Section 3
Site Conceptual Model

A site conceptual model (SCM) discussion presented here is intended to describe the dynamic nature of Calcasieu Estuary. By definition, an estuary is a complex set of interacting systems where change and variability is commonplace. The following sections will identify the primary elements from which to build an understanding of the complex interactions and relationships inherent to the estuarine system. Understanding these components and interactions will assist stakeholders in identifying impacts and potential receptors. The SCM will introduce the dynamic features of a generic estuary followed by a discussion of the features specific to the Calcasieu Estuary.

3.1 Introduction

Calcasieu Estuary is a complex estuarine system, consisting of numerous perennial wetland bayous and tributaries in a heavy industrial setting (Section 2). Surface water and sediment character (salinity, flow energy, sediment grain size, etc.) define the behavior of the estuarine environment.

The SCM is intended to describe the nature of the different environs of the estuary; identify the interrelationships between soil, sediment, surface water, and groundwater impacts to the system; and identify potential ecological and human receptors. Figure 3-1 presents a schematic overview of the estuary systems that exist in Calcasieu. The legend lists elements shown on Figure 3-1. The elements illustrate the site conditions, common activities, historic impacts to the system, and potential receptors.

It should be noted that the figure is intended to present general conditions schematically and does not represent a specific region of the estuary. The SCM provides an overview of the conditions and system dynamics that may control the presence or absence of chemicals throughout the estuary.

3.2 Nature of Calcasieu Estuary

The Calcasieu River is a major tributary in southwestern Louisiana, with its headwaters in Vernon Parish approximately 344 km north of its entry into the Gulf of Mexico. The estuary consists of numerous perennial wetland bayous and other tributaries. Calcasieu River in the area of interest (approximately 54 km from the saltwater barrier to the Gulf) empties into Calcasieu Lake and exits through Calcasieu Pass into the Gulf of Mexico. The history and environmental setting of Calcasieu Estuary are described in Sections 1 and 2.

The term estuary is used to describe, "a semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with freshwater derived from land drainage" (Pritchard 1967). Pritchard defines four types of estuaries based upon physical characteristics and geologic setting: drowned river valley, fjord, bar-built, and tectonic.

Calcasieu Estuary is a drowned river valley system. Pritchard's description of the drowned river valley is "a wide coastal plain; only a portion of the area affected by tides [eg.] is estuarine, based on salinity diluted by freshwater"(Pritchard 1967). This description is valid for Calcasieu as tidal activity, although minor, is sometimes experienced well into the upper portions of the estuary where salinity ranges from 1 to 10 parts per thousand (ppt).

Estuaries may be further defined based on salinity of the system (Chapman 2001). Classification is based upon the relationship between fresh and saltwater. There are effectively three types of estuaries based on salinity regime: salt-wedge, partially mixed systems, and vertically homogeneous (Chapman 2001).

Salt Wedge Estuaries

Salt-wedge estuaries are characterized by a freshwater/saltwater interface located near the mouth of the estuary. The saltwater is in the form of a wedge, with low salinity water located on top of and upgradient of the saltwater.

Salt-wedge estuaries are characterized by a large river flow compared to the tidal flow. The wedge forms when the freshwater flows seaward and encounters the denser seawater. The freshwater flows on top of the denser saltwater. The freshwater/saltwater interface is simultaneously pushed seaward due to shear in the fluid flow. When the shear reaches a critical threshold, waves form and break on the interface, and a thin layer of saltwater is mixed with the overlying freshwater. The process is termed "entrainment". A compensating landward flow occurs within the upper surface of the salt wedge. With the exception of the upper surface of the wedge, the salinity is nearly constant within the wedge. During flood tide, the salt wedge flows landward while the low salinity surface water continues to flow seaward. During ebb tide, the flow within the wedge can be reversed and flow seaward. Temperature appears to have an influence in development of the salt-wedge salinity regime, adding to the density stratification of the water column (Duke 1985). Salt-wedge estuaries tend to be narrow, which has the effect of decreasing the tidal prism (or total volume of water introduced by the tide) for a given tidal range compared to a wide estuary.

Partially Mixed Estuaries

Partially mixed estuaries have a greater tidal influence (compared to river influence) than highly stratified estuaries. The tidal influence causes the water within the estuary to oscillate, which has the effect of introducing a large amount of energy into the system. The energy is dissipated within the estuary by working against frictional forces on the bottom. The resulting turbulence works against the density gradients, producing partial mixing. Saltwater eddies mix with the overlying freshwater, which adds to the volume of the surface water, resulting in an enhanced seaward flow within the upper waters. The volume of water lost from the lower layer is compensated by landward flow of seawater. The result is a characteristic flow pattern within partially mixed estuaries.

