Sediment Management Alternatives for the Port of Bienville

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Executive Summary

The objective of this report is to present economical, environmentally friendly, and effective alternatives to maintenance dredging for the Port of Bienville and its access channels.

The Port of Bienville is located in Hancock County, directly off the Pearl River in the southeastern corner of Mississippi. Access to the Port from the Gulf of Mexico is provided by a channel that passes through Lake Borgne to the Rigolets, then through Little Lake to the Pearl River.

When ports such as Bienville experience sediment deposition that will ultimately lead to unacceptable loss of water depth, solutions to maintain navigability include the traditional method of dredging or one of many other alternatives that can be complete — eliminating sediment deposition — or partial — reducing sediment deposition so as to reduce dredging need. Solutions tend to be unique to each port, for a successful design depends on port layout, waterway configuration, flow conditions, and sediment type and supply; however, all solutions can be placed in three categories — methods that keep sediment out of the port, methods that keep sediment that enters the port moving (and prevents net deposition), and methods that remove sediment after it has deposited in the port.

The loss of all Port records during Hurricane Katrina required that other estimates of sedimentation volume, location and processes be made. In July 2008 the University of Southern Mississippi Hydrographic Science Program did a navigation chart comparison between their chart completed in July 2008 and NOAA's navigation chart from 1995, producing a map of depth changes along the Pearl River.

Field observations, a numerical hydrodynamic model, and standard sediment analyses were used to estimate sediment deposition in the Port as averaging 10,000 tons per year. Two alternatives are suggested – a sediment trap to capture sediment and prolong the periods between dredging and agitation to prevent sediment from consolidating on the bed. Neither will be cost effective at present sedimentation rates.

An alternative that would reduce access dredging requirements and provide easier, faster access is relocation of the navigation channel from Little Lake to the lower Pearl River directly to Lake Borgne. A proposed design for that relocation is provided. It will require some new work dredging and relocation of a railroad bridge, but will provide safer, easier access and reduced channel dredging.

Preface

The work described here was performed by the Civil and Environmental Engineering Department of the James Worth Bagley College of Engineering at Mississippi State University with funding and guidance from the Freight, Rails, Ports & Waterway Division of the Mississippi Department of Transportation (MDOT). Funding was provided under the terms of a master agreement between MDOT and the Transportation Research Center at MSU.

Project monitors at MDOT were Robby Burt, Director, and Wayne Parrish, Former Director of the Freight, Rails, Ports & Waterway Division, and Randy Beatty, Director of the Research Division.

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1. Introduction

Maintenance dredging is a significant challenge for channel and harbor sediment deposition. Dredging cost, limited disposal options, and environmental concerns make alternatives such as sediment management increasingly attractive, The objective of this report is to present economical, environmentally friendly, and effective alternatives to maintenance dredging for the Port of Bienville and its access channels.

The Port of Bienville Industrial Park is located in Hancock County, directly off the Pearl River (see Figure 1) in the southeastern corner of Mississippi. The Port is located at latitude and longitude of 89°40’ and 39°14’ respectively; which is ten miles south of Interstate 10, 45 minutes from the greater New Orleans metropolitan area, and 15 minutes from Bay St. Louis.

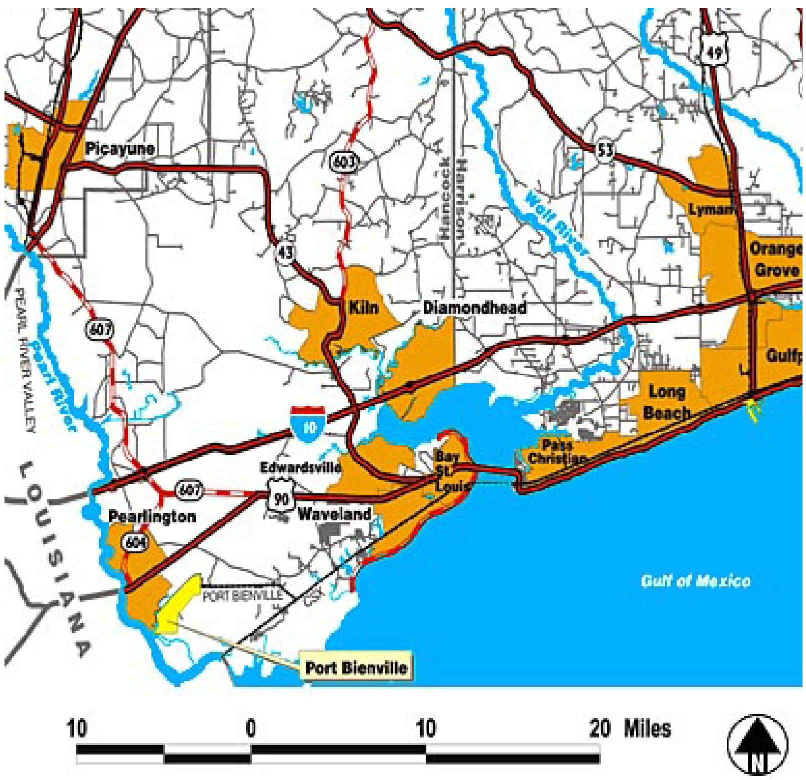

Figure 1 Port of Bienville (MDOT 2007)

The Port consists of a 1200-acre industrial park and accommodating berths (see Figure 2). There are more than five miles of man-made canals and a short line railroad connection supporting 16 industrial facilities (USACE 2006).

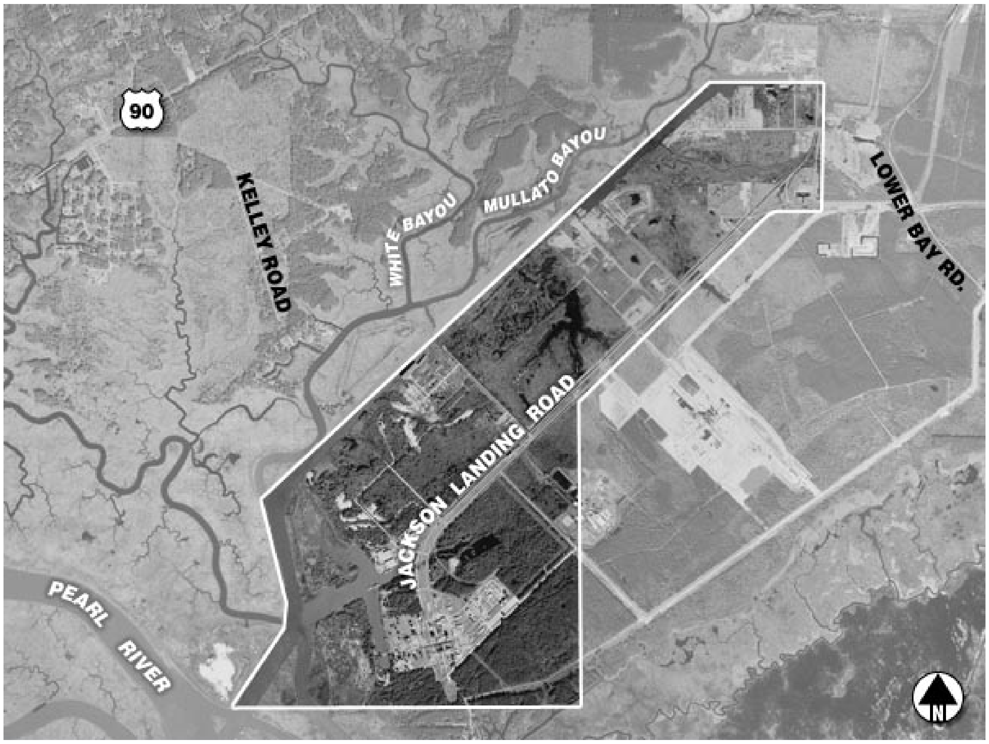

Figure 2 Port of Bienville Industrial Park Aerial Photo (MDOT 2007)

Bienville, a shallow draft port, is connected to the Mississippi Sound and the Intra-coastal Waterway by a 12-ft channel. The Port has 6 acres hard surface loading area; a 30,000 sq-ft dry storage warehouse; a 20,000 sq-ft transit shed; and a 10 inch diameter pipeline for the removal of ethylene glycol from barges (HCBS 2007). The facility has three deepwater (16-20 ft draft) berths. Two are 250 ft. long and one is 200 ft. long. There are also several barge berths (10-12 ft draft), which have dimensions of 400, 300, 200, and 150 ft. in length. Bienville has a horizontal clearance restriction of 132 ft limiting the facility to a two barge wide tow. The turning basin for the facility is 650 ft long and 400 ft wide. These factors limit the Port to accommodating vessels no larger than 400 ft. long and 100 ft. wide (MDOT 2007).

2. Sedimentation

2.1. Sediment and Sediment Behavior

Sediment, consisting of rock, mineral, and shell fragments plus organic materials, is naturally present in streams, rivers, lakes, estuaries, and ocean waters. It makes up the bed and banks of those water bodies, and flowing water transports it from place to place until it deposits. Some waters contain small amounts of sediment that are nearly invisible, while others contain so much sediment that the water becomes a chocolate brown. Visibility of the sediment also depends on how the water transports it. The nature and amount of the sediment and the flow determine whether the sediment is transported along the bed or suspended higher in the water.

Waterborne sediment is a valuable resource. Deposited on a river's floodplain, it forms rich farmland such as the Mississippi Delta between Memphis and Vicksburg. Sand and gravel deposits in rivers and ancient river courses provide construction materials. Some aquatic species, ranging from tiny daphnia to sturgeon, thrive in high levels of suspended sediment. Along coastlines, sediment deposits build land and marshes that protect against flooding and offer productive habitat for aquatic species. Having too little sediment in a waterbody can be both economically and environmentally damaging. The most dramatic example of such damages is coastal Louisiana, where several square miles of land are lost each year because of diminished sediment supply from the Mississippi River.

Despite its resource value, too much sediment or the wrong kind of sediment can also cause economic and environmental damage. For example, muddy deposits on gravel bars can kill mussels and fish eggs, and floodborne sediment can bury farms and damage homes. Few port or waterway operators see too little sediment as a problem. Excessive sediment deposition in ports and channels reduces their depth, forcing vessel operators either to time transits to high water periods, to light-load so as to reduce draft, or to limit passage to unsafe narrow passages, or preventing access altogether. The traditional solution to these problems was dredging and disposal of excess sediment. More recently, beneficial use of dredged sediment has recognized the value of the resource by using it for shoreline restoration, marsh creation, and construction material, but usually at increased cost to those performing the dredging (PIANC, 1992). Disposal other than beneficial uses has become constrained, with in-water placement often prohibited and on-land placement options diminishing.

Waterborne sediment can be classified by size of the primary grains, from largest to smallest, into boulders, cobbles, gravel, sand, silt, and clay. Larger sizes move mainly by rolling, sliding, or hopping along the bottom only when the water is moving swiftly; whereas, finer sizes and organic materials move in suspension throughout the water column. Sizes in the middle may move in either or both modes, depending on the water flow and bottom configuration. Sand-sized (grain diameter greater than 0.062 mm) and larger particles are noncohesive, so they move nearly independently of other particles. Because they are relatively large, they settle very rapidly to the bottom when flow slows down or stops. Clay particles are tiny (grain size 0.004 mm and smaller), and they tend to stick together (flocculate) and move as aggregates of many individual grains. They may settle very slowly, even in quiet water. Silt, falling between sand and clay in size, may behave either like sand or like clay. Organic materials include plant and animal detritus. They settle very slowly and may help bind sediment grains together.

Cohesion of sediment particles influences bed behavior also. New clay deposits are usually porous and easily resuspended. With time and overburden pressure clay deposits consolidate and become denser and more resistant to erosion.

2.2. Sediment Transport

Sediment is transported from one place to another by flowing water. Depending on the size and degree of cohesion of the sediment grains and intensity of the flow, the amount transported may be proportional to the speed of the flow or proportional to the speed squared, cubed, etc. So a doubling of flow speed may increase sediment transport as much as eight-fold. In some cases more sediment is transported in one storm event than in all the rest of the year.

The proportionality effect described above can also cause substantial sediment deposition. If a waterway's cross-section is suddenly increased by increased depth or width, the flow speed drops and the capacity to transport sediment falls even faster, so sediment will tend to deposit. This effect is a common cause of sedimentation in navigation channels and ports, and is sometimes used to force sediment deposition in a particular location, such as sediment trap.

Vessel traffic can suspend sediment from the bed and banks of a waterway through:

- Flow under and around the vessel as water moves from the front end of the vessel to the back.
- Pressure fluctuations beneath the vessel.
- Propwash striking the bed.
- Bow and stern waves agitating the bed and breaking against the bank.

Sediment suspended by vessel traffic can either quickly settle out (if the sediment consists of sand-sized material) or remain in suspension (if the sediment consists of very fine silts or clay-sized material). A fine sediment suspension has greater density than the surrounding water, so it can flow as a density current away from the point of suspension. The latter process can move sediment from the waterway centerline into relatively quiet berthing areas, where it settles out. This phenomenon has been documented in several locations (e.g., PIANC 2008).

Eddies, circular flow patterns formed by flow past an obstruction or in front of an opening like a port slip, have a complex three-dimensional circular structure with flow inward near the bottom and outward near the surface with a quieter zone in the middle. Sediment passing near an eddy is drawn into the eddy and pushed toward the center, like loose tea leaves in a stirred cup, where it tends to deposit. This phenomenon is a common cause of sedimentation in slips, side channels and berthing areas.

2.3. Sedimentation in Ports

Commercial vessels — deep water ships and shallow water tows — require navigable water depths that are equal to or greater than the sum of the draft of the vessel plus under-keel clearance allowances for vessel motion, water level fluctuations, etc. If available water depth in a port is less than navigable depth for a commercial vessel, the vessel must light-load (load less than a full cargo) to reduce draft if it is to use the port.

Natural waterways exhibit shallow areas and deep areas that may shift as flows change, sediment supply changes, or features migrate. They may naturally be deep enough in some locations to accommodate navigation, but often have at least some areas shallower than navigable depth. Ports are usually built close to shorelines where water is naturally shallow and so they tend to suffer sediment deposition that reduces the depth available for navigation.

Some ports have no significant sediment deposition, either because they are built in water naturally deeper than needed for navigability, because the sediment supply is very small, or because the waterway's currents sweep the sediment away. Coastal and estuarine ports are seldom in this category.

3. Engineering Solutions

When ports experience sediment deposition that will ultimately lead to unacceptable loss of water depth, solutions are needed to maintain navigability. Solutions can be complete — eliminating sediment deposition — or partial — reducing sediment deposition so as to better manage the problem. PIANC (2008) has produced a report documenting many of these solutions, which are briefly described here.

3.1. Solution Concepts

A variety of engineered solution approaches to reduce deposition problems is available. Solutions tend to be unique to each port, for a successful design depends on port layout, waterway configuration, flow conditions, and sediment type and supply; however, all solutions can be placed in three categories — methods that keep sediment out of the port, methods that keep sediment that enters the port moving (and prevents net deposition), and methods that remove sediment after it has deposited in the port. The following lists some of these solutions.

3.1.1. Methods that keep sediment out

Keeping excess sediment out of the port that might otherwise enter and deposit can be accomplished by:

- Stabilizing sediment sources.
- Diverting sediment-laden flows.
- Trapping sediment before it enters.
- Blocking sediment entry.

Examples include diverting freshwater flow out of Charleston Harbor, SC which reduced port and channel sedimentation by more than 70 percent (Teeter, 1989), and a sediment trap and tide gate combination in Savannah Harbor, GA that reduced port and waterway dredging by more than 50 percent (Committee on Tidal Hydraulics, 1995). The inland Port of Toronto (Torontoport, 2003) employs a sediment trap to keep its entrance channel open.

3.1.2. Methods that keep sediment moving

If very fine, slow-settling sediment can be kept suspended while the flow passes through the port, or if the flow maintains high enough tractive force (usually expressed as shear stress, or drag force per unit area) to keep coarser particles moving, sediment can enter the port and pass on through without depositing. Methods to keep sediment moving include:

- Structural elements that train natural flows.
- Devices that increase tractive forces on the bed.
- Designs and equipment that increase sediment mobility.
- Designs that reduce cohesive sediment flocculation.

Structural elements include transverse training (spur) dikes that are used in many locations to train flow and prevent local deposition of sediment. Devices to increase bed tractive forces, including submerged wings (Jenkins, 1987) and water jet manifolds (Bailard, 1987) were tested in the Navy berths of Mare Island Strait, CA and found to be effective in reducing sediment deposition locally. Cohesive sediment flocculation can be reduced by designs that reduce turbulence, such as solid wharf walls instead of piling supported wharfs.

3.1.3. Methods that remove deposited sediment

Sediment can be removed after it deposits. Methods include:

- Traditional dredging and disposal.
- Agitation of deposits so that the sediment becomes mobile again.

Removing sediment includes traditional dredging disposal in water or in confined disposal facilities, but also includes sediment agitation methods of intentional overflow, dragging, and propwash erosion. Agitation dredging is subject to regulation, just as traditional dredging is, and can be perceived as contributing to water quality problems.

3.2. Specific Solutions

3.2.1. Agitation

Removing deposited sediment by agitation includes using standard dredging equipment with intentional overflow or discharge into nearby waters, dragging, and propwash erosion. It is usually intended to suspend sediment such that currents carry it away. Anchorage Harbor, AK was dredged with a combination of agitation and dredge-and-haul in 2000 when normal dredge-and-haul could not achieve desired results soon enough. (Hilton, 2000) Dragging a rake behind a vessel to suspend sediment so that it can be carried away by currents has been practiced for centuries in China (Luo, 1986) and propeller wash is used in the same way in some ports, either intentionally or incidental to normal port operations (Richardson, 1984).

Propeller wash resuspension of deposited fine sediment can be achieved by a vessel (such as a tow) running its propeller at a high rate in areas of the port to disrupt and resuspend the deposited sediment. Once resuspended, some of the resuspended sediment will flow or diffuse out of the port, but some or even most will redeposit in the port. This method requires no design time, installation, or specialized training. Agitation can be scheduled so as not to conflict with other port operations or access. Prop agitation is widely used in tidal areas, where the agitation can be timed to coincide with seaward flowing currents to move the resuspended sediment away from the port, but can be employed in inland ports, also, if the sediment is sufficiently fine grained and either currents or slope is present to move the resuspended sediment away from the port.

A special case of agitation dredging involves use of specialized, vessel-mounted equipment to fluidize bed sediment such that it flows downslope or with ambient currents. (Hales, 1995)

Agitation dredging is prohibited in some locations because it increases turbidity, at least locally. Using agitation where it is not prohibited will require a Corps of Engineers permit. It will, by definition, increase turbidity; however, it will increase it by no more than normal tow traffic does, and turbidity returns to ambient levels. If the sediment contains organic materials in an anaerobic state, resuspension will increase the biological oxygen demand and depress dissolved oxygen (Johnson, 1976). Another aspect to this question is reaeration caused by barge traffic. Qaisi, et al, (1997) note that as much as 30% reaeration in high traffic waterways is due to barge traffic, so it might be expected that agitation dredging of the port by propwash may either increase or decrease DO, depending on local conditions. DO impacts will be minimized if the practice is employed at least once per month. A pilot study can be performed in which port deposits are agitated and DO measurements taken to document the degree and duration of impact.

3.2.2. Pneumatic Barrier

A pneumatic barrier, or bubble curtain, pumps compressed air through a submerged manifold. Bubbles rising from the manifold create a current that flows in toward the manifold at the bottom, upward toward the surface, and outward at the surface. As sediment particles approach the rising current they are carried upward away from the bed and toward the surface, then away from the bubbler.

The two most common configurations of pneumatic barriers are in a line across the mouth of a basin or in clusters throughout the basin. In the line arrangement, the pneumatic barrier acts as a curtain across the mouth of the port to reduce the amount of depositing sediment in two ways. The rising current of air entrains water, creating an upward flow near the bubble curtain, an inward flow near the bottom, and an outward flow at the surface. This flow pattern carries suspended fine particles upward, and a portion is transported away from the barrier. The rising air bubbles act as a physical barrier limiting the passage of particles to the other side of the curtain, thus reducing the amount of sediment entering the protected area. Increased bottom currents near the curtain will also prevent close-by deposition of fine sediments. Although the pneumatic barrier does not prevent all sediment from passing through it and depositing, it is a potential tool in the reduction of sedimentation (e.g., Gray's Harbor College, 1973).

Pneumatic systems are typically composed of three parts: an onshore air compressor, supply line, and a diffuser system. It is advised that a steel pipe be used as the first reach of the supply line to dissipate heat generated by compression of air. The air exiting the compressor is extremely hot and should be cooled before entering the water to prevent artificial warming.

