March 27, 2009

DRAFT TECHNICAL MEMORANDUM: RESTORATION 'CREDIT' ANALYSIS OF MARSH CREATION AND ENHANCEMENT VIA HYDRAULIC RESTORATION OF THE 1999 UNIT NEAR WEST COVE CANAL, IN THE SABINE NATIONAL WILDLIFE REFUGE

1. Introduction

Following the guidance for CERCLA, the Trustees have engaged in restoration planning and have developed a restoration-based plan to compensate for natural resource losses attributable to historical releases of hazardous substances from the ConocoPhillips and Sasol NA facilities located on Bayou Verdine, in the upper Calcasieu Estuary. In that restoration planning process, marsh creation and enhancement via hydraulic restoration of the 1999 Unit near West Cove Canal, in the Sabine National Wildlife Refuge (hereafter, 'Sabine 1999 Project') emerged as the Trustees' preferred restoration action to compensate for the losses attributable to releases from these facilities. Its emergence as a preferred action was based, in part, on a preliminary evaluation by the Trustees of its suitability to compensate for assessed resource losses, i.e., of whether, and to what extent the project would be able to generate enough environmental services (or 'credits'), over its expected lifespan to offset the quantified natural resource injuries [1]. The consideration of these questions is referred to as a 'restoration scaling' analysis. The Trustees' preliminary evaluation used readily available information, including best professional judgments of Refuge personnel. Uncertainties about the potential spatial influence of this project were minimal due to the discrete size of the project site, its position in the landscape, and recent topographic survey data for the site. The Trustees' preliminary scaling indicated the project could provide enough ecological service credits to compensate for the injuries to natural resources in the Calcasieu Estuary due to releases from the ConocoPhillips and Sasol NA facilities.

This technical memorandum refines the information used in the Trustees' preliminary scaling analysis of the Sabine 1999 Project and presents the information being relied upon by the Trustees in proposing the Sabine 1999 Project for use as compensation in the Draft DARP/EA for the Bayou Verdine Site. This memorandum briefly describes the restoration site, the need for restoration at the site, and the components of the Sabine 1999 Project proposed for implementation. It examines the biological conditions at the Sabine 1999 project site if no project is implemented (*i.e.*, under 'As Is' conditions), as well as the conditions that can be expected following project implementation based on data available in the literature. The analysis is focused on marsh sustainability, with consideration also given to edaphic and epiphytic algal production and fisheries utilization. Finally, the benefits (expressed in DSAYs) anticipated from implementation of the proposed restoration action are quantified.

[1] The injury assessment for the Bayou Verdine Site is described in the draft Technical Memorandum: Reasonable Worst Case Analysis Injury Assessment for Bayou Verdine and Coon Island Loop (LA Trustees 2004) and in the Draft DARP/EA for the Bayou Verdine Site, at Section 4.

2. Restoration Site Description

The approximately 280 acre (113 hectares) project area is in the Sabine National Wildlife Refuge, in Cameron Parish, LA, at the junction of LA Highway 27 and West Cove Canal (Figure 1). The area was created by the U.S. Army Corps of Engineers in 1999 using sediments dredged from the Calcasieu Ship Channel. This material was deposited into areas of broken marsh and shallow open water within containment dikes (spoil banks) in order to create a platform for the re-establishment of marsh habitat within the Refuge. The project area includes 246 acres of existing estuarine marsh, and 34 acres of mudflats and areas of shallow open water. Approximately 10,000 feet of nearly continuous spoil banks surround the project area.

An elevation survey conducted in 2005 indicates that the average marsh elevation throughout the project area is 1.35 feet (0.41 meters) North American Vertical Datum (NAVD). This elevation is conducive to hydrologic exchange through tidal inputs, a feature necessary to support and sustain functional marshes. However, the survey also indicates that the crests of the spoil banks at the site have an average elevation of 4.17 feet (1.27 meters) NAVD. This is too high for hydrologic exchange given typical tidal amplitudes along Louisiana's coast.

Figure 1. Approximately 280 acre dredged material disposal area in the Sabine NWR along Hog Island Gully Canal.

Across the project area, there is a nearly 1.35 foot (0.41 m) elevation gradient (also known as the inter-tidal zone) within the marsh. The dominant marsh on the higher southern end of the project area is saltmeadow cordgrass (*Spartina patens* (Ait.) Muhl.), but the dominant marsh changes to smooth cordgrass (*Spartina alterniflora* Loisel) on the lower, wetter, northern end. The project area has some hydrologic exchange via sheet flow along its northern boundary; however, lack of direct linkage to a waterway prevents normal intervals of tidal exchange. There are a few small "gaps" (5 – 10 meters wide) in the spoil bank, but these are too small to be conducive to adequate hydrologic exchange along the western, southern, and eastern boundaries under the guidelines presented by Turner *et al.* (1994). Flotation canals, a remnant of the initial construction, are situated between the spoil banks and the marsh platform.

2.1 Need for Restoration at the Project Site

Since the placement of dredged material in 1999, the soil has undergone de-watering and compaction, thereby decreasing the elevation of the marsh surface. The result of these processes is a marsh surface currently at elevations suitable for the establishment of vegetation – which has occurred (*Spartina alterniflora* and *Spartina patens*). Additionally, recent field visits anecdotally indicate that this vegetation has thrived (*i.e.,* desirable species have recruited, vegetative cover is high, and there were no signs of stress, such as herbivory, insectivory, or disease). From a visual inspection, it might appear the project site is structurally performing as intended. Refuge personnel, McNeese State University researchers, and the Trustees, however, believe the project area is on the verge of experiencing detrimental effects due to the continued presence of the spoil banks built to contain the dredge material in 1999.

Although the spoil banks initially protected the newly dredged sediments and allowed them to compact and dewater, these banks now actually obstruct and restrict tidal exchange. Without sufficient tidal exchange, adequate amounts of mineral sediments cannot reach and be deposited on the marsh surface. Mineral sediments must be incorporated into the soil profile in order to maintain healthy plants and adequately cycle nutrients. These sediments stimulate plant growth both above-ground as well as in subsurface roots and tillers, which also increases soil volume. The degradation of the spoil banks will facilitate tidal exchange and, therefore, allow for the deposition of mineral sediments onto the marsh surface. Mineral sediments import Iron (Fe) into the marsh which is needed for the lowering of Sulphite (SO_{-4}) concentrations. Without the lowering of SO_{-4} concentrations, the soil becomes toxic to plant roots, which causes a dieback of vegetation and lessens the site's ability to maintain surface elevations through accretion. If the lack of tidal exchange at the project site is not remedied soon, it will likely lead to degradation of the marsh in the near-term and loss of the marsh in the long-term.

Restricted tidal exchange resulting from the spoil banks also limits the ingress and egress of estuarine organisms. Access to marsh habitat is critical to maintaining these organisms as marshes serve as nurseries for juvenile fisheries and support a variety of benthic invertebrates. The reduced tidal exchange also impairs the quality of benthic habitat, the geochemistry of sediments, and food web dynamics. This situation will be greatly improved after restoration of the hydrology.

