Neptune Pass Sediment Mass and Volume Balance: An Approach to Evaluate Delta Splay Development in Bay Denesse and Quarantine Bay, Louisiana

Final Report to the Louisiana's Coastal Protection and Restoration Authority and the National Wildlife Federation

By

Alexander S. Kolker
Louisiana Universities Marine Consortium

H. Dallon Weathers
Delta Geo-Marine

Christy Swann
RCOAST, Inc.

December 22, 2023

Executive Summary/Abstract

This report describes recent research into Neptune Pass, a crevasse in the lower Mississippi River that expanded in 2019 or 2020, and its associated receiving basins. This study was conducted against the backdrop of a recent reports indicating that the flow Neptune Pass is about 15-17% of the lower Mississippi River (>3,000 m^3 s^{-1}, when the river is at high flow), concerns about the impacts of Neptune Pass's to navigation in the Mississippi River, and satellite images showing landform development in Neptune Pass's receiving basins, including Quarantine Bay and Bay Denesse.

To better understand how Neptune Pass and its associated receiving basins function, a series of marine and airborne geological, geophysical, and geospatial surveys were conducted in 2022 and 2023. These included sonar surveys that examined the bathymetry and subsurface geology of Neptune Pass that were augmented by core collections. In addition, aerial drone surveys employing a true color sensor and a Light Distance and Ranging (LiDAR) sensor, coupled with satellite image analysis, were used to examine the emergent and shallow water morphology of emerging deltas. One critical question was whether new deltaic deposits in Quarantine Bay were derived primarily from sediments sourced from the Mississippi River, or sediments scoured from Neptune Pass. This question was addressed using a sediment budget that compared the volume and mass of sediment in the Quarantine Bay Delta to the volume and mass of sediment scoured from Neptune Pass.

Overall, results show that the Quarantine Bay Delta was at least 27% and as much as 80% larger than the amount of sediment scoured from Neptune Pass during its enlargement. This indicates a large fraction of the material in Quarantine Bay is derived from Mississippi River sediments. Overall, these results suggest that the Neptune Pass/Quarantine Bay system is functioning like the river diversions that are part of Louisiana's coastal restoration strategies. This report further places Neptune Pass/Quarantine Bay growth in the context of the theoretical context for wetland development.

Suggested Citation. Kolker, A.S., Weathers, D., Swann, C., (2023). Neptune Pass Sediment Mass and Volume Balance: An Approach to Evaluate Delta Splay Development in Bay Denesse and Quarantine Bay, Louisiana. Final Report to the Louisiana's Coastal Protection and Restoration Authority and the National Wildlife Federation. 40p.

Table of Contents

List of Tables

List of Figures

List of Acronyms

ADCP: Acoustic Doppler Current Profiler: A sonar-based method of determining water current velocities.

CHIRP: A sonar-based method to determine the shallow stratigraphy of a marine or coastal environment. The name is originally derived from the term for a radar-based method to determine aerial structures, Compressed High-Intensity Radar Pulse.

CPRA: The Coastal Protection and Restoration Authority of Louisiana, a state agency.

DEM: Digital Elevation Model, a method of showing the bathymetry of topography of a region.

DEM+RBG: A Digital Elevation Model that also includes true color images in Red, Green and Blue.

DU: Ducks Unlimited: A conservation organization.

LDWF: Louisiana Department of Wildlife and Fisheries, a state agency.

LiDAR: Light Detection and Ranging, a method for determining ranges by targeting an object or a surface with a laser and measuring the time for the reflected light to return to the receiver.

NAVD 88: The North American Vertical Datum of 1988, a vertical datum for orthometric heights commonly used by surveyors in the United States. A value of 0 is close to elevation commonly referred to as, "sea level."

NWF: National Wildlife Federation: A conservation organization.

SDB: Satellite Derived Bathymetry

USACE: United States Army Corps of Engineers, a federal agency.

Acknowledgements

The report and all related items of information were prepared by the authors through a sub-contract with the Louisiana Coastal Protection and Restoration Authority, who was funded under Award No. GNTCP18LA0035 from the Gulf Coast Ecosystem Restoration Council (RESTORE Council). The data, statements, findings, conclusions, and recommendations are those of the authors and do not necessarily reflect any determinations, views, or policies of the RESTORE Council. This work represents contract #20220831Task Order No.4 to the Louisiana Universities Marine Consortium. We thanks Anne Patton for help preparing the manuscript and Southwings for providing the flight for the cover image.

1.0 Introduction

The development of the Neptune Pass system is an issue of growing importance for Louisiana's coastal community, as Neptune Pass is one of the largest distributary channels to develop in Louisiana in the past 100 years (Kolker and Weathers 2022). It is located in the lower Mississippi River about 38 km upstream of Head of Passes, across the river and slightly southeast of Empire Louisiana (Figure 1). Neptune Pass discharges into Quarantine Bay, an embayment in the Breton Sound Basin of the Mississippi River Delta that lies to the east and northeast of the Mississippi River.

As a new and large distributary system, Neptune Pass has the potential to both build large areas of land and affect shipping in the Mississippi River, which creates a need for research to understand this system and its potential impacts. The impetus for the present study is the rapid expansion of Neptune Pass in about 2019, in-situ data collected in 2022 that revealed the size and scale of the system (Kolker and Weathers 2022), and remote sensing data analyzed in 2022 that showed preliminary evidence of land development (Figure 2, Figure 3, and Figure 4). More specifically, a hydrodynamic flow survey conducted on May 24, 2022 (Table 1) indicated Neptune Pass had a discharge of 3360 m^3 s^{-1} (118,000 ft^3 s^{-1}), on a day when the river's flow at Belle Chasse was 22,080m^3 s^{-1} (776,000 ft^3 s^{-1}). Thus, this single channel had a discharge amounting to 15 to 17 % of the flow of the lower Mississippi River. Furthermore, this survey indicated that Neptune Pass was in a region where nearly 1/3 of the Mississippi River was flowing eastward, raising the prospect of large-scale shifts in the flow of the Mississippi River.

A multibeam survey conducted on June 6, 2022 (Figure 3) provided useful evidence of the scale of the Neptune Pass channel (Kolker and Weathers 2022). This survey revealed a scour hole at the entrance to Neptune Pass that was over 30 m deep and 600 m wide. This survey also indicated that the conveyance channel averaged 12-15 meters depth, with a secondary scour region- about 1 km from the channel's entrance that exceeded 20 meters deep.

Satellite imagery provided some evidence that Neptune Pass was leading to the formation of mouth bars and other landforms Quarantine Bay (Figure 4). Images from the European Space Agency's Sentinel-2 satellite suggest mouth bars were present in the fall of 2021 and spring of 2022. An image from July 21, 2022, indicated these systems had developed into subaerial islands likely totaling several km^2 in area. This preliminary evidence suggests Neptune Pass could be leading to one of the largest deltaic land building events since the emergence of the Wax Lake and Atchafalaya River Deltas in the 1970s (Roberts 1997; Shaw and Mohrig 2014).

While the emergence of land is of potential significance to the coastal community, it should also be viewed in the context of the erosion of the Neptune Pass channel, which could impact navigation in the Mississippi River (Schleifstein 2022; USACE 2022) Furthermore, the emergence of land comes with important questions about the source material for this land, which could impact the prospects for the sustainability of land growth. One hypothesis holds that this land represents "new" deltaic land building, with sediments sourced from the Mississippi River. Under this scenario, delta evolution would follow a progression similar to the river diversions that are part of Louisiana's Coastal Master Plan and ongoing restoration activities (CPRA 2023).

In this scenario, sustainable land development is likely. An alternate hypothesis posits this material is "redistributed" material sourced from the scour that occurred during the expansion of Neptune Pass. This hypothesis suggests that land building in the future would be minimal and governed only by further erosion of the Neptune Pass channel. Under this scenario, long-term sustainable land growth is less likely.

The major purpose of this study is to examine these competing hypotheses regarding the formation of this land, while also quantifying the system in enough detail to provide useful insights into the processes driving its evolution. One pragmatic way to examine these hypotheses is through a volume-balance or mass-balance approach. In this approach, the quantity (volume and/or mass) of sediment removed from Neptune Pass can be compared to the quantity of sediment deposited in the Quarantine Bay receiving basin. If the quantity of newly deposited sediments in Quarantine Bay exceeds the quantity of material extracted, this would support the "new land" hypothesis. If the volume is less, then this would support the "redistributed" hypothesis.

This study was conducted using marine geophysical tools, sediment core collections, aerial drone-based surveys, and satellite image analysis. While the primary goal was to determine the quantity of material deposited in Quarantine Bay, the approach was broad enough to provide data that can provide a geological context for the evolution of Neptune Pass and associated landforms. Ideally, this information will be useful to Louisiana's Coastal Protection and Restoration Authority and the National Wildlife Federation as they seek to understand how to manage Neptune Pass and Quarantine Bay.

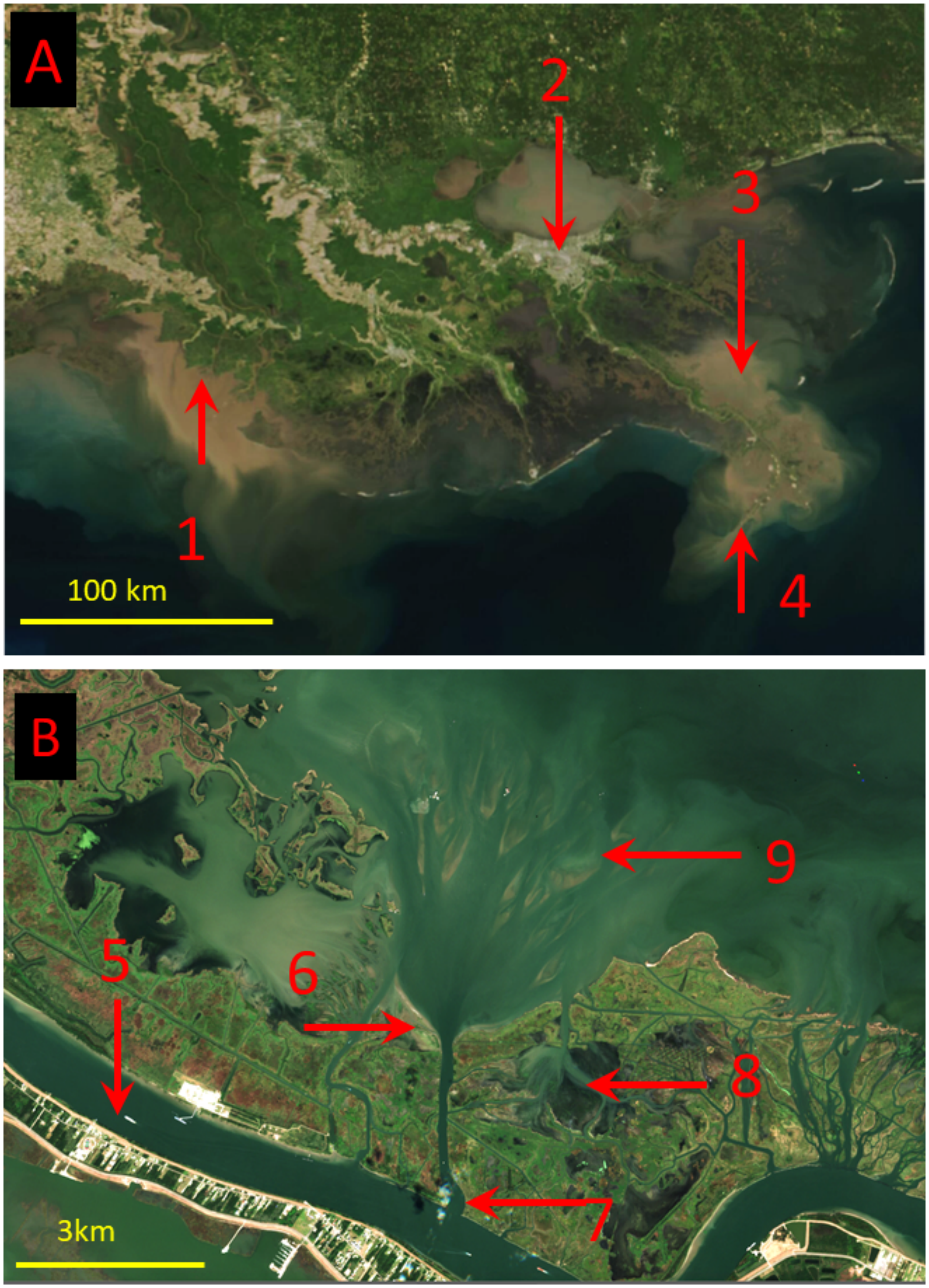

Figure 1: Map of coastal Louisiana with major features noted. A. Large scale view with the following locations noted: 1. The Wax Lake Delta of the Atchafalaya River. 2 New Orleans. 3. Neptune Pass. 4. Southwest Pass of the Mississippi River. Image Source: NASA-Modis. B. Close in view with the following locations noted; 5. The Mississippi River. 6. Ducks Unlimited Terraces. 7. Entrance to Neptune Pass. 8. Bay Denesse. 9. Quarantine Bay and the Quarantine Bay Delta. Image Source: European Space Agency/Sentinel-2

Table 1: Results From May 2022 Discharge Survey

Survey Location Or Calculation Information	Discharge $m^3 s^{-1}$	**Discharge $ft^3 s^{-1}$**
Mississippi River At Belle Chasse Gauge*	22,080	**776,000**
Mississippi River Above Neptune Pass	20,290	**713,000**
Neptune Pass	3,360	**118,000**
Mississippi River Below Neptune Pass	12,320	**433,000**
Total Eastward Flow	6,700 -7,970	**235,000-280,000**
% Of River Discharge At Neptune Pass	15 - 17 %	**15 - 17 %**
% Of River Discharged Eastward	30 - 36%	**30 - 36%**

* *Sources: The discharge at Belle Chasse is sourced from the US Geological Survey's Belle Chasse Mississippi River gauge #07374525. All other data is sourced from Kolker and Weathers (2022).*

Figure 2: Images showing Neptune Pass before (left) and after (right) the rapid expansion. Note: the yellow arrow in both pictures point to Neptune Pass.

