Numerical Experiment of Sediment Dynamics over a Dredged Pit on the Louisiana Shelf

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NUMERICAL EXPERIMENT OF SEDIMENT DYNAMICS OVER A DREDGED PIT ON THE LOUISIANA SHELF

A Dissertation

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College
in partial fulfillment of the requirements for the degree of Doctor of Philosophy

in

The Department of Oceanography and Coastal Sciences

by
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ABSTRACT

Sediment transport over Sandy Point dredge pit in the northern Gulf of Mexico was examined using field measurements and a finely resolved numerical model. Delft3D model with well-vetted computational grid and input parameters was used. Numerical experiments were performed to examine the effect of wind-generated waves, wind-driven currents and their interaction on sediment dynamics in our study area during a cold front in November 2014 and fair-weather conditions between July and August of 2015. Sediment dispersal from the lower Mississippi River, sediment resuspension, transport and deposition with high spatial and temporal resolution were simulated. A reliable satellite-derived near-surface suspended particulate matter (SPM) map was employed to provide an initial condition in a numerical model and support the model calibration/verification. To prepare SPM maps, short-wave infrared (SWIR) and near-infrared atmospheric correction algorithms on remote sensing reflectance (Rrs) products from Landsat-8 OLI and Management Unit of the North Sea Mathematical Models (MUMM) and SWIR.NIR atmospheric correction algorithms on Rrs products from MODIS-Aqua were evaluated. Results indicated that SWIR atmospheric correction algorithm was the suitable algorithm for Landsat-8 OLI and SWIR.NIR atmospheric correction algorithm outperformed MUMM algorithm for MODIS. Delft3D Flow, wave and sediment transport were validated using LSU WAVCIS (Wave-Current-Surge Information System) and NDBC (National Data Buoy Center) data for both events. Results suggested that the primary source of sediment for the Sandy Point dredge pit during a cold front was re-suspension due to the fortified bottom shear stress (BSS) by wind-induced waves and currents. Strong southward wind-driven currents during the cold front passage dispersed sediments from the Mississippi River passes and inhibited riverine sediment supply from the Sandy Point dredge pit. Results also showed that total cold front passages
in a year (30-40 passages per year) contribute to the sedimentation thickness over Sandy Point dredge pit from 16% to 24% of the total sedimentation thickness annually. Results indicated that during the fair-weather event, Mississippi River plays a pivotal role in providing sediment for Sandy Point dredge pit and about 60% of deposited sediments are from the Mississippi River plume.
CHAPTER 1: GENERAL INTRODUCTION

1.1 Introduction

1.1.1 Motivation

Coastal Louisiana has been experiencing unprecedented land loss from natural processes and anthropogenic activities (NRC, 2006). Natural processes and human activities have led to the retreat of Louisiana shoreline (NRC, 2006). These natural processes include sea level rise, land subsidence, hurricanes storm surges and inundation, and invasion of species. Human activities include construction of water control structures, oil-gas infrastructure, building of ports and harbor, etc. The results from these processes could be superimposed together. Since 1930s, after the Great Flood of 1927, the Army Corps of Engineers built a series of levees under the Flood Control Act of 1928. These artificial levees prevent the Mississippi River from depositing natural sediment onto its delta. The decrease in sediment supply inhibits the Mississippi River’s ability to replenish its delta. According to the National Oceanic and Atmospheric Administration (NOAA), southern Louisiana has the highest rate of relative sea level rise of any place in the country (http://www.noaanews.noaa.gov). Furthermore, the Louisiana coast is highly vulnerable to the tropical storms and hurricanes with a return period of 3.0 years (Keim et al., 2007). Tropical storms and hurricanes contribute to the land loss significantly affecting both the coastal lands and barrier islands in the northern Gulf of Mexico. During the last 50 years, land loss rates in Louisiana have at times exceeded 103.6 square kilometers (https://pubs.usgs.gov). Figure 1.1 shows the estimated and predicted land loss area along the Southeast Louisiana coast from 1932 to 2050. The barrier islands on the southern margin of Barataria Bay have decreased in size by 47% from the 1890s to the late 1980s (Williams et al., 1992). These islands separate the Gulf of Mexico from Barataria Bay and are thus an important first line of defense for the interior marshes of Louisiana. The
Barataria barrier shoreline and associated wetlands are the most rapidly eroding area in Louisiana (Boesch et al., 1994). Many species prefer back-barrier beaches and intra-island pond and tidal creeks (Wiliamas, 1998). Island fragmentation results in loss of habitat, as more area is exposed to storm surges and erosion.

![Southeast Louisiana Land Loss](https://www.lacoast.gov)

Figure 1.1. Map of estimated and predicted land loss along the Southeast Louisiana coast from 1932 to 2050. Image credit LaCoast, USGS (https://www.lacoast.gov)

As the islands are eroded away, both habitat and infrastructure behind the islands become increasingly vulnerable to damages from surge and waves (Kindinger et al., 2001). Erosion and deterioration of the shoreline and back-bay wetlands result from the increased relative sea-level rise, diminished sediment supply, repeated storm events, construction of canals and navigation channels; and high rate of subsidence (Kulp et al., 2001; Boesch et al., 1994). A healthy coastal marsh provides rearing habitat for shellfish and finfish, furnishes habitat for waterfowl, wading birds, small mammals, and numerous amphibians and reptiles; protects interior lands from storms; helps maintain water quality, and provides recreational services. Barrier islands provide
unique nursery, foraging, and spawning habitat for numerous marine and estuarine species of commercial and recreational impotence. Regarding the rate mentioned above of coastal deterioration, prescribing coastal protection and reclamation solutions is imperative. One plausible solution would be the reclamation of shoreline along the mainland and barrier islands using the extracted sand from offshore sand resources. This study was part of a project through a corporative agreement with BOEM titled “Assessment of Mud-Capped Dredge Pit Evolution on the Outer Continental Shelf of northern Gulf of Mexico” (LSU PI: Dr. Kehui Xu; Co-PIs: Drs. Sam Bentley, Chunyan Li; BOEM scientist: Dr. Mike Miner, with students participation including former PhD student Dr. Jeffrey Blake Obelcz of Sediment Dynamics Lab, Master Student Ms. Meg O’Connor of Department of Geology & Geophysics). The group conducted work on sediment dynamics of dredging pits, seabed coring, geophysical methods, radionuclides (Obelcz, 2017; O’Connor, 2017). O’Connor (2017) used 7Be in coastal marine sediments and suggested that pits are efficient sediment traps. In addition, she observed 26 cm of 7Be penetration on northwest of Sandy Point Dredge Pit. Obelcz (2017) studied sediment transport and slope stability in northern Gulf of Mexico using relatively high-resolution acoustic geophysical tools such as swath bathymetric echosounders and swept-frequency sub-bottom echosounders. He suggested that mud-capped dredge pits can be used as proxies for sediment deposition and slope stability along the Inner Continental shelf. Furthermore, he showed the important role resuspension and slope failure play in decadal and longer-scale sediment accumulation in this environment (Obelcz, 2017). Our knowledge about the source of sediment for Sandy Point Dredge Pit is limited. The novelty of my study is identifying the sources of sediment for Sandy Point Dredge Pit during two different weather conditions. In addition, this study sheds light on behavior of bottom boundary layer during a cold front passage in winter and fair weather in summer.
1.2 Sandy Point Barrow Area as a Sand Resource for Restoration Projects

The Barataria Barrier Island Complex Project (BA-38; CWPPRA; 2007, 2012) was proposed to restore two reaches of the Barataria Plaquemines shorelines: Pelican Island and Pass La Mer to Chaland Pass. This project was authorized under the Coastal Wetlands Planning, Protection, and Restoration Act (CWPPRA) of 1990 (Tetra Tech, 2004). A portion of the proposed Barataria Barrier Island Complex will involve use of sand resources located on the Outer Continental Shelf (OCS). The United States Government and specifically, Bureau of Ocean Energy Management (BOEM), has the jurisdiction over all mineral resources on the federal OCS. The objectives of this project were to create and protect barrier island habitat, to prevent breaching of the barrier shoreline by increasing its width and average height, enhance storm-related surge and wave protection, prevent overtopping during storms, and increase the volume of sand within the active barrier system.

The Pelican Island Restoration Project (BA-38-2; CWPPRA; 2012) began in May 2011 and was completed in December 2012. The Pelican Island segment lies between Scofield Pass and Fontanelle Pass and immediately east of the Empire Waterway. Over 2.6 million cubic yards of sand and silt were mined from two offshore borrow areas. This segment was restored to maintain the integrity of 3.86 km of shoreline on Pelican Island using about 6.4 MCY of mixed sediment and sand from 4 different borrow areas (EMPIRE Borrow Areas and Sandy Point Borrow Areas) in State and Federal waters ranging in distance from 3 to 19 km.

The Pelican Island project restored about 190 acres of dune, beach, and berm; and 396 acres of intertidal saline marsh. The Chaland Headland segment is about 5 km long and is located between Pass La Mer and Chaland Pass. Prior to the restoration, wetlands, dune, and swale habitats within the project area had undergone substantial loss due to subsidence, sea-level rise, oil and gas
activities (e.g., pipeline construction), and marine- and wind-induced shoreline erosion (gulfside and bayside) (Tetra Tech, 2004).

Southeast Sandy Point is located in the lee side of the west flank of the Mississippi River delta (20 km), and approximately 13 to 15 km offshore of the Pelican Island. The pit has provided a sufficient source of restoration-quality sand for the CWPPRA Pelican Island Restoration project, which meets the volumetric requirement to restore the Pelican Island (Tetra tech and CPE 2003). In 2012, a volume of 1.7 million m$^3$ of sandy sediment was excavated to restore Pelican Island. The Sandy Point is the relict of the Mississippi River paleochannels on the Outer Continental Shelf (OCS). As sea level rose and the river switched its courses, these channels were filled with sand. These sandy river paleochannels are usually narrow and deep (e.g., 10m), following the old fluvial topography. The modern Mississippi River Deltaic plain has experienced six delta-switching events over the last 7000 to 8000 years (Roberts, 1997) (Figure 1.2).

![Figure 1.2. The Mississippi River Deltaic Plain, presenting the location of six major delta along with ages and sizes (from Roberts, 1997)](image)

Roberts et al. (1997) suggested the deltaic cycles are divided by fluvially dominated regressive phases and marine-dominated transgressive phases, forming two types of shelf-stage deltas, thick inner shelf delta, such as the Balize Delta, or thin inner shelf deltas. The delta
switching or cycle explains the pattern of coastal formation (Figure 1.3) which occurred with an increment of 1000-2000 years of river avulsions (Coleman et al. 1998; Twilley et al., 2016). During the abandoned coastal deltaic phase, sediment source to coastal deltaic basin decreases, which leads to a decrease of land and increase the water portion of the coastal deltaic basin (Twilley et al., 2016).

Figure 1.3. The phase of the river, river abandonment, land formation and ecosystem development (from Penland et al., 1988; modified from Gosselink et al., 1998)

Over time, the sandy paleochannels were buried under overburden by Recent (Holocene) mud sediment from the Mississippi River (Suter et al. 1987). Nairn et al. (2005) coined the term of “mud capped” for this type of multilayer sandy resources. The evolution of muddy-capped pits differs from that of sandy pits.

In a muddy setting, the suspended sediment transport is dominant. Whereas in a sandy setting, bed load and near-bed suspended load transport occur. Muddy capped pits evolution involves pit margin erosion and pit infilling, but sandy pits involve the pit slopes. The sandy pits
may migrate where there is a net or residual sediment transport rate. Due to the lack of bed load and the ability of cohesive sediment slopes to remain near vertical for up to 5 m in height, the muddy-capped pits’ slopes may not change at all (Nairn et al., 2005). Obelcz et al. (2016) suggested that cohesive laminate overlaying the sandy infill has a significant role in pit wall stability or lack thereof. In addition, this study suggested a possible fluid mud layer covering the entire bed floor. The sediment plume from the Mississippi River has a significant impact on sedimentation of Sandy Point, especially when the longshore current is towards the west (Nairn et al., 2005). The pit is about 350 to 450 m wide in the east-west direction and 1,800 to 1,980 m long in the north-south direction. Figure 1.4 shows the location the pit in and the dredged area in 2012.

![Figure 1.4](image.png)

Figure 1.4. Location the of the Sandy Point dredge pit

Figure 1.5 shows a detailed view of the pit shape and dimensions. There are numerous oil and gas pipelines, platforms, wellheads, and other oil and gas-related infrastructures in the vicinity of the Sandy Point. The closest pipeline is located about 300 m northwest of the northwest tip of the pit (Nairn et al., 2005). Sand and gravel mining could impose a risk to platforms and pipelines, as well as modifying the action of waves, currents and sediment dynamics (Stone et al., 2009; Nairn et al., 2005). Mineral Management Service (MMS) has recommended 458 m buffer from mining activity to all platforms on the OCS (Tetra Tech, 2004). Hence, it is imperative to enhance...
our understanding of the hydrodynamics and sediment dynamics in this sand/mud mixed environment.

Figure 1.5. Details of southeast Sandy Point barrow area (Tetra Tech, 2004)

1.3 Hydrodynamics and Sediment Characteristics of the Louisiana Shelf

The circulation patterns over the Louisiana-Texas (LATEX) shelf have been studied using hydrographic measurements and numerical simulations (Cochrane and Kelly, 1986; Murray, 1994; Nowlin et al., 1998a; 1998b). In addition, the Mississippi River plume has been examined due to its influences on the coastal ecosystem (e.g., sediment load, water quality) (Mossa et al., 1996; Murray, 1997; Walker and Hammack, 2000; Chaichitehrani et al., 2013). The Louisiana inner shelf and its bottom boundary layer dynamics is an example of a low-energy system environment. Louisiana shelf experiences a wave field with a significant wave height of ~1.0 m (Stone and Xu, 1996; Write et al., 1997). Cochrane and Kelly (1986) studied the low-frequency circulation on the
LATEX continental shelf. They observed an elongated cyclonic gyre (counterclockwise) dominating part of the shelf circulation. The inshore limb of wind-driven gyre moves toward the west or south (a.k.a downcoast current). This circulation pattern prevails during most of the year except in July-August. The outer limb of gyre moves toward north or east. The prevailing counterclockwise (cyclonic) gyre disappears in summer and is replaced by a clockwise (anticyclonic) gyre (Figure 1.6).

Figure 1.6. Geopotential anomaly ($10^{-1}$ J/kg) of the sea surface relative to 0.7 MPa (from Cochran and Kelly, 1986)
A primitive equation ocean model (3D) was employed (Oey, 1995) to explain cyclonic gyre and mechanisms governing circulation (e.g., wind, river buoyancy and Loop Current eddies (LECs). Oey (1995) verified the wind-driven and eddy-forced shelf circulation over the LATEX. The study confirmed the inshore limb of the gyre is primarily wind-driven and moving toward the west, while the combination of wind and LECs generate currents on the other three limbs of the gyre. In addition, the model also suggested the LECs generate the shelf current, and the wind stress curl modulates this current with seasonally varying intensity. In addition, the numerical simulation results indicate that a surface layer of fresh Mississippi outflow water that moves along the Texas–Louisiana coastline profoundly influenced by local winds.

Cho et al. (1998) collected velocity data from 31 current meters using near-surface moorings at 10-15 m depth during the Texas–Louisiana Shelf Physical Oceanography Program (LATEX-A). The empirical orthogonal function (EOF) method was used to analyze the temporal and spatial variability of the measured current velocity. The first EOF was able to account for 89% of the monthly variance which was correlated with a long-shelf wind. The EOF modes agreed with results from previous studies suggesting that the low-frequency circulation is wind-driven. Ohlmann and Niiler (2005) deployed more than 750 surface drifters in the LATEX shelf and Florida-Alabama shelf from 1993 through 1998 to study the circulation in the northern Gulf of Mexico on synoptic to seasonal scales. Their results agreed with Cochran and Kelly (1986). They observed strong connectivity between the shelves (i.e., east and west of the Mississippi River delta) under an isolated period of strong wind condition associated with the passage of tropical storms. In addition, they showed that LCEs move the drifters cross-shore (i.e., either toward the deep water in Gulf or to shelf break). Walker et al. (2005) analyzed satellite imageries and in situ measurements to investigate wind- and eddy-driven circulation on the LATEX shelf. She observed
four distinct circulation regimes in non-summer months: (1) down-coast jet induced by wind on the western LATEX inner shelf; (2) Texas jet or cross-shelf entrainment; (3) slope eddies- induced seaward entrainment along the Mexico coast; (4) a cyclonic gyre on the outer Louisiana shelf.

In short, in the northern part of the Gulf, surface winds are predominantly from the south-southwest during summer, and mostly from the east during the remainder of the year (De Velasco and Winant, 1996; Wang, Nowlin and Reid, 1998). The effects of wind forcing have been shown by freshwater influenced stratified coastal current (Ohlmann and Niiler 2005). In addition, changes in sea-level during winter are associated with changes in along-shore wind stress (Chuang & Wiseman, 1983).

Also, the circulation over the LATEX shelf is recognized as cyclonic low-frequency circulation driven predominantly by local wind and influenced by Mississippi and Atchafalaya River discharge and LECs. The circulation has a cyclonic pattern throughout the year, however, during summer the direction of flow may reverse.

1.4 Numerical Models for Sandy Point SE Dredge Pit Evolution

Information on currents, waves, and suspended sediment concentration are indispensable for understanding the hydrodynamics, sediment dynamics and predicting the pit infilling rate and pit margin erosion in the study area. Our knowledge about the infilling rate and contribution of sediment sources in infilling the pit in concert with winter storms/hurricanes and the hydrodynamics of the Sandy Point is limited. In 2002, seventeen institutes from seven countries of the European Community conducted a study called SANDPIT to better understating the impacts (near field and far field) of dredged pits (e.g. the PUTMOR pit offshore the Netherlands, Svasek, 2001) impacts for Coastal Zone Management purposes (Van Rijn et al. 2005). Nairn (2005) used a theoretical analysis and a numerical model (MISED), to study morphological evolution of Holly Beach dredge pit and Sandy Point dredge pit. Holly Beach Dredge Pit is located offshore of the
western Louisiana in federal waters. His study suggested that pits in muddy (sand deposit capped by mud) and sandy settings have different morphologic evolution characteristics. He showed that the hydrodynamics and sediment dynamics at the Sandy Point site are much more complicated than the conditions at the Holly Beach Pit. In addition, based on the numerical model results, he showed an external source of suspended sediment concentration such as plumes from the Mississippi River (i.e., not from local re-suspension by waves and currents) reduces the pit margin erosion by contributing to pit infilling. Kobashi (2009) studied bottom boundary layer physics and sediment transport along Ship Shoal using in situ observations and a numerical model, MIKE.

In the present study, the fully three-dimensional hydrodynamic and sediment transport model Delft3D was used. This model was applied to simulate the hydrodynamics in the pit and surrounding areas. Delft3D is an open source code developed by Deltares which provides an integrated framework for a multi-disciplinary approach to create 3D simulations for rivers, lakes, and coastal and estuarine areas. Delft3D is composed of several modules (e.g., FLOW and WAVE) which are grouped on a mutual interface capable of interacting with one another.

1.5 Goals

There are three overarching goals for this research:

1) Assessing the potential impact of wave- and current- induced bottom shear stress associated with fair weather and cold front conditions on the sediment dynamics in Sandy Point dredge pit in a fully coupled manner;

2) Identifying the source (river input and/or local sediment resuspension) of deposited sediment in Sandy Point dredge pit during fair weather and a cold front;

3) Estimation of sediment resuspension and deposition in the dredged pit during cold front conditions
1.6 Approach

Given the objectives described above, I developed an integrated modeling system for hydrodynamics and sediment transport using Delft3D FLOW, WAVE and MOR modules. To enhance our knowledge about the sediment dynamics in Sandy Point dredge pit, the wave-current bottom interaction at the bottom of the pit was investigated during fair weather and a strong cold front condition. To achieve our goals the following steps were followed:

- Evaluation of an atmospheric correction algorithms and a regional, satellite-based suspended sediment concentration (SSC) retrieval algorithm to prepare SSC initial condition maps
- Input file preparations for Delft3D FLOW, WAVE, MOR modules
- Setup a coupled flow, wave and sediment transport model
- Calibration of hydrodynamics model considering wind friction coefficient, bottom friction, horizontal eddy viscosity, vertical eddy diffusivity. The calibration can be challenging regarding the profound effect of vertical eddy diffusivity on circulation (Goodrich, 1987; Zhang and Mike, 2007)
- Validate the hydrodynamic model with observed data
- Validate the sediment transport model with in situ and satellite data

Chapter 2 presents the evaluation of atmospheric correction algorithms and a regional SSC retrieval algorithm. The estimated SSCs from Aqua-MODIS and Landsat 8-OLI were compared with in situ data. In addition, SPM maps from this part were used as an initial boundary condition.

In Chapter 3, a Skill-assessed SWAN Model for Wave Generation and Propagation over the Louisiana Shelf was performed.
In Chapter 4, a fully-coupled hydrodynamic and sediment model using Delft3D for the northern Gulf of Mexico, with a focus on Sandy Point dredge pit was developed for fair weather conditions in July-August 2015. The flow model was validated by observations of water level and velocity at a number of stations in the northern Gulf of Mexico and Sandy Point dredge pit. In addition, the wave model was validated through a comparison of model results with the observations of wave heights, and periods at NDBC wave buoys.

In Chapter 5, a fully-coupled hydrodynamic and sediment model was developed and validated using the observed data during a cold front in November 2014. Finally, all the findings and conclusions were summarized in Chapter 6.
CHAPTER 2: DEVELOPING A SATELLITE-BASED ALGORITHM TO PREPARE SUSPENDED PARTICULATE MATTER MAPS OVER THE LOUISIANA SHELF

2.1 Introduction

The initial distribution of sediment concentration is essential for sediment transport modeling. The suspended sediment concentration is utilized in sediment transport model as an initial condition. In addition, in situ measured suspended sediment concentration is used to validate sediment transport models.

The lack of in situ measured suspended sediment concentrations in our study area led us to use satellite-derived suspended sediment concentration. Hence, an effort was made to prepare remote sensing-based suspended sediment concentration with optimal temporal and spatial resolutions. The successful use of satellite-derived suspended sediment concentration data in the modeling of sediment transport has been shown in previous studies (Quillon and Caussade, 1991; Ramakrishnan and Rajawat, 2012).

Total suspended particulate matter (SPM) is well recognized as a water quality indicator. SPM plays a major role in the biological and ecological status of inland, coastal, and shelf waters, and can cause detrimental effects on marine ecosystems (Ma et al., 2015; Joshi et al., 2017; Niroomandi et al., 2017) and has a strong influence on the phytoplankton productivity and abundance by changing photosynthetically active radiation (PAR) and euphotic depth (Kirk, 1994). The traditional method of monitoring SPM using ship and platform measurements is limited in spatial coverage, and it can be difficult to maintain regular monitoring programs for time-series assessments. However, with the advent of satellite-based sensors and computer simulation packages, some studies on SPM dynamics with high spatial and temporal resolutions have been done (Blaas et al., 2007; Allahdadi et al., 2011; D’Sa et al., 2011). A well-calibrated and validated
sediment transport model along with a reliable satellite-derived SPM data can provide spatially continuous near-surface maps of SPM. Among ocean color sensors and land imagers, the capability of Landsat-8, Operational Land Imager (OLI) and Aqua, Moderate Resolution Imaging Spectroradiometer (MODIS) to estimate SPM in coastal waters have been proven (Miller and McKee, 2004; Dogliotti et al., 2014; Vanhellemont and Ruddick, 2014; Ody et al., 2016). Landsat-8 was launched on February 11, 2013 and started operating on May 30, 2013. It has 11 spectral bands (433-12,500 nm), spatial resolutions of 30 m and 15 m in the panchromatic band, and a revisit time of 16 days. The high signal-to-noise ratio (SNR), the 12-bit quantization combined with 30 m spatial resolution of the Landsat-8 OLI enhance our ability to monitor SPM dynamics in coastal waters (Vanhellemont and Ruddick, 2015; Novoa et al., 2017). Landsat-8 OLI spatial resolution is sufficient to resolve the SPM plume and provide a map of the well-defined turbidity plume from the Mississippi River passes. However, with a designed revisit time of 16-days and an effective revisit time of c.a. seasonal when cloud cover is taken into account (Hestir et al., 2015), Landsat’s temporal resolution is highly limited for studying the SPM dynamics over regions with the high sediment dynamics regime. The area around the Mississippi River Delta, particularly during extreme meteorological events is an example of such a dynamic region (Roberts et al., 1987; Walker and Hammack, 2000; Georgiou et al., 2005; Feng, 2009; Li et al., 2011; Allahdadi et al., 2017; Allahdadi and Li, 2017). The Mississippi River Delta is a part of the Louisiana inner shelf that is characterized by the non-frequent effects of tropical storms and hurricanes during summer months and Fall (Allahdadi and Li, 2017) and the frequent effects of northerly cold fronts during non-summer months (Li et al., 2011). Cold front outbreaks over this area occur every 3-10 days from September through May with a typical duration of 12 to 24 hours, depending on the advancing speed (Roberts et al., 1987; Walker and Hammack, 2000; Li et al., 2011). Thus, a
sampling revisit time of daily or better is optimal for resolving the effects of such dominant events in this area. MODIS on the Aqua satellite with a revisit time of one day can overcome this shortcoming. MODIS is an ocean color sensor on the Aqua satellite launched on May 4, 2002. MODIS-Aqua has 36 spectral bands with spatial resolutions of 250 m, 500 m, and 1 km and temporal resolution of one image per day, which provides a wealth of information about the biological and physical properties of the ocean. The temporal resolution (daily) of MODIS-Aqua enables observations of the daily dynamics of SPM around the Mississippi River plume. Thus, to study sediment dynamics Landsat-8 OLI and MODIS-Aqua should be used in tandem in my study region partiality during extreme meteorological events.

SPM is retrieved from satellite data by relating its concentration to apparent optical properties (AOPs) (e.g., empirical algorithms) and inherent optical properties (IOPs) (e.g., semi-analytical and analytical algorithms) in high and in low to moderate turbid waters (Case-II and Case-I, respectively) (Kirk, 1994; Miller and McKee, 2004; D’Sa et al., 2007; Nechad et al., 2010; Chen et al., 2013; Dogliotti et al., 2015). Several studies have used remote sensing reflectance products in red and green wavelengths to estimate SPM concentration in Case-I waters from ocean color sensors (e.g., SeaWiFS, MODIS, MERIS) and land imagers (e.g., Landsat ETM/OLI) (Miller and McKee, 2004; Woerd and Pasterkamp, 2004; D’Sa et al., 2007; Nechad et al., 2011). However, several studies have shown that as the SPM concentration increases, the remote sensing signal saturates at short wavelengths (blue, green) and then eventually in red band and even in the near-infrared (NIR) band in Case-II waters, becoming less sensitive to increases in SPM concentration (Doxaran et al., 2002; Shen et al., 2010; Ody et al., 2016; Novoa et al., 2017). The increase in reflectance caused by increased SPM concentration in Case II turbid coastal waters necessitates not only careful selection of SPM retrieval algorithms, but also necessitates adaptation of
atmospheric correction algorithms (Doxaran et al., 2009; Vanhellemont and Ruddick, 2014). The pioneering atmospheric correction algorithm was developed for the global Case-I waters using MODIS’s two near-infrared (NIR) bands (748-869 nm). This method assumes that in clear water the NIR water-leaving radiance contributions to the top of atmosphere (TOA) signal is negligible, and any measured signal is due to aerosol scattering (Gordon and Wang, 1994; Gordon, 1997). Hence, NIR atmospheric correction algorithms for SPM retrieval in high turbidity waters can lead to an overestimation of aerosol reflectance and an underestimation of SPM concentration (Ruddick et al., 2000). While it has been shown that short-wave infrared (SWIR) atmospheric correction algorithms can perform well in high turbid coastal waters (Wang and Shi, 2007; Dogliotti et al., 2011). In recognition of difficulties for selecting the most effective atmospheric correction methods in high turbidity water, developing of atmospheric correction models based on the combination of NIR and SWIR bands or two SWIR bands has gained increased attention (, Wang 2007; Wang and Shi 2007; Wang et al., 2009; Vanhellemont et al., 2014; Vanhellemont and Ruddick, 2015). Shi and Wang (2009) presented the spectral optical feature of a sediment-laden plume of the Mississippi River using SWIR atmospheric correction algorithm.

In this study, accurate maps of satellite-derived surface SPM were prepared and used to initialize and to validate Delft3D sediment transport model.

2.2 Methods

The overarching goal of this study was to estimate SPM concentration using Landsat-8 OLI and MODIS-Aqua. To achieve this goal, the following steps were performed:

(1) Identify the most appropriate and suitable atmospheric correction methods across high- to low-turbidity waters

(2) Apply a standard SPM retrieval algorithm (D’Sa et al., 2007) across all corrected datasets
(3) Compare retrieved SPM concentration with *in situ*-measured SPM concentration

### 2.2.1 Study Area

This study area covers the northern Gulf of Mexico with the focus on west flank on the Mississippi River. The Mississippi River ranks as the seventh largest system in the world in terms of discharge and sediment load (Milliman and Fransworth, 2011; Twilley et al., 2016), with a mean freshwater discharge of $1.35\pm0.2\times10^4$ m$^3$.s$^{-1}$ (Hu et al., 2005), and transporting about 230 million tons of sediment to the Gulf of Mexico annually (Meade and Parker, 1984). Figure 2.1 presents a Rayleigh-corrected RGB Landsat-8 OLI image over the Mississippi River plume on 23 April 2016 showing turbid coastal waters with high sediment concentration (yellow-brown) around the Mississippi River passes, as well as the extension of sediment-laden waters from the Mississippi River to the Lousiana continental shelf.

