Sedimentation Management Alternatives for the Port Of Pascagoula

Hunter Neal Johnson, William H. McAnally, and Sandra Ortega-Achury
Civil and Environmental Engineering
James Worth Bagley College of Engineering
Mississippi State University

Prepared for Mississippi Department of Transportation

February 2010

Executive Summary

The purpose of this project is to develop proposed solutions to reduce the Port of Pascagoula dredging costs.

The Port of Pascagoula is located in Jackson County, Mississippi, in the southeastern portion of the state. It is the largest port in Mississippi and ranks in the top 20 ports for foreign cargo volume in the United States (JCPA 2007). The West Harbor, also known as the Pascagoula River Harbor, is located at the mouth of the Pascagoula River about 13 miles from the deep water shipping lanes. The West Harbor’s channel has a design depth of 38 ft. and contains 5 terminals. The East Harbor, also known as the Bayou Casotte Harbor, is located about 11 miles from the deep water shipping lanes. The harbor has a design depth of 42 ft. and a turning basin that is 940 ft. wide.

A large portion of the port access is designated a Federal channel and managed by the United States Army Corps of Engineers. The port authority is responsible only for the maintenance and dredging of the areas that they directly manage. While the focus of this report is the Jackson County Port Authority’s maintenance requirements, both the port and Federal maintenance requirements must ultimately be addressed together since they are contiguous. The local channel in the Bayou Casotte harbor needs to be dredged every 48 to 72 months and the local channel in the Pascagoula River harbor needs to be dredged every 18 months in order to maintain full channel dimensions. The Corps of Engineers Mobile District estimates that 3.06 million cu m of dredged materials from the Federal shipping channels will need to be removed and disposed of every 3 years for the next 40 years.

Dredged sediment from the port and access channels is mostly fine, cohesive material, often forming fluid mud – a high concentration fluid-sediment suspension at the bed that can flow downslope. Filed measurements and analyses of hydrographic surveys have shown where sedimentation problems occur first and that fluid mud formation is a primary component of the problem.

Recommended solutions include agitation dredging, a fluid mud trap, and the practice of active nautical depth, with active nautical depth, a practice employed in several European ports, offering the greatest potential cost savings. Adopting active nautical depth in partnership with the Corps of Engineers is recommended.

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.

Mr. Hunter N. Johnson, now employed at the U.S. Environmental Protection Agency, led this effort under the supervision of W. H. McAnally. Ms. Sandra Ortega-Achury participated in the preparation of this report and performed most of the laboratory analyses.

The authors extend their thanks to the Port of Pascagoula and U. S. Army Corps of Engineers Mobile District for generous sharing of their data and time.

Contents

1. Introduction

Ships have become larger in order to efficiently carry as much cargo as possible. Many port facilities are not naturally deep enough to accommodate these deeper draft vessels and so they require maintenance dredging to remove depositing sediment which reduces available depth. Many facilities dredge when the sediment build-up becomes a problem, but do nothing to prevent the problem from recurring. An increase in dredging costs and limitations on dredging and disposal of dredged material has increased interest in alternatives that prevent or reduce deposition of sediment in port facilities.

1.1 Purpose

The purpose of this project is to develop proposed solutions to reduce the Port of Pascagoula dredging costs.

1.2 MDOT Port Sediment Solutions – Gulf Coast

The Mississippi Department of Transportation (MDOT) tasked Mississippi State University (MSU) to examine the public ports that serve Mississippi's Gulf Coast for sedimentation problems which interfere with shipping operations. The four major public ports on the Mississippi Gulf Coast, are the Port of Bienville, Port of Biloxi, Port of Gulfport, and the Port of Pascagoula, as are pictured in Figure 1-1.

The project is also concerned with other aspects of sedimentation problem -- "the expense of dredging and disposal of sediment, and friction with shippers, who cannot transit and/or berth vessels in areas where sedimentation has reduced the depth available for navigation and loading/unloading" (MDOT 2007). The final goal of the project is to recommend engineering solutions that will reduce or eliminate each ports dependency on dredging for maintenance purposes.

The largest port on the Mississippi Gulf Coast is the Port of Pascagoula, which is the subject of this report.

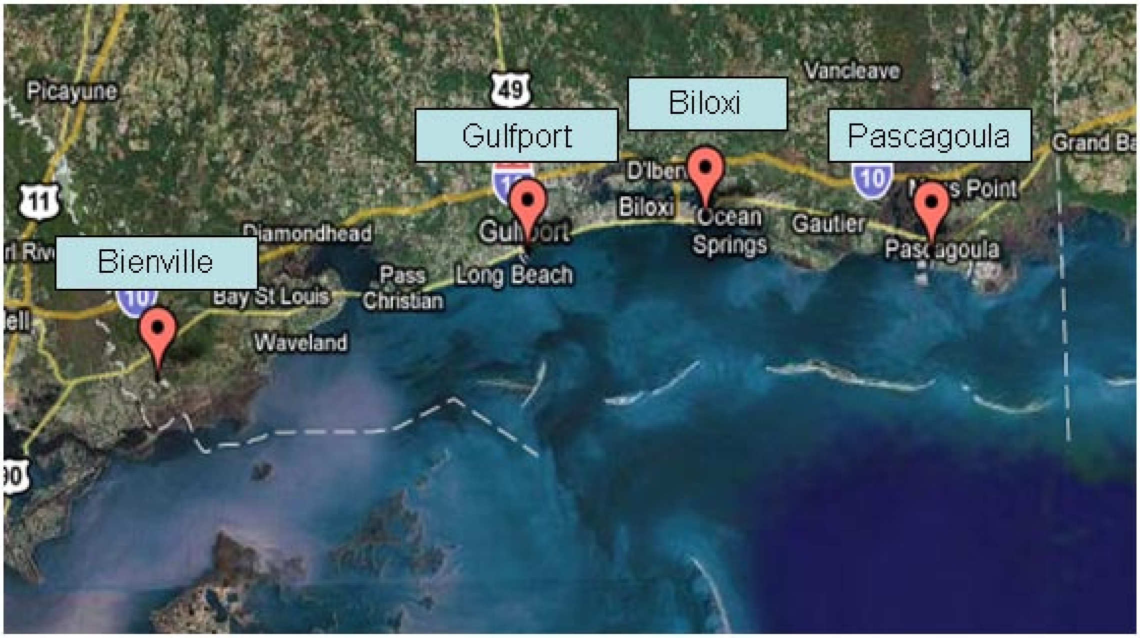


Figure 1-1 Ports of the Mississippi Gulf Coast (Adapted from Google Earth 2008)

1.3 Approach

The work presented here was completed in three different phases. In the first phase preliminary research was done to gather background information on the Port of Pascagoula by talking to individuals that had first-hand information on the port and searching for studies and projects that had been previously conducted on the design and maintenance of the port. The second phase of the research involved identifying problem areas in the harbors of the port. Once these problem areas were identified a field investigation was conducted to gather additional information about the sites. In the third and final phase, analysis was done on all the information that was collected in the first two phases in order to identify effective solutions to the Port of Pascagoula's sedimentation problems.

2. Sediment Transport

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.

2.4 Fluid Mud

Fluid mud, observed in many ports and waterways, is defined as “a high concentration aqueous suspension of fine-grained sediment in which settling is substantially hindered by the proximity of sediment grains and flocs, but which has not formed an interconnected matrix of bonds strong enough to eliminate the potential for mobility" (McAnally et al. 2007a). Despite the "mud" part of the name, fluid mud is just water with a very high concentration of suspended sediment – muddy water.

Fluid mud was originally thought to only be present in a few locations throughout the world, but it has been observed in numerous locations and is now known to be a common occurrence. Fluid mud normally forms in layers near the bottom of lakes, canals, estuaries, and other coastal waters but can occur in any water body that contains a sufficient amount of fine-sediments and experiences low intensity flow. These layers of fluid mud can be very thin or can be several meters thick depending upon the conditions at a given site. Its formation can be due to rapid settling of fine sediment flocs and to wave or vessel induced agitation of a soft mud bed. In lakes, bays, and estuaries, the coarser non-cohesive sediment tends to deposit upstream leaving the fine cohesive sediment, such as fluid mud, to be transported further downstream before it is deposited.

Since fluid mud, in many cases, is just an intermediate stage in the deposition process it can be directly linked to sediment build-up and shoaling problems. In some cases there is so much deposition from fluid mud that ports cannot dredge rapidly enough to keep the waterway clear. An example of this phenomenon is in the Atchafalaya Bar Channel, Louisiana. Many ports have problems with ships fathometers reading a false bottom from a density inflection in fluid mud. This can be problematic if ships believe that the waterway is too shallow for them to navigate safely, when it is deep enough but the fluid mud shows on the ship's fathometer as solid bottom.

Fluid mud has a density only slightly higher than water and vessels commonly sail through 3 to 10 ft thick layers in many world ports, including Rotterdam, as described in the following Section.

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, some of 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 one of three categories, which are an adaptation of those presented by PIANC (2008) , and are shown in Table 3-1.

Table 3-1. Sedimentation Solutions Categories

CATEGORY	**STRATEGY**	**EXAMPLES**
Prevention	KSP – Keep Sediment in Place	Erosion control on land and/or bed and banks
	KSO – Keep Sediment Out	Sediment Traps, Gates and Dikes, Channel Separations
	KSM – Keep Sediment Moving	Training Structures, Agitation, Flocculation Reduction , Flushing Flows
Treatment	KSN – Keep Sediment Navigable	Nautical Depth Definition, Aerobic Agitation
	DRS – Dredge and Remove Sediment	Placement in confined disposal facilities or offshore, Permanent beneficial uses
	DPS – Dredge and Place Sediment	Bypass sediment (KSM), Temporary beneficial uses
Accommodation	Adapt to Sediment Regime	Flexible infrastructure, opportunistic agriculture, coastal setbacks

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.

3.1.4 Methods that Keep Sediment Navigable

The name of this solution seems self contradictory, but is an economical solution practiced worldwide. It has been practiced for many years in some tropical ports and in the last 30 years has become commonplace in Europe. Recognition that fluid mud, described above, is really just extremely muddy water that will not harm vessels has led to new a new definition of channel depth, called “nautical depth.”

Nautical depth is typically defined as the distance from the water surface to a given suspension density, usually in the range of 1100 to 1300 kg/m^3. Extensive testing in Rotterdam and Antwerp harbors have shown that vessels can safely navigate through layers of fluid mud more than 6 ft thick as long as the suspension density is less that the specified value. Despite initial opposition, in 1976 the Port of Rotterdam adopted the concept of passive nautical depth, in which the port simply measures suspension density and maps the 1200 kg/m^3 density contour as the official water depth. That adoption hugely reduced total dredging cost since the port had to be dredged much less often and dredges can remove substantially greater sediment mass per hour of pumping (Kirby and Parker 1977; Parker and Kirby 1986; PIANC 2008).

A variety of field techniques have evolved to provide ready measurement of fluid mud density (McAnally et al. 2007b; PIANC 2008) and is an active subject of research and development at the Emden Centre for Sediment Innovation[1] (SICEM) and the U.S. Army Engineer Research and Development Center in Vicksburg Mississippi.[2]

Active nautical depth is a more recent solution, involving deliberate agitation of fluid mud to prevent it from consolidating into a sediment bed which must be dredged. It is believed that the combination of fluidization and reaeration of the fluid mud is key to this approach, so that incipient mud structure is disrupted and aerobic bacteria growth is facilitated. The result is a fluid mud cloud which need not be removed. (PIANC 2008)

---

[1] Personal communication with Dr. Robert Kirby of SICEM

[2] Personal communication with Mr. Tim Welp of ERDC.

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 Active Nautical Depth

Active nautical depth, described above, has been accomplished in Emden by using a hopper dredge that pumps fluid mud from the channel into the hoppers for aeration and then discharges it back to the channel. The method has been in successful use for more than 15 years and has reduced the annual dredging requirement from 4 million m^3 to zero (PIANC 2008).

At the port of Bremerhaven surface water is injected through a submerged diffuser manifold to accomplish floc breakage and oxygenation. During the 4 years it has been in use, standard dredge-and-remove has not been required.

Other agitation techniques and equipment may prove to be successful in establishing active nautical depth. Including some of those listed in section 3.2.1 above.

4. Port of Pascagoula

The Port of Pascagoula is located in Jackson County, Mississippi, in the southeastern portion of the state as shown in Figure 4-1. The Port is 32 miles west of the entrance to Mobile Bay, Alabama, and is 100 miles east of New Orleans, Louisiana. The Jackson County Port Authority governs the Port of Pascagoula. The entire facility consists of approximately 17 miles of channels for oceangoing vessels, about 10 miles of channels for barges and other shallow-draft vessels and 75 acres of terminal, 10.6 acres of which are hard surface loading areas. The facility also has 8 general cargo warehouses and 2 cold storage warehouses, which provide about 885,000 square feet of storage (JCPA 2007). The port consists of two separate harbors, the West Harbor located in the Pascagoula River, and the East Harbor located in Bayou Casotte. The Port of Pascagoula has 9 deepwater berths and one barge birth. Overall the Port of Pascagoula is the largest port in Mississippi and ranks in the top 20 ports for foreign cargo volume in the United States (JCPA 2007).

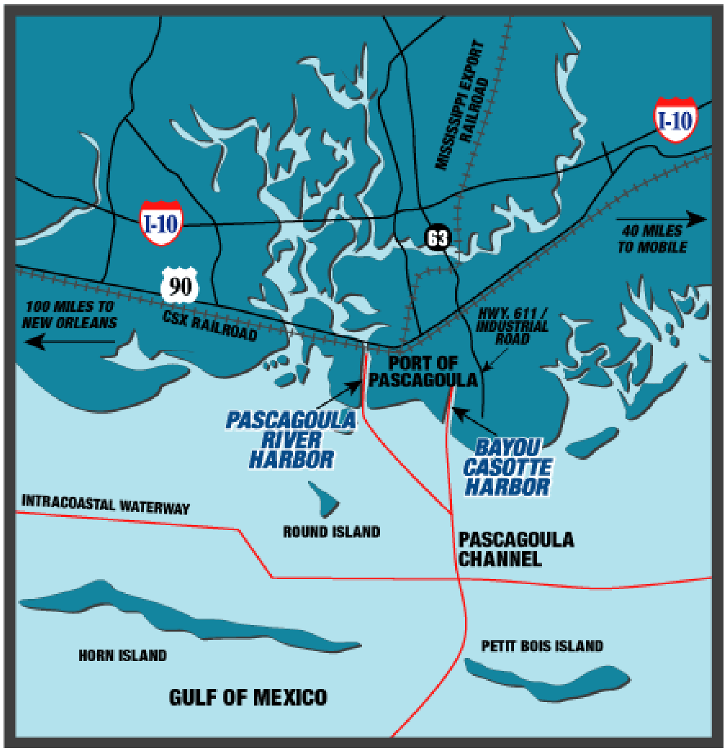
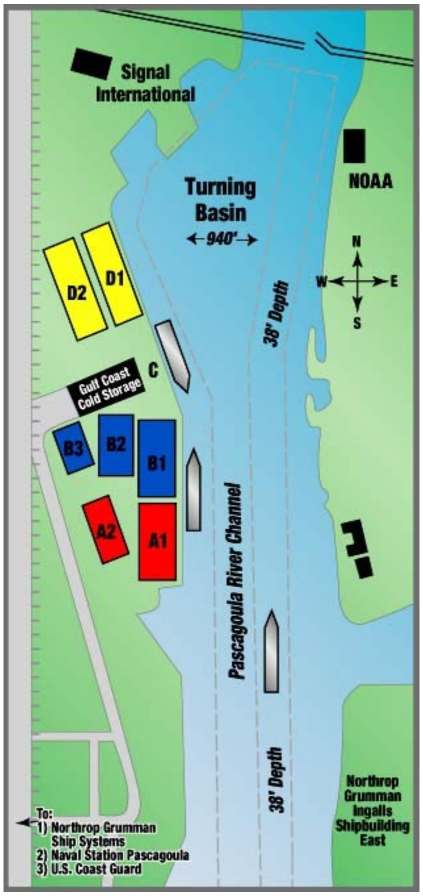


Figure 4-1 Port of Pascagoula (JCPA 2007)

4.1 Harbors of the Port of Pascagoula

The West Harbor, also known as the Pascagoula River Harbor, is located at the mouth of the Pascagoula River about 13 miles from the deep water shipping lanes. The West Harbor's channel has a design depth of 38 ft. and contains 5 terminals. The West Harbor is illustrated in Figure 4-2. The West Harbor's docks are located on the west bank of the harbor. As seen in Figure 4-2, Terminal D, depicted by yellow, is located at the northern end of the harbor and has a 500 ft. by 30 ft. wharf. Terminal B, depicted by blue, is a 544 ft. x 30 ft. wharf. Terminal C, located between Terminals B and D, has a cold storage facility and can accommodate vessels up to 718 ft in length. Terminal A, depicted by red, is a 500 ft. x 30 ft. wharf. The South Terminal Dock is located south of Terminal A and is a 800 ft. wharf which positioned next to the shipping channel.



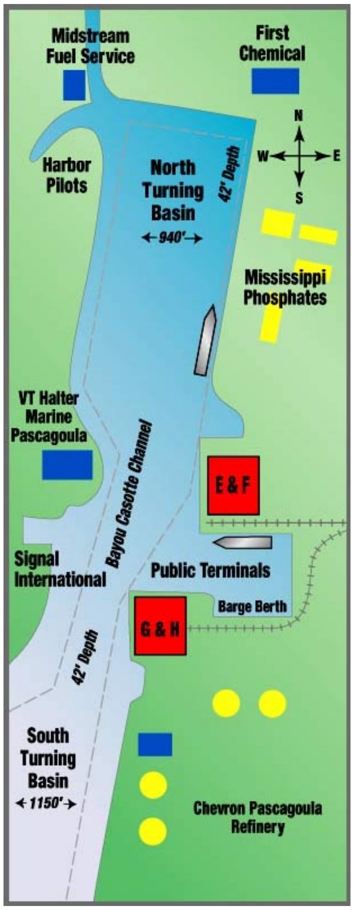


Figure 4-2 West Harbor (JCPA 2007)

Figure 4-3 East Harbor (JCPA 2007)

The East Harbor, also known as the Bayou Casotte Harbor, is located about 11 miles from the deep water shipping lanes. The harbor has a design depth of 42 ft. and a turning basin that is 940 ft. wide. The East Harbor, as seen in Figure 4-3, has a total of 4 terminals, which are all located on the eastern bank of the harbor. Terminals E and F are on the north end of the Bayou Casotte Channel. Terminal E has a 517 ft. x 37 ft. wharf, and Terminal F has a 737 ft. x 55 ft. wharf. Terminals G and H are both located on the southern side of the public terminals. Terminal G has a 516 ft. x 60 ft. wharf and a 695 ft. x 120 ft. barge berth, also Terminal H has a 556 ft. x 35 ft. wharf.

The Jackson County Port Authority is not responsible for dredging the entire facility. A large portion of the port access is designated a Federal channel and managed by the United States Army Corps of Engineers. The port authority is responsible only for the maintenance and dredging of the areas that they directly manage – much of the area along the west bank of the waterway, depicted by the dark gray area in Figure 4-4, and in Bayou Casotte the public terminal and the area surrounding it on the east side of the harbor, depicted by the dark gray area in Figure 4-5. The areas that are not shaded gray in Figures 4-4 and 4-5 are managed by the Army Corps of Engineers. While the focus of this report is the Jackson County Port Authority's maintenance requirements, both the port and Federal maintenance requirements must ultimately be addressed together since they are contiguous.

4.2 Sedimentation and Dredging History

In order to illustrate the sedimentation and dredging history, it will be necessary to discuss both the Federal and local channels. The Port of Pascagoula in both Federal and local channels experiences significant sedimentation and have been dredged on a regular basis. According to the Allen Moeller, the manager of the facilities at the Port of Pascagoula, the local channel in the Bayou Casotte harbor needs to be dredged every 48 to 72 months and the local channel in the Pascagoula River harbor needs to be dredged every 18 months in order to operate without problems. Over the years there has been frequent dredging of the Federal channels in the port and in the shipping channel, which connects the port to the Mississippi Sound, as shown in Table 4-1. There are plans for future dredging that would increase the depth of the Pascagoula River harbor channel from 38 ft. to 42 ft. This dredging could affect both the Federal and locally managed portions of the harbor.