In partially mixed estuaries with the appropriate depth and width, the tides can enter the mouth, propagate up the estuary, and reflect from the upstream end, either interfering with or amplifying the incoming waves. The tidal patterns can influence the flow velocities and can be used to explain turbidity maxima and deposition patterns within the estuary (Dyer 1972).

Vertically Homogeneous Estuaries

Vertically homogenous estuaries are characterized by very strong tidal influences compared to river flow and a high width to depth ratio. Like the partially mixed estuary, the tidal energy is dissipated by friction with the bottom. However, in the vertically homogenous estuary, a greater proportion of the bottom is in contact with the water (due to the high width to depth ratio), resulting in greater turbulence and more thorough mixing.

Salinity Fluctuations in Calcasieu Estuary

Salinity also fluctuates seasonally. On average, salinity freshens during winter and spring months, driven by increased groundwater recharge, wind forcing, precipitation, and decreased tidal surge. The bayous tend to be gaining streams, with groundwater discharge to the bayous from the saturated 10-foot, 20-foot, and 30-foot sands. The groundwater inflow, combined with the effect of offshore winds, tends to freshen the bayous.

As these conditions decrease or reverse by April or May, salinity increases, generally peaking around June or July. Salinity is generally higher during summer months due to tidal flooding associated with the cyclone season. Saltwater brought landward during flood tide is thought to become trapped in the system and slowly bleed out over subsequent ebb tides. Tidal flooding effects tend to predominate over precipitation.

The Calcasieu Ship Channel alters the salinity regime of the estuary by providing a greater avenue for saltwater intrusion. The effect can be noted in the salinity increases and the changes in vegetation present in the marshes throughout the estuary (LDNR 2002).

Surface water salinity measurements from various studies indicate that the Calcasieu Estuary system varies vertically, laterally, and spatially as noted in Figure 3-2, becoming fresh in the upstream segments of the bayous and approaching 20 ppt salinity in Moss Lake. The vertical component, however, is variable; it ranges from salt wedge to homogeneous, and varies notably with each season. RI sampling indicated a homogeneous salinity regime; this is in contrast to mid summer investigations which observed a salt-wedge regime (Duke 1985).

Calcasieu Estuary is a major hatchery; however, from 1948 through 1969, the estuary underwent significant habitat change (salinity increases and vegetation loss). The changes were the result of combined events. Hurricane Audrey, common oilfield drilling practices, a series of droughts, and nutria herbivory all attributed to the habitat changes noted in the early 1960s. Various habitat shifts have been noted for 1949, 1968, 1978, 1988, and 1997 using digital versions of coastal vegetation maps (Chabreck 1972; LDNR 2002). The greatest shift was noted from 1949 to 1960. Habitat shifts from intermediate to brackish and back to intermediate within Calcasieu marshes indicate the system is dynamic and sensitive to change.

Flow Rates

The three main types of estuaries can be described by the water balance, flow and salinity patterns, and the width to depth ratio of the cross section. However, a quantitative method for classifying an estuary based on stratification has been developed (Simmons 1955) by use of a parameter called the flow ratio. The flow ratio is simply the river flow per tidal cycle divided by the tidal prism. Simmons defined a highly stratified estuary as having a flow ratio greater than or equal to 1.0, a partially mixed estuary as having a flow ratio approximately equal to 0.25, and a vertically homogeneous estuary as having a flow ratio less than 0.1. While the quantitative classification is useful, it should not be used blindly without considering the other characteristics of the different estuary types. Exhibit 3-1 summarizes the criteria used to define each type.

Exhibit 3-1 Characteristics of Estuary Type[1]

Parameter	Highly Stratified Salt Wedge	Partially Mixed	Vertically Homogeneous Laterally Homogeneous
Flow Ratio	≥ 1.0	≈ 0.25	< 0.10
River Flow	High	Low-Intermediate	Low
Tidal Prism	Low	Intermediate-High	High
Width/Depth	Low	Intermediate	Intermediate
Depth	Shallow	Shallow-Intermediate	Shallow
Circulation Type	Seaward above interface Landward below interface	Seaward (surface) Landward (deep)	Seaward
Energy	Low	Intermediate	Intermediate - High

1. Characteristics are based on Pritchard (1955).

Based on published information, the Calcasieu Estuary is classified as vertically homogeneous. The influence of strong winds, tidal energy, and the overall shallow depth (about 2 m with the exception of the ship channel) result in a relatively high-energy environment and vertical mixing. The flow of the Calcasieu River is also generally low (~30 cubic meters per second [m^3/sec.] Lee et al. 1990) while the tidal prism is large (3.91×10^7 m^3 [Lee 1990]). The flow ratio is calculated to be 0.03 (30 m^3/sec./[3.91×10^7 m^3/44,760 sec.] = 0.03 unitless). The flow ratio, along with the estuary characteristics, strongly indicates a vertically mixed estuary (see Exhibit 3-1).