2.0 STUDY LOCATION

Neptune Pass is located along the southeast side of the lower Mississippi River, approximately 39 km above Head of Passes (Figure 1). It is across the river and slightly downstream of the town of Empire, Louisiana. It is in a reach of the Mississippi River that extends from the Bohemia Spillway to Head of Pass where- on the river's eastern bank- levees are not well maintained. (There are rock walls and jetties that maintain overall channel stability). In this reach, channels connect the Mississippi River to Breton Sound, many of which formed between 1972 and the present day. Neptune Pass is the newest and largest of these.

Prior to about 2019, the system now known as Neptune Pass was a small channel between the Mississippi River and Breton Sound (Figure 2). That system is unnamed but will be referred to in this report as "Proto-Neptune Pass." One survey of Proto-Neptune Pass, conducted during high flow of the Mississippi River in 2016, measured a discharge of approximately 300 $m^3 s^{-1}$ (Weathers et al. 2016; Kolker and Weathers 2022). Satellite images indicate that in about 2019, the system rapidly expanded (Figure 2). The pass increased from approximately 30-50 m wide and about 3-6 m deep in 2016 to an average of 200 m wide (and wider near the mouth) with depths reaching up to 30 m at present (Weathers et al. 2016; Kolker and Weathers 2022). As the size of the channel increased, the discharge increased by roughly an order of magnitude and possibly more (Table 1).

Neptune Pass discharges into Quarantine Bay, a part of the Breton Sound Hydrologic Basin on the eastern flank of the Mississippi River Delta. Breton Sound has lost about 42% of its wetlands over the past century (Couvillion et al. 2017). This is a result of factors that include the construction of canals, reductions in the delivery of sediment and freshwater to wetlands from levee construction, high rates of subsidence, storms, relative sea level rise, and oil spills (Day et al. 2007; CPRA 2023). Breton Sound is the proposed site of the Mid-Breton Sediment Diversion that was part of Louisiana's Coastal Master Plan in 2017 (CPRA, 2017). That project seeks to restart natural land building processes by diverting up to 1,416 $m^3 s^{-1}$ of freshwater- and the associated sediment load- from the Mississippi River to Breton Sound (CPRA 2023). As described in more detail in the discussion of the report (Section 5), the Neptune Pass/Quarantine Bay system is somewhat similar to the Mid-Breton Diversion, though Neptune Pass's maximum discharge is larger (~ 3400 vs 1416 $m^3 s^{-1}$ maximum), and its flow is not gated. Neptune Pass is also about 70 river km downstream from the proposed location of the Mid-Breton Sediment Diversion.

Neptune Pass's flow is currently unregulated, though there have been attempts to stabilize the channel. In 2022, the U.S. Army Corps of Engineers (USACE) placed rocks along the channel's bottom, at the entrance to Neptune Pass where it connects to Mississippi River. In 2023, the USACE placed rocks along the southern edge of the channel entrance. According to a presentation delivered by the USACE at the September 2023 CPRA Board Meeting, the USACE is considering plans to further reduce the flow of the system, though these plans have not been finalized. These plans are a partial modification/replacement to 2022 plans by the USACE, which proposed to reduce the flow of Neptune Pass by placing a rock dam in the middle of the Neptune Pass channel (USACE 2022).

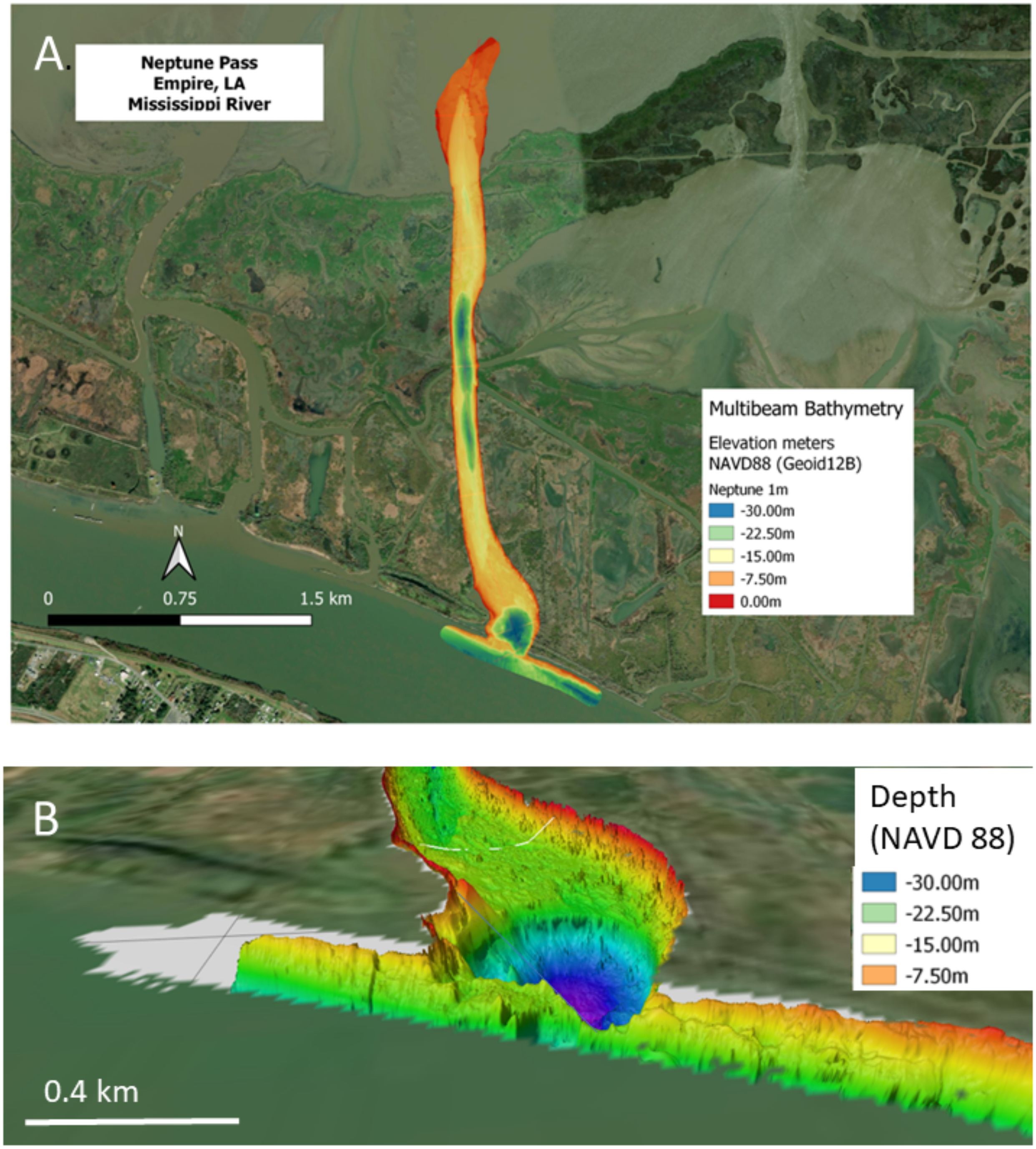

Figure 3: Multibeam bathymetry collected by Kolker and Weathers (2022). This bathymetry was used to determine the amount of scour in the Neptune Pass channel for the sediment budget. A (top). Plan view. B (bottom). Oblique view, as would be seen from an observer located above the Mississippi River looking towards the entrance to Neptune Pass.

Figure 4: The evolution of the Neptune Pass Plume and the Quarantine Bay Delta between 2018 (pre-expansion) to near the present day (August 20, 2023). The discharge at Belle Chasse, Louisiana (USGS Gauge (070374525) is noted in the lower left corner of each image. The images were selected to show both the temporal evolution and a diversity of river stages. The May 7, 2020 image relates to a discharge of 31,587 m^3 s^{-1}, which is near the maximum allowable flow in the lower Mississippi River (of 35,400 m^3 s^{-1}), and the July 21, 2022 and August 20, 2023 near historic low flow values. Image Source: European Space Agency/Sentinel-2; Data source: waterdata.usgs.gov

3.0 METHODS

3.1 Single-Beam Marine Bathymetry Survey

A single-beam bathymetric survey was conducted in Quarantine Bay between September and November of 2022 to determine seabed elevations and the morphology of subaqueous deposits. The survey employed an Odom Hydrotrac single-beam system, mounted on a pole operating at 200 kHz. A Trimble R8 real-time kinematic (RTK) GPS unit was mounted on the pole 1.86 m directly above the transducer. To correct for the impacts of boat movements on the survey, a Teledyne Dynamic Motion Sensor (DMS-25) was also mounted to the survey pole to measure heave, pitch, and roll. Survey data were integrated, collected, and processed in the Hypack software environment (Figure 5).

Surveys were conducted across Quarantine Bay (Figure 5) on the University of New Orleans' research vessel, the *R/V Mudlump*. The survey lines were informed by Sentinel-2 satellite images of Quarantine Bay captured in September and October 2022 (i.e. 2-6 weeks before the survey; Figure 4). They included areas where landforms were likely to be emerging and extend beyond these areas to ensure coverage of the distal extent of the depositional system.

Figure 5: A. The R/V Mudlump underway in Quarantine Bay. The CHIRP sonar is attached to the pontoons on the side of the vessel.
B. Aerial drone deployment from the edge of Neptune Pass.

3.2 Sub-Bottom Seismic Survey

A sub-bottom seismic survey was run concurrently to, and along the same survey lines, as the single-beam bathymetric survey. An Edgetech 3100-P CHIRP sub-bottom profiling system was used along with a SB-216 towfish to collect sub-bottom data. This system emits acoustic energy in a sweeping pulse in the frequency range of 2-16 kHz and collects returns in a transducer array in the towfish to generate sub-bottom imagery. Seafloor penetration is typically between 1–5 meters, depending on the water depth and the thickness, particle size, and bulk density of sediment (Figure 6). The sub-bottom investigation was conducted to image the sedimentary structures and geometry of the deposit, including the emerging landforms mentioned in Section 3.1. The track lines of the CHIRP sonar survey were the same as the single-beam bathymetric survey presented in Figure 7.

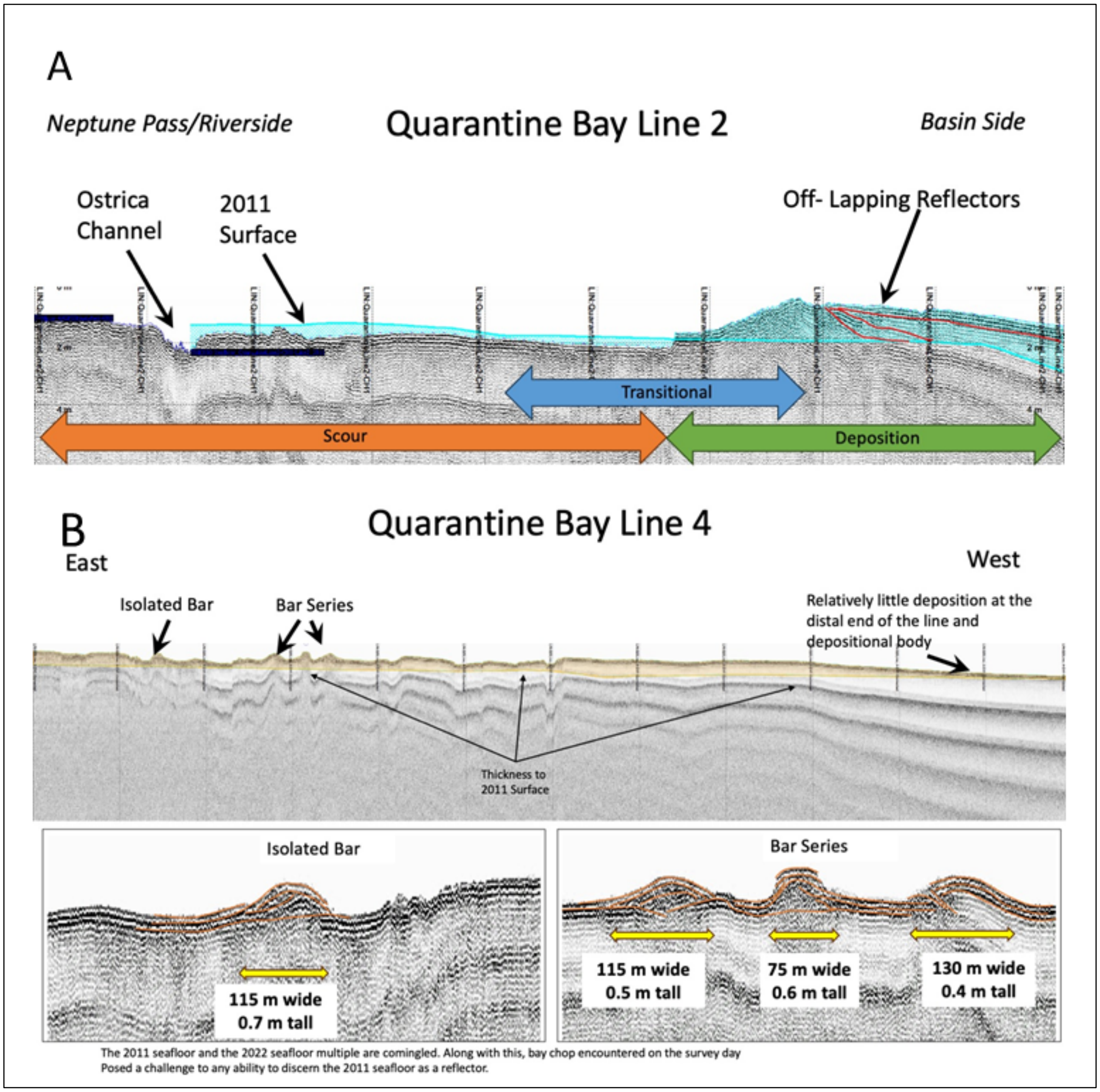

Figure 6: CHIRP sonar data for the Quarantine Bay Delta. A. A line that extends along-dip from the mouth of Neptune Pass (the riverside) to the bayside end of the Quarantine Bay Delta. This annotated image areas of erosion- near the mouth, along with a bar and multiple layers of sediment deposition. This image was also used to help determine the zones of erosion, transition, and deposition used in the sediment budget. B. An along-strike image of the Quarantine Bay Delta, with mouth bars and their spatial scale clearly noted.