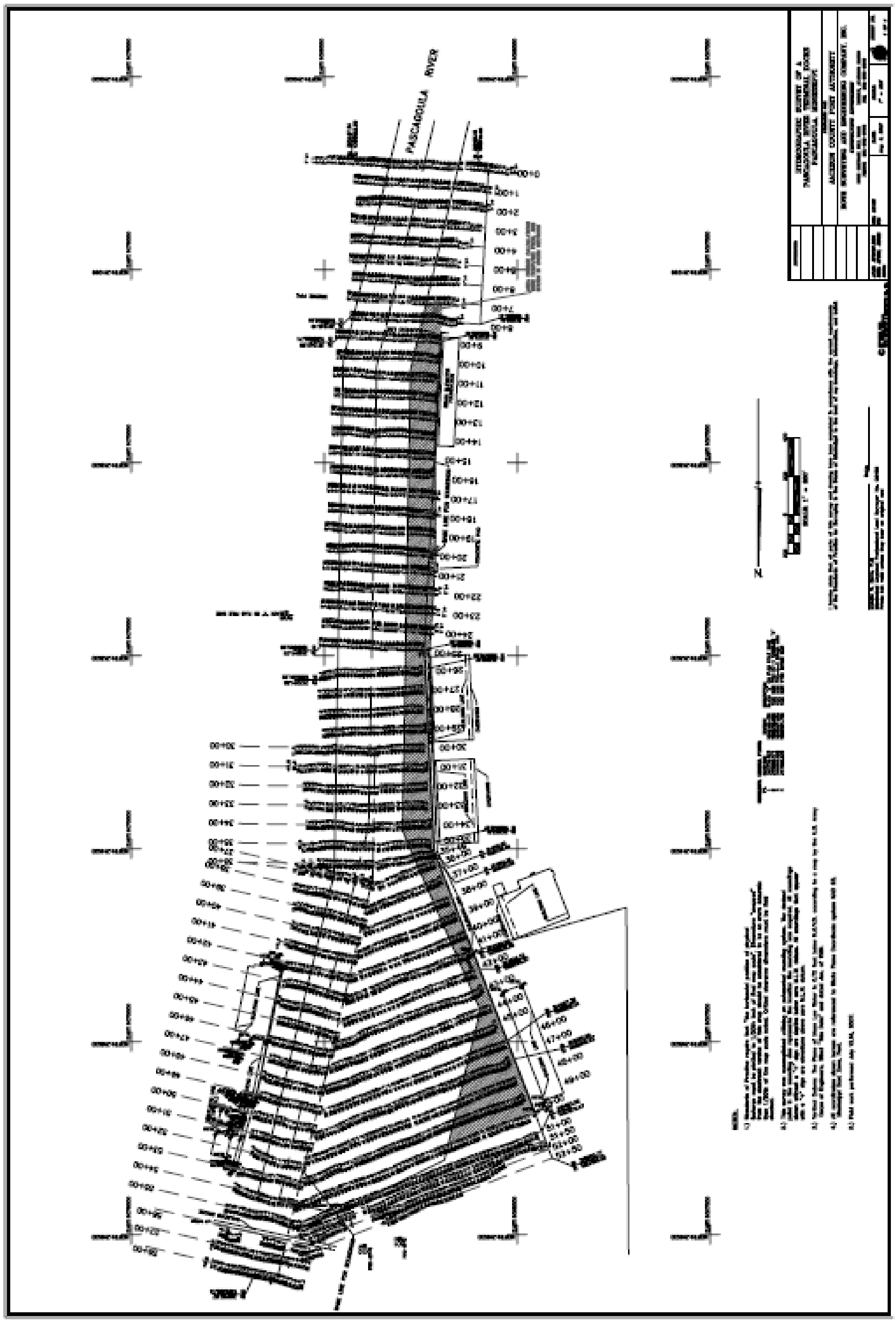


Figure 4-4 Jackson County Port Authority's Area of Responsibility for Pascagoula River Harbor (Area shaded gray illustrates region that is managed by the JCPA) (USACE 2008)

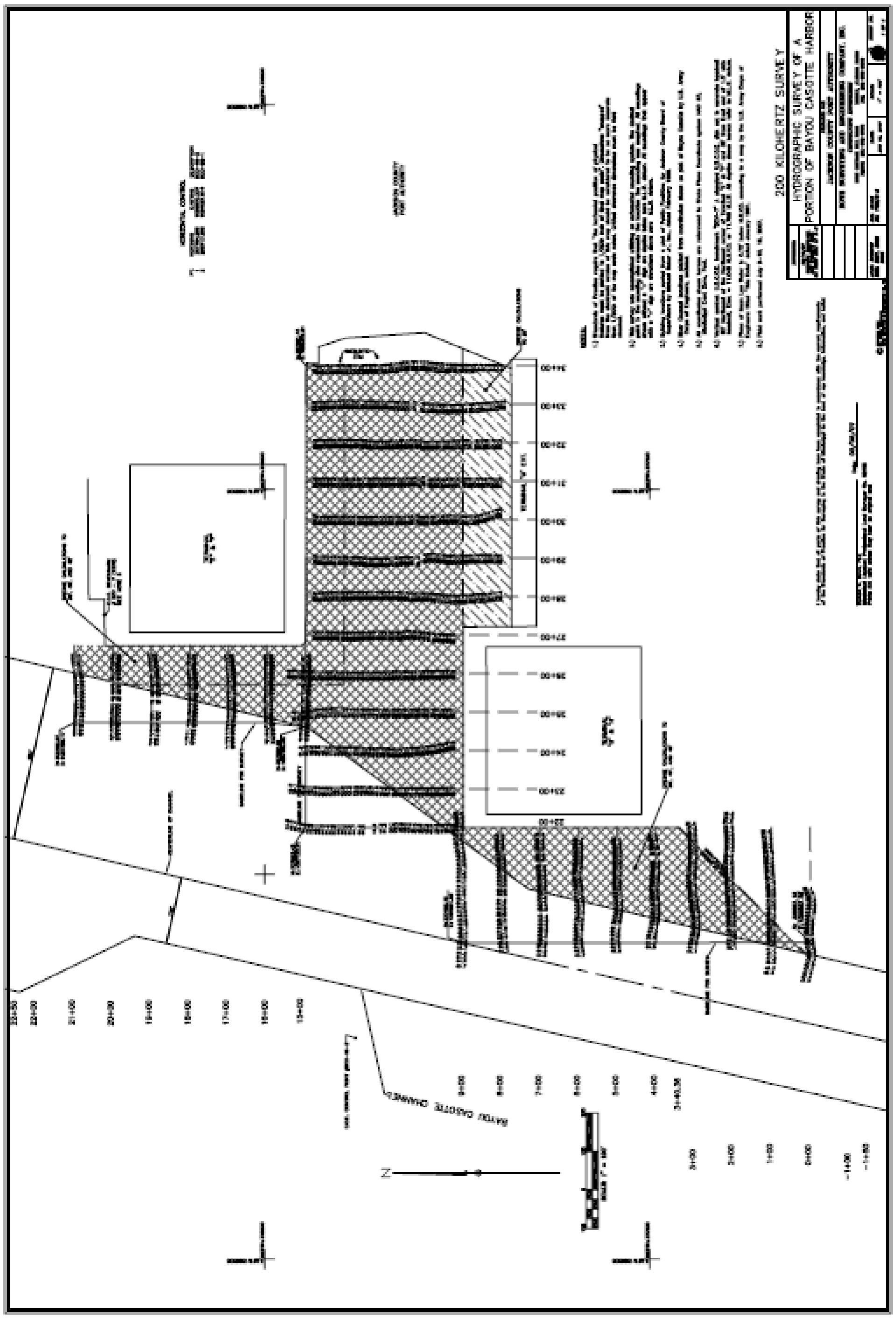


Figure 4-5 Jackson County Port Authority's Area of Responsibility for Bayou Casotte Harbor (Area shaded gray illustrates region that is managed by the JCPA) (USACE 2008)

Table 4-1 Dredged material placement at the Pascagoula offshore placement site (USACE 2006)

Year	Volume (cubic yards)	Material Type	Project	Classification of work
1992	168,200	O&M: Sand	Navy Channel	Federal
1993	1,161,000	O&M: Sand	Civil Works Channel	Federal
1998	1,600,000	O&M: Silt/Clay	JCPA	Port
1999	414,200	O&M: Sand	Civil Works Channel	Federal
2002	630,000	O&M: Sand	Civil Works Channel	Federal
2003	741,000 559,000	O&M: Mixture O&M: Mixture	Civil Works Channel Navy Channel	Federal
2004	1,009,000	O&M: Mixture	Civil Works Channel	Federal
2005	121,000	O&M: Mixture	Civil Works Channel	Federal

(NW=New Work; O&M= Operations & Maintenance; cy = cubic yards)

The Army Corps of Engineers Mobile District estimates that 3.06 million cu m of dredged materials from the Federal shipping channels will need to be removed and disposed of every 3 years for the next 40 years (USACE 2003). In the past, the dredged materials from the Federal channels have been placed in an Ocean Dredged Material Disposal Site (ODMDS), pictured in Figure 4-6. The materials that are removed from the areas that are managed by the Jackson County Port Authority are disposed of in one of the two Dredge Material Management Sites located on the west side of the Pascagoula River Harbor and the Bayou Casotte Harbor.

According to the manager of the facilities at the Port of Pascagoula, Allen Moeller, the last time that the Port Authority had to dredge areas under their jurisdiction was in 2005. In 2005 the Port Authority removed 56,881 cubic yards from its property in the Bayou Casotte harbor at a cost of $4.90 per cubic yard. The total cost of the dredging was $488,716.90 which included adjustments for disposal. The areas in the Bayou Casotte harbor which are managed by the port authority are reported to need dredging every four to six years. The last recorded dredging in the harbor prior to 2005 was in

1998. The last record obtained concerning the Pascagoula River harbor was from 2000. In 2000 the port authority had 96,857 cubic yards removed from their facility at a cost of $2.96 per cubic yard. The total cost of the dredging work was $325,146.72, which includes charges for down-time experienced by the dredging contractor.

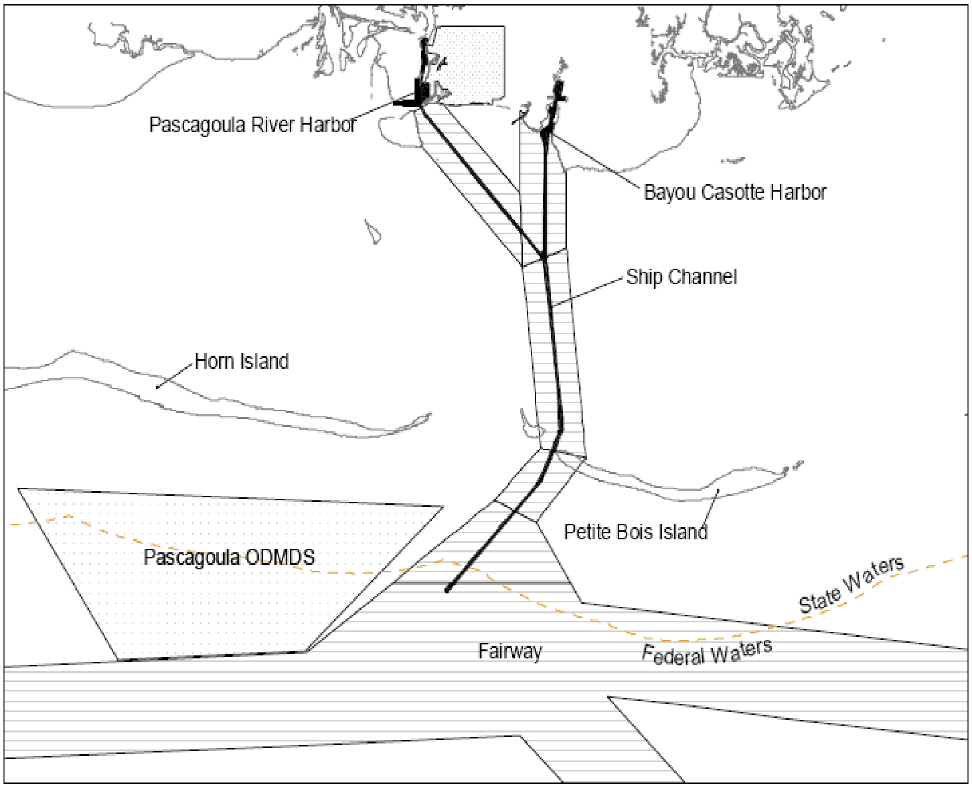


Figure 4-6 Ocean Dredged Material Disposal Site (USACE 2003)

The sediment from the last dredging conducted by the Army Corps of Engineers was tested and they concluded that the dredged materials are “primarily fine-grained silt/clay with a trace of sand” (USACE 2003). Also according to Unified Soil Classification System the material is classified as “a gray sandy clay” (USACE 2003). The sediment had a settling velocity of 0.226 ft/hr and properties as shown in Table 4-2.

Table 4-2 Sediment Characteristics (USACE 2003)

Characteristic	Value
Specific Gravity of Solids	2.74
Water Content	186.5%
Void Ratio	6.60
Solids Concentration (particulate)	315.0 g/l
Atterberg Limits	
Liquid Limit	136.0
Plastic Limit	37.0
Plasticity Index	99.0
Grain-Size Distribution	
Percent Gravel	0.0
Percent Sand	0.4
Percent Silt/Clay	99.6
Classification	Gray Sandy Clay

The sediment along the bottom of the main navigational channel consists of silt and clay/mud (less than 62 microns) to fine to medium sand (USACE 1985). The harbors themselves lie in a silt and clay/mud region. The channel bed leading to the East Harbor consists primarily of silt and clay sediment, while the channel leading to the West Harbor consists more of fine and very fine sands (62 to 250 microns). About two miles south of the West Harbor's mouth the channel becomes a silt and clay/mud mixture, which then returns to a sandy material upon the union with the East Harbor's channel (USACE 1985).

4.3 Sediment Transport Process

The distribution of sediment in the port can be caused by several factors, such as freshwater inflow, reworking of eroded sediments, storm events, flocculation of fine sediments, and water circulation (USACE 1985). Much of the circulation in the Pascagoula River Harbor is created by the freshwater discharge from the Pascagoula River. The average discharge of the Pascagoula River into the harbor is about 3,000 cubic feet per second[3]. The discharge of the river creates a very visible sedimentation plume as illustrated in Figure 4-7.

Figure 4-7 Sedimentation Plume (Adapted from Google Earth)

Other potentially important factors in sedimentation process are tides and waves. The port's tides are diurnal with a mean range being about 1.4 ft., except during storms when it increases to about 3.75 ft. (USACE 2007). The average monthly wave heights for the Port of Pascagoula are illustrated in the Figure 4-8.

---

[3] Personal communication with EPA Region 4 staff.

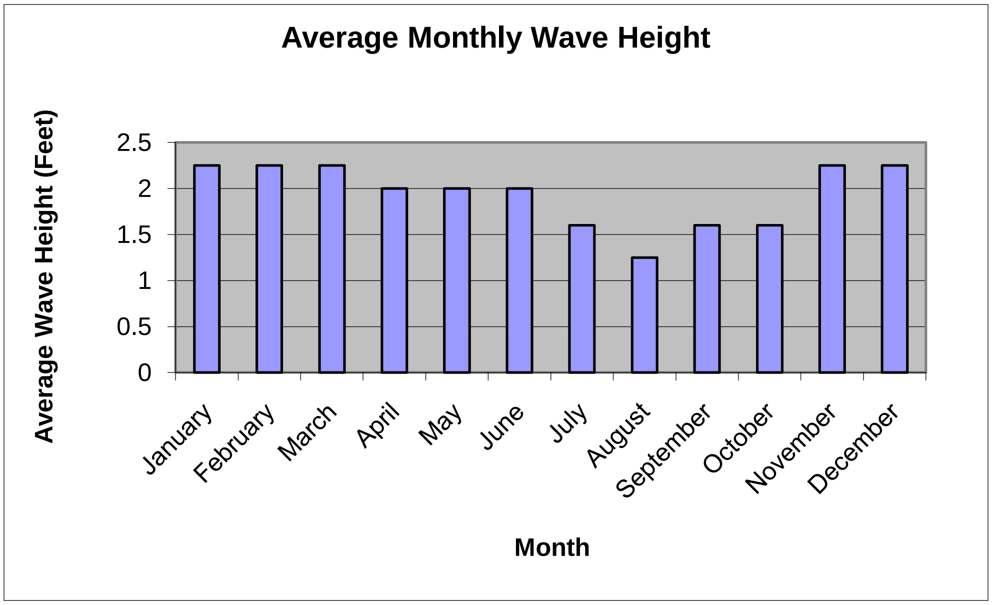


Figure 4-8 Average Monthly Wave Height (USACE 2007)

Wave agitation can disturb shallow bed areas causing sediment to be suspended and then transported to alternate locations by weaker coastal currents (driven by tides, winds, or waves). Figures 4-9 and 4-10 show the peak spring flood and ebb currents of the region, providing a better understanding of the tidal circulation that is occurring in the area. At peak flood the currents are generally slow, with speeds of about 0.15 m/sec, and have trajectories towards the west-northwest (USACE 2003). Currents closest to the shore generally run parallel to the coastline. The speed of the ebb current is higher with an average of about 0.27 m/sec around the discharge areas of the freshwater flows into the port. At these freshwater inputs there is a increased probability of sediment build up in the areas that are not in the main flow of the currents. These areas are usually inlets or coves that do not have the same current patterns and have static water flow. Figure 4-11 illustrates the bottom currents of the region to give a better understanding of the circulation.