However, in the early summer, the river flow can reach 300 to 400 m^3/sec., resulting in a flow ratio of 0.46, which is intermediate between partially mixed and highly stratified. This corresponds to observations by Duke in the summer of 1985 and the RI observations during the winter of 1999 and 2000.

In estuaries where the ratio of river flow to tidal flow changes seasonally, the estuary type can change from one time of the year to the next. For example, Calcasieu Estuary tends to become highly stratified in early summer due to a general reduction in precipitation and increase in water temperature that amplifies the water density effects, increasing salinity stratification.

Estuary type can also change from one portion of an estuary to another. For example, a partially mixed salinity profile near the mouth may give way to a salt-wedge structure toward the head of the estuary where tidal forces are less pronounced. Constrictions such as bridge abutments can also change the stratification patterns by forcing a given tidal flow through a smaller cross sectional area, which results in a greater flow velocity and degree of turbulence and mixing. Conversely, widening of the estuary can cause the degree of stratification to increase due to a decrease in the flow velocity; this effect is notable as the bayous enter the ship channel.

Wind forcing can affect estuary stratification and circulation patterns by enhancing or restricting surface water flows. The effect can be pronounced within shallow estuaries where the surface water makes up a greater fraction of the total volume of the estuary. Geyer (1997) studied wind effects on two shallow estuaries in Cape Cod and found that during offshore wind events the outward flow to the sea was enhanced and that the overall salinity of the estuary decreased as a result. Onshore winds resulted in an increased salinity. The effects of wind were less in areas with constrictions, which was evidenced by strong salinity fronts in these areas.

3.3 Energy System Classification

The nature of Calcasieu Estuary is best described by total energy. Specific regions of the estuary have been grouped into one of five energy system classes, including bayous, marshes, shallow lakes, shipping channels, and river (Figure 3-3). One small area that does not fit these broad energy system descriptions has been categorized as "other". The energy of a specific area will influence surface water variability and sediment nature and stability. Each system influences the nature and behavior of surface water and sediment differently.

Depositional environment, surface water conditions, and stability of the sediment can be used to group the energy regimes observed in the estuary and to describe the behavior of the system as a whole. Sediment stability was not measured directly but is inferred by total suspended solids (TSS), grain-size, relative surface water flow, and geometry. An overview of the characteristics and a description of the physical parameters of each of the energy systems are provided below. Detailed discussion of the physical parameters associated with each of the specific areas will be provided in Sections 7 through 10.

3.3.1 Bayou

The bayou is the natural tributary portion of the estuary (Figure 3-1; Item 1). The bayous of interest in this RI may contain fresh to intermediate salinity water and may flow into or through higher salinity marshes prior to connecting with a larger body of water (e.g., the ship channel, shallow lake, or river). In the undisturbed setting, each has similar flow and geometry characteristics. In the current industrialized setting, the primary bayous: Bayou Verdine, Contraband Bayou, Bayou d'Inde, Bayou Olsen, and Bayou Guy are receiving waters for NPDES industrial or municipal outfalls (Figure 3-1; Item 5). Some of the bayous receive run-off from rice or soybean fields or urban neighborhoods (Figure 3-1; Item 14). The bayou drainage basins are host to various industrial, municipal, and agricultural developments.

The upper reaches of Bayou Verdine and Bayou d'Inde (upstream of LA Hwy-108) are areas not heavily impacted by industrial development. These areas are typically steep sided, vegetated, supporting fresh to intermediate habitat, shallow tributaries (water column generally less than 3 m thick), with thick layers of soft, clayey silt sediments. The bayous are not dredged for ship traffic, and they receive the majority of their surface water input from natural sources (e.g., surface run-off and groundwater discharge). The upper reaches of the bayous and interior marshes provide extensive nursery habitat for estuarine-dependent species such as blue crabs, grass shrimp, black drum, striped bass, mullet, and killifish. Historically, the bayous are sediment transporters.

Data specific to the southern reach of Bayou Verdine has an estimated average flow of 8 cfs (Curry et al 1997). NPDES outfall flow data are also available and offer partial information on inflow to portions of the estuary. A summary of NPDES outfall data is available in Sections 7 through 10, depending upon the location of the outfall.

The areas are influenced by tidal changes. The tidal cycles have an important influence on sediment transport and deposition. During ebb tides, sediment is suspended and carried seaward while during flood tides sediments are suspended and carried landward. Marine sediments can be carried into the estuary and mixed with land-derived sediments during the flood tide. The degree of tidal influence is relatively small when compared to wind forcing or storm events. Tidal range in the bayous is generally less than 6 inches from high to low tide (USACE 1976). Flow velocities and flow direction are reported for the ship channel; values are not available for the individual bayous.