The cluster arrangement consists of several bubblers throughout an area. This configuration does not attempt to prevent the entrance of sediment into the port. Its objective is to prevent the deposition of sediment. The layout of the clusters depends on the size of the port and the depth of the water. This method will not completely prevent the deposition of sediment, but has shown reduction in sediment accumulation (e.g., Chapman and Douglas, 2003).

Installation of either pneumatic barrier arrangement will require port down time. Operation of the line pneumatic barrier could be continuous, but, depending on experience with the system, also could be activated only during tow passages in the waterway. Regular, periodic maintenance will be required of the compressor and the manifold.

3.2.3. Silt Screen

A silt screen, or silt curtain, a physical barrier that is opened only to allow the passage of vessels, provides positive control of sediment influx.

Silt screens are typically used to contain sediment plumes during dredging and disposal, but can be used to exclude sediment from a port if port traffic or current conditions do not make it impractical. As it is a solid membrane, no sediment will pass through it into the port while in use; however, if there are gaps in the curtain, particularly at the bed, some sediment will get past. The primary drawback of the sediment curtain solution is that it will require special training and a work boat to open it for vessel passage it and may disrupt daily activities of the port.

3.2.4. Sediment Trap

A sediment trap is designed to slow currents so that all or part of the sediment load is deposited within the trap. Since ports are often dredged deeper and wider than the natural channels in which they occur, ports serve as unintentional sediment traps. In general, sediment traps do not reduce the amount of required dredging (they may actually increase it); however, they may reduce the unit cost of dredging by avoiding conflicts with navigation during dredging operations. If a trap locates sediment accumulation outside the port area, the port will experience longer periods of full design depth even as sediment accumulates in the trap.

A sediment trap and tide gate combination in Savannah Harbor, GA reduced port and waterway dredging by more than 50 percent (Committee on Tidal Hydraulics, 1995). In the Savannah case, locating the sediment trap out of the port area reduced interference between dredging equipment and vessel traffic, placed the dredging closer to the disposal area, and reduced the unit cost. However, the project was alleged to cause salinity increases upstream, and was taken out of service.

Sediment traps can be environmentally beneficial compared with conventional dredging, for example, if fine sediments are allowed to consolidate so that low turbidity, low water volume methods such as clamshell dredging can be employed.

A sediment trap can either be dredged at intervals or regularly pumped out. eductor-type pumps have been used for sediment removal in a number of locations, usually in sand environments (e.g., Richardson and McNair, 1981; McClellan and Hopman, 2000). In a mud environment they will tend to be made inoperative unless operated regularly, since consolidated mud will not flow toward the pump. Deposition in a trap can be moved to a piece of fixed dredging equipment by a fluidizing pipe – a perforated pipe through water is pumped to fluidize the bed and cause it to flow down the trench. Fluidizing pipes have been used in sand bed locations but should work in mud beds if operated before the mud consolidates (Van Dorn, 1975).

3.2.5. Training Structures

Training structures are used worldwide to keep sediment moving and prevent deposition. Numerous examples are described by Parchure and Teeter (2002). They include transverse training (spur) dikes that are used in many locations to train flow and prevent local deposition of sediment, as in the Red River, LA (Pinkard, 1995) and specialized training structures such as the Current Deflector Wall, a curved training structure that reduced sedimentation in Hamburg Harbor’s Kohlfleet basin by 40 percent (Smith et al., 2001). Unlike some solutions, training dikes can be constructed so as to confer positive habitat benefits based on studies by multiple agencies (U. S. Army Corps of Engineers, 2003; Byars, et al., 2000; Lower Mississippi River Conservation Committee, 2003; Kuhnle, et al., 2003; Stauffer, 1991; and Shields, et al., 1995)

Transverse dikes have been found to be most effective when submerged during high flow events (Parchure and Teeter, 2002). Corps of Engineers' guidelines (Biedenharn et al., 1997) and generally accepted principles for training structures call for a dike top elevation between low water level and bankful stage, long enough to constrict the channel cross section to covey the sediment load, and dike spacing about 3 to 5 times the dike length.

Dikes may be constructed of riprap (stone), piles, and/or geotubes (geotextile fabric tubes filled with dredged material. If constructed of riprap, the dikes may be made solely of stone or of earth or rubble fill covered with a riprap blanket. Geotubes covered with riprap have been used in training structures and dredged material containment dikes.

Dikes may present a hazard to vessels, or they may prevent current conditions that adversely affect navigability. Dike placement can and must be designed with safe commercial and recreational traffic in mind.

3.2.6. Contract Dredging

Dredging in the ports has been accomplished by means of contract dredging in which bids are solicited and a contract awarded to private dredging companies. As noted in the introduction, small dredging jobs sometimes draw no bids, and when they do, the cost can be as much as $10 per cubic yard of sediment removed. Costs of dredge mobilization and demobilization are relative constant for both small volume jobs and large volume jobs, so the cost per cubic yard dredged goes up for small contracts. Corps of Engineers dredging contracts, which are substantially larger, may cost from $2 to $6 per cu yd.

4. Port Bienville Dredging

Dredging records provide insight as to the locations of shoaled areas and quantities accumulated, but in the case of Bienville, few data are available because all records for dredging in the Port were destroyed during Hurricane Katrina, but some dredging was done in the Port prior to the hurricane[1]. After Hurricane Katrina emergency dredging was performed to remove sediment deposits from the channel in Little Lake and in the Port of Bienville under a dredging permit issued 3 September 2005.[2] Four locations were dredged, as shown in Figure 6 with volumes removed listed in Table 1, and are the only dredging data available. However, lacking the specific location of deposition in the Port restricts the investigation, and usability of the data is limited since it was the removal of material deposited by Hurricane Katrina, in which the entire Port was flooded by approximately 4 feet [5], not typical sedimentation.

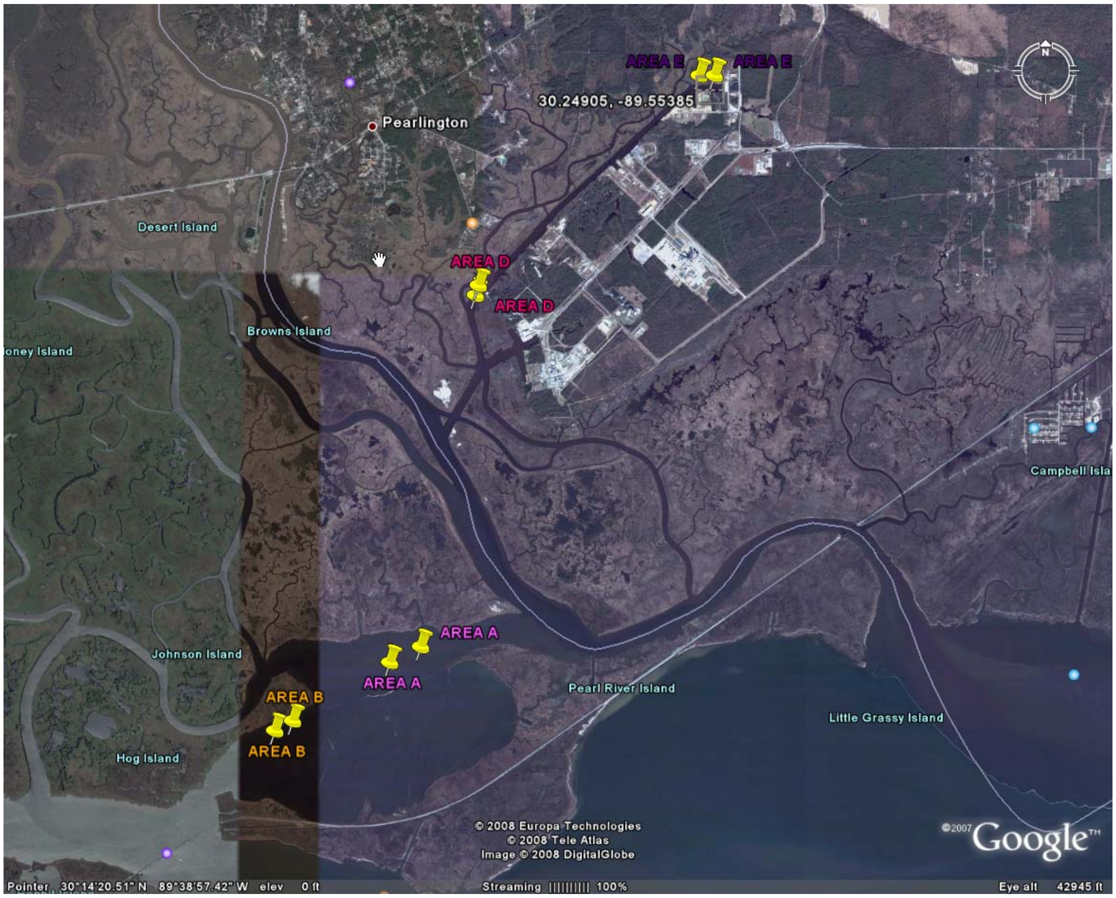

Figure 3 Emergency Dredging Locations (Courtesy of Google Earth)

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[1] Personal correspondence with Stephen Landry, Port Bienville, August 2008

[2] Personal correspondence with Compton Engineering, Bay Saint Louis February 2008

Table 1 Dredge Volumes Post-Katrina

	Volume, yds
Area A	17569
Area B	39831
Area D	2741
Area E	21377

From these data it is apparent that the worst problem areas were in Little Lake rather than in the port (see Figure 3). Section D is possibly the result of sediment entering the Port from the Pearl and settling out as soon as it encounters the still waters of the Port. Another possible problem at section E, located at the end of the Port, (see Figure 3 and Table 1) is coal spilled into the water from the unloading operation (see Figure 4).

Figure 4 Unloading of Coal at Bienville (courtesy of Google Earth)

An alternative to dredging data is the use of bathymetric surveys. In July 2008 the University of Southern Mississippi Hydrographic Science Program did a navigation chart comparison between their chart completed in July 2008 and NOAA's navigation chart from 1995 (see Figure 5). The boxes are rough estimates based on individual soundings differenced[3]. From this comparison it is seen that the majority of shoaling is occurring in both the spur and upper Port, and it indicates the long term trend of a possible shoaling problem in both the spur and upper port (see Figure 5).

[3] Personal correspondence from David Dodd and Kim Collins Pevey

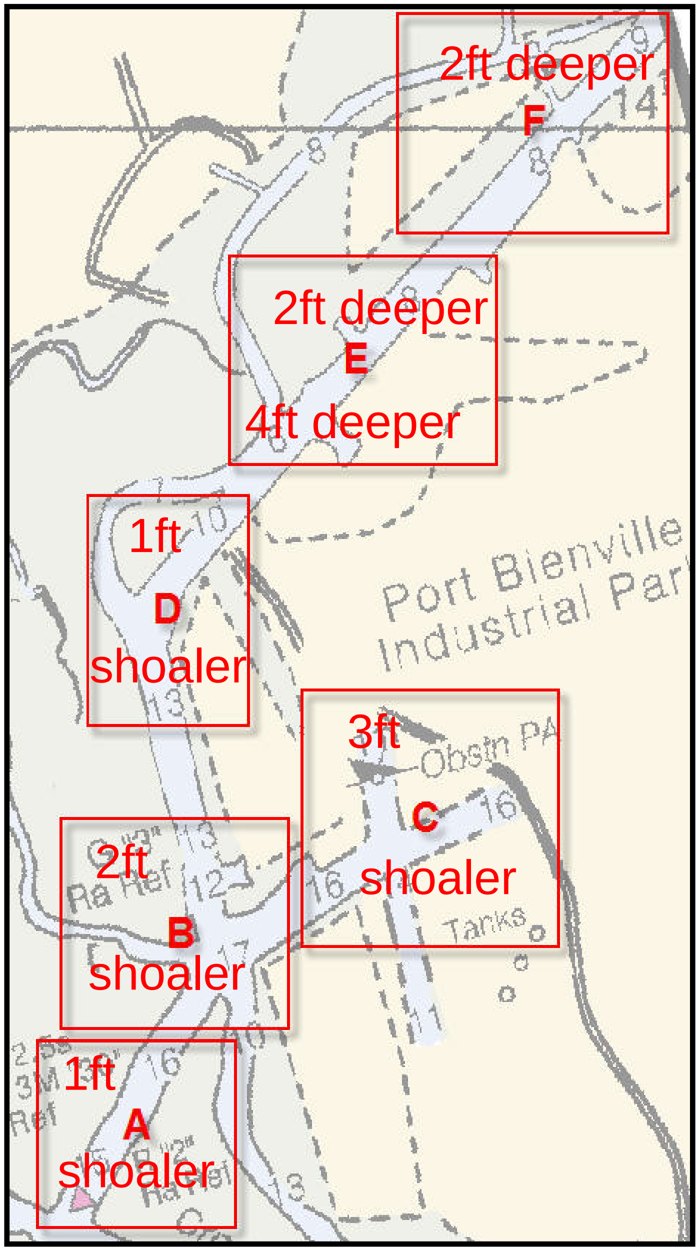

Figure 5. Depth Comparison Chart (Courtesy of University of Southern Mississippi)

Since there are limited dredging data and only a navigation chart comparison for the Ports potential shoaling issues, a more extensive process is implemented to attempt a quantitative understanding of the Port's annual shoaling amounts. However, sediment transport estimates provide a flux or volume and not the location of deposition. Therefore, the navigation chart comparison coupled with sediment transport estimates is important in attempting to complete the sedimentation picture.

5. Navigation Route

As stated previously, shoaling in Little Lake is an issue. One potential solution that addresses the problem as well as possibly increases Port productivity is a new navigation route. Navigation into the Port of Bienville is accomplished via the Intra-coastal Waterway or Rigolets Pass into Little Lake then north up the Pearl River (see Figure 6). This route has several potential hazards. A railroad bridge is located at the entrance of Little Lake and the channel that leads into the Rigolets. The distance between the piers only allows a two barge wide tow to pass[4]. As navigation continues onto Bienville, the next hazard is Little Lake, a shallow estuary. With shallow waters and low velocity fields, shoaling occurs, causing decreases in navigable depths (e.g. after Hurricane Katrina emergency dredging was done to re-open the channel). Once through Little Lake pilots must then make a hard port-side turn to head north up the Pearl River. Consideration of the above issues leads to the obvious proposal for location of a new access channel.

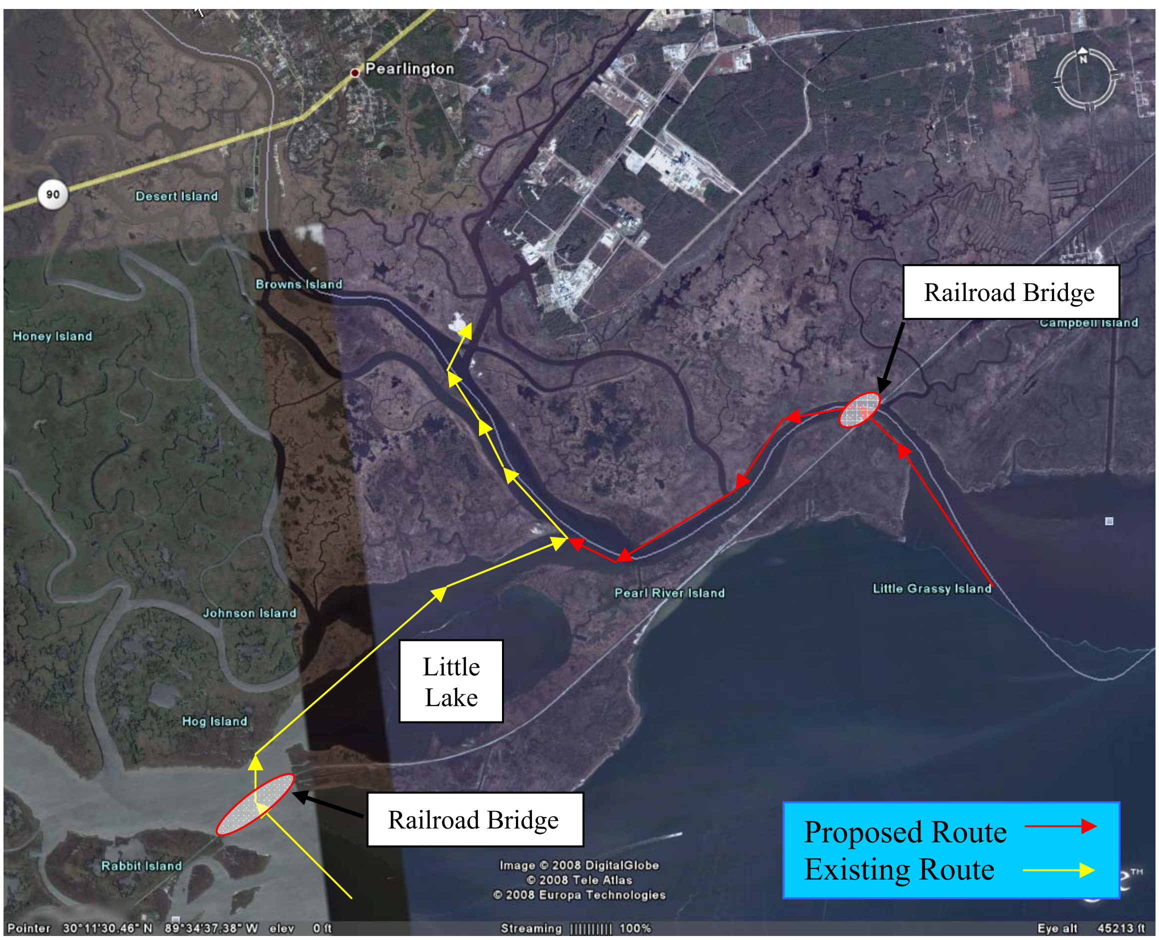

Figure 6 Google Earth Image of Existing and Proposed Navigation Route

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[4] Personal communication with Tom Leatherbury, February 18, 2008.

For the new route rather, than using Little Lake, the East Pearl can be used (see Figure 6). This will provide a more accommodating route into the Port and will eliminate having to pass through Little Lake. The more direct route will also decrease transit time enabling the Port to increase competitiveness .

Rerouting of the channel requires channel design, environmental assessment, and navigability comparisons of the existing and proposed channel design. The following presents proposed channel design recommendations for the new access channel.

5.1. Design Vessel

Currently the Port can accommodate a tow that is 100 feet wide and 400 feet long (MDOT 2007). For the purpose of increasing productivity and usability a larger vessel is selected for the design of the channel. The recommended design vessel is a 3x3 tow that is 105 feet wide and 600 feet long with the design barge classified as a jumbo (length 195 feet and breadth 35 feet) (USACE 1980). Although the specification of the design vessel is a tow, the horizontal clearances would be sufficient for ocean going vessels such as the ones that Linea Peninsular, Inc. navigated into the Port prior to Hurricane Katrina. These container vessels were 300 ft in length[5]. Furthermore, the required clearances needed for the design vessel are large enough to accommodate tows with super jumbo barges (length 250 – 290 feet, breadth 40 – 52 feet) (USACE 1980). With super jumbo barges, a pilot would be able to safely navigate a 2 by 2 tow. Accessibility for a larger tow could attract more clients to the Port and increase flexibility. However, the current Port clearances are not able to accommodate the proposed design vessel. Alternatively, a fleeting area at the entrance to the port could be constructed to provide a location where pilots can safely break their tows and navigate an appropriate number of barges into the port.

5.2. Depth and Channel Width

A channel 300 feet wide and 12 feet deep with corrected widths in the bends will accommodate design vessel maneuvering. The new channel would start just downstream of Little Lake and continue out to the Intra-coastal waterway via the East Pearl River as shown by the red arrows in Figure 6.

Section 5 of the Rivers and Harbors Appropriation Act specifies that “the channel depth shall be understood to signify the depth at mean low water in tidal waters tributary to the Atlantic and Gulf Coast”. Currently the depth leading into the Port from the Pearl River is

[5] Personal correspondence with Steve Landry, May 12, 2009

12 feet (MDOT 2007). It is recommended that 12 feet is continued into the new channel section. The 12 feet depth would adequately handle the design vessel, having a draft of 9 feet (USACE 1980) with three feet providing underkeel clearance for drawdown and shoaling. Currently, the lower East Pearl has depths that are in excess of 12 feet and it appears to be fairly stable. This would provide for a minimum amount of dredging for both maintenance and initial implementation. However, for increasing production and future growth of the Port, a 20 +2 channel depth is evaluated. This depth would allow for safer passage of ocean going vessels that previously used the Port prior to Hurricane Katrina.