![Figure 2.1. Rayleigh-corrected Landsat-8 OLI image over the Mississippi River plume, coastal water, and Lousiana continental shelf waters on 23 April 2016 representing high turbidity waters around the Mississippi River’ passes and coastal waters as well as the dispersion of sediment-rich water to offshore waters. Box 1, box 2 and box 3 represent high, moderate and low turbidity water](image-url)
The Mississippi River discharge at Belle Chasse (USGS 07374525) was relatively large (~19567 m³.s⁻¹) during Landsat-8 OLI passage on 23 April 2016. The sediment- and nutrient-laden fresh water from the Mississippi River plume influences the primary productivity and fishery activities in the northern Gulf of Mexico (Dinnel and Wiseman, 1986; Rabalais et al., 1996; Lohrenz et al., 1999; Tehrani et al., 2013; Allahdadi et al., 2017).

The SPM dynamics around the Mississippi River Delta is optically complex and variable in time and space. Sediment resuspension as a geomorphic response to extreme weather events (e.g., hurricanes and cold fronts) contributes to the turbidity and the complexity of the Mississippi River Delta and coastal waters in the northern Gulf of Mexico. Wind-generated currents and waves are the most important forces controlling sediment dynamics over the Louisiana continental shelf (Cochran and Kelly, 1989; Hitchcock et al., 1997; Allahdadi et al., 2011). The seasonal wind stress, discharge inertia, and the wave regime determine the spatial distribution of sediment-rich Mississippi River plume (Myint and Walker, 2002).

To investigate the performance of atmospheric correction algorithms and to select the most appropriate approaches in the study area, the study area was divided into three regions ranging from high-to-low turbidity (Figure 2.1). These three regions were selected based on the distance from the Mississippi River as well as assessing true color images obtained from different time periods. Box 1 is in the vicinity of the Mississippi River passes and encompasses the high turbidity water. This region is highly influenced by the Mississippi River sediment plume. Box 2 encloses the moderate turbid water, and this region is relatively far from the Mississippi River passes. This region is influenced by tidal-induced transport of suspended sediment from the Barataria Bay (see Figure 2.2 for location). Box 3 surrounds the low turbid water, which is far from the Mississippi River plume (Figure 2.1).
Figure 2.2. Map of the study area and the location of stations used to perform the match-ups between Landsat-8 OLI-, MODIS-derived SPM concentrations and *in situ* SPM concentrations (see Table 2.1 for detail). The geographic location of the Barataria Bay, the Mississippi River, Southwest Pass, and South Pass labeled as BR Bay, MR, SwP, and SP, respectively.

2.2.2 Landsat-8 OLI Data Collection and Atmospheric Correction

In this study, the remote sensing reflectance (Rrs) at 443 nm (coastal/aerosol), 483 nm (blue), 560 nm (green), 655 nm (red), 864 nm (NIR) and two SWIR bands at 1601 nm and 2380 nm were used in atmospheric correction algorithms and the subsequent SPM retrieval algorithm. A total of four atmospheric correction approaches were applied to the Landsat-8 OLI data, ACOLITE-NIR, ACOLITE-SWIR, SeaDAS-MUMM (Management Unit of the North Sea Mathematical Models), and SeaDAS-SWIR.

Table 2.1. Summary of data sets used in match-up comparisons between *in situ* and OLI-, MODIS-derived SPM.

<table>
<thead>
<tr>
<th>Date</th>
<th>Satellite</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 March 2013</td>
<td>MODIS-Aqua</td>
<td>Rabalais (2013)</td>
</tr>
<tr>
<td>13 June 2013</td>
<td>MODIS-Aqua</td>
<td>Rabalais (2013)</td>
</tr>
<tr>
<td>23 July 2013</td>
<td>MODIS-Aqua</td>
<td>Rabalais (2013)</td>
</tr>
<tr>
<td>13-14 September 2013</td>
<td>MODIS-Aqua</td>
<td>Lee et al. (2013)</td>
</tr>
</tbody>
</table>
Two orthorectified and terrain corrected Landsat-8 OLI Level 1T images in GeoTIFF format were obtained from U.S. Geological Survey (USGS) Earth Explorer portal (https://earthexplorer.usgs.gov/) for the northern Gulf of Mexico (Path: 21; Row: 40). Since a high Mississippi River flow peak typically occurs in spring, the Landsat-8 OLI cloud-free image on 23 April 2016 was acquired to test the performance of the atmospheric correction algorithms. Additionally, based on available in situ SPM concentration measurements (Rabalais, 2014) Landsat-8 OLI data were obtained on 30 July 2014. ACOLITE software package was used to obtain two of the four atmospherically corrected remote sensing reflectance images (ACOLITE-NIR and ACOLITE-SWIR) (Vanhellemont and Ruddick, 2014; Vanhellemont and Ruddick, 2015). ACOLITE is an atmospheric correction and processor for the Landsat-8, and Sentinel-2A (S2A) MultiSpectral Imager (MSI) developed at the Royal Belgian Institute of Natural Science (RBINS). Table 2.2 provides Landsat-8 OLI spectral bands, SNR and corresponding spatial resolution used in this study.

<table>
<thead>
<tr>
<th>Sensor/Satellite</th>
<th>Band Number</th>
<th>Central band (nm)</th>
<th>SNR at reference L_typ</th>
<th>Spatial Resolution (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landsat-8 OLI</td>
<td>1</td>
<td>443</td>
<td>237</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>483</td>
<td>367</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>561</td>
<td>304</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>655</td>
<td>227</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>865</td>
<td>201</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>1609</td>
<td>267</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>2201</td>
<td>327</td>
<td>30</td>
</tr>
<tr>
<td>MODIS-Aqua</td>
<td>9</td>
<td>443</td>
<td>2253</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>488</td>
<td>2270</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>678</td>
<td>2175</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>748</td>
<td>1371</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>869</td>
<td>1112</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1240</td>
<td>25</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>2130</td>
<td>12</td>
<td>500</td>
</tr>
</tbody>
</table>
Two following embedded atmospheric correction algorithms in ACOLITE were applied to Landsat-8 OLI data: 1. The NIR algorithm using the red (655 nm) and NIR (865 nm) bands (Vanhellemont and Ruddick, 2014) based on the MUMM method (Ruddick et al., 2000); 2. The SWIR algorithm using two high-quality SWIR bands at 1609 nm (SWIR I) and 2201 nm (SWIR II) with “Pahlevan R” gain for the vicarious calibration (Pahlevan et al., 2014; Vanhellemont and Ruddick, 2014).

In addition, ACOLITE enables modification of the epsilon value (ε) in the aerosol models. The epsilon is used to extrapolate aerosol reflectance in visible bands from NIR. In this study, the aerosol type was selected to be constant over a single Landsat-8 OLI tile for both approaches (Vanhellemont and Ruddick, 2014). Here, the fixed scene epsilon (ε = 1) was selected based on recommendations from previous studies (Dogliotti et al., 2011; Novoa et al., 2017). For both the ACOLITE-NIR and ACOLITE-SWIR approaches, the aerosol reflectance was estimated by assuming a linear relationship between marine reflectance in red (655 nm) and NIR (865 nm) (α = ρ_red/ρ_NIR = 8.7) (ACOLITE default value) (Ruddick et al., 2006; Vanhellemont and Ruddick, 2014; Vanhellemont et al., 2014; Concha and Schott, 2015). Cloud masking was performed using a threshold of 0.0215 on surface reflectance at 1609 nm. The other two atmospherically corrected remote sensing reflectance images (SeaDAS-SWIR and SeaDAS-MUMM) were obtained using the Sea-viewing Wide Field-of-View Sensor (SeaWiFS) Data Analysing System (SeaDAS) software version 7.4. (Franz et al., 2015). The SeaDAS package has been developed and distributed by NASA’s Ocean Biology Processing Group. From SeaDAS package, l2gen function, two atmospheric correction methods were selected: 1. SeaDAS-SWIR; 2. SeaDAS-MUMM. The SeaDAS-MUMM method was applied to Landsat-8 OLI data using bands (655) and (865) and tuning the calibration parameter (α) to 8.7. The atmospheric correction SeaDAS-SWIR method
was applied to Landsat-8 OLI data using two SWIR bands at 1609 nm and 2201 nm (Concha and Schott, 2015; Franz et al., 2015).

2.2.3 MODIS-Aqua Data Collection and Atmospheric Correction

MODIS-Aqua Level-1A data were downloaded from NASA Ocean Color website (https://oceancolor.gsfc.nasa.gov) (Table 2.1). The Level-1 A data were processed and was upgraded to Level 1B using SeaDAS (version 7.4.). Level-2 remote sensing reflectance at 443, 488, 555, and 678 nm were generated by applying MUMM (Ruddick et al., 2000) and SWIR.NIR atmospheric (Wang and Shi, 2007; Wang et al., 2009) correction methods using the l2gen function. The MUMM correction used two MODIS NIR bands at 748 nm and 869 nm, and the aerosol ratios were tuned to $\alpha = 1.95$ and $\varepsilon = 1.0$. The SWIR.NIR correction used was applied using two MODIS NIR bands at 748 nm and 869 nm and two SWIR bands at 1240 nm and 2130 nm. All Rrs products were generated at a resolution of 1 km. Table 2.2 summarizes the MODIS-Aqua bands used in this study.

2.2.4. SPM Retrieval Algorithm

The atmospherically corrected remote sensing reflectance products were used in a regional SPM-retrieval algorithm (D’Sa et al., 2007) to estimate SPM concentration from Landsat-8 OLI and MODIS-Aqua. D’Sa et al. (2007) developed a regional two-band (green-to-red) empirical algorithm to estimate SPM in the northern Gulf of Mexico from SeaWiFS. The SPM concentration retrieval algorithm (D’Sa et al., 2007) (Equation (2.1)) was developed using in situ remote sensing reflectance in red (670 nm) and green (555 nm) and was calibrated with in situ measurements. This algorithm performed better, and the errors were minimized compared to the previous single-band SPM retrieval algorithm in the northern Gulf of Mexico (Miller and McKee, 2004). In addition, the use of band (670 nm) closest to NIR bands makes this algorithm more robust than other visible
single-band algorithms (Miller and McKee, 2004). This algorithm is the only available band-ratio algorithm designed to estimate SPM concentration (mg.l\(^{-1}\)) from SeaWIFS in the northern Gulf of Mexico, but in this study the lack of \textit{in situ} Rrs led us to adjust this algorithm based on closest available bands in Landsat-8 OLI and MODIS-Aqua. In this study, the SPM-retrieval algorithm was modified. Remote sensing reflectance products were replaced with the closest available wavelengths in Landsat-8 OLI (560 nm and 655 nm) and MODIS-Aqua (555 nm and 678 nm). The algorithm was applied to the atmospherically corrected remote sensing reflectance products from Landsat-8 OLI and MODIS-Aqua.

\[
SPM = 17.783 \left( \frac{Rrs_{670}}{Rrs_{555}} \right)^{1.11}
\]

where SPM is the suspended particulate matter concentration in mg.l\(^{-1}\) and Rrs are the remote sensing reflectance in sr\(^{-1}\).

2.2.5 \textbf{In situ SPM Measurements}

To validate Landsat-8 OLI-derived SPM concentrations, \textit{in situ} SPM concentrations (Figure 2.2, Table 2.1) measured on 30 July 2014 were used (Rabalais, 2014). The time difference of ±3 hr between SPM measurements and Landsat-8 OLI overpass was considered (Bailey and Werdell, 2006). MODIS-estimated SPM concentrations were validated using the SPM concentrations measurements provided by NASA SeaWiFS Bio-optical Archive and Storage System (\textit{SeaBASS}) (https://seabass.gsfc.nasa.gov/search#bio) (Lee et al., 2013) and NOAA National Centers for Environmental Information (NCEI) (Rabalais, 2012; Rabalais, 2013; Rabalais, 2014). The \textit{in situ} SPM dataset collected in July 2012, March, June, July, September 2013, and July 2014 matched-up with MODIS-derived SPM concentrations (Figure 2.2, Table 2.1). The time difference between SPM measurements and MODIS-Aqua overpasses used in the validation was constrained to ±3 hr (Bailey and Werdell 2006).
2.3 Results and Discussion

2.3.1 Comparison of Atmospheric Correction Approaches for Landsat-8 OLI

The Landsat-8 OLI remote sensing reflectance products at 443 nm, 483 nm, 561 nm and 655 nm bands were corrected for atmospheric effects using ACOLITE SWIR and NIR. The effects of using a fixed epsilon versus a variable epsilon were investigated and compared. Results indicate using a variable epsilon provide a noisy image, and the correction failed in some regions (Figure 2.3). Result was consistent with the study of Vanhellemont and Ruddick (2015) over Belgian coastal waters.

![Figure 2.3. Remote sensing reflectance at 561 nm image over the Mississippi River plume on 23 April 2016 processed using SWIR algorithm with fixed (left) and variable (right) ε. The black arrows point to the regions that the algorithms with variable ε failed.](image)

The remote sensing reflectance products at 443 nm, 483 nm, 561 nm, and 655 nm from ACOLITE SWIR algorithm were compared against the ACOLITE NIR results. Table 2.3 summarizes the 5th, and 95th percentile, the percentage difference (Equation (2.2)), the median ratio (NIR to SWIR) and the semi-interquartile range (SIQR) values (Equation (2.3)) of the SWIR- and
NIR-corrected Rrs in high to low turbid waters (box1, box 2 and box3). The SIQR measures the spread of the data (Bailey and Werdell, 2006).

\[
\frac{|\text{SWIR} - \text{NIR}|}{\text{SWIR} + \text{NIR}} \times 100
\]

\[
SIRQ = \frac{Q_3 - Q_1}{2}
\]

where \(Q_1\) is the 25\(^{th}\) percentile and \(Q_3\) is the 75\(^{th}\) percentile.

Table 2.3. 5th and 95th percentile for Landsat-8 OLI-retrieved Rrs (sr\(^{-1}\)) products on 23 April 2016 processed by NIR and SWIR atmospheric correction algorithms, the percentage difference, median NIR to SWIR ratio, and SIQR in box 1, 2 and 3.

<table>
<thead>
<tr>
<th>Band</th>
<th>Box</th>
<th>5th percentile SWIR approach</th>
<th>95th percentile SWIR approach</th>
<th>5th percentile NIR approach</th>
<th>95th percentile NIR approach</th>
<th>Percentage Difference</th>
<th>Median Ratio (SIQR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>443</td>
<td>1</td>
<td>0.0066</td>
<td>0.0117</td>
<td>0.0052</td>
<td>0.0097</td>
<td>14.50</td>
<td>0.930 (±0.110)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.0035</td>
<td>0.0058</td>
<td>0.0032</td>
<td>0.0056</td>
<td>12.80</td>
<td>0.928 (±0.102)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.0024</td>
<td>0.0039</td>
<td>0.0019</td>
<td>0.0033</td>
<td>9.09</td>
<td>0.917 (±0.058)</td>
</tr>
<tr>
<td>483</td>
<td>1</td>
<td>0.0110</td>
<td>0.0171</td>
<td>0.0100</td>
<td>0.0140</td>
<td>20.49</td>
<td>0.959 (±0.067)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.0047</td>
<td>0.0072</td>
<td>0.0046</td>
<td>0.0071</td>
<td>17.28</td>
<td>0.953 (±0.069)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.0034</td>
<td>0.0048</td>
<td>0.0031</td>
<td>0.0043</td>
<td>16.60</td>
<td>0.945 (±0.041)</td>
</tr>
<tr>
<td>561</td>
<td>1</td>
<td>0.0185</td>
<td>0.0265</td>
<td>0.0184</td>
<td>0.0240</td>
<td>14.73</td>
<td>0.978 (±0.039)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.0046</td>
<td>0.0079</td>
<td>0.0044</td>
<td>0.0076</td>
<td>14.06</td>
<td>0.969 (±0.057)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.0026</td>
<td>0.0040</td>
<td>0.0024</td>
<td>0.0036</td>
<td>13.20</td>
<td>0.934 (±0.057)</td>
</tr>
<tr>
<td>655</td>
<td>1</td>
<td>0.0165</td>
<td>0.0320</td>
<td>0.0160</td>
<td>0.0280</td>
<td>33.18</td>
<td>0.982 (±0.031)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.0025</td>
<td>0.0049</td>
<td>0.0024</td>
<td>0.0045</td>
<td>15.00</td>
<td>0.948 (±0.078)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.0014</td>
<td>0.0025</td>
<td>0.0013</td>
<td>0.0022</td>
<td>14.24</td>
<td>0.894 (±0.107)</td>
</tr>
</tbody>
</table>

The 5\(^{th}\) percentile of the SWIR- and NIR-corrected Rrs at 483 nm were respectively ~0.0110 sr\(^{-1}\) and ~0.010 sr\(^{-1}\) and the 95\(^{th}\) percentile of the SWIR- and NIR-corrected Rrs were respectively ~0.0171 sr\(^{-1}\) and ~0.0140 sr\(^{-1}\) in high-turbidity waters (box 1) followed by 20.5% difference (Table 2.3). The percentage difference decreased to 16.6 in box 3 at 483 nm. In the red band (655 nm), the percentage difference between Rrs corrected by SWIR and NIR approaches was 33.18% in high turbidity waters and 15.0% in moderately turbid waters. In box 1, The NIR atmospheric correction algorithm retrieved negative or NAN Rrs values that were not included in match-ups. 27
The SWIR-corrected Rrs products had higher values compared to the NIR-corrected Rrs products. The maximum percentage difference (33.18%) was observed in box 1 (high turbid waters) at 655 nm. The computed percentage differences suggest that the difference between the SWIR- and NIR-corrected Rrs at each wavelength increased as the turbidity increased. The observed percentage difference between SWIR-and NIR-corrected Rrs values in high turbidity water could be due to the fact that the NIR-correction is only adapted to low to moderately turbid waters. The atmospherically corrected Rrs products using SWIR and NIR approaches were plotted and color-coded based on the distance (km) from the Southwest Pass (28°54'18" N 89°25'42" W) (Figure 2.4, left panel) and SPM concentration (mg.l⁻¹) (Figure 2.4, right panel).

The hydrodynamics around the Mississippi River plume is very complex, and sediment flux from the River is not restricted to any specific outlet. Figure 2.4, left panel shows the Rrs signal increases as the distance from the Southwest Pass decreases and the SPM concentrations increase. The linear relationship between corrected Rrs products was observed in band 1 through 4, while as the turbidity started increasing (moving toward box 1) the linear relationship failed as the data deviated from 1:1.

Figure 2.4a through d shows that remote sensing reflectance values at 443 nm and 483 nm increased as the water became more turbid and the data were strikingly pulled down from 1:1. Furthermore, Figure 2.4 depicts that the short wavelengths (443 nm: aerosol band and 483 nm: blue bands) were highly sensitive to increase in SPM concentration (mg.l⁻¹) compared to green (561 nm) and red bands (655 nm). The best agreement was obtained between SWIR-and NIR-corrected Rrs at 655 nm (slope = 0.92, R² = 0.98), and the lowest agreement was observed at between SWIR and NIR corrected Rrs at 443 nm (slope = 0.53 and R² = 0.46) for all data points located in three boxes (Figure 2.4a and c).
Figure 2.4. Scatter plots showing (a) through (h) the comparison of Landsat-8 OLI remote sensing reflectance (Rrs) at 443 nm, 483 nm, 561 nm, and 655 nm derived from the Landsat-8 OLI image on 23 April 2016 over the Mississippi River plume using NIR (y-axis) and SWIR (x-axis) atmospheric correction algorithms for low to high turbidity waters. Colors indicate the distance (km) from the Mississippi River, Southwest Pass (left panel) and SPM concentrations (mg.l$^{-1}$) (right panel). The black dashed line is 1:1 and regression line is drawn in red.
The non-linear relationship was pronounced for Rrs values larger than 0.009 sr\(^{-1}\) at 443 nm and greater than 0.015 sr\(^{-1}\) at 483 nm where the NIR algorithm retrieved lower Rrs values than the SWIR algorithm (Figure 2.4, a to d). The linear relationship between SWIR and NIR corrected Rrs at 655 nm observed for the values of Rrs smaller than \(~0.027\) sr\(^{-1}\) and the SPM concentrations lower than \(~20\) mg.l\(^{-1}\) in low and moderate turbid water (located at a distance greater than 25 km from the Southwest Pass) (Figure 2.4g and h). At 561 nm and 655 nm, nonlinearity was observed for values larger than 0.025 sr\(^{-1}\) and 0.028 sr\(^{-1}\), respectively.

Table 2.4 presents computed statistical parameters for Landsat-8 OLI Rrs products processed by NIR and SWIR atmospheric correction algorithms. As turbidity increased, the agreement between corrected Rrs products using NIR and SWIR algorithms decreased (Table 2.4).

<table>
<thead>
<tr>
<th>Band</th>
<th>Box</th>
<th>BIAS (%)</th>
<th>RMSE</th>
<th>SI</th>
<th>WI</th>
<th>R(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>443 nm</td>
<td>1</td>
<td>0.133</td>
<td>0.0025</td>
<td>0.27</td>
<td>0.39</td>
<td>0.008</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-0.030</td>
<td>0.0007</td>
<td>0.13</td>
<td>0.61</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.039</td>
<td>0.0005</td>
<td>0.10</td>
<td>0.72</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>0.087</td>
<td>0.0021</td>
<td>0.28</td>
<td>0.79</td>
<td>0.46</td>
</tr>
<tr>
<td>483 nm</td>
<td>1</td>
<td>0.121</td>
<td>0.0023</td>
<td>0.15</td>
<td>0.52</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-0.024</td>
<td>0.0006</td>
<td>0.09</td>
<td>0.78</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.033</td>
<td>0.0004</td>
<td>0.07</td>
<td>0.68</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>0.080</td>
<td>0.0019</td>
<td>0.16</td>
<td>0.93</td>
<td>0.83</td>
</tr>
<tr>
<td>561 nm</td>
<td>1</td>
<td>0.100</td>
<td>0.0021</td>
<td>0.08</td>
<td>0.79</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-0.017</td>
<td>0.0005</td>
<td>0.07</td>
<td>0.93</td>
<td>0.76</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.027</td>
<td>0.0004</td>
<td>0.09</td>
<td>0.89</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>0.070</td>
<td>0.0018</td>
<td>0.09</td>
<td>0.99</td>
<td>0.96</td>
</tr>
<tr>
<td>655 nm</td>
<td>1</td>
<td>0.092</td>
<td>0.0019</td>
<td>0.07</td>
<td>0.93</td>
<td>0.76</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-0.010</td>
<td>0.0003</td>
<td>0.10</td>
<td>0.95</td>
<td>0.92</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.019</td>
<td>0.0003</td>
<td>0.19</td>
<td>0.82</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>0.061</td>
<td>0.0015</td>
<td>0.08</td>
<td>0.99</td>
<td>0.98</td>
</tr>
</tbody>
</table>
The non-linearity found between Rrs products corrected by SWIR and NIR approaches in high turbidity water was likely due to overestimation of the atmospheric component of the NIR algorithm and then underestimation of Rrs products in high turbidity waters. The observed non-linearity with increasing SPM concentration emphasize that the NIR atmospheric correction overestimated the aerosol reflectance and underestimated of water remote sensing reflectance in visible bands. A good agreement was found between the corrected Rrs signals using NIR and SWIR atmospheric correction algorithms for bands 561 nm and 655 nm in low to moderate turbid waters (box 2 and box 3 (Figure 2.5)).

![Figure 2.5. Scatter plots presenting the comparison of Landsat-8 OLI Rrs at (a) 561 nm and (b) 655 nm derived from the Landsat-8 OLI image on 23 April 2016 over the Mississippi River plume using NIR (y-axis) and SWIR (x-axis) atmospheric correction algorithms for low and moderate turbid water. The black dashed line is 1:1 and regression line is drawn in red](image)

The slopes of regression started decreasing (<1) as the NIR atmospheric correction algorithm estimated lower Rrs values than the SWIR approach in bands 1 through 4. The NIR and SWIR atmospheric correction algorithms showed consistent results at 561 nm (slope = 1.04; \(R^2 = 0.91\)) and 655 nm (slope = 1.02; \(R^2 = 0.90\)) (Table 2.5 and Figure 2.5) in low and moderate turbid water (box 2 and 3).
Table 2.6 presents the determination coefficient resulting from the comparison of corrected remote sensing reflectance products using SWIR and NIR correction algorithms from ACOLITE software with MUMM and SWIR- correction algorithms from SeaDAS. The results suggest that atmospherically corrected remote sensing reflectance products at 561 nm and 655 nm using ACOLITE SWIR and NIR algorithms in high turbidity water were in good agreement with the corrections using SeaDAS SWIR and MUMM algorithms. In each type of water, as the wavelength became shorter the agreement between corrected products processed with ACOLITE and SeaDAS software decreased. In addition, as the turbidity decreased and the water became clearer, the agreement between remote sensing reflectance products corrected with ACOLITE SWIR and SeaDAS SWIR decreased.

This trend also was observed between Rrs products corrected ACOLITE NIR and SeaDAS MUMM (Table 2.6). The Rrs (sr⁻¹) products at 443 nm, 481 nm, 561 nm, and 651 nm from ACOLITE NIR and SWIR atmospheric correction were also compared visually (Figure 2.6). The left panel presents corrected Rrs products using SWIR approach, and the right panel shows the corrected Rrs product using the NIR approach. Figure 2.6 enhances our understanding of the performance of each approach and delivers the knowledge of which approach tends to overestimate and underestimate the remote sensing products. As expected, the NIR correction tended to underestimate Rrs products due to overestimation of the aerosols reflectance. activities. Figure 2.6 shows that the SWIR approach tends (right) to estimate the higher value of Rrs than NIR approach (left).
Table 2.6. The determination coefficient ($R^2$) obtained from the comparison of corrected remote sensing reflectance products using SWIR and NIR atmospheric correction algorithms from ACOLITE software and MUMM and SWIR atmospheric correction algorithms from SeaDAS software from Landsat-8 OLI image acquired on 23 April 2016.

<table>
<thead>
<tr>
<th>Band (nm)</th>
<th>Type of water</th>
<th>ACOLITE</th>
<th>SeaDAS</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>443</td>
<td>High turbid</td>
<td>SWIR</td>
<td>SWIR</td>
<td>0.803</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NIR</td>
<td>MUMM</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>Moderate turbid</td>
<td>SWIR</td>
<td>SWIR</td>
<td>0.120</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NIR</td>
<td>MUMM</td>
<td>0.110</td>
</tr>
<tr>
<td></td>
<td>Low turbid</td>
<td>SWIR</td>
<td>SWIR</td>
<td>0.046</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NIR</td>
<td>MUMM</td>
<td>0.12</td>
</tr>
<tr>
<td>483</td>
<td>High turbid</td>
<td>SWIR</td>
<td>SWIR</td>
<td>0.890</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NIR</td>
<td>MUMM</td>
<td>0.488</td>
</tr>
<tr>
<td></td>
<td>Moderate turbid</td>
<td>SWIR</td>
<td>SWIR</td>
<td>0.370</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NIR</td>
<td>MUMM</td>
<td>0.410</td>
</tr>
<tr>
<td></td>
<td>Low turbid</td>
<td>SWIR</td>
<td>SWIR</td>
<td>0.045</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NIR</td>
<td>MUMM</td>
<td>0.150</td>
</tr>
<tr>
<td>561</td>
<td>High turbid close</td>
<td>SWIR</td>
<td>SWIR</td>
<td>0.960</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NIR</td>
<td>MUMM</td>
<td>0.950</td>
</tr>
<tr>
<td></td>
<td>Moderate turbid</td>
<td>SWIR</td>
<td>SWIR</td>
<td>0.750</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NIR</td>
<td>MUMM</td>
<td>0.730</td>
</tr>
<tr>
<td></td>
<td>Low turbid</td>
<td>SWIR</td>
<td>SWIR</td>
<td>0.230</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NIR</td>
<td>MUMM</td>
<td>0.510</td>
</tr>
<tr>
<td>655</td>
<td>High turbid</td>
<td>SWIR</td>
<td>SWIR</td>
<td>0.991</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NIR</td>
<td>MUMM</td>
<td>0.990</td>
</tr>
<tr>
<td></td>
<td>Moderate turbid</td>
<td>SWIR</td>
<td>SWIR</td>
<td>0.690</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NIR</td>
<td>MUMM</td>
<td>0.735</td>
</tr>
<tr>
<td></td>
<td>Low turbid</td>
<td>SWIR</td>
<td>SWIR</td>
<td>0.210</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NIR</td>
<td>MUMM</td>
<td>0.575</td>
</tr>
</tbody>
</table>
Generally, the highest Rrs values were found in the vicinity of the Mississippi River passes and in shallow coastal waters where significantly influenced by the Mississippi River plume and waves.

Figure 2.6. Comparison between corrected Landsat-8 OLI Rrs at 443, 483, 561 and 655 nm using ACOLITE SWIR (left panel) and NIR (right panel) atmospheric correction algorithm.
2.3.2 Evaluation of Retrieved SPM from Landsat-8 OLI

Figure 2.7 (a and b) presents SPM concentration maps generated from SWIR- and NIR-corrected Rrs products. The results suggest that the Rrs products corrected by SWIR atmospheric correction algorithm resulted in higher SPM values compared to the SPM values obtained from Rrs products corrected by NIR method.

![Figure 2.7](image)

Figure 2.7. Comparison between retrieved SPM concentration (mg/l) (a) using SWIR-corrected Rrs (561 nm and 655 nm), and (b) using NIR-corrected Rrs (561 nm and 655 nm)

To validate the SWIR and NIR atmospheric correction approaches and SPM retrieval algorithm using Landsat-8 OLI data, the *in situ*-measured SPM obtained on 30 July 2014 (Rabalais, 2014) were compared with Landsat-8 OLI-retrieved SPM concentration (Table 2.7). Only SPM data pairs with a time difference of ±3 hr between *in situ* and Landsat-8 OLI were used. The retrieved SPM concentration using SWIR-corrected Rrs products (at 561 nm and 655 nm) agreed with *in situ*-measured SPM with an average percentage difference of 10.18%. Whereas, an average percentage difference of 18.26% was observed between the retrieved SPM concentration
using NIR-corrected Rrs products and \textit{in situ}-measured SPM. Results indicate that SWIR atmospheric correction algorithm is the most appropriated approach to measure SPM concentration in the study area. The observed discrepancies between Landsat-8 OLI-derived and \textit{in situ}-measured SPM were likely due to the error associated with field measurements, uncertainties related to the SPM retrieval algorithms and atmospheric correction algorithms, and the spatial differences between Landsat-8 OLI pixel location and the sampling locations.