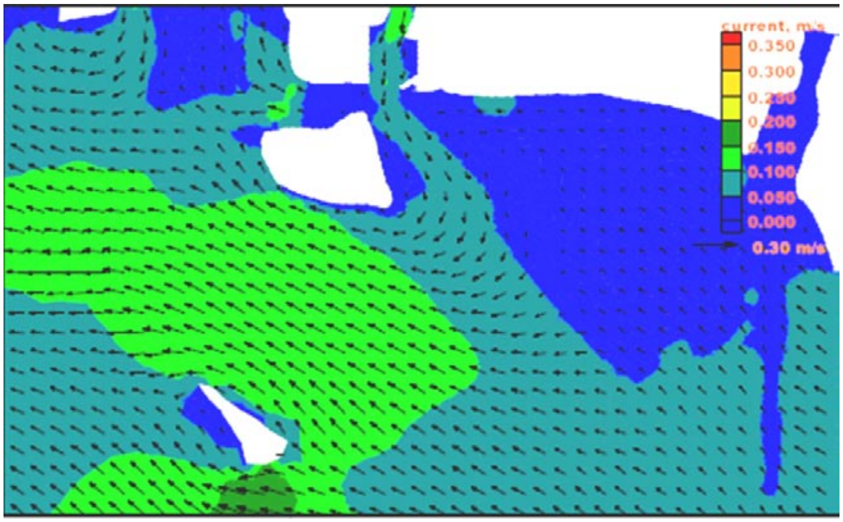


Figure 4-9 Current map of peak spring flood tide for existing-configuration Condition (USACE 2003)

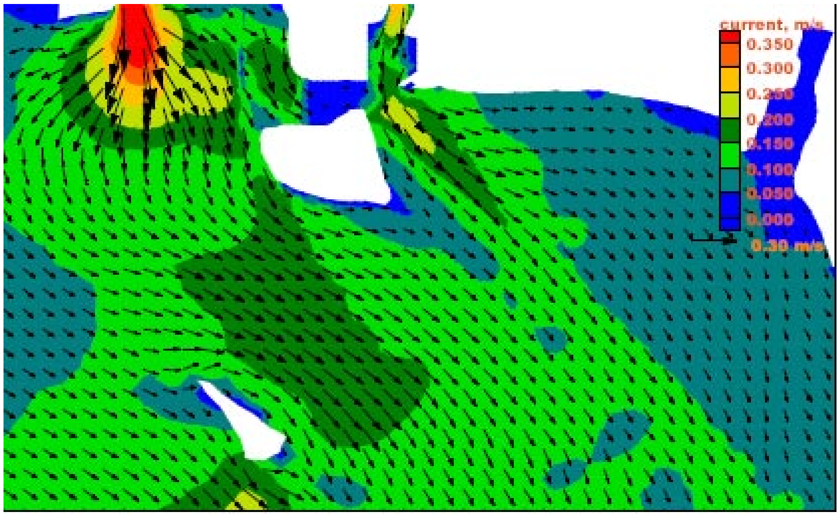
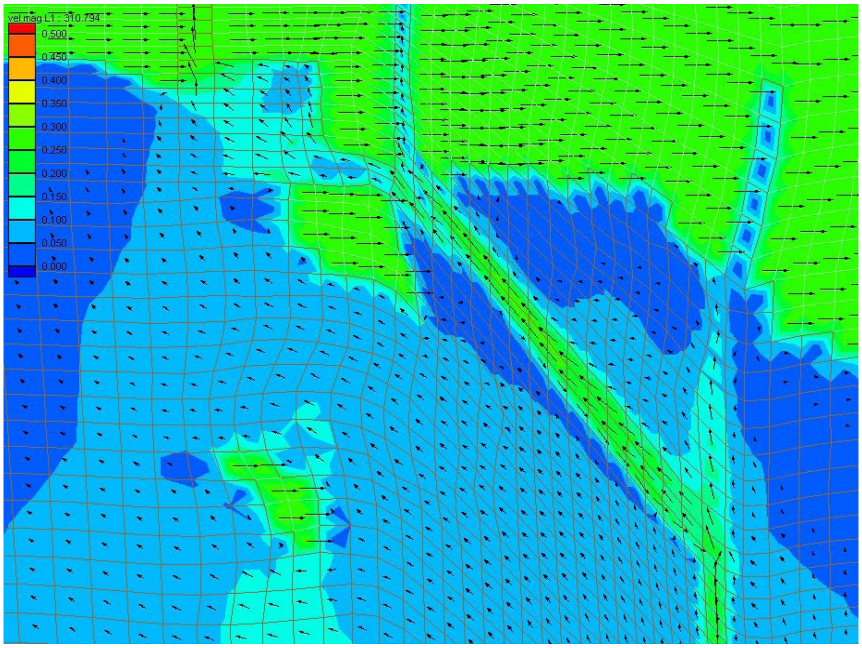


Figure 4-10 Current map of peak spring ebb tide for existing-configuration Condition (USACE 2003)



(Filled contours indicate current magnitude, vectors indicate current direction)

Figure 4-11 CH3D bottom currents for Alternative 00 (13 August 1990, 2200 GMT) (USACE 2003)

5. Field Investigation and Analysis

5.1 Problem Areas

Possible problem areas in both harbors were identified, in both the local and Federal channels, by analyses of hydrographic surveys prepared by the Mobile District of the United States Army Corps of Engineers which were available on their website (USACE 2008). Surveys which were conducted directly before dredging operations were instrumental in identifying shoaling in the harbors and were examined closely to see where the majority of sediment was being deposited. The depths of the pre-dredged and post dredged surveys were compared to determine the total amount of shoaling that was occurring. The remaining surveys were examined to identify how rapidly sediment was depositing in these same areas. If there is fluid mud present, in either of the harbors, it will be very difficult to accurately measure it. Acoustic surveys, even with dual frequency instruments, cannot reliably detect the interface between fluid mud and settled bed (McAnally et al. 2007b). There were several areas in Pascagoula River Harbor and in the Bayou Casotte Harbor that exhibited significant shoaling which are depicted in Figures 5-1 and Figure 5-2.

5.2 Field Investigation

A preliminary field investigation was conducted on June 3, 2008 in which samples were taken from the water column and sediment was sampled from the bed. General areas of interest, both in the local and Federal channels, were located prior to the field investigation but some onsite decisions were made to determine additional sampling locations. All of the areas that were determined to have sediment problems were sampled along with other sites to get a good representation of the entire port. A total of fifteen sites were sampled in the port, seven of which were located in the Pascagoula River Harbor, depicted in Figure 5-3, and eight were located in the Bayou Casotte Harbor, depicted in Figure 5-4.

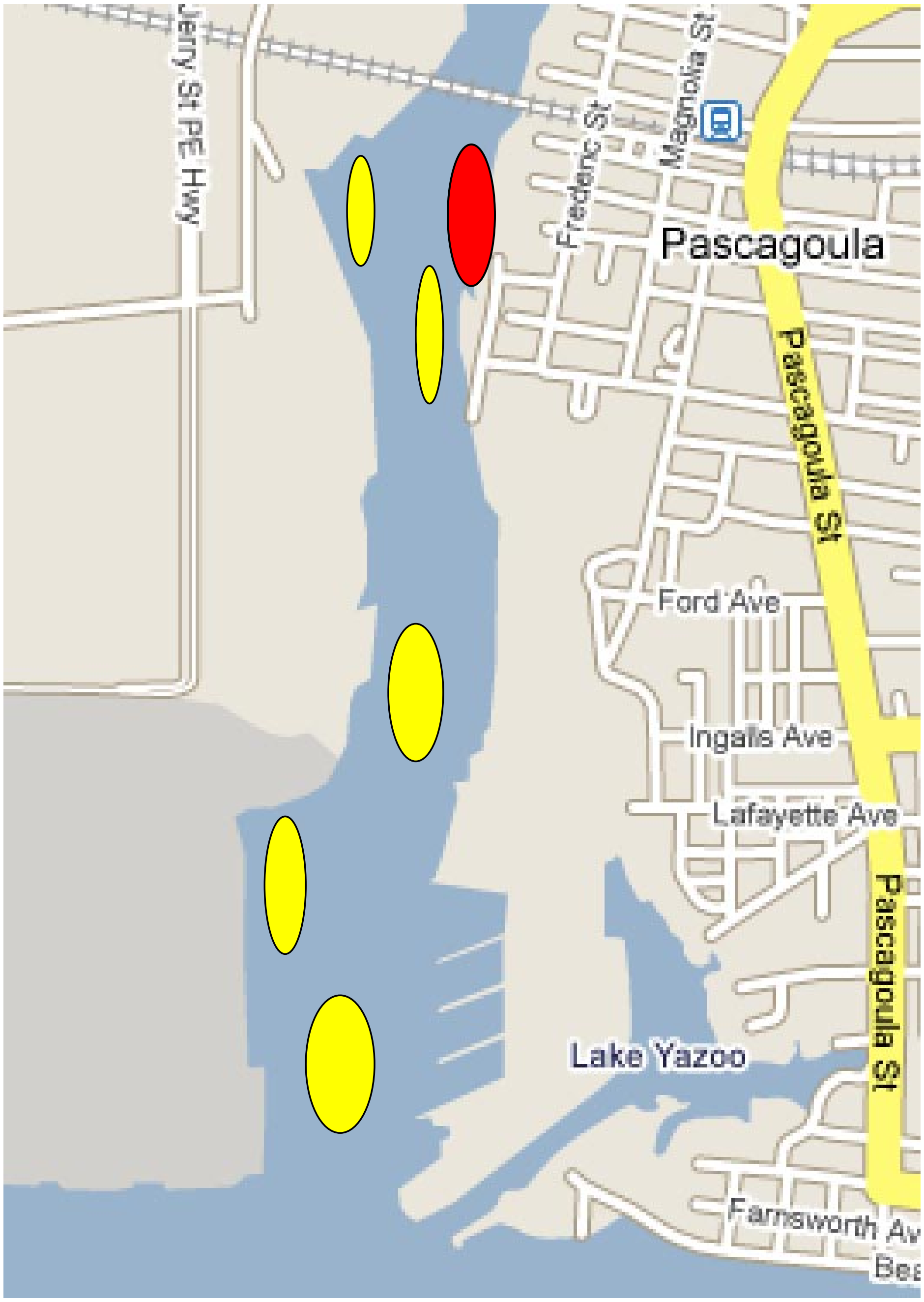


Figure 5-1 Problem areas in Pascagoula River Harbor (Yellow Ovals = located in areas managed by the Army Corps, Red Ovals = located in areas managed by JCPA) (Adapted from Google Maps)

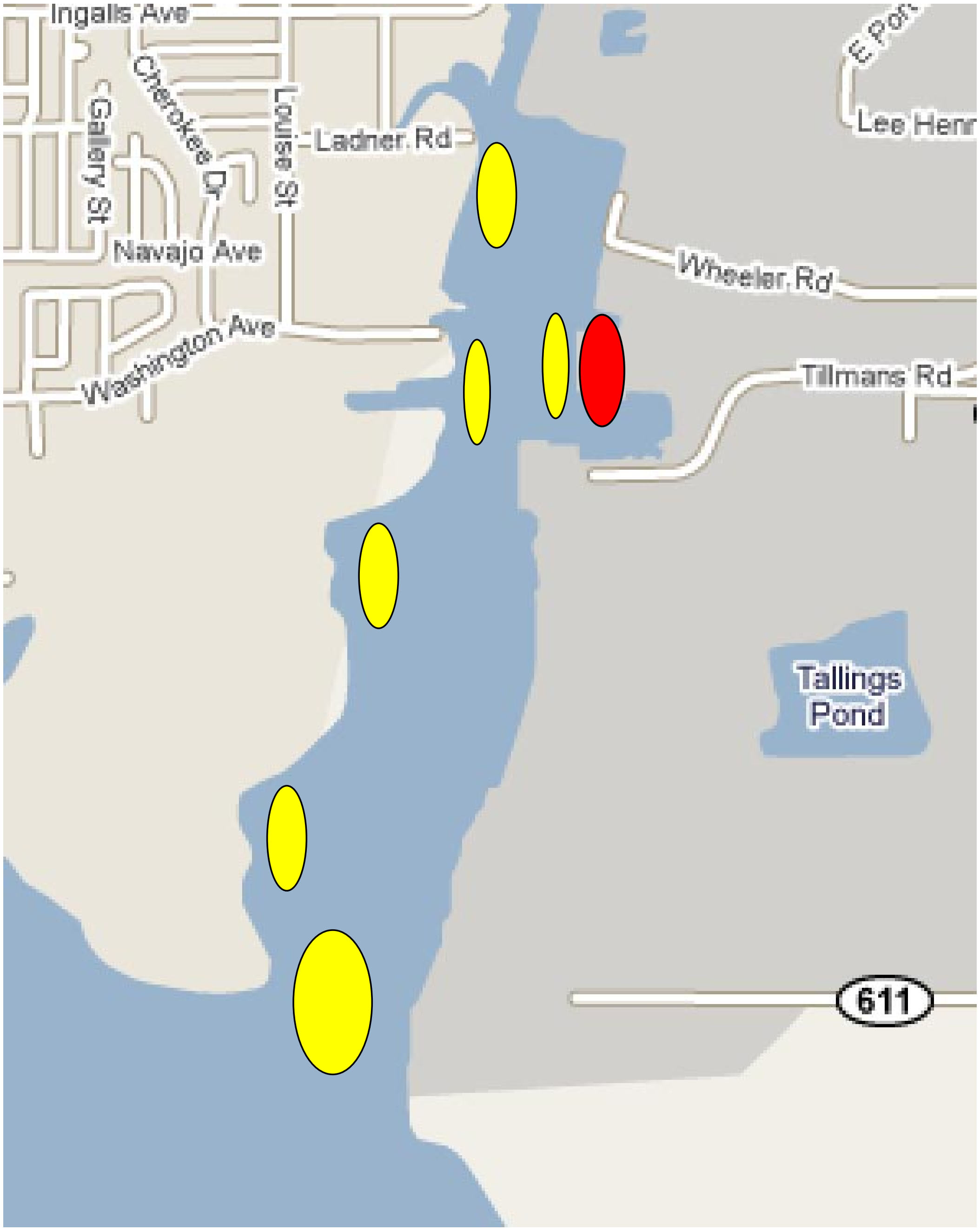


Figure 5-2 Problem areas in the Bayou Casotte Harbor (Yellow Ovals = located in areas managed by the Army Corps, Red Ovals = located in areas managed by JCPA) (Adapted from Google Maps)

Figure 5-3 Pascagoula River Harbor Sample Sites (Adapted from Google Maps)

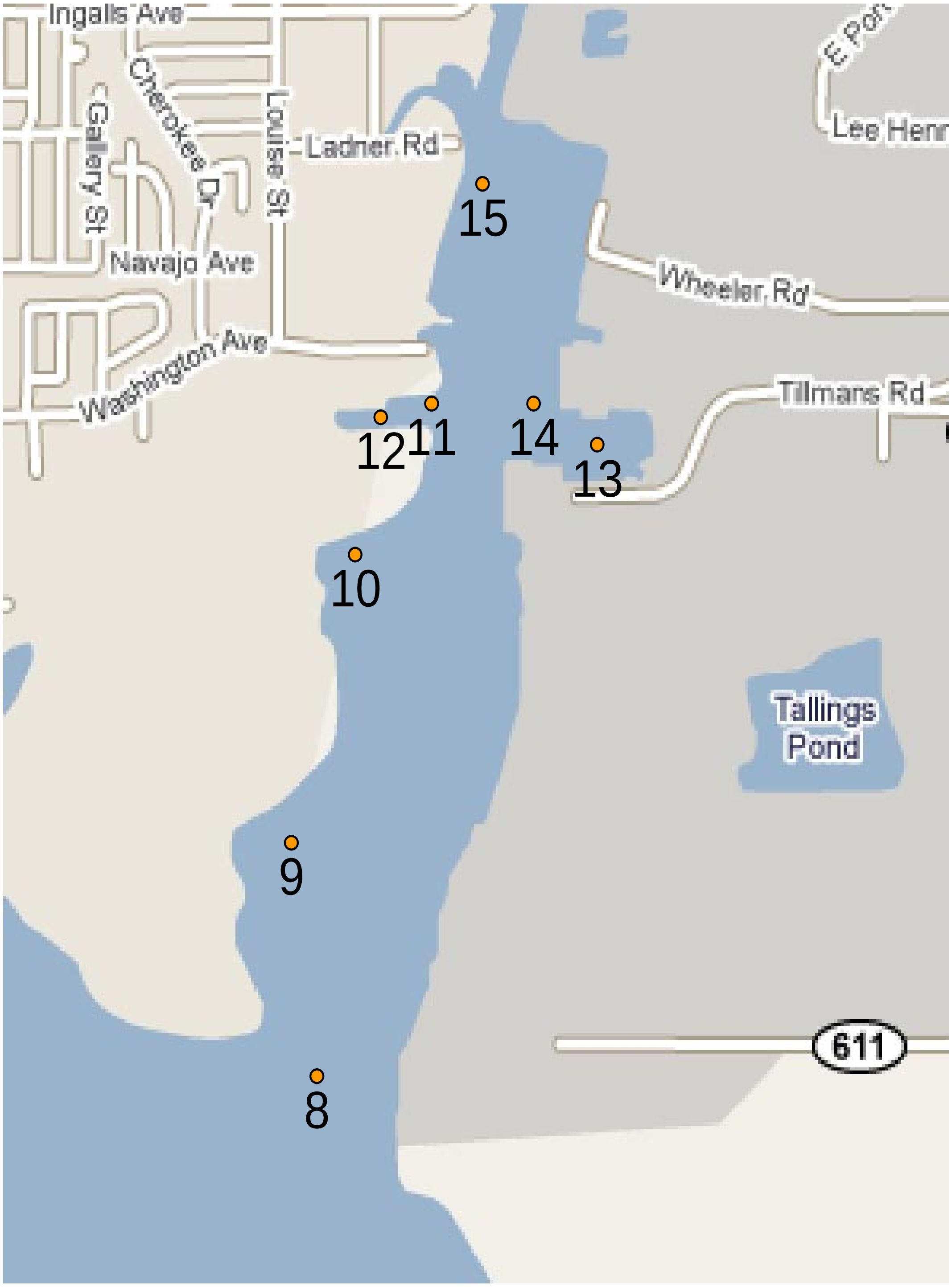


Figure 5-4 Bayou Casotte Harbor Sample Sites (Adapted from Google Maps)

The sediment samples from the bed were taken by using a shallow water dredge, which was lowered to the bottom to grab a sample of the bed sediment. The bed sediment samples were then transferred from the shallow water dredge to one gallon plastic buckets. Once a sample was transferred to a bucket, the bucket was then sealed shut and put on ice to preserve it. Samples were transported to the Mississippi State Civil and Environmental Engineering lab where they were then stored in a refrigerator until they were processed. A sieve and pipette analysis was conducted on each individual sample in order to determine the grain sizes of the sediment. The grain size samples that proved to be the most useful were those taken at the sites leading into the harbors. These sites are identified as sites 2, 7, and 8 and their particle size curves are depicted in Figure 5-5, Figure 5-6, and Figure 5-7.

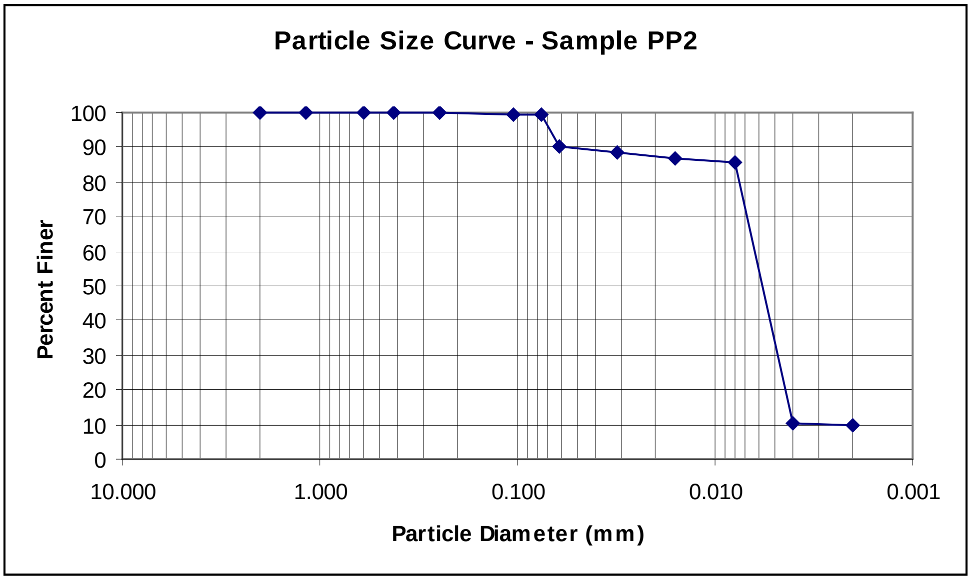


Figure 5-5 Particle Size Curve for Station 2.

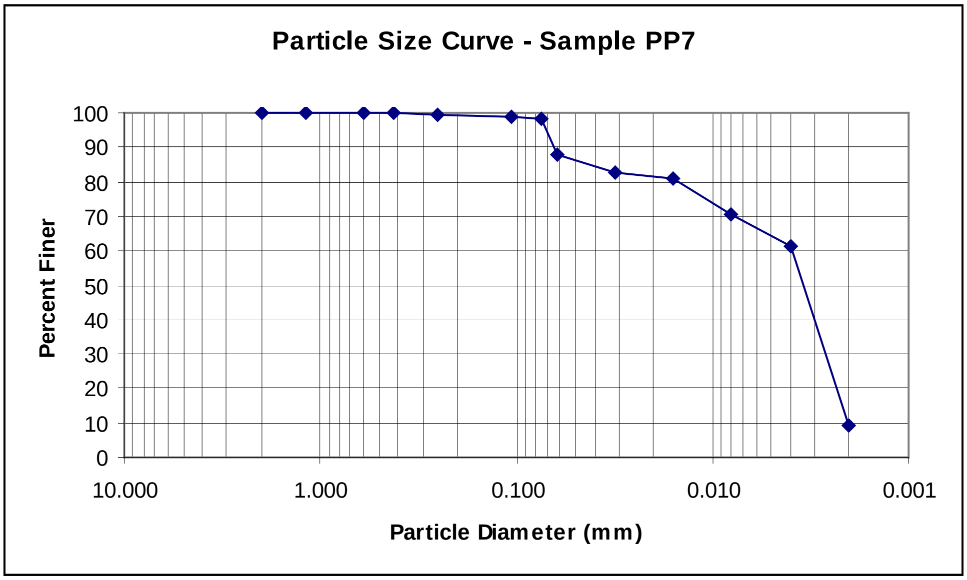


Figure 5-6 Particle Size Curve for Station 7.