The channel design width of 300 feet is chosen since it is the minimum recommended width for the design vessel in two-way traffic (USACE 1980). The crossovers the will accommodate two-way traffic; however, the bends require greater widths to account for the deflection/yaw angle. For safe navigation of one-way traffic headed downstream through the bends, a minimum design width of 310 feet is required. The corrected bend channel width is based on approximations of the two bend-way radiuses of 2000 – 2500 feet. For two-way traffic the bend-way widths need to be 620 feet. The two-way traffic width is impractical since the East Pearl, in sections, narrows to approximately 600 feet. Therefore, the bend-ways will be limited to one-way traffic As deemed appropriate by the Coast Guard, traffic control in the one-way sections is governed by Rule 9 Section f of the Coast Guard Navigation Rules that states:

> *A vessel nearing a bend or an area of a narrow channel or fairway where other vessels may be obscured by an intervening obstruction shall navigate with particular alertness and caution and shall sound the appropriate signal prescribed in Rule 34(e).*

5.3. Bridge

One limiting factor in using the East Pearl as the main navigation route, just as is the case for the West Pearl, is that there is the CSX railroad swing bridge that crosses the Pearl. The bridge will have to be removed and replaced or modified to allow for navigation of the design vessel. Inland bound, the existing bridging is located in the first bend of the Pearl with the swing on the inside of the bend; which is not ideal since this is the portion of the cross-section that experiences the most deposition The bridge should be relocated to a straight reach of the channel where upstream of the bridge, based on the design vessel, 3000 feet of straight channel for vessel alignment is available. During maneuvering in a bend a vessel experiences yaw/defection which results in a wider vessel breadth (USACE 1980). The yaw is a function of radius of the bend, tow size, length of bend up to 90 degrees, current alignment and velocity, tow speed, draft, channel depth, flanking maneuverability, travel orientation, and alignment of tow entering bend (ASCE 1998). If the bridge is not relocated then it is recommended that a navigation simulator study is conducted to analyze bridge retrofitting for the required navigation span. The required clearances both horizontal and vertical are the responsibility of the Coast Guard and should be finalized through their oversight (ASCE 1998).

If the bridge cannot be relocated then it should be modified to have as few piers in the water as possible with a center span that more than accommodates for any vessel yaw.

5.4. Port Entrance

Port Bienville's current entrance geometry and harbor geometry will not accommodate the larger design vessel. A fleeting area at the entrance where tows could be moored is required for the larger tow vessels so that individual barges or smaller tows could be broken out and pushed into the Port. The location of the entrance relative to the Pearl River is in a crossover section and is well situated for a fleeting area.

6. Discharge Evaluation

Prior to sediment transport estimates, flow evaluations of the regional discharges are necessary in order for a proper accounting of the sediment fluxes. Shortages in field data require estimates for effluent discharges. The primary source of flow both tidal and fresh water is from the Pearl River. Fresh water enters the system through the East Pearl, small bayous, and through overland flow, while tidal water enters either through Little Lake and then the Pearl or directly through the mouth of the Pearl River connected to the Gulf of Mexico. Here an attempt is made to quantify the primary splits individually to estimate flow discharge at the Pearl River (see See Figure 7).

The first major flow split headed downstream is the Pearl River Navigation Canal that connects Bogalusa, LA to the mouth of the West Pearl (see Figure 7). Located in the canal are three navigation locks with no spillways. The locks do not operate at present, having been placed in custodial care only.[6] At Lock 3, the upstream most lock, east of Sun Louisiana is USGS station 02490200. This station records only stage at the upstream end of the lock. Upstream, located on the East pearl, is USGS Station 02490193 that also records stage. It is assumed that the amount of flow through the canal is minor cand outflow is neglected.

The next downstream junction is a branch of the Pearl River that flows west to the West Pearl. At this location USGS Station 02492110 is slightly upstream of the branch, and station 0292111 is downstream in the West branch. Both stations only record stage with no available rating curves[7]. To evaluate the flow for each branch the Jones Formula, Equation 1, is applied (Overleir 2006).

$$Q = KS_o^{1/2} R^M A \sqrt{1 + \frac{1}{S_o c}\frac{\partial h}{\partial t}} \qquad \text{Equation 1}$$

$$\frac{\partial h}{\partial t} = \frac{h_i - h_{i-1}}{\Delta t}$$

Where:

A = wetted cross-sectional area, Ft^2
R = flow depth, Ft
K = 1.3 (as recommended by Fread 1975)
h = stage
Δt = time step, change in time between stages
C = celerity
M = friction exponent

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[6] Personal communication with Ron. C. Goldman, Corps of Engineers.
[7] Personal communication with Michael S. Runner, Chief, Hydrologic Data Section of USGS

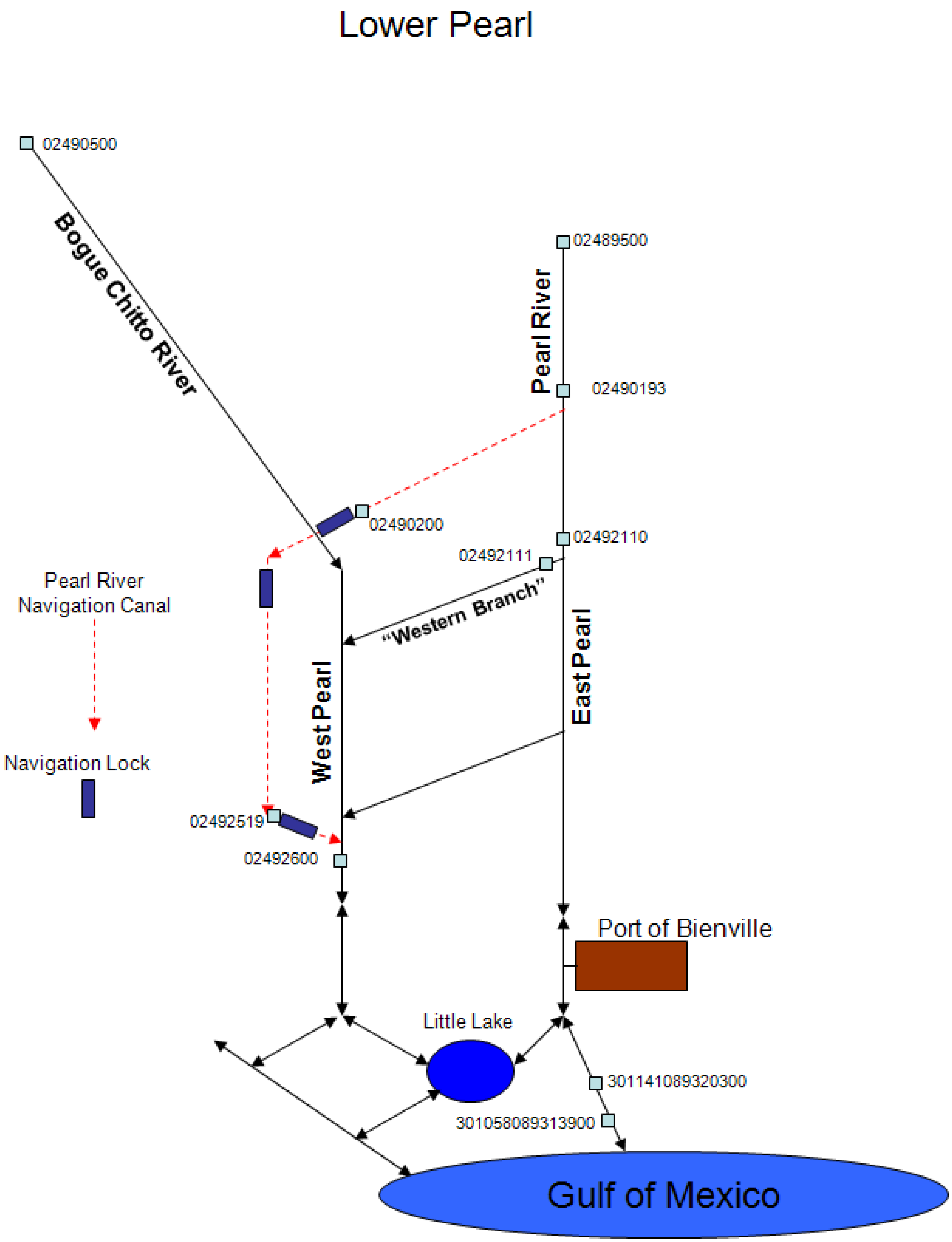


Figure 7 Location and Direction of flow splits from the East Pearl

Since station 02492110 is a new station the time of record for this analysis is limited to January 2008 – present. For both stations the gage height is used with Equation 1 to estimate a flow. With the evaluation of the flow before (02492110) the branch and flow after (0292111) the branch; it is shown that (January 2008 – July 2008) an average of approximately 75 % of the flow continues down the East Pearl with the remaining 25% diverted to the West Pearl. Although the West branch is wider than the east it is estimated that more flow passes through the East than the West. Satellite images of the branch show a dike/training structure on the west branch that allows more flow down the East Pearl.

South of the previously discussed West Branch is a branch that crosses wetlands and diverts water from the East to the West Pearl. Downstream of that is a web of channels that spreads and diverts more flow from the East Pearl. The remaining diversions currently lack the proper data for an accurate evaluation, and data collection for these is outside the scope of this project.

All contributing watersheds in the basin are accounted for in the sediment transport analysis as either routed through a gaging station, or, for ungaged areas, as a sediment yield per area based on gauging stations. According to the USGS Station 301141089320300, the most downstream station on the East Pearl, the Pearl River Watershed has a contributing area of 8,674 mi^2. USGS Station 02489500 is at the upstream end of CV 5 (see Figure 17) on the East Pearl its contributing area is 6,573 mi^2. The difference between the upstream and downstream contributing areas is 2,101 mi^2. Between these two stations there is station 02492360 and 02492343 that route flow into the East Pearl and have a combined contributing area of 261 mi^2. Then on the West Pearl, Station 02490500, routes 492 mi^2. The combined contributing area for the three stations results in a total of 753 mi^2 that is accounted area. The ungaged area is estimated by subtracting 753 mi^2 from 2,101 mi^2 that results in 1,348 mi^2 of watershed that is not monitored through a gaging station. Obviously this area includes both the East and the West Pearl but with the available information separation of the two is impossible. Therefore, it is assumed that the ungaged area does in its entirety contribute to the East Pearl.

7. Numerical Model of Bienville

Stemming from the necessity of understanding the Port's flow and ultimately the sediment supply, a numerical hydrodynamic model, Adaptive Hydraulics, ADH, is used to estimate flows and velocities. ADH is a finite element–multi-dimensional model that solves the shallow water equations and is developed by the US Army Corp of Engineers. The 2-dimensional version was used here. The challenge with Bienville is to model enough of the multiple bayous and off-channel storage areas so that the tidal prism and corresponding flows are captured. The grid is composed of 12,960 nodes (see Figure 22). With such a large mesh and limitations in computation ability, runtimes were long; therefore, the simulation used is limited to a seven-day event. The modeled time corresponds to the period of data collection, January 21, 2009 12:00 am – January 28, 2009 12:00 am. Boundary conditions for the model are comprised of incoming flow from the Pearl River and a NOAA tidal station located near Bay Saint Louis, MS. Model validation is achievable only with the use of two NOAA stations, the New Canal Station and Shell Beach Station (see Figure 8). As of April 13, 2009 gage height from USGS 301058089313900 used early, in calculating the inlet flux, is unavailable for this period of record.

The primary goal of this model is to determine the flows during the time that sediment sampling in the port occurred so that sediment rating curves can be constructed for inside the port.

For the Shell Beach Station (see Figure 10) the tidal elevations appeared to match relatively well; were as with the New Canal Station (see Figure 11) convergence of the observed and simulated tide varies with some degree. Further validation is achievable through an examination of the models relative error. The error in the port is consistent indicating proper convergence; however, outside the area of interest the model error is relatively large with fluctuations throughout the grid. The primary cause is believed to be insufficient bathymetric data. Shown in the figure below is a zoomed in image of the Bienville Grid where the Port is located, and the primary area of interest. Likewise Figure 12 illustrates the velocity vectors at the entrance during the ebb tide.

Fundamentally, the model provides a base for future analysis of the Port. It is recommended that for any future Ports changes the proposed designs are analyzed using this model or a similar model that can provide insight into the behavior of the flow and sediment supply into and out of the Port due to modifications.

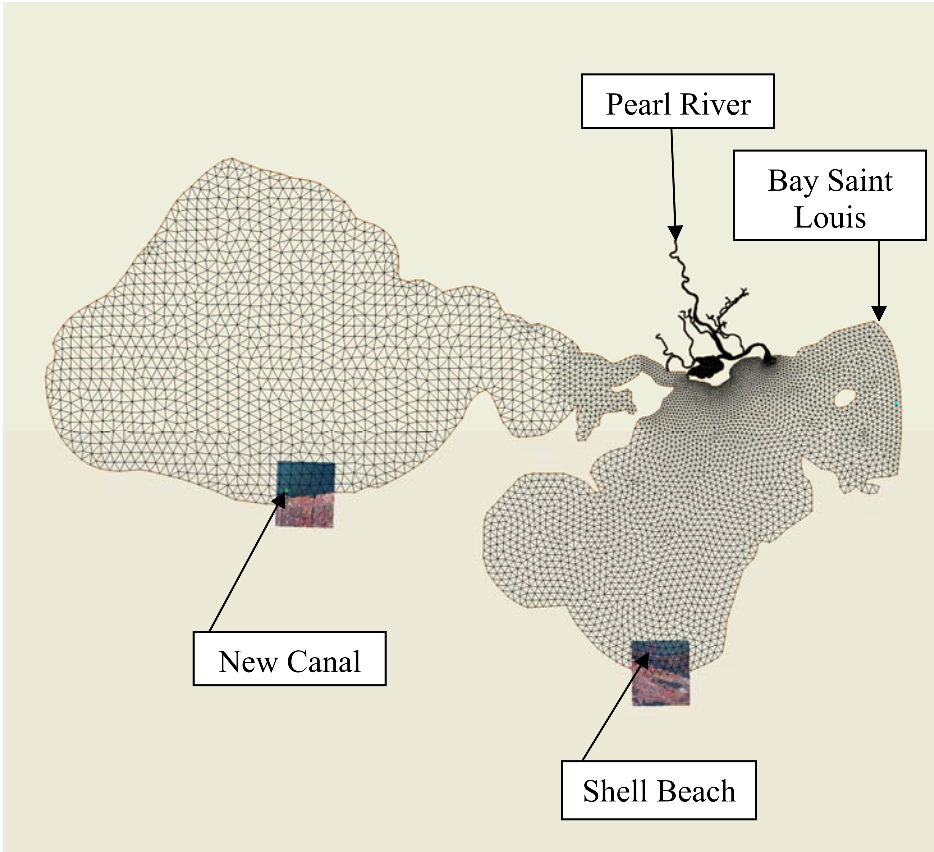


Figure 8 Bienville ADH Mesh with Tidal Station and Boundary Conditions

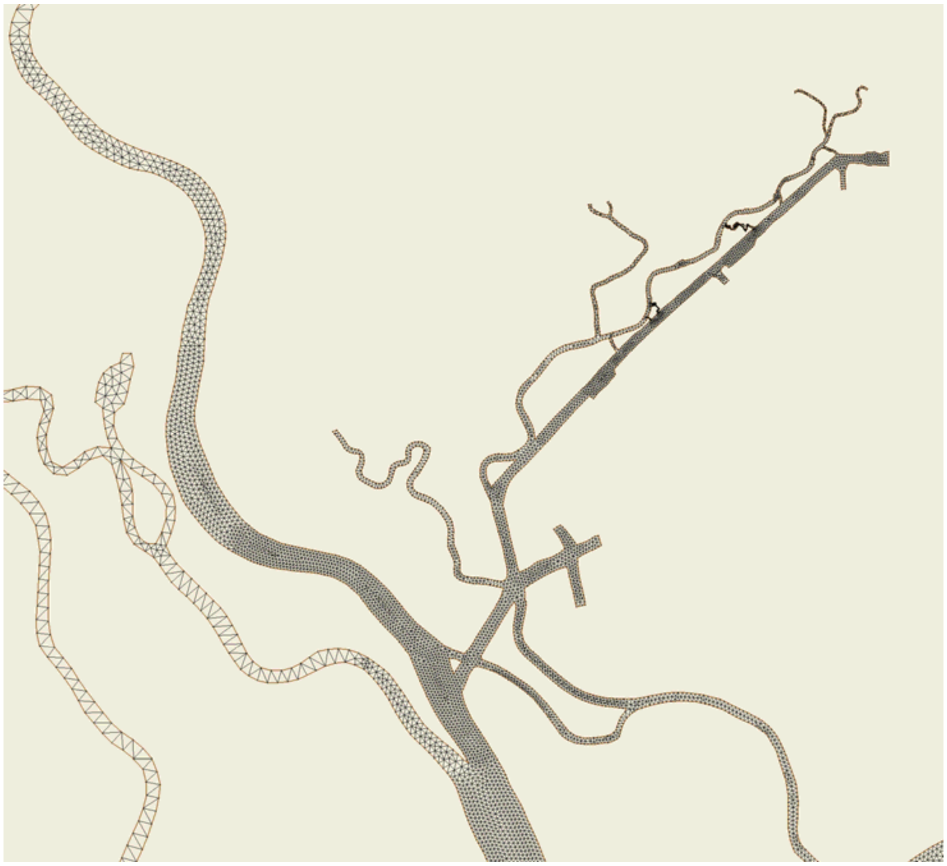


Figure 9 Bienville Grid Port Detail

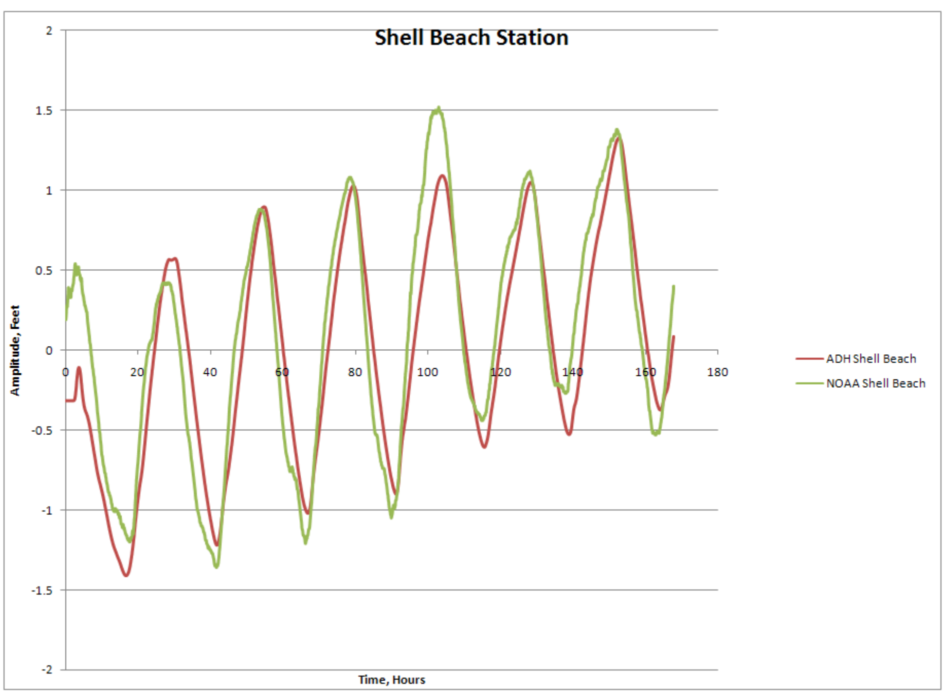


Figure 10 Shell Beach Tidal Comparison

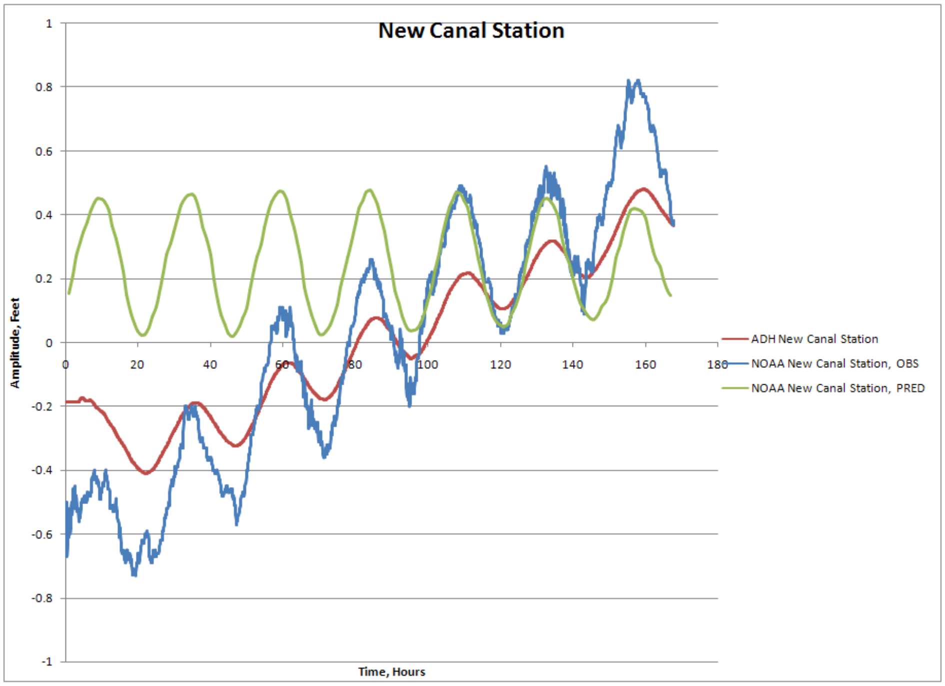


Figure 11 New Canal Tidal Comparison

Figure 12 Simulated Ebb flow on January 23 10:15, near ISCO 11

8. Quantifying Port Sedimentation

Sediment fluxes and depositions were analyzed using several approaches. The simplest is implementation of USGS data in a sediment budget; this method of quantifying sediment in a holistic approach has been shown to be fairly reliable and fast (Sharp 2007 and 2009b). Since the Port of Bienville is in a tidally influenced area then application of the sediment flux calculator is required to estimate the sediment flux through the inlet. Finally, collected sediment data along with the port's trap efficiency is applied to determine locations of entrapment. From these estimates the objective is to define the most appropriate sedimentation solutions.