Lateral gradients in salinity (upstream to downstream) are observed, ranging from 0.1 to 3.3 ppt; however, vertical stratification (a salt-wedge regime) has not been reported in the upper portions of the bayou as was noted in the ship channel. Upper bayou salinity was found to be vertically homogeneous during the winters of 1999 and 2000.

Surface water flow rates are not available in Bayou Verdine or Bayou d'Inde; the nearest gage is at the saltwater barrier in the ship channel. The long-term annual mean measured at the saltwater barrier (Figure 3-1; Item 15) is 2600 cfs (USACE, 1976). Seasonal lows were reported for April and averaged 147 cfs up to a high in December of 3,100 cfs (Duke 1985). Flow within the bayous is significantly lower.

The sediment typically consists of undisturbed, fine-grained silt and clay sediments in the upper reaches, becoming coarse in the lower portions. Sediment thickness ranges from 11 to 19.5 feet thick in lower Bayou d'Inde (Fluor Daniel, Inc. 1997); this is probably typical of the bayous given the source of sediment is terrestrial in origin (Duke 1985). Dredging does not occur in these areas, and channel geometry is un-altered. Sediment deposition is from overland soil erosion. LDNR has estimated total solids loading rates for various segments of the entire Calcasieu River drainage basin (Plummer and Associates 1984). The rate is estimated at 6.1 million pounds of total solids per inch of rainfall (for the portion of the Calcasieu River from the saltwater barrier to the northern inlet of Calcasieu Lake). Sediment dating indicates that sedimentation rates are constant (Mueller 1987). Areas with narrowed openings, such as areas where bridge abutments force the tides through a smaller cross sectional area, also tend to amplify tidal surge.

Sediment movement occurs with each change in tide; however, scouring is most prevalent during major storms. Strong winds and/or tide significantly alter water levels, turbidity, and salinity.

Numerous major rain events occur each year in the area (Figure 3-1; Item 6), and the net effect is a general increase in sediment loading due to flooding of tilled farmland, predominantly rice and soybean fields (Plummer and Associates 1984). Industrial storm run-off from areas associated with spills or material storage may be a possible source to some bayous.

3.3.2 Shallow Lakes

Lake Charles, Prien Lake, and Moss Lake are each members of the shallow lake energy system (Figure 3-1; Item 3). They are each connected to the Calcasieu River Ship Channel, receiving water from the channel, but having limited flow and/or circulation energy. They are shallow by nature, ranging from a 3- to 30- m water column.

The geometry of these lakes is similar; however, salinity and inflow sources vary. Lake Charles is the most upgradient and largest of the three lakes. Lake Charles has the lowest salinity, and a portion of the lake is dredged to support boat traffic on the western side of the lake. Prien Lake salinity is low to moderate; its sediments are thick and silty, with well-established vegetation, marginal marsh edges, and a shallow sloping bank. The ship channel and a municipal POTW outfall feed the lake. Prien Lake receives direct inflow from the mouth of Bayou d'Inde across the Calcasieu River Ship Channel, as indicated in recent USGS rhodamine dye tests.

Moss Lake is also shallow, but salinity tends to be the highest, measured at a maximum of 20 ppt during the RI. The ship channel and Bayou Olsen feed the lake. Moss Lake sediment contains a higher percentage of sand, possibly indicating that it receives more marine sediment than Prien Lake or the bayous. Vegetation is also marginal to brackish in nature. The land area adjacent to the each of the lakes varies in the degree of development, industrial or otherwise. Input from adjacent sources has an impact on sediment and water chemical characteristics.

The degree of influence imparted by tides varies across the lakes, Moss Lake flow being the most impacted by tides; the mean range is about 4 m. Prien Lake and Lake Charles experience about 6 inches fluctuation each day (Duke 1985). Each of the lakes is influenced by wind; predominant northerly winds during winter can significantly lower water levels in Prien and Moss Lakes. Tides affect salinity within the lakes, increasing during flood tide. Wind effects on salinity are less in Prien Lake given the smaller cross section open to the ship channel. None of the lakes showed salt-wedge salinity stratification in the RI although stratification was noted in both Moss Lake and Prien Lake by Duke in 1985.

The lakes are sediment sinks, receiving bodies for both marine and fluvial sediments. Sediment deposition rates are not available but are estimated to be among the highest in the estuary. This is magnified by the fact that transport out of these shallow lakes is typically limited. Moss Lake tends to have the greatest degree of circulation or flushing and likewise the lowest sediment retention. Sediment sorting (well-sorted sediments) tend to be an indicator of a greater degree of flushing or circulation.