Table 2.7. \textit{In situ} and OLI-retrieved SPM concentration (mg.l\(^{-1}\)) using SWIR and NIR corrected Rrs products on 30 July 2014. The computed percentage difference between \textit{in situ} and OLI-retrieved SPM using SWIR and NIR atmospheric correction methods.

<table>
<thead>
<tr>
<th>in situ SPM (mg.l(^{-1}))</th>
<th>OLI SPM (mg.l(^{-1})) (SWIR method)</th>
<th>OLI SPM (mg.l(^{-1})) (NIR method)</th>
<th>Percent Difference Between in situ &amp; OLI SPM (SWIR method)</th>
<th>Percent Difference Between in situ &amp; OLI SPM (NIR method)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.0</td>
<td>14.10</td>
<td>12.62</td>
<td>6.12</td>
<td>17.20</td>
</tr>
<tr>
<td>5.0</td>
<td>5.47</td>
<td>5.97</td>
<td>8.97</td>
<td>17.68</td>
</tr>
<tr>
<td>16.8</td>
<td>13.62</td>
<td>12.41</td>
<td>20.90</td>
<td>30.05</td>
</tr>
<tr>
<td>10.4</td>
<td>11.82</td>
<td>8.86</td>
<td>12.78</td>
<td>15.99</td>
</tr>
<tr>
<td>9.2</td>
<td>9.40</td>
<td>8.20</td>
<td>2.15</td>
<td>10.40</td>
</tr>
</tbody>
</table>

2.3.3 Comparison of Atmospheric Correction Approaches for MODIS-Aqua

The Rrs products at 443, 488, 555, and 678 nm from SeaDAS SWIR.NIR algorithm were compared against the SeaDAS MUMM results. Table 2.8 provides the computed 5\textsuperscript{th} and 95\textsuperscript{th} percentile, percentage difference (Equation (2.4)), the median ratio (SWIR.NIR to MUMM) and SIQR (Equation (2.3)) for Rrs products in each type of water.

\[
\frac{|MUMM-\text{SWIR,NIR}|}{MUMM+\text{SWIR,NIR}} \times 100
\]  \quad (2.4)
Table 2.8 suggests as the turbidity increased (i.e., influenced by sediment discharge from the Mississippi River), the percentage difference increased.

Table 2.8. 5th and 95th percentile for MODIS-retrieved Rrs (sr⁻¹) processed by SWIR.NIR and MUMM atmospheric correction algorithms, the percentage difference, median SWIR.NIR to MUMM ratio, and SIQR in box 1, 2 and 3 on 13 September 2013

<table>
<thead>
<tr>
<th>Band</th>
<th>Box</th>
<th>5th percentile (SWIR.NIR)</th>
<th>95th percentile (SWIR.NIR)</th>
<th>5th percentile (MUMM)</th>
<th>95th percentile (MUMM)</th>
<th>Percentage Difference</th>
<th>Median Ratio (SIQR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>443 nm</td>
<td>1</td>
<td>0.0008</td>
<td>0.0050</td>
<td>0.0031</td>
<td>0.0060</td>
<td>42.26</td>
<td>0.503 (± 0.072)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.0016</td>
<td>0.0023</td>
<td>0.0034</td>
<td>0.0055</td>
<td>38.81</td>
<td>0.443 (± 0.024)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.0013</td>
<td>0.0032</td>
<td>0.0027</td>
<td>0.0046</td>
<td>26.16</td>
<td>0.434 (± 0.058)</td>
</tr>
<tr>
<td>488 nm</td>
<td>1</td>
<td>0.0014</td>
<td>0.0074</td>
<td>0.0042</td>
<td>0.0089</td>
<td>30.02</td>
<td>0.653 (± 0.068)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.0025</td>
<td>0.0031</td>
<td>0.0040</td>
<td>0.0057</td>
<td>29.68</td>
<td>0.583 (± 0.023)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.0023</td>
<td>0.0035</td>
<td>0.0033</td>
<td>0.0048</td>
<td>27.50</td>
<td>0.568 (± 0.036)</td>
</tr>
<tr>
<td>555 nm</td>
<td>1</td>
<td>0.0049</td>
<td>0.0128</td>
<td>0.0062</td>
<td>0.0138</td>
<td>30.42</td>
<td>0.837 (± 0.034)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.0019</td>
<td>0.0054</td>
<td>0.0049</td>
<td>0.0069</td>
<td>28.38</td>
<td>0.746 (± 0.025)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.0015</td>
<td>0.0019</td>
<td>0.0023</td>
<td>0.0029</td>
<td>25.56</td>
<td>0.653 (± 0.019)</td>
</tr>
<tr>
<td>678 nm</td>
<td>1</td>
<td>0.0025</td>
<td>0.0094</td>
<td>0.0031</td>
<td>0.0099</td>
<td>34.27</td>
<td>0.823 (± 0.044)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.0034</td>
<td>0.0024</td>
<td>0.0037</td>
<td>0.0028</td>
<td>32.06</td>
<td>0.658 (± 0.049)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.0002</td>
<td>0.0003</td>
<td>0.0007</td>
<td>0.0009</td>
<td>29.52</td>
<td>0.339 (± 0.027)</td>
</tr>
</tbody>
</table>

The MODIS-Aqua SWIR.NIR- and MUMM-corrected remote sensing reflectance products were plotted against each other and color-coded based on SPM concentrations in low to high turbidity waters (Figure 2.8). The best agreement was observed between atmospherically corrected Rrs at 678 nm ($R^2 = 0.93$, slope = 0.98) followed by Rrs at 555 nm ($R^2 = 0.91$, slope = 0.99). The low $R^2$ was obtained for the shorter wavelengths at 488 nm and 443 nm (0.54 and 0.27).

Figure 2.8 (a to d) shows that the estimated Rrs resided above 1:1, which implies that the MUMM algorithm tended to estimate the higher value of Rrs than SWIR.NIR.

The observed difference could be due to the low SNR of the MODIS-Aqua SWIR bands. The comparison of atmospheric correction approaches for MODIS-Aqua indicates that SWIR.NIR algorithm estimated the lower value of Rrs than the MUMM algorithm. Figure 2.9 presents the visual comparison of the corrected remote sensing reflectance products using SWIR.NIR.
panel) and MUMM (right panel) atmospheric correction algorithms from SeaDAS in the northern Gulf of Mexico on 13 September 2013.

Figure 2.8. Scatter plots (a-d) present the comparison of the MODIS-Aqua atmospherically corrected remote sensing reflectance (Rrs) at 443, 488, 555, and 678 nm using SWIR.NIR (x-axis) and MUMM (y-axis) algorithms on 13 September 2013 image for low to high turbidity waters. The color bar indicates the SPM concentrations (mg.l$^{-1}$). The black dashed line is 1:1 and regression line is drawn in red.

Table 2.9 presents the statistical parameters for MODIS-Aqua Rrs products corrected using SWIR.NIR and MUMM atmospheric correction algorithm. The results indicate that the agreement between the Rrs products processed by SWIR.NIR and MUMM decreased as the turbidity increased. For example, at 678 nm the $R^2$ value decreased from 0.87 (in box 3; low turbid) to 0.38 (in box 1; high turbid) as the distance from the Mississippi River which supplies sediment decreased.
Figure 2.9. The atmospherically corrected Remote sensing reflectance (Rrs, sr$^{-1}$) at 443 nm, 488 nm, 555 nm and 678 nm using SWIR.NIR-SeaDAS (right panel), MUMM-SeaDAS (left panel) on 13 September 2013.

Figure 2.10 presents the MODIS-derived SPM concentration maps using corrected Rrs (555 nm and 678 nm) by SWIR.NIR (Figure 2.7a) and MUMM (Figure 2.7b) approaches on 13 September 2013.

Table 2.9. Statistics for estimated MODIS Rrs (sr$^{-1}$) products processed by SWIR.NIR and MUMM atmospheric correction algorithms in box 1, 2, 3, and all data points.

<table>
<thead>
<tr>
<th>Band</th>
<th>Box</th>
<th>BIAS (%)</th>
<th>RMSE</th>
<th>SI</th>
<th>Willmott Index</th>
<th>R$^2$</th>
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<tr>
<td>443 nm</td>
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<td>-0.161</td>
<td>0.0019</td>
<td>0.24</td>
<td>0.43</td>
<td>0.28</td>
</tr>
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<td>2</td>
<td>-0.238</td>
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<td>0.10</td>
<td>0.26</td>
<td>0.52</td>
</tr>
<tr>
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<td>3</td>
<td>-0.150</td>
<td>0.0015</td>
<td>0.08</td>
<td>0.42</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>0.190</td>
<td>0.0020</td>
<td>0.20</td>
<td>0.42</td>
<td>0.27</td>
</tr>
<tr>
<td>488 nm</td>
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<td>-0.190</td>
<td>0.0019</td>
<td>0.07</td>
<td>0.21</td>
<td>0.44</td>
</tr>
<tr>
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<td>-0.160</td>
<td>0.0018</td>
<td>0.17</td>
<td>0.70</td>
<td>0.64</td>
</tr>
<tr>
<td></td>
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<td>-0.120</td>
<td>0.0012</td>
<td>0.06</td>
<td>0.42</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>0.160</td>
<td>0.0017</td>
<td>0.16</td>
<td>0.58</td>
<td>0.54</td>
</tr>
<tr>
<td>555 nm</td>
<td>1</td>
<td>-0.089</td>
<td>0.0009</td>
<td>0.06</td>
<td>0.24</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
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<td>0.0016</td>
<td>0.09</td>
<td>0.35</td>
<td>0.48</td>
</tr>
<tr>
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<td>3</td>
<td>-0.120</td>
<td>0.0014</td>
<td>0.10</td>
<td>0.90</td>
<td>0.87</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>0.110</td>
<td>0.0013</td>
<td>0.41</td>
<td>0.92</td>
<td>0.92</td>
</tr>
<tr>
<td>678 nm</td>
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<td>-0.055</td>
<td>0.0005</td>
<td>0.07</td>
<td>0.17</td>
<td>0.38</td>
</tr>
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<td>0.47</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
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<td>-0.072</td>
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<td>0.15</td>
<td>0.94</td>
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</tr>
<tr>
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<td>0.071</td>
<td>0.0008</td>
<td>0.21</td>
<td>0.95</td>
<td>0.93</td>
</tr>
</tbody>
</table>
In general, SPM concentration values from corrected Rrs by MUMM approach were higher than SPM concentration values retrieved from SWIR.NIR-corrected Rrs. Converse to the corrected Landsat-8 OLI Rrs products, the point cloud feature dipping below 1:1 (Figure 2.4) was not observed in Figure 2.8. The lower radiometric sensitivity of MODIS may explain why this feature was not observed for MODIS-Aqua. The MODIS data from September 2013 were collected when the Mississippi River exhibited a much lower discharge (~6698.4 m³.s⁻¹ at Belle Chasse station) compared to the discharge of the Mississippi River at Belle Chasse during the Landsat-8 OLI overpass (~22115 m³.s⁻¹) in April 2016, which could have led to substantially more turbid waters, and thus brighter red reflectance.

![Figure 2.10. Comparison between MODIS-retrieved SPM concentration using corrected remote sensing reflectance products by (a) SWIR.NIR and (b) MUMM methods on 13 September 2013](image)

The maximum value of ~0.0155 sr⁻¹ was observed in high turbidity at Rrs (655 nm) retrieved from MODIS (Figure 2.8b), whereas the maximum value of Landsat-8 OLI Rrs at 655 nm on 23 April 2016 was 0.035 sr⁻¹ (Figure 2.4g). In addition, the use of high-quality SWIR bands
of Landsat-8 OLI leads to an accurate quantification of the aerosol contribution to the top of the atmosphere and Rrs products. Whereas, MODIS SWIR bands (1240 nm and 2130 nm) are quite noisy due to the low SNR, which is considered as a shortcoming of the sensor in terms of atmospheric correction approach (Wang and Shi, 2012).

### 2.3.4 Evaluation of Retrieved SPM from MODIS-Aqua

Figure 2.11 shows the match-ups between MODIS-derived SPM concentration and *in situ*-measured SPM concentration. I observed a relatively high agreement (Figure 2.13a) between MODIS-derived SPM concentration processed with SWIR.NIR atmosphere correction algorithm ($R^2 = 0.79$, bias=0.63), while retrieved SPM concentration processed with MIMM algorithm suggest a lower agreement (Figure 2.11b) with field data ($R^2 = 0.76$, bias = 1.23), see Table 2.1 and Figure 2.1 for data points used in the comparison. To perform the match-up comparison, the time difference of ±3 hr between *in situ*-measured SPM and MODIS-Aqua overpasses was constrained.

![Figure 2.11. Comparison of *in situ*-measured SPM concentration (mg/l) with MODIS Aqua-retrieved SPM concentration processed using (a) SWIR.NIR and (b) MUMM](image)

The performance of each atmospheric correction algorithms in retrieving SPM was assessed using bias, root mean square error (RMSE), scatter index (SI), and the coefficient of determination ($R^2$) (Table 2.10). The comparison between *in situ* SPM and MODIS-derived SPM
suggest that the SWIR.NIR atmosphere correction algorithm is the most appropriate algorithm in
the study area (Figure 2.11 and Table 2.10).

Table 2.10. Statistics for SPM concentration obtained from MODIS-Aqua Rrs products
corrected by SWIR.NIR and MUMM atmospheric correction methods.

<table>
<thead>
<tr>
<th>Product</th>
<th>BIAS</th>
<th>RMSE</th>
<th>SI</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPM from SWIR.NIR-corrected Rrs</td>
<td>0.63</td>
<td>1.91</td>
<td>0.27</td>
<td>0.78</td>
</tr>
<tr>
<td>SPM from MUMM-corrected Rrs</td>
<td>1.23</td>
<td>2.27</td>
<td>1.23</td>
<td>0.76</td>
</tr>
</tbody>
</table>

The observed disagreement between MODIS-derived and *in situ*-measured SPM is attributable
to the low spatial resolution (1 km) of MODIS, low SNR values of MODIS-Aqua SWIR bands. In
addition, errors associated with the atmospheric correction processes and SPM retrieval algorithm
would exacerbate the disagreement between satellite-derived and field SPM concentration.

2.4 Summary and Conclusion

To monitor SPM dynamics using satellite data in Louisiana coastal and shelf waters,
appropriate atmospheric correction algorithms and robust SPM retrieval algorithms are required.
The performance of the four atmospheric correction algorithms was evaluated: the SWIR and NIR
atmospheric correction algorithms for Landsat-8 OLI and the MUMM along with the SWIR.NIR
correction for MODIS-Aqua. Results suggest that the NIR algorithm retrieved lower values of Rrs
products from Landsat-8 OLI in high turbidity waters.

The SPM retrieval algorithm was applied to the corrected Rrs products from Landsat-8
OLI and MODIS-Aqua to estimate SPM concentration. The Landsat-8 OLI Rrs products corrected
atmospherically by the SWIR algorithm, retrieved more accurate SPM concentration in the study
area. In addition, a good agreement was found between MODIS-derived SPM processed with
SWIR.NIR algorithm and field data. However, more *in situ* SPM data are needed to stress the
robustness of these algorithms in the study area. The observed imperfections between satellite-
derived and *in situ*-measured SPM concentration could be due to several factors related to the
satellite’s characteristics and errors and assumptions in the SPM retrieval algorithm used in this study.

Results underline the necessity of in situ measurements of Rrs products and SPM data to validate SPM retrieval algorithms. In addition, it is highly recommended to perform the sensitivity analysis to examine how the variability in $\alpha$ influences the results. Furthermore, my findings highlight that multi-conditional SPM retrieval algorithms based on turbidity level must be considered in the study region. Use of multi-conditional SPM retrieval algorithms switching from red-NIR algorithms to visible band ratio algorithms would improve the accuracy of retrieved SPM. Hence, hyperspectral reflectance measurements must be carried out over low- to high turbidity waters. Results of SPM concentration derived from satellites were used to initialize and validate sediment transport (Chapter 3 and 4).
CHAPTER 3: A SKILL-ASSESSED SWAN MODEL FOR WAVE GENERATION AND PROPAGATION OVER THE LOUISIANA SHELF WITH A FOCUS ON SANDY POINT DREDGE PIT

3.1 Introduction

Waves are the primary cause of sediment resuspension in coastal water and estuaries. Hence, it is imperative to understand in detail wave generation and propagation. Generation and propagation of gravity waves are one of the most immediate effects of atmospheric forcing in the oceans, seas, and other water bodies.

Waves are primarily generated by wind shear interacting with the water surface. Waves can travel a long distance without wind forcing in the form of swells. Determination of accurate wave characteristics with appropriate spatial and temporal resolution is of great importance in different applications in offshore and coastal engineering. Wave parameters including height, period, and frequency spectra are directly used for designing offshore and coastal structures.

Wave parameters are also a critical component of hydrodynamics modeling in the coastal areas with the final implication on mixing and transport in coastal waters. Determination of waves is a key to sediment transport modeling. Although currents contribute to producing bed shear stress in addition to their role in sediment advection, the role of waves in increasing bed shear stress and sediment re-suspension depends on the water depth and wavelength (Allahdadi et al., 2011).

A high accuracy wave field can significantly increase the performance of sediment transport models in simulating sediment reworking from the bed and inside the bottom boundary layer which is a fundamental step in a successful sediment transport modeling. Louisiana inner shelf in the northern Gulf of Mexico is an example of a relatively shallow region where waves significantly contribute to sediment re-suspension and transport (Allahdadi et al., 2011; Xu et al.,
Northern Gulf of Mexico is occasionally affected by passing hurricanes and tropical storms. The waves generated by hurricanes in the Gulf of Mexico are well studied, especially using numerical models (Siadatmousavi et al., 2009; Siadatmousavi et al., 2010; Dietrich et al., 2011; Atkinson et al., 2007; Bunya et al., 2010, Kim et al., 2008; Wang and Oey., 2008).

There are different dominant meteorological conditions in the region throughout the year. From mid-September to mid-May, Louisiana shelf is highly affected by cold fronts after which there are strong winds from general northerly directions (Mossa and Roberts, 1990; Walker and Hammack, 2000; Feng and Li, 2010; Li et al., 2011; Li et al., 2017,2018). Cold fronts occur with a frequency of 3-10 days and last for 2-4 days induration. Due to the direction and severity of the associated winds, relatively large non-hurricane waves over the Louisiana shelf are expected during cold fronts, while non-significant swell waves can be expected from outside of the shelf (from the southern quadrant). Easterly to southwesterly winds are dominant during the pre-frontal periods. Summer is characterized by southeasterly to southerly winds with a significant decline in wind energy (Allahdadi et al., 2013) when in general wave heights are smaller over the shelf compared to non-summertime. However, shelf area can be significantly affected by swell waves from the southeast to southwest. Field observations and numerical models have been used to address cold front-generated waves over the Louisiana shelf (Keen, 2002; Kobashi et al., 2007; Jose et al., 2007; Siadatmousavi et al., 2011; Siadatmousavi et al., 2012; Siadatmousavi and Jose, 2015). Kobashi et al. (2007) analyzed measured wave data over Ship Shoal in the western Louisiana shelf during and after a cold front in spring 2006. By examining the 2-D wave spectra, they found out that during the pre-frontal phase, low-frequency waves dominate the spectrum, while as the wind veered to the north, higher frequency waves occurred. This shift from low frequency to high frequency in the wave spectrum was also reported by Siadatmousavi and Jose.
Siadatmousavi et al. (2012) obtained wave data from extensive fieldwork over the Tiger and Trinity Shoal off the Atchafalaya Bay in the western Louisiana shelf implemented for studying sediment transport and morphological changes. They suggested that during the cold front, local waves responded quickly to changes in wind speed and direction and within a few hours after wind direction veered to the north wave height significantly increased. Combination of pre-frontal low-frequency wave energy and frontal high-frequency energies resulted in bimodal frequency spectra with significant energy levels for both sea and swell waves.

A few modeling studies of cold-front generated waves over the northern Gulf of Mexico demonstrated the effectiveness of numerical models in the generation of waves during cold fronts over the Louisiana shelf (Siadatmousavi et al., 2011; Siadatmousavi et al., 2012; Jose et al., 2007; Jose and Stone, 2009). Siadatmousavi et al. (2011) implemented a Gulf-wide model including the Louisiana shelf using unstructured SWAN to evaluate two different wind inputs and whitecapping formulation suggested by WAM Group including WAM-3 and WAM-4 approaches. They used several buoys in the Gulf of Mexico including two stations over the Louisiana shelf to evaluate model results in March 2007. They concluded that using wind input formulation of WAM-4, in combination with the whitecapping dissipation of WAM-3, may improve simulation results. However, there is a lack of detailed examination of the model physics, model performance for the Louisiana shelf region, and wave spectra during cold fronts and other times. The main purpose of this study was to develop a skill-assessed wave model for the Louisiana shelf during non-hurricane conditions (i.e., relatively high energy cold front season and the relatively low energy condition in summer) and examining wave fields during different meteorological conditions. The final implication of this evaluated model will be studying sediment transport over Sandy Point dredge pit; on the west of the Mississippi bird-foot delta. In this Chapter, the performance of two different
classes of formulations for quantifying whitecapping dissipation incorporated in the spectral wave model was evaluated. Whitcapping formulations included Komen (1984) which is based on the mean spectral parameters and Van der Westhuysen (2007) that estimates whitecapping dissipation based on the saturation concept of the wave groups. The main purpose of this Chapter was to determine the most appropriate approach for wave simulation in this region regarding its wind and wave climate. During the target simulation periods (cold front outbreak and summertime fair-weather) both conditions of wind-wave only or seas and swell combination may exist.

3.2 Study Area

The study area is on Louisiana shelf in the northern Gulf of Mexico with a focus on Sandy Point dredge pit (Figure 3.1). Location of NDBC stations 42040 and LOPL1, as well as WAVCIS station CSI-6 used for evaluation of model results, are shown in Figure 3.1 as well as locations of three points for the investigation of simulated wave spectra in the Sandy Point dredge pit (P1, P2, and P3) are marked.

Figure 3.1. Study area (A) location of wave buoys on the Louisiana shelf used for model evaluation, and (B) locations of selected points in the Sandy Point dredge pit for studying spectral patterns
3.3 Model Specifications

3.3.1 Numerical Model

Wave generation and propagation over the Louisiana shelf was modeled using Simulation WAve Nearshore (SWAN) model which has been incorporated in the Delft3D package as WAVE module (Deltares, 2012b; SWAN user manual, 2015). The Delft3D WAVE module can be coupled with Delft3D FLOW module. SWAN is a 3rd generation spectral phases averaged model that solves the equation of conservation of wave action energy density:

\[
\frac{\partial \hat{N}}{\partial t} + \frac{\partial}{\partial \phi} (c_\phi \hat{N}) + \frac{\partial}{\partial \lambda} (c_\lambda \hat{N}) + \frac{\partial}{\partial \sigma} (c_\sigma \hat{N}) + \frac{\partial}{\partial \theta} (c_\theta \hat{N}) = \frac{S_{tot}}{\sigma}
\]  

(3.1)

\[\hat{N} = NR^2 \cos \phi\]  

(3.2)

\[N = \frac{E}{\sigma}\]  

(3.3)

where \(E\) is wave energy that varies with relative angular frequency and propagation direction, \(\hat{N}\) is wave action density, \(\phi\) and \(\lambda\) denote longitude and latitude, respectively, \(c_\phi, c_\lambda, c_\sigma, c_\theta\) represent wave group velocity in the direction of longitude, latitude, in the frequency space, and in directional space, respectively; \(R\) is the radius of the earth; \(S_{tot}\) is the sum of all source terms accounting for generation or dissipation of wave energy; \(\sigma\) is relative wave radian frequency (with no current), and \(t\) is time. The source term \(S_{tot}\) on the right hand side of Equation (3.1) is the sum of several terms representing different parameters in deep or shallow water:

\[S_{tot} = S_{in} + S_{nl3} + S_{nl4} + S_{ds,w} + S_{ds,b} + S_{ds,br}\]  

(3.4)

In the above equation \(S_{in}\) is wave growth by the wind, and \(S_{nl3}\) and \(S_{nl4}\) are nonlinear transfer of wave energy through three-wave and four-wave interactions respectively. Dissipation terms include \(S_{ds,w}, S_{ds,b}\) and \(S_{ds,br}\) that represent wave decay due to whitecapping, bottom friction, and depth-induced wave breaking, respectively.
The wave growth by wind, four-wave interaction, and whitecapping dissipation are active over the modeling area regardless of water depth, but the three-wave interaction (triad), bottom friction, and depth-induced wave breaking are specific effective only in shallow to very shallow areas.

3.2 Wind Input and Whitecapping Formulations

Two mechanisms including linear and exponential waves are considered in SWAN for simulating wave growth by wind input energy:

\[ S_{in}(\sigma, \theta) = A + BE(\sigma, \theta) \quad (3.5) \]

In the above equation, \( A \) represents the linear wave growth by wind, while the second term which is the product of coefficient \( B \) and spectral energy \( E(\sigma, \theta) \), accounts for the exponential growth. \( A \) and \( B \) are functions of wind shear stress, wave phase velocity, and the ratio of air to water densities. Using linear wave growth in SWAN is optional and is estimated based on Cavaleri and Malanotte-Rizzoli (1981). Selecting the exponential wave growth formulation depends on the whitecapping approach used in the simulations and can be selected based on Komen et al. (1984), Janssen (1991), or Yan (1987). Two classes of whitecapping formulations are included in SWAN: traditional formulations based on the mean wave steepness over the wave spectra and a newer approach based on the local wave steepness that is able to include the effect of swell waves on wave growth and dissipation separately. The formulation proposed by Komen et al. (1984) is the main whitecapping approach based on the mean wave steepness that is incorporated in SWAN:

\[ S_{ds,w}(\sigma, \theta) = -\Gamma \bar{\sigma} \frac{k}{\bar{k}} E(\sigma, \theta) \quad (3.6) \]

\[ \Gamma = C_{ds} \left( (1 - \delta) + \delta \frac{k}{\bar{k}} \right) \left( \frac{\epsilon}{\bar{S}_{PM}} \right)^p \quad (3.7) \]

\[ \bar{S}_{PM} = (3.02 \times 10^{-3})^{1/2} \quad (3.8) \]

\[ \bar{S} = \bar{k} \sqrt{E_{tot}} \quad (3.9) \]
In the above equations, $S_{ds,w}(\sigma, \theta)$ is the rate of energy dissipation by whitecapping, $\bar{\sigma}$ is the average of wave frequency over the spectra, $k$ is wave number for the specific spectral component for which calculations are performed, $\bar{k}$ is the average of wave number over the spectra, $E(\sigma, \theta)$ is the energy spectral component corresponding to frequency of $\sigma$ and direction of $\theta$, $C_{ds}$ is the white capping coefficient, $\delta$ is a parameter for adjusting wave period that varies between 0 and 1, $\bar{S}$ is the mean spectral steepness, $\bar{S}_{PM}$ the spectral steepness corresponding to the Pierson-Moskowitz spectrum, and $E_{tot}$ is the total energy of the wave spectrum. The whitecapping formulation by van der Westhuysen et al. (2007) considers the interaction of shore waves generated by wind with longer swell waves by representing the dissipation based on the local wave number and wave steepness. This formulation considers separate relationships for dissipation of each wind waves and swells and combines them using a smoothed transition function ($f_{br}(\sigma)$):

$$S_{ds,w}(\sigma, \theta) = f_{br}(\sigma)S_{ds,break} + [1 - f_{br}(\sigma)]S_{ds,non-break}$$

(3.10)

where $S_{ds,w}(\sigma, \theta)$ represents the total dissipation due to whitecapping, $S_{ds,break}$ denotes dissipation of breaking waves (wind-waves), and $S_{ds,non-break}$ is the dissipation term for non-breaking waves (swell waves).

3.4 Input Data

3.4.1 Modeling Area and Bathymetry Data

A rectangular modeling area that covers the entire region included in the hydrodynamics/sediment transport model (see Chapter 4) was considered for simulation of wave generation, and propagation over the Louisiana shelf and Sandy Point dredge pit. Model extends from longitudes of -90°W to -88°W, and from latitudes of 28°N to 31°N. The overall spatial resolution of this finite difference grid is 2 km with a finer resolution of 50 m over the Sandy Point dredge pit (Figure 3.2A). Bathymetry data obtained from different sources were used to interpolate
water depths over the computational grid (Figure 3.2B). Two sets of bathymetric data were used. The overall depth information over the eastern and western Louisiana shelves, as well as deepwater areas, were obtained from National Geophysical Data Center’s (NGDC) Coastal Relief Model (CRM) with a spatial resolution of 3 arc-sec (~90 m) (National Geophysical Data Center, 1999). In addition, a local bathymetric data (Obelcz, 2017) along with bathymetric data measured by Acoustic Doppler Current Profiler (ADCP) (WAVCIS Lab, LSU; Dr. Chunyan Li) at Sandy Point dredge pit obtained during a survey in July 2015 was incorporated into the dataset mentioned above.