3. Sabine 1999 Restoration Project Summary

The Sabine 1999 Project involves activities to provide for spoil bank degradation, marsh creation, and spoil bank gapping (Figure 2). Approximately 2,500 feet of the nearly 10,000 feet of spoil bank that served as containment for the marsh platform constructed in 1999 will be degraded to elevations similar to the interior marsh. Material will be excavated from the levees using a marsh buggy or similar track-propelled machinery. The material from the spoil bank degradation will be deposited in the flotation canals between the levees and the marsh platform. The deposition of this material will increase the elevation in the canals to between 0.85 and 1.75 feet (0.3 meters and 0.53 meters) NAVD. This action is expected to provide approximately 14.7 acres (5.95 hectares) of additional substrate for the natural recruitment and re-colonization of native, desirable marsh vegetation. Close proximity of an appropriate seed source should facilitate the establishment of native marsh vegetation in these areas within two growing seasons. The narrowness of the created areas facilitates encroachment of vegetation from the surrounding marsh.

In addition to the levee degradation described above, five cuts or ‘gaps’ will be made in the levees remaining: one each in the west, north, and east levees, and two in the south levee. Each of these gaps, designed to aid in tidal flushing of the marsh platform, will be constructed where a channel previously existed. The width of the gaps will be determined in the engineering and design phase of the project, but the basic guidelines outlined by Turner *et al.* (1994) will be used to guide those decisions.

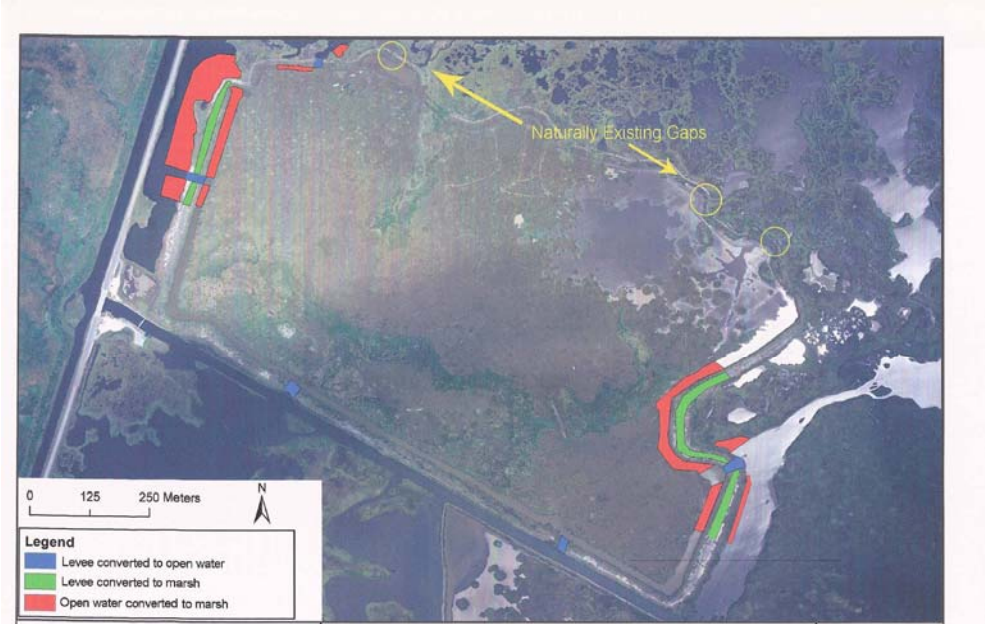

Figure 2. Proposed project components for the hydrologic restoration and marsh creation project in the Sabine NWR

The Sabine 1999 Project site has three components able to generate restoration 'credits' following implementation: created marsh, restored marsh, and open water.

4. Effects of spoil bank levees and their removal

The importance of hydrology for many coastal wetland functions is well established. Alterations to tidal exchange frequently contribute to marsh deterioration (Burdick *et al.* 1997; Hood 2004; Roman *et al.* 1984) by increasing marsh subsidence. In Louisiana, one of the most common disruptions of marsh surface hydrology is associated with spoil banks created from dredge material excavated in past decades (Turner 1987). Disrupting the hydrology of a marsh has numerous detrimental effects including:

- Limited marsh sustainability through:
    - Decreased soil accretion
    - Decreased bulk density;
    - Decreased plant health; and
- Reduced plant, edaphic, and epiphytic algal production; and,
- Severely restricted access to the marsh surface for estuarine organisms.

The following subsections elaborate on these effects with supporting information from peer-reviewed literature. Results and data in the literature provide evidence of the biological response that can be expected following the implementation of the Sabine 1999 Project.

4.1 Marsh Sustainability

In order for a marsh to persist in the landscape, it must have the ability to maintain its elevation (through accretionary processes) and counteract the effects of subsidence and sea-level rise. Both subsidence and sea-level rise are occurring at scales much larger than the project area and they cannot be influenced on either a project area or regional basis. Sediment accretion, however, is a factor that can be influenced at a project-level basis, and contributes to marsh sustainability. Presently at the Sabine 1999 project site, the spoil banks limit sediment transport and deposition; thereby, limiting sediment accretion at the site. This limiting of sediment accretion allows the effects of subsidence and sea-level rise at the site to proceed relatively unchecked. The current lack of mineral soil deposition coupled with a reduced rate of tidal flushing also poses a serious long-term risk to plant health at the site. Because subsidence, sea-level rise, vertical accretion and plant health are the primary factors affecting marsh sustainability for the Sabine 1999 project, they are addressed in the subsections below.

4.1.1 Subsidence and Sea-level Rise

Subsidence, in the simplest of terms, refers to the sinking of land. Louisiana experiences high rates of subsidence (especially in the eastern portion of the state) because of the young geologic age of its soil. Louisiana's most recent (within the last 5,000 to 6,000 years) deposits continue to undergo dewatering and compaction, processes that result in decreases in elevation. Though subsidence is a natural geologic process, it is countered to some extent by accretion (described below).

Sea-level rise also influences the relative elevation of land and is thought to be the result of two processes: expansion of sea water as the oceans warm, and increases in the volume of sea water due to the melting of ice over land. While sea-levels have trended higher over the past 6,000 years, local (Gulf of Mexico) rates have been recorded to be higher than eustatic (world-wide) rates. Therefore, we realize that both subsidence of coastal land and local sea-level rise need to be factored into the calculation of marsh sustainability.

Both published and unpublished data on the rates of subsidence and sea-level rise are available for the region and for the general Sabine 1999 project area. For the region, the Trustees have relied upon estimates published by Penland *et al.* (1989), White *et al.* (2002), and Baumann and DeLaune (1982). Penland *et al.* (1989) estimated subsidence by analyzing the hydrologic record from continuous water level recorders deployed across coastal Louisiana. The recorder most applicable to the region surrounding the Sabine 1999 project site was located at Calcasieu Pass near Cameron, LA. The subsidence rate at that station during the study's second sampling epoch from 1976 to 1988 was 0.94 cm/yr. This calculation equates to 3.09 feet of subsidence per century prior to

accounting for sea-level rise or accretion. To estimate sea-level rise, Penland *et al.* (1989) used a 0.23 cm/yr (0.75 foot per century) rise in sea-level specific to the Gulf of Mexico region published by Gornitz *et al.* (1982). White *et al*. (2002) measured submergence (defined as sea-level rise and subsidence) in three fluvial-deltaic systems in Texas and found an average subsidence rate of 0.9 cm/yr in the Trinity Delta – the delta adjacent to the Calcasieu Estuary. They also applied a 0.23 cm/yr rate of sea-level rise reported by Gornitz *et al.* (1982). Baumann and DeLaune (1982) investigated the rates of sedimentation and apparent sea-level rise as factors affecting land loss in two Louisiana marshes. For data collected in Louisiana's Chenier Plain, they reported an apparent sea-level-rise (sea-level rise and subsidence reported together) of 1.2 cm/yr. Unpublished data (Hoffpauir, pers. comm.) collected in the Sabine NWR was also obtained. The average subsidence for three marshes (two created and one natural) in the Sabine NWR was slightly greater than 1.0 cm/yr. The rate of sea-level rise applied to the Hoffpauir data was that reported by Gornitz *et al.* 1982.