8.1. Sediment Budget

With the exclusion of long term dredging data the sediment quantities required for a proper Port evaluation are first estimated using the Sediment Budget Template, SBT, outlined by Sharp (2007) along with later modifications from Sharp (2009b) for tidally influenced areas. By creating a sediment budget the amount of sediment that enters the Port and channel is quantified. This allows a rough approximation of the annual removal amounts and the capital cost of dredging the material. From a preliminary analysis of the current sedimentation patterns in and around the Port of Bienville; it is assumed that the majority of the sediment source is from the Pearl River.

Initial model set up requires collecting available suspended sediment, annual flood flow, and daily mean flow data from the USGS (see Figure 13). Sediment flow is defined by constructing sediment rating curves and using channel discharge. Next, a conceptual sediment budget is created to help define the basic nature of the system. After that a second and more refined approach is taken that further analysis the result from the conceptual sediment budget. Then if deemed necessary and appropriate a third calculation is done that uses the Sediment Impact Assessment Model, SIAM, in HEC-RAS to create a sediment budget based on total load equations.

8.2. Sediment Rating Curves

Prior to any sediment evaluations, rating curves that define the system are formulated. The sediment rating curves are constructed using the Power Curve Program (Sharp 2007). These curves use USGS sediment data with a power curve trendline (see Equation 2).

$$Q_s = AQ^B \qquad \text{Equation 2}$$

Where: Q_s = suspended sediment flux, tons/day

Q = local discharge, cfs
A = power curve coefficient
B = power curve exponent

For the Pearl River watershed a set of curves are created based on all the sediment data, data separated by HUCs, and data for individual stations. The table below shows the values associated with each curve, including the R^2 correlation coefficient.

Table 2 Sediment Rating Curve Coefficient Values

	Discription	A	B	R^2
Total	Pearl River	0.8561	0.9827	0.6285
Eight digit HUCs	Middle Pearl Silver MS	0.0042	1.43	0.9237
	Middle Pearl Strong MS	0.3694	1.1546	0.661
	Lower Pearl	0.0025	1.4766	0.872
USGS Stations	2485574	0.0939	1.5011	0.9231
	2485590	0.0105	1.8515	0.9363
	2485601	0.0003	1.667	0.929
	2486000	0.0385	1.1564	0.9843
	2486500	1.0315	0.7929	0.6504
	2489000	0.0069	1.3598	0.8738
	2489500	0.0009	1.6022	0.8814

There are more than three HUCs in the Pearl River watershed; however, only three are found to contain stations with sediment data. Multiple stations, not included in the above table, have suspended sediment data but only have stage with no associated rating curve. Furthermore, some data have discontinuities which are due to station discontinuation, stage-only specified, new station, or backwater effects[8]. The following two Figures are examples of the rating curves, and are the two curves primarily used for the sediment flux in the Port.

[8] Correspondence via email with Michael S. Runner, Chief, Hydrologic Data Section of USGS

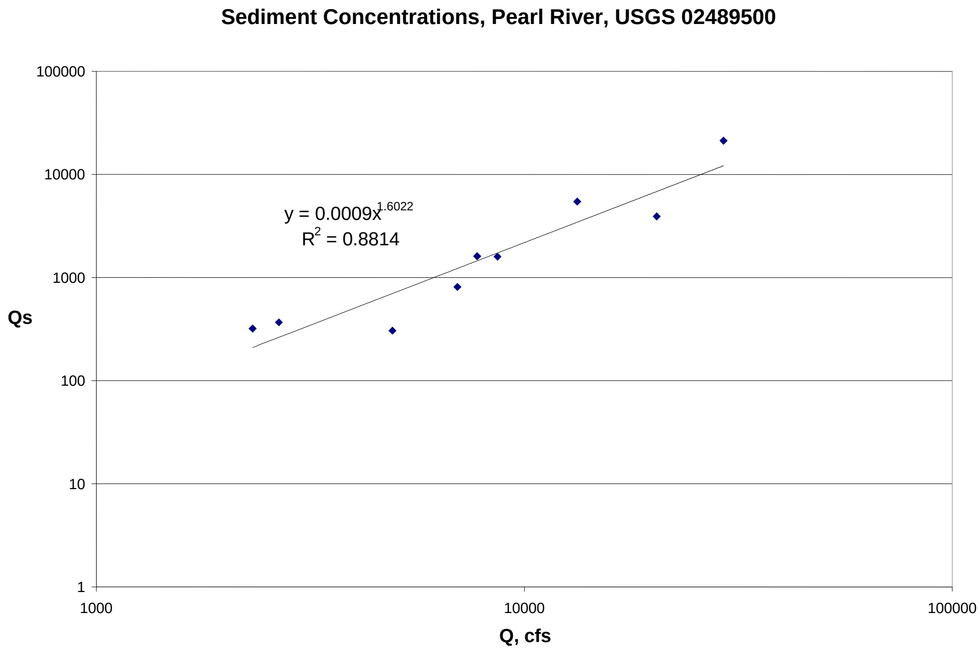


Figure 13 Sediment Rating Curve for the USGS Station 02489500

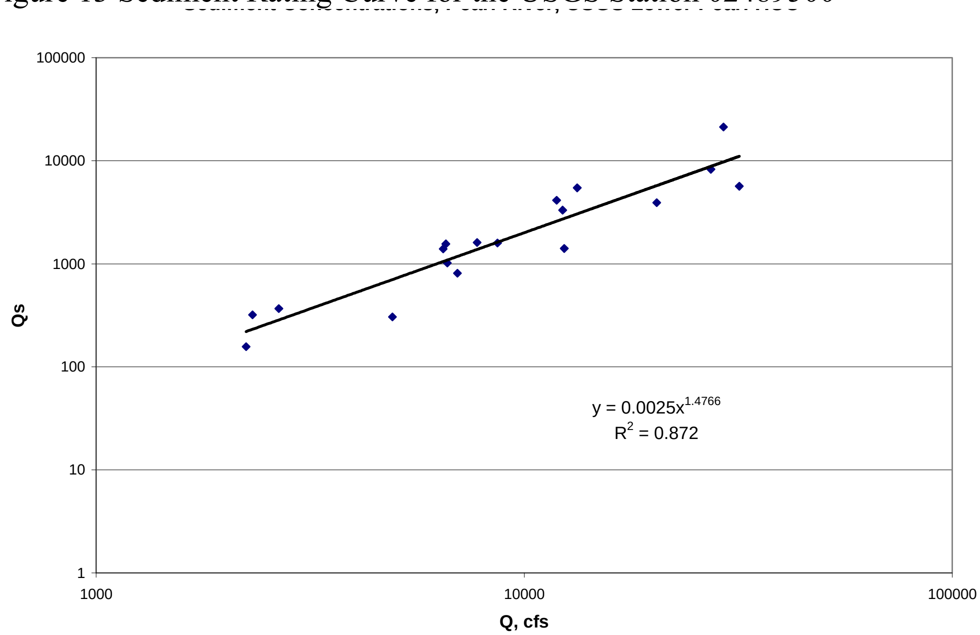


Figure 14 Sediment Rating Curves for the Lower Pearl HUC

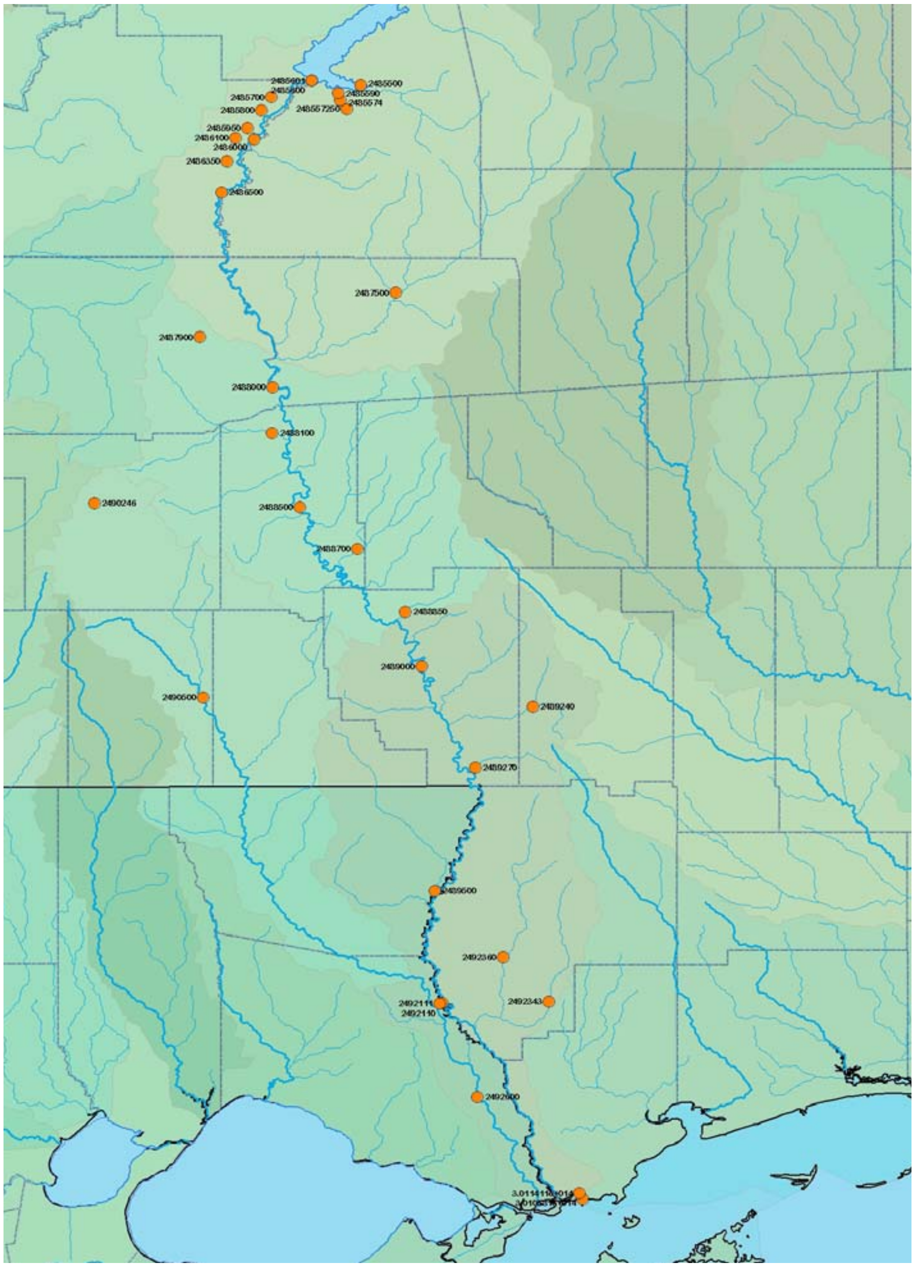


Figure 15 USGS Station Locations, Pearl River

8.3. Inlet Sediment Flux

The sediment flux through the inlet is used in the sediment budget calculations. The flow volume is established based on inlet cross sectional area, tidal prism, and tidal stages based on USGS Station 301058089313900 and NOAA bathymetry data. The Station's data set includes July 2000 thru July 2008 with a major gap from August 2005 thru April 2006, and with recordings of daily maximum and minimum stage only. The tidal data are used to calculate the daily high and low water cross sectional area and are used to estimate the daily tidal prism. The tidal prism is then used along with the sediment data to estimate the sediment flux at the inlet. Further explanation of this method is given by Sharp (2009a). As a first approximation for the conceptual sediment budget, the daily tidal prism is calculated using a regressed empirical equation based on regional field date, and is of the power equation form. This equation (Equation 2) is one of many that were developed by James T. Jarrett for various locations on the East, West, and Gulf Coasts of the United States (Jarrett 1976).

$$A = 5.02 \times 10^{-4} \times TP^{0.84} \qquad \text{Equation 3}$$

Where:

A = area of the inlet, ft^2

TP = tidal prism ft^3

Equation 3 is then solved using Equation 2 which provides an estimate for the sediment flux.

$$Q_S\,(\text{Daily}) = (TP + \overline{Q_{River}})C - (TP)KC \qquad \text{Equation 4}$$

Where:

K = empirical value based on field conditions from suspended sediment differential

Q_{River} = river flow

TP = tidal prism

C = suspended sediment concentration

From this method it is estimated that the exiting sediment flux at the inlet ranges from 5 – 6 million tons annually.

The second sediment budget analysis, Tier 2, uses a second approximation for the tidal prism. This is the only effluent flow that varies from what is used in the conceptual sediment budget, and is achieved using an equation derived by Krishnamurthy (1977) of the following form:

$$TP = 1.25 B y_o V_{fc} T \left(1 + \frac{2a_o}{\pi y_o}\right)\left(\ln \frac{10.93 y_o}{k}\right) \qquad \text{Equation 5}$$

Where:

TP = tidal prism

B = width of inlet

y_o = depth of flow at mean sea level

V_{fc} = friction velocity corresponding to critical shear stress

T = tidal period

a_o = amplitude of ocean tide
k = roughness coefficient of flow

Equation 5 considers impacts to the tidal prism due to energy losses. The critical shear for the Lower Pearl is determined from collected samples in the port. Here the D_{50} is estimated at 0.007 mm which falls into the range of cohesive particles. For this range of fine to very fine silt critical shear stress is 0.0378 – 0.0630 N/m^2 (Berenbrock and Tranmer 2008). For this analysis a critical shear stress of 0.05 N/m^2 is used. Using this value in Equation 5, and the rating curves from USGS Station 02489500 and Lower Pearl HUC the sediment flux at the inlet is estimated at 300,000 tons/year.

8.4. Conceptual Sediment Budget

The conceptual sediment budget evaluates the sediment behavior for the Pearl and Lower East Pearl. It is used as the initial step in the process of the sediment budget construction. The sediment budget is extended up to USGS Station 02486000 near Jackson, MS on the Pearl. Examining the upstream conditions provides useful insight into the regional sediment trends.

For calculation purposes the upper Pearl is sub-divided into four control volumes (CV) (see Figure 16). Each CV uses different USGS stations located in the respective watershed to quantify the flow and sediment. Then the lower East Pearl is the fifth CV (Port of Bienville is located here), which extends down to the East Pearl River inlet (see Figure 17).

For the ungaged area (as discussed in Section 4.1) a sediment yield per area is estimated to account for the sediment load. The sediment yield per area is estimated using the following equation:

$$\text{Sediment Yield} = \frac{\text{sediment flux}}{\text{contributing area}} \Rightarrow {}^{tons}\!/_{mile^2} \qquad \text{Equation 6}$$

Using the sediment flux calculated for station 02489500 (the furthest downstream sediment station) and its contributing area it is estimated that the sediment yield is 1050 tons/mi^2 annually, and yielding 1.4 million tons/year of influent suspended sediment estimated by multiplying the sediment yield by the ungaged area flowing into CV5.

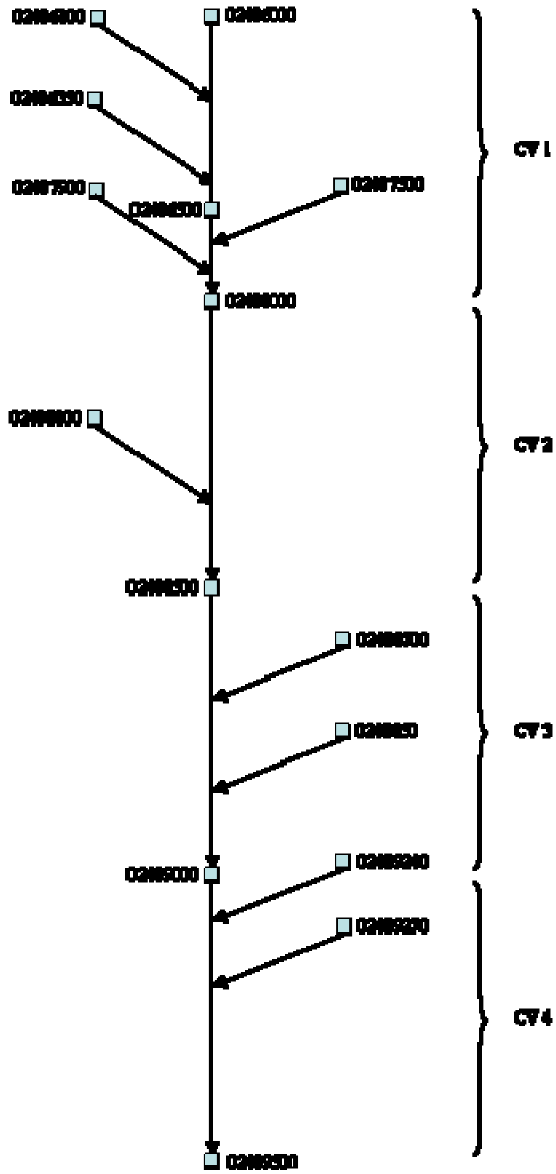


Figure 16 Flow Directions of the Upper Pearl

For each control volume a deposition/erosion rate is calculated as well as the influent and effluent sediment fluxes by using a bankfull discharge based on a 1.5 year event along with the sediment rating curves. From this the annual tendencies of the system are determined.

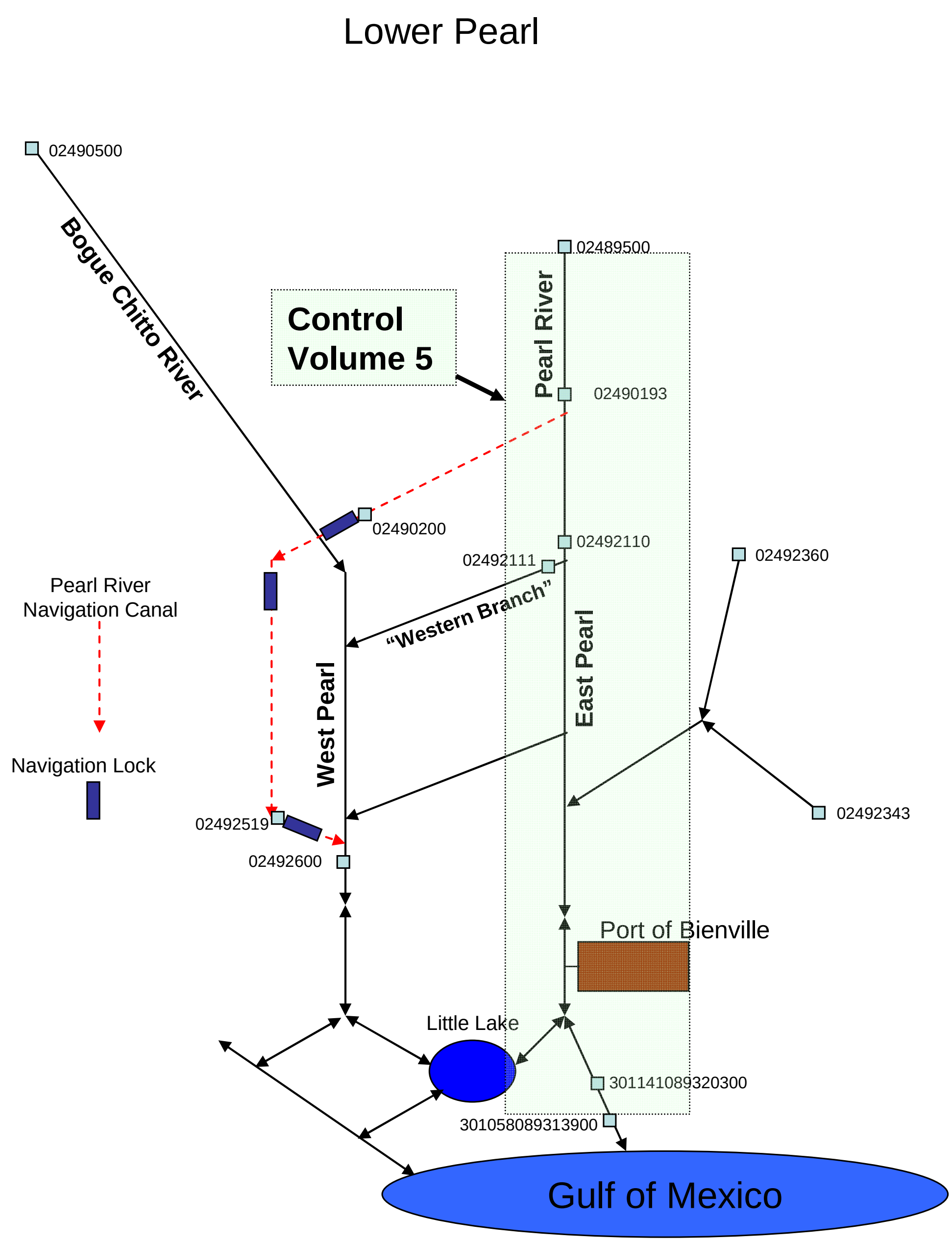


Figure 17 Flow Directions of the Lower East and West Pearl

The first four CVs are evaluated in order to determine the sediment behavior of the Pearl River. Problems in the upper Pearl can cause issues in the lower Pearl and must be appraised. Table 2 shows the calculated amounts of sediment deposition or erosion based on the different sediment rating curves. The four upper CVs are outside the area of tidal influence, as indicated by the obtained USGS data. Negative values are net erosion and positive values are net deposition. The highlighted changes in volumes are those that are based on sediment rating curves in or near the CV location, and represent a range of possible volume changes. From the values in Table 3 it is evident that the upper three CVs, CV1…CV3, are experiencing deposition with CV1 occasionally experiencing erosion. Deposition in the Upper Pearl is an indication of the adverse impacts from development in the greater Jackson, MS area. Then for CV 4 it is estimated that erosion is occurring.