3.3 Drone Surveys

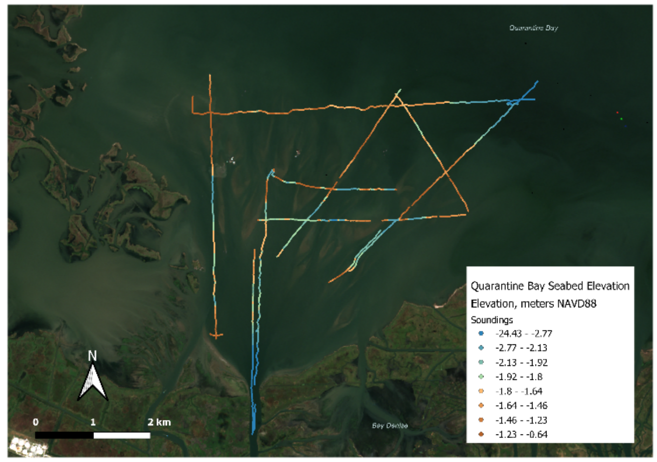

Figure 7. Track lines and bathymetry for Quarantine Bay single-beam survey. Note: these track lines were also used for the CHIRP sub-bottom profiler survey

Airborne drone surveys were launched on October 13, 2022 and March 28, 2023 using a Matrice 300 RTK system mounted with a Zenmuse L1 which houses both a LiDAR (Light Detection and Ranging) and a high-resolution true color, red, green and blue (RGB) camera. The LiDAR unit sends out pulsed light and records the time for pulses of light to return to the sensor, as well as the amount of light returning to the sensor for each pulse. These two methods produce a high-resolution 3D point cloud of the scanned area. Coupling the LiDAR with the RGB pixels from the sensing camera, this analysis created true-color 3D topography and classified surface characteristics such as vegetation type from the amount of light that is absorbed.

` The program DJI Terra (https://enterprise.dji.com/dji-terra) and CloudCompare (https://github.com/CloudCompare/CloudCompare/releases/) were used to build digital elevation models (DEM) from the dense 3D point clouds to create continuous surfaces of the scanned area, and georeferenced each of the scanned areas using real-world coordinates. Data were processed to produce both mosaics of Visible Light and True Color imagery as well as DEMs, using the 3D topography from LiDAR.

The drone surveys covered three primary areas (Figure 1):

- A region of mudflats, vegetation, and marsh terraces located to the west of the region where Neptune Pass discharges into Quarantine Bay. The terraces- essentially linear features of mud and sand, were placed here by the group Ducks Unlimited as part of their restoration program. These terraces will be referred to as the "DU Terraces" throughout this report.

- Bay Denesse and its delta. Bay Denesse is a ~ 3.5 km^2 bay to the east of the main channel of Neptune Bay. It is hydrodynamically connected to Neptune Pass by two primary channels and may receive additional sediment and water from ancillary flow paths. The primary flow pathways are connected to an emerging delta that is comprised of a mixture of both herbaceous and woody vegetation, such as Black Willow (*Salix Nigra*) and Delta Duck Potato (Sagittaria platyphylla). Similar plant communities are found in other young deltas (Paola et al. 2011; White and Visser 2023).

- The Quarantine Bay Delta. As described in the introduction, a large (~20 to 30 km^2) delta is developing in Quarantine Bay. It has a series of shallow submerged and emergent landforms. These areas were evaluated for drone mapping.

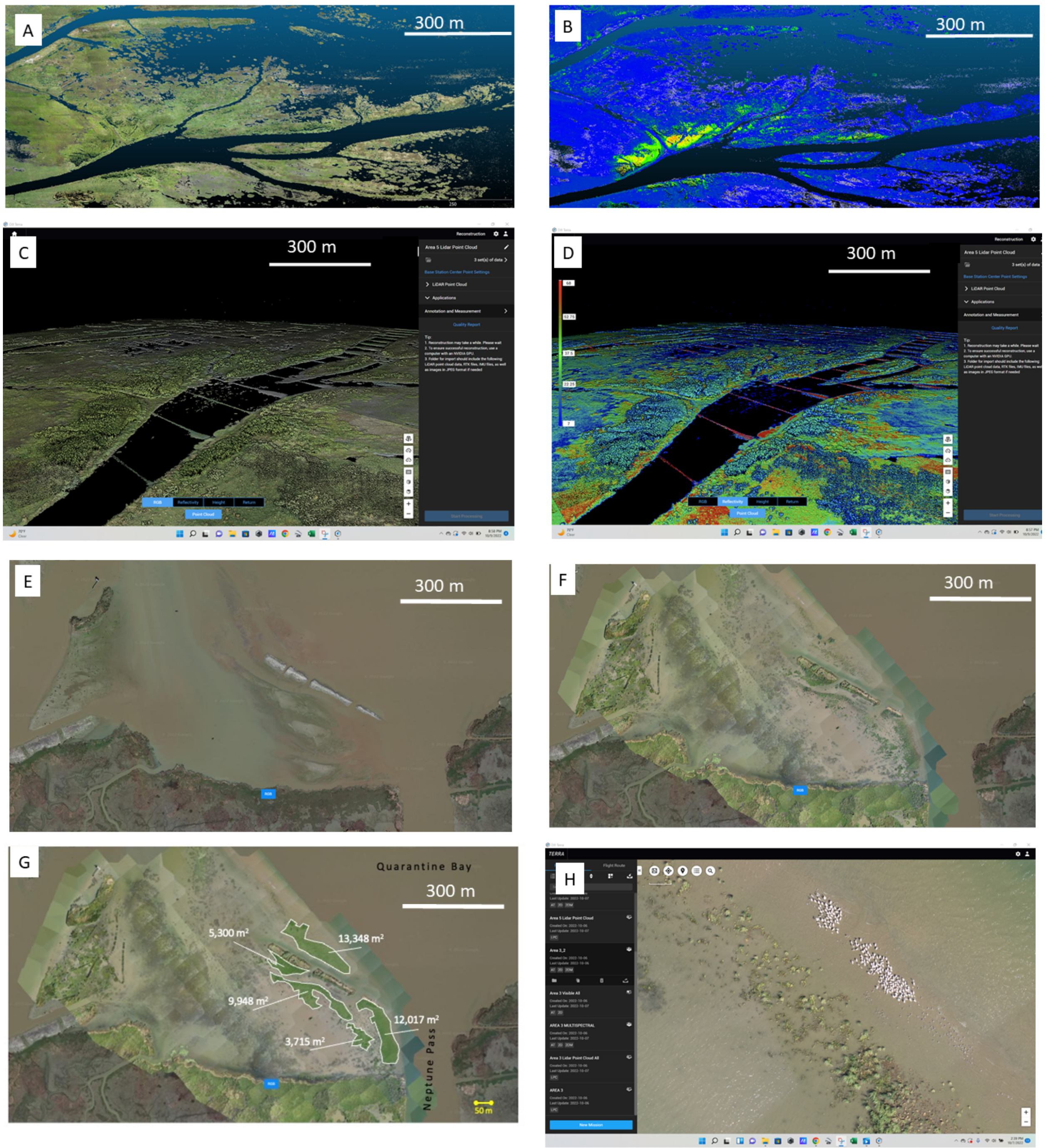

Figure 8: Images of land development near Neptune Pass. A: Aerial drone imagery with true color and elevations (RGB+DEM) of the Bay Denesse Delta. B. Reflectivity values for this same delta. The reflectivity scale is relative, and bluer areas have lower reflectivity while the redder areas have less reflectivity. Note that the high grounds in the RGB+DEM images roughly correspond with areas of greater reflectivity, indicating higher, drier land that reflects a greater amount of light to the drone's sensor. C. RGB+DEM image of the entrance to the Bay Denesse Delta. D. Reflectivity image of the entrance to the Bay Denesse Delta. E. Overhead view of the DU Terraces from Google Earth on 1/17/2021. F and G. Drone images collected in October 2022 of the same terraces with the Google Earth image in the background. G shows areas of new growth highlighted, with the areas noted. H. Close up of this region showing white dots that are wetland birds, likely either gulls, terns, or white pelicans.

3.4 Development of Satellite-Derived Bathymetry

To further understand the bathymetry of this shallow-submerged deltaic system, report authors developed a method of satellite-derived bathymetry (SDB). SDB is an emerging technique to determine the bathymetry of an underwater system (Ashphaq et. al., 2021; Traganos et al. 2018). It often involves using a remotely-sensed proxy correlated with ocean depth. SDB methods have been applied in coastal systems across the world, usually in clear water. To the best of our knowledge, SDB has not yet been applied to settings in coastal Louisiana. This report presents the use of SDB in Quarantine Bay by combining Sentinel-2 satellite imagery and in-situ hydrographic surveys with a tidal correction.

This analysis developed an algorithm that relates Sentinel-2 visible imagery to in-situ measurements of seabed elevation collected by our single-beam surveys. More specifically, this algorithm relates the pixel intensity of the red band (band 4) of a Sentinel-2 image collected on October 24, 2022 to water depths collected during the October 2022 surveys (Section 3.1, Figure 7, Figure 9). The algorithm works on the concept that light is reflected from mouth bars that are in shallow water relatively strongly, whereas light is reflected from the seafloor in deep water relatively weakly. The red band was used because empirically, it had the highest correlation to bar morphology. It was hypothesized that the red band represents sands and oxidized sediments, which can have an orange or reddish color. The blue and green bands used in SDB methods in other settings (clear water), were less effective in Quarantine Bay. It is hypothesized that the blue band works best in clear water- which is not present in Quarantine Bay, while the green band likely picks up algae, which is obscured by suspended sediment in Quarantine Bay (Ashphaq et al. 2021; Traganos et al. 2018). The October 24 image was chosen because this day was cloud-free, the mouth bars were clearly visible, and it was close to the dates of the bathymetric survey.

This study conducted a regression analysis to predict Quarantine Bay depth using a relationship that predicted and observed seabed elevation and red band pixel intensity, P_R, from Sentinel-2. The predictions were limited water depths from -0.5 m NAVD 88 to extinction depth of -3.m NAVD 88, which eliminated emergent land on the shallow end, and depth associated with the channel on the deep end. The relationship was $Q_{depth} = 2.98(-1.13* P_R$,. It yielded an R^2 of 0.37 and a root-mean squared error of 0.32, indicating the relationship is strong, but not perfect (Figure 9). Since the variability is on the order of 10^{-2} to 10^{-1} m in the vertical, and many of the features are 10^0 meter thick, 10^1 to 10^2 wide, and 10^2 to 10^3 meters long, the overall scale of the variability is likely to be small relative to the amount needed to calculate a sediment volume.

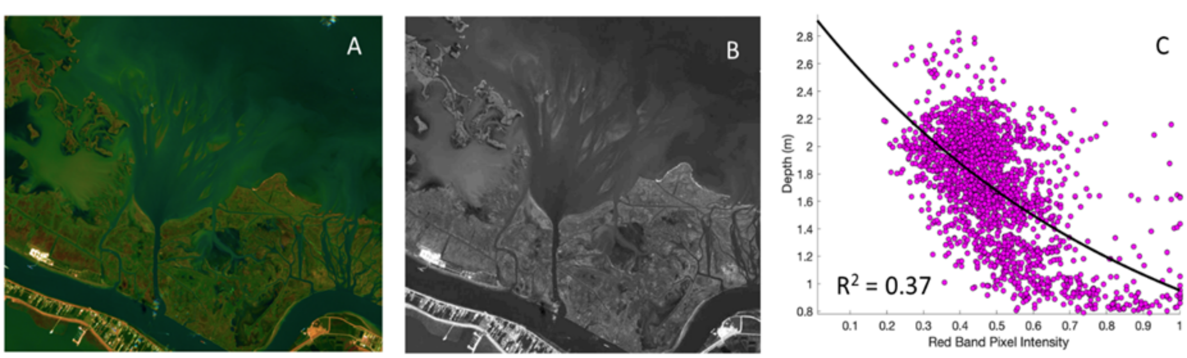

Figure 9 Information used to develop the satellite-derived bathymetry. A. Sentinel-2 true color image of the Quarantine Bay Delta on October 24, 2022. B. Sentinel-2 image from October 23, 2022 in the red band (band 4). C. Relationship between in-situ measured water depth (Figure 7) and pixel intensity in the red band (b).

3.5 Sediment Core Collection

Sediment cores were collected in Quarantine Bay on June 12 and 13, 2023. The location of sediment cores was informed and selected based on water depth, CHIRP sub-bottom profile data, and satellite images. The goal of the core collection was to understand the shallow geology of Quarantine Bay in enough detail to evaluate the thickness of recently sediment deposited in that bay. Cores were collected with a Vibracorer, a commonly-used method for collecting sediment cores in the Mississippi River Delta and other coastal systems (Shields et al. 2017; Fitzgerald et al. 2004). A total of 12 cores were collected ranging in length from about 2-4 m (Table 2). The core length was governed by the depth of refusal- the depth at which the corer cannot easily penetrate deeper. This depth also roughly corresponds to the thickness of recently formed mouth bars in other nearby settings in the Mississippi River Delta. (Esposito et al., 2013; Wright 1977). The pipe diameter was 7.6cm and the pipe material was aluminum. While collecting sediment cores, the amount of compaction was determined by comparing the depth of the sediment in the core barrel to the depth of the water. Cores were processed and described at the University of New Orleans's Department of Geology and Geophysics, (Fitzgerald et al. 2004; Brooks et al. 1995). The location of sediment cores is displayed in Figure 10, while a map with the location of single-beam sonar lines and the location of a relict oyster reef is displayed in Figure 11.