Figure 3.2. (A) Model grid used for the SWAN wave modeling, and (B) depth map used for preparing bathymetry data
3.4.2 Wind Forcing

Time series of wind speed and direction were obtained from measurements at the BURL1 station located at the Mississippi River Southwest pass (see Figure 3.1 for location). At this station, the wind is measured at an elevation of 38 m above sea level. The measured wind speed was converted to wind speed at 10 m elevation using the standard power law (Kamphuis, 2000):

\[ U_{10} = U_z \left( \frac{10}{z} \right)^{1/7} \]  

(3.11)

where \( U_{10} \) and \( U_z \) are wind speed at elevation 10 m and \( z \), respectively. Using the spatially uniform wind for simulation of currents and wave over the Louisiana shelf have been examined by several studies and found out to be an appropriate choice (Wang and Justic, 2009; Xu et al., 2011).

Three time periods: (1) summer 2015 (from 5 July to 22 August, period 1 hereafter), (2) November 2014 (from 15 November to 21 November, period 2 hereafter), and (3) March 2012 (from 1 March to 31 March, period 3 hereafter) were selected for the simulations (Table 3.1). Timeseries of wind vector variations are shown in Figure 3.3. In addition, the wind roses associated with each period are shown in Figure 3.4.

| Table 3.1. Selected time periods for wave simulation over the Louisiana shelf. |
|--------------------------|--------------------------|--------------------------|
| Time period | Start | End |
| 1 | 05/07/2015 00:00:00 UTC | 22/08/2015 23:00:00 UTC |
| 2 | 15/11/2014 00:00:00 UTC | 21/11/2014 00:00:00 UTC |
| 3 | 01/03/2012 00:00:00 UTC | 31/03/2012 23:00:00 UTC |

During period 1, the typical summertime wind pattern of the Louisiana shelf with southerly to southwesterly winds was dominant (Allahdadi et al., 2013), although occasionally winds shifted to the northerly or southeasterly direction. In period 2 in November 2014, there were cold fronts affecting the study region every 3-7 days.
Figure 3.3. Timeseries of wind vector for simulation periods in (A) summer 2015, (B) November 2014 (the red box shows selected simulation period during November 2014), and (C) March 2012
Figure 3.4. Wind roses from the Pilot station for (A) November 2015, (B) July-August 2015

3.4.3 Boundary Conditions

Boundary conditions along the model open boundaries were obtained from the Gulf of Mexico and the Northwest Atlantic (see Figure 3.5 for database geographical extent) 30-year hindcast by NOAA.

Figure 3.5. Geographical extent of WWIII hindcast database for the Gulf of Mexico and NW Atlantic (from http://polar.ncep.noaa.gov/waves/hindcasts/nopp-phase2.php)
The database was prepared by long-term simulation of waves using WAVEWATCH-III (WWIII) (Tolman, 1999) forced by hourly winds from the NCEP Climate Forecast System Reanalysis and Reforecast (CFSRR). The spatial resolution of the model is 1/6 degree, and the temporal resolution is three hours. Model uses the Cavalieri and Malanotte-Rizzoli (1981) formulation for wind input characterization, discrete interaction approximation for resolving the nonlinear wave interaction term, JONSWAP bottom friction formulation for bottom friction, Batjes-Jansen formulation for depth-induced wave breaking, and the ST4 physics package for including exponential wave evolution and whitecapping. This package includes the flux computation in the source term that can appropriately resolve whitecapping dissipation by both wind waves and swell waves (Ardhuin et al., 2010). Wave height, wave direction, and peal period with a time resolution of 3 hours were extracted along the model three open boundaries. Timeseries of wave parameter from WWIII database used as the model boundary condition along the southern open boundary are shown in Figures 3.6 and 3.7. For the simulation period 1, wave height was always less than 1 m with an average of 0.5 m which was the result of a substantial decline in wind stress over the inner and outer Louisiana shelf during summertime (Allahdadi et al., 2013). Regardless of small wave heights, peak periods were relatively long with a maximum longer than 10 sec and average of 4.5 sec which implied that some swell waves propagation toward the inner Louisiana shelf. Dominant wave direction during this period was south to the west (180-270 degree), typical during this time of the year (Figure 3.6). Severe northerly winds associated with cold fronts during period 2 in November 2014, was associated with larger wave heights (~ 2.5 m and with an average of 1.3 m) compared to period 1. Wave direction variation was relatively intermittent changing from northerly to southeasterly corresponding to the pre-frontal, frontal, and post-frontal phases of cold fronts with four cold fronts occurred during this period (Figure 3.7).
Figure 3.6. Timeseries of wave parameters: wave height (top panel), peak period (middle panel), and wave direction (bottom panel) from the WWIII hindcast in the middle of model southern boundary during period 1.

Figure 3.7. Timeseries of wave parameters: wave height (top panel), peak period (middle panel), and wave direction (bottom panel) from the WWIII hindcast in the middle of model southern boundary during period 2.
3.5 Model Setup

Different methods and data sources were used to find appropriate modeling parameters for model setup. Since the non-stationary mode was used for the present simulation, the computational time step was one of the key parameters. According to the recommendations of the users’ manual of SWAN and Delft3D and sensitivity tests, the time step of 10 min was selected. Furthermore, spectral characteristics including number of frequency and directional bands, minimum frequency, and maximum frequency were obtained based on the tested values in the literature (Allahdadi et al., 2017; Yang et al., 2017). The rest of the parameters for resolving different source terms were selected based on the default values from SWAN documentation. For whitecapping dissipation and wind input, both approaches presented by Komen (1984) (Komen hereafter) and van der Westhuysen et al. (2007) (Westhuysen hereafter) were examined to determine the most appropriate one for the study area. Table 3.2 summarizes model setup for the present simulations.

3.6 Model Validation

Model was run based on the data and setup described in the previous sections for the three periods (Section 3.4.2; Table 3.1). Selecting the most appropriate formulation for whitecapping dissipation is a crucial step in finalizing model setup regarding the significant potential impact on wave generation and dissipation during different wave events (Yang et al., 2017). For the present simulation examining different whitecapping formulation could be relevant due to different wave climates of the Louisiana shelf during summer, fall, and spring.

In the study area, local wind effects are dominant during the non-summer months, while swell waves are dominant during summer. Model simulations were performed for each of the three modeling time periods (Table 3.1) based on whitecapping dissipation approaches presented by Komen and Westhuysen. For each period, model results for wave height and wave period (for
available data) were compared with observations at the location of NDBC and WAVCIS buoys (see Figure 3.1 for locations).

### Table 3.2. Summary of model setup parameters

<table>
<thead>
<tr>
<th>Model Parameters</th>
<th>Value</th>
<th>symbol</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time step (non-stationary mode)</td>
<td>10 min</td>
<td>$\Delta t$</td>
<td>sensitivity analysis</td>
</tr>
<tr>
<td>Number of directions</td>
<td>36</td>
<td>Ndir</td>
<td>Literature</td>
</tr>
<tr>
<td>Number of frequency bins</td>
<td>24</td>
<td>Nf</td>
<td>Literature</td>
</tr>
<tr>
<td>Lowest frequency</td>
<td>0.05</td>
<td>N/A</td>
<td>Literature</td>
</tr>
<tr>
<td>Highest frequency</td>
<td>1</td>
<td>N/A</td>
<td>Literature</td>
</tr>
<tr>
<td>Dissipation Coefficient</td>
<td>1</td>
<td>$\alpha$</td>
<td>Battjes and Janssen (1978)</td>
</tr>
<tr>
<td>Breaker Parameter</td>
<td>0.73</td>
<td>$\gamma$</td>
<td>Battjes and Janssen (1978)</td>
</tr>
<tr>
<td>Bottom Friction Coefficient (JONSWAP)</td>
<td>0.067</td>
<td>C</td>
<td>Hasselmann, et al. (1973)</td>
</tr>
<tr>
<td>Whitecapping</td>
<td>N/A</td>
<td>N/A</td>
<td>Komen et al. (1984) and van der Westhuysen et al. (2007)</td>
</tr>
</tbody>
</table>

Four standard metrics including Pearson Correlation Coefficient ($R$), bias, root mean square error (RMSE) and scatter index (SI) were employed to quantify model performance (Tehrani et al., 2013; Yang et al., 2017):

\[
R = \frac{\sum_{i=1}^{N} (M_i - \bar{M})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{N} (M_i - \bar{M})^2 (\sum_{i=1}^{N} (P_i - \bar{P})^2)}} \tag{3.12}
\]

\[
\text{bias}(P) = \frac{\sum_{i=1}^{N} (P_i - M_i)}{N} \tag{3.13}
\]

\[
\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N} (P_i - M_i)^2}{N}} \tag{3.14}
\]
\[ SI = \frac{\text{RMSE}}{\bar{M}} \] (3.15)

where \( P_i \) represents model prediction at a specific time step \( i \), \( M_i \) is the corresponding buoy measurement, \( \bar{P} \) is the average of model predictions, \( \bar{M} \) is the average of measurements, and \( N \) is the number of data points. Simulation for period 1 included summer months, from 15 July to 22 August 2015. Summertime in the northern Gulf of Mexico is characterized by the significant decline in wind stress (Allahdadi et al., 2013) that means less local wave energy and more swells over the shelf. Simulation results for wave height during this time period were compared with observations at two stations, 42040 and LOPL1 (at these two locations only wave height measurements were available). Buoy data at both locations showed that wave height during July and August of 2015 was always smaller than 1.5 m. Simulation results using both the Komen and the Westhuysen whitecapping approaches were included (Figure 3.8).

Figure 3.8. Timeseries comparisons of simulated wave heights based on different whitecapping formulas with observations at stations NDBC 42040 and LOPL1 during July-August 2015
For both whitecapping approaches, simulation results generally agreed with observations at two buoy locations. Model performance in simulating wave height was evaluated using the metrics mentioned in Equations 3.12-3.15. Scatter plots of modeled and observed wave heights for both whitecapping formula along with the calculated metrics are presented in Figure 3.9. Station 42040 is located on the east of the bird-foot delta and 63 km south of Dauphin Island, AL where water depth is 183 m. At this location, both whitecapping approaches produced satisfactory wave heights with acceptable error (Yang et al., 2017).

Figure 3.9. Scatter plots of simulated wave heights versus buoy measurements during July-August 2015 at NDBC 42040 (upper panels) and station LOPL1 (lower panels). The left side panels show verification for the Komen approach, and the right side panels show model results for the Westhuysen approach. The red line is 1:1 and regression line is drawn in black.
Results with the Westhuysen whitecapping approach were slightly more accurate than that of the Komen whitecapping approach. This could be due to the location of NDBC 42040 being on the outer shelf that is more exposed to the swell waves and also because the Westhuysen approach simulates the swell dominant wave field more accurately (van der Westhuysen et al., 2007). Station LOPL1 is located on the inner Louisiana shelf at about 60 km southeast of the Sandy Point dredge pit. At this location higher model performance metrics were resulted compared to NDBC 42040. Model simulation based on the Komen whitecapping approach resulted in higher accuracies compared to the Westhuysen whitecapping approach. The difference between the computed Pearson correlation coefficient, and bias obtained from these approaches at this station were relatively significant. The better performance of the Komen approach at this location was the result of less swell interference over the inner shelf. In general, the relatively poor accuracy of model results using both the Komen and the Westhuysen whitecapping approaches for this period could be likely due to low accuracy of WWIII model outputs that provided the boundary condition data for the present modeling. Significant biases have been observed from this model especially for the peak wave period values. This discrepancy in the simulation of offshore wave characteristics was especially crucial for simulation period 1 regarding the specific direction of prevailing winds and substantial impact of swell waves on the Louisiana shelf. The main atmospheric feature during the simulation period 2 in November 2014 was a cold front passage, which is characterized by the three different phases including pre-frontal, frontal, and post-frontal (Mossa and Roberts, 1990). While during the pre-frontal phase, southeasterly winds are dominant, winds with the general direction of northerly are prevailing during the post-frontal phase. After the cold front is dissipated, wind directions rotate clockwise to easterly and to southeasterly. Regarding the dominant northerly direction of the wind during this time the minimum effect of the
swell waves from the outer shelf is expected over the Louisianan shelf (see Figure 3.7). The
timeseries comparisons of simulated wave heights during this period with observations at NDBC
42040 and LOPL1 suggested that model simulations, using the Komen whitecapping approach,
were in a good agreement with observations (Figure 3.10), while model results using the
Westhuysen approach, significantly underestimated the wave height, especially at station LOPL1
which is closer to the main study area at Sandy Point dredge pit.

Figure 3.10. Timeseries comparisons of simulated wave heights based on different whitecapping
formulas with observations at stations NDBC 42040 and LOPL1 during November 2015

The observed peak of wave height at LOPL1 during the cold front is 2.1 m, comparing to
2 m by the Komen and 1.4 m by the Westhuysen whitecapping approach. Even during the low
energy phase after 11/20/2014 that wind direction changed to easterly-southeasterly, model results
with Komen were more consistent with observations. At station 42040 the trend was more or less similar to LOPL1. The Westhuysen approach worked better at station 42040 compared to LOPL1. Scatter plots of simulated wave height versus observations at two stations, and for both Komen and Westhuysen whitecapping approaches illustrated the same conclusions (Figure 3.11).

![Scatter plots of simulated wave heights versus buoy measurements during November 2014 at NDBC 42040 (upper panels) and station LOPL1 (lower panels). The left side panels show verification for the KOMEN approach, and the right side panels show model results for the Westhuysen approach. The red line is 1:1 and regression line is drawn in black](image)

At station 42040 statistics for the simulation using the Westhuysen whitecapping approach showed better performance, although the overall error metric (bias) was smaller for the simulation using the Komen whitecapping approach. At LOPL1, model results with the Komen approach
resulted in smaller values of bias, RMSE, and SI and larger value of correlation coefficient, which indicated that the Komen whitecapping approach was significantly more accurate than the Westhuysen approach. Modeling results for wave height during the simulation periods 1 and 2 revealed that the Komen formulation for whitewcapping resulted in higher accuracies. To examine this conclusion for an independent time period, model was run for March 2012, period 3 (Figure 3.12).

![Figure 3.12](image)

The simulation time from 1 to 31 March 2012 included strong southeasterly winds with speeds up to 13 ms\(^{-1}\) and several periods of cold front outbreak including two events between 18 and 25 March. Wave simulation results for this period demonstrated the high accuracy of the Komen whitewcapping approach for resolving wave dissipation. Two stations on the Louisiana shelf including WAVCIS CSI-6 (water depth of 20 m) and LOPL1 were used to evaluate modeling results. Observations from CSI-6 included mean wave period in addition to the significant wave
height. Therefore, simulated wave period was evaluated as well. The timeseries comparisons of simulated wave heights with observation showed a very good agreement between model and measurements at both stations. For example, at station LOPL1 two peaks in wave heights were observed; one between 3/4/2012 and 3/11/2012 which was 2.5 m and the other one was about 2.9 m occurred between 3/18/2012 and 3/25/2012. Model simulation computed the values of 2.6 m and 3 m for these two peaks. Scatter plots and error metrics also showed high accuracies (Figure 3.13). At both stations, high correlation coefficients and small values of bias, RMSE, and SI were obtained which are consistent with Yang et al. (2017).

![Scatter plots of simulated wave heights using KOMEN whitecapping versus buoy measurements during March 2012 at WAVCIS station CSI-6 (left) and station LOPL1 (right). The red line is 1:1 and regression line is drawn in black.](image)

**Figure 3.13.** Scatter plots of simulated wave heights using KOMEN whitecapping versus buoy measurements during March 2012 at WAVCIS station CSI-6 (left) and station LOPL1 (right). The red line is 1:1 and regression line is drawn in black.

Simulated mean wave period at CSI-6 was also compared with observations (Figure 3.14A and 3.14B). While the wave period showed a good agreement with observations during most of the simulation period (Figure 3.14A), some discrepancies significantly affect the error metrics presented in Figure 3.14B. An examination shows that these events of inaccuracies were corresponding to the time that winds are from the southern sector (i.e., outer shelf swells affect the wave pattern over the shelf). Since the effect of swell waves was considered by applying WWIII
data along the model open boundaries, low accuracy of wave period obtained from WWIII affected the accuracy of simulated wave period over the shelf.

Figure 3.14. (A) timeseries comparison of simulated mean wave period versus observed wave period at CSI-6, (B) scatter plot and error metrics corresponding to the comparison. The red line is 1:1 and regression line is drawn in black

3.7 Simulation Results and Discussion

The wave model evaluation presented in the previous section indicated that both Komen and Westhuysen formula for resolving whitecapping dissipation resulted in acceptable wave heights. However, simulation accuracy using Komen, especially during the cold fronts was significantly higher. In this section model results on the Louisiana shelf were further examined and compared. For the simulation period 1 in July-August 2015, two timesteps were selected. Timestep 1 was corresponding to 8 July 2015 at 9:00 UTC when southerly to southeasterly winds were dominant and swell waves from the outer continental shelf were affecting the inner shelf, and
timestep 2 was corresponding to 3 August at 2015 at 9:00 UTC when southwesterly winds were prevailing. The wave height, mean wave period, and wave direction vectors for this time step regarding both Komen and Westhuysen whitecapping approaches are presented in Figure 3.15.

Figure 3.15. Simulation results for wave height, wave period, and wave vectors at selected timestep 1 (8 July 2015, 9:00 UTC) using (A, C, and E) Komen and (B, D, and F) Westhuysen whitecapping approach. Location of the Sandy Point dredge pit on the Louisiana shelf is marked with a dark circle
Spatial variations of wave heights resulted from the Komen and the Westhuysen whitecapping approaches are very similar (Figure 3.15A and 3.15B). However, over the Louisiana shelf, the Komen approach resulted in slightly larger wave heights which were consistent with the conclusion presented in Section 3.6. While wave height over the offshore regions of Louisiana shelf was about 0.8-0.9 m, wave height decreased to about 0.5 m at Sandy Point dredge pit. This decrease could be due to the partial sheltering effect of the southwest pass handle of the Mississippi delta against southeasterly swells and wind waves and wave refraction effect in the coastal areas. Like wave height, variations of mean wave periods over the modeling area (Figure 3.15C and 3.15D) were very similar for model results based on the Komen and the Westhuysen approach with slightly larger wave periods simulated by Komen over the Louisiana shelf. The wave directions (Figure 3.15E and 3.15F) were almost identical from both simulations and complied with the general southeasterly direction of swells and wind. In the vicinity of Sandy Point dredge pit and the surrounding coastal areas along the west flank of the Mississippi Delta, the wave directions changed to southerly as a result of wave refraction over shallower areas. Differences in simulated wave height and period between two modeling scenarios were more pronounced during selected timestep 2 with prevailing wind direction from the southwest (Figure 3.16A and 3.16B).

At this time, wave height offshore of the Barataria Bay was 1.2 m from the Komen approach, while the Westhuysen approach resulted in a wave height of 1 m at this location (Figure 3.16A and 3.16B). At Sandy Point dredge pit, the Komen and the Westhuysen approaches resulted in wave heights of 1 m and 0.8 m, respectively. The greater differences in wave height between the two scenarios at this time compared to timestep 1 could be due to an underestimated trend of the wave energy during the dominant wind wave events by the Westhuysen approach.
Figure 3.16. Simulation results for wave height, wave period, and wave vectors at selected timestep 2 (3 August 2015, 9:00 UTC) using (A, C, and E) Komen and (B, D, and F) Westhuysen whitecapping approach. Location of the Sandy Point dredge pit on the Louisiana shelf is marked with a dark circle.
This was illustrated during the simulation for a cold front in Section 3.6 and has also been reported by Mulligan et al. (2008). Similar overestimations by comparison to the Westhuysen approach was observed in the shelf-wide maps of mean wave period at this time (Figures 16E and 16F). At this time mean the wave period simulated by the Komen and the Westhuysen approaches were 4.5 and 3.5 seconds, respectively. In contrary to timestep 1, at timestep 2 almost no refraction-induced changes in the wave direction were observed at the location of Sandy Point dredge pit (Figures 3.16E and 3.16F). Zoomed-in views of the simulated wave heights and direction over the Sandy Pit at selected timesteps 1 and 2 and for both simulation scenarios are shown in Figure 3.17. In Figure 3.17 simulated larger wave heights by the Komen approach compared to the Westhuysen approach were conspicuous.

Figure 3.17. Close view of simulated wave height and wave vector over the Sandy Point for selected timesteps 1 (8 July 2015) using: (A) Komen and (B) Westhuysen, and for selected timestep 2 (3 August 2015) using: (C) Komen and (D) Westhuysen
As discussed for Figure 3.15, the southeasterly wave direction of the outer shelf region at timestep 1 turned to southerly over the pit as a result of the refraction over the shallower coastal/shelf areas. The refraction induced by the depth difference at the northern tip of the pit caused slightly smaller wave heights in this area compared to the southern pit area. Wave height difference between Komen and Westhuysen was more pronounced for timestep 2 as illustrated in Figure 3.16 for the entire shelf area.

Samples of model outputs during the simulation period 2 which was corresponding to a cold front outbreak are presented in Figure 3.18. Results were plotted for 17 November 2014 at 15:00 UTC when a severe wind with speed of 13 ms\(^{-1}\) from the northwest was recorded at the BURL1 station. This time was almost corresponding to the peak of the cold front wind. Model results were presented only for the Komen whitecapping approach, regarding because of its significant advantage over the Westhuysen whitecapping approach during the cold front (see Section 3.6). Simulated wave heights at this timestep (Figure 3.18A) showed wave heights as large as 2-2.5 m in the offshore areas of the Louisiana shelf. At Sandy Point dredge pit, a wave height of about 1.4 m was generated. The simulated mean wave periods over the offshore area and at Sandy Point dredge pit were 5.5-6 seconds and 4 seconds, respectively. These relatively small values of mean wave period demonstrate the dominant effect of high-frequency waves in the wave energy spectrum. The dominant wave direction over the shelf was northwesterly following the wind direction (Figure 3.18C).

The variations of wave characteristics over Sandy Point dredge pit and effect of different whitecapping approaches were further investigated by examining frequency-direction wave spectra (2D spectra) for locations in the south (P1), in the middle (P2) and in the north of the pit (P3). Location of these points are shown in Figure 3.1.
Figure 3.18. Simulation results for wave height, wave period, and wave vectors using KOMEN whitecapping approach in on 17 November 2014, at 15:00 UTC. Location of the Sandy Point dredge pit on the Louisiana shelf is marked with a dark circle.
Figures 3.19 and 3.20 show the comparisons at timesteps 1 and 2 during the simulation period 1, respectively. Point 1 located outside of the pit in the south where water depth is 13.20 m. At time step 1, the 2D spectra at this point show similar dominant directions, spectral spreading, and dominant frequencies for both whitecapping approaches. The main spectral feature at this time was two distinct dominant frequencies: one with a frequency of 0.18 Hz and the other with a frequency of 0.35 Hz that account for two different wave components including swell waves (lower frequency) and local wind waves (higher frequency). The Comparison of the Komen and the Westhuysen approaches (Figures 3.19A and 3.19B) suggested that for swell waves, the Westhuysen approach resulted in higher energies, while wave energy associated with seas were larger in value based on the Komen approach.

This difference was due to the different approach that these two formulations resolve whitecapping dissipation. The Komen whitecapping approach employs mean spectral frequency and wave number for estimating whitecapping dissipation. This approach can be accurate during the pure wind waves (as seen for simulation period 2 in Section 3.6) but overestimates wave energy in the presence of swells. The Westhuysen whitecapping approach distinguishes between whitecapping dissipation of low and high-frequency waves (seas and swells) based on the local wave numbers and frequencies. For other two points (point 2 in the middle of the pit with a water depth of 20 m and point 3 outside of the pit in the north where water depth is 8.26 m) simulated spectra from Komen and Westhuysen qualitatively were compared as it was performed for point 1. Moving from the southern location (P1) to the northern one (P3) the energy associated with the lower frequencies increased and the width of the low-frequency zone in the spectra was extended in both frequency and directional space. At the same time, the higher frequency portion of spectra experienced fewer variations.
Figure 3.19. Comparison of wave frequency-direction spectra at locations P1, P2, and P3 over and in the vicinity of the pit (see Figure 3.1 for locations) for two whitecapping approaches: Komen (right panel) and Westhuysen (left panel) at selected timestep 1 (7/8/2015 at 9:00 UTC)
It indicated that more low-frequency components were added to the wave spectra as moving northward. This was consistent with the southeasterly direction of the wind.

As moving northward from the location of P1, next locations received more wind energy that was transferred to the lower frequencies through the non-linear wave interaction process (Young, 2007). In comparison to the peak of energy at P1, the peak of energy observed at the northern stations experienced small to relatively large changes in the direction (Figure 3.19A, C, and E). While the direction for the peak of energy at location P1 was 175, at P2 and P3, it was 170 and 165, respectively. This directional change in the peak of energy could be due to the refraction produced as a result of the depth differences between the pit and surrounding area.

Wave spectra at the selected timestep 2 of the simulation period 1 were corresponding the southwesterly winds over the Louisiana shelf (Figure 3.20). At this time all locations including P1, P2, and P3 showed single peak wave spectra with the approximate peak frequency of 0.25 Hz that accounts for only local wind waves. At all locations, wave spectra from the Komen and the Westhuysen approaches were similar.

However, the Komen approach showed a larger directional spreading, especially toward the northwestern sector. Regarding the direction of the dominant wave, all three locations were exposed to similar wave energies, and therefore 2D spectra for them were very similar.

Spectral properties of simulated waves during July-August 2015 are further investigated by examining frequency spectra of location P2 (see Figure 3.1 for location) in the middle of the pit for timesteps 1 and 2 (Figure 3.21). The spectra were obtained by integrating frequency-direction spectra in the directional space. At timestep t1, both simulations using these two approaches resulted in a bi-modal frequency spectrum with two spectral peaks at low and high frequencies that were produced by swells and seas respectively.
Figure 3.20. Comparison of wave frequency-direction spectra at locations P1, P2, and P3 over and in the vicinity of the pit (see Figure 3.1 for locations) for two whitecapping approaches: Komen (right panel) and Westhuysen (left panel) at selected timestep 1 (3 August 2015, at 9:00 UTC)
Simulated frequency-direction spectra were also presented for three different times during the simulation period 2 in November 2014 (Figure 3.22), when the study area was affected by a cold front. Before the northerly winds spread over the Louisiana shelf, southeasterly winds generated a relatively narrow energy spectrum with the peak direction from southeast to the south (Figure 3.22A).

The spectrum was single peaked with a spectral peak at high frequency (about 0.28 Hz). This indicated that at this time effect of swell waves from the outer shelf was not significant. During the peak of cold front with prevailing northwesterly winds, the dominant direction of propagation of wave energy almost the same as wind direction from the northwest (Figure 3.22B). The energy spread from 270 to 30 degrees, showing a relatively broad distribution. Wave spectrum for the time after the northerly winds resided and wind direction shifted to easterly to southeasterly (Figure 3.22C) showed small wave energies (<2 J/m2/Hz/degree) and a large directional spreading. The larger directional spreading at this time was due to the different direction of local winds and swell waves that caused to distinct directional peaks in the spectrum. While wind direction was
easterly (90 degree) at this time, another peak observed in the spectrum was swell waves from the southeast.

Figure 3.22. Simulated frequency-direction spectra using Komen whitecapping approach at location P2 in the middle of the Sandy Point dredge pit during the cold front event of November 2014: A) before the cold front, B) during the cold front, and C) after the cold front.
3.8 Summary and Conclusion

In this chapter, a wave modeling study using SWAN (Delft3D- WAVE module) was implemented over the Louisiana shelf with the main focus on Sandy Point dredge pit. Since the main implication of this simulated wave field was used in the sediment transport model to account for wave-induced sediment re-suspension at the seabed, having a high accuracy wave model was imperative. Input data including wind from the BURL1 station, waves along the open boundaries from the WWIII database, and high-quality bathymetric data along with modeling parameters from reliable resources were used to prepare the initial model setup. Regarding the significant effect of whitecapping dissipation on wave simulation, two different approaches for resolving the whitecapping dissipation including Komen (1984) and van der Westhuysen et al. (2007) were used to determine the most appropriate approach for the present modeling.

Wave modeling was done for two contrasting atmospheric conditions during July-August 2015, and November 2014 and results were controlled using the third simulation period in March 2012. Examining simulations based on both whitecapping approaches by comparing with buoy data at three different stations and calculating error metrics (Pearson correlation coefficient, RMSE, bias, and SI) showed that Komen produced a higher accuracy wave field for the study area. Simulation results were further examined by plotting maps of wave height, wave period, and wave vector and investigating wave height variations over Sandy Point dredge pit.

These results confirmed that the Westhuysen approach generally underestimated wave height and period over the Louisiana shelf. Examining wave frequency-direction spectra at three different locations in the south, north, and over Sandy Point dredge pit suggested that during the southerly wave incidents, depth-induced refraction can deviate direction of energy peaks over the pit and in the north by as much as 20 degrees. Spectra confirmed the conclusion about energy
underestimation by the Westhuysen approach, especially when the study area was under the influence of the pure wind.
CHAPTER 4: NUMERICAL STUDY OF SEDIMENT RESUSPENSION
OVER THE SANDY POINT DREDGE PIT DURING A COLD FRONT

4.1 Introduction

4.1.1 Background

South Louisiana is experiencing significant land loss as a result of both natural processes and anthropogenic activities (NRC, 2006). If no action is taken, Louisiana will lose more than one million acres of coastal wetlands, an area larger than the state of Rhode Island, by the year of 2040 (Watzin and Gosselink 1992).

It is believed that the combined effect of sea level rise, land subsidence, hurricanes storm surges, invasive species, construction of water control structures, and oil-gas extraction activities have contributed to the land loss (Penland and Ramsey, 1990; NRC, 2006).

One solution to land loss is to renourish the shoreline along the coastline and barrier islands by sand extracted from the outer continental shelf (OCS) where there is availability of viable sand resources and accessibility to the target area (Drucker et al., 2004; Pepper and Stone, 2004). Those offshore sand resources have been used for large-scale coastal restoration, particularly along the northern Gulf coast (Michel et al., 2001; Maa et al., 2004; Pepper and Stone, 2004). The Barataria Barrier Island Complex Project (BA-38; CWPPRA; 2007, 2012) was proposed to offset further degradation and to restore two reaches of the Baratara Plaquemines shorelines: Pelican Island and Pass La Mer to Chaland Pass using OCS sand resources.