Table 1 summarizes the regional elevation changes (sea-level rise and subsidence) reported by each author cited in this subsection.

Table 1. Reported rates of subsidence and sea-level rise for the Chenier Plain, LA.

Source Literature	Subsidence (cm/yr)	Sea-level rise (cm/yr)	Elevation change (cm/yr; ft/century)
Penland et al. (1989) Cameron[2]	-0.94	-0.23	-1.17; -3.84
Penland et al. (1989) Hackberry	-0.37	-0.23	-0.6; 1.97
White *et al.* (2002)	-0.90	-0.23	-1.13; -3.7
Baumann and DeLaune (1982)	-0.97	-0.23	-1.2; -3.94
Sabine NWR 1993 (Hoffpauir)	-1.00	-0.23	-1.23; -4.04
Sabine NWR 1983 (Hoffpauir)	-1.10	-0.23	-1.33; -4.36
Sabine NWR Reference (Hoffpauir)	-1.00	-0.23	-1.23; -4.04
Average	- 0.90	-0.23	-1.13; -3.7

The results presented in Table 1 indicate that, on average, marshes in the Chenier Plain (including the Sabine NWR), as well as an adjacent watershed in

[2] Continuous water level recorder at Calcasieu River near Cameron, LA. Results from a continuous water level recorder at Calcasieu River near Hackberry, LA do exist; however, the variability in the results makes interpretation of the results difficult to use.

Texas, are experiencing relative sea-level rise (subsidence and sea-level rise) at a rate of -1.13 cm/yr (-3.7 ft/century). Since relative sea-level rise cannot be influenced by the components of the proposed Sabine 1999 project, the Trustees investigated whether the proposed project actions were likely to result in meaningful improvements/increases in accretion rates at the site.

4.1.2 Sedimentation Rates and Vertical Accretion

Extensive research has been conducted in Louisiana over the past two decades on the impact of levees, hydrologic management, and structural management on accretion rates in marshes. While the names and/or techniques may differ, each involves or has the effect of restricting tidal waters and, therefore, the results of papers examining and describing the effects of these actions will be relied upon equally throughout this memorandum. For instance, Boumans and Day (1994) studied the effects of hydrologic restrictions on the sedimentation rates in four Louisiana marshes: two restricted and two unrestricted. They found that short-term sedimentation rates were significantly different (0.57 and 1.02 g/m^2/day for restricted and unrestricted at site 1, respectively, and 1.68 and 3.82 g/m^2/day for restricted and unrestricted at site 2, respectively). Cahoon (1994) studied vertical accretion in the same areas and found that the unrestricted marshes experienced vertical accretion at a rate of three to eight-times greater (Table 2) than the restricted marshes. Cahoon (1994) forecast that marshes succumbing to subsidence, coupled with a general rise in global sea levels and a reduced capacity to accrete vertically, will have a shortened life compared to natural, unrestricted marshes.

Table 2. Vertical accretion rates g m^{-2} day^{-1} as reported by Cahoon (1994).

Site	Treatment	
	Unrestricted (n)	Restricted (n)
Fina La Terre	0.30 ± 0.09* (31)	0.07 ± 0.01 (31)
Rockefeller Refuge	0.98 ± 0.11** (40)	0.12 ± 0.04 (36)

*Indicates significance at the: *=0.05 or **=0.10 levels.*

Reed *et al.* (1997) studied the effects of hydrologic management on marsh-surface sediment deposition in the Mississippi deltaic plain and found significant differences between impounded and un-impounded sites, with un-impounded sites showing higher rates of marsh surface sediment deposition than impounded sites. Over three years of sampling, the un-impounded marshes experienced three times more accretion on average than the impounded sites (1.2 g m^{-2} day^{-1} and 0.4 g m^{-2} day^{-1}, respectively). Kuhn *et al.* (1999) studied a largely impounded Louisiana marsh and conducted bi-weekly sampling of marsh surface sediment deposition in unmanaged and managed marshes for a period of one year. They too found that the unmanaged sites averaged three times more sediment deposition than the managed sites (1.24 g m^{-2} day^{-1} and 0.41 g m^{-2} day^{-}

[1], respectively) and concluded that the hydrologic restriction (as a result of the management) significantly impeded tidal/sediment access to the marsh and that the sediment deficit will promote eventual wetland loss. This outlook was also offered by Boesch *et al.* (1994) when they concluded that reduced rates of sedimentation in a managed marsh are likely to translate into increased relative rates of subsidence and, hence, submergence within the area.

4.1.3 Soil Bulk Density

Just as the differences in rates of sediment deposition/vertical accretion are significant, so are the proportions of mineral sediment between impounded and un-impounded areas. This is important because soils with a high mineral content (*i.e.,* bulk density) have a greater ability to sorb nutrients (Mitsch and Gosselink 2000) and have been shown to provide more nutrients on a per volume basis relative to more organic salt marsh soils (DeLaune *et al.* 1979). DeLaune and Patrick (1979) were the first to publish a threshold and suggested that bulk densities above 0.20 g cm^{-3} are essential for the healthy growth of *Spartina alterniflora*.

Kuhn *et al.* (1999) found that in addition to higher rates of sediment deposition between the formerly managed and unmanaged sites, the bulk density of the soil at the unmanaged site was significantly higher than the soil at the formerly managed site (average of 0.263 g/cm^3 and 0.17 g/cm^3, respectively). They concluded that the greater soil bulk densities in the unmanaged marsh would have likely improved plant growing conditions over those in the managed marsh by improving soil nutrient status (see additional discussion of their research in Section 4.2). Additionally, they state that because saline marshes, as compared to other marsh types, require sustained rates of sediment input, management regimes (*i.e.,* some level of impoundment) that limit input (*i.e.,* any that limit tidal input or diminish tidal frequency) are inappropriate. Cahoon (1994) found that in addition to higher rates of vertical accretion in the unrestricted sites, both the bulk density and the mineral content of soil were significantly higher in those sites as well (Tables 3 and 4). Reed *et al.* (1997) concluded that higher bulk densities in the unimpounded marsh are due to unrestricted tidal access, which maximizes sediment access and deposition within the salt marsh.

Table 3. Soil bulk density g/cm^3 as reported by Cahoon (1994).

Site	Treatment	
	Unrestricted (n)	Restricted (n)
Fina La Terre	0.13 ± 0.01** (31)	0.06 ± 0.004 (31)
Rockefeller Refuge	0.27 ± 0.01** (40)	0.14 ± 0.01 (36)

*Indicates significance at the: *=0.05 or **=0.10 levels.*

Table 4. Soil organic/mineral content (%) as reported by Cahoon (1994).