Table 3 Estimates of Deposition/Erosion on the Upper East Pearl (tons/year)

Upper East Pearl				
Rating Curve	***CV1***	***CV2***	***CV3***	***CV4***
Pearl River	5,660,000	3,020,000	2,880,000	1,220,000
Middle Pearl Silver MS	618,000	905,000	654,000	-565,000
Middle Pearl Strong MS	9,280,000	6,150,000	5,470,000	511,000
Lower Pearl	435,000	840,000	578,000	-641,000
2485574	17,200,000	39,900,000	26,800,000	-33,400,000
2485590	-120,000,000	139,000,000	52,500,000	-269,000,000
2485601	-116,000	636,000	339,000	-860,000
2486000	980,000	652,000	579,000	51,600
2486500	1,460,000	679,000	675,000	441,000
2489000	704,000	767,000	592,000	-325,000
2489500	60,400	1,010,000	597,000	-1,170,000

If erosion is occurring in CV 4, then either erosion continues completely or partially into CV 5, similar to CV 4, and/or deposition is occurring in CV 5 due to excessive sediment loads from upstream in CV 4. Both cases result in a possible need for Port modification that eliminate/reduce material from entering the still water of the Port and depositing. The lower East Pearl (see Figure 17) contains Control Volume 5 where the Port of Bienville is located; here most of the efforts are focused. Several limiting factors hinder the investigation of sediment in CV 5; in turn making it difficult to predict the sediment tendencies in the Port and surrounding area. As transitions occur between the upland reaches and the lower coastal zones, the energy slope flattens, and water flows into multiple channels and wetlands. Understanding the flow directions require a more inclusive and detailed numerical model along with a longer simulation time. However, for the purpose of this study the previously defined flow discharges (see Section 4) are used to define the effluent sediment fluxes.

Now using the inlet flux estimates it is possible to determine the total net change in CV5. Net deposition is estimated at a rate of 550,000 tons/year. If deposition evenly occurs over the entire reach of CV5 then approximately 10,000 tons/mile of sediment deposits. Using a specific gravity of 1.6 (Julien 2002) the deposition is 7,400 yds/mile or 1.5 inches of evenly distributed deposition annually. At this depositional rate the Port might be experiencing as much as 42,000 tons or (using a SG of 1.6) 31,000 cu yds of deposition a year.

For confirmation of the conceptual sediment budget in CV5 the Tier 2 approach is implemented to estimate the amount of deposition. Once again the same effluent flow approximations at the different branches used for the conceptual sediment budget are used for Tier 2.

The influent flux for CV 5 is calculated using the Tier 2 Program of the SBT. The Tier 2 uses daily flow, local sediment rating curves, and estimates the bed load as a percent of the suspended load resulting in a total annual load budget. With this modification the influent flux from the ungaged areas is calculated at approximately 200 tons/mile^2-year; substantially less than the 1,050 tons/mile^2-year calculated for the Tier 1.

The net effect of sediment in CV 5 from the Tier 2 analysis is similar to that of the Conceptual Sediment Budget. For the Tier 2 analysis a net deposition of 1,062,000 tons/year is calculated (see Table 4). This indicates that approximately 20,000 tons/mile of sediment is depositing in the Lower Pearl, and if evenly distributed (with the same approach that is used in the conceptual sediment budget) then there are approximately 3 inches of deposition. For Port shoaling this indicates a total deposition of 100,000 tons/year or (using a SG of 1.6) 74,000 cu yds/year of deposition, with the primary difference in the Tier 1 and 2 being the exiting among of sediment.

Table 4 Tier 2 Sediment Budget, Breakdown

	Tier 2 Sediment Budget		
		Sediment Flux (tons/year)	
	Location	**Suspended Load**	**Bed Load**
	2489500	1,300,000	270,000
	2492360	7,600	1,500
	2492343	3,400	700
Influent	*Nonpoint*	250,000	50,000
	Western Branch	400,000	81,000
Effluent	*Inlet*	300,000	40,000
Total		861,000	201,200
Combined Total		1,062,200	

9. Field Observations

Field sampling was conducted to provide insight into the sedimentation characteristics of the port. Two ISCO automated water samplers were deployed to collect total suspended solids (TSS) samples, along with the collection of grab samples of both suspended sediment and bed samples (see Figure 17). For the ISCO's data were collected over a twenty-four hour period from January, 23 – 24 2009.

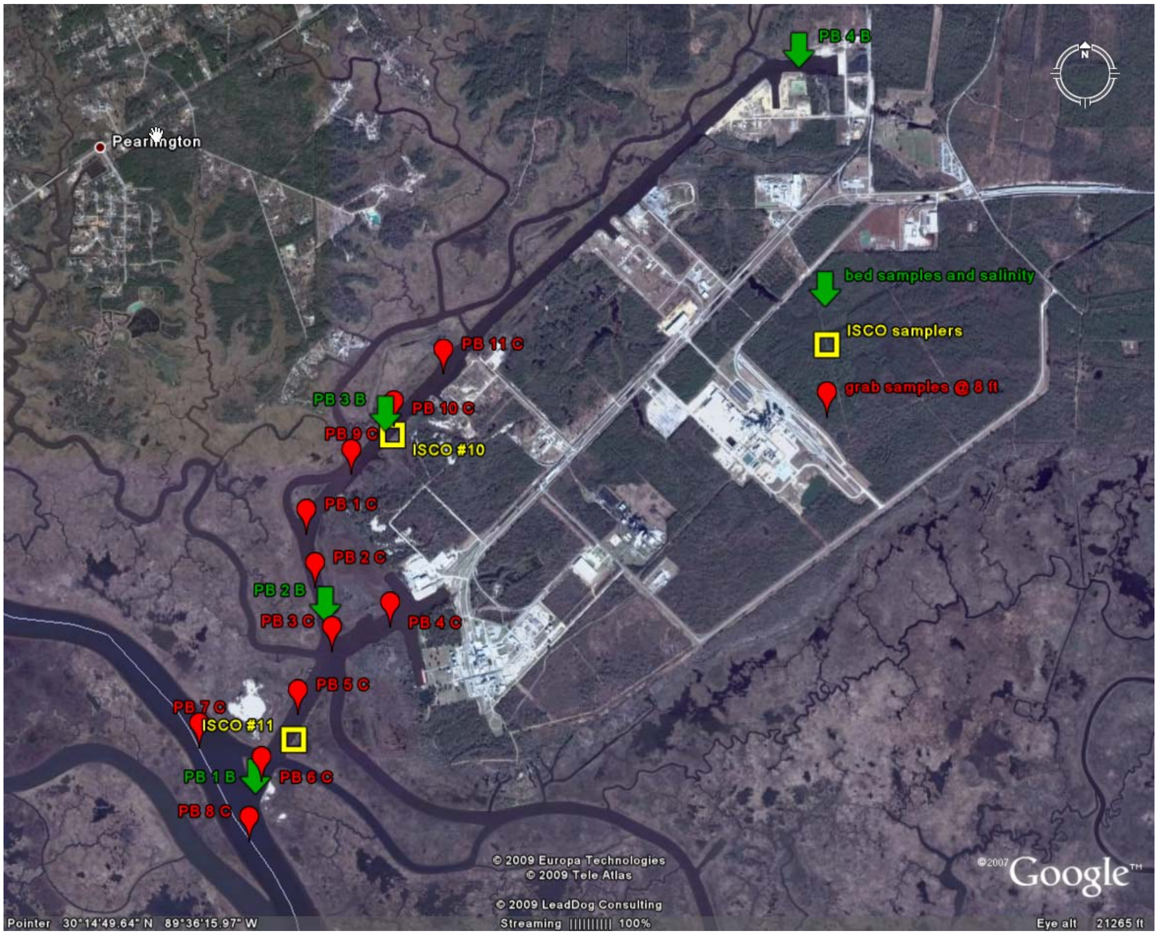


Figure 18 Location of Collected Samples (Adaptation of Google Earth image)

The ISCOs provided samples collected every hour over a twenty-four hour period to determine the sediment behavior as related to the tidal profile (see Figure 19 and 20). Then grab samples of suspended sediment where collected at a depth of approximately eight feet and provide a snapshot of the suspended sediment profile over the length of the Port. Finally, bed samples were analyzed for grain size distribution.

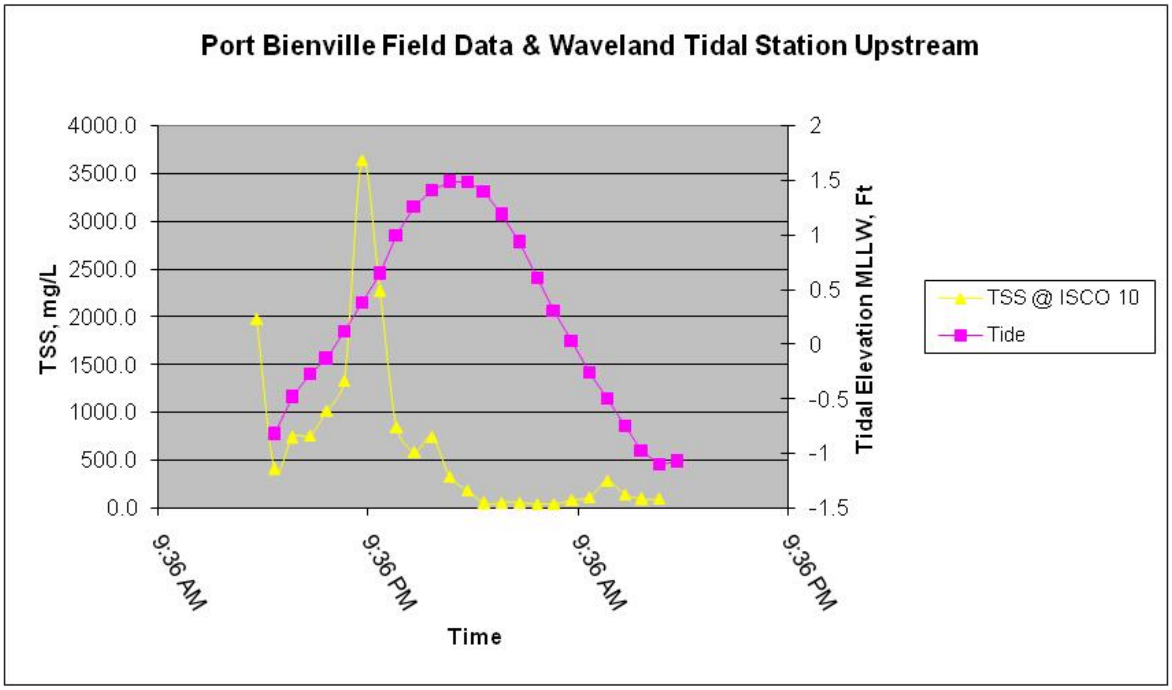


Figure 19 ISCO 10 Samples inside the Port

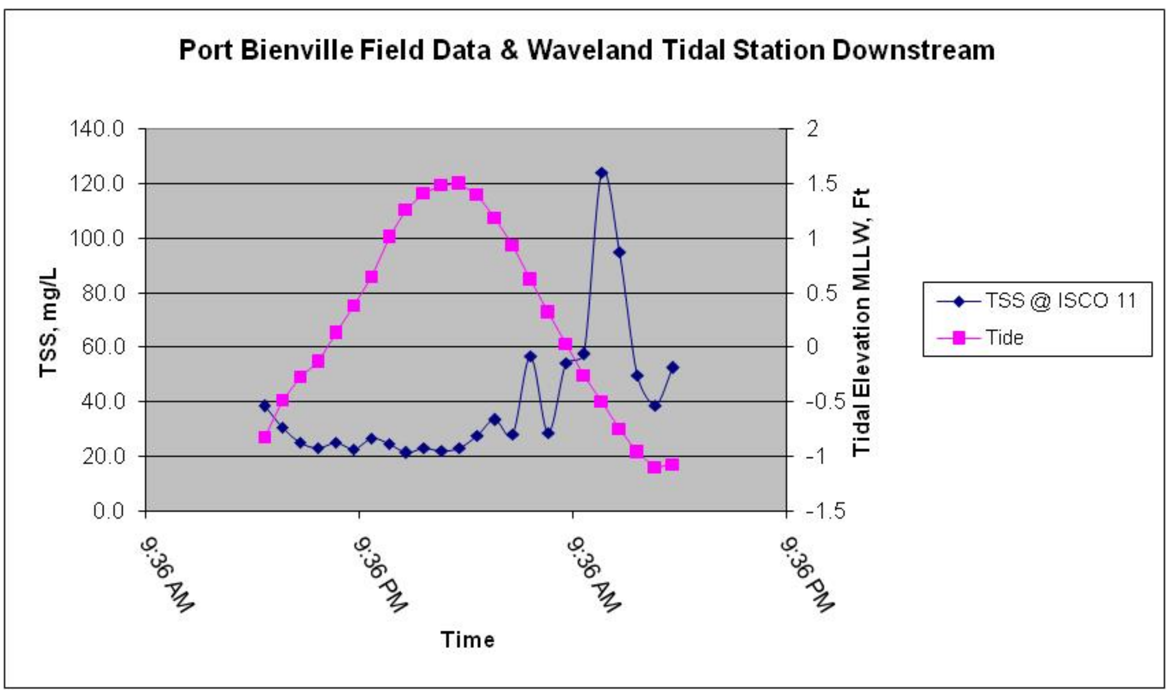


Figure 20 ISCO 11 Samples Entrance of the Port

Visual inspection of the samples in Figures 19 and 20 show a spike of suspended sediment during the ebb tide. However, the concentrations in Figure 19 are significantly higher than those in Figure 20. Additionally, Figure 18 shows an even higher spike during the flood phase. For this anomaly several possibilities exist as to the explanation. The most likely of these is increased sediment concentration from intake misalignment such that the intake could have been pushed down into the bed where it took samples from the bed. However, it is possible that this spike is capturing a realistic process that is occurring. As for the corresponding spike on the ebb tide this may indicate a sediment cloud that pulses back and forth with the tidal variation.

For an analysis of the bed composition three bed samples were taken with a sediment grab sampler. Methods of wet sieving, hydrometer, and pipette were used to determine the grain size distribution of the bed samples (see Figures 21 – 24). The median grain size, D_{50}, is approximately 0.007 mm which falls into the fine silt range and is of a size for fluid mud formation. At this size individual grains are cohesive. With a large percentage of the total grain size distribution being cohesive, the probability of the occurrence of fluid mud in the system increases.

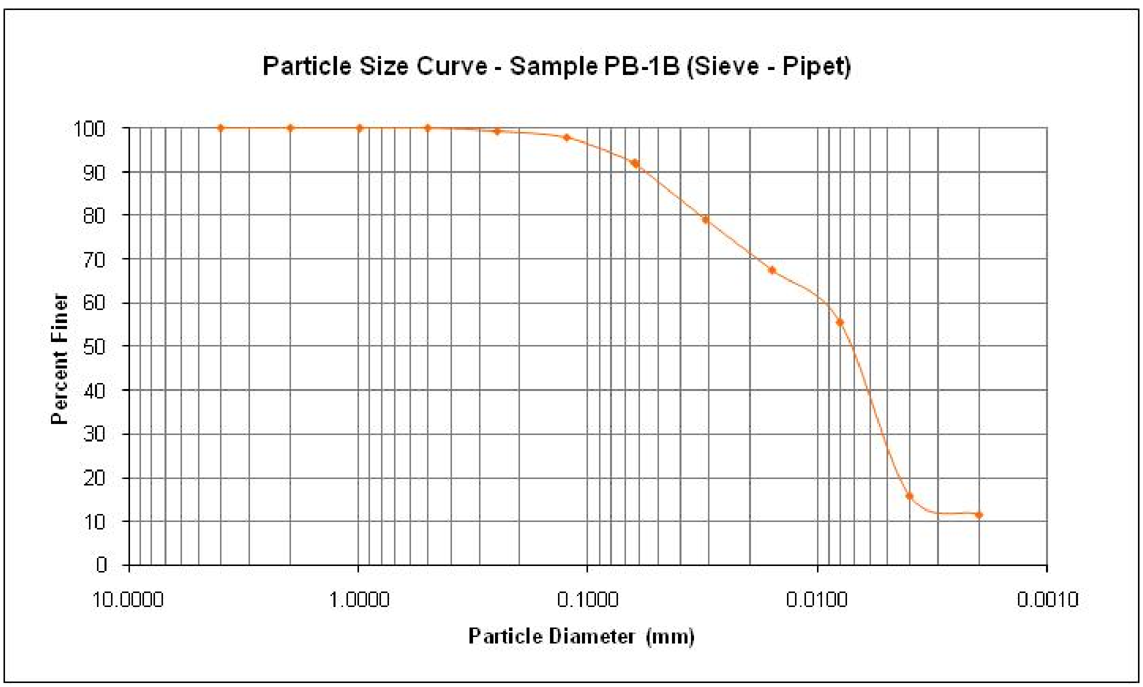


Figure 21 Gradation of PB-1B (Pipette)

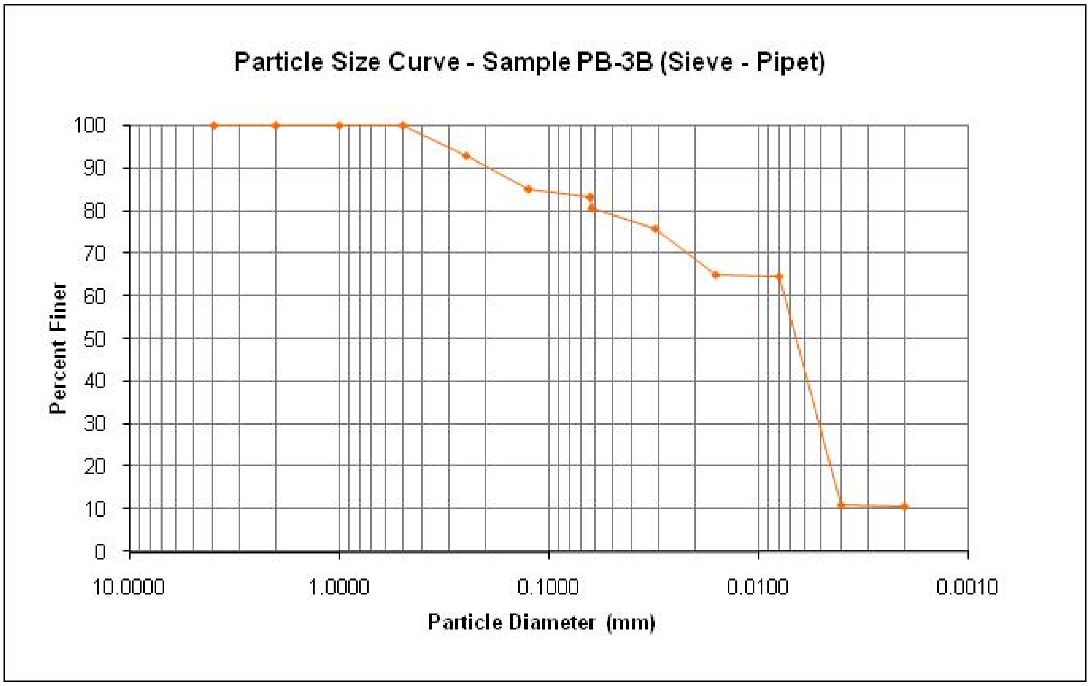


Figure 22 Gradation of PB-3B (Pipette)

