XBeach parameter settings input file                                     %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% Flow boundary condition parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
front        = nonh_1d
left         = no_advec
right        = no_advec
back         = abs_2d
bedfriction  = manning
bedfriccoef  = 0.02
CFL           = 0.55

%%% General %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
avalanching  = 0
dtheta_s     = 10
single_dir   = 1

%%% Grid parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
gridform     = delft3d
xyfile       = Grid05r_rot2.grd
depfile      = Dep05r_rot2.dep
posdwn       = -1

%%% Initial conditions %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
zs0          = 3.92

%%% Model time %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
tstop        = 2700

%%% Physical processes %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
flow         = 1
sedtrans     = 0
morphology   = 0
nonh         = 1

%%% Wave boundary condition parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
instat = jons_table

%%% Wave-spectrum boundary condition parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
bcfile       = jonswaptable.txt
rt           = 2700
dtbc         = 1

%%% Wind conditions
windfile     = wind.txt

%%% Output variables %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
outputformat = netcdf
tintm        = 2700
tintp        = 0.2
tintg        = 2
tstart       = 0

nglobalvar   = 1
zs

nmeanvar     = 7
zb0
zs
u
v
vmag
hh
thetamean

npointvar    = 6
zs
u
v
vmag
hh
thetamean

npoints = 50
7.730000E+005  3.2234000E+006
7.731625E+005  3.2231497E+006
…

wind.txt
0.0 52.6 147.0
2700.0 52.6 147.0

jonswaptable.txt
5.88 15.5 147.0     3.3 10.0 2700.0 0.2
```

Appendix 3. Example of XBeach simulation for 100-year return period (present time)

33F646F5.mp4

Bibliographic information

Classification	Restricted
Report Number	SR.20.00492
Title	Extreme water level conditions for Fourchon Junction under different climate scenarios and their impact on deck elevation design
Author(s)	O.E. Sequeiros (GSNL-PTP/I/PN) S. Jaramillo (GSUSI-PTP/D/GC)
Keywords	Port Fourchon, subsidence, sea level rise, hurricanes, inundation, flooding, waves, surges, extreme values, climate change, Louisiana, Gulf of Mexico
Date of Issue	April 2020
Reviewed by	D.M. Dauterive (SPLC-DPE/4) S. Fan (GSUSI-PTP/D/GC) J.A. Newlin (SIEP-PTP/D/GC)
Approved by / Content owner	O.E. Sequeiros (GSNL-PTP/I/PN)
Issuing Company	Shell Global Solutions International B.V., Rijswijk

Report distribution

Electronic distribution (PDF)

Name, Company, Ref. Ind. *PDF*

PT Information Services, PTT/TIKE, PT-Information-Services@Shell.com
Bos, Peter P GSNL-PTP/I/PN
Dauterive, David M SPLC-DPE/4
Dykhno, Leonid A GSUSI-PTP/E/O
Engel, Dico C GSNL-PTP/I/P
Fan, Shejun SIEP-PTP/D/GC
Jaramillo, Sergio GSUSI-PTP/D/GC
Newlin, Jason A SIEP-PTP/D/GC
Sequeiros, Octavio E GSNL-PTP/I/PN
Tuck, Joni L SEPCO-ERUP/UG