3.3.3 Estuarine Marsh

Marshes within Calcasieu Estuary are shallow, partially inundated, inland swamps (Figure 3-1; Item 2). They tend to vary in salinity, ranging from brackish to fresh. Marshes are defined as sediment sinks, having shallow depth, thick sediment layer, vegetation and aquatic habitat with limited water circulation. Conditions are often reducing and anoxic. Lockport Marsh is the most familiar; however, marshes are identified along Prien Lake, Coon Island Loop, at the mouth of Maple Fork along Bayou d'Inde, and the old river above Clooney Island.

Marshes are affected by tides; overall daily effect ranges from 6 to 12 inches. The most significant effect is on salinity and water level within the marshes. Ebb tides, combined with offshore winds during winter, lower the water surface 1 to 2 feet effectively dewatering shallow marshes (USFWS 1957). These conditions were observed during the RI.

Salinity varies across the various marshes; the mouth of Maple Fork (as it enters Bayou d'Inde) and the two marshes located on the old river are considered fresh to intermediate salinity marshes. Prien Lake marshes and Lockport Marsh tend to be intermediate to brackish salinity bodies and are susceptible to storm surge flooding. The areas were noted as requiring several months to drain saline floodwater infused by Hurricane Audrey (Morgan et al 1958).

Lockport Marsh, located in lower Bayou d'Inde, is an intermediate to saline marsh. Petroleum drilling and production in the estuary has impacted Lockport Marsh with levee and road building activities that create shallow embayments, further limiting flow (Figure 3-1; Item 16). Oil field production water (typically brackish and containing petroleum byproducts) is often discharged directly to the marsh.

Lockport Marsh is connected to Bayou d'Inde and the ship channel through several small openings in the levees; however, the size of the openings limits circulation. During high rainfall events, the levees are inundated, with the marsh receiving flow from Bayou d'Inde, the ship channel and the PPG Canal. The flow rate within Lockport Marsh is low, which is typical of each of the marsh areas.

Physical parameters for sediment within the marshes indicate that the sediment is generally anoxic and organic rich. The sediment is also very fine grained, in the clay to silty clay range, with generally higher total organic carbon (TOC) values and reducing conditions due to decomposition of organic detritus. The marshes generally provide excellent habitat for clams and blue crabs.

3.3.4 Ship Channel

The ship channel is that portion of the estuary that has had significant modification to the natural geometry of the drainage (Figure 3-1; Item 4). This group includes the Calcasieu Ship Channel from Lake Charles to the Gulf, the Coon Island Loop turning basin, and Clooney Island Loop. The ship channel has been expanded such that it is 40 times larger than when first dredged in the late 1800s. The effect of dredging is significant on the estuary in three principal ways: channeling of saltwater into a formerly low-salinity estuary, increased drainage of riverine inflow when tide ebbs, and increased tidal amplitude within the estuary (LDNR 2002).

Tidal fluctuation tends to range from 30 to 60 centimeters (cm) per day. Storm surge tides can range up to 2 m, as noted at the saltwater barrier during Hurricane Audrey in 1957 (Morgan et al 1958).

The salinity regime in the ship channel varies from vertically homogenous to salt wedge. During the RI, conditions were generally low-water conditions, and the ship channel salinity was homogenous, but readings from summer months in previous studies indicate a distinct salt-wedge regime (Duke 1985).

Dredged sections of the estuary are routinely maintained to meet design characteristics. Maintenance schedules vary depending upon the reach and the uses of the area, but they currently run on a 2- to 4-year cycle. The 40 to 45 km segment was last dredged in 2001. The areas of interest to this RI are Clooney Island Loop, Coon Island Loop, and the Calcasieu Ship Channel from Lake Charles to the southern end of Moss Lake (Figure 2-2).

The geometry of these sections has changed over time; the channel has been widened and deepened from 40 m to 75 m wide, and from 10 m to 15 m deep. A bank-edge ledge has been maintained and is typically 6 m to 12 m wide and under about 0.6 m to 3 m of water. The shallow ledge tends to be a settling point for sediments throughout the ship channel and is considered representative of settle-able sediment in these areas. This ledge was the area sampled during the RI. Historically, samples were collected from the bottom of the ship channel; however, dredging removes this sediment on average every 4 years.

Given the extent of the ship channel and the spatial distribution of the areas of interest throughout the estuary, natural and anthropogenic variations in water chemistry exist. Salinity, temperature, pH, TSS, dissolved oxygen content, sediment grain size, and oxidation-reduction potential (ORP) vary in the dredged portions of the channel when compared to nearby un-modified areas.