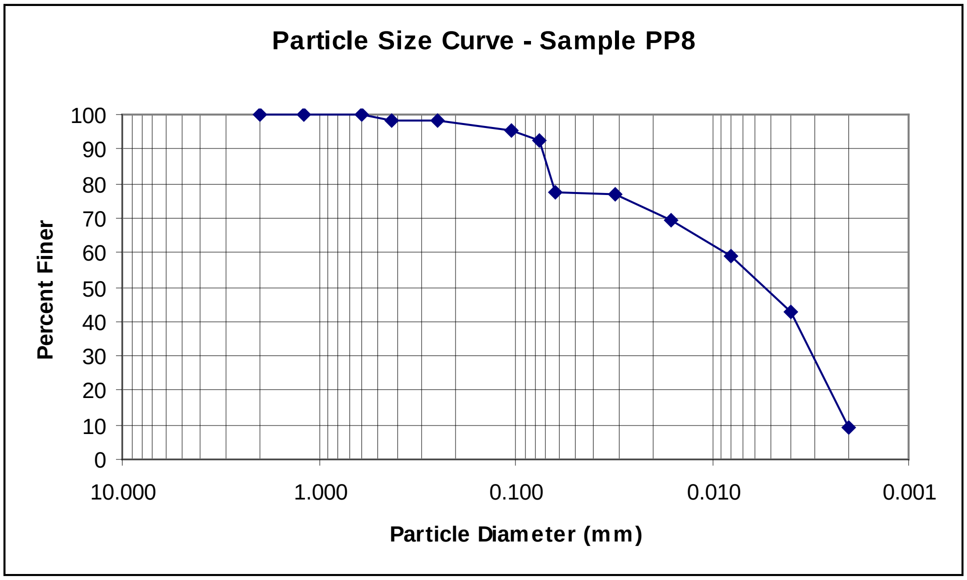


Figure 5-7 Particle Size Curve for Station 8.

At each site, three water samples were taken in order to give a profile of the water column. Samples were taken, for the majority of the sites, at depths of one foot, fifteen feet, and at one foot above the bottom. There were a few sites that were relatively shallow so for these sites, the fifteen foot sample was not taken but a sample at the mid depth was.

Several duplicate samples were taken to verify the results of the analysis process. A total of 60 one-liter samples were taken by using a Niskin tube water sampler. Once taken, each sample was transferred into a one liter plastic sample bottle which was then placed in a cooler containing ice. The samples were preserved on ice until they were analyzed at the lab. Once at the lab, a total suspended solids analysis was performed. Like the sediment samples, the sites that proved to be the most relevant in the analysis were 2, 7, and 8, which are depicted in Table 5-1. The entire sampling set table is located in the Appendix.

While sampling in the port, a layer of fluid mud (defined in Chapter 2) was detected along the bottom of the Pascagoula River Harbor. This layer of fluid mud was estimated to have a thickness of approximately two feet but this may increase during different tidal stages. When the water samplers were lowered down to sample one foot from the bottom, the fluid mud would flow directly into the sampler. Since the fluid mud was observed, it was concluded that a sample right above the fluid mud would be more useful to show what the total suspended sediment was above the fluid mud.

On July 14, 2008 ISCO automatic water samplers were positioned in both harbors, and were set to take samples every hour for twenty four hours. Since the port’s tidal cycle is diurnal, the twenty four hours of samples was necessary to capture every stage of the cycle. A total of forty-eight water samples were taken. Samples were then transferred to coolers where they were iced until they were transported back to the lab at Mississippi State University.

Table 5-1 Analysis of Sample Stations

Sample ID	Sample Description	Volume Filtered (mL)	Filter Weight (g)	Filter + Resid. Weight (g)	TSS (mg/L)
A-40	Station 2 depth of 1’ (water sample)	500	0.1336	0.1426	17.90
D-3	Station 2 depth of 15’ (water sample)	500	0.1334	0.1411	15.40
B-34	Station 2 bottom sample (water sample)	500	0.1329	0.1425	19.20
A-29	Station 7 depth of 1’ (water sample)	500	0.1322	0.1372	10.00
C-24	Station 7 depth of 15’ (water sample)	500	0.1327	0.1388	12.10
B-30	Station 7 bottom sample (water sample)	500	0.1350	0.1587	47.40
B-24	Station 8 depth of 1’ (water sample)	500	0.1329	0.1403	14.70
B-8	Station 8 depth of 15’ (water sample)	500	0.1351	0.1500	29.80
C-19	Station 8 bottom sample (water sample)	500	0.1343	0.3811	493.70

Figure 5-8 Second sampling in Pascagoula River Harbor (Yellow Dots = Additional Water Sampling Stations, Red Dots = ISCO Sampling Stations) (Adapted from Google Maps**)**

Figure 5-9 Second Sampling in Bayou Casotte Harbor (Yellow Dots = Additional Water Sampling Stations, Red Dots = ISCO Sampling Stations) (Adapted from Google Maps)

Additional water samples were also taken in the port to validate findings from the preliminary investigation. Samples were taken at the entrance to Mississippi Sound, at both harbors, and at the north end of the Pascagoula River Harbor. These sampling Stations identified as 2, X, and Y are depicted in yellow in Figure 5-8 and Figure 5-9. Each station was sampled in the morning and in the evening to get a concentration at different times in the tidal cycle. While sampling at station X, a layer of fluid mud was observed in both the morning and evening sampling times. Also, there was a layer of fluid mud observed at station 2 but it did not appear to be as thick as the layer sampled at station X.

Aamples from both the ISCOs and the Niskin tubes were analyzed to determine the total suspended solids (TSS) in each of the samples. The results from the ISCO sampling are represented in Figures 5-10 and Figures 5-11. TSS for the Pascagoula River Harbor showed an average concentration of about 25 mg/L over a tidal cycle. Bayou Casotte TSS data showed an average concentration around 85 mg/L during this sampling period.

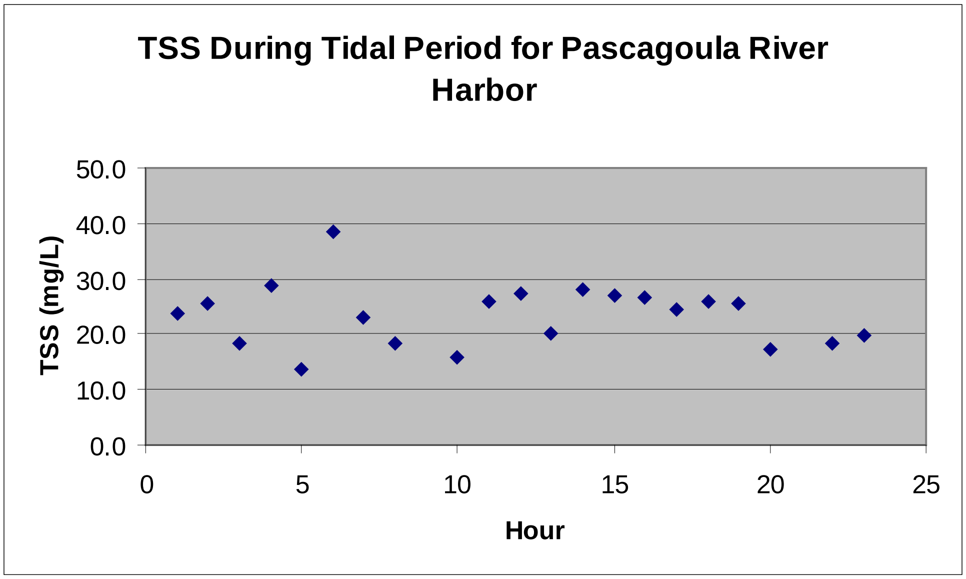


Figure 5-10 TSS During Tidal Period for Pascagoula River Harbor

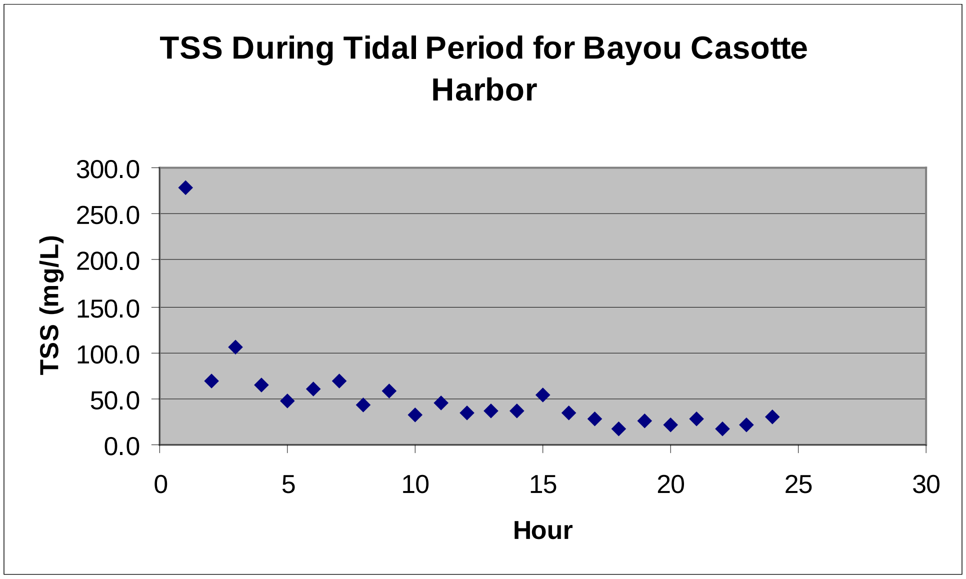


Figure 5-11 TSS During Tidal Period for Bayou Casotte Harbor

The samples that were taken at stations 2, X, and Y appear to give a good representation of what is going on at each station during different stages of the tidal cycle; those values are in Table 5-2. It should be noted that there was an increased amount of traffic in the port on July 17 and this traffic might have agitated some of the sediment.

5.3 Interpretation of Samples

Several calculations were made in order to interpret the values of the samples that were collected from the Port of Pascagoula. During the calculations for interpretation of the samples, there was no distinction made between the Federal and local channels since the problems that affect the local channels will also affect the Federal channels. The first step was to try to discover the main source of the sediment.

The Bayou Casotte harbor was evaluated first, since, with no major freshwater inflows there is only one probable source of sediment – Mississippi Sound. TSS from each depth and the average of the depths, as seen in Figure 5-12 and Figure 5-13 were examined. These figures also take into consideration the range that is exhibited throughout the entire tidal cycle. The majority of the analysis will be conducted using the stations at the mouth of the port, since this appears to be where the sediment enters.

Table 5-2 TSS of water samples from July 15 and 17, 2008

Sample Description	Volume Filtered (mL)	Filter Weight (g)	Filter + Resid. Weight (g)	TSS (mg/L)
Station 2 depth of 1’ (8:22) July 15, 2008	500	0.1287	0.1328	8.1
Station 2 bottom sample (8:22) July 15, 2008	500	0.1297	0.1451	30.9
Station X depth of 1’ (8:33) July 15, 2008	500	0.1292	0.1329	7.4
Station X bottom sample (8:33) July 15, 2008	500	0.1296	0.1357	12.1
Station Y depth of 1’ (9:03) July 15, 2008	500	0.1288	0.1358	14.0
Station Y bottom sample (9:03) July 15, 2008	500	0.1289	0.1413	24.8
Station Y depth of 1’ (17:40) July 15, 2008	500	0.1282	0.1325	8.7
Station Y bottom sample (17:40) July 15, 2008	500	0.1294	0.1467	34.7
Station 2 depth of 1’ (17:50) July 15, 2008	500	0.1295	0.1331	7.3
Station 2 depth of 1’ (8:17) July 17, 2008	500	0.1304	0.1385	16.2
Station 2 bottom sample (8:17) July 17, 2008	500	0.1293	0.1674	76.2
Station X depth of 1’ (8:24) July 17, 2008	500	0.1291	0.1328	7.4
Station X bottom sample (8:24) July 17, 2008	500	0.1299	0.1402	20.7
Station Y depth of 1’ (8:40) July 17, 2008	500	0.1283	0.1438	31.0
Station Y bottom sample (8:40) July 17, 2008	500	0.1272	0.1435	32.7
Station Y depth of 1’ (15:33) July 17, 2008	500	0.1284	0.1340	11.2
Station Y bottom sample (15:33) July 17, 2008	500	0.1303	0.1366	12.6
Station 2 depth of 1’ (15:54) July 17, 2008	500	0.1295	0.1339	8.8
Station 2 bottom sample (15:54) July 17, 2008	250	0.1279	0.2108	331.6
Station X depth of 1’ (16:04) July 17, 2008	500	0.1286	0.1475	37.9
Station X bottom sample (16:04) July 17, 2008	500	0.1292	0.1423	26.3

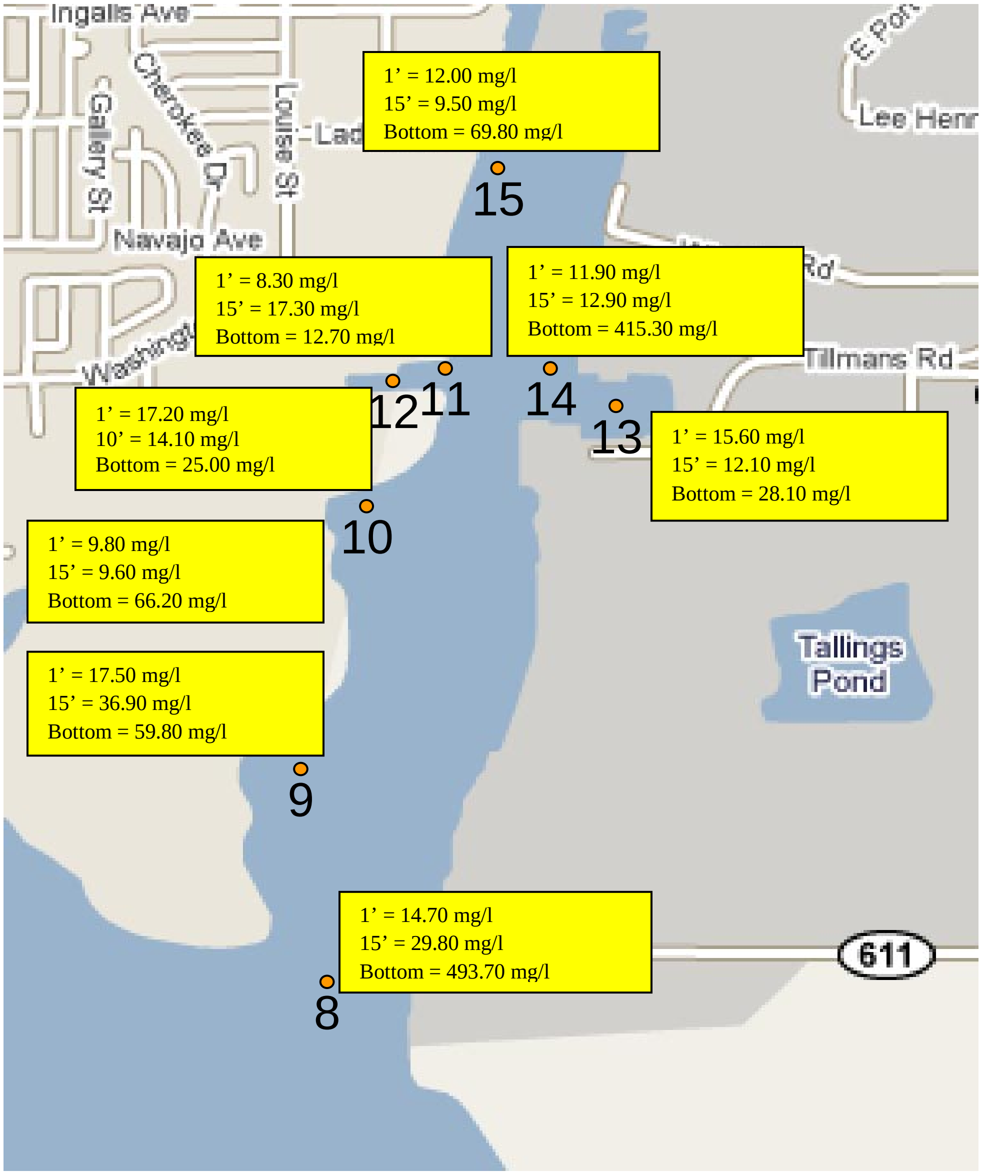


Figure 5-12 TSS of Bayou Casotte Harbor (Adapted from Google Maps)

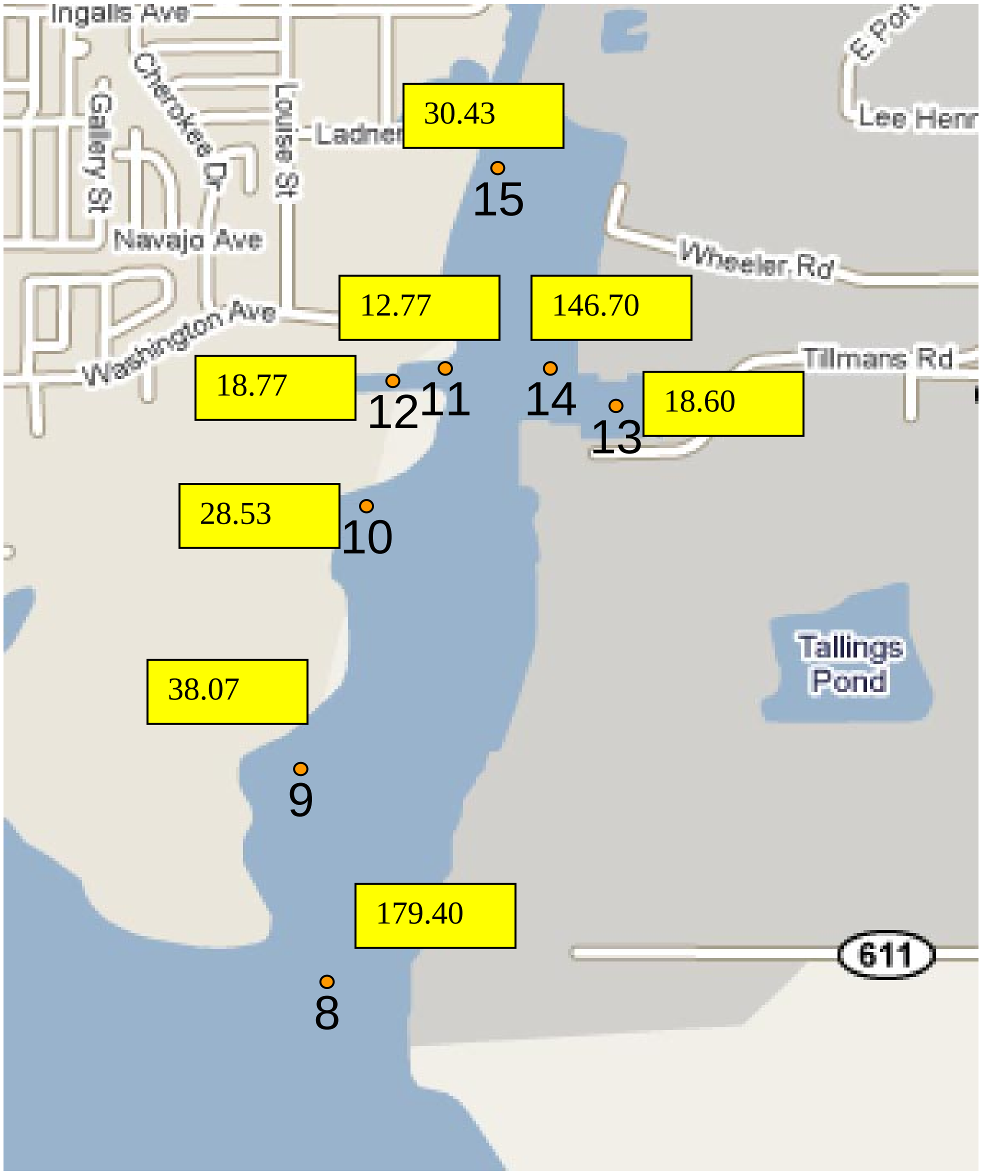


Figure 5-13 Average of TSS Bayou Casotte (Adapted from Google Maps)

The area of the Bayou Casotte harbor, including both Federally and locally managed areas, is around 7,155,000 ft^2. The tidal prism for small harbors is calculated by multiplying the area by the mean tidal range (1.4 ft), which gives a value of 10,017,000 ft^3. The tidal prism can be used to calculate the amount of sediment that is suspended in the port by doing some simple unit conversions and multiplying by the suspended sediment concentration at a point then dividing by the specific gravity, which is calculated by Equation 5.1.

$$G = \frac{\gamma_s}{\gamma} \tag{5.1}$$

Where:

G = specific gravity of solids

γ_s = specific weight of the in-situ sediment deposits

γ = specific weight of water at 70° F

In this situation a range of specific gravities from 1.1 to 1.6 will be used in order to account for a variety of sediment beds, and the specific weight of water at 70° F is 62.30 lb/ft^3. A specific gravity of 1.1 yields a specific weight of 68.53 lb/ft^3 for the sediment, and a specific gravity of 1.6 yields a specific weight of 99.68 lb/ft^3. These values are then used to calculate the amount of sediment that is entering the harbor, using the average concentration of all the stations, by doing the following conversions and calculations:

Weight of Sediment = (Volume of Water)(Concentration of Sediment) (5.2)

$$10017000\,ft^3\left(\frac{59.16mg}{1l}\right)\left(\frac{28.31685l}{1ft^3}\right)\left(\frac{1g}{1000mg}\right)\left(\frac{1lb}{453.59237g}\right)=36{,}993.62lb$$

For specific gravity of 1.6: $36{,}993.62lb\left(\frac{1ft^3}{99.68lb}\right)\left(\frac{1yd^3}{27ft^3}\right)=13.75yd^3$

For a specific gravity of 1.1: $36{,}993.62lb\left(\frac{1ft^3}{68.53lb}\right)\left(\frac{1yd^3}{27ft^3}\right)=19.99yd^3$

These calculations give the amount of sediment that is entering the harbor in a single day, so to calculate the amount that is entering in a given year multiply by 353 tidal (lunar) days, which yields 4850 yd^3/yr, for a specific gravity of 1.6, and 7,050 yd^3 /yr for a specific gravity of 1.1. These calculations give a relatively low estimate for the range of sediment entering the harbor compared with the estimated dredging volumes. In order to account for the concentration that was observed during the sampling the average from station 8 will be applied to the same calculations. When the concentration of 179.40 mg/l is substituted into the calculations it shows that the range is between 15,000 yd^3 and 22,000 yd^3 enter the port per year via tidal exchange. These two ranges give an indication of how much sediment would enter the harbor if there was a low concentration year around and if the concentration observed during the sampling period was constant year around. This might still be a low range, since the concentrations found during the sampling period might not represent a high concentration situation (strong winds and/or high sediment supply to the Sound from either the Pascagoula or Mobile Rivers), so further calculations will need to be conducted to calculate a high range.