Table 2: Core Locations And Key Information

Core ID	Collection Date	Latitude	Longitude	Top Elevation NAVD88 (cm)	Core Length (cm)	Water Depth (cm)	Comp action (cm)	Notes
QB-03	6/12/2023	29.416537	-89.473728	-92	326	162.6	29.2	Lost 2 cm from bottom of core
QB-04	6/12/2023	29.427043	-89.49138	19	329	188	200.7	
QB-05	6/13/2023	29.426818	-89.517666	-97	340	101.6	45.7	Core lost on 1st attempt.
QB-06	6/13/2023	29.432375	-89.817549	-119	301	147.3	100.3	
QB-07	6/13/2023	29.406568	-89.517763	-146	284	172.7	53.3	
QB-08	6/13/2023	29.392086	-89.517867	-113	161	119.4	12.7	Short core because pipe sheared at refusal.
QB-09	6/12/2023	29.409169	-89.49318	-41	405	61	132.1	
QB-10	6/12/2023	29.418928	-89.492183	-87	359	101.6	147.3	
QB-11	6/13/2023	29.409523	-89.501079	-174	189	190.5	-2.5	Short core because pipe sheared at refusal.
QB-12	6/13/2023	29.417251	-89.50527	-29	357	45.7	15.2	
QB-13	6/13/2023	29.39333	-89.496384	-27	343	35.6	48.3	
QB-14	6/12/2023	29.409565	-89.472691	-87	318	106.7	134.6	

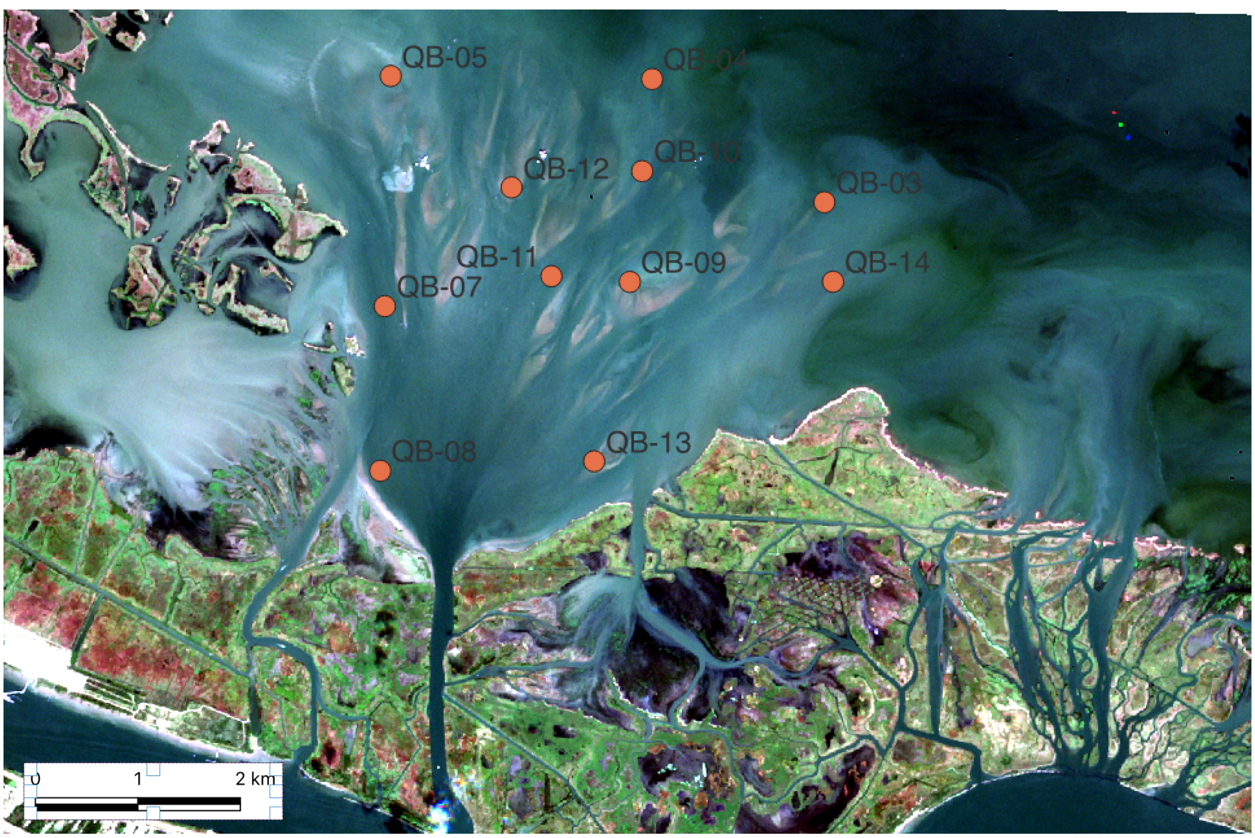

Figure 10. Location of sediment cores in collect in Quarantine Bay. Image background: Sentinel-2.

3.6 Calculation of Sediment Budget

One key component of this project was to calculate the amount of sediment deposited in Quarantine Bay, and to compare that to the amount sediment scoured from Neptune Pass. This budget sediment would help determine if the delta developing in Quarantine Bay was comprised entirely of sediments scoured from Neptune Pass, or if some of the material in the Quarantine Bay Delta was sourced from recent sediment transport along the Mississippi River.

To do this, the volume of sediment extracted from Quarantine Bay was determined via a volumetric difference approach. It compared the channel volume determined from a (pre-expansion) January 2016 survey to the channel volume determined from a (post-expansion) May 2022 survey (Kolker and Weathers 2022; Weathers et al. 2016). The January 2016 survey used an Acoustic Doppler Current Profiler (ADCP) to measure the channel dimensions at the head and mouth of Proto-Neptune Pass, and channel dimensions were assumed based on a linear interpolation between the two. The 2022 survey used a multibeam sonar survey to measure the depth of the entire channel (Fig. 3). Google Earth images suggest relatively little change in the channel between 2016 and 2019- directly before the opening of Neptune Pass.

The volume of material in the Quarantine Bay deposit was determined by creating an isopach map. In this map, the deepest part of the deposit was determined from survey lines collected by Louisiana's Department of Wildlife and Fisheries (LDWF) in 2011 (Bio-West 2011). This is the most recent and most accurate survey of the area conducted before the opening of Neptune Pass. It is referenced to NAVD 88, and its validity is corroborated by sediment cores that have shells at the same locations, and interpolated elevations, where the LDWF found oyster reefs (Figure11). The LDWF survey was further adjusted for subsidence, assuming a rate of 22 mm yr^{-1}, as per literature values (Veatch 2017). The higher end of the Quarantine Bay deposit was determined from the surveys presented herein.

For the sediment budget calculation, the bay was split into three main regions: an erosional zone (near the channel mouth), a transitional zone of mouth bars and channels, and a net depositional change (Fig. 11). These zones were determined from the CHIRP sonar- which revealed patterns of erosion and deposition, as well as the in-situ and satellite-derived bathymetry and sediment cores (Figure 6, Figure 11). These data reveal overall morphological patterns in the bay, while the sediment core data further help corroborate patterns and volumes of deposition and erosion. In each of these three zones, the mean depth change (accounting for subsidence and adjusted to NAVD 88) between the 2011 and 2022 surveys was determined, and the volume was calculated from the area of each zone.

To further evaluate the amount of sediment scoured and deposited, the total mass of sediment of scoured and deposited sediment was determined. This was done using the equation Mass (kg) = volume (m^3) x porosity (P) x sediment density. In all cases, the sediment density was assumed to be 2600 kg m^{-3}, the density of many aluminosilicate rocks and coastal sediments (Blum and Roberts 2012; Smith et al. 2015). The calculation was applied to two different porosity scenarios. In the “standard case" the porosity of the scoured and eroded sediment was assumed to be 0.4, a commonly used porosity for coastal sediments. In the "conservative case" it was hypothesized the scoured sediment could be more tightly packed (lower porosity, P = 0.3) than typical, whereas the recently deposited sediment could be less tightly packed (higher porosity, P = 0.5) than typical (Blum and Roberts 2012; Smith et al. 2015). This assumption would provide a conservative view on the amount of sediment that could be deposited. Using both cases allows one to understand the range of scenarios in which sediment was deposited.

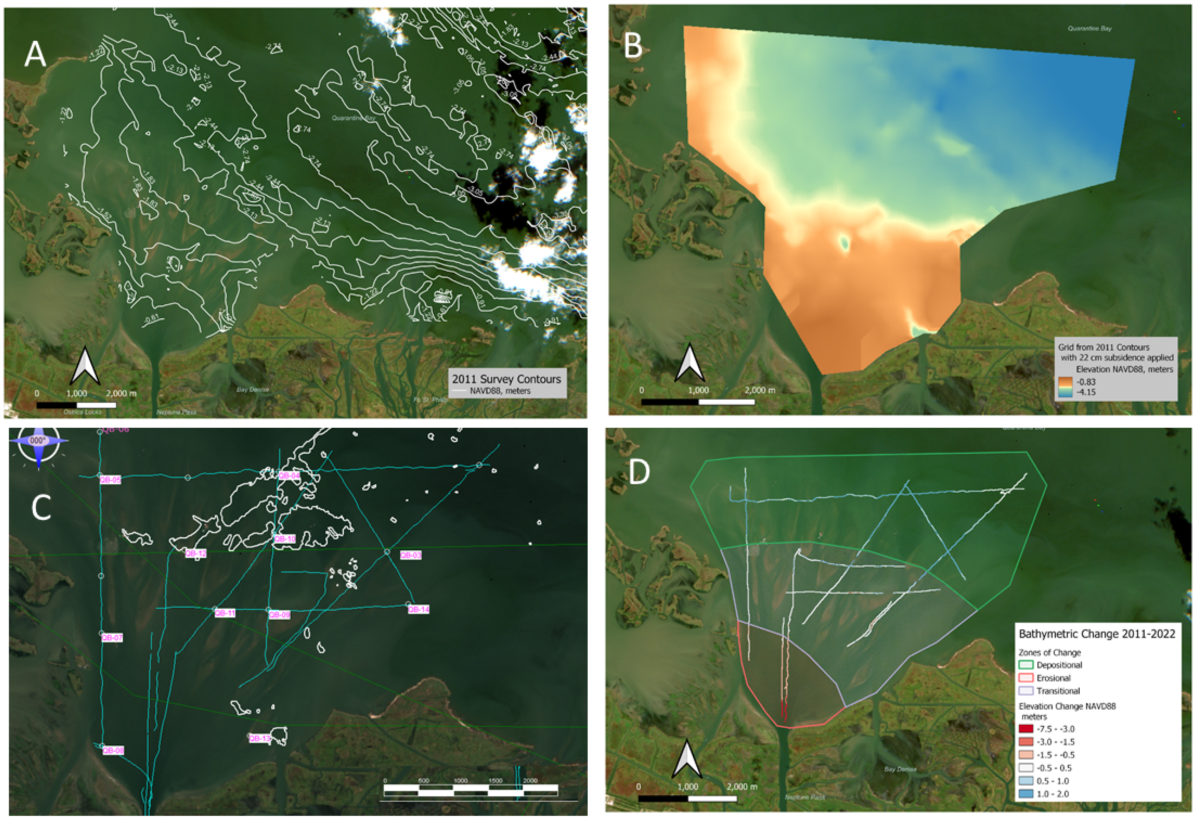

Figure 11: Information used for the development of the sediment budget. A and B. The 2011 survey of Quarantine Bay, expressed as contours (A) and as a color coded grid (B). C. The core locations with the oyster reef highlighted. D. The difference map between the 2011 and 2022 surveys, with the erosional, transitional, and depositional zones used in the sediment budget highlighted.

4.0 RESULTS

Results from this project are available in the attached data folders that have been delivered to CPRA and NWF. These folders consists of five main datasets:

* *Single-beam bathymetry*
* *CHIRP seismic sub-bottom profiles*
* *Subaerial topography via drone-based LiDAR and photogrammetry*
* *Satellite-derived bathymetry*
* *Sediment Core characterization*

4.1 Bathymetry

Figure 7 shows the single-beam bathymetry of Quarantine Bay, overlaid over a Sentinel-2 image of the region. This image shows a deep area, near where Neptune Pass debouches into Quarantine Bay and areas of alternating high and low grounds about 2-5 km from Neptune Pass's mouth. This corresponds to a network of mouth bars and channels; each of which have lengths of the scale of 10^2 m, widths of the scale of 10^0 to 10^1 m and elevations on the order of 1 to 2 m. This area eventually grades into deeper water- particularly towards the northeast in this dataset- which likely indicates the edge of the Quarantine Bay Delta deposit. Overall, the tops of the mouth bars are about -0.1 to -1.0 m NAVD 88, with negative values indicating area below a geological surface that approximates sea level. This places them in the lower intertidal/high subtidal zone. In common language the bar tops are likely to be exposed when water levels in Quarantine Bay are low and covered with shallow water when water levels in Quarantine Bay are high. Shapefiles of the bathymetry describing Quarantine Bay sediment deposits are available in the folder Neptune_Pass_Data_Folder/Quarantine Bay Single Beam/spatial.