Sediment stability is a function of sediment characteristics, water energy, and salinity. Flow direction within the estuary is governed by various conditions; tide is the primary influence, followed by wind forcing and flood tide surge. Surface water flow rates vary widely across the estuary; reported values ranged from 300 to 65,000 cfs above tidewater (USFWS 1957). During non-storm periods, the upstream and downstream flows are roughly equivalent in magnitude and balanced in duration. Flow direction is governed by tide. Exhibit 3-2 provides a snapshot of flow characteristics during a non-storm day, as measured in the main ship channel at the I-10 Bridge.

Exhibit 3-2 Calcasieu River Ship Channel Surface Water Flow Rates at the I-10 Bridge

Date and Time Measured	Surface Water Flow Rate (cfs)	Date and Time Measured	Surface Water Flow Rate (cfs)
June 18 0522 hrs	+9098	June 18 1708 hrs	+1458
June 18 0700 hrs	+12163	June 18 1800 hrs	+4650
June 18 0800 hrs	+10623	June 18 1915 hrs	+5042
June 18 0910 hrs	+4515	June 18 2000 hrs	+4853
June 18 0955 hrs	-2737	June 18 2130 hrs	+7550
June 18 1100 hrs	-2712	June 18 2210 hrs	+5387
June 18 1203 hrs	-2882	June 18 2300 hrs	+4692
June 18 1321 hrs	-2808	June 19 0056 hrs	+8019
June 18 1509 hrs	-196	June 19 0300 hrs	+3537
June 18 1630 hrs	+831	June 19 0525 hrs	+12287

Note: (+) indicates downstream flow, (-) indicates upstream flow. Taken from Duke 1985.

Sediment is transported by each of the tributaries and eventually deposited into the ship channel. Sediment that accumulates within the channel tends to be larger grained material, silts, and sands. Ship channel sediments are generally moderately to well sorted. Tidal cycles have an important influence on sediment transport and deposition; during ebb tides, sediment is suspended and carried seaward while during flood tides sediments are suspended and carried landward.

The channel receives and transports significant amounts of sediment based upon the maintenance dredging records. Alteration of the channel banks and subsequent sloughing to the channel may artificially increase the apparent sedimentation rate, and so examination of the USACE dredging information, provided in Table 3-1, in the tables section at the end of this report, should be carefully considered.

An empirically derived sedimentation rate for the smaller ship channel in middle Bayou d'Inde, near the PPG Canal (Mueller 1987), was calculated at 0.74 cm/year or 0.29 inches/year. The rate was calculated using two radioisotope dating methods, ^{137}Cs and ^{210}Pb, with good correlation.

3.3.5 River

The upstream sections of the estuary above Lake Charles are considered the old river (Figure 3-1; Item 21). This energy system differs from the ship channel and bayous in its geometry and total flow. The river tends to be wider and deeper than the bayous, with a higher flow rate. This section of the estuary provides fresh to intermediate salinity conditions for aquatic vegetation and biota.

Tidal influence is minor, typically less than 0.3 m fluctuation per day. Sediment accumulates in the natural bends of the river, with equal percentages of sand, silt, and clay in the channel and predominately silt on the channel margins. Flow rates are not available for the area; nearest measurements are from the ship channel at the I-10 Bridge. The area is susceptible to tidal surge, the effects of wind forcing, and flood tide.

3.3.6 Other

Indian Marais Lagoon is a confined shallow embayment, receiving limited inflow. The lagoon is connected to the ship channel through a pier or levee along most of its length. During low flow, this levee serves as a barrier; however, during high tide or winds, water moves over or through the levee.

Salinity tends to be intermediate to saline. The water column is 1 to 2 m thick. The water body is void of significant vegetation or aquatic species.

Sediment thickness is disturbed by storm events where the pier levee is breached and the pond is in communication with the ship channel. Tidal surge is minor during low tide; however, during storms, tidal impact is amplified by the breached narrow opening to the ship channel.

During low-flow conditions, the pond is a sediment sink isolated from the ship channel, receiving input primarily from the Citgo facility. However, during storms it is a source of sediment and suspended solids.

3.4 Interactions among Energy Systems

Investigators have found that the vast majority of the contaminant distribution within estuaries can be explained by evaluating suspended particulate matter and sediment erosion and deposition patterns. The deposition/erosion of sediments is controlled by the following:

- Energy of the environment
- Salinity
- Turbidity of the river flow
- Impacts to the system (storms/drought conditions, dredging, releases)

The following sections describe these processes in greater detail.