One of the economic and technically feasible options is to use sediment from Sandy Point site, which is located at about 20 km west of the Mississippi River bird-foot delta, and approximately 12.87 to 15.28 km offshore of Pelican Island (Figure 4.1). Figure 4.1 shows the location of Sandy Point Dredge Pit, Pelican Island, Grand Pass, and Southwest Pass. The sand extraction activity resulted in an elongated dredge pit.
There are oil and gas pipelines, platforms, wellheads, and other oil and gas-related infrastructure in the vicinity of the Sandy Point dredge pit. The closest pipeline is located about 300 m northwest of the pit (Nairn et al., 2005). Sand and gravel mining could impose a risk to the platforms and pipelines, as well as modifying the action of waves, currents and sediment dynamics (Stone et al., 2009; Nairn et al., 2005). Hence, it is necessary to evaluate the evolution of the dredge pit by studying the hydrodynamics and sediment dynamics. In this chapter, I focused on the hydrodynamics including currents, waves, and sediment deposition processes, during cold fronts. This will help us understand and predict the pit infilling rate in the dredge pit area.
### 4.1.2 General Pattern of Circulation and Sediment Dynamics over the Louisiana Shelf

Two distinct patterns characterize general circulation over the Louisiana shelf: downcoast and upcoast currents with dominant westward and eastward directions over the shelf respectively (Cochrane and Kelly, 1986). Downcoast current is dominant during non-summer months and is generated by easterly to southeasterly winds while upcoast current is generated as a result of southerly to southeasterly winds during summer (Crout et al., 1984; Cochrane and Kelly, 1986; Jarosz, 1997; Allahdadi et al., 2012; Chaichitehrani et al., 2014). The Louisiana shelf is characterized by a low energy regime, except during cold fronts and hurricanes (Curray, 1960; Adams et al., 1987; Wright et al., 1997, Georgiou et al., 2005). During fair weather condition, significant wave height ($H_s$) in the area is typically less than 1.0 m on top of diurnal or mixed diurnal tides with an average amplitude of 0.4 m (Stone and Xu, 1996; Write et al., 1997). Wright et al. (1997) observed a mean combined wave-current shear velocity of less than 0.7 cm$^{-1}$ and small shear stress in western Louisiana during fair weather conditions, which is not large enough to re-suspend bottom sediment. During cold fronts and hurricanes, bottom shear stress (BSS) exceeds the critical BSS, resulting in re-suspension and transport of bottom sediment (Adams et al., 1987; Wright, 1995; Wright et al., 1997). Cold fronts can have significant impacts on sediment remobilization in coastal waters in the northern Gulf of Mexico because of spatial coverage and frequent occurrence (Roberts et al., 1987; Moeller et al., 1993; Pepper et al., 1999; Feng and Li, 2010; Li et al., 2011; Lin et al., 2016; Carlin et al., 2016; Li et al., 2017). Every year from October to May about 30 to 40 cold fronts pass through the Louisiana Shelf. Each storms may last with a typical duration of 12 to 24 hours and recurring periods of 3 to 7 days (Moeller et al., 1993; Georgiou et al., 2005; Feng and Li, 2010; Lin et al., 2016; Li et al., 2011). Rapid changes in wind direction and speed associated with cold fronts disturb westward (downcoast) current, and veer the

4.1.3 Numerical Modelling Background

Several numerical models were developed to simulate hydrodynamics, advection of substances (i.e., sediment and organic matter) and morphological changes over the Louisiana shelf under extreme meteorological events (for example, Justic et al., 2007; Keen et al., 2004; Kobashi, 2009; Xu et al., 2011; Siadatmousavi et al., 2012; Allahdadi, 2014; Chaichitehrani et al., 2014; Liu, 2016; Xu et al., 2016). Jaffe et al. (1997) performed the Glenn-Grant-Madsen model (Grant and Madsen, 1979; Glenn and Grant, 1987) and their results suggested that sediment transport rate on the Louisiana inner shelf during a strong cold front passage would be ~10^3 higher than that during fair weather. Allahdadi (2014) developed a three-dimensional model based on the Finite Volume Community Ocean Model (FVCOM) to simulate hydrodynamics and salt/heat transport over the Louisiana shelf from Hurricane Katrina. The study showed that a bottom compensation current tends to flow in the opposite direction of surface current due to the pressure gradient. Nairn (2005) used a theoretical analysis and a numerical model (MISED) to study morphological evolution of a dredged pit at Holly Beach located offshore of western Louisiana and Sandy Point dredge pit. He suggested that pits in muddy (sand deposit capped by mud) and sandy settings have different morphologic evolution characteristics. He showed that the hydrodynamics and sediment dynamics at the Sandy Point site are much more complicated than the conditions at the Holly Beach. In addition, based on the numerical model results, an external source of SSC (i.e., not from local re-suspension by waves and currents) such as plumes from the Mississippi River contributed to reducing the pit margin erosion. Notwithstanding the extensive research effort on hydrodynamics and sediment transport of the Louisiana shelf, our knowledge about the bottom
boundary characteristics on the west flank of Mississippi River delta, the fate of sediment from the Mississippi River plume as well as re-suspended sediment from local water during cold front passages is yet very limited.

### 4.2 Objectives

In this chapter, a high-resolution model for the Louisiana shelf was developed to enhance our understanding of the BBL characteristics over the Sandy Point dredge pit and sedimentation pattern during a cold front. The three overarching goals of this research were:

1. Assess the potential impact of wave- and current- induced bottom shear stress associated with a cold front on the sediment dynamics in Sandy Point dredge pit;
2. Identify sediment supply (river input and/or local sediment resuspension) for Sandy Point dredge pit during a cold front; and
3. Estimate of sediment resuspension and deposition in the dredged pit during cold front events. In general, this high resolution model will provide a means to quantify the pit’s evolution in response to cold front driven hydrodynamics. Results from this study provide a baseline for further studying potential submarine geo-hazard associated with mud-capped dredge pits.

### 4.3 Method and Data

#### 4.3.1 Study Area

The Sandy Point dredge pit is located west of the modern Mississippi River bird-foot delta (Figure 4.1). It was formed as a sandy paleochannel with extensive muddy overburden, thus the name mud-capped dredge pit (Nairn et al., 2005). The fluvial sediments from the Grand Pass located approximately 12.5 km northeast of the pit has a decisive impact on the pit morphodynamics (Nairn et al. 2005). The study area is characterized by predominantly muddy seabed as a result of the long-term sediment dispersion from the Mississippi River. Bed sediments
over this region consist of 90% mud (finer than 63 μm in diameter) and 10% sand (Nairn et al. 2005).

4.3.2 Modelling Approach

Here I used a fully coupled Delft3D-FLOW model with MOR and WAVE modules. Delft3D is a 3D hydrodynamic model, allowing modules for water quality and sediment dynamics in fluvial, estuaries, and coastal environments (Deltares, 2011). It computes the non-steady flow and transport forced by wind, wave, tide, and river discharge. Here, I used the Delft3D model with well-vetted computational grid and input parameters (e.g., wind, sediment sources, and river discharge) to simulate Mississippi River sediment dispersal, sediment resuspension, transport, and deposition of cohesive (mud) and non-cohesive (sand) fractions. The model was run from 15 through 21 November 2014. A time step of 3 seconds was used for the Delft3D-FLOW simulations to meet the Courant number criterion.

4.3.2.1 Delft3D-FLOW Module

Physical processes are important drivers of sediment transport and morphological evolution of Sandy Point dredge pits. The Delft3D-FLOW was employed to simulate currents and sediment transport on Louisiana shelf with a focus on Sandy Point dredge pit. Delft3D solves the Reynolds-averaged Navier-Stokes equations for an incompressible fluid under the shallow water and Boussinesq assumptions based on finite difference method on a curvilinear grid (Deltares, 2011a). The momentum equations derived from the Reynolds-averaged Navier-Stokes equations with a Boussinesq approximation and the depth-averaged continuity equations are given by:

\[
\begin{align*}
\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} + \frac{w}{h} \frac{\partial U}{\partial \sigma} - fV &= \\
-\left( g \frac{\partial \zeta}{\partial x} + g \frac{h}{\rho_0} \int_0^\sigma \left( \frac{\partial \rho}{\partial x} + \frac{\partial \rho'}{\partial x} \frac{\partial \sigma'}{\partial x} \right) \partial \sigma' \right) + \nu_H \left( \frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} \right) + M_x
\end{align*}
\]
\[ \frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} + \frac{w}{h} \frac{\partial V}{\partial \sigma} + fU = (4.2) \]

\[-(g \frac{\partial \zeta}{\partial y} + g \frac{h}{\rho_0} \int^{0}_{\sigma} \left( \frac{\partial \rho'}{\partial y} + \frac{\partial \rho}{\partial \sigma'} \frac{\partial \sigma'}{\partial y} \right) \frac{\partial V}{\partial \sigma'} \) + \nu_H \left( \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} \right) + M_y \]

where \( U \) and \( V \) are the depth-averaged generalized Lagrangian mean velocity components (\( \text{ms}^{-1} \)) including waves (Stokes drift components), \( f \) is the Coriolis coefficient (\( \text{s}^{-1} \)), \( g \) is gravitational acceleration (\( \text{ms}^{-2} \)), \( h \) is water depth (m), \( \nu_H \) is the horizontal eddy viscosity (\( \text{m}^2\text{s}^{-1} \)), \( \rho \) is the fluid density (\( \text{kgm}^{-3} \)), \( \rho_0 \) is the reference density of water (\( \text{kgm}^{-3} \)), \( \sigma \) is the vertical topography following coordinate (m), \( \zeta \) is the water surface elevation above reference datum (m), and \( \omega \) is the vertical velocity component in the sigma coordinate system (s-1). \( M_x \) and \( M_y \) represent contributions from external sources and sinks of momentum (\( \text{ms}^{-2} \)).

### 4.3.2.2 WAVE Module

Both currents and waves are responsible for the sediment resuspension over Louisiana continental shelf during extreme meteorological events. Wave-induced shear stress could be the dominant forces in re-suspending sediment from the seabed, which influences the sediment texture distribution (Wiberg et al., 1994; Dalyander et al., 2013). Hence, it is imperative to take into account the combined effect of waves and currents to examine the bottom boundary layer characteristics. Delft3D allows to couple FLOW and WAVE modules. The coupled modeling system enables us to estimate wave and current concurrently and calculate combined wave-current stress (Lesser et al., 2004). The spectral wave model SWAN (Simulating Waves Nearshore), a fully spectral mode (Holthuijzen et al., 1993), was integrated into Delft3D as a wave module which simulates the evolution of the incoming wave field. SWAN is a 3\textsuperscript{rd} generation phase-averaged numerical wave model and computes wave propagation, wave generation by wind, non-linear (quadruplet and triad) wave-wave interaction and dissipation in deep, intermediate and shallow
waters through solving the discrete spectral action balance equation (Equation 4.3) (Booij et al., 1999; Ris et al., 1999; Holthuijsen et al., 2007). In addition, SWAN accounts for diffraction, shoaling, dissipation due to white-capping, refraction, frequency shifting due to currents and non-stationary depth, reflection, bottom friction and depth-induced breaking. The Delft3D-WAVE module calculates radiation stress fields and wave parameters (e.g., orbital bottom velocity) which will be used as forcing by the FLOW/MOR modules. Here, an online coupling of WAVE with FLOW module was used, and a two-way wave-current coupling was performed. This coupled system takes into account the effect of waves on currents (forcing, enhanced turbulence and BSS) along with the effect of flow on waves (e.g., set-up, current refraction, and enhanced bottom friction) (Deltas, 2011b). The non-linear enhancement of the BSS in the presence of waves was taken into account by means of the wave-current interaction model of Van Rijn et al. (2004). In SWAN, the waves are simulated by solving the two-dimensional wave action density spectrum (N (σ, θ)):

\[
\frac{\partial}{\partial t} N + \frac{\partial}{\partial x} C_x N + \frac{\partial}{\partial y} C_y N + \frac{\partial}{\partial \sigma} C_\sigma N + \frac{\partial}{\partial \theta} C_\theta N = \frac{S_{tot}}{\sigma}
\]  

(4.3)

The first left-hand term represents the local rate of change of action density (N) in time (t). The second and third term represent propagation of action density with propagation velocities of \(C_x\) and \(C_y\) in x and y directions. The fourth term represents shifting of the relative frequency due to variations in depths and currents with propagation velocity (\(C_\sigma\)) in σ-space. Last term represents depth-induced and current induced refraction with propagation velocity (\(C_\theta\)) in θ-space. On the right-hand, the term \(S_{tot}\) represents the energy density source terms that includes generation, dissipation (due to white-capping, bottom friction, depth-induced breaking) and non-linear wave-wave interactions. The action density is equal to the energy density divided by the relative frequency (N (σ, θ) = E (σ, θ)/σ). For the present simulations, wave conditions were updated every
60 minutes using the hydrodynamic field provided by the flow module. The wave-induced forces computed by wave module were provided for a hydrodynamic model in order to simulate wave-related phenomena such as wave set-up, wave-induced current and mixing. On the other hand, the flow model returns water levels and current for the wave model (Booij et al., 1999). In this study, FLOW and WAVE modules were coupled and run with multiple processors using distributed (OpenMPI) memory architectures. The wave boundary layer is one of the main conduits delivering fine sediments from the nearshore to continental shelves.

**4.3.2.3 MOR Module**

In this study, a fully three-dimensional sediment transport and morphological model was added directly into existing Delft3D-FLOW and used to simulate sediment transport and morphological changes in the study area. The built-in MOR module combines the information provided by the flow and wave modules to compute sediment transport fluxes, morphological changes and updates the seabed morphology at each computational time step. Results from each time step have a dynamics feedback on FLOW and WAVE modules and will affect flow and wave computations. In this study, two different type of sediments, cohesive and non-cohesive were considered. I distinguished “mud” (cohesive), and “sand” (non-cohesive) fractions. The modeling of cohesive sediment transport requires an approach that is fundamentally different from modeling of sand transport. For very fine sediment size (e.g., silt or clay-sized), the inter-particle forces due to ionic charges become significant relative to the gravitational forces. As a result, processes including flocculation, hindered settling, and bed consolidation have important roles in the movement of cohesive particles (Deltaires, 2011a). Delft3D solves the advection-diffusion equation (Equations 4.4-4.6) for suspended sediment. The sediment transport and morphology module support bedload and suspended load transport of non-cohesive sediments and suspended
load of cohesive sediments. The non-cohesive sediment transport simulations will be performed by the implementation of the Van Rijn (1984) formulation. Three-dimensional transport of suspended sediment is calculated by solving the three-dimensional advection-diffusion equation for sediment concentration:

$$\frac{\partial c^{(l)}}{\partial t} + \frac{\partial uc^{(l)}}{\partial x} + \frac{\partial vc^{(l)}}{\partial y} + \frac{\partial (w - w_s^{(l)})c^{(l)}}{\partial z} +$$

$$- \frac{\partial}{\partial x} \left( \varepsilon_s^{(l)} \frac{\partial c^{(l)}}{\partial x} \right) - \frac{\partial}{\partial y} \left( \varepsilon_s^{(l)} \frac{\partial c^{(l)}}{\partial y} \right) - \frac{\partial}{\partial z} \left( \varepsilon_s^{(l)} \frac{\partial c^{(l)}}{\partial z} \right) = 0 \quad (4.4)$$

With erosion and deposition terms as bed boundary conditions:

$$-w_s^{(l)} c^{(l)} - \varepsilon_s^{(l)} \frac{\partial c^{(l)}}{\partial z} = D^{(l)} - E^{(l)}, \text{ at } z = z_b \quad (4.5)$$

where:

$c^{(l)}$ mass concentration of sediment fraction $(l)$ (kgm$^{-3}$)

$u$, $v$ and $w$ flow velocity component (ms$^{-1}$)

$\varepsilon_s^{(l)}$, $\varepsilon_s^{(l)}$, and $\varepsilon_s^{(l)}$ eddy diffusivities of sediment fraction $(l)$ (m$^{2}$s$^{-1}$)

$w_s^{(l)}$ (hindered) sediment settling velocity of sediment fraction $(l)$ (ms$^{-1}$)

Flow velocities are computed by FLOW module, and eddy diffusivity is calculated from eddy viscosity. Settling velocity for a cohesive fraction (mud) is provided by the user and of non-cohesive sediment (sand) is computed from sediment diameter using the Van Rijn (1993):

$$w_{s,0} = \begin{cases} 
\frac{(s-1)gD_s}{18\mu} & \text{if } 65um < D_s \leq 100um \\
\frac{10\mu}{D_s} \sqrt{1 + \frac{0.01(s-1)gD_s^3}{\mu^2}} - 1 & \text{if } 100um < D_s \leq 1000um \\
1.1\sqrt{(s-1)gD_s} & \text{if } 1000um < D_s \end{cases} \quad (4.6)$$

where

$s$ is sediment density relative to water density $\rho_s/\rho_w$
$D_s$ is sediment particle diameter

$\mu$ is kinematic viscosity coefficient of water ($m^2s^{-1}$)

Sediment fluxes between the water phase and the bed are computed using the Partheniades-Krone formulations (Partheniades, 1965).

$$E^{(l)} = M^{(l)} S(\tau_{cw}, \tau_{cr,e}^{(l)})$$ (4.7)

$$D^{(l)} = w_s^l c_b^l S(\tau_{cw}, \tau_{cr,d}^{(l)})$$ (4.8)

$$c_b = c \left( z = \frac{\Delta z_b}{2}, 2 \right)$$ (4.9)

where:

$E^{(l)}$ erosion flux ($kg m^{-2} s^{-1}$)

$M^{(l)}$ user-defined erosion parameter ($kg m^{-2} s^{-1}$)

$S(\tau_{cw}, \tau_{cr,e}^{(l)})$ erosion step function

$D^{(l)}$ deposition flux ($kg m^{-2} s^{-1}$)

$w_s^{(l)}$ fall velocity (hindered) ($ms^{-1}$)

$c_b^{(l)}$ average sediment concentration in the near-bottom computational layer ($kgm^{-3}$)

$S(\tau_{cw}, \tau_{cr,d}^{(l)})$ deposition step function

$\tau_{cw}$ maximum BSS due to current and waves as calculated by the wave-current interaction model selected by user

$\tau_{cr,e}^{(l)}$ user-defined critical erosion shear stress ($Nm^{-2}$)

$\tau_{cr,d}^{(l)}$ user-defined critical deposition shear stress ($Nm^{-2}$)

Superscript $(l)$ implies that this quantity applies to sediment fraction $(l)$. The erosion flux $E$ is directly proportional to $M$ which means increasing $M$ will linearly increase the amount of eroded
sediment, which then becomes suspended in the water column. Alternatively, the deposition flux $D$ is proportional to $w_s$; increasing $w_s$ will linearly increase the amount of sediment deposition. The values of the erosion and deposition critical shear stresses will determine the thresholds conditions for which erosion or deposition begins and effectively scale the predicted erosion or deposition fluxes.

$$S\left(\tau_{cw}, \tau_{cr,erosion}\right) = \begin{cases} 
\left(\frac{\tau_{cw}}{\tau_{cr,erosion}} - 1\right), & \text{when } \tau_{cw} > \tau_{cr,erosion} \\
0, & \text{when } \tau_{cw} < \tau_{cr,erosion}
\end{cases} \tag{4.10}$$

$$S\left(\tau_{cw}, \tau_{cr,deposition}\right) = \begin{cases} 
\left(\frac{\tau_{cw}}{\tau_{cr,deposition}} - 1\right), & \text{when } \tau_{cw} < \tau_{cr,deposition} \\
0, & \text{when } \tau_{cw} > \tau_{cr,deposition}
\end{cases} \tag{4.11}$$

4.4 Model Inputs and Set-up

4.4.1 Model Grid and Bathymetry

The model grid is curvilinear in a horizontal plane with $\sigma$-layers for vertical grid which can follow topographical changes. The vertical grid in spherical co-ordinate was divided into 19 layers to resolve the bottom and surface boundary layers with higher vertical resolutions. The computational domain was chosen to encompass Louisiana inner shelf from Gulf Shores, Alabama to the east of Terrebonne Bay with the southern boundary extended offshore beyond the shelf edge. It contains 384\times371 curvilinear orthogonal grids in the horizontal which extends from longitudes of 91.00° W to 87.5° W and from latitudes of 28.15° N to 30.81° N (Figure 4.2A). The model’s horizontal resolution varied from 10 m over the Sandy Point dredge pit to 3 km near the offshore boundary. The bathymetry data were from National Geophysical Data Center (NGDC) coastal relief model (Divins and Metzger, 2008) with the approximate spatial resolution of 90 meters (www.ngdc.noaa.gov/mgg/coastal/crm.html), local bathymetric survey conducted at Sandy Point dredge pit by LSU, Sediment Dynamics Lab (Obelcz, 2017) and ADCP measurements performed
by LSU, WAVCIS Lab. Figure 4.2B depicts the overall depth of the modeling area, and Figure 4.2C shows the local depth at Sandy Point dredge pit. Wave model’s grid resolution varied between 2 km and 58 m.

Figure 4.2. (A) The 384 x 371 curvilinear orthogonal computational grid. The mesh resolution varies from 10.5 m to 2.8 km, (B) Bathymetry used in the model for the general modeling area, and (C) a close view of bathymetry for Sandy pit area (Obelcz, 2017)
4.4.2 Wind Data

Spatially uniform and temporally variable wind data (at 38m above sea level) were obtained and verified from station BURL1 (Wang et al. 1998; Xu et al., 2011) maintained by National Data Buoy Center (NDBC) located at 28°54'21" N 89°25'43" W (see Figure 4.1 for locations). Wind speeds were converted to that at 10 m above the surface \(U_{10}\) using the power law (Kamphuis, 2000).

The wind drag coefficients \(C_d\) were selected as functions of wind speed, which reflects the sea surface roughness increase with wind speed (Smith and Banke, 1975). Figure 4.3 shows time variations of wind vector obtained from BURL1 for November 2014.

![Figure 4.3](image)

Figure 4.3. Time series of wind vectors obtained from BURL1 for November 2014. The red rectangular shows wind field during the simulation period

4.4.3 Open Boundary Condition

In model, the open ocean boundary was an arc which defines a semi-enclosed model domain. The sea surface elevation was specified along the open boundary with amplitude and phase of tidal constituents. The amplitude and phase of the three astronomical diurnal tidal constituents \((O1, K1, Q1)\) and four semi-diurnal tidal constituents \((M2, S2, N2, and K2)\) as well as, \(M4\) and \(M6\) were extracted from the USACE’s Eastcoast 2001 computed by ADCIRC 2DDI (the depth-integrated version of the ADCIRC) (Westerink, 1993; Mukai et al., 2001) and prescribed to the open boundary.
4.4.4 River Discharge

Mississippi River discharge was obtained from the USGS Belle Chasse, LA station, located at 29°51′25″N and 89°58′40″W (USGS 07374525). The water discharge for each Mississippi River pass was calculated based on the portion defined by Allison et al. (2012). Rego et al. (2008) reported that the Mississippi River discharge to the eastern side of the bird-foot delta is 15% less than that of the western side. Momentum-type boundary condition was imposed to each pass (Deltares, 2011a).

The SSC discharged from the Mississippi River was obtained using the equation provided by Snedden (2006), based on the relationship between river discharge and SSC. The velocity of flow from each outlet was obtained based on simulated values from Gonzalez (2014). The river discharge from nine outlets (Grand Pass, Southwest Pass, South Pass, West Bay, Small Cuts, Pass a Loutre, Cubit’s Gap and Baptist Collette) of the Mississippi River were incorporated into the model.

4.4.5 Physical Parameters

Delft3D-FLOW offers several options for introducing/calculating vertical eddy viscosity (Kolmogorov, 1942; Prandtl, 1945; Deltares, 2011): constant user-defined coefficient; algebraic eddy viscosity closure; $k-L$ turbulence closure model, and $k-\varepsilon$ turbulence closure model. In this study, a $k-\varepsilon$ turbulence closure model was applied following Allahdadi et al. (2017).

Turbulence effects in horizontal plane were considered in the model using constant background horizontal eddy viscosity and diffusivity coefficient. Background horizontal eddy viscosity was set to 1 (m$^2$s$^{-1}$), and 10 (m$^2$s$^{-1}$) for horizontal eddy diffusivity. The initial value for bottom roughness based on Chézy formula was the default value of 65.0 m$^{1/2}$ s$^{-1}$ that was later tuned by comparing the results with field data.
4.4.6 Sediment Properties

4.4.6.1 Bed-Sediment Composition

A seabed sediment classification study has been carried out by the U.S. Geological Survey (USGS) for the northern Gulf of Mexico (usSEABED) (Williams et al., 2006), which has been used by many studies (Siadatmousavi, 2012; Xu et al., 2015; Liu et al., 2017). In model, two types of bed sediments including mud (cohesive) and sand (non-cohesive) were considered (Xu et al., 2011). The usSEABED initial seabed composition was interpolated and incorporated into the model as two different maps. A uniform bed layer with an initial thickness of 2 meters was considered in the model. Bottom sediment composition of the study area is mainly mud, due to the influx of fine-grained sediments primarily from the Mississippi River. It has been reported that sediment becomes cohesive as mud content exceeds 30% (Mitchener and Torfs, 1996; Dufois et al., 2008). Figure 4.4 presents an interpolated mud fraction map based on the usSEABED database and confirms that Sandy Point dredge pit and adjacent regions contained >80% of mud in the model domain.

4.4.6.2 Initial Condition

A near-surface SSC map was derived from NASA MODIS-Aqua (Moderate Resolution Imaging Spectroradiometer) data on 15 November 2014, 07:35:00 PM. Remote sensing reflectance (Rrs) products were corrected atmospherically using SWIR-NIR (Short Wave Infra-Red and Near Infra-Red) atmospheric correction algorithm. To retrieve SSC, the atmospherically corrected Rrs products (based on 555 nm and 678 nm wavelengths) were processed using a regional algorithm developed for the study area by D’Sa et al. (2007). The space-varying surface SSC map for layer 1 was integrated into the model as model’s initial condition for a cohesive fraction. For other
vertical layers (all other 18 layers) in model, SSC values were assigned to zero. A warm-up time of two weeks was included to simulate suspended sediment concentration across the water column. Since the non-cohesive sediment concentrations adapt quickly to equilibrium conditions, a uniform zero condition was taken into account for this fraction (Deltares, 2011a).

Figure 4.4. Interpolated seabed (A) mud and (B) sand fractions (%) based on the usSEABED database, USGS

4.4.6.3 Sediment Properties

A range of physical and numerical input parameters is required for modeling sediment transport and morphological evolution under the combined action of waves and currents. Key model parameters were assumed within recommended ranges and were tuned using field data of SSC, satellite-derived concentration maps and observed morphological changes. In model, four parameters were used (Partheniades, 1965) for cohesive sediments: the settling velocity ($w_s$); the erosion rate ($M$); and critical shear stress thresholds for erosion ($\tau_{cr,erosion}$) and deposition ($\tau_{cr,deposition}$).

The BSS ($\tau_b$) induced by currents and waves controls the mechanism of erosion and deposition of sediment. BSS is generated within the bottom boundary layer due to the velocity
gradient. Boundary shear stress acts to initiate sediment motion, and aids in particle diffusion away from the seabed (acting against the gravitational settling of particles). In typical continental shelves, wave-induced BSS varies in time, and sediment can be resuspended/deposited when the flow intensity varies.

In general, the critical shear stress for the erosion of muddy seabed is difficult to determine due to possible consolidation, flocculation, and biological effects (Sanford, 2008; Winterwerp et al., 2012), and it is typically determined through in situ measurements or laboratory tests. If the BSS is larger than a critical value for erosion, the Partheniades’ formulation is used, while if BSS is less than a critical value for deposition, deposition is modeled using Krone’s formulation. Table 4.1 lists the pivotal values used by other studies in different environments. The critical shear stress for erosion of 0.2 N m$^{-2}$ was selected as the threshold for cohesive sediment re-suspension based on recommended value from previous studies (Van Rijn, 2007; Deltares, 2013; Xu et al., 2016; Liu, 2017). The critical shear stress for deposition ($\tau_{cd}$) was assigned to 0.08 Nm$^{-2}$ (Wang et al., 2015). The BSS due to wave forces was taken into account through the wave-current interaction model of Fredsøe (1984). The erosion parameter ($M$) plays a significant role on model predictions. A relatively small erosion rate values for ($M$) in the range of $1\times10^{-5}-1\times10^{-6}$ kgm$^{-2}$s$^{-1}$ has been suggested (Whitehouse R. et al., 2000; Van Maren B., 2013). The calibration efforts initially focused on this parameter while keeping other parameters unchanged.

The erosional parameter ($M$) regulates the rate of sediment resuspension (Sanford and Maa, 2001; Warner et al., 2008; Moriarty et al., 2014). To evaluate the sensitivity of calculations to uncertainties in erosion parameter, the model was run three times using values $5\times10^{-5}$; $3\times10^{-5}$, and $1\times10^{-5}$ for $M$ parameter. During this sensitivity test, other model parameters including critical shear stress for deposition and erosion, and settling velocity were held unchanged.
Table 4.1. Critical shear stress for erosion ($\tau_{cre}$), deposition ($\tau_{crd}$), erosional parameter (M), and settling velocity ($w_s$) used in literature and this study.