Site	Treatment	
	Unrestricted (n)	Restricted (n)
Fina La Terre	52/48 ± 4** (31)	75/25 ± 2 (31)
Rockefeller Refuge	26/74 ± 1** (40)	59/41 ± 3 (36)

*Indicates significance at the: *=0.05 or **=0.10 levels.*

4.1.4 Plant Health Improvements via Nutrient Input and Soil Aeration

As illustrated by the above studies, sediment deposition, and the corresponding deposition of mineral sediments, is a function of tidal flushing and frequent flooding of the marsh surface. It is also well known that nutrients (phosphorous, potassium, and micro-nutrients) are sorbed to the imported soil and are typically beneficial to the growth of plants. However, there are two other and more important functions provided by the import of soil: increased soil aeration and the buffering of phytotoxins. Both contribute to the sustained health of marshes, as explained below.

Increased elevation decreases the depth of flooding and improves soil aeration. When the depth of flooding is decreased, the water table more often falls below the soil surface and allows for soil drainage and the direct exchange of gases between the air and the soil. Lessening in the depth of flooding also facilitate aeration of the rhizosphere (the soil and plant root interface). In situations where the soil is poorly aerated, plant growth can be restricted because of an oxygen deficiency in the rooting zone which forces plants to rely more heavily on anaerobic metabolism for their energy production (Mendelssohn *et al.* 1981). However, Mendelssohn *et al.* (1981) and Mendelssohn and McKee (1988) concluded that when soils were less flooded and more aerated at higher elevation sites, the roots of plants in these areas could likely respire aerobically, and result in more growth (Wilsey *et al.* 1992).

Improved soil aeration associated with increased elevation also lowers the concentration of phytotoxins that develop in salt marsh soils with a high frequency of flooding and/or increased depth of flooding, a condition frequently referred to as 'reduced salt marsh soils' (*i.e.*, the reduction/oxidation reaction has been driven to the "reduced" state). The major plant toxin typically produced in reduced salt marsh soils is free sulfide (Gambrell and Patrick 1978; Mendelssohn and McKee 1988). Sulfide restricts plant growth by impacting energy production; thereby, inhibiting metabolic processes such as plant uptake of ammonium nitrate (Bradley and Morris 1990; Koch *et al.* 1990) Ammonium nitrate is the primary limiting nutrient to salt marsh plant productivity (Valiela and Teal 1974; Mendelssohn and Morris 2000). Mendelssohn *et al.* (1981) found that soils with higher mineral content had greater concentrations of iron (Fe) and manganese (Mn) in the interstitial water. These elements are important for their ability to precipitate sulfides and thereby reduce toxic soluble sulfide concentrations (Gambrell and Patrick 1978).

4.2 Plant Productivity

Tidal exchange is the main pathway for nutrients to enter a wetland (Mitsch and Gosselink 2000). Kuhn *et al.* (1999) investigated the impacts of Structural Marsh Management (SMM) on salt marsh plant performance; specifically, whether plant growth was negatively affected by reduced tidal exchange in a Louisiana marsh dominated by *Spartina alterniflora* and *Spartina patens*. The marsh in this study was originally managed through the use of water control structures, but these had deteriorated to a state that allowed free exchange of water through the structures. The managed marsh was also subject to very restricted flow through several small breaks in the levee system (a degree of impoundment similar to the Sabine 1999 project site). While the investigators found no significant differences in aboveground biomass between the unmanaged and managed areas (1150 g/m^2 and 1263 g/m^2 in the unmanaged and managed areas, respectively), there was significantly greater net annual primary productivity (NAPP) for the unmanaged marsh than the managed marsh. NAPP was estimated using the Smalley method to be 401 g m^{-2} yr^{-1} and 304 g m^{-2} yr^{-1} for the reference and managed marshes, respectively. In a similar study of the effects of reduced tidal exchange on Louisiana brackish marsh structure and function, Flynn *et al*. (1999) found significantly greater aboveground live biomass in an unmanaged site when compared to a managed site (1356.5 +/- 97.2 g m^{-2} and 897.2 +/- 63.7 g m^{-2}, respectively). Additionally, like Kuhn *et al.* (1999), Flynn *et al.* (1999) found that the unmanaged reference areas had significantly greater (more than double) estimate of net growing-season primary productivity (g m^{-2}), using the Smalley method, when compared to the managed marsh (3036.2 +/- 662.0 g m^{-2} versus 1486.6 +/- 285.9 g m^{-2}, respectively).

Edaphic and ephiphytic algae are an important contributor to overall plant productivity within a marsh. Edaphic and ephiphytic algae primarily include chlorophyta, cyanobacteria, and diatoms, though diatoms are a dominant component of these communities (Fallon *et al*. 1985). Edaphic and ephiphytic algae form a layer on the surface of the mud and the lower stems of marsh plants, often as two distinct but overlapping assemblages. Prior studies indicate they contribute from 10% to 60% of the overall marsh productivity in the Atlantic and Gulf of Mexico regions (Sullivan and Currin 2000, and Mitsch and Gosselink 2000). Recent communications with other experts suggests that range can be narrowed to an estimated 25-30% (J. Fleeger, M. Sullivan and W. Stowe, pers. comms, 2007). Edaphic and ephiphytic algae account for the greatest marsh productivity during the winter and early spring seasons (Jackson et al. 2006) when plant production is at its lowest and, thus, increasing their importance as a contributor to estuarine productivity. Isotope uptake studies indicate that higher trophic organisms are more dependent upon algal organisms than plants for their nourishment (Sullivan and Moncreiff 1988, 1990).

Algae are both autotrophic and heterotophic[3] and, according to one expert consulted, streamside algal communities are more autotrophic while interior algal communities are more heterotrophic (W. Stowe, pers. comm., 2007). Algal communities are, therefore, most productive in hydrologic regimes with frequent wetting and drying, with the greatest rate of productivity occurring while surfaces are in the process of drying but still moist (W. Stowe, pers. comm., 2007; Pinckney and Zingmark 1991 and Jones 1980). This may be a result of greater sunlight and carbon dioxide available for photosynthesis under those conditions than when stems and sediments are submerged. In addition, prolonged periods of desiccation are detrimental to these communities and therefore a shorter interval between wettings, which is currently lacking at the Sabine 1999 site, would favor increased production.

Because anecdotal evidence indicates that the herbaceous plant productivity within the impounded area at the Sabine 1999 site is currently high, further analysis of potential changes in plant productivity associated with the proposed restoration action will focus on edaphic and epiphytic algal production.

4.3 Estuarine Organism Access

The critical importance of the water-marsh interface to the utilization, survival, and productivity of U.S. Gulf Coast fisheries has been well documented (Minello *et al.* 1989, Minello and Webb 1997, Minello and Zimmerman 1983, Minello and Zimmerman 1991). The current ability of the Sabine 1999 site to provide these critical functions can generally be characterized as muted, or diminished, due to the presence of nearly continuous spoils banks. In a study of the effects of spoil banks on coastal marsh function (fish utilization being just one function), Reed *et al.* (2006) sampled nekton (free swimming organisms) along the edge and interior of natural marsh, as well as along spoil banks and in the small "gaps" in the spoil banks created during construction. They found that while the nekton data were complex, greater densities of four species (bayou killifish [*Fundulus pulverous*], grass shrimp [*Palaemonetes pugio*], sheepshead minnow [*Cyprinodon variegatus*], and sailfin molly [*Poecilia latipinna*]) were found in the natural marsh compared to the banked and/or gapped sites. Differences in densities were between 34% and 94% greater in the natural marsh than in the constructed marsh, and greater densities of nekton were especially noted in areas dominated by smooth cordgrass (*Spartina alterniflora*) with low plant densities and higher salinities. Reed *et al.* (2006) associated lower elevations with improved access for nekton and noted that gapping of spoil banks in lower areas, dominated by *S. alterniflora*, could therefore enhance nekton densities. Unfortunately, this study did not widen the gaps to investigate the nekton response.