In order to estimate a range that might be more accurate for the entire harbor it is necessary to examine the dredging amounts from the local channels to allow for an approximation of the amount of sediment entering the harbor in both the local and Federal channels each year. Earlier it was discussed that about 57,000 yd^3 of sediment was removed from the local channel the last time Bayou Casotte harbor was dredged. The local channel only accounts for about 10% of the total area in the harbor. If it is assumed that the Federal channels are dredging at the same frequency as the local channels then this would mean that around 380,000 yd^3 is removed each dredging period. If the harbor is dredged every four years, and it is assumed that roughly the same amount of material is removed as in the last dredging, then this would mean that about 95,000 yd^3 of material is depositing in the port per average year. If the harbor is dredged every six years then about 63,300 yd^3 of material is depositing every year. These two estimates are higher than earlier estimates, and it would take an average concentrations of around 750 mg/l to account for 95,000 yd^3 entering the harbor each year. This concentration is not entirely implausible since rough seas or other episodic weather events could agitate the bed creating very high concentrations. From the low range and the high range it can be concluded that between 15,215 yd^3 and 95,000 yd^3 of material is entering the harbor each year. Adding possible fluid mud inflows from the Sound could easily provide the observed dredging rates.

The sediment samples taken from the port allowed for a profile analysis of the concentration of sediment in the water column. From the bed samples, the median (d$_5$) grain size was estimated by using the particle size curve for each station. In the Bayou Casotte Harbor the most useful station is station 8, since this is where the majority of the sediment is entering the harbor and its d$_5$ is 0.0055 mm. This value is then applied to the Rouse Equation to calculate a Rouse Profile which will give insight to where the majority of the sediment is found in the water column. The Rouse Equation is defined in *River Mechanics* (Julien 2002) as the following:

$$C = C_a \left[\left(\frac{h-z}{z} \right) \left(\frac{a}{h-a} \right) \right]^{\frac{\omega}{\kappa u_*}} \qquad (5.3)$$

Where:

C = sediment concentration at an elevation z

C_a = sediment concentration at an elevation a

h = flow depth

κ = von Karman constant ($\kappa \approx 0.4$)

w = settling velocity

u_* = shear velocity

To calculate the shear velocity it is necessary to have a current velocity for the calculations. The main current velocities for the area are the velocity from the Pascagoula River current, which is 0.46 m/sec, and the ebb velocity, which is 0.27 m/sec. In order to calculate the shear velocity these current velocities are applied to the following equation:

$$u_* = \sqrt{0.005(\mathit{CurrentVelocity})^2} \tag{5.4}$$

From these equations a Rouse Profile was produced for each station. Since there is no discharge from the north side of the Bayou Casotte Harbor, the calculations are done assuming the ebb current is the dominating current affecting the stations. Station 8’s Rouse Profile is depicted in Figure 5-14 and 5-15, and shows that the majority of the concentration of the sediment is spread out through the entire water column. This does not agree with the samples that were taken in the harbor since there was much more suspended sediment near the bottom of the channel, probably as a result of fine sediment flocculation. The majority of the profiles for the port look very similar, so according to the profiles the sediment concentrations are about the same.

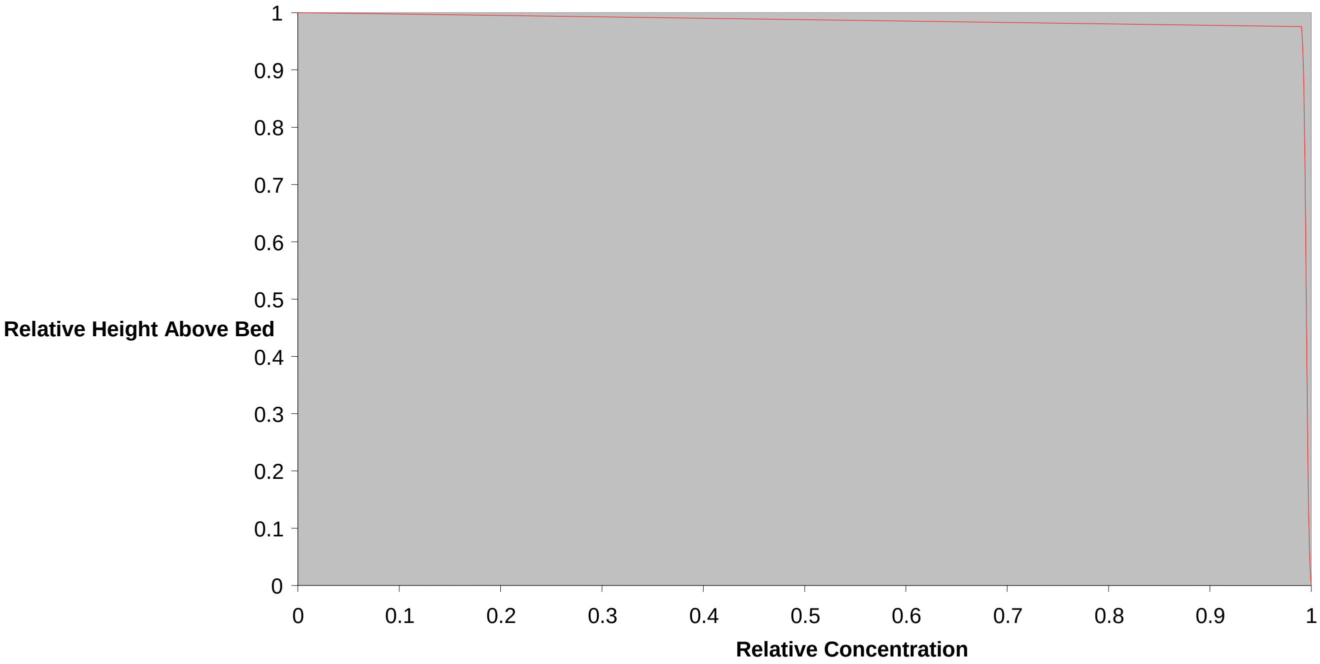


Figure 5-14 Station 8 Rouse Profile at Ebb Current

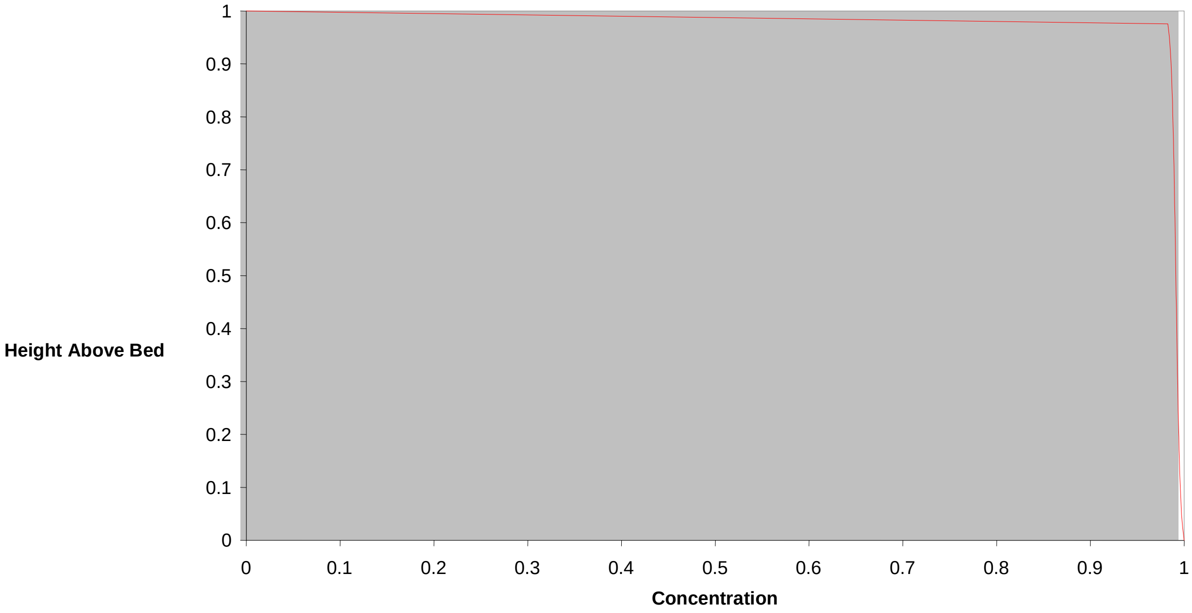


Figure 5-15 Station 8 Rouse Profile at Flood Current

The Pascagoula River Harbor has two possible contributing sources to the sediment deposition – Mississippi Sound the Pascagoula River -- and the amount that each source contributes needs to be estimated.

As stated earlier, about 97,000 yd^3 of sediment were removed from the local channel in 2000, and it is estimated that the harbor needs to be dredged every 18 months. Assuming that about the same amount of material is removed each time the harbor is dredged then about 65,000 yd^3 of sediment enter the harbor and deposit each year in the portion of the channel that is managed by the port authority. This estimate does not include the amount of material that deposits in the Federal channel. In order to account for the amount of sediment that is depositing into the Federal channel it will be necessary to estimate the amount that is settling in the entire harbor. The local channel accounts for about 15% of the total area of the harbor. If it is assumed that the amount settling in the local channel is representative of the entire harbor, then around 430,000 yd^3 of material is depositing in the harbor each year, which is probably a high estimate.

As done for Bayou Casotte, an examination of the TSS from the Pascagoula River Harbor was conducted. The TSS from each depth is depicted in Figure 5-16, and the average TSS at each station is depicted in Figure 5-17. The amount of sediment entering from Mississippi Sound will be calculated first. The area of the harbor is estimated to be around 7,837,000 ft^2. Using the mean tidal range of 1.4 ft, it is calculated that the tidal prism is 10,971,800 ft^3 .The average sediment concentration of the stations from the entire port is used in the same calculations and conversions as was conducted for Bayou Casotte. These calculations yield the following:

$$10971800\, ft^3 \left(\frac{20.99mg}{1l}\right)\left(\frac{28.31685l}{1ft^3}\right)\left(\frac{1g}{1000mg}\right)\left(\frac{1lb}{453.59237g}\right) = 14377.04lb$$

For specific gravity of 1.6: $14377.04lb\left(\frac{1ft^3}{99.68lb}\right)\left(\frac{1yd^3}{27ft^3}\right) = 5.34yd^3$

For specific gravity of 1.1: $14377.04lb\left(\frac{1ft^3}{68.53lb}\right)\left(\frac{1yd^3}{27ft^3}\right) = 7.77yd^3$

From these calculations it is determined that the annual deposition range is between 1,950 yd^3/yr and 2,836 yd^3/yr. This seems to be a very low range but since this harbor is very similar in size to the Bayou Casotte Harbor and has the same mean tidal range these values seem reasonable in comparison.

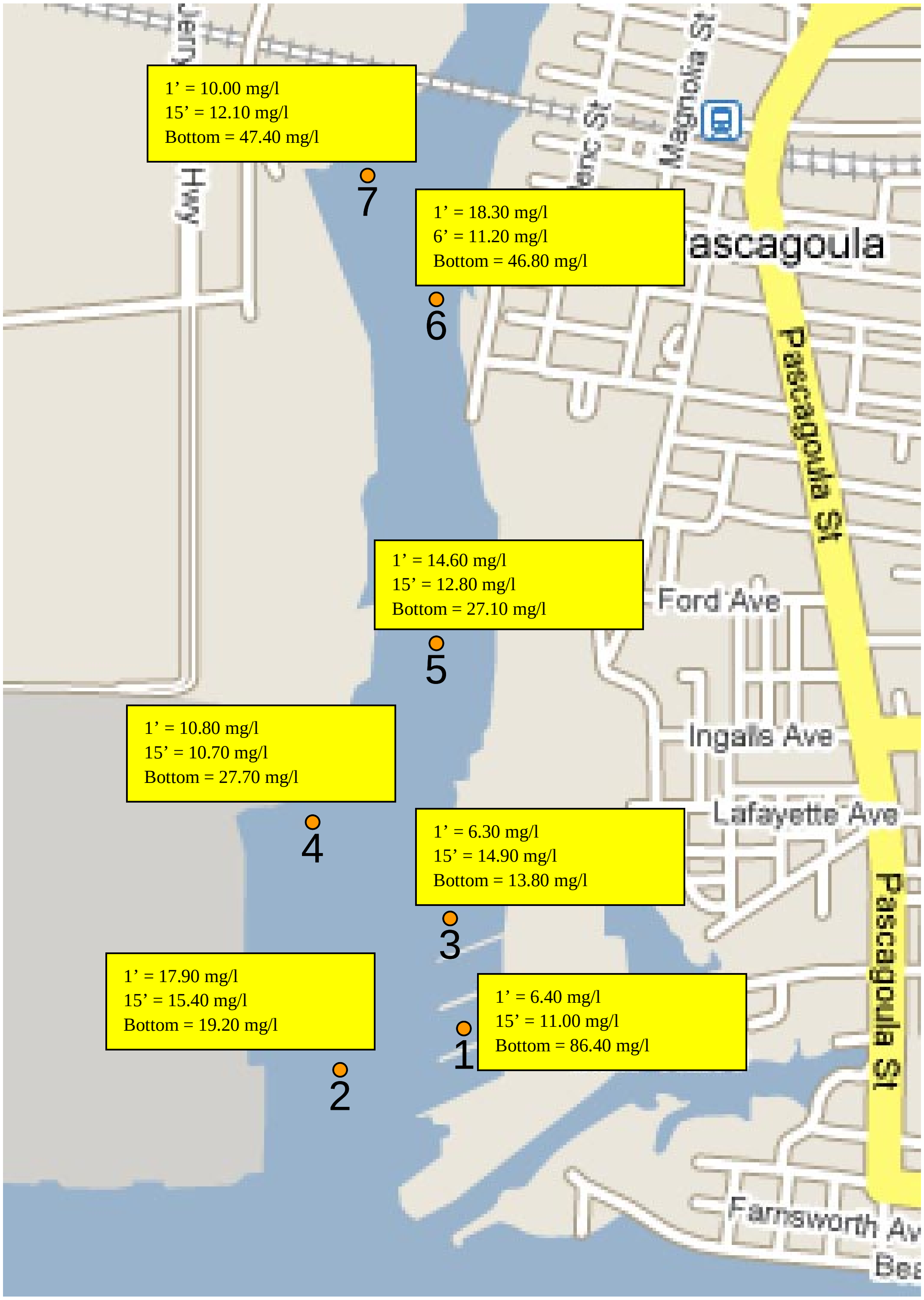


Figure 5-16 TSS of water Samples (Adapted from Google Maps)

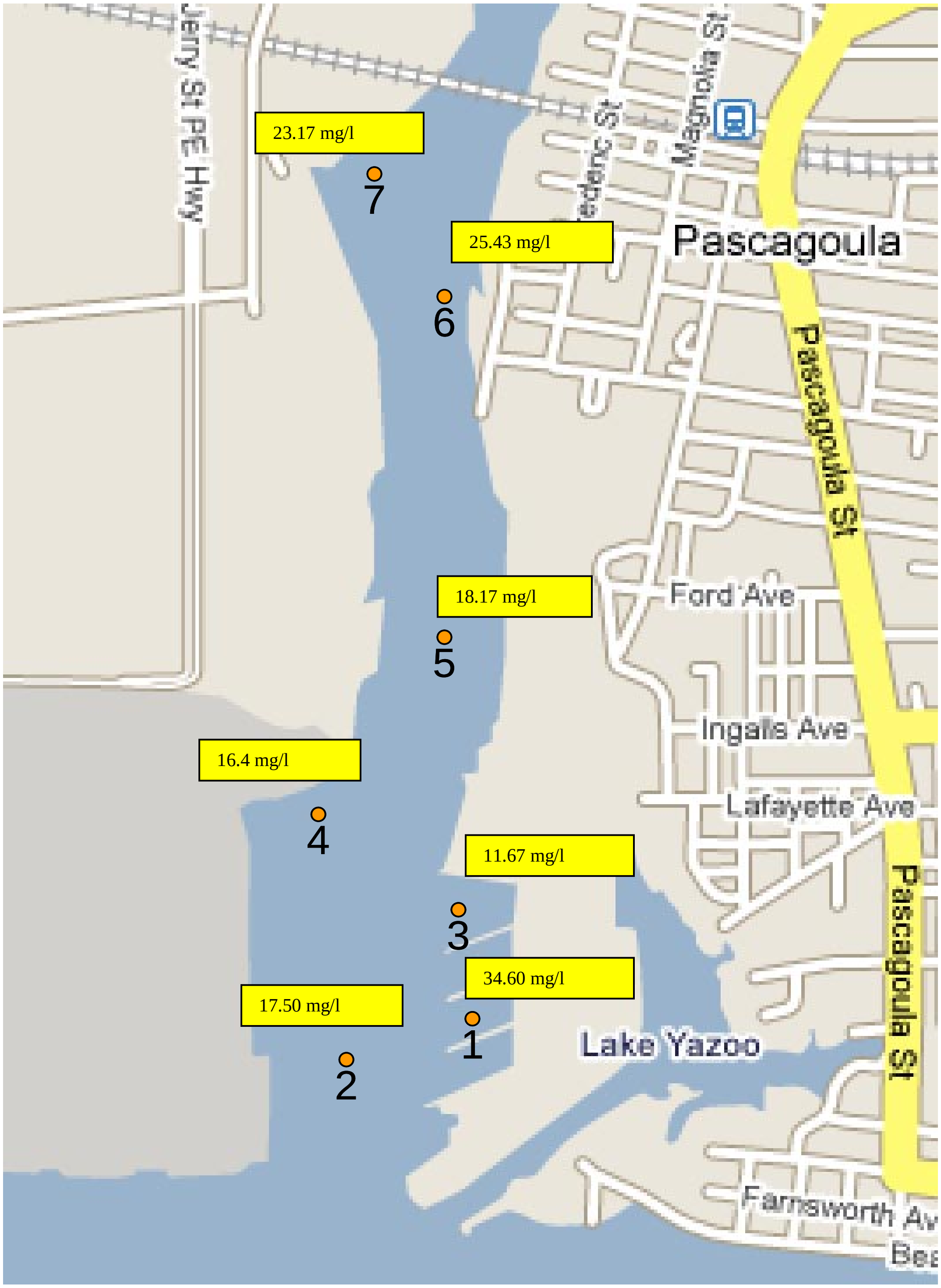


Figure 5-17 Average TSS of water samples (Adapted from Google Maps)

In order to calculate the sediment load that is contributed from the river for the harbor, Equation 5.3 will be used, from the USACE Engineering Manual 4000 (USACE 1989). As seen below.

$$Q_s = 0.0027 \times Q \times C \times k \tag{5.3}$$

Where:

Q_s = sediment discharge, tons/day

0.0027 = converts cfs to tons/day/1000000parts

Q = mean daily water discharge, cfs

C = sediment concentration

k = ppm to mg/l, for concentrations less than 16,000 ppm, k = 1

By using the average concentration for the port and the average discharge of the river, which is 3,000 cfs, a value of 170.02 tons/day is calculated. In order to convert this value into cubic yards it is necessary to incorporate the specific gravity. By using both a specific gravity of 1.1 and a specific gravity of 1.6 a range of 126 yd^3/day to 184 yd^3 /day is calculated. This means that if the discharge of the river were constant throughout the year there would be between 46,000 yd^3/yr and 67,100 yd^3/yr of sediment entering the port. It must be pointed out that this is probably a very low estimate since the average concentration is relatively low. In order to account for a higher range it will be necessary to examine the estimated yearly sediment deposition throughout the harbor, which is 430,000 yd^3. In order to account for this much sediment each year the average concentration would only need to be around 135 mg/l, which is a very reasonable concentration. This suggests the river as the main contributor to the sedimentation problem.