<table>
<thead>
<tr>
<th>Literature</th>
<th>Study Area</th>
<th>$\tau_{cre}$ (Nm$^{-2}$)</th>
<th>$\tau_{crd}$ (Nm$^{-2}$)</th>
<th>M ($10^{-4}$ kg m$^{-2}$ s$^{-1}$)</th>
<th>$w_s$ (mms$^{-1}$)</th>
<th>Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vinh et al. (2016)</td>
<td>Mekong Delta</td>
<td>0.2</td>
<td>1000</td>
<td>0.2</td>
<td>0.05, 0.325</td>
<td>Delft3D</td>
</tr>
<tr>
<td>Nardin and Edmonds (2014)</td>
<td>Wax Lake Delta</td>
<td>0.1 and 0.2</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>Delft3D</td>
</tr>
<tr>
<td>Moriarty et al. (2014)</td>
<td>Waipaoa Shelf, New Zealand</td>
<td>0.15</td>
<td>NA</td>
<td>4.5, 0.1</td>
<td>0.1, 0.15, 0.3</td>
<td>ROMS</td>
</tr>
<tr>
<td>Edmonds and Slingerlal (2010)</td>
<td>Atchafalaya Bay</td>
<td>0.1, 0.2</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>Delft3D</td>
</tr>
<tr>
<td>Xu et al. (2016)</td>
<td>Texas-Louisiana Shelf</td>
<td>0.034-0.219</td>
<td>NA</td>
<td>0.5, 1.0, 5.0 and 10.0</td>
<td>0.5, 1.0, 5.0 and 10</td>
<td>ROMS</td>
</tr>
<tr>
<td>Liu et al. (2017)</td>
<td>Louisiana Shelf</td>
<td>0.05, 0.1, 0.2</td>
<td>NA</td>
<td>0.5, 1.0, 5.0</td>
<td>0.1, 0.25, 0.1</td>
<td>Delft3D</td>
</tr>
<tr>
<td>This study</td>
<td>Louisiana Shelf</td>
<td>0.2</td>
<td>0.08, 0.1</td>
<td>0.5, 0.3 and 0.1</td>
<td>0.1</td>
<td>Delft3D</td>
</tr>
</tbody>
</table>
4.4.6.4 Boundary conditions for Wave model

To setup the wave model, boundary conditions for three open boundaries were obtained from WAVEWATCH-III (WWIII) (Tolman, 2002). Hourly data for significant wave height ($H_s$), wave peak period ($T_p$) and mean wave direction ($\theta_p$) accounting for remote swells were obtained from NCEP/NOAA (http://polar.ncep.noaa.gov/waves/) and prescribed along the model open boundaries.

4.5 Scenarios

Hydrodynamics determine the spatial and temporal variations of SSC over the Sandy Point dredge pit, sediment discharge from the Mississippi River, and background SSC. Obviously, currents, waves, and sediment flux from the Mississippi River all play a role in the erosion, resuspension, and deposition of Sandy Point dredge pit. Three model scenarios were set up to assess the importance of the hydrodynamics and seabed interaction processes. The sensitivity of different components (waves and river discharge) on the sediment dynamics is investigated. Scenario 1 took into account the combined action of waves and currents along the sediment flux from the Mississippi River passes.

In this scenario, sediment resuspension under wave-current effects, dispersal of re-suspended sediment and discharged sediment from the passes associated with hydrodynamics and bottom boundary characteristics of Sandy Point dredge pit during the passage of the cold front are addressed. In scenario 2 the sediment flux from the Mississippi River passes was not included, to just compute the sedimentation rate with waves and currents. Scenario 3 excluded waves action. The goal of performing this scenario was to determine the role of the fluvial plume from the Mississippi River passes in providing sediment for Sandy Pit by understanding dynamical processes controlling the fate of Mississippi River waters.
4.6 Calibration and Verification of models

All three modules used in the present simulation including flow, wave, and sediment transport were verified against *in situ* or satellite data. Validation for flow and wave models were conducted using various *in situ* data from deployed ADCP and buoys. Flow model was verified under two conditions: (1) tides only and (2) realistic forcing with tides, surface winds, waves and Mississippi River discharge. Simulated water level variations (m) were compared with NOAA stations at Southwest Pass and South Pass as well as water level variation at Breton Island station provided by International Hydrographic Organization (IHO) (Figure 4.5A-C and see Figure 4.1 for locations of tidal stations).

![Graphs showing comparison between modeled and measured water levels](image)

Figure 4.5. Comparison between modeled (blue line) and measured (red line) water level from November 1-30, 2014 at (A) Southwest Pass, (B) South Pass, and (C) Breton Island station

Results showed a good agreement between numerical results and observations at these stations. Given the lack of current data during simulation period (15-21 November 2014), another simulation was run from July 15th through August 15th, 2015. Simulated total current velocities were compared with measurements at WAVCIS CSI-6, and ADCP mounted on a tripod inside the
Sandy Point dredge pit (29°06.2170’ N, 89°30.5910’ W). The simulation included wind, waves, tides, and river discharge.

In the flow model, bed roughness used as the main calibration parameter. Different values of Chezy parameter from 32 to 65 were examined to achieve the best march with field data of current velocity. Chezy parameter of 65 resulted in the best match with field data. The validation included a visual comparison of both timeseries data (Figures 4.6 and 4.7) as well as statistical analysis (Table 4.2).

In station CSI-6, no velocity data were available from August 3rd through August 5th. Comparison of simulated and measured currents was quantified using the index presented in Willmott (1981). The index is represented as:

\[
I_w = 1 - \frac{\sum_{k=1}^{N}(V_{model} - V_{measured})^2}{\sum_{k=1}^{N}[|V_{model} - \bar{V}_{measured}| + |V_{measured} - \bar{V}_{measured}|]^2}
\]  

(4.12)

where \(V_{model}\), \(V_{measured}\), and \(V\) are simulated, measured, and mean values, respectively. \(N\) is the number of data. If the two parameters are correlated well, \(I_w\) is close to 1. Figure 4.6 and 4.7 present comparisons between the modeled and measured surface current velocity components \(u\) and \(v\) at CSI-6 and the ADCP inside the Sandy Point dredged pit. Results show a satisfactory agreement between the two, with high \(I_w\) values (Table 4.2).

<table>
<thead>
<tr>
<th>Station</th>
<th>u-velocity component (m/s)</th>
<th>v-velocity component (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSI-6 (Surface)</td>
<td>0.72</td>
<td>0.68</td>
</tr>
<tr>
<td>Sandy Point (Surface)</td>
<td>0.69</td>
<td>0.70</td>
</tr>
</tbody>
</table>

Table 4.2. Willmott’s indexes for comparison of observed and simulated current velocities at stations CSI-6 and Sandy Point dredge pit (ADCP location).

To validate the Delft3D-WAVE module, a comparison was made between the simulated significant wave height (m) and the measurements at LPOL1 (Louisiana Offshore Oil Port, LA;
28°53'7" N 90°130" W) and SPLL1 (South Timbalier Block 52, LA/CSI-6; 28°52'0" N 90°29' 0" W) (Figure 4.1) during the selected cold front period in November 2014. The simulated and measured significant wave heights at LPOL1 and SPLL1 were also compared in Figure 4.8A and 4.8B, respectively.

Figure 4.6. Comparison of simulated (A) u-velocity component (ms\(^{-1}\)) and (B) v-velocity component (ms\(^{-1}\)) of surface current velocity (solid blue line) with measured data (dashed red line) at CSI-6. No measured velocity was available between August 3\(^{th}\) and August 5\(^{th}\).

Figure 4.7. Comparison of simulated (A) u-velocity component (ms\(^{-1}\)) and (B) v-velocity component (ms\(^{-1}\)) of surface current velocity (solid blue line) with measured data (dashed red line) at Sandy Point dredge pit (ADCP location).
The performance of sediment transport module was evaluated with surface SSC at four points (see Figure 4.9 for locations) (Table 4.3) measured inside the West Bay (Xu et al., 2016).

Table 4.3. Comparison between modeled SSC and field data.

<table>
<thead>
<tr>
<th>Study Area</th>
<th>Station</th>
<th>Field trip Date (Xu et al. 2016)</th>
<th>in situ SPM (mg/l)</th>
<th>Modeled SPM (mg/l)</th>
<th>Percent Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>West Bay</td>
<td>W1</td>
<td>19 Nov 2014</td>
<td>12.95</td>
<td>11.75</td>
<td>9.26</td>
</tr>
<tr>
<td></td>
<td>W2</td>
<td>20 Nov 2014</td>
<td>11.25</td>
<td>11.02</td>
<td>2.04</td>
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<td></td>
<td>W3</td>
<td>19 Nov 2014</td>
<td>17.10</td>
<td>15.98</td>
<td>6.54</td>
</tr>
<tr>
<td></td>
<td>W4</td>
<td>20 Nov 2014</td>
<td>10.75</td>
<td>9.86</td>
<td>7.16</td>
</tr>
</tbody>
</table>

Modeled SSC values agreed with in situ data with an average difference of 6.25%. Points were located in relatively high turbid water and characterized by 61% mud fraction (Xu et al., 2016).

Figure 4.8. Comparison between modeled (blue line) and measured (dotted red line) significant wave heights at (A) SPLL1 station and (B) LOPL1.
Figure 4.9 presents the Rayleigh-corrected true-color image of Landsat 8 OLI at the bird-foot Delta including Sandy Point dredge pit, P1, P0, P2, and sites where SSC was measured (points 1-4) inside the West Bay.

Simulated surface SSC were also compared visually with MODIS-derived SSC on 21 November 2014 (Figure 4.10). Model results generally agreed with the satellite imagery that presents a typical dispersal pattern during the post-frontal phase. The model produced higher than observed values of surface sediment concentration on the west of the Mississippi River in very
shallow coastal waters. This was most likely due to the failure of sediment retrieval algorithm from satellite data in very shallow coastal waters. In addition, the observed discrepancies could be due to bathymetric map which is not very accurate in very shallow water.

Figure 4.10. Comparison between simulated (A) and MODIS-derived (B) surface SSC (mg/l) on 21 November 2014 at 07:30 PM.

4.7 Results and Discussion

4.7.1 Overall Sediment Dynamics

Meteorological conditions affect bottom sediment dynamics. The complexity of fine-grained sediment resuspension and deposition within the wave boundary layer is defined by the interactions between surface waves and bottom sediment. During the passage of winter storms in
the northern Gulf of Mexico, there are three different stages of wind, i.e. the pre-frontal, frontal, and post-frontal phases, that influence the area (Moeller et al., 1993). The pre-frontal phase of winter storms is characterized by warm, humid weather, and mild winds from the southern quadrant toward the advancing front; while, the frontal phase is distinguished by an abrupt shift in wind direction from a southerly to a westerly component. The post-frontal phase or cold air outbreak is associated with cold winds from the northern quadrants causing a significant reduction in onshore wave action, where the fetch is minimized (Roberts et al., 1989; Mossa and Robersts, 1990; Moeller et al., 1993). The abrupt wind and wind-induced currents shift, and wave action associated with cold front passages re-suspend fine-grained sediments and transport them horizontally. In this study for the sake of convenience and a detailed investigation of sediment dynamics, the three different conditions were considered: (1) before the front, when winds are out of southern quadrant, (2) during the front, when the strong winds blow from the northern quadrant, and (3) after the post-frontal phase, when winds from the northern quadrant dissipate and wind direction shifts back to southerly, southeasterly, or southwesterly.

Figures 4.11, 4.12 and 4.14 present modeled current velocity (ms\(^{-1}\)), significant wave height (m), and surface SSC (kgm\(^{-3}\)) at selected times representing each of the above-mentioned stages referred hereafter as before, during, and after the cold front. Figure 4.11 shows the simulations results for the representative time as the “before the cold front” condition on November 16, 2014, at 03:00:00 PM. During this time wind at the NDBC BURL1 was from the southeast with a speed of 9.74 ms\(^{-1}\). As a result of the southeasterly wind, the current speed at water surface significantly increased up to 0.8 ms\(^{-1}\) on the west flank of the Mississippi River (Figure 4.11A). The current-induced shear stress caused sediment resuspension over shallow coastal waters. Figure 4.11B presents simulated significant wave height (m).
Figure 4.11. Maps of modeled (A) surface current velocity (ms\(^{-1}\)), (B) significant wave height (m), and (C) surface SSC (kgm\(^{-3}\)) on 16 November 2014, 03:00:00 PM (before cold front passage)
On the west flank of the Mississippi River adjacent to Sandy Point dredge pit, the significant wave height over Sandy Point dredge pit reached ~1 m. The BSS due to waves and currents ($\tau_{cw}$) (Figure 4.12A) exceeded the threshold bed shear stress (0.2 Nm$^{-2}$) in very shallow waters on the east and west flanks of the Mississippi River. The overall surface sediment concentrations showed (Figure 4.11C) values smaller than 0.008 kgm$^{-3}$ over the shelf area. Around Southwest Pass, surface SSC increased to ~0.018 kgm$^{-3}$ as a result of sediment flux and sediment resuspension over shallow areas under the wave action with a significant height of 1.5 m.

The relatively large wave height in this area was the result of swells propagating from the southern quadrant. Around the bird-foot delta (e.g., Southwest Pass) and especially on the east side of the delta, the SSC reached up to 0.02 kgm$^{-3}$ and higher. This was consistent with the model results in Allahdadi et al. (2011). These regions are supplied with fluvial sediment flux from the Mississippi River passes (e.g., Southwest Pass, South Pass, and Pass a Loutre). The combination of re-suspended and dispersed sediments from river outlets increased surface SSC along the western flank to about ~0.012 kgm$^{-3}$. Sediment sources for Sandy Point dredge pit were from both Mississippi River passes and locally re-suspended sediment from shallow coastal waters. The river-borne sediments and re-suspended sediment were advected toward the Sandy Point dredge pit by south/southwesterly currents.

In addition, relatively strong BSS (Figure 4.12D) resulting from waves and currents interaction over very shallow areas along the eastern delta flank resuspend bed sediments which were transported northward by currents. Currents carried sediment from the Southwest Pass and other outlets toward the north. The west flank of the bird-foot delta and the unique location of Sandy Point dredge pit were relatively sheltered against swell waves by the Southwest Pass handle, so over this area wave height was < 0.8 m.
Figure 4.12. Modeled BSS (Nm$^{-2}$) induced by combination of waves and currents ($\tau_{cw}$) for (A) before cold front passage, (B) during cold front passage, and (C) after cold front passage.
In addition, the sheltered area was not as shallow as the eastern flank, and less resuspension occurred by wave actions. Hence, smaller values of sediment concentration were observed (0.005-0.01 kgm\(^{-3}\)) on the west flank of the Mississippi River. The onset of a cold front on 17 November 2014 at 10:00:00 AM, where wind direction suddenly veered from the southern to the northern quadrant. Winds from northern quadrant prevailed for a prolonged period of almost three days. Strong northerly wind generated southward to southwestward surface currents with speeds larger than 0.8 ms\(^{-1}\) over the inner shelf (Figure 4.13A). Figure 4.12B shows the wave pattern over the eastern and western flanks of the Mississippi River delta at the time corresponding to the peak of the cold front. The northerly wind deviated the Mississippi River plume from northwestward to southwestward (Figure 4.13C). Wind conditions on 18 November 2014, 6:00:00 AM was considered as the representative for the “during the cold front” stage. At this time the northerly wind speed reached a peak of 13 ms\(^{-1}\).

The velocity of southward wind-driven surface current reached to ~1.5 ms\(^{-1}\) over the Sandy Point dredge pit. The model results illustrated substantial dispersal of fine fluvial sediments due to the cold front-driven currents. Significant wave height (m) was larger than 2 meters for most of the shelf, except shallow coastal bays with small wind fetches. Southward waves affect almost the entire shelf area. This combination of large wave heights and strong current speeds significantly promoted sediment resuspension and results in significant increase of surface SSC over the inner shelf (Figure 4.13C). As a result, the fine sediments from the bays, lagoons and the Grand Pass along with re-suspended sediments from the bottom were transported toward Sandy Point dredge pit. Along the western Mississippi flank especially midway between the Southwest Pass handle and the entrance of Barataria Bay with shallow waters, sediment concentration increased to more than 0.2 kgm\(^{-3}\).
Figure 4.13. Maps of modeled (A) surface current velocity (ms$^{-1}$), (B) significant wave height (m), and (C) surface SSC (kgm$^{-3}$) on 18 November 2014, 06:00:00 PM (during the cold front)
Over this area, strong BSS (>0.25 Nm\(^{-2}\)) resulted from wave-current interaction exceeded the threshold for sediment suspension and critical BSS (0.2 Nm\(^{-2}\); defined in the model) (Figure 4.12B) causing an increase in the sediment re-suspension and the SSC over the Louisiana inner shelf. Wave orbital velocities decreased exponentially with water depth from the sea surface; hence, the influence of waves in shallow water was noticeable. The re-suspended sediment clearly reached water surface and covered the inner shelf due to strong sediment re-suspension and storm-induced turbulence. The Sandy Point dredge pit area was significantly affected by a high surface SSC zone with the maximum concentration of 0.12 kgm\(^{-3}\) (Figure 4.14). During the “post-cold front” condition northerly winds shifted to southerly-southeasterly wind. The wind speed decreased from ~13 ms\(^{-1}\) to 7 ms\(^{-1}\) within three days after the peak of a cold front on 21 November 2014 at 3:00:00 PM. The current was in the wind direction. Over the inner shelf, the current velocity decreased from 0.8 ms\(^{-1}\) (associated with the peak of cold front) to 0.4 ms\(^{-1}\). The current velocity reached ~0.55 ms\(^{-1}\) around South Pass (Figure 4.15A). At this time, the significant wave height around the Sandy Point dredge pit reached ~0.6 m which was significantly lower than the modeled significant wave height of ~2 meters when the strong northerly wind is blowing (Figure 4.13B and 4.15B).

Figure 4.14. Timeseries of modeled surface SSC (kgm\(^{-3}\)) over Sandy Point dredge pit at P0 site in the middle of the pit

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The southeasterly current pushed re-suspended sediment toward the west and northwest of the Louisiana Bight. During this period, the fluvial sediment load from Southwest Pass, West Bay, and Grand Pass was advected toward Sandy Point dredge pit by the northwestward current with a velocity of $0.35 \text{ ms}^{-1}$. The relatively strong southeasterly winds triggered this dispersal shift comparing to the previous condition (during the front). During the waning phase of a cold front, the re-suspended sediments were re-deposited onto the inner shelf due to the substantial decrease in wave activity and onshore current velocities (Figure 4.15A and 4.15B).

Consequently, the surface SSC over the inner shelf decreased as sediment was being deposited or transported by northwestward currents. The surface SSC reached to $0.016 \text{ kgm}^{-3}$ on average over the pit (Figure 4.15C) compared to $0.12 \text{ kgm}^{-3}$ during the cold front. Given the fact that wave orbitals during this phase reached to the bottom of the shallow coastal region on the west side of the Mississippi, more fluvial sediments were introduced to the sediment flux directing toward northwest and west.

Sediments were reworked over the shallow areas under the influence of the combined effect of waves and currents. BSS ($\tau_{cw}$) was strong enough ($>0.2 \text{ Nm}^{-2}$) to re-suspend bottom sediment inside the west Bay and around the Southwest Pass. As a result, the fine sediments from the river along with re-suspended sediments from the bottom were transported northwestward during this period.

Suspended material over the Sandy Point dredge pit had three major sources of sediment after a cold front passage: (1) background sediment advected from far field (e.g., Barataria Bay) during frontal passage, (2) locally reworked and re-suspended sediment in shallow coastal waters under the wave-current interaction, and (3) sediment flux from the Mississippi River passes dispersed by currents toward the Sandy Point dredge pit.
Figure 4.15. Maps of modeled (A) surface current velocity (ms$^{-1}$), (B) significant wave height (m) surface SSC (kgm$^{-3}$), (B, and (C) surface SSC (kgm$^{-3}$) on 21 November 2014, 03:00:00 PM (post cold front condition)
4.7.2 Sediment Dynamics over Sandy Point Dredge Pit

In the sediment model, physical parameters were defined based on several sensitivity tests. Figures 4.16A and B present an example of the comparison between two tests based on two different M values ($0.5 \times 10^{-4} \text{ kg m}^{-2} \text{ s}^{-1}$ and $0.1 \times 10^{-4} \text{ kg m}^{-2} \text{ s}^{-1}$).

Figure 4.16. Thickness of cumulative erosion-sedimentation (m) with M value of (A) $0.1 \times 10^{-4} \text{ kg m}^{-2} \text{ s}^{-1}$ and (B) $0.5 \times 10^{-4} \text{ kg m}^{-2} \text{ s}^{-1}$

Sediment dynamics over the Sandy Point dredge pit during a cold front is driven by intense currents and waves generated by the cold front. While wave action significantly contributes to
producing an active BBL (Section 4.7.3), re-suspended sediments over the pit and sediments from the adjacent areas were transported by currents toward/from the pit. Hence, bottom currents could contribute to sediment transport in BBL where sediments were predominantly fine-grained silt and clay (i.e., cohesive sediment). Simulation results for the currents generated before, during, and after the front suggested that generally the surface and bottom currents flowed in opposite directions (Figure 4.17).

Figure 4.17 Modeled near-surface (A-C) and near-bottom (D-F) current velocity (ms⁻¹), for before the front (A and D), during the front (B and E), and after the front (C and F)
On 16 November 2014, 3:00:00 PM and before the northern frontal winds initiate, the southerly-southeasterly wind-driven currents moved toward north and northeast on the surface of Sandy Point dredge pit with a velocity of ~0.3 ms\(^{-1}\) (Figure 4.17A). Current velocity was almost uniform from the south to the north of the pit. Over the near-bottom layer, currents moved toward southwest with velocity ~0.025 ms\(^{-1}\) in the middle and south of the pit and with a velocity of ~0.05 ms\(^{-1}\) on the north and the northeast corner of the pit (Figure 4.17D) which was likely due to shallower water depth on the north of pit. During northerly wind, surface southward currents were strong (Figure 4.17B). Near-surface current velocity of ~1.2 ms\(^{-1}\) was observed over the pit. The direction of near-bottom currents during this condition was northeastward with a velocity of ~0.06 ms\(^{-1}\) (Figure 4.17E). As the wind direction shifted from northerly to southerly (after the cold front condition), the induced near-surface currents were directed predominantly northwestward over the pit with a velocity of 0.04 ms\(^{-1}\) (Figure 4.17C), while the near-bottom currents directed to the east with a velocity of ~ 0.012 ms\(^{-1}\) (Figure 4.17F).

The general conclusion was that near-surface currents over the pit varied depending on wind direction; however, near-bottom currents flowed almost in the opposite direction of surface currents. The reverse bottom current was observed even during Hurricane Katrina over the Louisiana shelf (Allahdadi and Li, 2017). This was similar (Figure 4.18) at P0, P1, and P2 (Figure 4.9). P1 is located north of the Sandy Point dredge pit where water depth is about 10.5 m. P0 is in the middle of the pit with a water depth of 20 m. P2 is in the south of the dredged area with a water depth of 11.5 m. Timeseries show that near-surface current velocities are almost the same for all three points. For the near-bottom currents, both current velocity components, especially north-south component (y-component) predominantly show opposite current direction compared to the near surface components.
At the peak of a cold front, the location on the south of the pit (P2) shows larger near-bottom currents which could be due to the larger depth gradient in the vicinity of this point. The major part of sediment resuspension during a cold front over the pit or elsewhere over the Louisiana shelf was due to wave action and wave-induced shear stresses (Kobashi, 2009; Allahdadi et al., 2011).

![Figure 4.18. Timeseries of current velocity components (x and y) for near surface and near-bottom at P0 (blue line), P1(red line), and P2 (green line) sites](image)

Examining the simulated wave patterns over the pit and adjacent regions during all phases showed an almost uniform wave field over the pit (Figure 4.19). A day before the northerly wind prevails, a uniform southeasterly-southerly wave with a significant height of ~0.5 m was simulated over the pit area (Figure 4.19A). Two days later during the peak of cold front, the dominant wave height over the pit was about 2 m from northwest to north (Figure 19B). Just two days after the peak of cold front the prevailing waves were from the southeast with a height of ~0.75 m (Figure 4.19C).
Figure 4.19. Significant wave height (m) overlaid with vectors of wave mean direction for (A) before cold front passage, (B) during passage of northerly wind, and (C) after cold front passage.
Timeseries variations of significant wave height (m) at P0, P1, and P2 sites showed that at least for two days during the cold front from 17 through 19 November 2014, the significant wave heights over the pit were >1.5 m (Figure 4.20).

Figure 4.20. Timeseries of significance Wave Height (m) at P0 (blue line), P1(red line), and P2 (green line) sites

Before cold front passes, the condition was characterized by mild wind speed and moderate wave heights. BSS over the entire Sandy Point dredge pit and other areas around the pit was about 0.05 Nm$^{-2}$ which was substantially below the critical shear stress for erosion (Figure 4.21A). During the northerly wind, wave height and bottom currents increase, and shear stress reached the threshold value (i.e., critical shear stress) above which bottom sediment was suspended. Cold front-induced wave and current increased BSS to the values of >0.2 Nm$^{-2}$ over the shallower areas around the pit, especially on the east side (Figure 4.21B). Inside the pit, BSS was smaller (0.1 Nm$^{-2}$ for the middle part and 0.05 Nm$^{-2}$ for the northern part) than the critical value. In the shallower areas inside the pit, BSS exceeded the critical value. Therefore, during the cold front, bed resuspension can potentially occur in shallow areas around the pit. Inside the pit, bed sediment remobilization and re-suspension was most active in the southern area with shallower depths. During a cold front with southward near surface current, the bottom currents were mostly northward, a near-bed cross-shore mud flow from south to north in the pit was expected.
Figure 4.21. BSS (Nm$^{-2}$) variations over the Sandy Pit when wave force was considered (A) before the cold front, (B) during cold front passage, and (C) after the cold front
This contributes to the accumulation of advected sediment on the north of the pit. Two days after the cold front, and BSS in the pit and adjacent areas significantly decreased (Figure 4.21C). Cumulative erosion/sedimentation (m) (Figure 4.22A-C) at the end of simulation that includes all time periods before, during, and after cold front was examined for three above-mentioned scenarios (see Section 4.5).

Figure 4.22. Thickness of cumulative erosion-sedimentation (m) during simulation period (A) including wave force and river discharge, (B) including wave force and excluding river discharge (C) without wave force and including river discharge
The comparison of results for these three scenarios suggested that the major bed level change inside the pit was associated with wave action. The scenario with considering all forces (Figure 4.22A) that represent the most accurate change inside the pit showed the larger sedimentation over the pit occurred in the northern part of the pit. Sedimentation amount decreased as approaching to the south of the pit. This was likely due to the flow of bottom sediments from the south to the north of the pit during a cold front as a result of near-bottom northward currents as illustrated in Figure 4.17 and 4.17. Scenario 2 that includes all forces and excludes river discharge generally depicted the same pattern. However, compared to scenario 1, the intensity of sedimentation was lower, and smaller areas, especially along the eastern and western edge of the pit were affected by sedimentation (Figure 4.22B). Sedimentation map resulted for scenario 3 showed the effect of riverine sediment on the pit without considering the wave action. Although the sedimentation pattern associated with this scenario was generally similar to scenario 1 and 2, the maximum sedimentation was less than 19% of those two scenarios. This could be due to the prevailing southward current during the cold front that prevents riverine sediment flux from Grand Pass and Southwest Pass, and West Bay from being transported toward the Sandy Point dredge pit. During fair weather conditions, although northward surface currents were in favor of transporting river sediments toward the pit, they were fairly weak and had a small contribution to the transport of riverine sediments flux toward the pit. The scenario 1 with considering all forces estimated that the maximum sedimentation over the pit reached to ~9 mm and the average sedimentation over the pit was 4 mm during the cold front passage. Assuming that the Louisiana shelf is affected typically by 30-40 cold front passages per year (Roberts et al., 1987), the annual average sedimentation associated with cold front would be 12 cm to 16 cm (0.12 m to 0.16 m) at Sandy Point dredge pit. The annual sedimentation thickness over Sandy Point dredge pit,
calculated from 7Be radionuclide data (O’Connor, 2017) and model results (Lu and Nairn, 2010), vary from 50 cm to 100 cm. Therefore, cold front passages could contribute to the total annual sedimentation thickness over Sandy Point dredge pit from 16% to 24%.

4.7.3 Dynamics of Bottom Boundary Layer over the Sandy Point Dredge Pit

During the cold front outbreak shown in the previous section, surface SSC significantly increased over the Louisiana shelf including Sandy Point because of large wave heights and currents. The amount of suspended sediment on the surface was dependent on the wave and current interactions with the bed sediment within the bottom boundary layer. Dynamics of the bottom boundary layer was investigated for two scenarios with and without including the waves. Timeseries of simulated BSS before, during, and after the cold front for a location over the Sandy Point (P0, see Figure 4.9 for location) for two scenarios were examined (Figure 4.23). In this Figure, the red dashed horizontal shows the critical BSS for erosion as defined in the model setup. For the scenario without considering the effect of surface waves on the BSS, the BSS values were always smaller than the threshold shear stress (0.2 Nm$^{-2}$).