[3] Autotrophs are organisms that use inorganic substances as energy sources and carbon dioxide as a carbon source. In contrast, heterotrophs are living organisms that obtain energy from carbohydrates and other organic material.

Rozas and Minello (1999) identified and articulated two different ways altered hydrologic exchange can affect access of nekton to marsh: by affecting direct access and by affecting habitat access. Direct access is related to the volume of water exchanged between a marsh system and the surrounding watershed (Rozas and Minello 1999). Levees and water-control structures restrict direct access of nekton by reducing tidal exchange (Montague *et al.* 1987, Rogers *et al.* 1994). The young of most fishery species are carried into marsh systems as organisms that drift with the current (plankton). Decreasing water exchange will thus reduce the number of marine fishery organisms recruited into a marsh area (Hoese and Konikoff 1995, Rogers *et al.* 1992).

Hydrological management can also restrict habitat access. Habitat access relates to the ability of organisms to access emergent marsh vegetation and their habitat functions. By restricting hydrologic exchange, emergent marsh becomes unavailable to some aquatic animals. Studies in Louisiana and Texas show that many fishery species select for emergent vegetation (when it is available) over subtidal non-vegetated bottom (Baltz *et al.* 1993, Minello and Zimmerman 1985, Rozas and Minello 1998, Thomas *et al.* 1990, Zimmerman *et al.* 1984, Zimmerman *et al.* 1990, Zimmerman and Minello 1984). Therefore, access to emergent marsh vegetation appears important in sustaining productivity of fishery species, and reduced access can reduce growth rates (Zimmerman *et al.* 1999) and increase mortality (Minello 1993, Minello *et al.* 1989, Minello and Zimmerman 1983).

The proposed hydrologic restoration actions – spoil bank degradation and gapping – should improve both types of access to marshes at the Sabine 1999 project site. Though access will be improved, there will likely still be differences in nekton densities between the restored site and natural sites in the vicinity. Minello and Webb (1997) compared decapod crustacean (examples of ten legged crustaceans are shrimp and crabs) and nekton densities between natural and created (3 to 15 years) marshes in Texas and found all but the densities of *Palaemonetes pugio* (daggerblade grass shrimp) to be significantly lower in created marshes than natural marshes. Since different methods of sampling were used by Reed *et al.* (2006) and Minello and Webb (1997), their results are not directly comparable. However, the significant differences found in the density of daggerblade grass shrimp between natural and leveed habitats, and the lack of significant differences in their density between natural and created marshes, taken together, suggests that the observed differences in density could be a result of access differences. This inference lends itself to quantification of the gain in marsh service levels that be expected to follow from spoil bank degradation.

5. Scaling Analysis for Sabine 1999 Project

The information outlined in Section 4.0 offers compelling support for the conclusion that implementation of the Sabine 1999 Project will benefit the sustainability of the estuarine habitats existing, and to be created, within the Sabine 1999 Project area, the quality of those habitats, and the estuarine organisms utilizing these habitats. This section presents the Trustees' quantification of the benefits of hydrologic restoration on marsh sustainability (as a result of accretion) as well as on the marsh service level gain throughout the project site. This approach 1) reflects the central role of hydrologic restoration in the Sabine 1999 Project; and 2) can technically be implemented and supported using data and information from existing, quality scientific literature.

5.1 SUMMARY OF INJURY ANALYSIS FOR BAYOU VERDINE SITE

Since restoration scaling in an NRDA context addresses the question of whether a restoration project will generate enough ecological services (or 'credits') over time to offset assessed resource injuries, this subsection summarizes the results of the injury assessment for the Bayou Verdine Site. The injury assessment for the Site is explained in more detail in Section 4.0 of the Draft DARP/EA for the Bayou Verdine Site.

The Trustees found benthic resources in Bayou Verdine and Coon Island Loop had been injured by hazardous substance releases attributable to the ConocoPhillips and Sasol NA facilities. These injuries were quantified in terms of the ecological services of these resources lost over time. The results of this analysis (see Table 5) indicate that compensation for assessed benthic resource losses is achieved by providing ecological services equivalent to 1,075 DSAYs ('discounted-service-acre-years') of marsh habitat.

Table 5. – Results of Benthic Resources Injury Analysis.

Area Name	Area (acres)	Injury (ca. 1992) % LOS	Injury % LOS (Year % LOS is reached)	Time to recovery	EqDSAYs Lost
Bayou Verdine	17.61	100%	100% (2008)	2 years after dredging	163
Bayou Verdine Wetland	1.53	100%	100% (2008)	2023	76
Coon Island Channel	57	48.5%	7.9% (2008)	2 yrs after maintenance dredging	206
Coon Island Loop	254	36.5%	7.9% (2000)	2023	630
Total					1,075

5.2 PROPOSED SABINE 1999 PROJECT - 'CREDIT' FOR CREATED MARSH & OPEN WATER COMPONENTS

The proposed Sabine 1999 Project has three components expected to generate ecological credits (DSAYs) following implementation: newly created marsh, open water and restored marsh hydrology.

The 'credit' quantification for the Project's newly created marsh and open water components is presented in Subsection 6.1.5 of the Draft DARP/EA. The DSAYs estimated to be provided by these two Project components are summarized in Table 6. These two components are estimated to provide 228 DSAYs of 'credit' toward the 1,075 DSAYs needed to offset the assessed benthic injury.

Table 6. HEA "credit" model input parameters and estimated DSAYs for Sabine 1999 Project's Created Marsh and Open Water components.

	Acres	Years to Full Service	Relative Value of Restored Services	DSAYs
Created Marsh	14.7	15	71.3%	198.24
Open Water	34	5	5%	30.12
Total Project Benefits	48.7			228

The remainder of this memorandum presents the Trustees' analysis of whether the remaining 847 DSAYs can be provided via the restored marsh hydrology component of the Sabine 1999 Project.

5.3 Proposed Sabine 1999 Project - 'Credit' Analysis for the Restoration of Site Hydrology (the 'Restored Marsh' Project component)

Based on the research results cited throughout Section 4, it is reasonable to conclude that:

- The Sabine 1999 project area and other marshes in the region are experiencing similar rates of relative sea-level rise (see Table 1 in subsection 4.1.1).
- The productivity of edaphic and epiphytic communities within the Sabine 1999 project area is likely reduced under current hydrologic conditions.
- Fisheries utilization of the Sabine 1999 project is diminished due to decreased access as a result of the nearly continuous spoil bank surrounding the project area.