4.2 CHIRP Sub-bottom Profiles

Figure 5 illustrates how CHIRP sub-bottom data can image below the seafloor and provide insight to the geometry and thickness of the sedimentary deposit. This figure indicates numerous mouth bars that are about 40 to 80 m wide and 1 to 2 m thick. These values are consistent with the true-color satellite images, the single-beam bathymetry, and the SDB (Figure 4, Figure 7, Figure 11). These CHIRP data also help reveal patterns of scour and deposition, as determined by the apparent removal of stratigraphic layers (for erosional surfaces), and the presence of bars and overlapping sequences (for depositional surfaces). These patterns were then used to determine baywide zones of erosion, deposition, and transition in the sediment budget.

CHIRP sub-bottom profile data and waterfall images can be found in the folder, Neptune_Pass_Data_Folder/CHIRP Subbottom. Raw data is in the Jstar format (.jsf) and can be opened and viewed in Edgetech Discover software, which is free, and Chesapeake Sonar-Wiz software, which requires a paid license. These data provide insights into the geology of the region. In particular, they can be used to determine the thickness of the mouth bars in Quarantine Bay.

4.3 Aerial Drone Imagery

The aerial drone LiDAR imagery is presented in two ways: true color images that incorporate a digital elevation model (DEM+RGB), and reflectivity images that are color-coded by the intensity of the LiDAR signal return (Fig. 8). The former is useful for understanding interactions between horizontal patterns of land growth and vertical patterns of change. This information is useful for understanding a wetland's relationship to sea level which is a critical control on wetland stability (Reed 2002). The latter provides information useful for understanding the relationship between wetland morphology and vegetation, which is also a critical parameter governing wetland development (Paola et al. 2011; Ameen et al. 2017; White and Visser 2023). In both datasets the horizontal resolution of the images is < 1m, and in the case of the DEM the elevation control is < 10 cm. The reflectivity data is presented on an arbitrary scale from 0 to 1, with 0 being complete signal absorption and 1 being complete signal reflection.

The data collected at Bay Denesse and the DU Terraces provide clear examples of developing land (Fig. 8). The Bay Denesse digital elevation model with red, green and blue colors (DEM+RGB) image shows two deltas. One delta is in roughly the center of the bay, and has a distinct fan-shaped morphology, while another delta is more oblong-shaped with some fan-shaped offshoots visible. In the central delta, the DEM reveals differences in elevation, channel edges are generally high ground, and splay interiors are generally low ground. Additionally, the reflectivity data show that the high grounds tend to have greater reflectivity values, likely indicating a relatively dry plant community that yields stronger signal returns. Patterns are generally similar in the northern delta, but not as distinctive given the somewhat oblong shape of the delta.

In the region around the DU Terraces show a different pattern. Here there is an elongated and growing sand bar, bounded by the Ostrica Channel flow path of the left (western) side and Neptune Pass on the right (eastern) side. The DEM+RGB and reflectivity data indicate that the edges of the bar-system are relatively high ground. These data, when coupled with Google Earth and Sentinel-2 data indicate the area interior to this developing bar has been vegetating for a period of about 3 years. Additionally, the DEM+RGB data also reveals wildlife (e.g. alligators and wading birds) in high enough resolution that individual organisms can be identified, raising the prospect that future research could use this drone for wildlife survey in deltas.

4.4 Satellite Derived Bathymetry

Figure 9 shows the regression used to develop the satellite-derived bathymetry (SDB). The relationship between water depth and pixel intensity in the red band is best described by a quasi-asymptotic relationship, in which shallower water is correlated with increasing pixel density. This is most likely due to the fact that in shallow water light from the bars is better reflected to space, relative to deep water, where light is less well reflected to space. The regression's limits were defined by the depth the vessel could conduct a survey on the shallow side, and the area of the main delta deposit on the deep side. Very deep water, such as occurs near the Neptune Pass's mouth in Quarantine Bay, has been removed from this regression as light reflection/depth dynamics are likely to be governed by qualitatively different factors.

Figure 12 presents the SDB for the Quarantine Bay domain. It shows a broad field of mouth bars and shallow deposits interspersed with a network of channels. The inset of the image delineates the depth along a marked pathway. Overall, the image displays the range of dimensions found in the mouth bars: hundreds to thousands of meters long, tens to hundreds of meters wide, and 1-2 meters in elevation. These finds are consistent with the in-situ sonar and CHIRP measurements, as well as the progression of satellite images (Figures 4, Figure 5, Figure 7)

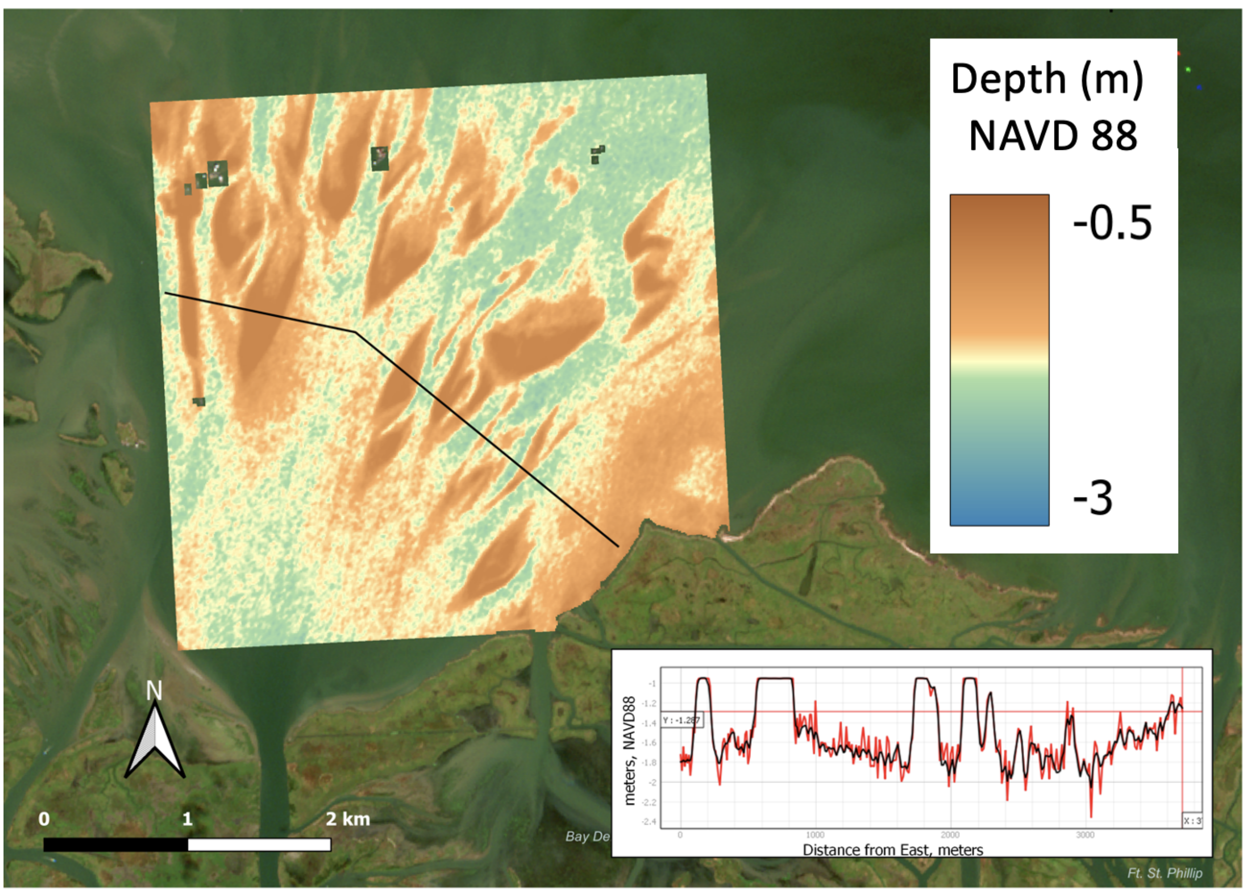

Figure 12 Satellite-derived bathymetry of Quarantine Bay and its delta. The linear bathymetric profile in the lower right-hand corner corresponds to the line that traverses across the delta in the main image.

4.5 Sediment Cores

A total of 12 sediment cores were collected from Quarantine Bay. These were collected across the bay, in a variety of water depths, and with a range of surficial sediments (Fig. 10, Table 2). The elevation of the top of the sediment cores ranges from +19 to -146 cm NAVD88. These cores ranged from 151 cm to 405 cm in length. Compaction in these cores range from -0.1% to 5.7%, with the negative value indicating expansion- which was only found in 1 core. Overall, these core extractions are relatively typical of Vibracoring efforts in the Mississippi River Delta.

Sediments in these cores are mostly siliciclastic sediments, consisting of a combination of both fine (i.e. silt and clay-sized) and coarse (i.e. sand sized) sediment (Figure 13). These sediments are typically found in interbedded material, with bedding existing on scales of 10^1 cm. Such arrangements are common in accreting deltaic deposits in the Mississippi River Delta.

Several features of these cores point towards recent sediment deposition. For example, cores 9, 11, 14, and 10 have oxidized (yellow and brownish) sands near the surface. The presence of oxidized sediments suggests recent deposition, as sediments in the Mississippi River Delta's organic rich and often low-oxygen environments tend to yield reduced (black and gray) sediments. Also of particular interest is the presence of multiple, overlapping oyster shells in cores 11 (at 135-160 cm) and 9 (at 220 cm). These cores likely reflect the oyster reef present in the 2011 survey conducted by LDWF, and subsequent burial of these reefs by Neptune Pass derived sediments (Figure 11).

Satellite imagery is available in the folder Neptune_Pass_Data_Folder/Sentinel 2 Satellite Imagery. It contains two 10-m resolution images of the lower Mississippi River Delta, including Neptune Pass. The original data comes from the European Space Agency's Sentinel-2 satellite.

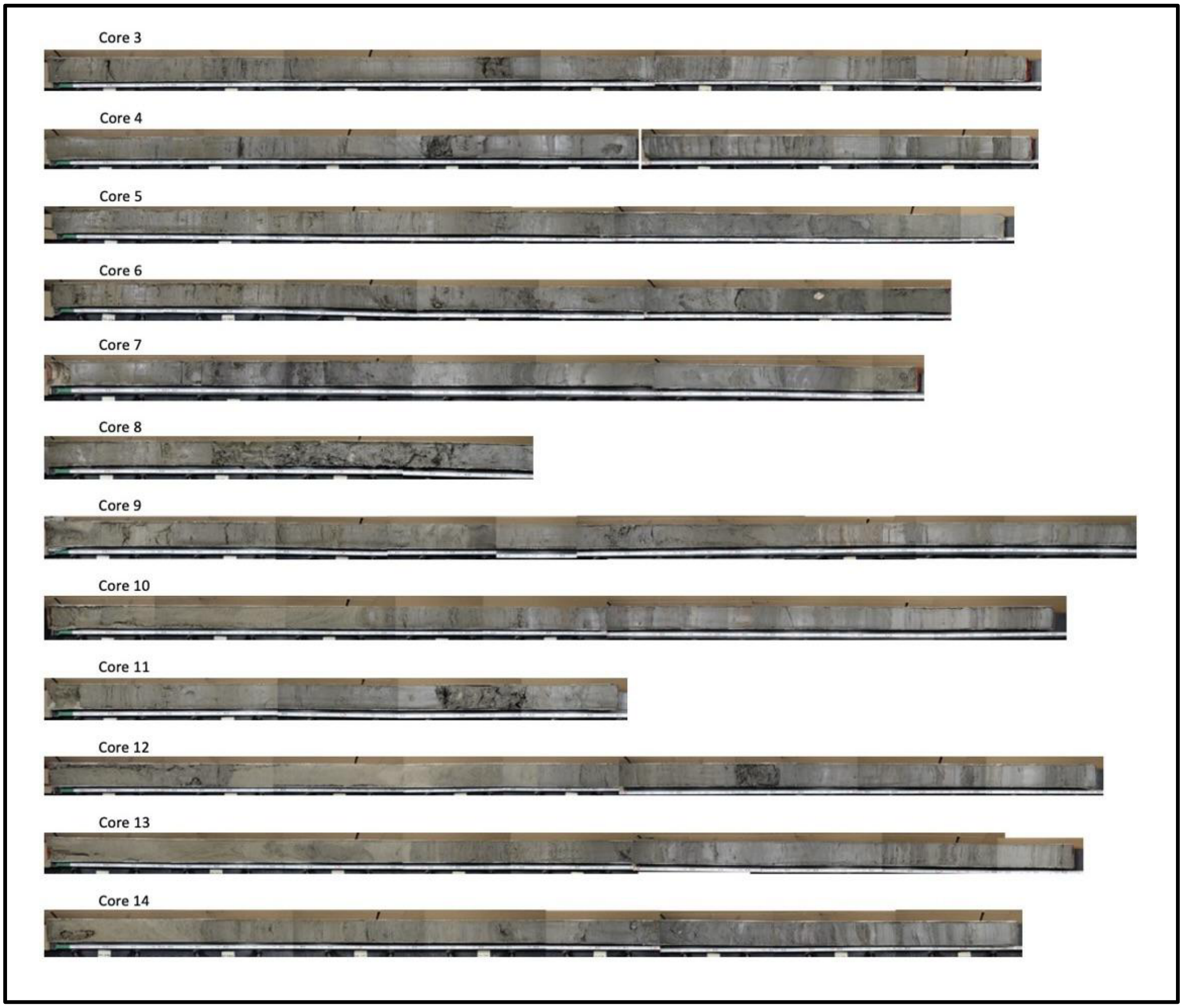

Figure 13: Photographs of the sediment cores collected in this study.