This layer of fluid mud observed during the field investigation seemed to be following the current from the river and flowing into the port. Fluid mud typically exhibits concentrations of tens to hundreds of grams per liter (McAnally et al. 2007a). Even if the fluid mud that is entering the harbor has concentration on the low end of that range -- 10,000 mg to 100,000 mg per liter and the flow rate around 500 cfs, the fluid mud would still be responsible for the transport of about 10,000 yd^3/day. This would mean that the fluid mud is responsible for bringing large amounts of sediment into the harbor but this phenomenon might not be an everyday occurrence since fluid mud can consolidate into an immobile bed (McAnally et al. 2007a). This combined with the above calculations points to the Pascagoula River as the main source of the sediment that is depositing in the harbor.

As before, a Rouse Profile gives an indication of how the suspended sediment is acting throughout the harbor. In this case, there are two dominant currents acting on the harbor. The stations at the north end of the harbor were calculated using the current from the river, whereas the stations at the south end used the ebb current. As expected, the concentration levels for station 2 look very similar to that of the Bayou Casotte Harbor, as seen in Figure 5-18. Station 2's profile shows that the concentration of suspended sediment is distributed throughout the entire water column, which supports the data that were collected onsite. For station 7, which is located at the discharge from the river, the profile is very different, depicted in Figure 5-19. It seems that the concentration is not as distributed as station 2 and the suspended sediment is settling out much quicker, which is representative of the samples that were taken in the harbor. So the amount of sediment that separates itself from the water column will be much higher at this station when compared to station 2.

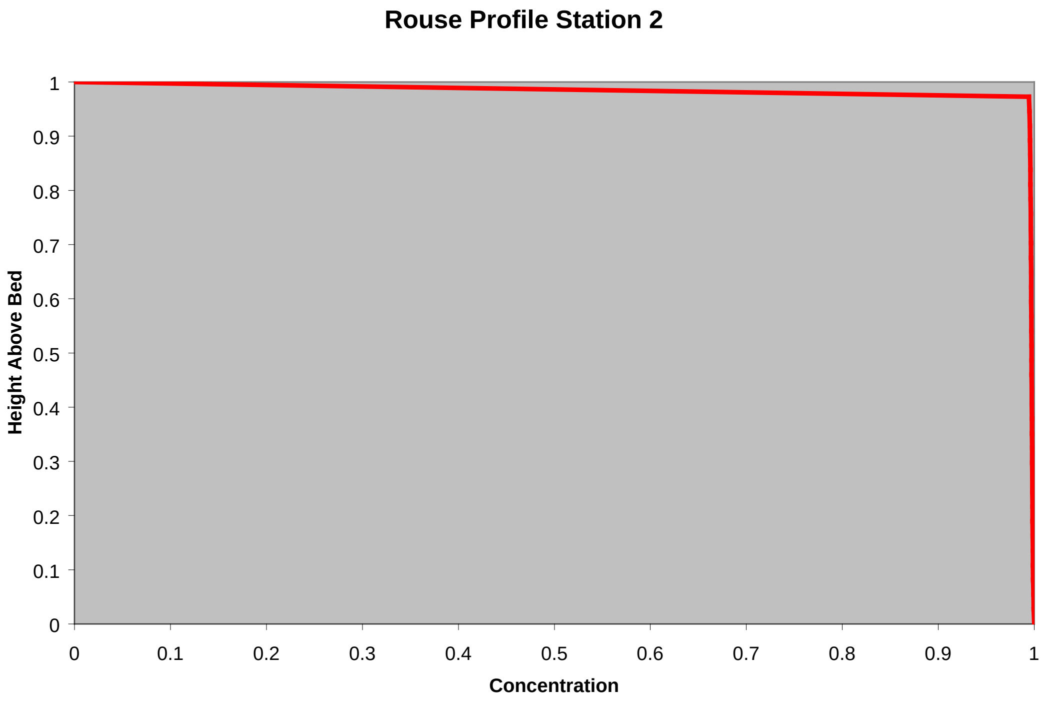


Figure 5-18 Station 2 Rouse Profile for Ebb Current

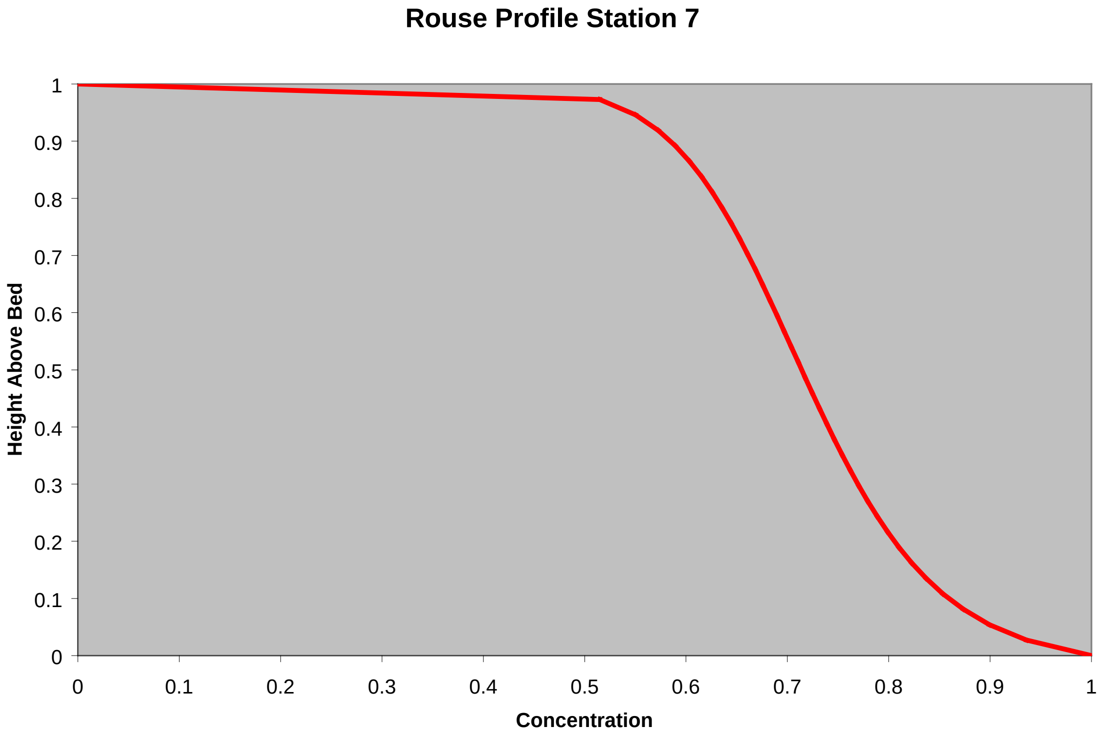


Figure 5-19 Station 7 Rouse Profile

According to calculations using the amounts from previous dredging operations, the Bayou Casotte Harbor only accounts for between 13% and 18% of the materials that need to be dredged for the Port of Pascagoula. The Mississippi Sound accounts for nearly 100% of the sediment that is entering the Bayou Casotte Harbor and therefore solutions that slow or stop this deposition need to be evaluated. The Pascagoula River Harbor accounts for between 82% and 87% of materials that are dredged from the port. Since there are two possible sources of the sediment, both sources were considered when searching for the main source. From the calculations conducted, it was determined that between 1,950 yd^3/yr and 2,836 yd^3/yr of sediment is entering the port from the Mississippi Sound, and between 46,000 yd^3/yr and 430,000 yd^3/yr entering from the Pascagoula River. Given that the fluid mud would contribute a large amount of sediment in short periods of time, the fluid mud needs to be regarded as the main problem associated with the Pascagoula River. Since the Pascagoula River is contributing virtually all of the sediment into the port, solutions need to be developed to address this as the primary sediment source.

6. Solutions

Since each harbor in the Port of Pascagoula has different sedimentation circumstances, they will be examined separately in order to provide applicable solutions. Even though the main focus of this work is to provide solutions for the locally managed channels, the solutions that are proposed will in most cases, benefit not only the local channels but also the Federally managed channels as well. Most solutions must have at least the Corps of Engineers' consent and perhaps its active participation, since the solution will probably affect the Federally maintained channel as well.

6.1 Bayou Casotte Harbor Solutions

Analysis indicates that the main source of depositing sediment in the Bayou Casotte Harbor is tidal inflow carrying suspended sediment from the Mississippi Sound. The currents in the sampled area appear to predominantly transport sediment into the harbor from the southeast direction, as shown in Figure 4-7. Much of the sediment originates from the Mobile Bay and is transported to the area by a predominant westerly current, as shown in Figures 6-1 and 6-2, but temporary reversals of current can bring Pascagoula River sediment to the harbor. This process should be the main focus of a solution designed to keep sediment out.

One potential solution would be to construct a dike that would be designed to reduce the sediment entering into the port. If a dike, depicted in red in Figure 6-3, were to be constructed on the east side of the harbor and extended outward toward the Gulf on the east side of the shipping channel, depicted by the yellow doted lines, it could reduce the amount of sediment that is being transported into the harbor by the westward moving currents. The dike would redirect the currents around the entrance of the harbor which in turn would redirect much of the sediment away from the harbor's entrance. This redirection of the current could also allow for the cleaner water from the west side of the Mississippi Sound to enter the harbor during the tidal cycle. Further studies would need to be conducted in order to obtain a final design and to determine quantitative effectiveness and what changes the new current patterns would have on the areas around the harbor.

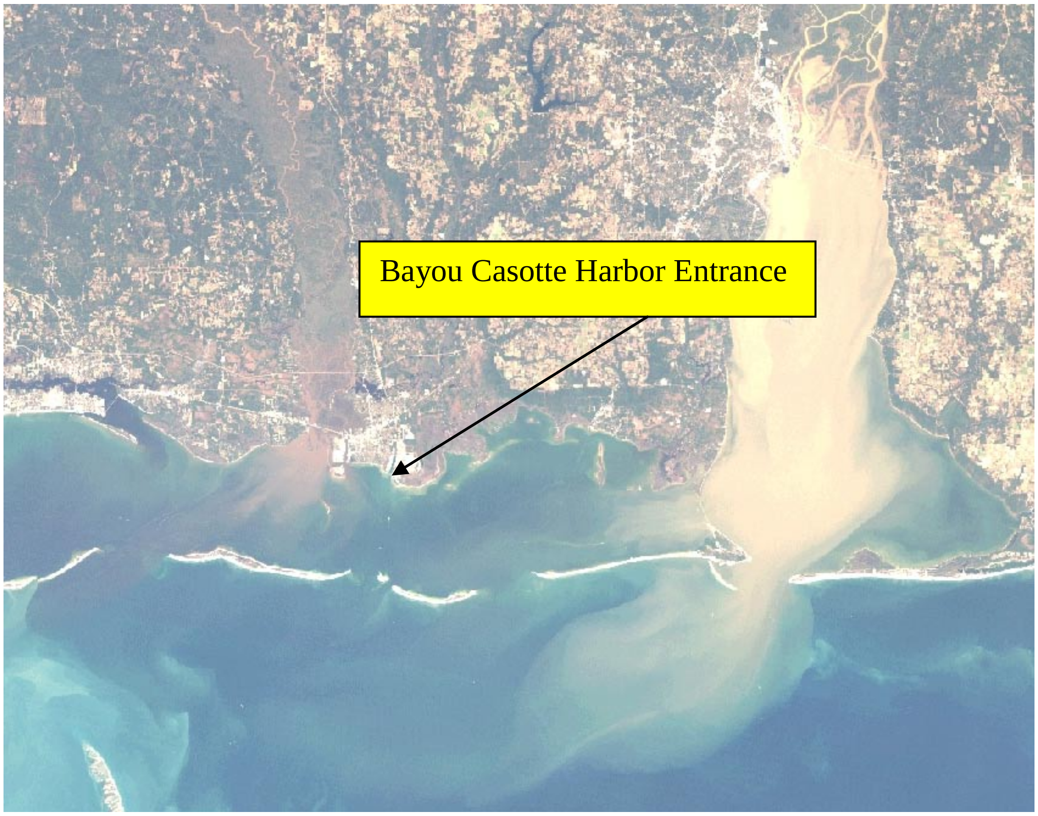


Figure 6-1 Landsat Satellite Photo of Mississippi Sound 12/18/04.

Figure 6-2 Landsat Satellite Photo of Mississippi Sound 01/06/03

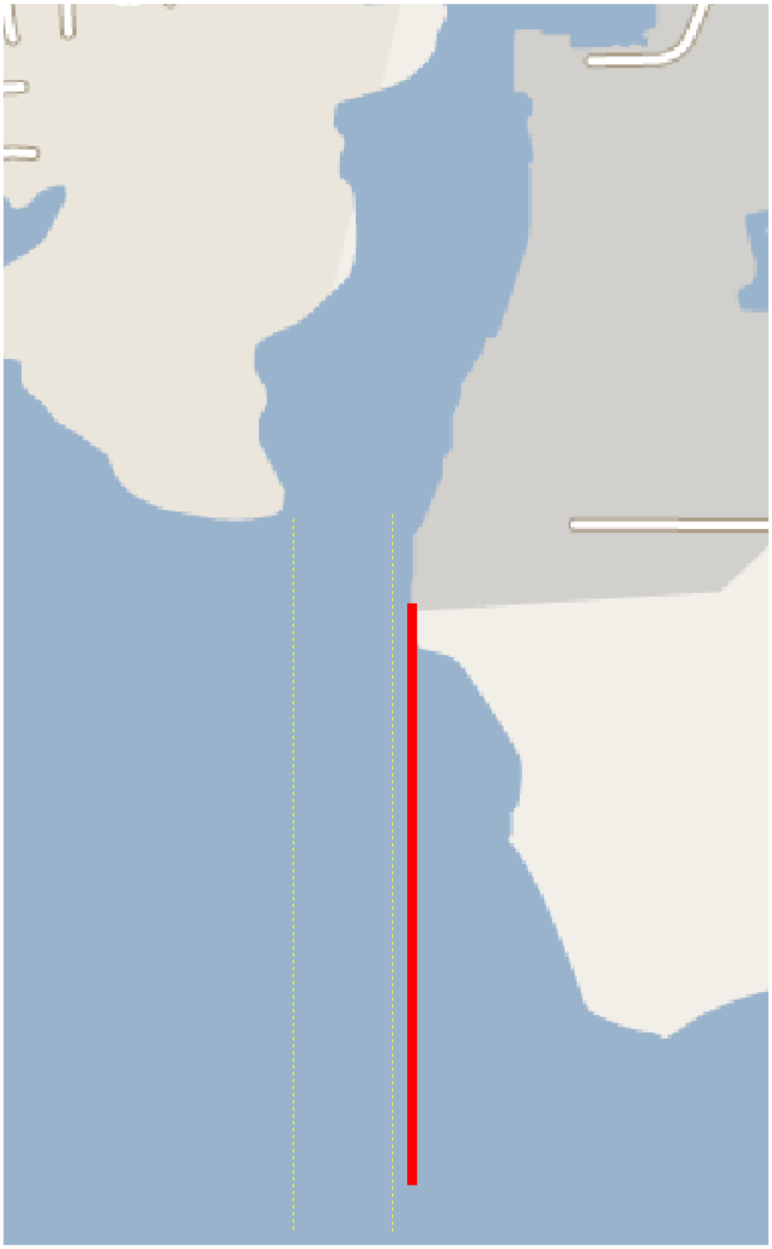


Figure 6-3 Dike Solution for Bayou Casotte (Adapted from Google Maps)

A dike would reduce the amount of sediment entering the port but the cost of constructing a dike large enough to protect the Bayou Casotte Harbor could be great (at least several tens of millions) that it is highly unlikely provide a return on investment sufficient to justify it.

Another possible solution is that of agitation, which has proven effective in several locations. Any vessel that creates a large enough propwash could be used to suspend fine sediment that has deposited on the bottom of the port. Another option is dragging a rake behind a ship to cause the agitation of the deposited sediment. Once the sediment is re-suspended, the ebb phase tidal flows would be the only mechanism for moving the sediment out of the port since there is no significant discharge from the north end of the port to push the material out into the sound.

There are a few factors that are associated with this solution that need to be addressed. Even though there is very little advance preparation necessary in order for agitation to take place, there are several expenses that must be taken into consideration. Table 6-1 illustrates an estimate of how much it would cost to fuel a variety of tugboats. Maintenance costs and personnel costs will also need to be factored in before a final decision can be made. Also agitation practices will need to be approved by the Army Corps of Engineers since some of the agitated materials will deposit in Federally maintained channels.

Table 6-1 Estimates of Fuel Costs* for Tugboats

Horsepower of Tugboats	Hourly Cost for Fuel	4 Hour Cost for Fuel	Annual Cost of Operation for 4 Hours Monthly	Annual Cost of Operation for 4 Hours Weekly
3500	$770	$3,080	$36,960	$160,160
2000	$440	$1,760	$21,120	$91,520
1350	$297	$1,188	$14,256	$61,776

* At $4 per gal

Once the sediment is re-suspended using agitation, how far will the sediment travel relying on tidal currents? Figure 6-4 depicts the distance a particle might travel during a daily tidal cycle. This chart was calculated using the settling velocity of 2.66 mm/s (0.0087 ft/s), which was determined from the particle sizes of the on-site sediment samples, and using an average ebb current of 270 mm/s (0.89 ft/s), which was assumed constant over a 12 hour time period (USACE 2003). From this chart, it is evident that if a particle were suspended to the very top of the water column it could be transported approximately 4,300 ft. out into Mississippi Sound before it was deposited back to the bottom of the channel, which is 42 ft. deep. It should be noted that the majority of the particles are not going to be suspended to the top of the water column. Areas outside the port, that are not in the shipping channel, are much shallower then 42 ft., thus the majority of the suspended sediment will travel a much shorter distance before being depositing on the bed. Once the tidal current changes and starts to flow back into the port, some of the suspended sediment will be transported back into the port where it could deposit itself again. Even if the sediment is not transported completely out of the harbor, the agitation would allow for sediment from areas that are experiencing shoaling to be suspended and distributed to areas that are not having shoaling problems. Agitation of the harbor will need to be examined to see its effects are on the Federal channel. This practice might not completely rid the harbor of excess sediment, but could postpone the need for dredging, resulting in a cost savings in dredge mobilization/demobilization.