To determine the overall benefits of the restored marsh component, the Trustees have relied upon published scientific literature, other relevant data, and communications with experts to evaluate the affects of the proposed hydrologic restoration on marsh sustainability, edaphic and epiphytic communities, and estuarine organism utilization at the Sabine 1999 site. The Trustees used the

Habitat Equivalency Analysis (HEA) model[4] to quantify the amount of marsh DSAYs that the Sabine 1999 site is expected to provide under two scenarios: 1) if nothing is done to restore or improve the site's hydrology (i.e., if hydrologic conditions remain 'As-Is'), and 2) if the hydrologic restoration action is undertaken as proposed. This approach results in quantification of the 'credit' - in terms of marsh DSAYs gained - that can reasonably be expected to be achieved via implementation of the Sabine 1999 Project's hydrologic restoration component.

5.3.1 Sabine 1999 Site – Marsh Sustainability

Assessment of Marsh Sustainability under 'As Is' Condition
An elevation change rate of -3.15 feet per century is estimated for the Sabine 1999 site under current conditions (Table 7). Two data inputs were used in calculating this rate: relative sea-level rise (subsidence and sea-level rise) and accretion rate. The average rate of relative sea-level rise for Louisiana's Chenier Plain reported in Table 1 in subsection 4.1.1 was used in this calculation. For the accretion rate, the Trustees relied upon results provided by Hoffpauir (Pers. Comm.) following the analysis of data collected in the Sabine 1999 project area. Hoffpauir reported an accretion rate of +0.17 cm/yr within the Sabine 1999 site. Unlike subsidence, accretion is not affected by compaction and dewatering processes. It is influenced by tidally deposited mineral sediment (mineral sediment input) and vegetative growth (organic material input). Therefore, Hoffpauir's accretion rate was used in calculating the current rate of elevation change at the Sabine 1999 site, while the other inputs are regionally based.

Table 7. Sabine 1999 Site – Projected Rate of Elevation Change if 'As-Is' Condition remains.

	Relative sea-level rise		Accretion (cm/yr)	Net Elevation Change (cm/yr; ft/century)
	Subsidence (cm/yr)	Sea-level rise (cm/yr)		
Sabine 1999 site "As Is"	-0.90	-0.23	+0.17	-0.96; -3.15

Elevation data was collected at the Sabine 1999 site in 2005. Using this data, the Trustees were able to estimate when portions of the marsh surface at the site would turn to open water and stop providing marsh services. This was accomplished by applying the 'As Is' elevation change rate (-3.15 ft/century; -.0315 ft/yr) to each elevation point from the 2005 site survey. When elevations were projected to drop below 0.85 feet (level inappropriate to support marsh function), the area was considered to have fully converted to open water. Table 8 illustrates the approach, using one elevation point from the 2005 survey and

[4] The HEA model is described in Section 4.0 and 6.0 of the Draft DARP/EA for the Bayou Verdine Site.

applying the 'As Is' elevation change rate (-.0315 ft/yr). Under the scenario in Table 8, the marsh surrounding that individual elevation point is estimated to convert to open water by 2013.

Table 8. Example of application of 'As Is' elevation change rate to 2005 survey data from Sabine 1999 site.

	Year							
Elevation in 2005 (feet)	2006	2007	2008	2009	2010	2011	2012	2013
1.108	1.0765	1.045	1.0135	0.982	0.9505	0.919	0.8875	0.856

The effect of the 'As Is' rate of elevation change on total marsh acreage and lifespan at the site is graphically presented in Figure 3. Under current conditions, the Sabine 1999 site is projected to be fully converted to open water by the year 2034.

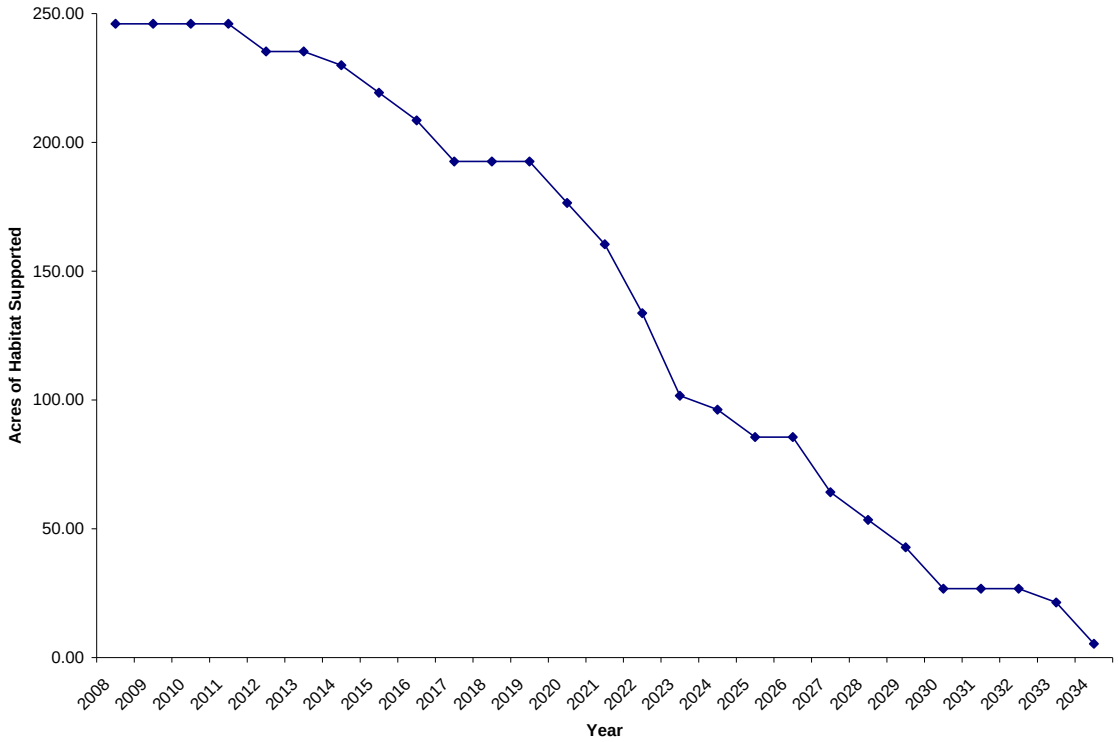

Figure 3. Graphic representation of acres of marsh habitat projected to exist through time if Sabine 1999 site conditions remain "As Is".

Assessment of Marsh Sustainability with Proposed Hydrologic Restoration at Site
While the proposed Sabine 1999 Project cannot affect the rate of relative sea-level rise (a factor that defines the net rate of elevation change at the site),

changes in the rates of accretion can be anticipated following the removal of portions of the spoil banks and further gapping of those remaining. As described in Section 4.1.2, the response to hydrologic restoration actions like those proposed for the Sabine 1999 Project is typically significant. Accretion rates have repeatedly been shown to be three times greater in tidally unrestricted versus restricted marshes. Therefore, the Trustees estimated the degree to which implementation of the Project's hydrologic restoration actions will affect marsh sustainability at the site under the scenario that the rate of accretion increases three-fold after implementation.

The approach to this analysis was the same as that used for the 'As Is' scenario, except that new elevation change rates were calculated and then applied to each of the 2005 site survey data points. The rate of relative sea-level rise remained the same as did the assumption that areas fully converted to open water when elevations dropped below 0.85 feet (level inappropriate to support marsh function). The rate of accretion experienced by the Sabine 1999 site if conditions remain 'As Is', however, is multiplied by three for this analysis. Table 9 incorporates this result (+0.51 cm/yr) and the rate of elevation change at the site (-2.03 ft/century) with accretion rates increased three-fold.