4.6 Sediment Budget Calculations

Table 3 presents the sediment budget that compares the amount of material scoured from the Neptune Pass channel to the amount of material deposited in the Quarantine Bay Delta. This budget indicates that a total of 6.1 x 10^6 m^3 of sediment was scoured from Neptune Pass, while a total of 1.1 x 10^7 m^3 of sediment was deposited in Quarantine Bay. Overall, this indicates a net deposition of 5.0 x 10^6 m^3 in Quarantine Bay. Converting these volumes to mass, and assuming no difference in the porosity between the scoured and deposited sediments ("typical case", section 3.6) indicates a net deposition of 7.9 x 10^9 kg. Converting these volumes to masses, and assuming lower than usual scoured porosities and higher than usual deposited porosities ("extreme case", section 3.6) indicates a net deposition of 3.3 x 10^9 deposition.

Estimate of excavation in Neptune Pass			
Date	Mean Channel Area	Channel Length	Channel Volume
	(m^2)	(m)	(m^3)
2016 ADCP	317	2,632	8.3E+05
2016 above Transducer	-	-	2.6E+03
2022 Multibeam	-	-	7.0E+06
		Net Erosion	**-6.1E+06**

Estimate of deposition in Quarantine Bay			
Zone	Mean Seafloor Change	Area	Net Volume Change
	(m)	(m^2)	(m^3)
Erosional	-1.11	5.1E+06	-5.7E+06
Transitional	0.05	7.3E+06	3.6E+05
Depositional	0.92	1.8E+07	1.6E+07
Total		3.0E+07	**1.1E+07**

Estimate of net deposition in Quarantine Bay			Typical Case		Extreme Case	
Date	Volume	Density	Porosity	Mass	Porosity	Mass
	(m^3)	(kg/m^3)	(%)	(kg)	(%)	(kg)
Channel Scour	-6.1E+06	2600	40%	-9.5E+09	30%	-1.1E+10
Bay Deposition	1.1E+07	2600	40%	1.7E+10	50%	1.4E+10
Net Deposition	**5.0E+06**			**7.8E+09**		**3.3E+09**

Table 3. Sediment budget for Neptune Pass and Quarantine Bay. The data in the top table are from Weathers et al., (2016), the table in the middle table are from Kolker and Weathers (2022), while all of the remaining data are from this project.

5.0 DISCUSSION

5.1 Causes of Neptune Pass Development

Remotely sensed images indicate that Neptune Pass rapidly expanded after early 2019, and that the initial phase of expansion was complete by about 2021. Further development may continue, and given the size of Neptune Pass, deserves attention by future researchers. While a comprehensive examination of the causes of Neptune Pass' development would require additional research and analysis, data in this report, in combination with other publicly available data, point to five non-mutually exclusive hypotheses for the system's rapid expansion.

Extended periods of high river water. The period from 2008 to 2020 had multiple extended high-water events, including 7 openings of the Bonnet Carre Spillway, which occur when the lower Mississippi River reaches its maximum allowable flow (rivergauges.com). This time period also had at least 3 additional flood seasons when the Mississippi River's flow approached, but did not reach, the threshold for a Bonnet Carre Spillway opening (rivergauges.com). Multiple years of high flow would have put pressure on the Proto-Neptune Pass system, creating erosive forces that could have led to its rapid expansion.

Degrading Infrastructure. The levee systems along the east bank of the Mississippi River south of Bohemia, Louisiana are not well maintained. While there are some channel stability projects, such as rock walls and revetments, this region is prone to crevassing. This is evidenced by multiple crevasses near Neptune Pass, including the roughly 12 crevasses near Fort St. Philip, as well as crevasses near the Ostrica Locks and Mardi Gras Pass.

Hurricane Impacts. Hurricanes can cause storm surges that travel up the Mississippi River, which can put pressure on channel structures. During Hurricane Barry (July 12-13, 2019) there was a small (~ 0.3 m) storm surge up the Mississippi River (rivergauges.com), which occurred when the river was at high flow (~ 28,500 $m^3 s^{-1}$), and within about 1 year of the rapid expansion of Neptune Pass. However, Barry's surge was substantially smaller than surges during Hurricanes Katrina (~5m; 2005) and Isaac (~ 2. 5 m; 2012), which did not seem to appreciably impact other crevasses near Neptune Pass.

Backstepping of the Mississippi River Delta. Some scholars suggest the mouth of the Mississippi River is moving inland, a result of the combined impacts of rising global sea levels and subsiding lands (Maloney et al. 2018). This hypothesis leads to the prediction that crevasses would develop upstream of the river's current mouth as the delta "backsteps" and retrogrades landward. The development of Neptune Pass and other nearby crevasses, such as the Fort St. Philip Crevasse Complex and Mardi Gras Pass are consistent with this theory of deltaic backstepping.

Faulting. Geological faults are present below the ground in Louisiana. One study from 2014 shows faults near Neptune Pass (Armstrong et al. 2014). It is possible these faults created a weakness or low-elevation point in the river's levee, which was vulnerable to erosive forces of the Mississippi River.

While the above factors are not mutually exclusive and could have acted synergistically to increase the size of Neptune Pass, in the judgment of report authors the combination of years of high flow and degrading infrastructure are the most likely causes of the expansion. High river flows would place intense forces on the Proto-Neptune Pass, while infrastructure deterioration would have created weaknesses. It is intriguing that Hurricane Barry's storm surge in the Mississippi River occurred at about the same time as the Neptune Pass expansion, but Barry's surge was relatively modest and short-lived, particularly when compared to duration of river floods. The backstepping hypothesis is intriguing and has been discussed in parts of Louisiana's coastal community for several years (Maloney et al. 2018). Though the development of Neptune Pass is consistent with backstepping theory, more rigorous evidence is probably needed to fully link Neptune Pass to the backstepping hypothesis. Finally, there is insufficient evidence in the published literature to evaluate the faulting hypothesis- though the available evidence is not inconsistent with it.

5.2 Development of Neptune Pass in The Context of Deltaic Development

5.2.1 *The Delta Cycle*

The development of Neptune Pass and the Quarantine Bay Delta can be understood in the context of the geological literature on deltaic development (Figure 14). One key element is the delta cycle, which envisions deltaic development as a cyclical process of channel and splay growth and decay (Roberts 1997). The cycle starts with a crevasse in a river channel that rapidly expands. This expansion is governed by a positive feedback loop in which rapidly flowing water erodes the channel, drawing more water, increasing the erosive power of the channel, which causes further crevasse expansion. The expansion of a new channel results in less flow through the old channel. During early and mid-stage development, the crevasse discharges into an open bay.

Over time, the sediment input results in landform development, often resulting in a complex that includes mouth bars, natural levees, mudflats, and marshes (Roberts 1997). In later stages of the delta cycle, flow becomes restricted as landform develop to their maximum size, resulting in less sediment input and reduced marsh accretion. During these late phases, the channel becomes less hydrodynamically efficient, resulting in more water flow in the original channel, creating pressure that eventually leads to the formation of a new crevasse- restarting the delta cycle elsewhere (Roberts 1997).

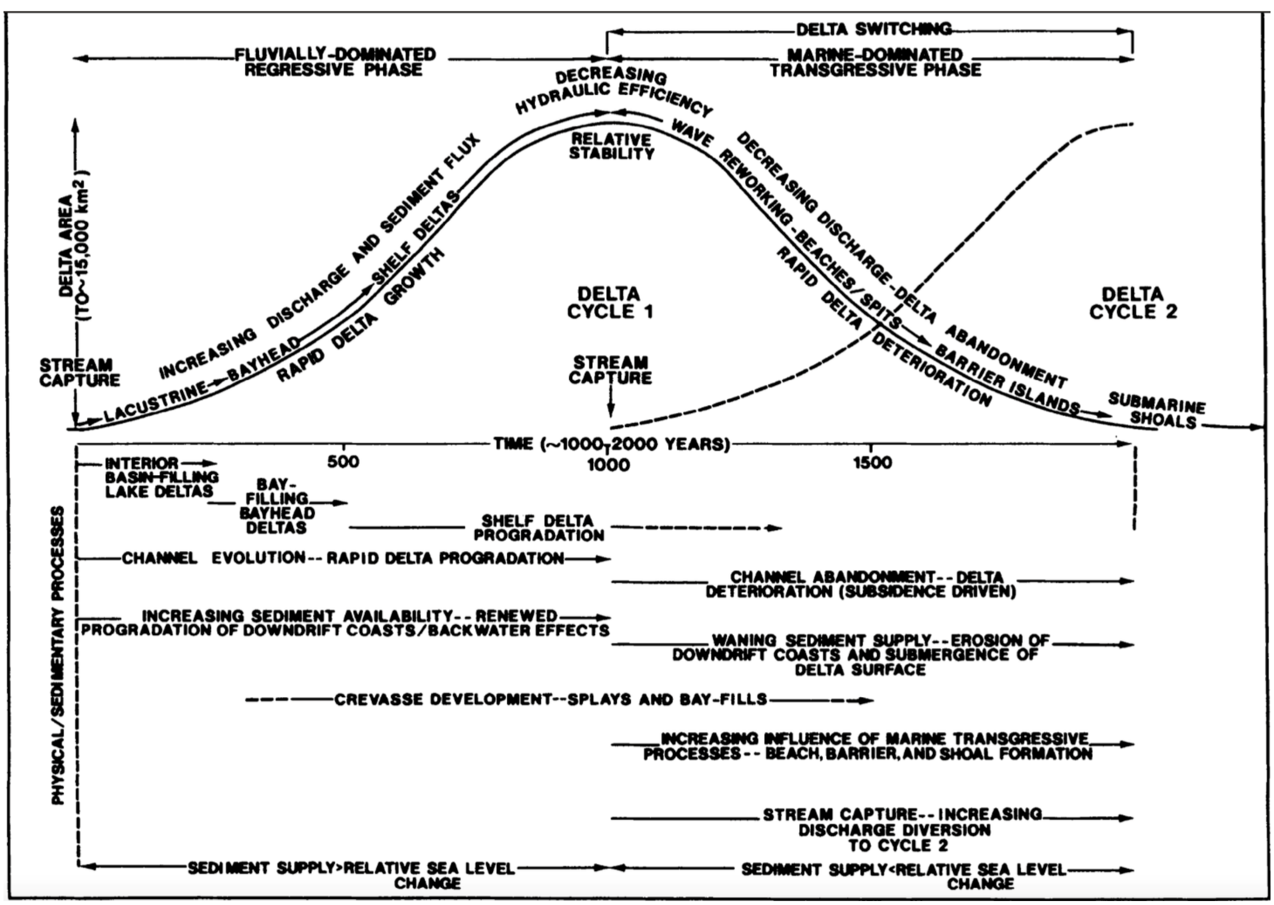

Figure 14: The temporal progression of the delta cycle, from Roberts (1997).

The overall spatial patterns associated with the delta cycle are relatively consistent across the Mississippi River Delta Plain, but the temporal and spatial scale of systems vary considerably. Small channels tend to have a discharge of about 50 to 500 m s^{-1} and create splays with areas of about 10^{-1} to 10^{1} km^2 that last decades (Wells and Coleman 1987; Day et al. 2007). Medium-sized channels have discharges of about 500 to 5,000 m^3 s^{-1}, and create subdeltas with areas of 10^1 to 10^2 km^2 that last decades to centuries (Wells and Coleman 1987). The largest channels have discharges 5,000 to 50,000 m^3 s^{-1}, and create delta lobes areas of 10^3 to 10^4 km^2 that last centuries to millennia (Wells and Coleman 1987; Day et al. 2007). Neptune Pass appears to be a medium sized system that could last decades to centuries in the absence of other human impacts and in the presence of slow rates of relative sea level rise.

The development of Neptune Pass is comparable to parts of the delta cycle, including**:**

Rapid channel expansion. Delta cycle theory predicts new crevasses should rapidly expand, a result of a positive feedback loop between channel discharge and channel scour (Roberts 1997). The rapid expansion of Neptune Pass in 2019 and 2020 follows this pattern of rapid expansion.

Mouth bar development. The development of mouth bars in Quarantine Bay is consistent with the land-building phase of delta development (Roberts 1997; Wright 1977; Esposito et al., 2013; Allison et al. 2017). The islands observed in Quarantine Bay are morphologically similar to mouth bars in other well-known developing deltas such as the Wax Lake Delta today and early 20th century maps of the Cubit's Gap Subdelta (Gagliano and Coleman 1964; Wellner et al. 2006).

Reduced hydrodynamic efficiency in the main channel. Shoaling in the Mississippi River observed downstream of Neptune Pass (Schleifstein 2022; USACE 2022) is consistent with delta cycle theory noting a reduction in hydrodynamic efficiency in the main channel as flow is diverted into a newly developing crevasse (Roberts 1997).

5.2.2 *Sediment Dynamics at River Mouth*

The development of the landforms associated with Neptune Pass also follow geomorphological theory regarding river mouths (Wright 1977; Gagliano and Coleman 1964; Esposito et al. 2013). The geomorphology of sediment-rich rivers that discharge into shallow basins is governed, in large part, by friction. (NB: While the Mississippi River carries less sediment than it did 100 years ago, the system remains, relative to many other rivers, sediment rich; Blum and Roberts 2012). Closest to the river mouth, where velocities are high, crevasses have a zone with no deposition or erosion (Figure 15, Figure 16, and Figure 17). Further from the river mouth, the flow spreads out and velocities decrease, inducing sedimentation. The heaviest, coarse-grain material settles out first, creating a bar that is often tear-drop shaped. The interiors of these bars tend to receive less sediment, and the sediment they do receive tends to be relatively fine-grained. The result is an area of poorly consolidated mud and open water in the zone between the natural levees (Esposito et al. 2013; Paola et al. 2011).