![Figure 4.23](image_url)

Figure 4.23. Simulated BSS (Nm$^{-2}$) with wave force (black line) and without wave force (blue dotted line) at P0 (located at a depth of 20 m). Red dashed line depicts the critical shear stress for erosion introduced to the model
Even during the peak of the cold front, the BSS was about 4 times smaller than the threshold value. Therefore, currents were too weak to stir up the bottom sediment into the flow. During the peak of cold front, the BSS exceeded the threshold for sediment suspension and reached \( \sim 0.45 \, \text{Nm}^2 \). The computed BSS was consistent with simulated BSS reported (\( \sim 0.5 \, \text{Nm}^2 \)) in Kobashi (2009) during a winter storm (2005) in the northern Gulf of Mexico. This prolonged period corresponded to an increase in the sediment resuspension and the SSC (Figure 4.13C). The value was sufficiently large for several hours between 17-18 November to re-suspend bed sediments even over the relatively deep Sandy Point dredge pit. This suggested that over the Sandy Point dredge pit, BSS induced by waves were a primary driving force for sediment resuspension and currents mainly contributed to subsequent advection and transport of the sediments over the pit area. The fluctuation of surface SSC at P0 site (Figure 4.14), in general, was in phase with the BSS (Figure 4.23; solid black line). Effect of cold front-generated BSS on the sediment concentration within the bottom boundary layer (about 0.05 m above the bed) was investigated by examining timeseries of simulated bed concentration for both scenarios with and without including waves (Figure 4.24). For the waves-included scenario sediment concentration within the bottom boundary layer reached its peak values almost at the peak of cold front for all locations (Figure 4.24A). At P0 site, as BSS increased from an ambient value of \( \sim 0.05 \, \text{Nm}^2 \) to a peak of \( \sim 0.45 \, \text{Nm}^2 \) (Figure 4.23), the bottom SSC increased from a background value of \( \sim 2 \, \text{kgm}^{-3} \) to a maximum of 35 \( \text{kgm}^{-3} \). At this time, the bottom SSC at P1 and P2 reached 42 \( \text{kgm}^{-3} \) and 25 \( \text{kgm}^{-3} \) respectively. South of the pit (P2) it showed a significantly smaller peak of sediment concentration (\( \sim 25 \, \text{kgm}^{-3} \)) that occurred several hours before P1 and P0. The phase difference could be due to refraction of waves at the southern edge of the pit when propagating from the deeper to the shallower areas outside of the pit.
Figure 4.24. Near-bed (5 cm above seabed) SSC (kgm$^{-3}$) of P0, P1, and P2 (A) wave force considered and (B) no wave force considered.

The lower peak at this location can be the result of near-bed mudflow from south to north as discussed in Section 4.7.2. When the effect of wave-induced shear stress on the bed was not considered in the simulation (Figure 4.24B), sediment concentration within the bottom boundary layer substantially decreased. The peak of concentration for this scenario changed from 25 kgm$^{-3}$ to ~0.5 kgm$^{-3}$ for P2, from 42 kgm$^{-3}$ to ~1.1 kgm$^{-3}$ for P1, and from 35 kgm$^{-3}$ to ~2.2 kgm$^{-3}$ for P0, showing 15-50 times decrease in concentrations compared to the wave included scenario. An increase in the bottom sediment concentration during strong wave events in the region was reported by Allison et al. (2000). They measured concentration of about 25 kgm$^{-3}$ at 20 cm above
the bed during the passage of a cold front in the northern Gulf of Mexico. In the no-wave scenario
the peak of sediment concentration at P2 was in phase with those at P1 and P0. This proved the
effect of the wave on different behavior of sediment dynamics at this location, especially the phase
shift of the concentration peak (Figure 4.24). Time variations of the suspended sediment across
the water column including the bottom boundary layer at P1, P0, and P2 for both scenarios with
and without waves demonstrated the formation of an active bottom boundary layer during cold
front mainly as a result of wave action (Figure 4.25).

Figure 4.25. Time variations of simulated SSC across the water column for wave included scenario
(A, B, C) and no-wave scenario (D, E, F) at P1, P0, and P2
Combination of cold front-generated wave and current, significantly contributed to increasing of bed sediment concentration at all three locations (Figures 4.24A-C). This high sediment concentration zone that represents the bottom boundary layer was formed during the peak of a cold front within 1 m above the bed. The re-suspended sediment load caused by the cold front within the BBL moved from south to north following the bottom currents. This bottom mud flow accounted for the increase in the height of the boundary layer from south to north (or from P2 to P1). Outside of the boundary layer, sediment concentration significantly decreased. For example, at point P0 which was located in the middle of the pit, sediment concentration during the peak of the cold front varied from 35 kgm\(^{-3}\) near the bottom to about 0.008 kgm\(^{-3}\) at the water surface. Right above the bottom boundary layer, sediment concentration declined to about 0.01 kgm\(^{-3}\) and SSC exhibited small variations across the water column up to the surface. This means that during the cold front the major amount of sediment transported over the pit and surrounding area occurred near the bed and within the bottom boundary layer. The transport of bed sediments from the shallow regions in the south of the dredged area toward the pit contributed to the bed level changes inside the pit in the form of sedimentation (section 4.2). Due to the substantial decline in the wave height and current speed where fairly weak southerly wind prevailed, no active BBL was formed, and near-bed SSC was almost zero. However, at this time surface SSC at all stations increased to ~0.016 kgm\(^{-3}\). This could be due to resuspension of bed sediments over of shallow areas around the Mississippi River passes that are located on the south of the pit. The re-suspended load from these areas and from the Grand Pass and the Southwest Pass dispersed toward the pit which increased SSC over the pit. This transport was driven by northward surface currents produced after the cold front. For the no-wave scenario, very thin active BBL's was formed (Figures 4.24D-4.24F). Variations of SSC above the BBL and across the water column, in this case, was more or
less similar to the case with including waves. This is another demonstration that BBL dynamics over the pit and surrounding area was mostly limited to the bed and vertical dispersion of bed sediments did not significantly affect the water column SSC. After the cold front, waves and currents were significantly weakened. The no-wave scenario showed no active BBL, and very small or zero sediment concentrations across the water column and at the surface were observed. Zero surface SSC is due to the fact that no wave action is considered to re-suspend sediments over the shallow areas on the west flank of the Mississippi River.

4.8 Summary and Conclusion

The overarching purpose of this study was to determine the response of sediment dispersal and resuspension to a cold front passage by numerical simulations using a three-dimensional model. A fully-coupled depth-averaged hydrodynamic, sediment transport and wave model Delft3D in three dimensions was implemented to extend our understanding about the combined effect of waves and currents on sediment resuspension, deposition and advection of re-suspended sediments in Sandy Point dredge pit during a cold front. The model was forced by tides, river discharge, wind, and waves. Three different scenarios were investigated: (1) with all forces; (2) excluding river discharge, and (3) excluding waves. Results of waves, currents and sediment transport, were in a good agreement with in situ observations and satellite images. Results suggested that the combined action of waves and currents had a crucial effect on sediment dynamics in Sandy Point dredge pit and the intensity of the BSS and the turbulence near the seabed in Sandy Point dredge pit increased significantly where the wave effect was considered. The energetic cold front triggered a large resuspension event due to the superposition of effects from the wind-induced waves and currents. The northerly-northeasterly wind impedes the sediment-rich water entrainment of fine-sediment to the Sandy Point dredge pit. During the waning phase of the
storm as the wind direction shifted from the northern quadrant to the southern quadrant, sediment-laden water discharged from the Mississippi passes was entrained toward the Sandy Point dredge pit. In the absence of sediment flux from the Mississippi River scenario, results revealed that the delivery and dispersal of fine riverine sediment from the Mississippi River passes played an insignificant role in determining the seabed state of the Sandy Point dredge pit during the passage of the cold front. In addition, results indicated that the destination of riverine and re-suspended sediments was highly dependent on the interaction of river plume and wind driven currents. Results suggested that the complexity of sediment resuspension and deposition within bottom boundary layer during a cold front was due to the interaction between waves and currents, and fine bottom sediment in the Sandy Point dredge pit. Wave-induced shear stress above the threshold for sediment suspension clearly illustrated significant re-suspension during the storm, suggesting the importance of sediment suspension and associated dispersal due to storm waves and currents. The sediment transport during the cold front had an important implication for the ecosystem. The ecosystem can be affected by flux of nutrients and biogeochemical materials through entrainment of sediment. Understanding the near-bed response to wind, waves, and currents may help better understand the sediment dynamics, and improve predictive capabilities for resuspension and transport during winter cold fronts.
CHAPTER 5: NUMERICAL STUDY OF SEDIMENT RESUSPENSION OVER THE SANDY POINT DREDGE PIT DURING THE SUMMER FAIR WEATHER CONDITION

5.1 Introduction

In this chapter, following the modeling work of Chapter 4, I investigated sediment dynamics over the Sandy Point dredge pit and inner Louisiana shelf during fair-weather in summer. In contrast to the cold front period, the prevailing wind during summer is from the south quadrant (Zavala-Hidalgo et al., 2014). This may impose specific characteristics of sediment transport because the direction of the prevailing wind and associated surface currents are favorable for discharged sediment from the Mississippi River to be transported to the Sandy Point dredge pit. This can produce a different sedimentation pattern compared to the cold front period.

During a cold front event, sediment-laden waters are basically transported away from the Sandy Point by southward currents during a cold front; however, under the influence of this northward summertime currents, sediment-rich waters from the major outlets (e.g., Southwest Pass and Grand Pass) can be readily advected toward the pit. During non-summer months, a significant portion of sediment-laden waters from the Mississippi River is transported westward (downcast) by coastal currents (Cochrane and Kelly, 1986; Nowlin et al., 2005).

During summer, sediment-rich waters from the Mississippi River can move toward the north quadrant by the wind-induced currents. The wind changes seasonally over the Louisiana shelf. In summer (June-August), meteorological forcing usually is not strong. Wind becomes weak and in favor of upwelling conditions, while during non-summer (September-May) strong and the downwelling-favorable wind is dominant (Cochrane and Kelly, 1986; Cho et al., 1998; Nowlin et al. 1998; Allahdad et al., 2012). Figure 5.1 presents wind stress variations based on wind speed measurement at WAVCIS CSI-6. The significant decline of wind stress during summer over the
Louisiana shelf was followed by a sustainable decrease of wave energy, and the associated sediment resuspension (Allahdadi et al., 2011). The hydrodynamics could also dictate the sediment dynamics and the infilling rate in the Sandy Point dredge pit.

Figure 5.1. Wind stress variation based on wind speed measured at WAVCIS CSI-6 from June-November 2009 (from Allahdadi et al. 2012)

A coupled modeling system in Chapter 4 was developed to understand sediment dynamics over the study area during a cold front. In this chapter, the same framework was followed. However, the input data were for 5 July-22 August 2015. In this chapter, specific objectives were to: (1) determine hydrodynamics and sediment dynamics under fair-weather conditions during summer, (2) identify the major source of sediment for the Sandy Point dredge pit under the summertime fair-weather conditions and to determine if sediment transported directly from the Mississippi River to the pit area or the resuspended sediment by wave activities was the main source of sediment over the pit, and (3) assess the impact of the Sandy Point dredge pit on current velocities and wave heights.

This chapter is organized as follows: Sections 5.2 presents method and data. The coupled FLOW, WAVE and sediment transport model for fair-weather conditions in summer 2015 were briefly discussed in Section 5.3, 5.4, and 5.5. The Delft3D coupled modeling system including
wind, tide, waves, sediment processes along with the governing equations discussed extensively in Chapter 4. Section 5.6 provides FLOW model verification for the simulation period. The WAVE model verification during fair-weather conditions was discussed extensively in Chapter 3. The impacts of the Sandy Point dredge pit on hydrodynamics are presented in Section 5.7. The results presented in this chapter are site-specific. However, the methodology could be applied to any dredge pit site that features primarily cohesive sediment.

5.2 Method and Data

5.2.1 Study Area

The Sandy Point Dredge Pit is a mud capped pit on the west flank of the Mississippi River (Figure 5.2), which is highly influenced by sediment-laden water discharged from the Mississippi River distributaries, mainly by Grand Pass and Southwest Pass.

![Figure 5.2](image.png)

Figure 5.2. (A) The location of stations used to obtain initial boundary conditions and to validate the model, (B) the Sandy Point dredge pit and the location of P1, P2, and P3 used for the detailed study of the pit. Geographic locations of the Sandy Point dredge pit, Southwest Pass, Grand Isle and Pelican Island labeled as SP, SWP, GI, and PI, respectively
5.2.2 Modelling Approach

To study sediment dynamics under the fair-weather conditions, a coupled Delft3D FLOW, WAVE, and sediment transport model was implemented from July 5, 2015, through August 22, 2015. The Delft3D WAVE model was used to simulate the evolution of wind-generated waves. The sediment transport formulation proposed by Van Rijn (1991), considering both waves and currents was used. Table 5.1 provides an overview of model specific setting for fair-weather conditions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value/Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLOW simulation time step</td>
<td>0.05 min</td>
</tr>
<tr>
<td>Coupling interval FLOW-WAVE</td>
<td>180 min</td>
</tr>
<tr>
<td>WAVE simulation time step</td>
<td>30 min (non-stationary)</td>
</tr>
<tr>
<td>WAVE whitecapping scheme</td>
<td>Komen et al. (1984)</td>
</tr>
<tr>
<td>Sediment transport formulation</td>
<td>Van Rijn (1991)</td>
</tr>
</tbody>
</table>

To identify the source of sediment for the Sandy Point dredge pit during fair-weather, two different scenarios were examined: (1) the model includes all forces along with discharged sediment from the Mississippi River distributaries, and (2) the model includes all forces and excludes sediment supply from the river distributaries. In addition, to investigate the influence of
the Sandy Point dredge pit on the hydrodynamics over the pit and surrounding areas two different bathymetric configurations, (1) with the Sandy Point dredge pit, and (2) without the Sandy Point dredge pit during fair-weather were considered.

5.3 Model Inputs and Set-up

5.3.1 Model Grid and Bathymetry

The same bathymetry data and grids employed in Chapter 4 were used (see Figure 4.2) for the present simulation. In short, to resolve the complex geometry of the study area, a horizontal curvilinear grid with spatial resolution varying from 10 m to 3 km with the σ co-ordinate was used in the flow model (the pit area was resolved with a spatial resolution as fine as 10 metres). The grid has 19 vertical layers.

The σ co-ordinate approach allows using a constant number of layers along the depth with the spatially variable vertical resolution depending on the water depth at each location. Figure 5.3 presents an example of σ layers. The layer thickness implies a percentage of the entire water column (Trefferes, 2009).

Figure 5.3. A schematic of σ layers (Trefferes, 2009)
In this study, the vertical resolution was higher near the surface and near the bottom compared to the mid-depth to resolve the surface and the bottom boundary layers. In the wave model, the grid resolution varies between 58 m to 2 km (see Chapter 3 for details), and the bathymetry data were similar to the data used in preparing a bathymetric map in FLOW module.

The bathymetry data was obtained from National Geophysical Data Center (NGDC) coastal relief model (spatial resolution of 90 meters) (see Chapter 4 for details) that was combined with a local hydrographic survey conducted at the Sandy Point dredge pit in July 2015.

### 5.3.2 Wind Data

For all scenarios, the model was forced with spatially uniform and time-varying wind speed and direction at 1 hour intervals. The data were obtained from BURL1 at 28°54′18″ N and 89°25′42″ W (see Figure 5.2 for location), the buoy station is maintained by the National Data Buoy Center (NDBC). The height of the anemometer for this station is 38 m above the sea level. Therefore wind speeds were reduced to that at the standard height of at 10 m ($U_{10}$) using Equation 5.1 (Kamphuis, 2000):

$$
\frac{U_{10}}{U_z} = \left(\frac{10}{z}\right)^{1/7}
$$

where $z$ is the anemometer height (m), and $U_z$ is the measured wind speed at height $z$ (ms$^{-1}$).

Figures 5.4A, B present time variations of wind vectors, and the wind rose obtained from the BURL1 station from July 15 to August 21, 2015. The wind data obtained from the BURL1 station was used in FLOW and WAVE models. The wind drag coefficients used in the FLOW model were selected as functions of wind speed (Smith and Banke, 1975). The wind drag coefficient reflects the increasing roughness of the water surface with increasing wind speed. The three wind drag coefficients compute three breakpoints in the piece-wise linear function of wind drag coefficient.
and wind speed (Deltares, 2011). The wind data then converted to a Delft3D readable format (.wnd).

Figure 5.4. (A) Timeseries of wind vectors, and (B) wind rose compiled from the BURL1 station from July 15, 2015, through August 22, 2015
5.3.3 Boundary Condition

The FLOW model along the open ocean boundary (see Figure 5.5 for the location of the open boundary) was forced by tides using the tidal constituents computed by ADCIRC-2DDI (the depth-integrated version of the ADCIRC; Westerink, 1993; Westerink et al., 1993; Mukai et al., 2002).

![Figure 5.5](image1)

Figure 5.5. The 384 x 371 curvilinear orthogonal computational grid. The mesh resolution varies from 10 m to 3 km. The red dot shows the location of the Sandy Point dredge pit, and semi-circular red line presents the FLOW model open boundary

The amplitudes and phases of the tidal constituents were interpolated onto the open boundary nodes. The water level variations were constructed along the open boundary using amplitude and phase of tidal constituents (Figure 5.6).

![Figure 5.6](image2)

Figure 5.6. Variations of water level prescribed to the open boundary at a point in the middle of the open boundary based on tidal constituents’ amplitude and phase

The FLOW model contained 9 tidal constituents including three diurnal constituents ($O1$, $K1$, $Q1$), four semi-diurnal astronomical tidal constituents ($M2$, $S2$, $N2$, and $K2$) along with two
overtides of $M2$ ($M4$ and $M6$) that were extracted from the USACE’s Eastcoast 2001 computed by ADCIRC 2DDI and applied to the FLOW model open boundary (Table 5.2). Data of amplitude and phase for different tidal constituents were used to combine them and establish the timeseries of tidal variations using the following equation:

$$\zeta(x, y, t) = \sum A_i(x, y) f_i(t_0) \cos \left[ \frac{2\pi}{T_i} (t - t_0) + V_i(t_0) - \Psi_i(x, y) \right]$$

(5.2)

where $A_i(x,y)$ and $\Psi_i(x,y)$ are the amplitude and phase, respectively, at the location $(x,y)$ of interest for constituent $i$, which are provided by the Eastcoast 2001 tidal database (Mukai et al., 2002). The periods $T_i$ (hours) for each of the 9 constituents were presented in Table 5.2. Parameter $f_i(t_0)$ is the nodal factor, and $V_i(t_0)$ is the equilibrium argument which are provided by the Eastcoast 2001 database (Mukai et al., 2002, Table 4 therein).

<table>
<thead>
<tr>
<th>Tidal Constituent</th>
<th>Description</th>
<th>Period (hour)</th>
<th>Amplitude (m)</th>
<th>Phase (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O1</td>
<td>Lunar diurnal constituent</td>
<td>25.82</td>
<td>0.1488</td>
<td>20.784</td>
</tr>
<tr>
<td>K1</td>
<td>Lunisolar diurnal constituent</td>
<td>23.93</td>
<td>0.1501</td>
<td>17.779</td>
</tr>
<tr>
<td>Q1</td>
<td>Larger lunar diurnal elliptic</td>
<td>26.87</td>
<td>0.0309</td>
<td>4.632</td>
</tr>
<tr>
<td>M2</td>
<td>Principal lunar semi-diurnal constituent</td>
<td>12.42</td>
<td>0.0108</td>
<td>112.818</td>
</tr>
<tr>
<td>S2</td>
<td>Principal solar semi-diurnal constituent</td>
<td>12.00</td>
<td>0.0075</td>
<td>100.822</td>
</tr>
<tr>
<td>N2</td>
<td>Lunar elliptic semi-diurnal constituent</td>
<td>12.66</td>
<td>0.0029</td>
<td>132.182</td>
</tr>
<tr>
<td>K2</td>
<td>Lunai-solar semi-diurnal constituent</td>
<td>11.97</td>
<td>0.0028</td>
<td>97.561</td>
</tr>
<tr>
<td>M4</td>
<td>M2-derived higher harmonic constituent</td>
<td>6.21</td>
<td>0.0017</td>
<td>293.652</td>
</tr>
<tr>
<td>M6</td>
<td>M2-derived higher harmonic constituent</td>
<td>4.14</td>
<td>0.0005</td>
<td>274.964</td>
</tr>
</tbody>
</table>
5.3.4 Mississippi River Discharge

Mississippi River discharge was obtained from the USGS Belle Chasse, LA station, located at 29°51' 25" N and 89° 58' 40" W (USGS 07374525) (Figure 5.2). The water discharge for each Mississippi River pass was calculated based on the portion recommended by Allison et al. (2012) (Figure 5.7). Suspended sediment concentration (SSC) discharged from the Mississippi River was obtained using the equation provided by Snedden (2006), based on the relationship between the river discharge measured at Belle Chasse and SSC (Figure 5.8).

Figure 5.7. Average annual water discharge (km³y⁻¹) measured from 2008-2010 for natural and man-made outlets of the Mississippi River (from Allison et al. 2012)
Figure 5.8. Log-log relationship between Mississippi River discharge and SSC concentrations in surface water samples ($n = 158$) obtained at Belle Chasse, LA, from 1991-2004 (from Snedden, 2006)

The velocity of flow from each outlet was obtained based on simulated values by the study of Gonzalez (2014). The river discharge timeseries from eleven outlets (Table 5.3) located on the eastern, western, and southern sides of the Mississippi River along with their associated sediment concentrations were prepared as inputs to the model.

Table 5.3. Water discharge (%) from Mississippi River’s outlet (from Allison et al. 2012, Figure 5.6.)

<table>
<thead>
<tr>
<th>Station Name</th>
<th>Discharge Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southwest Pass</td>
<td>30.92</td>
</tr>
<tr>
<td>South Pass</td>
<td>8.9</td>
</tr>
<tr>
<td>Grand Pass</td>
<td>9.8</td>
</tr>
<tr>
<td>Cubit’s Gap</td>
<td>9.8</td>
</tr>
<tr>
<td>Pass a’Loutre</td>
<td>8.15</td>
</tr>
<tr>
<td>Baptiste Collete</td>
<td>9.2</td>
</tr>
<tr>
<td>West Bay</td>
<td>6.2</td>
</tr>
<tr>
<td>Small Cut</td>
<td>1.89</td>
</tr>
<tr>
<td>FT ST. PHILIP</td>
<td>5.88</td>
</tr>
<tr>
<td>OSTRICA</td>
<td>1.51</td>
</tr>
<tr>
<td>BOHEMIA</td>
<td>0.18</td>
</tr>
</tbody>
</table>
Figure 5.9A and B illustrate Mississippi River discharge measured at Belle Chasse, LA for the simulation period in July and August 2015 and total SSC obtained from the equation provided by Snedden (2006).

Figure 5.9. (A) Mississippi River discharge (m³ s⁻¹) and (B) SSC (kg m⁻³) obtained from Belle Chasse station (USGS 07374525), LA for July and August 2015

5.3.5 Physical Parameters

Delft3D-FLOW offers several options for introducing/calculating vertical eddy viscosity (Kolmogorov, 1942; Prandtl, 1945; Deltas, 2011): constant user-defined coefficient; algebraic eddy viscosity closure; k-L turbulence closure model, and k-ε turbulence closure model. In this study, a k-ε turbulence closure model was applied following Allahdadi et al. (2017). Turbulence effects in horizontal plane were considered in the model using constant background horizontal eddy viscosity and diffusivity coefficient. Background horizontal eddy viscosity was set to of 1
(m²s⁻¹), and a value of 10 (m²s⁻¹) was used for horizontal eddy diffusivity (Delatares, 2011). The initial value for bottom roughness based on Chézy formula was the default value of 65.0 m¹/² s⁻¹. This value was tuned based on sensitivity tests.

5.4 Sediment Transport Model

5.4.1 Sediment Properties

To setup sediment transport model which is integrated into Delft3D-FLOW module, sediment properties for two sediment classes, mud and sand, were assigned similar to the values tuned in a cold front scenario (Chapter 4). The usSEABED data (Williams et al., 2006) were used as the initial composition of mud and sand on the bed (see Chapter 4, Figure 4.4). Table 5.3 summarizes sediment properties considered in this study. The specific density and dry bed density for cohesive sediments were assigned to 2650 kgm⁻³ and 500 kgm⁻³ (default values; Deltares, 2011) respectively. For non-cohesive sediment dry bed density was set to 1600 kgm⁻³ (default value; Deltares, 2011). Erosion and sedimentation critical shear stress values for cohesive sediment (mud) were tuned based on values suggested by previous studies (Van Rijn, 2007; Deltares, 2013; Xu et al. 2016; Liu 2017). For non-cohesive sediment type, these values were computed by model based on default mean diameter (D₅₀) (250 µm) and threshold parameter calculated by the model according to the classical Shields curve as modeled by Van Rijn (1993) (Equation 5.3)

\[ \tau_{cr}^{(l)} = (\rho_s^{(l)} - \rho_w) g D_{50}^{(l)} \Omega_{cr}^{(l)} \]  

where:

- \( \tau_{cr}^{(l)} \) critical bed shear stress of sediment fraction (Nm⁻²)
- \( \rho_s^{(l)} \) density of sediment fraction (kgm⁻³)
- \( \rho_w \) density of water (kgm⁻³)
- \( g \) gravitational acceleration
\[ D_{50}^{(l)} \] median sediment diameter (m)

\[ \theta_{cr}^{(l)} \] threshold parameter \( \theta_{cr} \) calculated according to the classical Shields curve as modeled by Van Rijn (1993) as a function of the nondimensional grain size \( D \)

Table 5.4. Sediment properties in the sediment transport and morphology model.

<table>
<thead>
<tr>
<th>Sediment type</th>
<th>( \tau_{cr} ) for erosion (Nm(^{-2}))</th>
<th>( \tau_{cr} ) for deposition (Nm(^{-2}))</th>
<th>( w_s ) (mms(^{-1}))</th>
<th>( M ) (10(^4) m(^{-2})s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cohesive</td>
<td>0.2</td>
<td>0.08</td>
<td>0.1</td>
<td>0.3</td>
</tr>
</tbody>
</table>

5.5 WAVE Module

The WAVE model computes wave propagation, non-linear wave-wave interaction, and wave dissipation (by whitecapping and depth-induced breaking). Here, as shown in Chapter 3, results confirmed that the most effective whitecapping formulation is Komen (Komen et al. 1984), especially for the selected modeling time window (fair-weather, summer months) when prevailing southwesterly winds account for the major part of wave action over the Louisiana shelf.

The WAVE model was set up with online coupling with FLOW model and sediment transport. The boundary conditions for the three open boundaries were extracted from WAVEWATCH III model for the simulation period (July 5- August 22, 2015) (see Chapter 3 for details).

5.6 Models Validation

The FLOW and WAVE models were calibrated and validated with observational data collected from July 5\(^\text{th},\) 2015 through August 22\(^\text{nd},\) 2015 at different stations. The same values assigned to the physical parameters used in Chapter 4 were used here for the model calibration.
5.6.1 Model Verification for Tidal Force

Although here I did not aim to study tidal currents, it is imperative to evaluate the model performance in the simulation of tidal propagation from the offshore open boundary to the study area. The model was forced only by tidal constituents (see Section 5.3.3, Table 5.2) for the period of July 5 to August 22, 2015 to simulate tidal water level and tidal currents and to compare them with observations. To validate the performance of the model in predicting water level variations, the simulated water level variations were compared with data obtained from NOAA Tide Prediction database at South West Pass, LA (ID #8760783) and Grand Isle, LA (ID #8761724) (see Figure 5.2 for location). The validation included visual comparison (Figure 5.10A and B) and statistical analysis (Table 5.5). The simulated water level variations were in very good agreement with NOAA water level predictions.

Figure 5.10. Comparison between modeled water level variation at (A) Southwest Pass and (B) Grand Isle with NOAA predicted water level
Table 5.5. The summary of errors for compared modeled and NOAA predicted water level variations at Southwest Pass and Grand Isle.

<table>
<thead>
<tr>
<th>Station</th>
<th>$R^2$</th>
<th>RMSE</th>
<th>Bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southwest Pass</td>
<td>0.96</td>
<td>0.036</td>
<td>0.00044</td>
</tr>
<tr>
<td>Grand Isle</td>
<td>0.95</td>
<td>0.039</td>
<td>0.00038</td>
</tr>
</tbody>
</table>

To compare simulated tidal currents with measurements, a harmonic analysis was performed on timeseries of measured current velocity at WAVCIS CSI-6 and the Sandy Point dredge pit to extract tidal currents from the total recorded current. Then, modeled tidal current velocity (u and v components) were compared with extracted tidal current velocity (u and v component) measured at WAVCIS CIS-6 and the Sandy Point dredge pit. Figures 5.11A, B present comparison for u and v velocity components at water surface at WAVCIS CSI-6. Results suggest that the modeled tidal current velocity components agreed well with the measured components at WAVCIS CSI-6.

![Figure 5.11. Comparison of modeled tidal (A) u- and (B) v- velocity components with measured tidal current velocity at water surface at WAVCIS CSI-6](image-url)
The Comparison between measured and simulated tidal currents was also performed at the Sandy Point dredge pit that suggested a very good agreement (Figures 5.12A, B).

![Figure 5.12. Comparison of modeled tidal (A) u and (B) v velocity components with measured tidal current velocity at the Sandy Point dredge pit](image)

### 5.6.2 Current Velocity Comparisons for a Realistic Case

For a realistic case, the simulation took all forces including wind, wave, tide, and river discharge into consideration.

The comparisons between the modeled and measured total current velocity components (u and v) at WAVCIS CSI-6 and the Sandy Point dredge pit were plotted in Figures 5.13 and 5.14. At station CSI-6, no velocity data were available from August 3rd through August 5th. The model results at these two stations were comparable with measured data. The comparisons were quantified using the index presented by Willmot (1980). The index is represented as:

\[
d = 1 - \frac{\sum_{j=1}^{n} [y(j) - x(j)]^2}{\sum_{j=1}^{n} [y(j) - \bar{y} + |x(j) - \bar{x}|]^2}
\]  

(5.4)
where \( x(j) \) are measured values, \( y(j) \) are simulated values, and \( \bar{x} \) and \( \bar{y} \) represent the mean values of measurement and simulation, respectively. Index values vary between 0 for poor agreement and 1 for a perfect match.

Figure 5.13. Comparison of modeled (blue line) near-surface (A) u component, and (B) v component of total current velocity with measurements at the Sandy Point dredge pit (red dashed line)

Figure 5.14. (A) Comparison of modeled near-surface u component and (B) modeled near-surface v component (blue line) of total current velocity with measurements at CSI-6 (red dashed line). No measured velocity was available between August 3\(^{th}\) and August 5\(^{th}\)
The index was calculated for comparisons at both WAVSIS CSI-6 and the Sandy Point dredge pit for the surface and bottom currents (Table 5.4), respectively. Index values show an appropriate model performance as indicated by Wang and Justic (2009).