Table 9. Projected elevation change rate for Sabine 1999 site if accretion rates increase three-fold.

	Subsidence (cm/yr)	Accretion (cm/yr)	Sea-level rise (cm/yr)	Net Elevation Change (cm/yr; ft/century)
Sabine 1999 site with three-fold increase in accretion	-0.90	+0.51	-0.23	-0.62; -2.03

Again using the elevation data collected at the Sabine 1999 site in 2005, the Trustees estimated when portions of the marsh surface would turn to open water and stop producing marsh DSAYs. This was accomplished by applying the elevation change rate calculated for the three-fold increase in accretion (-2.03 ft/century rate; or -0.0203 ft/yr) to each elevation point in the 2005 survey. Table 10 illustrates the approach using one elevation point from the 2005 survey and indicates the marsh surrounding that individual elevation point is estimated to convert to open water by 2017 (4 years longer than the same point under the 'As-Is' scenario).

Table 10. Example of application of Scenario 2 elevation change rate (accretion rates increase three-fold) to 2005 survey data from Sabine 1999 site

	Year											
Elevation in 2005 (feet)	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
1.11	1.09	1.07	1.05	1.03	1.01	0.99	0.97	0.95	0.93	0.91	0.88	0.86

The effect of this elevation change rate on total marsh acreage and lifespan at the site, as compared to the 'As Is' scenario, is graphically presented in Figure 4. Overall, with a three-fold increase in accretion rates, the Sabine 1999 site is projected to fully convert to open water by the year 2050 (16 years longer than the current 'As-Is' marsh is projected to persist).

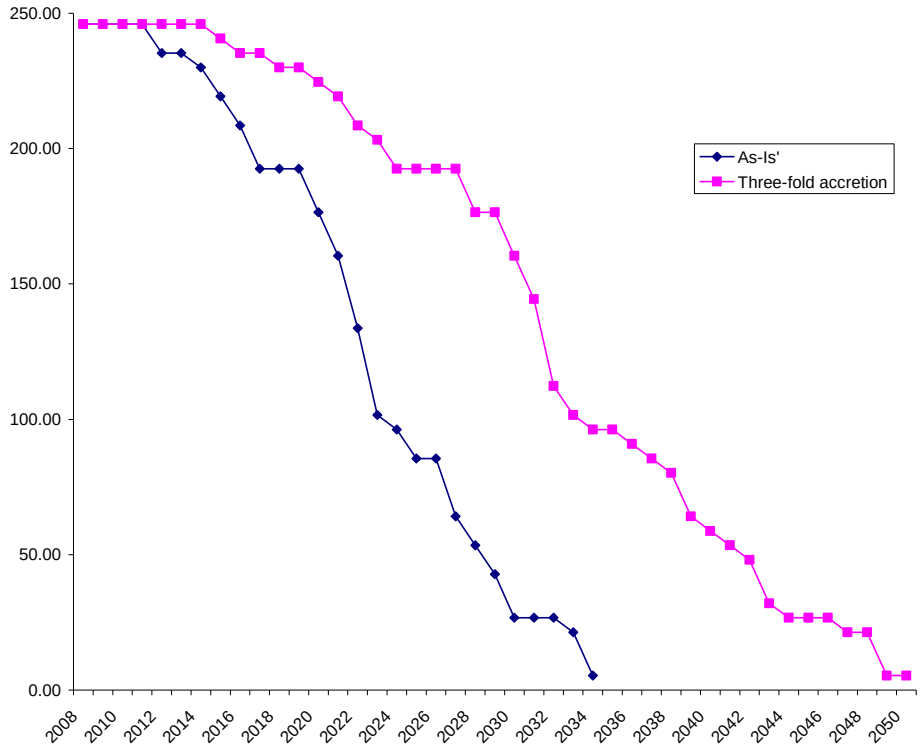

Figure 4. Graphic representation of acres of marsh habitat projected to exist through time if Sabine 1999 site accretion rates increase three-fold above the 'As Is' scenario.

5.3.2 Sabine 1999 Site – Marsh Service Levels

Marsh sustainability (via accretion) is the principal component of the credit analysis because it influences the longevity of the marsh – an input parameter of the HEA model, enabling the site to provide more ecological services to the public over time. However, the credits (DSAYs) generated by the hydrologic restoration component of the Sabine 1999 Project cannot be determined by

longevity alone. The level of services (percent services) provided by the marsh after the restoration action is undertaken will be greater than those provided by marsh under 'As Is' conditions. Therefore, in estimating the DSAYs gained due to the restoration action, the net change in services provided by the marsh is also assessed.

Determination of level of marsh services for restored marsh

State and federal trustees involved in recent NRDA's in both Texas and western Louisiana have determined that a fully functioning created marsh provides 71.3% services of those provided by a natural marsh (*e.g.,* Lavaca Bay, TX). Following implementation of the proposed hydrologic restoration actions at the Sabine 1999 site, therefore, the Trustees expect marshes at the Sabine site to attain a 71.3% service level (compared to natural marsh). The Trustees also recognize that, due to the current impounded condition of the marsh at the Sabine 1999 site, the marsh at the site would not attain that level of service without the restoration action.

Determination of 'As-Is' level of marsh services

To determine the level of services provided by marsh under 'As-Is' conditions, the Trustees focused on the expected change in service levels of the epiphytic/edaphic algal communities and in estuarine organism access. The Trustees first determined the expected percent change in both epiphytic/edaphic algal communities and estuarine organism access anticipated from the restoration action. The corresponding values were then subtracted from the percent services provided by a fully functioning created marsh (71.3%) to yield the percent service level for marsh under 'As is' conditions. The following describes the analysis.

Assessment of Change in Edaphic and Epiphytic Algal Production

As mentioned in section 4.2.2, researchers have estimated that approximately 25% of the overall productivity of a salt marsh can be attributed to edaphic and ephiphytic algae production. Whether autotrophic or heterophic in nature, this group provides a vital role in making carbon available to higher trophic organisms (*i.e.*, daggerbladed shrimp, and sheepshead minnow) (Quinones-Rivera and Fleeger, 2005). Under restricted hydrological conditions (i.e., like the conditions found at and currently affecting the Sabine 1999 marsh), productivity in these communities is likely to be 10% of the overall productivity of a fully functioning marsh (15% less than the potential 25% noted above (J. Fleeger and M. Sullivan, pers. Comms. 2007). Hydrologic improvements will increase frequency of flooding and drying, wetting of a large portion of plant stems, and greater delivery of nutrients to these communities and, thus, can be expected to result in edaphic and epiphytic algae productivity gains at the site. If edaphic and epiphytic algae productivity within the present Sabine 1999 marsh increases by 15% within a marsh environment that will provide only 71.3% of the services of a natural marsh, then the overall improvement in productivity within the restored habitat

would be 10.7% (15% of 71.3% of services). The inputs and results are listed in Table 11.