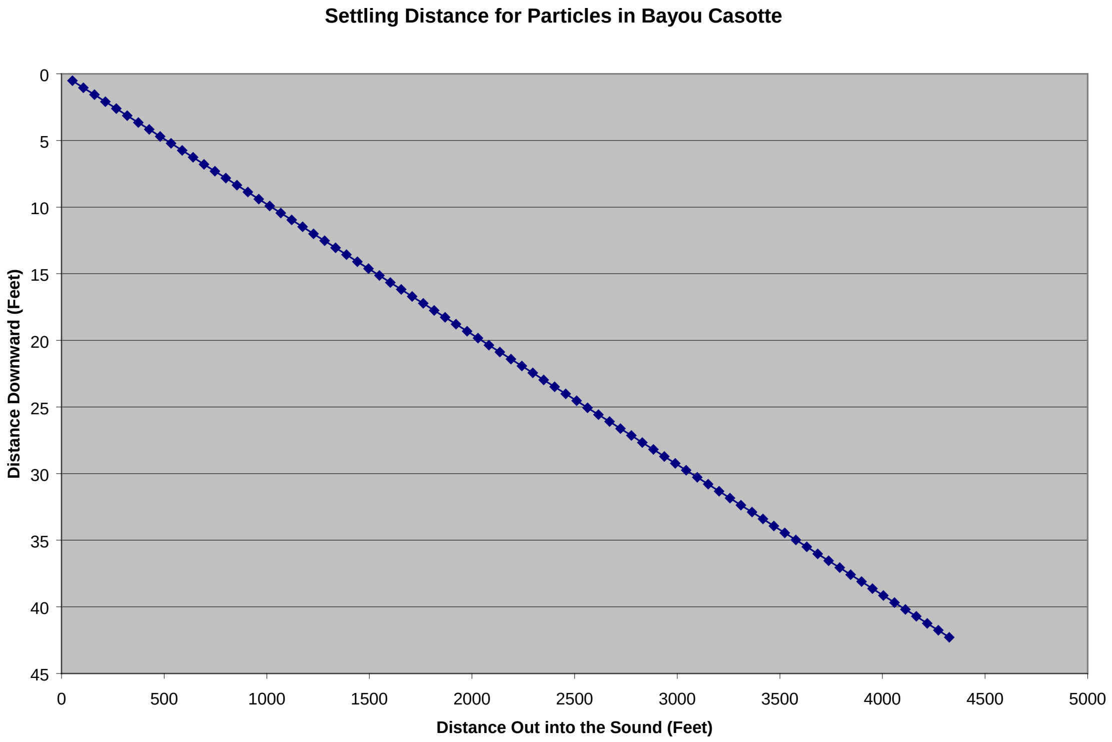


Figure 6-4 Settling Distance for Particles in Bayou Casotte

Since agitation may not fully rid the harbor of excess sediment, it will be necessary to dredge when shoaling becomes a problem. According to officials at the Port of Pascagoula, the local channel of the Bayou Casotte Harbor only has to be dredged every four to six years. With the help of agitation, this timeframe could be extended by several more years. If the agitation were to add a year or two to the frequency of the dredging operations then it would reduce overall costs.

Adoption of a nautical depth standard, either passive or active, might be a viable solution for Bayou Casotte if it is adopted for the Pascagoula River Harbor, discussed below.

6.2 Pascagoula River Harbor Solutions

The main source that contributes to the depositing of sediment in the Pascagoula River Harbor is the Pascagoula River. We believe that a layer of fluid mud is being transported from the Pascagoula River into the harbor causing sedimentation problems. If the fluid mud is contained, it will dramatically reduce the amount of sediment that needs to be removed from the harbor during each dredging operation.

Even though the practice of maintenance dredging is incorporated into the solution for the Bayou Casotte Harbor, it is probably not the best solution for the Pascagoula River Harbor. Since the Pascagoula River Harbor is currently dredged every 18 months, compared to Bayou Casotte every 48 to 72 months, there needs to be a solution proposed that reduces the harbor's dredging costs. In 2000 the Jackson County Port Authority spent around $330,000 to remove 97,000 cubic yards of material. If the cost of dredging is considered constant, the Pascagoula River Harbor costs the Port Authority twice as much in dredging costs as the Bayou Casotte Harbor does every five years. With increases in fuel prices the costs associated with dredging and disposal of sediment materials has gone up since 2000 and undoubtedly will cost the Port Authority much more in the near future. Once all the costs of dredging have been examined, it will be prudent to consider alternative solutions that might decrease the costs associated with dredging.

One solution is be to keep the majority of the sediment out of the harbor by damming tributaries and redirecting most of the river flow from the portion of the Pascagoula River that feeds the harbor to the West Pascagoula River. This type of solution would require constructing multiple dams and other structures. Cost would probably make this solution infeasible, but environmental issues would be the primary determinant. Depriving this section of the majority of its normal flow and cutting potential fish migratory pathways are just a few of the impacts that make this solution impractical.

Trapping sediment into one location where it can be easily removed will allow dredging equipment to be used only in one localized area which will reduce dredging costs even if the dredged volume is not reduced. A single location will allow simpler fixed dredging plant and can take place in an area that will not disrupt the traffic of the port. If the trap is located in an area that is close to a Dredge Material Management Site then the cost associated with the transport and disposal of the material can also be reduced. A sediment trap was implemented in the Savannah Georgia Harbor and was responsible for reducing the unit cost of dredging per cubic yard by half (McAnally et al. 2007b).

Since fluid mud is believed to be the main factor contributing to the transportation of sediment into the harbor, its characteristics need to be taken into trap design consideration. Fluid mud will flow down waterways slopes, so a sloped bottom can channel the fluid mud into a trap. The exact slope that would be necessary to accommodate the characteristics of the harbor sediment would need to be determined experimentally. However, according to a report conducted for the Army Corps of Engineers, a 0.0003 ft/ft slope would be sufficient in many situations (Teeter et al. 2003). This design will have an initial cost for dredging the slope, but this initial cost will be offset by the savings that would be generated by the solution.

Once the fluid mud is moving in the desired direction, then it is necessary to capture it so that it does not deposit in the harbor. This can be done by constructing a fluid mud trap deeper than the rest of the (sloped) channel. The fluid mud would be forced into the trap and then deposit onto the bottom of the trap where it will slowly consolidate until it is removed by dredging.

A sloped bottom and the fluid mud trap, as seen in Figure 6-5, is suggested. The trap would need to be large enough to accommodate the amount of fluid mud that will be entering the port for a given period of time. The size of the fluid mud trap will also depend upon what type of method is used to extract the materials, which will be discussed later. If the trap was to be dredged frequently, then the trap could be relatively small, but if it was to be designed to accommodate the fluid mud that would accumulate within an entire year, then it would need to be fairly large. Dredging a true slope is impractical for most dredging equipment, but a series of level steps descending toward the trap can be easily accomplished.

There are two locations that this solution could be implemented, both of which are located in a Federal managed channel. Since both locations are in Federal channels, cooperation of the Army Corps of Engineers will be needed in order to implement this solution. The Corps of Engineers will benefit from this solution also and it could be part of a Federal project.

The first location is just north of the Pascagoula River Harbor in the river channel, as seen in Figure 6-6. The sloped section is depicted in green and the fluid mud trap is depicted in orange. This location will allow for the fluid mud to be captured in the fluid mud trap before it gets to the harbor. This solution will not help that much with the sediment that is suspended higher in the water column, but will dramatically cut down on the amount of sediment that is entering the harbor as fluid mud from the north.

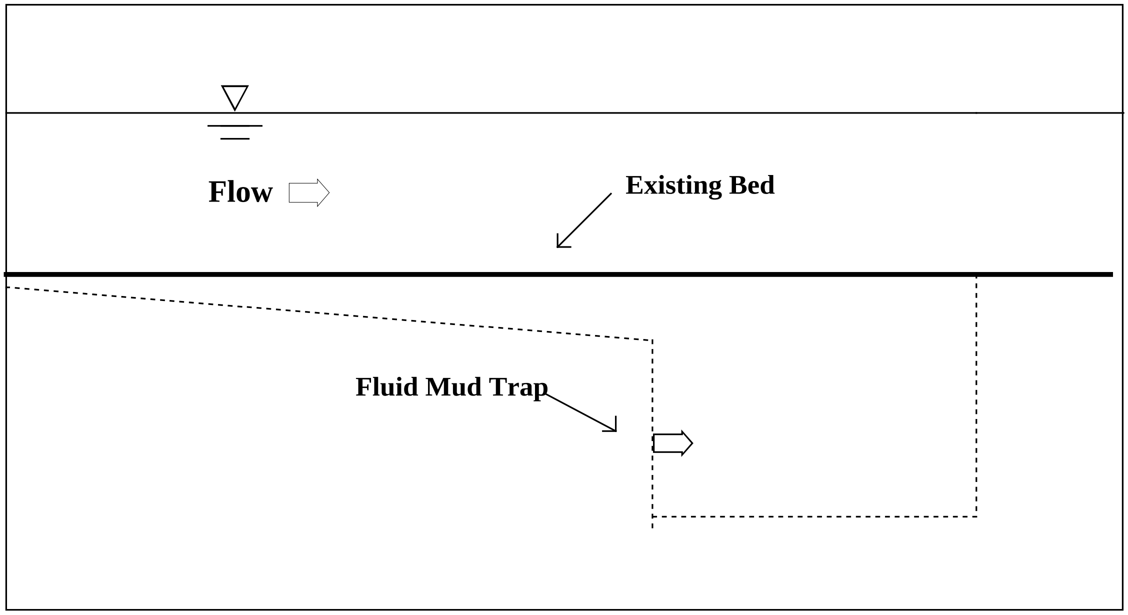


Figure 6-5 Sloped Bottom and Fluid Mud Trap

This site north of the harbor allows the trap to be located out of the main ship channel, leaving the harbor virtually undisturbed during dredging operations. This will allow the harbor to have ships enter on a regular schedule without having to wait for a dredge to finish its operation, thus increasing Port revenues. This area already has a constant slope, depicted with a fluid mud trap in Figure 6-7, which might actually be sufficient to keep the fluid mud moving. However, this slope would have to be examined and studied before a final decision about this site is made.

Figure 6-6 Proposed Trap area north of the harbor (Adapted from Google Maps)

An alternative to locating this solution north of the harbor would be to locate it in the Federal channel within the harbor. This of course would mean that the trap would be either in the shipping channel or directly connected to it, but it would still allow for the sediment to be trapped in a single area. Additional studies would need to be conducted to determine the most effective area for the trap to be placed.

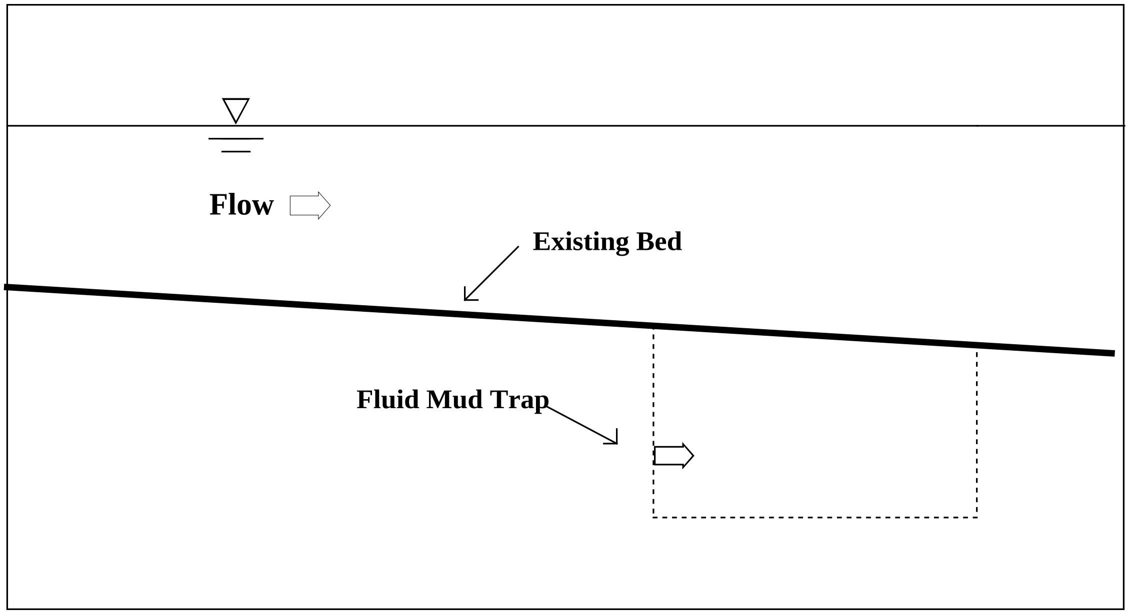


Figure 6-7 Existing Sloped Bottom with Fluid Mud Trap

Once the size and location of the trap are decided, it will be necessary to determine what method to extract the sediment and where to dispose of it. Both proposed locations are relatively close to a Dredge Material Management Site managed by the Jackson County Port Authority. According to Port Engineer, Michael Smith, this Dredge Material Management Site is located on the west bank of Pascagoula River Harbor. If the port authority decides to use this facility, it allows for several options to be considered. One of the methods that could be considered is installing a pump which could be turned on periodically to remove the settling fluid mud and deposit it straight into the Dredge Material Management Site. The Port of Leer in Germany has used a similar method of pumping and it has proven to be successful (PIANC 2008). This method would need to be further examined to ensure that the pump would be able to extract the material effectively. If this method proved to be useful, then the trap could be designed to hold fluid mud that would accumulate in short periods of time. For example, if it was determined that a trap needed to accommodate around 5,000 cubic yards of sediment for a given time period, then this trap would need to be about 50 yards wide, 10 yards long, and 10 yards deep. These dimensions are only used as an example and would need to be changed in order to accommodate the particular area that the trap would be serving.

The Fluid Mud Trap could also be dredged by using a more conventional grab dredge or clamshell dredge which is already being used in the harbor. This method of extraction would require the trap to be relatively large in order to accommodate fluid mud for a longer period of time. If it is decided that the trap would be dredged every year, then the trap would need to be large enough to hold the amount of material that normally settles in both the local and Federal channels. It would also be wise to make the trap larger than the expected amount of fluid mud that deposits in the harbor in order to contain the amount of fluid mud that would have normally passed through the harbor without depositing. The cost for this dredging method will go down since the material will be located in a central area and there is a Dredge Material Management Site nearby. Since this method of dredging is currently being utilized in the harbor, it would be a wise choice as the primary removal method.

There are few issues that would need to be addressed before a plan like this one was adopted as a solution for the harbor. Issues such as possible eutrophication and hypoxia would need to be addressed to see if they would occur in the trap.

This solution might increase the amount of material that needs to be dredged since it will be trapping materials that would have normally passed through the port, but it will reduce costs associated with dredging. Just as in Savannah, Georgia, the unit price could go down as much as 50% which could potentially save the port authority $165,000 for dredging operations in a single year. It will allow for the majority of the sediment deposition to be located in one area which would not only reduce costs, but will allow the port to operate with minimal interruption from dredging which in turn would reduce vessel delays. Both locations, and both methods of dredging, will need to be modeled and further detailed designs made order to decide which variation is best for this harbor's situation.

Another option to be considered by both the Army Corps and the Port Authority is the adoption of the Nautical Depth concept. Adopting a density and viscosity definition of the bed cold produce a dramatic decrease in dredging costs, as in Rotterdam and other world ports as discussed in section 3.1.4. With some sand content, the agitation process may have to be adapted to reduce the effects of non-cohesive materials. (Wurpts 2005).

Active nautical depth is most likely to be successful in Bayou Casotte, where no net flow occurs. In Pascagoula River Harbor, with some net through-flow from the Pascagoula River, modeling and full-scale experiments will be required to determine the relative effectiveness and best procedures for keeping the fluid mud navigable.

Since the areas maintained by the Port and the Corps are contiguous, both would have to implement the practice in order to make it effective.

7. Conclusions and Recommendations

Sedimentation in the Port of Pascagoula is a costly problem for the Jackson County Port Authority and Corps of Engineers.

Bayou Casotte Harbor has fine, cohesive sediment constantly entering the harbor from Mississippi Sound. This sediment deposits itself in several different areas in the harbor, both in the local and Federal channels. Over time, this sediment reduces water depths below that needed for ships using the harbor and requires dredging every 4 to 6 years. Of the sedimentation reductions solutions examined -- construction of a dike, to keep the sediment out; agitation, to get the sediment moving again, and active nautical depth, to enable ships to sail through fluidized sediment suspension – only the latter two are practical. If adopted for both Pascagoula Harbors, active nautical depth is recommended. If active nautical depth is not implemented for Pascagoula River Harbor, then simple agitation dredging is recommended.

The main source of sediment entering the Pascagoula River Harbor is the Pascagoula River. A layer of fluid mud flows into the harbor from the river at the northern end of the harbor. Since fluid mud follows the slope of the bed, it was determined that one course of action will be to slope the bed in the direction of a fluid mud trap. The fluid mud trap will capture the fluid mud in one area where it can be more economically dredged. This proposed solution will reduce the amount of dredging, but should reduce the cost associated with dredging since the dredging operations will be localized to one area. In addition, if the fluid mud trap is located near a Dredge Material Management Site costs will be further reduced.

The Active Nautical Depth concept will allow the fluid mud to be managed by keeping it at a navigable density and viscosity. This approach could substantially reduce or completely eliminate the need for dredging in the harbor.

The Army Corps of Engineers should be approached as a partner for any these solutions, since they will only be effective if adopted for both the Pascagoula Port and Federal channels. The more extensive Federal channels offer a potential for even greater cost savings.

REFERENCES

Bailard, J. A. 1987, Controlling Sedimentation in Harbor Berthing Areas Using Scour Jet Array Systems, in *Sedimentation Control to Reduce Maintenance Dredging of Navigational Facilities in Estuaries*, Marine Board, National Research Council, 141-152

Berenbrock, C. and A. W. Tranmer. 2008. Simulation of Flow, Sediment Transport, and Sediment Mobility of the Lower Coeur d'Alene River, Idaho. USGS Scientific Investigation Report 2008-5093. Reston, Virginia.

Bhowmik, N. G., Adams, J. R., Bonini, A. P., Gou, C. Y., Kisser, D. J. and Sexton, M. A. 1981, *Resuspension and Lateral Movement of Sediment by Tow Traffic on the Upper Mississippi and Illinois Rivers*, Contract Report 269, State Water Survey Division, Illinois Institute of Natural Resources.

Butts, T.A. 1974, *Measurements of Sediment Oxygen Demand Characteristics of the Upper Illinois Waterway*, Report of Investigation 76, Illinois State Water Survey.

Byars, Morgan. S., Lyle W. Zevenbergen, and Peter F. Lagasse, 2000, Hydraulic Design for Channel restoration on the Santa Ana Reach of the Rio Grande, Building Partnerships, Joint conference on Water Resources Engineering and Water Resources Planning and Management, 91/4, American Society of Civil Engineers, Washington, DC.

Chapman, J. E., and W. S. Douglas, 2003, Evaluation of a Berth Sedimentation Control Technology in the Kill can Kull: The Airguard Pneumatic Barrier System, http://www.state.nj.us/transportation/maritime/FINAL%20DRAFT%20022502.pdf Accessed: August 2003.

EIA (2008). Energy Information Administration website. www.eia.doe.gov/, Accessed: (8/25/08).

Executive Office of the President of the United States, USACE, U.S. Department of the Interior, NOAA 2003. *Federal Agencies Reach Consensus Ending Development of the Oregon Inlet Jetty Proposal.* Washington DC.

Francingues, N. R., and Palermo, M. R. 2005. "Silt curtains as a dredging project management practice," *DOER Technical Notes Collection* (ERDC TN-DOER

Francingues, N. R., Clarke, D. G and Palermo, M. R. 2002, Silt Curtains: A Water Column Control Measure for Dredging Operations. DOER Technical Notes. U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Garcia, M., Rodriguez, J., and Admiraal, D. 1999, Effects of navigation on sedimentation, *Proceedings of the 28th Congress of the International Association for Hydraulic Research*, Graz, Austria.

Google Earth (2008). Image of Port of Pascagoula. www.earth.google.com, Accessed: (5/15/08).

Google Maps (2008). Maps of Pascagoula, Mississippi. http://maps.google.com/maps?hl=en&resnum=0&q=pascagoula&um=1&ie=UTF-8&sa=X&oi=geocode_result&resnum=1&ct=image, Accessed: (6/20/08).

Grays Harbor Community College, 1973, *Research to determine the Effectiveness of the Air Bubbler System, Grays Harbor, Wash.* Aberdeen, Washington.

Hales, L. Z. 1995, *Dredge Plant Equipment and Systems Processes; Summary Report For Technical Area 3*, TR DRP-95-10, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Hilton, James D. 2000, U.S. Army Corps of Engineers Dredging Program, Sea Technology, Vol 41, No. 3, March, 21-24.

JCPA (2007). Jackson County Port Authority website. www.portofpascagoula.com, Accessed: (9/13/07).

Jenkins, S. A. 1987, Passive Remedial Sedimentation Control in Parallel Berths and Channels, in *Sedimentation Control to Reduce Maintenance Dredging of Navigational Facilities in Estuaries*, Marine Board, National Research Council, 153-176.