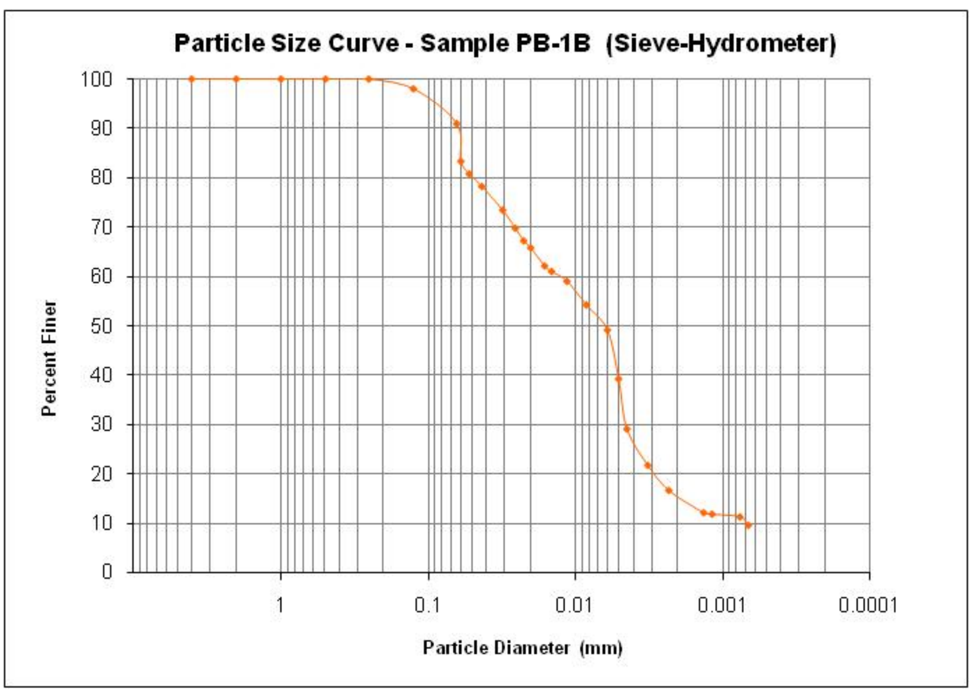


Figure 23 Gradation of PB-1B (Hydrometer)

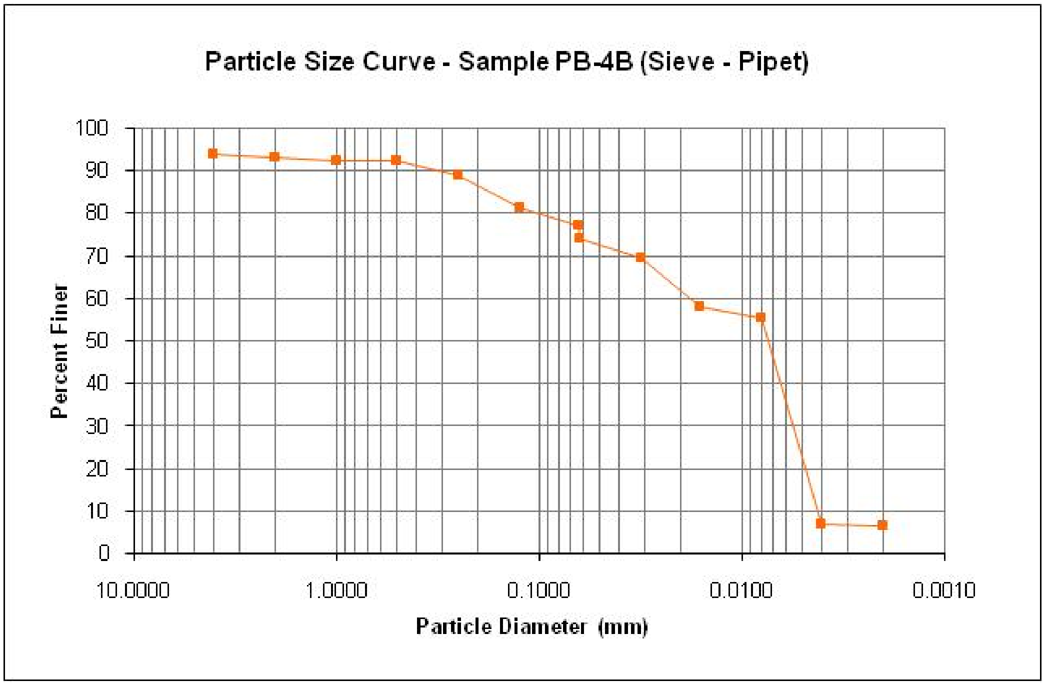


Figure 24 Gradation of PB-4B (Pipette)

9.1. Fluid Mud Analysis

Fluid mud is defined as "a high concentration aqueous suspension of fine-grained sediment in which settling is substantially hindered" (McAnally et al. 2007). Dredging of fluid mud is a cumbersome prospect since it has a low density which substantially decreases the mass of material removed and increases the volume of dredge material due to water content Furthermore, if not properly removed then it can flow back into the location where it was dredged.

One bed sample collected that has indications of fluid mud is PB-1B (see Tables 5 – 8). This sample was collected near the entrance of the port at 3:15 pm January 22, 2009. Further lab analysis beyond that of the other samples was done on PB-1B to determine if it is a fluid mud. Both organic matter and TSS was determined along with the pipette and hydrometer analysis for grain size distribution. From this analysis and visual inspection it was determined that this sample is probably a combination of newly deposited bed and fluid mud.

Table 5 PB-1B Lab Analyses Results

Sample ID	Sand (gm) part A	Fines (gm)part B)	Total Sample (gm)	Moisture (%)	Organic Matter (%)	TSS (g/L)
PB - 1B	2.44	26.75	29.19	477.7	11.54	229

Typical values for TSS as associated with fluid mud are normally in the hundreds of grams per liter. For this sample it is shown that the TSS is 229 g/L and is well within the range of a typical fluid mud suspension, f 50 – 350 kg/m^3 (Teeter 1992). As suggested by McAnally et al (2007a) the sand component is usually less than a few percent. The percentage of sand of PB-1B is 8% while the fines compose 92% of the total solids. This percentage of sand would suggest that the sample might also contain deposited material to heavy to be in suspension in a coastal environment with low shear stresses, an indication that a partial bed sample was also extracted.

The organic content can also play a role in maintaining the stability of fluid mud. From lab analysis the sample contains 11.54 % in organics where as typical samples contain less than 2% organics (Hedges and Keil 1999; Leithold and Hope 1999). This too might be further indication that a partial fluid mud and bed sample were actually collected in the sample. It also indicates the stability of the fluid mud from entrapped air in the mixture that prolongs the entrainment. Tables 6 and 7 show the grain size distribution results.

Table 6 Sieve Method (Part A)

Sieve #	Diameter (mm)	Mass retained (gm)	% Retained	% Passing
5	4.0000	0.00	0.00	100.00
10	2.0000	0.00	0.00	100.00
18	1.0000	0.00	0.00	100.00
35	0.5000	0.00	0.00	100.00
60	0.2500	0.15	0.51	99.49
120	0.1245	0.46	1.58	97.91
230	0.0635	1.63	5.58	92.33

Table 7 Pipette Method (Part B)

Particle Size (mm)	**% Finer than**
0.062	91.794
0.031	79.120
0.016	67.773
0.008	55.476
0.004	15.793
0.002	11.562

Sieve #	**Diameter (mm)**	**Mass Retained (gm)**	**% Retained**	**% Passing**
5	4.0000	0.00	0.00	100.00
10	2.0000	0.00	0.00	100.00
18	1.0000	0.00	0.00	100.00
35	0.5000	0.00	0.00	100.00
60	0.2500	0.00	0.00	100.00
120	0.1245	0.81	2.04	97.96
230	0.0635	2.72	6.86	91.09

Table 8 Hydrometer Results

Elapsed Time (min)	**Adjusted % Finer (F230/100)**	**D (mm)**
0.50	83.44	0.0600
0.67	80.94	0.0525
1	78.44	0.0432
2	73.44	0.0310
3	69.70	0.0256
4	67.20	0.0223
5	65.95	0.0200
8	62.20	0.0160
10	60.95	0.0144
16	59.21	0.0114
30	54.21	0.0084
60	49.21	0.0060
90	39.22	0.0050
120	29.23	0.0045
240	21.73	0.0032
480	16.74	0.0023
1440	12.24	0.0013
1920	11.74	0.0012
4320	11.24	0.0008
5760	9.49	0.0007

All the bed samples collected were from a soft mud bottom that can become easily agitated by vessel movement, and tidal fluctuations. Both processes cause either liquefaction resulting in a fluid mud suspension or erosion that later might settle out into fluid mud. Exhibiting both the physical sediment properties and system process required, Port Bienville has clear indications that fluid mud is present. If fluid mud is forming then the spike during the flood phase on Figure 18 could be explained from the passage of a fluid mud cloud that was being driven into the Port.

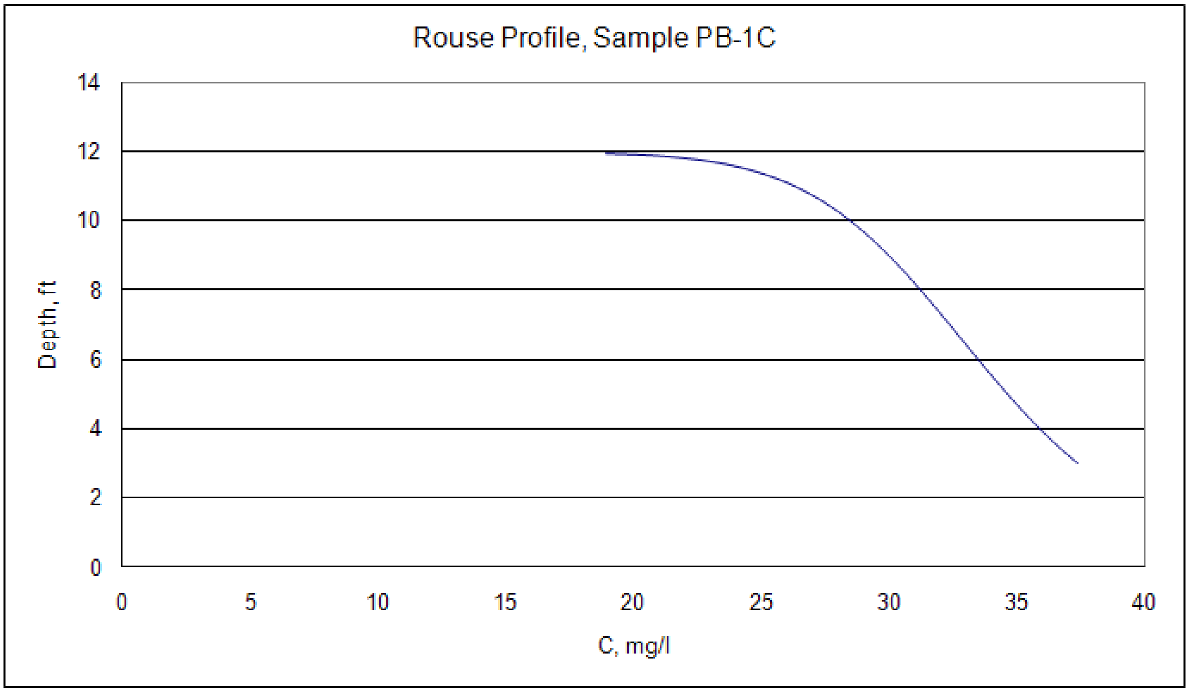
9.2. Rouse profiles and Sediment Rating Curves for the Port

Rouse profiles can be used to estimate the depth integrated suspended sediment concentration from a single point sample. With the integrated samples capturing the concentration across the depth, then the estimated ADH flows are used in conjunction to calculate a sediment flux that is applied to analysis the sediment flow and shoaling potential in the Port. The following table and rouse profiles show the concentration of suspended sediment over the depth. Along with the collected concentrations, the intergraded samples indicate an increasing concentration with distance into the Port during high tide.

Using the ADH model to obtain a flow at each ISCO location enables the creation of sediment rating curves (see Figure 27 and 28) with the use of the collected data shown in Table 11 and 12 and the Power Curve program previously used.

Table 9 Grab Sample Locations

Sample ID	Collected Concentration, mg/l	Integrated Concentration, mg/l
PB - 1C	42.5	125
PB - 2C	50.8	149
PB - 3C	30.3	89
PB - 4C	71.5	211
PB - 5C	26.8	79
PB - 6C	47.5	140
PB - 7C	31.5	93
PB - 8C	31.3	92
PB - 9C	76.2	225
PB - 10C	86.2	254
PB - 11C	96.0	283
PB - 11C-D	99.3	293



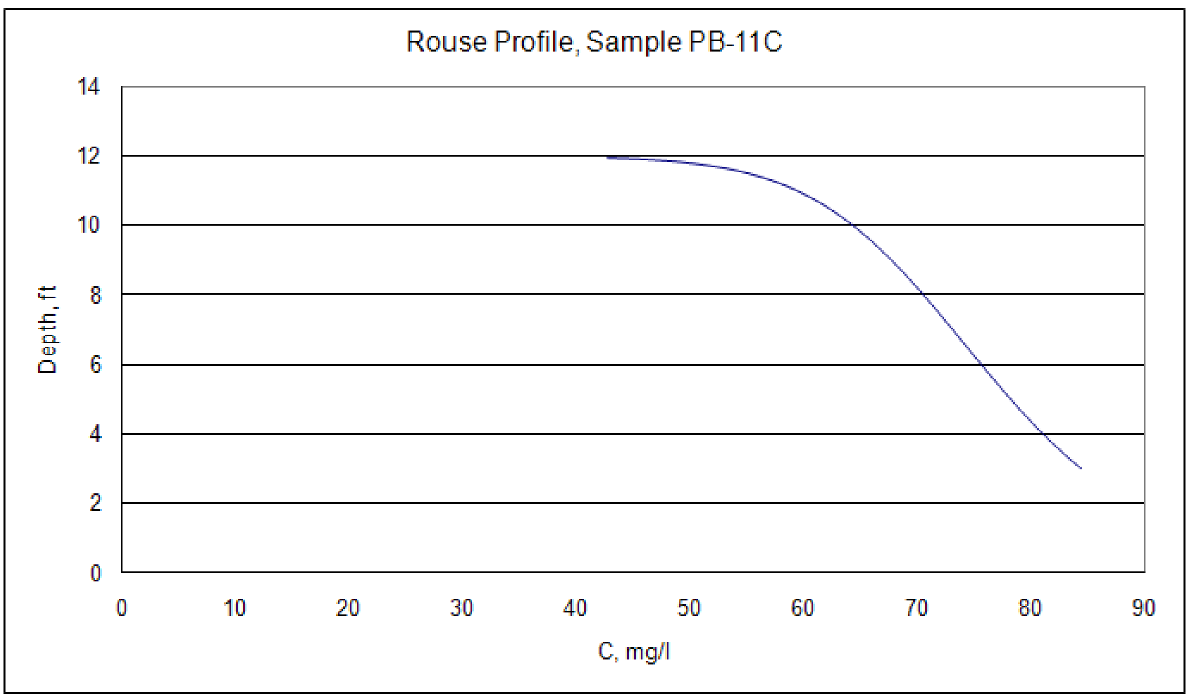
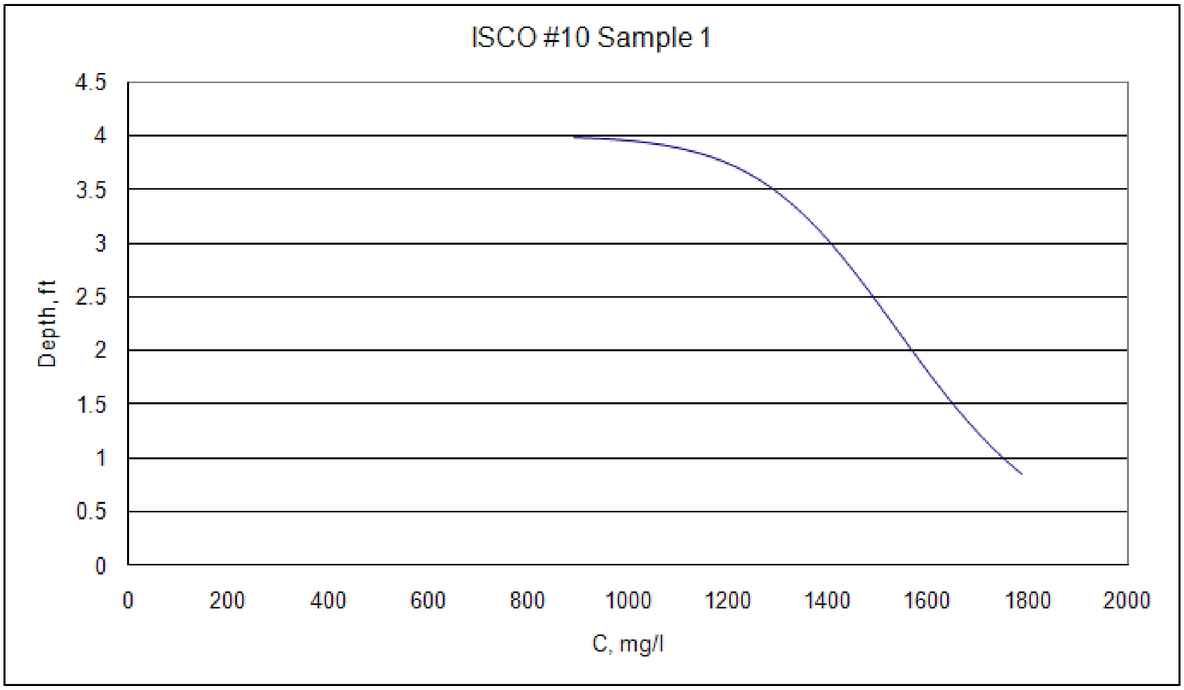


Figure 25 Typical Rouse Profiles for Grab Samples

Table 10 ISCO Collected Samples

	ISCO 11			ISCO 10		
Sample Short ID	Sample ID	Measured	Integrated	Sample ID	Measured	Integrated
		mg/l			mg/l	
1	LB 1	-0.2		PB - 1	1981.0	5930.0
2	PB - A1	38.2	114.3	PB - 2	408.8	1221.3
3	PB - A2	30.4	91.0	PB - 3	737.5	2206.2
4	PB - A3	25.0	74.8	PB - 4	761.8	2280.3
5	PB - A4	23.0	68.8	PB - 5	1014.3	3036.1
6	PB - A5	24.8	74.2	PB - 6	1338.0	4005.2
7	PB - A6	22.6	67.7	PB - 7	3640.0	10896.1
8	PB - A7	26.6	79.6	PB - 8	2274.0	6807.1
9	PB - A8	24.4	73.0	PB - 9	848.3	2539.2
10	PB - A9	21.2	63.5	PB - 10	586.8	1756.4
11	PB - A10	22.8	68.3	PB - 11	746.5	2234.6
12	PB - A10-D	24.6	73.6	PB - 12		
13	PB - A11	21.8	65.3	PB - 13	333.3	997.6
14	PB - A12	22.8	68.3	PB - 14	185.5	555.3
15	PB - A13	27.6	82.6	PB - 15	47.8	142.9
16	PB - A14	33.2	99.4	PB - 15-D	59.7	178.9
17	PB - A15	28.0	83.8	PB - 16	59.0	176.6
18	PB - A16	56.6	169.4	PB - 17	44.7	134.0
19	PB - A17	28.6	85.6	PB - 18	43.8	131.0
20	PB - A18	54.0	161.6	PB - 19	84.0	251.4
21	PB - A19	57.4	171.8	PB - 20	116.8	349.5
22	PB - A20	123.8	370.6	PB - 21	285.8	855.4
23	PB - A21	94.6	283.2	PB - 22	143.0	428.1
24	PB - A22	49.6	148.5	PB - 23	90.0	269.4
25	PB - A23	38.6	115.5	PB - 24	103.0	308.3
26	PB - A24	52.4	156.9			