Table 5.5. Comparison of observed and simulated current velocities (Willmot’s index) for stations CSI-6 and ADCP location inside the Sandy Point dredge pit.

<table>
<thead>
<tr>
<th>Station</th>
<th>u-velocity component</th>
<th>v-velocity component</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSI-6 (Surface)</td>
<td>0.72</td>
<td>0.68</td>
</tr>
<tr>
<td>Sandy Pit (Surface)</td>
<td>0.69</td>
<td>0.70</td>
</tr>
<tr>
<td>Sandy Pit (4m above seabed)</td>
<td>0.79</td>
<td>0.71</td>
</tr>
</tbody>
</table>

5.6.3 WAVE Model Validation

The WAVE model was validated through the comparison of model results with the observations of wave heights, periods and direction at CSI-6, LOPL1, and 42040. The comparisons were discussed in detail in Chapter 3, Section 3.6 for fair-weather simulation period.

5.7 Results and Discussion

5.7.1 Overall Sediment Dynamics

The morphodynamic processes on Louisiana shelf are highly dominated by bottom currents, waves, and water depth (Allahdadi et al., 2011; Xu et al., 2016). Louisiana shelf bottom undergoes sediment resuspension due to strong wind-driven currents and wave action. Kobashi (2009) argued that if waves are not strong to suspend fine sediments, upper-layer unconsolidated sediment can be potentially transported by even weak currents. During the summer fair-weather months, weak winds are dominant and currents over the Louisiana-Texas shelf are upcoast in the opposite direction of the non-summer months (downcoast regime). To study sediment dynamics over the study area during fair-weather, two different timesteps was selected: (1) on 8 July 2015, 09:00:00 AM, when the prevailing winds were from south and southeast, and (2) on 3 August 2015, 09:00:00 AM, when the when southwesterly winds were dominant. Figure 5.15 shows snapshots of modeled current velocity (ms⁻¹), significant wave height (m), and surface SSC (kgm⁻
on 8 July 2015 at 09:00:00 AM. At this timestep, the NDBC BURL1 recorded relatively weak winds from the southeast with speed of 4.95 ms$^{-1}$.

Figure 5.15. Maps of modeled (A) surface current velocity (ms$^{-1}$), (B) significant wave height (m), and (C) surface SSC (kgm$^{-3}$) on 8 July 2015, 09:00:00 UTC; the black dot shows the location of the Sandy Point dredge pit
The velocity of wind-driven currents at the water surface reached to a maximum value of ~0.25 ms\(^{-1}\) on the west flank of the Mississippi River and in the vicinity of the Sandy Point dredge pit (Figure 5.15A). The simulated relatively weak south-southeasterly currents can be explained as a response to weak surface wind stress. Simulated significant wave height (m) over the Louisiana shelf for this time step is presented in Figure 5.15B. The significant wave height reached to ~0.2 m on the west flank of the Mississippi River, coastal waters adjacent to the Sandy Point dredge pit, and the wave direction was from southeast following the predominant wind direction. However, Louisiana outer shelf experienced the waves with significant height of 0.7 m. The dispersal of the sediment-rich plume from the Mississippi River outlets (e.g., Southwest Pass, Grand Pass) toward the Sandy Point dredge pit responded to southeasterly wind is illustrated in Figure 5.15B. In very shallow coastal waters on the west flank of the Mississippi River delta, the combined bottom shear stress (BSS) induced by currents and waves (\(\tau_{cw}\)) (Figure 5.16A) exceeded the threshold bed shear stress (0.2 Nm\(^{-2}\)) (i.e., critical shear stress for erosion). Whereas, for other areas over the Louisiana inner and outer shelf BSS values were less than 0.1 Nm\(^{-2}\). Surface SSC reached to a maximum value of 0.015 kgm\(^{-3}\) in very shallow coastal waters and advected to the north-northwest by southeasterly currents (Figure 5.15C).

As a result of relatively high sediment flux from the Mississippi River outlets and sediment resuspension under strong BSS (>0.2 Nm\(^{-2}\), Figure 5.16A), surface SSC reached up to 0.02 kgm\(^{-3}\) and higher around the Mississippi River (Figure 5.15B). However, the overall surface sediment concentration was ~0.013 or smaller over the continental shelf as a result of weak re-suspending forces. At this timestep, the surface SSC was ~0.011 kgm\(^{-3}\) over the Sandy Point dredge pit where it was highly influenced by the northwestward transport of fluvial sediments from the western outlets of Mississippi River (e.g., Southwest Pass and Grand Pass).
Figure 5.16. Modeled BSS (Nm$^{-2}$) induced by combination of waves and currents ($\tau_{cw}$) on (A) 8 July 2015, 09:00:00 AM, and (B) 3 August 2015, 09:00:00 AM
Simulated current velocity, significant wave height, and surface SSC at timestep 2 (3 August 2015 at 09:00:00 AM) are presented in Figure 5.17. At this timestep, the wind direction shifted from southeasterly to southwesterly. Eastward wind-induced currents were dominant over the Louisiana shelf during this timestep (Figure 5.17A). The current velocity reached up to 0.5 ms\(^{-1}\) over the shelf as a result of relatively strong southwesterly wind (8.28 ms\(^{-1}\)). This eastward current could impede the dispersal of the fluvial fine sediment toward the Sandy Point dredge.

Figure 5.17B presents the wave pattern over the eastern and western flank of the Mississippi River delta at this timestep. The significant wave height (m) for most of the shelf and over the Sandy Point dredge pit except in the shallow coastal bays was ~1 m. The wave direction was consistent with the prevailing wind. These southwesterly waves affected almost the entire shelf area. Figure 5.17C shows the response of fluvial fine sediment dispersal to the southwesterly current produced by this relatively strong southwesterly wind. Although, BSS values were higher than the threshold value (0.2 Nm\(^{-2}\)) over coastal and nearshore waters (Figure 5.16B) and there was a potential for sediment resuspension and dispersion, as a result of the eastward shelf currents under which the sediments were pushed toward shorelines.

Consequently, re-suspended sediments were not dispersed over the shelf. However, surface SSC over the Sandy Point dredge reached up to ~0.015 kgm\(^{-3}\) (Figure 5.17C) due to local sediment re-suspension resulting from relatively strong BSS (>0.2 Nm\(^{-2}\)) (Figure 5.16B). It should be noted that the simulated SSC over the Sandy Point dredge pit was mostly produced by the bed sediment re-suspension under the current and wave actions and river sediments had a small contribution. Eastward shelf currents pushed river sediments from the river outlets toward the shoreline, and they could not be transported toward the Sandy Point dredge pit.
Figure 5.17. Maps of modeled (A) surface current velocity (ms$^{-1}$), (B) significant wave height (m), and (C) surface SSC (kgm$^{-3}$) on 3 August 2015, 09:00:00 UTC; the black dot shows the location of the Sandy Point dredge pit
5.7.2. Impact of the Sandy Point Dredge Pit on Hydrodynamics

Seabed mining has negative impacts on the environment in a number of ways. The presence of the dredge pit may change the location of wave breaking and modify the wave field through refraction and to a lesser extent diffraction (Demir et al., 2004). Regardless of the final destination of marine sand, topographic changes caused by underwater dredge holes have immediate effects on nearshore waves and currents. Nearshore dredging conducted without proper investigation of local morphologic conditions may cause significant and lasting physical and environmental damage to the coast. To assess the impact of dredging at the Sandy Point on current hydrodynamics and wave propagation, Delft3D-FLOW and WAVE models were implemented for the study area, considering two bathymetric configurations: one with the pit included and the other without it. Simulated currents for two scenarios with and without pit at different locations including P0, P1, and P2 were compared. Since the results were similar at these three locations, the comparison was only presented for P0 located in the middle of the pit (Figure 5.2B for location). As illustrated in Figure 5.18, simulated currents for the two scenarios were similar. The presence of the pit decreased the current speed, especially during the peak of current.

![Simulated near-surface current velocities at P0 location](image)

Figure 5.18. Simulated near-surface current velocities at P0 location with pit (dotted blue line) and without pit (solid red) bathymetric configurations

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Variations of near-surface current speed over the pit area at timestep 2 (3 August 2015 at 09:00:00 AM) for the scenarios with and without the pit were compared in Figure 5.19A and B. The near-sea-surface current velocity reached up to the value of 0.8 ms\(^{-1}\) when the pit was not considered, while in the scenario with the pit, the current velocity decreased by ~19%.

Figure 5.19. Near sea-surface current velocity map over the Sandy Point dredge pit area: (A) the pit was excluded in simulation, and (B) the pit bathymetry was included.

The impact a borrow pit on the wave field and adjacent shoreline depends on the seafloor geology, wave climate, and design characteristics of the pit such as distance from offshore, depth of cut, orientation, and cross- and alongshore extent (Benedet et al., 2013).

The comparison of simulated significant wave height over the pit area for the scenarios with and without the pit showed that the presence of the dredge area had only a slight effect on characteristics of simulated waves (Figures 5.20A, B).

Some differences were observed along the northern edge of the pit while southerly to southwesterly waves propagated toward the pit area. Figure 5.20A shows the simulation results for the case without the pit when waves from southwest propagated toward the study area. Almost
no wave refraction occurred because spatial variations in the water depth were not significant. In Figure 5.20B the pit bathymetry was included, and some slight variations in wave direction and a decrease in wave height were observed in the northeast corner of dredge area (area specified with the white circle). This slight directional change was more likely due to the refraction caused by the bathymetry changes at this location.

Examining more simulation results with almost the same direction showed that the convex topography of the northern part of the pit caused wave refraction when wave height was larger than 1 to 1.2 m. The effect of the convex topography was a diversion of wave rays and consequently spreading wave energy and decreasing wave heights. Figure 5.21 presents a schematic of wave refraction over convex and concave bathymetry that clearly shows the diversion effect of the convex topography on wave rays.

![Figure 5.20](image)

**Figure 5.20.** Modeled significant wave height (A) the Sandy Point dredge pit bathymetry was not included, (B) the Sandy Point dredge pit was included on August 3, 2015
5.7.3 Sediment Dynamics over the Sandy Point Dredge Pit

Prevailing currents and waves highly influence surface SSC and sediment dynamics over the Sandy Point dredge pit. The BSS induced by currents and waves plays a critical role in sediment resuspension if the BSS value exceeds the critical shear stress for erosion. One of the main sediment sources for Sandy Point dredge pit could be fluvial fine sediments from the Mississippi River plume. The Mississippi River supplies sediment for the pit during the times that northward currents are dominant due to southeasterly and to some extent southwesterly winds. The southeasterly and southwesterly winds are dominant during summer. Figure 5.22 presents near-surface and near-bottom currents on 8 July 2015, 09:00 AM (Figure 5.22A and B) and on 3 August 2015, 09:00:00 AM (Figure 5.22C and D). On 8 July 2015, 09:00:00 AM, the prevailing southeasterly wind generated northwestward currents with a velocity of ~0.15 ms$^{-1}$ at the surface of the Sandy Point dredge pit (Figure 5.122A).

Consequently, fluvial fine sediments from the Mississippi River were advected toward the pit. Local sediment resuspension at the Sandy Point and the adjacent regions was not significant
due to weak wave activity (see Figures 5.15B and 5.16A). Figure 5.22B shows the westward near-bottom currents with the velocity of less than 0.05 m·s⁻¹ in the pit at this timestep. At timestep 2, on 3 August 2015, wind direction shifted from the southeasterly to the southwesterly.

Figure 5.22. Modeled near-surface (A and C) and near-bottom (B and D) current velocities (m·s⁻¹) on 8 July 2015, 09:00:00 AM (timestep 1) and 3 August 2015, 09:00:00 AM (timestep 2), respectively
The near-surface wind-driven currents were strong (0.45 ms\(^{-1}\)) over the pit area, and the currents were consistent with the southwesterly wind (Figure 5.22C). Figure 5.22D illustrates that the reversed near-bottom currents with a velocity of 0.05 ms\(^{-1}\) directed toward the west. This reversed near-bottom currents also was observed during cold front passage (see Chapter 4, Section 4.4.2) and could have a substantial contribution to the sediment transport within the Sandy Point dredge pit bottom boundary layer. Figure 5.23 presents simulated significant wave height over the pit and adjacent regions on 8 July 2015, 9:00:00 UTC and 3 August 2015, 9:00:00 UTC. A uniform southerly wave field with a significant height of ~0.4 m over the pit at timestep 1. On 3 August 2015 (timestep 2), as the wind intensity increased, the wind-generated wave height reached up to ~1 m over the pit.

Figure 5.23. Significant wave height (m) overlaid with vectors of wave mean direction on (A) 8 July 2015, 09:00:00 AM (timestep 1), and (B) on 3 August 2015, 09:00:00 AM (timestep 2)
On 8 July, the wind stress was not enhanced enough to generate strong waves over the Sandy Point dredge pit. BBS over the entire Sandy Point and area around the pit was remarkably below the critical shear stress value (Figure 5.24A), hence wave- and current- induced BSS was too small (<0.02 Nm⁻¹) to cause any disturbance and sediment resuspension inside the pit and areas around the pit. On the contrary, on 3 August the BSS was high (Figure 5.24B) associated with strong waves and enhanced wind stress. BSS reached up to the values higher than critical shear stress for erosion (>0.2 Nm⁻²) over the pit and adjacent regions. BSS was strong enough to stir up the BBL and re-suspend sediment within the BBL.

Figure 5.24. Modeled BSS (Nm⁻²) variations over the Sandy Pit (A) on 8 July 2015, 09:00:00 AM, and (B) on 3 August 2015, 09:00:00 AM

The near-bottom re-suspended sediment was transported toward the western edge of the pit by the westward near-bottom currents (see Figure 5.22D) and contributed to sedimentation over this side of the pit. A similar sedimentation mechanism was observed during cold front passage
and discussed extensively in Chapter 4, Section 4.4.2. In the middle of the pit with larger depth (~20 m), BSS did not exceed the threshold value and the maximum value of 0.14 Nm\(^{-2}\) was observed, which was smaller than the threshold value for erosion.

**5.7.4 Dynamics of Bottom Boundary Layer in the Sandy Point Dredge Pit**

The bottom boundary layer characteristics play a key role in sediment transport processes. To understand the dynamics of BBL and sediment dynamics in the Sandy Point dredge pit under the summertime fair-weather conditions, three different scenarios were examined: (1) all forces including wave, wind, river discharge, and tide were incorporated, (2) all forces except wave were accounted, and (3) all forces except river discharge were considered. The initiation of sediment movement is the result of maximum BSS overreaching the critical shear stress. In scenarios (1 and 3) for which the disturbance of BBL under wave action was simulated, high BSS during the occasions associated with enhanced wind stress was observed. In Figure 5.25, the simulated BSS at P0 located in the middle of the Sandy Point dredge pit for the two scenarios with or without wave forcing are presented. Obviously, the values of BSS induced by currents and waves were higher than BSS induced by currents only. Figure 5.25 shows that combined current-wave induced BSS exceeded the critical shear stress (0.2 Nm\(^{-2}\)) in several occasions, while the current induced BSS did not reach up to critical shear stress even during strong wind stress.

![Figure 5.25. Simulated BSS (Nm\(^{-2}\)) with wave force (black line) and without wave force (blue dotted line) at P0 (located at a depth of 20 m). Red dashed line depicts the critical shear stress for erosion introduced to the model](image-url)
As the probability of exceeding BSS of critical shear stress increases, the probability of initiation of sediment movement increase as well. For example, on 3 August 2015, as wind speed increased, the wave height increased. Consequently, sediments were re-suspended from the bottom once the BSS exceeded the threshold value above which bottom sediment was suspended (Figure 5.25). To investigate the effect of the Mississippi River in supporting sediment source for bed sediment re-suspension, timeseries of near-bed sediment concentration at different locations over the pit were compared for two different simulations cases including simulation by considering all forces and simulation by skipping sediment discharge from the river outlets. Figure 5.26A presents modeled timeseries of near-bed SSC for three points P0, P1, and P2 (see Figure 5.2B for locations) in the scenario when all forces were considered. Simulated timeseries of near-bed SSC’s were also shown at these three locations for the scenario that the main source of sediment from the Mississippi River was excluded (Figure 5.26B). In both scenarios, SSC increased at P0, P1, P2 during the events that BSS surpassed the threshold values. In scenario 1, in addition to local sediment resuspension which contributed to an increase of SSC above the bed, sediment supply from the Mississippi River played an important role in increasing SSC, especially at P0 and P2 due to the closer proximity to the Mississippi River outlets.

In fact, including sediment discharge from the river in simulation significantly increased SSC at these two locations. At these two locations, the peak of SSC increased from ~15 kgm\(^{-3}\) for the scenario excluding the river sediments (Figure 5.26B) to ~30 kgm\(^{-3}\) in the scenario that the river was included (Figure 5.26A).

Compared to P0 and P2, at P1 which is located in the north of the pit with a larger distance to riverine sediment sources, the effect of the river on SSC was less pronounced. The comparison between timeseries of simulated SSC (Figure 5.26) and timeseries of simulated BSS (Figure 5.25)
clearly suggests the synergy of bed sediment resuspension with wave action, even during this relatively low energy fair-weather summer months condition.

Figure 5.26. Near-bed (5 cm above seabed) SSC (kg m\(^{-3}\)) of P0, P1, and P2 for (A) with including wave force and river discharge, (B) with including wave force and excluding river discharge.

The contribution of riverine sediment on vertical profiles of SSC was investigated by examining timeseries of simulated SSC variations across the water column (Figure 5.27A and B) at P0 and for the scenarios with and without sediment discharge from the Mississippi River. During the peak of wave action between 8/2/2015 and 8/15/2015, near-bed SSC and the vertical profile of SSC were similar for both scenarios due to the fact that wave action was included in both scenarios. Scenario 1 with riverine sediment showed higher values of near-bed SSC throughout the simulation period (from 8/2/2015 to 8/15/2015) and across the water column as a result of both riverine sediments and local re-suspension at the bottom of the pit. During other part of simulation period when wave action was too weak to re-suspend bed sediment, sediment concentration at the
bed and across the water column significantly declined. For the scenario excluding river sediments, sediment concentration was very small throughout the modeling period and across the water column, except for the period with high wave action that resuspension from bed occurs (Figure 5.27 B). This underlines the importance of the transported sediments from river outlets to the pit area during fair-weather.

Figure 5.27. Time variations of simulated SSC across the water column for (A) all forces included scenario, and (B) all forces included except sediment discharge from the Mississippi River scenario at P0

Figure 5.28A and B present cumulative erosion/sedimentation (m) at the end of simulation for scenario 1 (all forces included) and scenario 3 (all forces except river discharge). The comparison suggested that once the sources of sediment from the Mississippi River was excluded, the cumulative sedimentation decreased significantly. The maximum simulated sedimentation thickness over the pit was observed at the north of the pit and was 0.25 m when all forces were included. By excluding the riverine sediment, the maximum value plummeted to ~0.1 m, which indicates that about 60% of sedimentation over this area was caused by sediments from the riverine
sources. For scenario 1, two zones of maximum sedimentation were observed, one was located in the north of the pit with a larger area, and the other was a narrow zone with a smaller area in the south. The comparison between scenario 1 (Figure 5.28A) and scenario 3 (Figure 5.28B, without riverine sediment) suggested that the southern sedimentation peak was likely due to the direct effect of riverine sediment, while the northern peak was likely formed as results of both riverine sediment and dynamics of bottom boundary layer under the effect of waves and near-bed currents. Average sedimentation inside the Sandy Point dredge pit for scenario 1 (all forces included) at the end of the simulation (simulation time of about 48 days) was ~0.12 m (120 mm). This suggested that the sedimentation rate was about ~2.5 mm per day.

Figure 5.28. Thickness of cumulative erosion-sedimentation (m) at the end of 48-day simulation period in (A) all forces included scenario, and (B) all forces included except river discharge scenario.
5.8 Summary and Conclusion

In this chapter, a coupled flow-wave-sediment transport model integrating winds, tides, waves and river discharge was implemented to explore sediment dynamics during fair weather, in July-August 2015 on Louisiana self. Through comprehensive numerical simulations, I suggested that the combined action of waves and currents had an effect on sediment dynamics just in very shallow coastal areas. The BSS induced by waves and currents did not exceed the critical shear stress for erosion near the seabed in Sandy Point dredge pit or adjacent areas. In addition, results indicated that following the southeasterly wind, the sediment-rich water from the Mississippi River outlets dispersed toward the Sandy Point dredge pit. While, in response to the southwesterly wind, induced eastward shelf currents pushed sediments toward the shoreline.

Furthermore, the impact of the Sandy Point Dredge Pit on hydrodynamics and wave propagation was investigated. I performed two different scenarios, with and without the pit. I noticed that the sandy point dredge pit could decrease the current velocity by 19%. the pit did not have any significant impact on wave height. However, the pit changed the direction of waves caused by refraction in the northeast corner of the pit. Results suggested that during fair-weather event, The Mississippi River played a critical role in providing sediment for the Sandy Point dredge pit.
CHAPTER 6: SUMMARY AND CONCLUSION

6.1 Introduction

I implemented a Delft3D coupled modeling system integrating winds, tides, waves, and river discharge to understand hydrodynamics and sediment dynamics on the west flank of Mississippi River with a focus on the Sandy Point dredged pit. Through comprehensive numerical simulations, I identified the source of sedimentation in the Sandy Point dredge pit under two different weather conditions including cold front and fair weather. In addition, the numerical modeling system also helped us to quantify sedimentation rate for different scenarios. This chapter summarizes the major findings and discusses potential future research.

6.2 Highlights

6.2.1 Approach

Numerical experiments using Delft3D were implemented to study hydrodynamics-driven sediment dynamics and morphological changes in Sandy Point dredge pit. The experiments considered several scenarios with different sets of forcing conditions (e.g., tides and river discharge). The coupled wave-current-sediment transport Delft3D model was successfully initialized using initial and boundary conditions. For example, the initial surface suspended sediment concentration obtained from MODIS Aqua was introduced to Delft3D- FLOW module. The flow model was tuned with properly selected bottom roughness, wind friction coefficient, and vertical eddy viscosity.

In addition, two different white capping approaches were evaluated. Simulated wave parameters were compared with observations, and the appreciate approach was selected. The flow and sediment transport model results were compared to observations to validate the hydrodynamic
model and to tune the sediment transport parameterization. For example, the time series of water level were compared with field data provided by NOAA at different stations.

6.2.2 Data

Different datasets were used for model setup, initialization, validation, and evaluation. Water level variations along the open boundary were obtained from the tidal constituents extracted from ADCIRC. Mississippi River discharge was included in the simulation, and the river discharge at Louisiana Belle Chasse was obtained from USGS 07374525. The spatially uniform and temporally variable wind data at the BURL1 station were provided by National Data Buoy Center (NDBC), NOAA.

To provide initial surface suspended sediment concentration for the model, corrected remote sensing reflectance products from MODIS-Aqua and Landsat-8 OLI were used. MODIS-Aqua Level-0 and Landsat-8 OLI data were downloaded from NASA Ocean Color (https://oceancolor.gsfc.nasa.gov) and USGS Earthexplorer (https://earthexplorer.usgs.gov).

The flow model for tidal currents was evaluated using tidal predictions from NOAA. Simulated wind-induced and tidal currents were assessed using currents data from WAVCIS CSI-6 station (www.wavcis.lsu.edu) and measured data at Sandy Point dredge pit.

The Satellite-retrieval algorithm and sediment transport model were evaluated by the data provided by NOAA National Centers for Environmental Information (NCEI) (https://www.ncei.noaa.gov/) and NASA SeaBASS (https://seabass.gsfc.nasa.gov/). In addition, the boundary conditions for the wave model were obtained from the simulated results from WAVEWATCH-III (WWIII) model provided by NOAA (http://polar.ncep.noaa.gov/waves/index2.shtml). The wave model was evaluated using measurements at stations NDBC 42040 and LOP1 and WAVCIS CSI-6.
6.2.3 Results

The following summarizes each chapter:

Chapter 2:

In this chapter, four different atmospheric correction algorithms were evaluated. MODIS-Aqua and Landsat-8 OLI atmospherically corrected remote sensing reflectance products were plugged into a regional SPM-retrieval algorithm. The SPM-retrieval algorithm was also validated by comparing retrieved SPM values with in situ data. The time difference between field data and satellite passage was limited to 3hrs. Surface suspended sediment maps were integrated into flow/sediment transport model as initial conditions. Sediment transport model was assessed quantitatively using field data and qualitatively by MODIS-retrieved SPM map. The main results of this study are as follows:

1. The SWIR atmospheric correction algorithm was the best algorithm to correct remote sensing reflectance products atmospherically and to retrieve SPM from Landsat-8 OLI.

2. The SWIR.NIR atmospheric correction algorithm was the most appropriate algorithm to correct remote sensing reflectance products atmospherically and to retrieve SPM from MODIS-Aqua.

3. The NIR atmospheric correction algorithm retrieved lower values of reflectance products and SPM in high turbidity waters.

4. SPM map obtained from MODIS-Aqua and Landsat-8 OLI using a regional band-ratio algorithm was integrated as an initial condition into the sediment transport model.

5. A good agreement was found between MODIS-derived SPM processed with SWIR.NIR algorithm and in situ data ($R^2=0.78$).
6. A satisfactory percent difference (2-21%) was obtained between Landsat-8 OLI-derived SPM processed with SWIR algorithm and in situ data.

Chapter 3:

A high accuracy wave model using Delft3D- WAVE module (SWAN) was implemented to model waves over the Louisiana shelf and at Sandy Point dredge pit. Wind data and waves along the open boundaries were obtained from NOAA BURL1 station and WWIII database, respectively.

In addition, to determine the most appropriate whitecapping approach for the study area two different approaches for resolving the whitecapping dissipation including Komen (1984) and van der Westhuysen et al. (2007) were evaluated.

The important results are:

1. The Komen whitecapping approach performed better than the van der Westhuysen in the study area.

2. The Westhuysen approach, generally underestimate wave height and period over the Louisiana shelf.

Chapter 4:

A coupled Delft3D flow-wave-sediment transport model was implemented to study sediment dynamics in Louisiana shelf with the main focus on Sandy Point dredge pit during a cold front in November 2014. Hydrodynamics model was validated using field data of currents, waves, water level variations. Two potential sediment sources for Sandy Point were examined: fluvial sediment from the Mississippi River and re-suspended sediments from the seabed.

In addition, sedimentation rate was estimated for the whole simulation period. The main conclusions are:
1. During cold front, shear stress from wave motions played a significant role in sediment resuspension.

2. The maximum cold front related wave impact on sediment re-suspension can increase the near-bed sediment concentration by 20-50 times.

3. The primary source of sediment for the Sandy Point dredge pit during a cold front was re-suspension due to the fortified bottom shear stress (BSS) by wind-induced waves and currents.

4. Strong southward wind-driven currents during cold front passage dispersed sediments from the Mississippi River passes and inhibited riverine sediment supply from the Sandy Point dredge pit.

5. Cold front passages (30-40 cold fronts in average per year) contribute to the sedimentation thickness over Sandy Point dredge pit from 16% to 24% of the total sedimentation thickness annually.

Chapter 5:

This chapter discusses the sediment dynamics over the Sandy Point dredge pit and inner Louisiana shelf during fair-weather in July-August 2015. Unlike a cold front event, the direction of the prevailing wind and associated surface currents were favorable for discharged sediment from the Mississippi River to be transported to the Sandy Point dredge pit.

Hence, sediment-laden water from the Mississippi River outlets (located on the west flank of the Mississippi River) could be advected toward the Sandy Point dredge pit. The coupled flow-wave-sediment transport model was run two times, with and without Sandy Point dredge pit. In addition, various scenarios were examined to identify the source of sediment for Sandy Point during the simulation period. The major results are:
1. Weak winds were dominant, and currents over the Louisiana-Texas shelf were upcoast.
2. Only in very shallow coastal waters the BSS induced by currents and waves exceeded the critical shear stress for erosion.
3. The eastward shelf currents pushed re-suspended sediment and sediment from the River toward shorelines. Hence, sediment could not be transported toward the Sandy Point dredge pit.
4. With the presence of the pit, the current velocity decreased by ~19%.
5. Sandy Point dredge pit had a small impact on characteristics of simulated waves.
6. Depth-induced wave refraction was observed on the northeast corner of Sandy Point dredge pit during the southerly wave incidents.
7. The Mississippi River supplied sediment for the pit during the times that northward currents were dominant.
8. About 60% of sedimentation over this area was provided by sediments from the riverine sources.

6.3 Model Limitations

This study has some limitations. It did not include flocculation, aggregation, fluid mud, consolidation, pit margin failure, temperature and salinity, and stratification/mixing induced by temperature and salinity. During a cold front, stratification/mixing induced by temperature and salinity does not have a significant impact on results because of the weak stratification in November. During summer fair-weather condition, although there is relatively strong stratification over the Louisiana Shelf (Allahdadi et al., 2017), the vertical eddy viscosity was tuned based on the current measurements over the pit and so the effect of stratification on current hydrodynamics
was minimized. This can be improved by explicitly including stratification in future modeling studies.

6.4 Suggestion for Future Research

To improve the model predictive skill, more field data of SPM are needed to validate SPM-retrieval algorithm and the model performance. In addition, physical parameters of sediment must be measured precisely in the field or in a laboratory. The choice of physical parameters could significantly influence the sedimentation rate in Sandy Point dredge pit. In the present research, I used a barotropic model, with constant temperature and salinity across the water column. To improve the performance of hydrodynamics model especially during summertime, a baroclinic model considering temperature and salinity and vertical stratification may provide new insight to the dynamics that was not discussed in this dissertation.
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