3.4.1 Energy Environments

High-energy environments within an estuary result in suspension of sediment while sediments are deposited within low-energy areas. The tidal cycles have an important influence on sediment transport and deposition. During ebb tides, sediment is suspended and carried seaward while during flood tides sediments are suspended and carried landward. Marine sediments can be carried into the estuary and mixed with land-derived sediments during the flood tide. The larger than normal tidal range seen during spring tide increases sediment suspension (Grabemann et al 1997). The energy is increased during spring tide due to the larger than normal tidal range. Grabemann observed maximum turbidity within similar estuaries during spring tide.

Other high-energy environments include areas where the estuary narrows, such as where constrictions such as bridge abutments force the tides through a smaller cross sectional area. Dams can trap coarse sediment while allowing finer sediment to continue downstream, resulting in fine-grained sediment deposits in the lower reaches (Menon et al 1998). High winds can increase the energy of otherwise stagnant bodies of water, resulting in re-suspension of sediment especially in shallow estuaries.

Low energy environments include marshes, holding ponds, or lagoons (e.g., Indian Marais Lagoon), and embayments. Deposition of sediment can occur following the flood and ebb tides during periods of slack water. Grabemann (1997) found that slack tide velocities are typically only about 0.2 m/sec, which allows for flocculation and settling of silt to clay size particles (up to 200 micrometers [μm] in diameter).

During periods of low tide, the water within marshes can be isolated from the rest of the estuary, resulting in a very low energy environment. Tidal flats and salt marsh areas above the high tide line can be inundated during storms and during spring tides. However, under normal conditions, these areas are stagnant and poorly drained, which often results in hypersaline conditions and even the precipitation of salts and metal sulfate minerals due to evaporation (Borrego et al 2002).

Dredging of the ship channel and the associated river traffic can stir up sediment within the estuary. One of the major effects of dredging on the individual systems is the removal of available sediment (depravation) to the marshes and shallow lakes.

Removal of enough dredged sediment can change the sediment mass balance in the system and produce a sediment-limited system as was observed by Grabemann et al. (1997) for the Weser estuary.

3.4.2 Settling Energy and Salinity Effects

Salinity can have a major impact on the suspended sediment load within estuaries, as well as on the deposition of contaminated sediment. Suspended particles with a specific gravity greater than water (>1 gram per cubic centimeter [g/cm^3]) would be expected to settle out. The repulsive forces between negatively charged particles lessen settling. Adsorption of positively charged ions from high-salinity seawater can neutralize the surface charge on the particles, alternately increasing settling.

Investigators have found that turbidity maxima occur within the freshwater portions of estuaries due to salinity induced settling (Grabemann et al 1997; Menon et al 1998). Often, the maximum turbidity area is just upgradient of the freshwater/saltwater interface where salinity is low and tidal energy is relatively high. While the tidal energy typically increases seaward, the effect is neutralized by salinity induced settling. The location of the saltwater/freshwater interface and the zone of maximum turbidity can change seasonally due to changes in flow. Grabemann et al (1997) found that the zone of maximum turbidity moves up-estuary during low flow in the Weser and Tumar estuaries due to the relative dominance of tidal inflows compared to river flows.

3.4.3 Turbidity

The sediment load within the river and bayou inflow is the primary source of sediment into an estuary. Sediment loads can be an order of magnitude higher than normal during flood and storm events.

3.4.4 Impacts to the System

Other impacts to the system occur via natural occurrences such as seasonal changes, rain/drought cycles, tropical storms, hurricanes, or activities initiated by man such as dredging. These impacts are discussed below.

3.4.4.1 Seasonal Changes

The major effects of seasonal changes are temperature driven salinity/water density changes and the freshwater recharge to the system. During the warm summer months, water temperatures increase significantly, resulting in strong salinity stratification (Duke 1985). Salt-wedge conditions were noted across the lower portions of Bayou d'Inde and throughout the ship channel during the July 1985 fieldwork. Conceivably, during the drier spring months, surface-water levels drop and groundwater discharge to the bayous increases until the hydraulic head equilibrates. This results in increased groundwater recharge to the bayous.

3.4.4.2 Rain/Drought Cycles

The RI sampling (both Phase I and Phase II) was conducted during winter (November 1999 through February 2000, and November 2000 through February 2001). February 2000 and December 2000 were each considered drought periods. February 2000 was one of the driest Februarys on record, receiving less than 2 cm of rain. January and February precipitation, combined, measured only 5cm. Precipitation averages 10 cm or more per month.

Conditions observed during the RI included moderate northerly winds (average 9 to 15 kilometers per hour [km/h]). Depressed water levels were noted across the estuary as a result of wind forcing. Dewatering of some of the marshes and shallow lakes was noted.