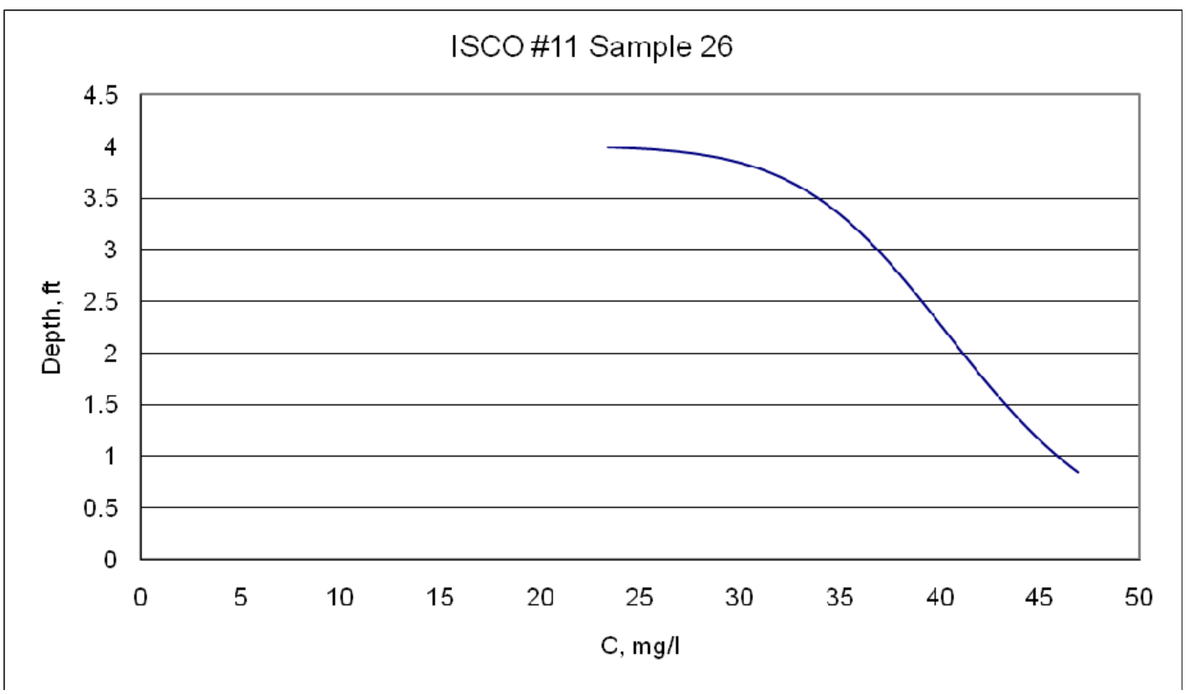


Figure 26 Typical Rouse Profiles for ISCO Samples

Table 11 ISCO 11 Concentrations and Simulated Flows

ISCO 11				
Flood Phase Values				
Date	**Model Time**	**Flow**	**Corrected Flow**	**Concentration**
yyyymmdd	***hh:mm***	***cfs***	***abs(cfs)***	***mg/l***
20090122	16:18	-634.439	634.439	114.3
20090122	17:18	-726.611	726.611	91.0
20090122	18:18	-713.658	713.658	74.8
20090122	19:18	-643.666	643.666	68.8
20090122	20:18	-454.005	454.005	74.2
20090122	21:18	-276.441	276.441	67.7
20090122	22:18	-336.306	336.306	79.6
20090122	23:18	-174.013	174.013	73.0
20090123	4:18	-9.646	9.646	82.6
20090123	15:18	-22.309	22.309	156.9
Ebb Phase Values				
20090123	0:18	321.263	321.263	63.5
20090123	1:18	1145.162	1145.162	68.3
20090123	2:18	843.301	843.301	65.3
20090123	3:18	324.63	324.63	68.3
20090123	5:18	405.247	405.247	99.4
20090123	6:18	964.023	964.023	83.8
20090123	7:18	843.83	843.83	169.4
20090123	8:18	678.382	678.382	85.6
20090123	9:18	707.439	707.439	161.6
20090123	10:18	840.583	840.583	171.8
20090123	11:18	484.133	484.133	370.6
20090123	12:18	259.858	259.858	283.2
20090123	13:18	216.106	216.106	148.5
20090123	14:18	133.689	133.689	115.5

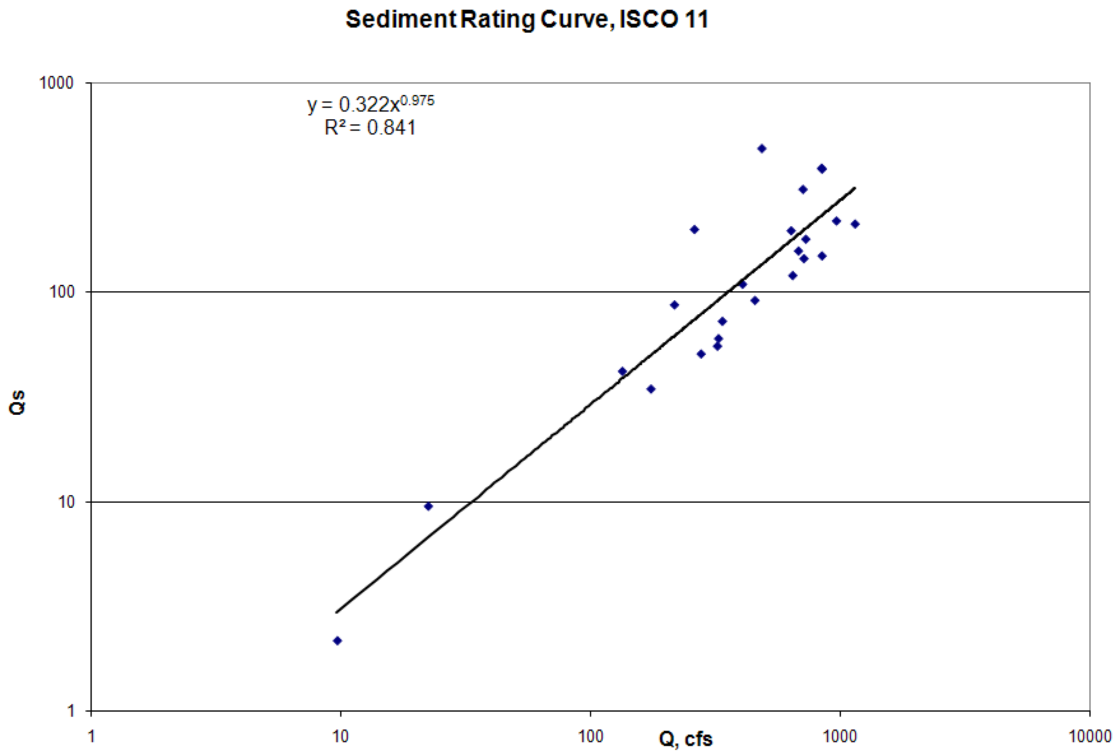


Figure 27 Sediment Rating Curve ISCO 11

Table 12 ISCO 10 Concentrations and Simulated Flows

ISCO 10				
Flood Phase Values				
Date	**Model Time**	**Flow**	**Corrected Flow**	**Concentration**
mm/dd/yyyy	***hh:mm***	***cfs***	***abs(cfs)***	***mg/l***
1/22/2009	16:15	127.035	127.035	1221.3
1/22/2009	17:15	469.916	469.916	2206.2
1/22/2009	18:15	293.612	293.612	2280.3
1/22/2009	20:15	145.733	145.733	4005.2
1/22/2009	21:15	421.137	421.137	10896.1
1/22/2009	22:15	301.742	301.742	6807.1
1/22/2009	23:15	179.266	179.266	2539.2
1/23/2009	0:15	468.607	468.607	1756.4
1/23/2009	1:15	208.478	208.478	2234.6
1/23/2009	2:15	115.056	115.056	997.6
1/23/2009	3:15	70.649	70.649	555.3
1/23/2009	4:15	39.568	39.568	142.9
Ebb Phase Values				
1/23/2009	5:15	-123.949	123.949	178.9
1/23/2009	6:15	-232.114	232.114	176.6
1/23/2009	7:15	-162.641	162.641	*134.0*
1/23/2009	8:15	-376.704	376.704	*131.0*
1/23/2009	9:15	-274.176	274.176	*251.4*
1/23/2009	10:15	-253.371	253.371	*349.5*
1/23/2009	11:15	-305.64	305.64	*855.4*
1/23/2009	12:15	-217.238	217.238	*428.1*
1/23/2009	13:15	-225.833	225.833	*269.4*
1/23/2009	14:15	-230.946	230.946	*308.3*
1/22/2009	19:15	-75.872	75.872	*3036.1*

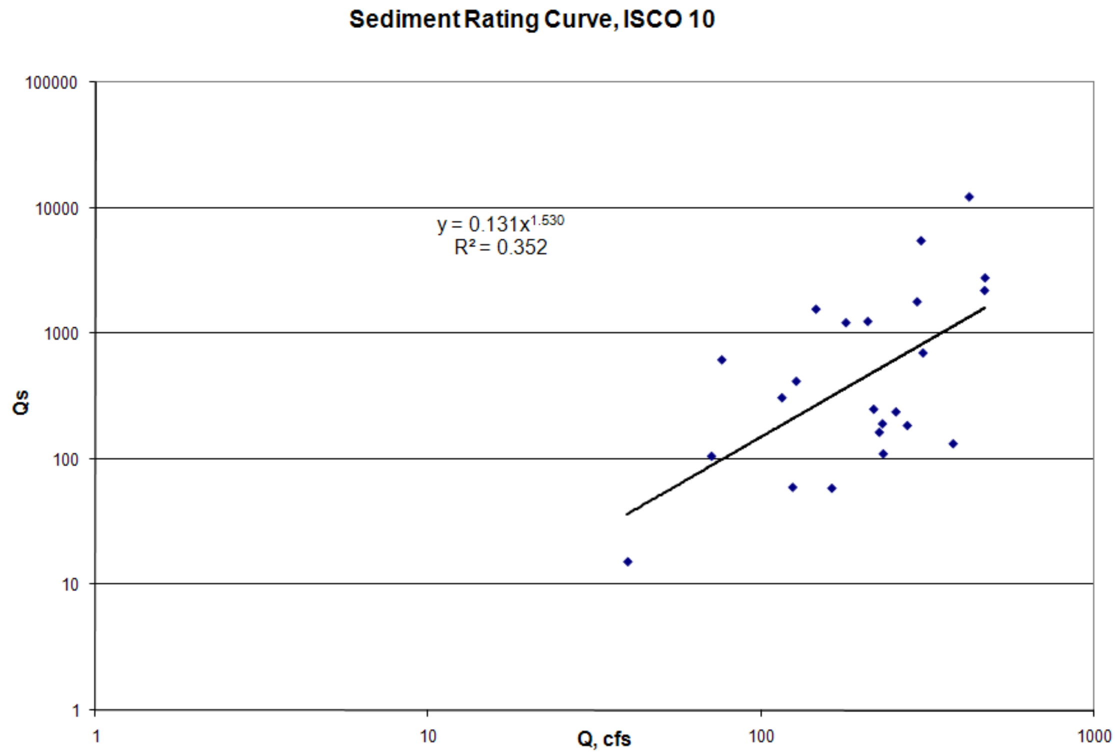


Figure 28 Sediment Rating Curve ISCO 10

With rating curves inside the Port it is now possible to construct a local sediment budget. This is done in similar fashion to that of the Pearl River sediment budget, only limited to the Port. With the only sediment flux located at the entrance of the Port, so only the sediment inlet calculator will be used.

9.3. Sediment Flux Estimates in the Port

Using the curves created from the ISCO samples as well as the previous curves from the USGS station, sediment flux across the port entrance is calculated based on the tidal data from the ADH model by using it in the inlet flux calculator. The sediment rating curve from ISCO 10, used with the mean tidal exchange flow from ADH, produced an incoming value of 35,000 tons/year (see Table 13). This is probably due to the uncertain quality of collected samples that had high sediment concentrations. However, it is in agreement with the estimated amounts of deposition from the sediment budget and shows the required high concentrations for the Tier 1 and 2 estimates. Application of the sediment rating curve for ISCO 11 estimated a lower net deposition of 4,300 tons/year. Lower still are the estimated fluxes from the rating curves based on the USGS data; here the entrance flux is estimated to cause 350 to 500 tons/year deposition. Further resolution and evaluation of the discrepancy to determine the location of deposition is conducted with the Port's sediment trap efficiency.

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Table 13 Sediment Fluxes through the Ports Entrance

Port Entrance Sediment Flux			
	Coefficients		Shoaling
Rating Curve	A	B	tons/year
2489500	0.0009	1.6022	**-357**
Lower Pearl HUC	0.0025	1.4766	**-503**
ISCO 11	0.322	0.975	**-4300**
ISCO 10	0.131	1.53	**-35000**

9.4. Trap Efficiency for Port

A Port's sedimentation tendency is directly related to the following equation (PIANC 2008).

$$\text{Siltation Rate} = pQc_a \qquad \text{Equation 7}$$

Where: p = basin trapping efficiency

Q = rate of water exchange between the harbor basin & surrounding water

c_a = ambient suspended sediment concentration outside the harbor.

Siltation can be reduced by minimizing one of the three terms in the above equation. A reduction in ambient suspended sediment is possible by directing sediment-laden flow away from the Port. Additionally, minimizing the water exchange rate will keep sediment out of the Port. This can be accomplished by rerouting the flow, or changing the entrance geometry of the basin. Further harbor siltation reduction is achieved by reducing the basin's trap efficiency and can be accomplished by the installation of sediment traps, the use of bubblers, or realignment of basin entrance.

The probability of entrapment of the sediment in the Port is estimated using the following equation:

$$p = 1 - e^{\left(-\frac{W_s}{h}\left[1-\left(\frac{u}{u_c}\right)^2\right]_{Basin} T_h\right)} \qquad \text{Equation 8}$$

Where:

p = Trapping Efficiency

W_s = Sediment Settling Velocity

h = Basin Water Depth

u = Average Basin Velocity

u_c= Critical Velocity for Sedimentation

T_h= Horizontal Residence Time V/Q

V= Basin Volume
Q= Discharge through Harbor Entrance

Equation 8 is used in Equation 7 to calculate the shoaling rate of the Port. From these two equations it is found that the Lower Port has negligible entrapment probability while the Upper Port and Spur of the Port experience an entrapment probability of 0.36 and 0.74 respectively. This results in a yearly deposition of the Upper Port and Spur of 80 and 130 tons/year respectively, and coincides with the sediment flux estimated at the Ports entrance using the USGS data. Furthermore, it indicates that shoaling occurs at the upper end and Spur of the Port

9.5. Port Shoaling Process

From the gathered and calculated information a hypothesis for port sedimentation processes is formulated. As shown by the collected TSS samples a gradual increase in the Ports sediment concentration profile with respect to length helps to support the possibility of fluid mud formation in the upper Port. Tidal action pushes fine sediment into the Port and then it gradually settles as fluid mud and slowly flows back down the length of the Port during ebb tide. Then when flood tide occurs the fluid mud is driven back into the Port only to continue the cycle. The continual formation of fluid mud is increased by intermittent times of agitation from vessels, tides, and wind followed by periods of typical settling.

9.7. Port Shoaling Volumes and Cost of Dredging

The several calculated values associated with the potential shoaling in the Port were initially estimated in the process from the SBT to be 42,000 to 100,000 tons/year respectively. However, these amounts are not concrete since they are based on an open river system calculated from rating curves upstream in the watershed and outside the tidal influence. The two rating curves in the Port from the ISCO water samples indicated a deposition amount of 4,000 to 35,000 tons/year. The second higher value is the result of integrated suspended sediment samples with concentrations of 140 – 11,000 mg/l (ISCO 10) and is clearly in the range for fluid mud. If we assume that fluid mud is transported in the bottom 5 – 15% of the flow depth and that the rating curve associated with the high concentrations represents a system with purely fluid mud only, then it is estimated that approximately 15% of the 35,000 tons/year is the bed load amount. This yields a value of 5,250 tons/year of bed load. Since it contains all integrated suspended sediment concentrations less than 170 mg/l then it is assumed that ISCO 11 curve appropriately represents the suspended load. Combining the two values produces a total yearly deposition amount of 10,000 tons/yr and is the value that is used as the basis for Port

Dredging alternatives. More importantly, if this is correct, then 50% of the total load is transported as fluid mud.

With an estimate for the amount of volume of sediment depositing, the cost of removing it from the Port is also estimated. Based on the volume and the cost of dredging in the Port of Pascagoula it is reported that in 2005 the Bayou Casotte Harbor was dredged for a cost of \$4.90/yd^3 (Johnson 2008). Depending on the composition of the material and its SG this would cost the Port on average about \$40,000 to \$50,000/year. Calculations, based on the inlet flux calculator and changing only the inlet geometry and exchange, indicated that if the port were deepened to a depth of 20 ft + 2 then the volume of dredging would increase by 75% effectively doubling the cost of current dredging requirements.

10. Recommendations

Given the estimated amount and assumed location of deposited sediment in the Port several recommendations are possible. However, only a few are practical. One that is not easily done but would produce the most benefit is a Port design where recirculation of flow could be achieved. Recirculation would allow the system to flush itself of sediment on a daily basis. With only one entry for flow and no major freshwater influx, shoaling is enhanced. Correcting this issue might cause major environmental impacts and be cost prohibitive for dredging reduction alone. A more realistic solution is the placement of a sediment trap designed so that the fluid mud could flow into the trap reducing the required dredged area and regularity of dredging. For a more immediate solution agitation of the fluid mud during the ebb phase of the tide is recommended. Agitation can be achieved by either a drag or prop wash.

10.1. Sediment Trap

Although simple in concept the sediment trap if placed correctly is an effective method for keeping sediment out and confining it. As shown in Figure 29 the sediment trap can be located at the junction of the spur, main channel, and the exiting bayou. The dimensions of the trap are 4 feet deep, 300 feet long and 900 feet wide. The trap is designed to hold approximately 40,000 cu yds, and could potentially limit dredging to every 4 years if the trapped material's SG is 1.1 (fluid mud) or every 5 years if the trapped material's SG is 1.6 (typical sediment). Furthermore, since sediment will migrate to the trap dredging would be confined only to the location of the trap which is ideal since the dredge could maneuver into the Bayou for passing vessels and reduce Port downtime.

To direct fluid mud into the trap the main channel would be sloped on a 0.0004 ft/ft grade with the spur having a slope of 0.0016 ft/ft. Theoretically these slopes would produce enough vertical gradient difference to drive the fluid mud into the trap. Also by increasing the bed slope, the draft of the port would be deepened, further increasing the interval between required dredging. The sloped bed on the main channel would extend from the mouth of the Port to the trap. Here it would be sloping away from the trap to direct sediment into the Pearl River (see Figure 30). Then from about midway into the Port, sloped in the direction of the trap, the main channel would be contoured to direct fluid mud into the trap from the upper port (see Figure 30). In the spur a sloped bed, sloped toward the trap, would extend the main length of the spur to the trap (see Figure 31). For the Bayou the slope would be directed seaward away from the sediment trap and have a grade of 0.0033 ft/ft so that the majority of the sediment would be flushed out of the canal (see Figure 32). Prior to implementing the sediment trap a detailed study of the required slopes is recommended such that the pressure gradient is capable of driving the fluid mud into the trap. Since sloped dredging is impractical, a series of steps can be dredged to create the approximate slope needed.