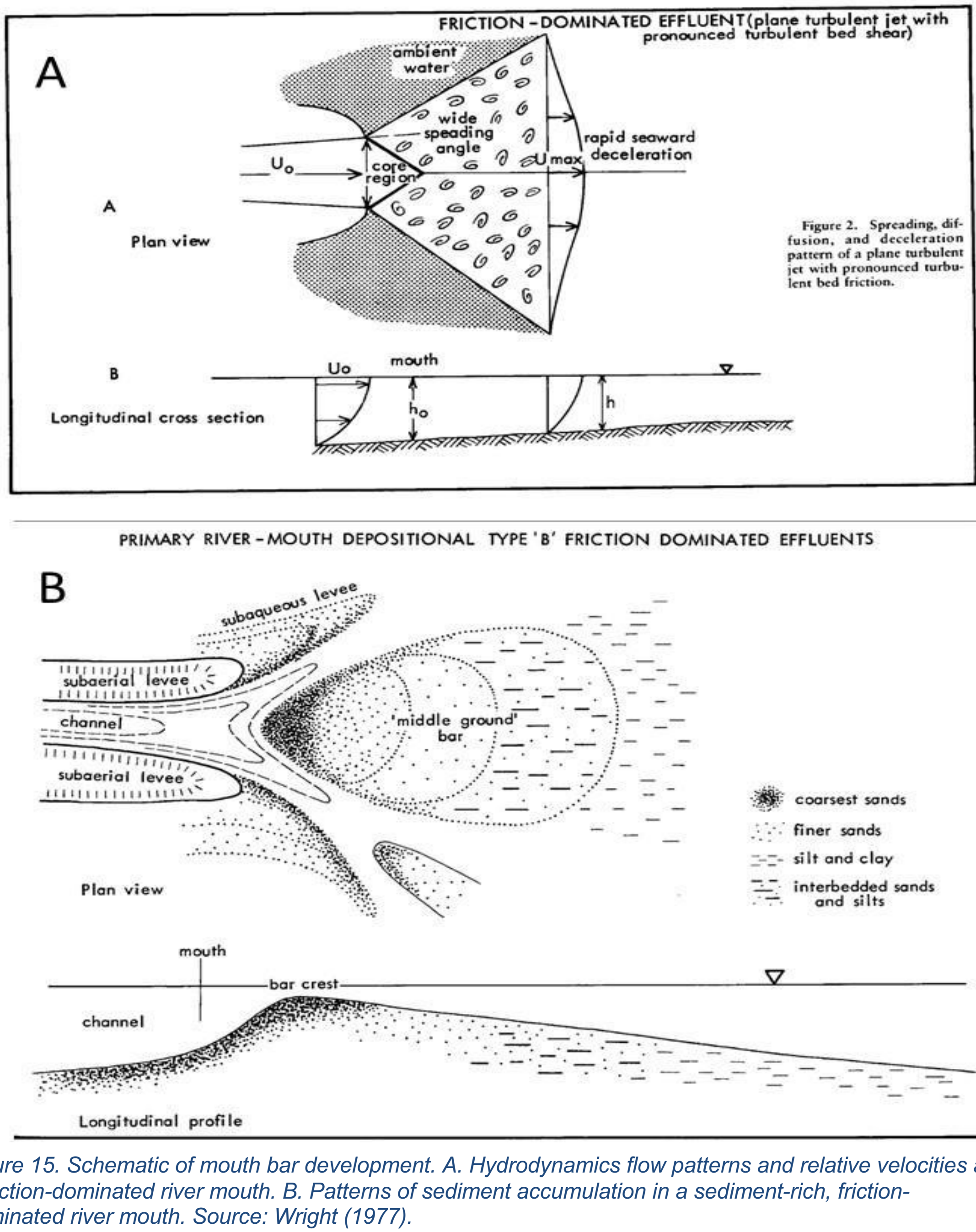

Figure 15. Schematic of mouth bar development. A. Hydrodynamics flow patterns and relative velocities at a friction-dominated river mouth. B. Patterns of sediment accumulation in a sediment-rich, friction-dominated river mouth. Source: Wright (1977).

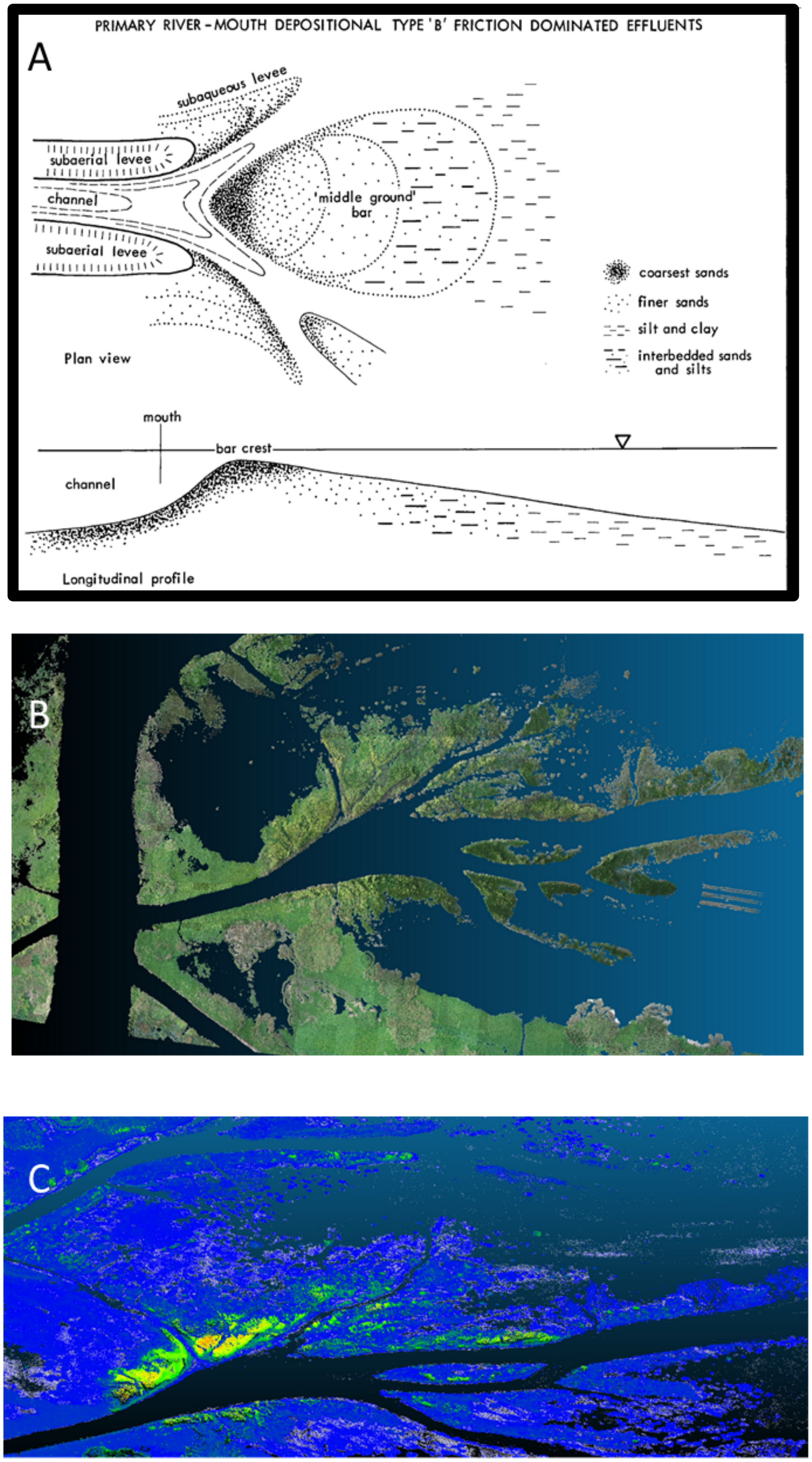

Figure 16: A. Patterns of sediment accumulation in a sediment-rich, friction-dominated river mouth from Wright (1977). B. Lidar true color and DEM imagery of the Bay Denesse Delta. C. Reflectivity of the Bay Denesse Delta. Note how the theoretical patterns of mouth bar development in A are similar to the actual shapes that develop in the Bay Denesse Delta.

This pattern of deltaic development is present in the data presented herein, most notably the Sentinel-2 imagery of Quarantine Bay, the satellite-derived bathymetry of Quarantine Bay, and the aerial drone LiDAR imagery of Bay Denesse. All the images show tear-dropped shaped islands, while the two images with explicit elevation data (aerial drone and SDB) indicate that mouth bar edges are higher than the interiors. Morphologically, this pattern in elevation looks similar to other developing deltas, like the Wax Lake Delta, the Cubit's Gap Subdelta, and the delta in the Davis Pond Freshwater Diversion (Paola et al. 2011; Roberts 1997; Amer et al, 2017; Keogh et al. 2019).

The return flow of sediments, after their discharge in a bay, is another potentially important geomorphic pathway. This pathway was articulated for the Wax Lake Delta in southwest Louisiana (Roberts et al. 2015). Roberts et al., (2015) hypothesized that some sediments carried by the main conveyance channel (i.e. the Wax Lake Outlet) initially discharged beyond the delta, could be transported to posterior regions by strong onshore winds. This contributed to sediment accumulation in inshore marshes.

The impacts of return flow is apparent in DU terraces, and the accreting sandbar northwest of the mouth of Neptune Pass. A combination of pre-2020 Google Earth imagery, the aerial drone imagery, and Sentinel-2 images reveals a zone of accretion (Figure 17). Areas of open water have become vegetated, and the sandbar is elongating at a rate of >100 m yr^{-1}. The interpretation is that sediments are ejected from Neptune Pass into the northeastward direction, and then returned eastward via winds and waves.

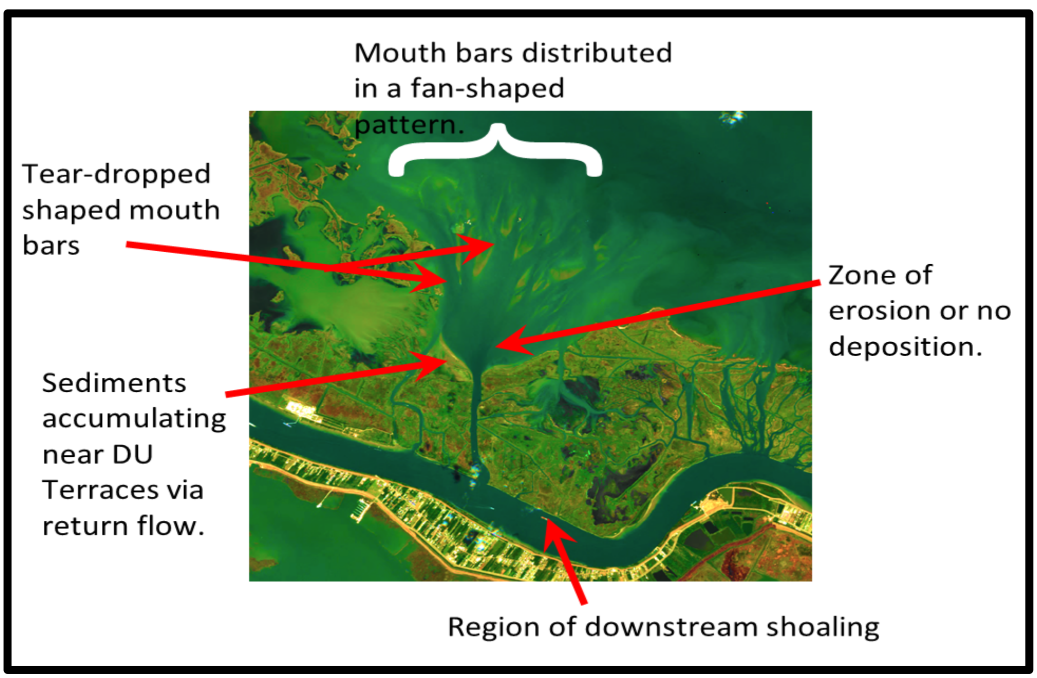

Figure 17: The Quarantine Bay Delta, annotated with major deltaic features noted.

5.2.3 The Role of Vegetation

Vegetation can also play an important role in deltaic development because stems and shoots can slow water flow which traps sediments, while roots and rhizomes can promote accretion (Paola et al. 2011; Day et al. 2009; Ameen et al., 2017). The development of vegetated areas is not simply a mark of stable land, but also a key factor in its development.

Vegetation appears to be taking root in the Bay Denesse Delta and the DU terraces, as indicated by both on the ground observations and aerial drone data. Furthermore, patterns of vegetation seem to match patterns expected from geomorphological theory (Figure 16). For example, the reflectivity image of the Bay Denesse Delta shows greater reflectivity on delta edges relative to the delta interior. Field observations (A. Kolker pers observation) indicate that these high grounds include plants like Roseaucane (*Phragmites australis)* and Black Willow (*Salix nigra*), which are commonly found in developing deltas (Paola et al. 2011; Bevington and Twilley 2018). Reflectivity values are lower in the bar interior, and field observations indicate that these areas are dominated by plants like Arrowhead *(Sagittaria latifolia*). Additionally, reflectivity data points to submerged aquatic vegetation, most likely widgeon grass (*Ruppia maritima*), in some areas on anterior and lateral edges of the Bay Denesse Delta. This pattern of elevation and vegetation is broadly consistent with geomorphic theory, and patterns observed in other developing deltas like the Wax Lake Delta, the Cubit's Gap Subdelta, and the West Bay Mississippi River Diversion (Paola et al. 2011; Baustain et al. 2017; Johnson et al., 1985; Allison et al. 2017)

5.3 Sediment Budget Interpretation and Landscape Evolution

The results from the sediment budget help to address one important question about the Neptune Pass/Quarantine Bay system: is the system building land? More specifically, are the emerging lands in Quarantine Bay "new land," i.e. material derived from the Mississippi River. Alternatively, are these lands composed of simply "redistributed sediment," i.e. material scoured from the erosion of Neptune Pass's main channel?

This is a question that can be addressed through a sediment volume and mass balance. In this approach, the volume (or mass) of sediment removed from Neptune Pass can be compared to the volume (or mass) of sediment that has been deposited in Quarantine Bay. If the quantity of newly-deposited sediments in Quarantine Bay exceeds the volume of material extracted, then this would support the "new land" hypothesis because it would imply a large input of sediment from somewhere else, and the Mississippi River is the only significant source. If the volume deposited is less that the volume scoured, it would support the "redistributed" hypothesis because it would suggest sediment input from the Mississippi River has little net significant impact on land development- at least at the spatial and temporal scales measured here.