Johnson, J. 1976, Effects of tow traffic on the resuspension of sediments and on dissolved oxygen concentrations in the Illinois and Upper Mississippi Rivers under normal pool conditions, *Technical Report Y-76-1,* Environmental Effects Laboratory, U.S. Army Engineer Waterways Experiment Station.

Julien, P.Y. 2002. *River Mechanics.* Cambridge: Cambridge University Press.

Karaki, S, and J. vanHoften, 1974, *Resuspension of Bed Material and Wave Effects on the Illinois and Upper Mississippi Waterways Caused by Boat Traffic,* Engineering Research Center, Colorado State University, Fort Collins.

Kelderman, P. D. B. Kassie, M. M+Bijlsma, L. C. Okonkwo, and A. A. T. Doppenberg, 1998, Effect of External Shipping Traffic on the Transport of Polluted Sediments into the Inner City Canals of Delft, *Water Science and Technology,* Vol 37, No. 6-7, pp 63-70.

Krishnamurthy, M. 1977. Tidal Prism of Equilibrium Inlets. Journal of the Waterway Port Coastal and Ocean Division. American Society of Civil Engineers.

Kuhnle, Roger A., Carlos V. Alonzo, and Fletcher D. Shields, Jr. 2003, Local Scour Associated with Angled Spur Dikes: Implications for Bank Stability and Aquatic Habitat, U.S. Agricultural Research Service TEKTRAN, March.

Lower Mississippi River Conservation Committee, 2003, Habitat, http://lmrcc.org/Recreation/Fishing/habitat.htm, Accessed 20 October 2003.

Luo, Zhaosen, and Gu Peiyu, 1982, Sedimentation Associated with Tidal Barriers in Chinas Estuaries and Measures for its Reduction, in *Estuarine Comparisons*, Victor Kennedy, ed., Academy Press, New York. pp 611-622.

McAnally, W. H. 1973, *Mixing of Salinity-Stratified Waters by Pneumatic Barriers*, Research Report H-73-4, USAE Waterways Experiment Station, Vicksburg, MS.

McAnally, William H., Friedrichs, C., Hamilton, D., Hayter, E., Shrestha, P., Rodriguez, H., Sheremet, A., Teeter, A. 2007a, Management of Fluid Mud in Estuaries, Bays, and Lakes. I: Present State of Understanding on Character and Behavior. Journal of Hydraulic Engineering, January, American Society of Civil Engineers.

McAnally, William H., Friedrichs, C., Hamilton, D., Hayter, E., Shrestha, P., Rodriguez, H., Sheremet, A., Teeter, A. 2007b, *Management of Fluid Mud in Estuaries, Bays, and Lakes. I: Measurement, Modeling, and Management.* Journal of Hydraulic Engineering, January, American Society of Civil Engineers.

McLellan, T. Neil and Robert J. Hopman, 2000, *Innovations In Dredging Technology: Equipment, Operations, and Management*, ERDC DOER TR-5, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

MDOT (2007). Mississippi Department of Transportation website. “Pascagoula facilities page.” http://www.mdot.state.ms.us/ports/PscgFac.htm, Accessed: (9/13/07).

MDOT 2004, McAnally, William H., Julie F. Haydel, and Gaurav Savant. *Port Sedimentation Solutions for the Tennessee-Tombigbee Waterway in Mississippi.* Department of Civil Engineering. Mississippi State University.

NOAA (2007). National Oceanic and Atmospheric Administration website. “Mobile District Dredging Activities.” http://www.noaa.gov/, Accessed: (9/19/07).

Parchure, T. M. and A. M. Teeter, 2002, *Potential Methods of Reducing Shoaling in Harbors and Navigation Channels*, CHETN-XIV-6, Engineer Research and Development Center, Vicksburg, MS, June.

PIANC 2008, Minimizing Harbor Siltation. Report No. 102-2008, World Association for Waterborne Transport Infrastructure, Brussels, Be.

Pinkard, C. Fred, 1995, Red River Waterway*:* A Sedimentation Challenge*, Proceedings of the 1st International Conference on Water Resources*, Part 1, American Society of Civil Engineers, Washington, DC.

Qaisi, K.M.; Constant, W.D.; Thibodeaux, L.J. 1997, Impact of Barge Traffic on Stream reaeration: Laboratory Experiments, *Journal of Environmental Engineering*, p 716-719, July.

Richardson, T. W. 1984, *Agitation Dredging: Lessons and Guidelines from Past Projects,* Technical Report HL-84-6, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Richardson, T. W. and E. C. McNair, 1981, A guide to the Planning and Hydraulic Design of Jet Pump Remedial Sand Bypassing Systems, IR-81-1, USAE Waterways Experiment Station, Vicksburg, MS.

Rodriguez, F. J., Garcia, M. H., Admiraal, D. M. and Lopez, F. 2000, Statistical analysis of unsteady bed shear stresses: Implications for sediment resuspension," *Proceedings 14th Engineering Mechanics Conference*, Austin, TX.

Rodriguez, F. J., Garcia, M. H., and Admiraal, D. M. 1999, Computation of Navigation-Induced Sediment Resuspension, *Proceedings of the 1999 International Water Resources Engineering Conference*, Seattle, WA.

Shields, F. D., S. S. Knight, and C. M. Cooper, 1995, Streambank Protection and Habitat Restoration, Proceedings of the 1st International Conference on Water Resources, Part 1, American Society of Civil Engineers, Washington, DC.

Smith, T. J., R. Kirby, and H. Christiansen, 2001, "Entrance flow control to reduce siltation in tidal basins," in *Coastal and Estuarine Fine Sediment Processes*, W. H. McAnally and A. J. Mehta, Eds., Elsevier, Amsterdam.

Teeter, A. M. 1989, *Effects of Cooper River Rediversion flows on shoaling Conditions at Charleston Harbor, Charleston, South Carolina,* Technical Report HL-89-3, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Teeter, A. M., Fagerburg, T., Waller, T., Benson, H., Brister, D., and McAdory, R. 2003, *Factors Affecting Fluff and Fluid Mud Accumulation in the Atchafalaya Bar Channel,* U.S. Army Corps of Engineers Research and Development Center, Vicksburg, Mississippi.

Torontoport. 2003, Dredging up an environmental solution, http://www.torontoport.com/thc/portprofile.asp, accessed October 2003.

USACE (2008). United States Army Corps of Engineers Mobile District website. "Hydrographic Surveys." http://navigation.sam.usace.army.mil/surveys/index.asp, Accessed: (5/12/08).

USACE, 1985, Pascagoula Harbor, Mississippi Feasibility Report on Improvement of the Federal Deep-Draft Navigation Project, U.S. Army Engineer District, Mobile.

USACE, 1989, Engineering and Design – Sedimentation Investigations of Rivers and Reservoirs, U.S. Army Corps of Engineers.

USACE, 2002, Lessons Learned from Existing Projects on Shoaling in Harbors and Navigation Channels, U.S. Army Corps of Engineers, ERDC.

USACE, 2003, Environmental Engineering on the Mississippi River, The Solutions, St. Louis District, http://www.mvs.usace.army.mil/engr/river/EnvironEng/en12.htm. Accessed 25 July 2003.

USACE, 2003, Evaluation of Island and Nearshore Confined Disposal Facility Alternatives, Pascagoula River Harbor Dredged Material Management Plan, U.S. Army Engineer District, Mobile.

USACE, 2006, *Site Management and Monitoring Plan*, U.S. Army Engineer District, Mobile.

USACE, 2007, *Pascagoula Harbor Navigation Channel*, U.S. Army Engineer District, Mobile.

Van Dorn, William G., D. L. Inman, and R. W. Harris, 1975, *The Evaluation of Sediment Management Procedures, Phase I Final Report, 1974-1975*. SIP Reference Series 75-32, Scripps Institution of Oceanography, University of California, La Jolla.

Wikipedia (2008). "Dredging." http://en.wikipedia.org/wiki/Dredging, Accessed: (7/22/08).

Wurpts, R. 2005, 15 Years Experience with Fluid Mud: Definition of the Nautical Bottom with Rheological Parameters. Terra et Aqua, Issue 99 June 2005.

APPENDIX: Sediment Data

Table A-1 Complete TSS Port of Pascagoula June 3, 2008

Filter ID	Sample ID	Sample Description	Volume Filtered (mL)	Filter Weight (g)	Filter + Resid. Weight (g)	TSS (mg/L)
1	LB-1	Laboratory Blank # 1	500	0.1331	0.1329	-0.30
2	B-35	Station 1 depth of 1’ (water sample)	500	0.1349	0.1381	6.40
3	B-23	Station 1 depth of 15’ (water sample)	500	0.1334	0.1389	11.00
4	A-23	Station 1 bottom sample (water sample)	500	0.1327	0.1759	86.40
5	A-40	Station 2 depth of 1’ (water sample)	500	0.1336	0.1426	17.90
6	D-3	Station 2 depth of 15’ (water sample)	500	0.1334	0.1411	15.40
7	B-34	Station 2 bottom sample (water sample)	500	0.1329	0.1425	19.20
8	B-21	Station 3 depth of 1’ (water sample)	500	0.1329	0.1360	6.30
9	C-4	Station 3 depth of 15’ (water sample)	500	0.1324	0.1398	14.90
10	Dupl-1	Laboratory Duplicate # 1(sample C-4)	500	0.1324	0.1406	16.40
11	B-31	Station 3 bottom sample (water sample)	500	0.1336	0.1405	13.80
12	B-4	Station 4 depth of 1’ (water sample)	500	0.1319	0.1373	10.80
13	B-2	Station 4 depth of 15’ (water sample)	500	0.1330	0.1383	10.70
14	A-24	Station 4 bottom sample (water sample)	500	0.1336	0.1474	27.70
15	A-14	Station 5 depth of 1’ (water sample)	500	0.1350	0.1423	14.60
16	A-13	Station 5 depth of 15’ (water sample)	500	0.1339	0.1403	12.80
17	C-14	Station 5 bottom sample (water sample)	500	0.1345	0.1481	27.10
18	B-9	Station 6 depth of 1’ (water sample)	500	0.1325	0.1416	18.30
19	A-32	Station 6 depth of 15’ (water sample)	500	0.1333	0.1389	11.20
20	LB-2	Laboratory Blank # 2	500	0.1341	0.1337	-0.80
21	C-8	Station 6 bottom sample (water sample)	500	0.1330	0.1564	46.80
22	A-29	Station 7 depth of 1’ (water sample)	500	0.1322	0.1372	10.00
23	C-24	Station 7 depth of 15’ (water sample)	500	0.1327	0.1388	12.10

Table A-1 (continued)

24	B-30	Station 7 bottom sample (water sample)	500	0.1350	0.1587	47.40
25	B-24	Station 8 depth of 1’ (water sample)	500	0.1329	0.1403	14.70
26	Dupl-2	Laboratory Duplicate # 2 (sample B-24)	500	0.1334	0.1409	15.00
27	B-8	Station 8 depth of 15’ (water sample)	500	0.1351	0.1500	29.80
28	C-19	Station 8 bottom sample (water sample)	500	0.1343	0.3811	493.70
29	D-1	Station 9 depth of 1’ (water sample)	500	0.1321	0.1409	17.50
30	A-6	Station 9 depth of 15’ (water sample)	500	0.1343	0.1528	36.90
31	B-10	Station 9 bottom sample (water sample)	500	0.1336	0.1635	59.80
32	B-33	Station 10 depth of 1’ (water sample)	500	0.1327	0.1376	9.80
33	A-33	Station 10 depth of 15’ (water sample)	500	0.1342	0.1390	9.60
34	D-2	Station 10 bottom sample (water sample)	500	0.1340	0.1671	66.20
35	A-37	Station 11 depth of 1’ (water sample)	500	0.1332	0.1373	8.30
36	Dupl - 3	Laboratory Duplicate # 3 (sample A-37)	500	0.1350	0.1395	9.00
38	C-7	Station 11 depth of 15’ (water sample)	500	0.1342	0.1428	17.30
40	LB-3	Laboratory Blank # 3	500	0.1334	0.1338	0.90
41	A-10	Station 11 bottom sample (water sample)	500	0.1325	0.1389	12.70
43	A-28	Station 12 depth of 1’ (water sample)	500	0.1309	0.1395	17.20
45	C-10	Station 12 depth of 15’ (water sample)	500	0.1320	0.1390	14.10
46	Dupl-4	Laboratory Duplicate # 4 (sample C-10)	500	0.1333	0.1397	12.80
48	B-38	Station 12 bottom sample (water sample)	500	0.1324	0.1449	25.00
50	A-34	Station 13 depth of 1’ (water sample)	500	0.1325	0.1403	15.60
52	B-36	Station 13 depth of 15’ (water sample)	500	0.1341	0.1402	12.10
54	A-19	Station 13 bottom sample (water sample)	500	0.1326	0.1466	28.10
56	Dupl-5	Laboratory Duplicate # 5 (sample A-19)	500	0.1329	0.1458	25.80
57	B-16	Station 14 depth of 1’ (water sample)	500	0.1327	0.1387	11.90

Table A-1 (continued)

59	B-7	Station 14 depth of 15’ (water sample)	500	0.1322	0.1387	12.90
61	B-28	Station 14 bottom sample (water sample)	500	0.1310	0.3387	415.30
63	D-4	Station 15 depth of 1’ (water sample)	500	0.1331	0.1391	12.00
65	B-18	Station 15 depth of 15’ (water sample)	500	0.1338	0.1386	9.50
67	C-11	Station 15 bottom sample (water sample)	500	0.1320	0.1669	69.80
69	LB-4	Laboratory Blank # 4	500	0.1330	0.1331	0.20

Table A-2 Complete TSS Port of Pascagoula June 15 and 17, 2008

Filter ID	Sample ID	Sample Description	Volume Filtered (mL)	Filter Weight (g)	Filter + Resid. Weight (g)	TSS (mg/L)
1	LB 1	Laboratory Blank # 1	500	0.1305	0.1303	-0.4
2	X-1	Station 2 depth of 1' (8:22)	500	0.1287	0.1328	8.1
3	D-3	Station 2 bottom sample (8:22)	500	0.1297	0.1451	30.9
4	X-2	Station X depth of 1' (8:33)	500	0.1292	0.1329	7.4
5	C-14	Station X bottom sample (8:33)	500	0.1296	0.1357	12.1
6	X-3	Station Y depth of 1' (9:03)	500	0.1288	0.1358	14.0
7	A-34	Station Y bottom sample (9:03)	500	0.1289	0.1413	24.8
8	C-11	Station Y depth of 1' (17:40)	500	0.1282	0.1325	8.7
9	A-28	Station Y bottom sample (17:40)	500	0.1294	0.1467	34.7
10	X-4	Station 2 depth of 1' (17:50)	500	0.1295	0.1331	7.3
11	X4-D	Laboratory Duplicated of sample X4	500	0.1284	0.1325	8.3
12	X5-D	Laboratory Duplicated of sample X5	500	0.1290	0.1361	14.2
13	X-5	Station 2 depth of 1' (8:17)	500	0.1304	0.1385	16.2
14	A-40	Station 2 bottom sample (8:17)	500	0.1293	0.1674	76.2
15	LB 2	Laboratory Blank # 2	500	0.1291	0.1291	-0.1
16	B-38	Station X depth of 1' (8:24)	500	0.1291	0.1328	7.4
17	A-29	Station X bottom sample (8:24)	500	0.1299	0.1402	20.7

Table A-2 (continued)

18	C-7	Station Y depth of 1’ (8:40)	500	0.1283	0.1438	31.0
19	B-30	Station Y bottom sample (8:40)	500	0.1272	0.1435	32.7
20	B-36	Station Y depth of 1’ (15:33)	500	0.1284	0.1340	11.2
21	X-6	Station Y bottom sample (15:33)	500	0.1303	0.1366	12.6
22	B-7	Station 2 depth of 1’ (15:54)	500	0.1295	0.1339	8.8
23	X-7	Station 2 bottom sample (15:54)	250	0.1279	0.2108	331.6
24	C-10	Station X depth of 1’ (16:04)	500	0.1286	0.1475	37.9
25	C-24	Station X bottom sample (16:04)	500	0.1292	0.1423	26.3
26	B1	Pascagoula hour 1	500	0.1279	0.1399	23.9
27	B2	Pascagoula hour 2	500	0.1301	0.1428	25.4
28	B3		500	0.1287	0.1379	18.3
29	B6-D	Laboratory Duplicated of sample B6	250	0.1296	0.1402	42.4
30	LB 3	Laboratory Blank # 3	500	0.1311	0.1311	-0.1
31	B4	Pascagoula hour 4	500	0.1294	0.1438	28.8
32	B5	Pascagoula hour 5	500	0.1280	0.1348	13.6
33	B6	Pascagoula hour 6	250	0.1304	0.1401	38.6
34	B7	Pascagoula hour 7	500	0.1306	0.1422	23.1
35	B8	Pascagoula hour 8	500	0.1301	0.1392	18.2
36	B9	Pascagoula hour 9				
37	B10	Pascagoula hour 10	500	0.1283	0.1361	15.7
38	B11	Pascagoula hour 11	500	0.1299	0.1429	25.9
39	B12	Pascagoula hour 12	250	0.1298	0.1367	27.4
40	B12-D	Laboratory Duplicated of sample B12	250	0.1309	0.1388	31.6
41	B13	Pascagoula hour 13	500	0.1297	0.1397	20.0
42	B14	Pascagoula hour 14	500	0.1293	0.1433	27.9
43	B15	Pascagoula hour 15	500	0.1293	0.1427	26.8
44	B16	Pascagoula hour 16	500	0.1293	0.1426	26.6
45	LB 4	Laboratory Blank # 4	500	0.1294	0.1292	-0.4
46	B17	Pascagoula hour 17	500	0.1295	0.1417	24.5
47	B18	Pascagoula hour 18	450	0.1296	0.1413	26.0
48	B19	Pascagoula hour 19	500	0.1288	0.1416	25.6
49	B20	Pascagoula hour 20	500	0.1306	0.1393	17.3
50	B21	Pascagoula hour 21				
51	B22	Pascagoula hour 22	500	0.1293	0.1384	18.2
52	B23	Pascagoula hour 23	500	0.1285	0.1384	19.8
53	A1-D	Laboratory Duplicated	250	0.1285	0.1873	235.0

Table A-2 (continued)

54	B24	Pascagoula hour 24				
55	A1	Bayou hour 1	250	0.1281	0.1975	277.8
56	A2	Bayou hour 2	500	0.1283	0.1626	68.7
57	A3	Bayou hour 3	500	0.1288	0.1817	105.9
58	A4	Bayou hour 4	500	0.1295	0.1621	65.2
59	A5	Bayou hour 5	500	0.1291	0.1533	48.3
60	LB 5	Laboratory Blank # 5	500	0.1275	0.1273	-0.4
61	A6	Bayou hour 6	500	0.1276	0.1579	60.6
62	A7	Bayou hour 7	500	0.1285	0.1629	68.9
63	A8	Bayou hour 8	500	0.1266	0.1483	43.4
64	A9	Bayou hour 9	500	0.1281	0.1568	57.4
65	A10	Bayou hour 10	500	0.1281	0.1443	32.3
66	A11	Bayou hour 11	500	0.1283	0.1513	46.1
67	A12	Bayou hour 12	500	0.1279	0.1457	35.5
68	A13	Bayou hour 13	500	0.1289	0.1468	35.7
69	A14	Bayou hour 14	500	0.1285	0.1472	37.3
70	A15	Bayou hour 15	500	0.1291	0.1556	52.9
71	A16	Bayou hour 16	500	0.1285	0.1456	34.3
72	A17	Bayou hour 17	500	0.1285	0.1426	28.1
73	A18	Bayou hour 18	500	0.1293	0.1383	17.9
74	A19	Bayou hour 19	250	0.1295	0.1361	26.4
75	LB 6	Laboratory Blank # 6	500	0.1280	0.1278	-0.4
76	A19-D	Laboratory Duplicated of sample A19	250	0.1278	0.1344	26.4
77	A20	Bayou hour 20	500	0.1294	0.1401	21.4
78	A21	Bayou hour 21	500	0.1262	0.1405	28.7
79	A22	Bayou hour 22	500	0.1283	0.1372	17.9
80	A23	Bayou hour 23	500	0.1291	0.1396	20.9
81	A24	Bayou hour 24	500	0.1279	0.1428	29.7
82	LB 7	Laboratory Blank # 7	500	0.1293	0.1292	-0.3