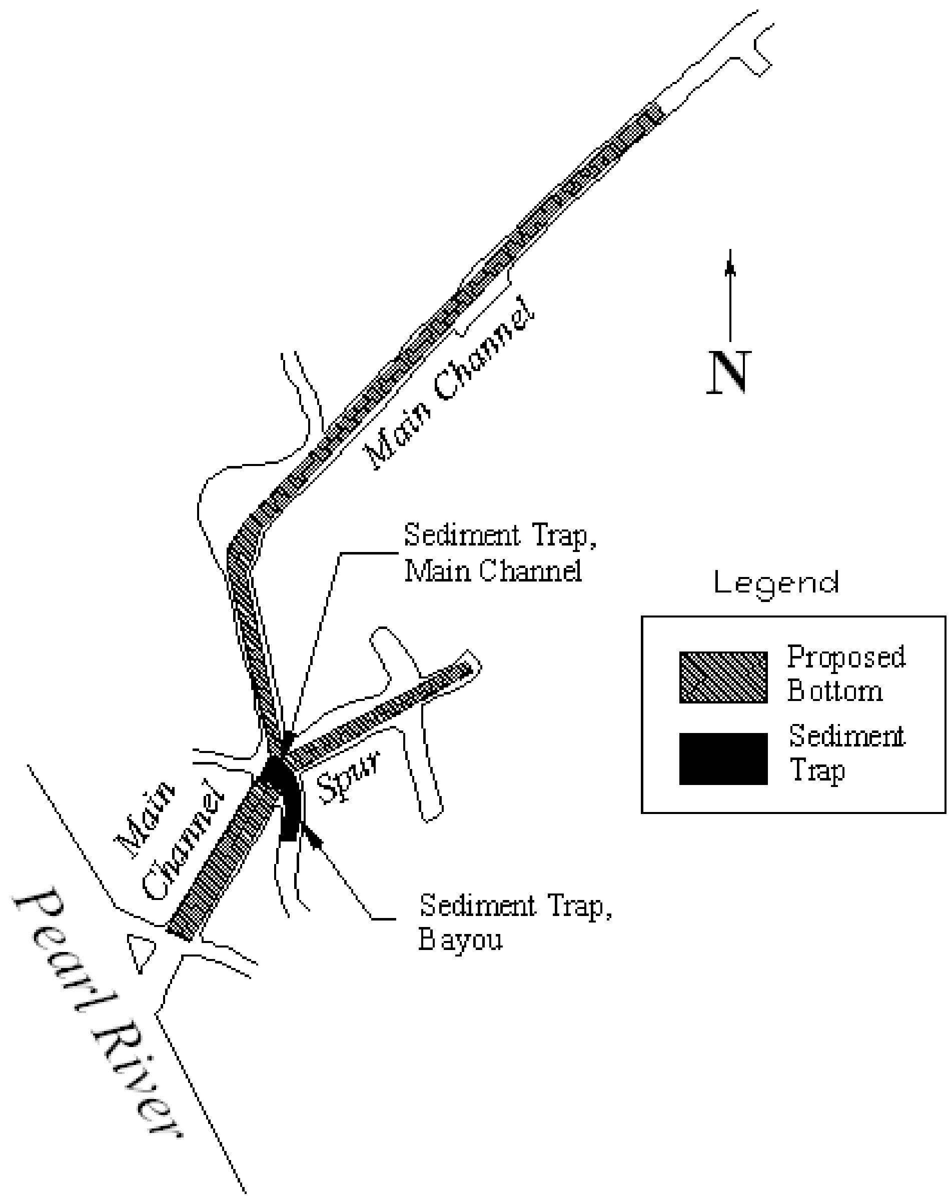


Figure 29 Sediment Trap Location

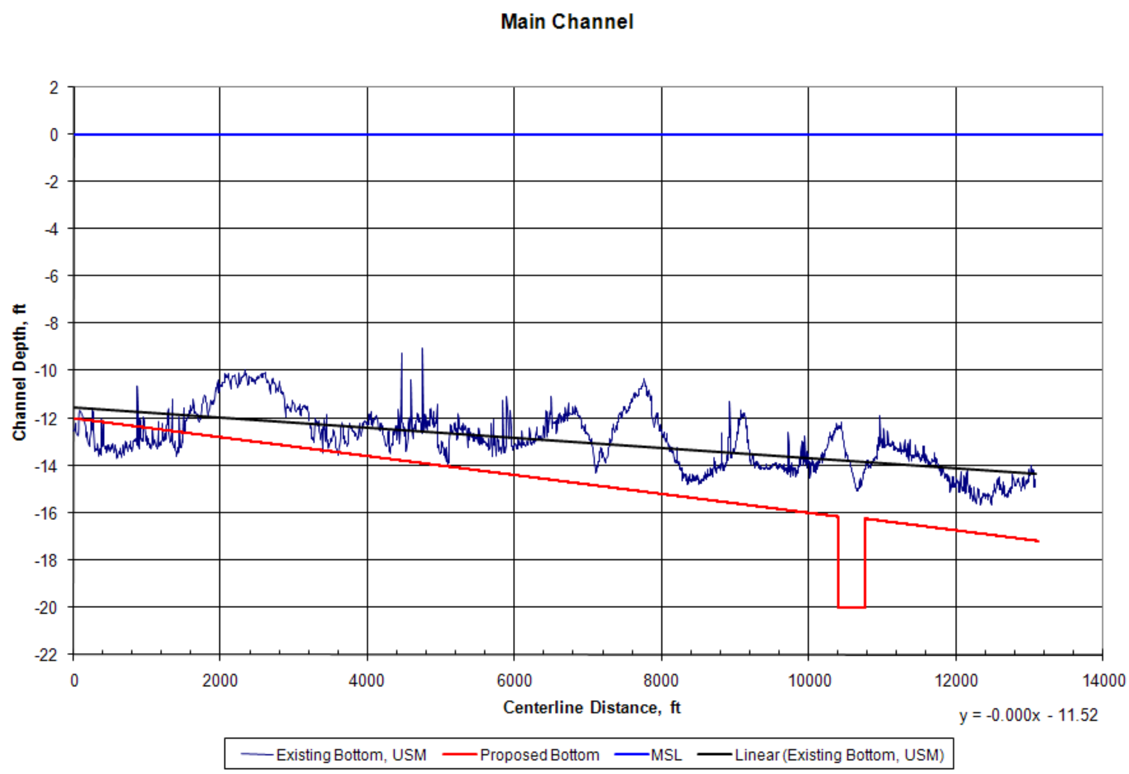


Figure 30 Sediment Trap Profile for Main Channel

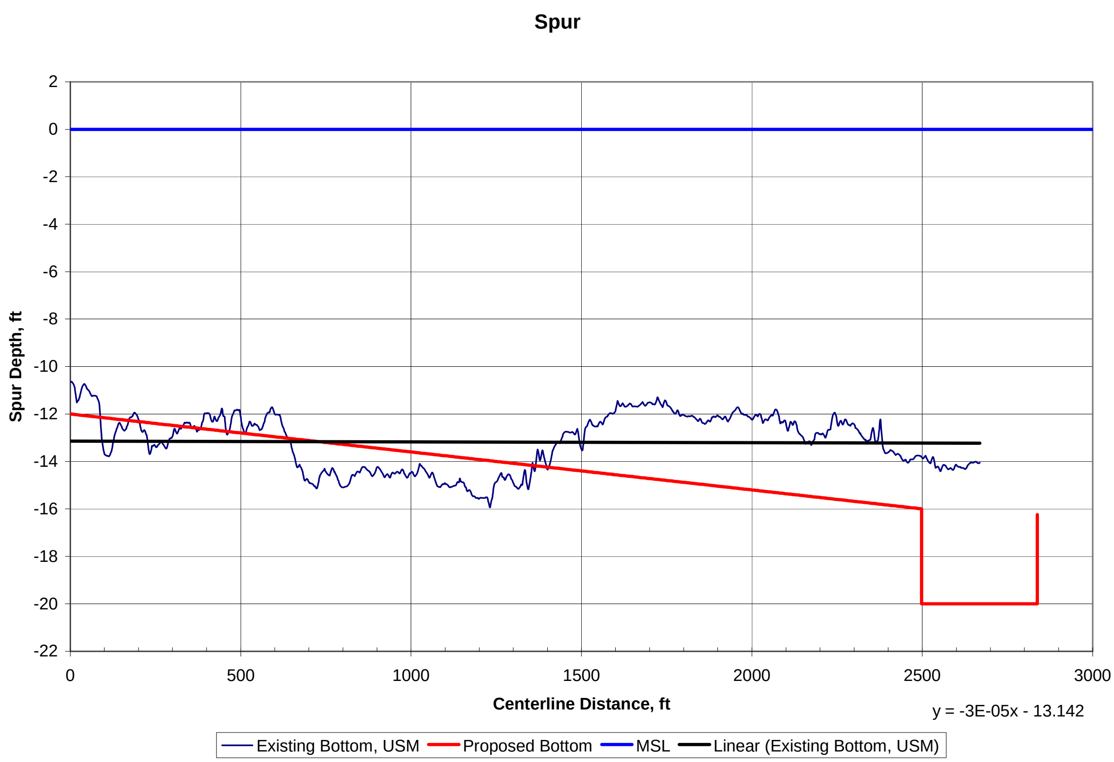


Figure 31 Sediment Trap Profile for Spur

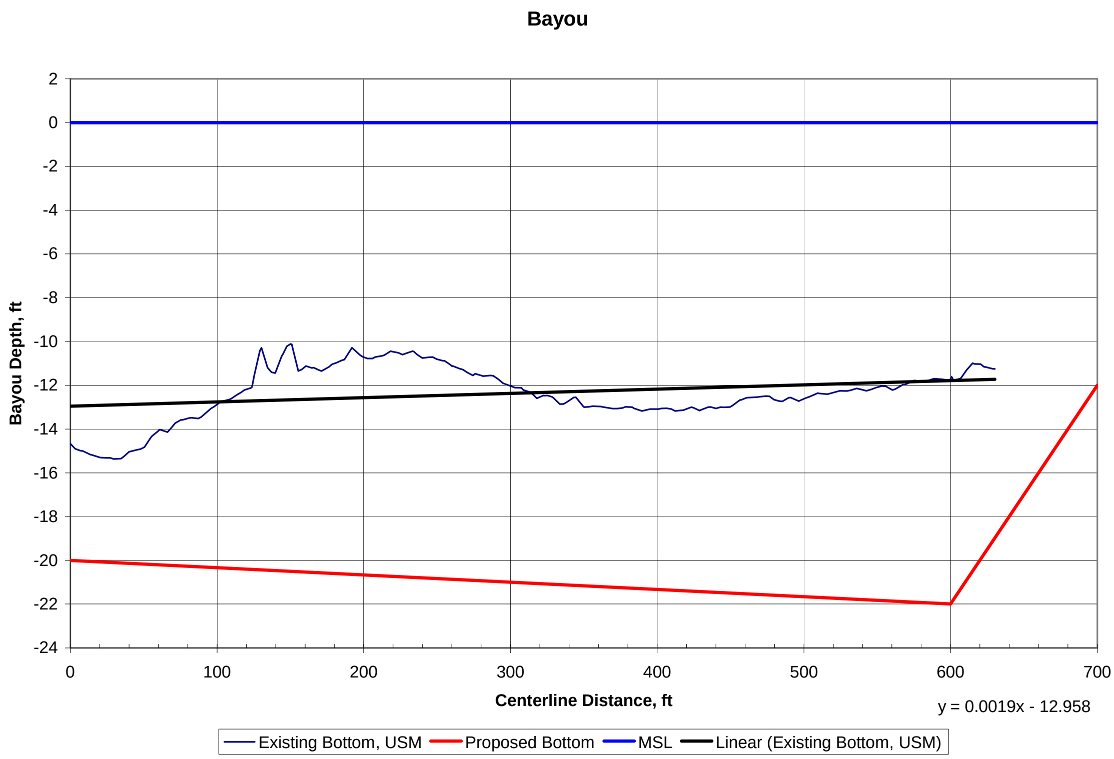


Figure 32 Sediment Trap Profile for Bayou

10.2. Agitation

An alternative to the construction of a sediment trap is harbor agitation during the ebb tide, which has been proven effective in some locations (PIAC 2008). Fundamentally all agitation does is use a drag or tugboat propwash to resuspend fluid mud into the main water column such that the ebb phase of the tide can remove it from the system. Using a 2000 HP tugboat and the current cost of fuel the annual cost of operating the vessel for a four hour period during ebb tide would cost an estimated $45,000 a year (based on modified estimates from Hunter 2008). Though this price is roughly the same cost of dredging, there is no dredge mobilization/demobilization cost s. If there is not a vessel available then the Port could encourage vessel passage to occur during ebb tide. Even if this was not fully implemented partial use could help keep some of the sediment from depositing.

11. Conclusions

Although sediment deposition is an issue it does not appear to be the primary one hindering the Port of Bienville's optimum use. Rather, improving the Port's access is more imperative. Faster, safer access is possible if the East Pearl River seaward of Little Lake is modified such that the vessels pass through this section of river. The major issue with directing traffic through the proposed route is the CSX Railroad Bridge. Modifications to the bridge or relocation are needed for this pass to be the most effective route, but once implemented the usability of the Port increases as well as future possible expansion both in vertical and horizontal clearances.

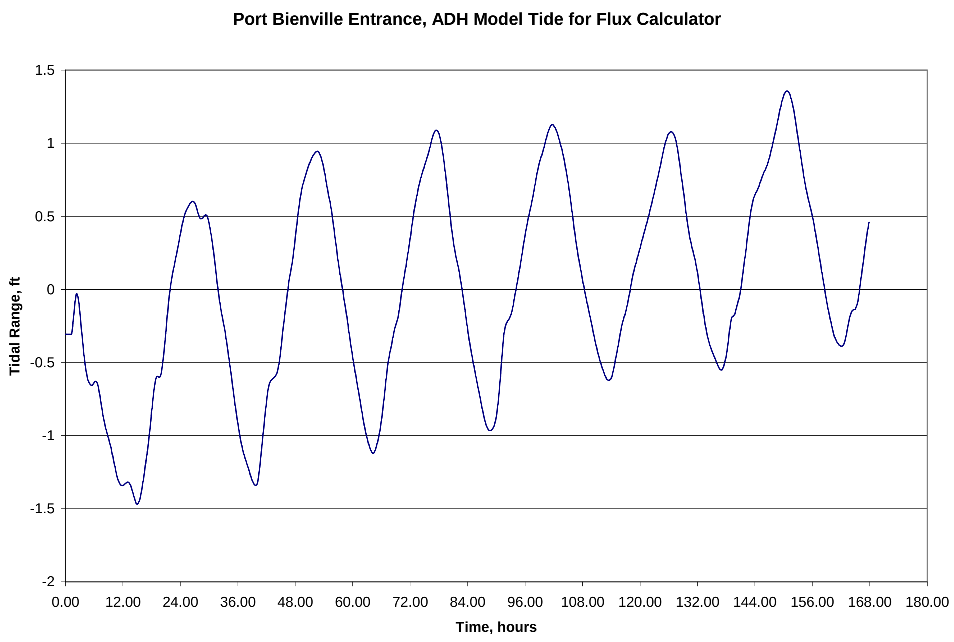
Although dredging data are limited an attempt is made to quantify the amount of depositing sediment. From the use of several methods that included regional and local rating curves developed from USGS data and locally collected samples it is determined that approximately 10,000 tons/year of sediment is depositing in the Port. The Primary form of deposition is fine sediment forming fluid mud by initially being entrapped in the port. The fines form flocs which settle and form fluid mud. Once in formation the only fluid mud that will escape is any that has been re-entrained and then flushed by the ebb tide. The process of fluid mud formation is a continual one that varies in magnitude determined by several controlling factors primarily being tidal range, fresh water flow, sediment supply, and degree of Port agitation all of which must be closely examined prior to the final design and implementation of a dredging solution.

A sediment trap and agitation dredging will decrease dredging costs by extending the period between required dredging; however, currently the deposited volumes are not large enough to merit implementation of any of the proposed design solutions. However, upon future expansion of the Port it is recommended that dredging alternatives outlined in this paper are explored in the design phase to determine the cost saving advantages of the proposed solutions.

Appendix A: Calculations

Port Bienville Inlet Area, Inlet Flux Calculator					
Length	**Depth**	**f(x)**			
33	0	0		**Minimum =**	33
125.618	-8.852	-17.70		**Maximum =**	475.442
138.49	-10	-20.52			
161.533	-11.426	-22.85		**n =**	44.2442
245.4	-14.782	-29.56			
316	-13	-26.32			
367	-11.4	-22.80			
438	-5.935	-11.87			
460	-4	-8.11			
475	-4.876	-4.88			
	Inlet Area	**3,642**	ft^2		

Port Bienville Inlet Flux Calculator Parameters					
Cross-section area of inlet @ MSL =	3642	cf	Mannings =	0.03	
Top width of inlet @ MSL =	475	ft	Slope =	0.000001	ft/ft
Sediment Differential =	1.16		Depth @ MSL =	14	ft
Mean River Flow, Q =	0	cfs	Sea Water Density =	64.4	lbs/cf
			Critical Shear =	0.001045	lbs/sf
			K =	0.25	



Location	Velocity, ft/s	Average, cfs
Total Avg	0.056	
PT6	0.116	0.080
PT7	0.057	
PT8	0.081	
PT9	0.106	
PT10	0.063	
PT11	0.057	
PT12	0.037	0.021
PT13	0.016	
PT14	0.009	
PT15	0.015	0.015

Figure A1 Locations of Model Velocities

Trap Efficiencies for Spur and Upper Port

Spur				
Ws	9.84E-05	ft/s	uc	0.023269
h	12.9	ft	Th	276190.1
u	0.014	ft/s		
V	19333308	cf	**P =**	**0.739233**
Q	70	cfs		
Critical Shear	0.001045	lbs/sf		
Density	1.93	lbs/cf		

Upper Port				
Ws	9.84E-05	ft/s	uc	0.023269
h	11.7	ft	Th	251177.8
u	0.0207	ft/s		
V	28383096	cf	**P =**	**0.356425**
Q	113	cfs		
Critical Shear	0.001045	lbs/sf		
Density	1.93	lbs/cf		

Shoaling Rates for Spur and Upper Port Based on Trap Efficiencies

Spur					
TR =	1.86	ft	Tidal Vol. =	2996663	cf
A =	1611109	sf	Flow Exchange =	67.03943	cfs
Ca =	89	mg/L			
Conversion =	1.12E-06		**SR =**	**4.25E+02**	lbs/day
P =	0.739233				

Upper Port					
TR =	1.867	ft	Tidal Vol. =	4415937	cf
A =	2365258	sf	Flow Exchange =	98.79053	cfs
Ca =	200	mg/L			
Conversion =	1.12E-06		**SR =**	**6.79E+02**	lbs/day
P =	0.356425				

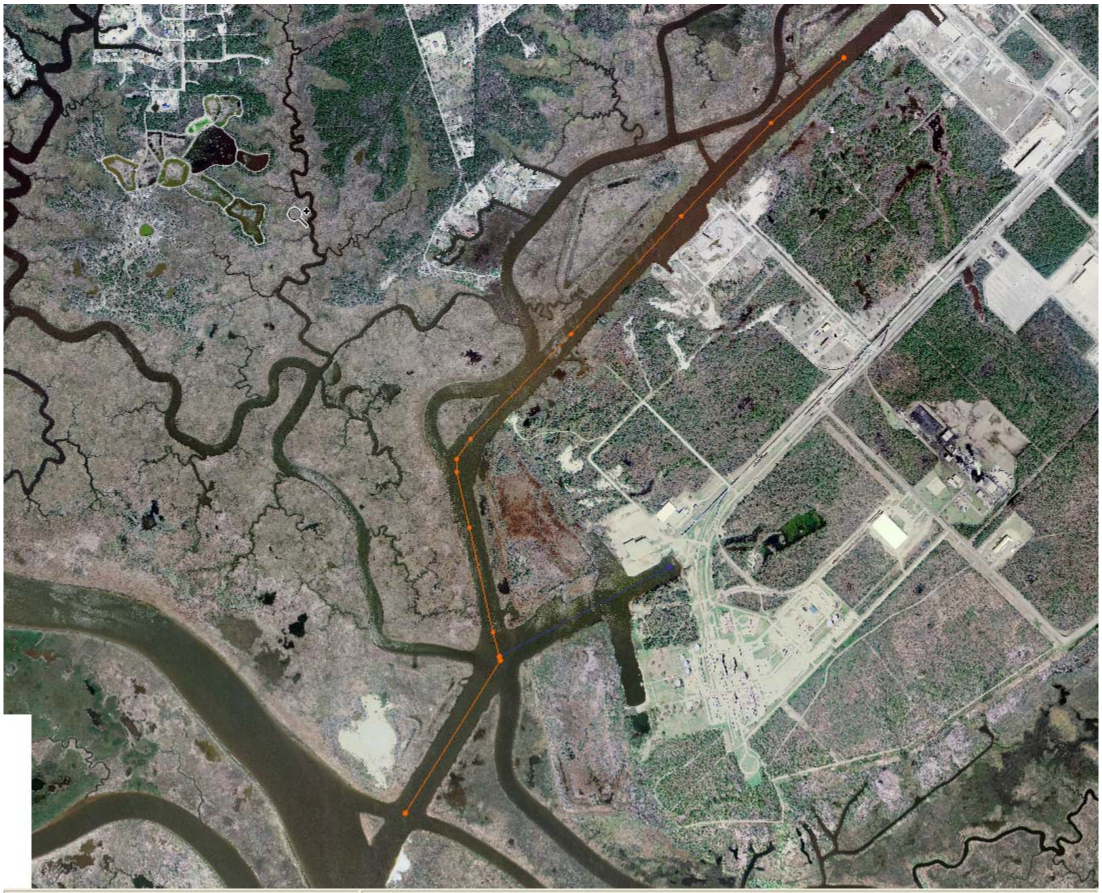
Trap Efficiencies for Lower Pearl

Lower Port

Ws	9.84E-05	ft/s	uc	0.023269
h	15	ft	Th	179101.6
u	0.08	ft/s		
V	83640470	cf	**P =**	**-331904**
Q	467	cfs		
Critcal				
Shear	0.001045	lbs/sf		
Density	1.93	lbs/cf		

Lower Port

Ws	9.84E-05	ft/s	uc	0.023269
h	15	ft	Th	76925.19
u	0.07	ft/s		
V	35924066	cf	**P =**	**-57.0988**
Q	467	cfs		
Critcal				
Shear	0.001045	lbs/sf		
Density	1.93	lbs/cf		


(743664.0, 266946.0)


(743297.0, 260620.0)

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