Results from the sediment budget indicate a net deposition of 5.0 x 10^6 m^3 of sediment in Quarantine Bay (Table 3). Using standard estimates of sediment porosity and volume, this indicates 7.8 x10^9 kg of sediment was deposited in Quarantine Bay. Under the more conservative scenario (i.e. assuming that eroded material was less dense than usual and deposited material was more dense than usual), an estimated 3.3 x 10^9 kg of sediment was deposited in Quarantine Bay. Overall, these results indicate the Neptune Pass/Quarantine Bay system is a net-depositional system. Given the geography of the region, this positive balance of sediment is likely coming from the Mississippi River.

These results have implications for coastal management, as they suggest that the Neptune Pass/Quarantine Bay system functions somewhat similar to the sediment diversions that are part of Louisiana's coastal restoration strategies (CPRA 2023). These diversions aim to mimic the fluvial-deltaic processes that created the Mississippi River Delta, and its smaller subdeltas (Roberts 1997; Gagliano et al., 1981; Day et al. 2007). As described above, the Quarantine Bay Delta, the Bay Denesse Delta, and parts of the Ducks Unlimited Terraces appear to be following well documented pathways of deltaic sediment transport, deposition, and land growth (Roberts 1997; Blum and Roberts 2012; Esposito et al, 2013; Wellner et al. 2006; Amer et al 2017; Roberts et al. 2015).

There are a few caveats to the above-mentioned findings. First, the "new land" vs "redistributed land" hypotheses are not entirely mutually exclusive. It is theoretically possible, and even likely, that sediments deposited in Quarantine Bay could be derived from both channel scour and the Mississippi River. Indeed, the sediment budget provides a net-accounting of sediment and does not specifically analyze every transport pathway. However, given the resources available, this sediment budget approach, coupled with the other data presented herein, provides the most information for the greatest value. Future research on sediment transport and deposition in the Neptune Pass/Quarantine Bay system could well provide additional useful information for geologists and managers alike.

5.4 The Future of Neptune Pass

The future status of Neptune Pass is unknown and depends on a range of factors, including its behavior under current day conditions, which are mostly unregulated, and future conditions that may include more control structures. Report authors are aware the US Army Corps of Engineers is developing plans to reduce the flow of Neptune Pass, and potentially add sediment retention devices in Quarantine Bay. Since detailed plans have not yet been made public, it is premature to address their specific impacts. However, it is possible to use geomorphic theory to make some general assessments about the future of the Neptune Pass/Quarantine Bay system.

Overall, the future of the Quarantine Bay Delta is likely to be governed by a balance between multiple factors that include: sediment input, the efficiency of sediment trapping, patterns of vegetation growth, wind-driven waves, and relative sea level rise (Roberts 1997). Factors that could promote delta growth include high sediment input and high rates of sediment trapping- which can be augmented by vegetation. Factors that could slow or reverse the rate of delta growth include a wave climate that results in erosion, reduced sediment input, low rates of sediment trapping, slow vegetation growth, and high rates of relative sea level rise.

One parameter affecting the influence of these factors is the delta's position in the tidal frame. A relatively high position in the tidal frame could promote vegetation growth, which could lead to a positive feedback loop of land growth (Paola et al. 2011; Passalacqua et al. 2013). Under this scenario, a high elevation could promote vegetation growth, which would enhance sediment trapping, leading to wetland accretion that create sediment trapping landforms (Paola et al. 2011; Ameen et al., 2017; Keogh et al. 2019). On the other hand, a relatively low position in the tidal frame could lead to a positive feedback loop that hinders land building. Under this scenario, a low elevation could promote the formation of wind-driven waves, which would erode landforms, reduce vegetation growth and sediment trapping. This would allow subsidence and sea level rise to continue to lower the system's place in the tidal frame (Reed 2002).

Within this context it is possible to understand some of the potential impacts of a plan to scale back the flow of water (and its associated sediment load) into Neptune Pass. Generally speaking, reduced sediment input would hinder wetland development in the Quarantine Bay Delta by decreasing wetland accretion while allowing waves and relative sea-level rise to become proportionately more important. Conversely, sediment trapping structures in Quarantine Bay could increase sediment retention, thus increasing the potential for sediment accretion and land development. The full impacts of any plan should be viewed in the context of these relative factors, more detailed modeling and field studies, and management concerns that include coastal restoration, flood protection, and navigation in the Mississippi River.

6. Works Cited

Allison, M. A., B. T. Yuill, E. A. Meselhe, J. K. Marsh, A. S. Kolker, and A. D. Ameen. 2017. "Observational and Numerical Particle Tracking to Examine Sediment Dynamics in a Mississippi River Delta Diversion." Estuarine, Coastal and Shelf Science 194: 97–108.

Ameen, A. D., A. S. Kolker, and C. M. Taylor. 2017. "Vegetation and Shear Strength in a Delta-Splay Mouth Bar." Wetlands 37 (6): 1159–68.

Amer, R., A. S. Kolker, and A. Musciatta. 2017. "Propensity for Erosion and Deposition in a Deltaic Wetland Complex: Implications for River Management and Coastal Restoration." Remote Sensing of Environment.

Armstrong, C., Mohrig, D., Hess, T., George, T., and K. M. Straub. 2014. "Influence of Growth Faults on Coastal Fluvial Systems: Examples from the Late Miocene to Recent Mississippi River Delta." Sedimentary Geology 301 (March): 120–32.

Ashphaq, M., P. K. Srivastava, and D. Mitra. 2021. "Review of near-Shore Satellite Derived Bathymetry: Classification and Account of Five Decades of Coastal Bathymetry Research." Journal of Ocean Engineering and Science 6 (4): 340–59.

Baustain, M. M., C. L. Stagg, C. L. Perry, L. C. Moss, T. J. B. Carruthers, and M. A. Allison. 2017. "Relationships Between Salinity and Short-Term Soil Carbon Accumulation Rates from Marsh Types Across a Landscape in the Mississippi River Delta." Wetlands 37: 313–24.

Bevington, A. E., and R. R. Twilley. 2018. "Island Edge Morphodynamics along a Chronosequence in a Prograding Deltaic Floodplain Wetland." Journal of Coastal Research 34 (4): 806–17.

Bio-West. 2011. "Water Bottom Assessment (Survey) in Breton Sound." Submitted To Louisiana Department of Wildlife And Fisheries 15p.

Blum, and H. H. Roberts. 2012. "The Mississippi Delta Region: Past, Present and Future." Annual Review of Earth and Planetary Sciences 40: 655–83.

Brooks, Gregg R., Jack L. Kindinger, Shea Penland, S. Jeffress Williams, and R. A. McBride. 1995. "East Louisiana Continental Shelf Sediments: A Product of Delta Reworking." Journal of Coastal Research 11 (4): 1026–36.

Couvillion, B. R., H. Beck, D. Schoolmaster, and M. Fischer. 2017. "Land Area Change in Coastal Louisiana (1932 to 2016)." Scientific Investigations Map 3381. US Geological Survey 16.

Coastal Protection and Restoration Authority of Louisiana (CPRA). 2023. Louisiana's

Comprehensive Master Plan for a Sustainable Coast. Coastal Protection and Restoration Authority of Louisiana. Baton Rouge, LA

Day, J. W., D. F. Boesch, E. J. Clairain, G. P. Kemp, S. B. Laska, W. J. Mitsch, K. Orth, et al. 2007. "Restoration of the Mississippi Delta: Lessons from Hurricanes Katrina and Rita." Science 315 (5819): 1679–84.

Day, J. W., J. E. Cable, J. H. Cowan Jr, R. DeLaune, K. De Mutsert, B. Fry, H. Mashriqui, et al. 2009. "The Impacts of Pulsed Reintroduction of River Water on a Mississippi Delta Coastal Basin." Journal of Coastal Research, 225–43.

Esposito, Christopher R., Ioannis Y. Georgiou, and A.S. Kolker. 2013. "Hydrodynamic and Geomorphic Controls on Mouth Bar Evolution." Geophysical Research Letters 40 (8): 1540–45.

Fitzgerald, D.M., Kulp, M., Penland, S., Flocks, J., and J. Kindinger. 2004. "Morphologic and Stratigraphic Evolution of Muddy Ebb-Tidal Deltas along a Subsiding Coast: Barataria Bay, Mississippi River Delta." Sedimentology 51 (6): 1157–78.

Gagliano, S., and J. Coleman. 1964. "Cyclic Sedimentation in the Mississippi River Deltaic Plain." Gulf Coast Association of Geological Societies Transactions 14: 67–80.

Gagliano, S. M., K. J. Meyer-Arendt, and K. M. Wicker. 1981. "Land Loss in the Mississippi River Deltaic Plain." Transactions Gulf Coast Association of Geological Societies 31: 295–300.

Johnson, W. B., C. E. Sasser, and J. G. Gosselink. 1985. "Succession of Vegetation in an Evolving River Delta, Atchafalaya Bay, Louisiana." The Journal of Ecology 73 (3): 973–86.

Keogh, M. E., A. S. Kolker, G. A. Snedden, and A. A. Renfro. 2019. "Hydrodynamic Controls on Sediment Retention in an Emerging Diversion-Fed Delta." Geomorphology 332: 100–111.

Kolker, A. S., and H. D. Weathers. 2022. "Technical Report: Discharge Study At Bayou Tortillion." https://coastalclimates.org/2022/05/31/technical-report/.

Maloney, J. M., S. J. Bentley, K. Xu, J. Obelcz, I. Y. Georgiou, and M. Miner. 2018. "Mississippi River Subaqueous Delta Is Entering a Stage of Retrogradation." Marine Geology 400: 12–23.

Paola, C., Twilley, R.R., Edmonds, D.A., Kim, W., Mohrig, D., Parker, G., Viparelli, E., and V. R. Voller. 2011. "Natural Processes in Delta Restoration: Application to the Mississippi Delta." Annual Review of Marine Science 3: 67–91.

Passalacqua, P., Lanzoni, S., Paola, C., and A. Rinaldo. 2013. "Geomorphic Signatures of Deltaic Processes and Vegetation: The Ganges-Brahmaputra-Jamuna Case Study." Journal of

Geophysical Research: Earth Surface 118 (3): 1838–49.

Reed, D. J. 2002. "Sea-Level Rise and Coastal Marsh Sustainability: Geological and Ecological Factors in the Mississippi Delta Plain." Geomorphology 48 (1-3): 233–43.

Roberts, H. H., DeLaune, R.D., White, J.R., Li, C., Sasser, C.E., Braud, D., Weeks, E., and S. Khalil. 2015. "Floods and Cold Front Passages: Impacts on Coastal Marshes in a River Diversion Setting (Wax Lake Delta Area, Louisiana)." Journal of Coastal Research, 1057–68.

Roberts, H. H. 1997. "Dynamic Changes of the Holocene Mississippi River Delta Plain: The Delta Cycle." Journal of Coastal Research 13 (3): 605–27.

Schleifstein, M. 2022. "'Power of the River': New Mississippi River Channel Prompts Corps to Take Action." The Times Picayune-Nola.com, 2022.

Shaw, J.B., and D. Mohrig. 2014. "The Importance of Erosion in Distributary Channel Network Growth, Wax Lake Delta, Louisiana, USA." Geology 42 (1): 31–34.

Shields, M. R., T. S. Bianchi, D. Mohrig, J. A. Hutchings, W. F. Kenney, A. S. Kolker, and J. H. Curtis. 2017. "Carbon Storage in the Mississippi River Delta Enhanced by Environmental Engineering." Nature Geoscience 10: 846–51.

Smith, J. E., S. J. Bentley, G. A. Snedden, and C. White. 2015. "What Role Do Hurricanes Play in Sediment Delivery to Subsiding River Deltas?" Scientific Reports 5: 17582.

Traganos, D., D. Poursanidis, B. Aggarwal, N. Chrysoulakis, and P. Reinartz. 2018. "Estimating Satellite-Derived Bathymetry (SDB) with the Google Earth Engine and Sentinel-2." Remote Sensing 10 (6).

US Army Corps Of Engineers (USACE). 2022. "Draft Environmental Assessment, Mississippi River, Baton Rouge To The Gulf Of Mexico, Louisiana, Neptune Pass Rock Closure, Plaquemines Parish, Louisiana." EA #589. US Army Corps Of Engineers, Mississippi Valley Division.

Veatch, W. C. 2017. "2015 Updated Atlas of U.S. Army Corps of Engineers Historic Daily Tide Data in Coastal Louisiana." 14. US Army Corps Of Engineers, Geomorphology And Potamology Program 40p.

Weathers, H. D., M. A. Allison, C. G. Ramatchandirane, and B. Yuill. 2016. "Water and Sediment Dynamics in the Fort St. Philip Crevasse During the 2016 Highwater Event." In State of the Coast 2016 Conference.

Wellner, R., R. Beaubouef, J. Van Wagoner, Roberts H.H., and T. Sun 2006. "Jet-Plume Depositional Bodies—The Primary Building Blocks of Wax Lake Delta." Gulf Coast Association of Geological Societies Transactions 55: 867–909.

Wells, J. T., and J. M. Coleman. 1987. “Wetland Loss and the Subdelta Life Cycle.” Estuarine, Coastal and Shelf Science 25 (1): 111–25.

White, D. A., and J. M. Visser. 2023. “Twenty-Eight Years of Plant Community Development and Dynamics in the Balize Mississippi River Delta, Louisiana, USA.” Water 15: 3481. Wright, L. D. 1977. “Sediment Transport and Deposition at River Mouths: A Synthesis.” Geological Society of America Bulletin 88 (6): 857–68.