3.4.4.3 Tropical Storms

Calcasieu Estuary is subjected to tropical cyclone and hurricane activity that enters the Gulf of Mexico (Figure 3-1; Item 6). In general, the estuary receives heavy rainfall, storm tidal surge (reported ranges of 1 to 3 m of surge), high winds, and depressed barometric pressures. Overall, this tends to result in net sediment transport. Storms can have a mixed net effect on sediment thickness, the rains bring increased soil erosion and sediment deposition while storm surge tends to scour the channel. The rains add significant freshwater to the system, lowering salinity, while the tidal surge pushes seawater further up the estuary. Manmade modification to the river system has removed some of the natural barriers, which protected or dampened the effect of tidal surge in the past, effectively magnifying the impact of storm surge.

Table 3-1 summarizes the hurricane history for the region, indicating the duration of the storm, the total rainfall amounts, the maximum storm surge and maximum sustained wind, where available.

This chronology indicates that major storms have occurred in the region every 4 to 5 years. Heavy rain-producing tropical storms in 1979, 1980, and 1989 have likely brought significant sediment into the estuary.

Hurricane Audrey, a large hurricane that made land at the mouth of Calcasieu Estuary, created an enormous saltwater flooding of the inland marshes and bayous. Calcasieu Lake historically served as a large freshwater reservoir for the estuary, preventing direct flow through and allowing salinity conditions to equilibrate, buffering the upstream river, lakes and bayous. Heavy tides associated with Hurricane Audrey caused significant storm surge flooding of Calcasieu Lake and most inland marshes throughout the estuary. The inland sediments are poorly drained, and the fine-grained materials slowed drainage of the water, compounding the effect of the increased salinity in terms of vegetative impact (LDNR 2002).

3.4.4.4 Dredging Events

As noted in Section 2, major dredging has occurred since the 1930s. Dredging of the ship channel (Figure 3-1; Item 8) was initiated in 1938 and continued through deepening of the channel in 1943 and 1946. The USACE performs routine maintenance dredging. Significant maintenance dredging occurred in 1967, 1973 (Coon Island Loop enlargement), and 1975 (Table 3-2). The most recent major dredging event was completed in 2001. One of the major effects of dredging on the individual systems is the removal of available sediment (depravation) to the marshes and shallow lakes.

Dredging increases water flow rate and salinity throughout the channel. This tends to result in loss of surface layers of organic material (U.S. Department of Agriculture [USDA]-Natural Resources Conservation Service [NRCS] 2001]), potentially impacting both the channel and lower sections of the bayous. Turbulence throughout the ship channel is increased, associated with larger water-craft (shipping barges and tankers), potentially impacting biota habitat and bank stability. Maintenance dredging removes any natural barriers that may impede water flow and associated sand bar development. In general, these activities increase saltwater intrusion and impede sediment and water exchange within interior mashes and lakes.

3.5 Exposed Populations

Both humans and ecological receptors are important considerations in the SCM. Pathways of exposure and the relationships between receptors and affected media are discussed below.

3.5.1 Ecological Receptors

Identified exposure routes are those exposure pathways considered complete for receptors in the area and include ingestion of sediments by detritivores and bottom dwellers, ingestion of contaminated prey items by ecological receptors, and inhalation and direct contact with the surface water micro layer. Ecological pathways are evaluated in Section 13.0, the Baseline Ecological Risk Assessment (BERA). The ecological receptors identified are believed to frequent the region, and behavior models support the selected exposure routes. Additional detail on development of these pathways and receptors can be found in the BERA Problem Formulation (CDM 2001).

3.5.2 Human Receptors

Potential human exposure to contaminants is presented in Section 14.0 of this document. Exposure routes of primary interest here are the direct contact (both human and ecological receptors), human consumption of impacted fish and shellfish, both by subsistence and recreational receptors (Figure 3-1; Item 9). These are important considerations of the SCM.

3.6 Summary of Sources Addressed in RI

The RI media of concern include sediments and surface water (Figure 3-1; Item 18). Understanding and reporting the impacts specific to each media, as well as their interactive relationships, are the focus of this RI.

Groundwater (Figure 3-1; Item 19) and air (Figure 3-1; Item 20) were not evaluated under this RI as they are regulated under separate congressional acts. Impacted groundwater in the industrial area is addressed under other State and Federal regulations, and no further investigation of groundwater was conducted under this RI. Historic release evaluations have been considered in evaluating sources and fate and transport of contaminants.

Air releases are addressed under Title V of RCRA and National Emission Standards for Hazardous Air Pollutants (NESHAP) and were not further addressed under this RI. Potential impacts from air releases were addressed with the reference area and sampling design.

This SCM provides an overview of the nature of the various impacted media. An understanding of the behavior of each of these impacts is necessary to effectively manage the Calcasieu Estuary system.