Table 11. Projected service level increase (relative to total project size) for edaphic/epiphytic algal productivity following hydrologic restoration of the Sabine 1999 project site

Parameter	Acres Benefited	Time to maturity	Service increase
Edaphic/Epiphytic Algal productivity	246	1 year	10.7%

Assessment of Change in Estuarine Organism Access & Utilization

While the literature cited in subsection 4.4 is limited and does not allow identification of a precise estimate of the level of improvement, it does indicate that estuarine resource utilization can be expected to increase following the removal of barriers that prohibit access to a marsh. The cited literature documents increases in estuarine organism utilization of between 66% and 94% following the removal of barriers, which equates to a pre-restoration level of utilization of between 34% and 6%, respectively. Because the literature does not give rise to a more precise estimate, the Trustees used 66% improvement (equating a pre-restoration level of utilization of 34%) in quantifying the benefits to estuarine organisms. This is the most conservative (i.e., favorable to the environment and public) within the range.

Rozas and Minello (2002) found that utilization of marsh by estuarine organisms primarily occurs within 100 feet from the marsh edge. This also corresponds to a zone of greatest abundance for infauna and other prey organisms when hydrological conditions are adequate (Whaley and Minello 2002, Minello *et. al.* 1994). Areas beyond that distance are not typically accessible by organisms that feed or take refuge in a marsh ecosystem. Therefore, in calculating DSAYs based on this expected benefit (66% increase in utilization), the area associated with this benefit has to also be taken into account. The distance from the marsh edge, as well as the amount of marsh edge estimated to be accessible to estuarine organisms following removal of the spoil banks at the Sabine 1999 site were used to calculate the total area realizing this benefit. The Trustees measured the length of marsh edge on aerial photography using Geographic Information System software and determined that 6,000 feet of marsh edge will be fully accessible following removal of the spoil banks. Therefore, 13.77 acres of marsh (calculated by multiplying 6,000 feet of edge by 100 feet of access; result (600,000 square feet) then converted to acreage) will be accessible to estuarine organisms. Table 12 details the inputs and overall percent service increase as a result of the restoration action. As before with edaphic and epiphytic algal production, the percent service increase attributable to the hydrologic improvements at the site is calculated relative to the maximum 71.3% service increase for created marsh, as documented in the literature. Applying

66% to that maximum 71.3% results in a 47% service increase in estuarine organism access and utilization creditable to the hydrologic restoration, as reflected in Table 12. This identified percent service level was adjusted to the total size of marsh at the site to allow the Trustees to determine the 'As-Is' level of marsh services for the entire project site, equating to a 2.6% increase for that purpose .

Table 12. The projected service level increase (relative to total project size) for estuarine organism utilization following hydrologic restoration of the Sabine 1999 project site

Parameter	Acres Benefited	Time to maturity	Service increase	Percent of total project area	Service increase adjusted to the size of the project
Estuarine Organism Access/Utilization	13.77	1 year	47%	5.6%	2.6%

Overall Percent Service Provided by the 'As-Is' Marsh for Use in Credit Analysis
As explained at the outset of Section 5.3.2, the Trustees' approach to determining the reduced level of services being provided by the 'As-Is' marsh focused first on determining the increases in services expected following hydrologic restoration for algal and epiphytic production, and estuarine organism utilization, as two key indicators of overall marsh function and productivity. The Trustees assumed the 'As-Is' marsh at the site will improve as predicted for these two components of the marsh and that, following restoration, marsh at the site will attain a maximum service level of 71.3% (maximum level services of fully functioning created marsh relative to natural marsh). The 'As-Is' service level of the marsh at the site is calculated by subtracting the expected percent service increases for algal and epiphytic production (10.7%) and estuarine organism utilization (2.6%) from the services provided by a fully functioning created marsh (71.3%). The result is that the 'As-Is' marsh is estimated as providing a current level of marsh services that are 58% of a natural marsh.
((71.3% - (10.7% + 2.6%)) = 58%).

5.4 Proposed Sabine 1999 Project – 'Credit' Quantification for Restoration of Site Hydrology (the 'Restored Marsh' Project component)

To quantify the total credit (DSAYs) associated with the Sabine 1999 Project's hydrologic restoration component, the Trustees have relied on the estimates of marsh longevity and the increased marsh services level that could reasonably be expected to result from implementation of the restoration action. The corresponding inputs to the HEA are summarized in Table 13.

Table 13. HEA parameters used for the 'As-Is' and three-fold increase in accretion scenarios.

	Marsh Condition	
HEA Input	'As-Is'	Three-fold increase in accretion (post-restoration action)
Percent services	58%	71.3%
Project life	26	42
Acreage*	Variable	Variable

*Acreage is listed as variable because the HEA model reflects the decreasing acreage calculated for each scenario in sub-section 5.3. However, the area estimated to be affected by the action is 246 acres.

The Trustees have applied a HEA model to estimate the marsh DSAYs that the site will generate under each of the above scenarios. The full suite of parameters used in the analysis and the model output are included in Appendices A and B. This analysis indicates that an additional 1,322 marsh DSAYs would be generated by the proposed hydrologic restoration at the site beyond those that would occur if hydrologic conditions at the site remain 'As Is'. Adding hydrologic restoration credits to the 228 marsh DSAYs previously quantified for the Project's created marsh and open water components (see Section 5.2; Table 6), results in a total of 1,550 marsh DSAYs estimated to be provided by implementation of the proposed Sabine 1999 Project. This predicted credit is sufficient to compensate for the assessed benthic resource losses (equivalent to 1,075 marsh DSAYs) associated with historical hazardous substances releases from the ConocoPhillips and Sasol NA facilities.

6. Conclusion

The information described herein indicate that accretion rates at the Sabine 1999 site have the potential to increase three-times over current rates following implementation of the hydrologic restoration actions that are part of the Sabine 1999 Project and further, that implementation of these actions will increase marsh longevity and marsh services levels at the site. The Trustees' credit analysis estimates that 1,550 marsh DSAYs will be generated following implementation of the Sabine 1999 Project and, on that basis, the Trustees project that the Sabine 1999 Project will produce sufficient marsh DSAYs to offset ConocoPhillips' and Sasol NA's assessed liability for benthic resource losses in Bayou Verdine and Coon Island Loop.

7. Literature Cited

Baltz, D.M., C. Rakocinski, and J.W. Fleeger. 1993. Microhabitat use by marsh-edge fishes in a Louisiana estuary. Environmental Biology of Fishes 36:109–126.

Baumann, R.H. and DeLaune, R.D. 1982. Sedimentaiton and apparent sea-level rise as factors affecting land loss in coastal Louisiana. Proceeding – Conference on Coastal Erosion and Wetland Modification in Louisiana: Causes, Consequences, and Options. Published by the U.S. Dept. of Interior, Fish and Wildlife Service. FWS/OBS-82/59, pp. 2 – 13.

Boesch, D.F., M.J. Josselyn, A.J. Mehta, J.T. Morris, W.K. Nuttle, C.A. Simenstad, D.J.P. Swift. 1994. Scientific assessment of coastal wetland loss, restoration and management in Louisiana. Journal of Coastal Research Special Issue 20:103.1-103.

Boumans, R.M. and Day, J.W. 1994. Effects of two Louisiana marsh management plans on water and materials flux and short-term sedimentation. Wetlands 14: 247-261.

Bradley, P.M. and J.T. Morris. 1990. Influence of Oxygen and sulfide concentration on Nitrogen uptake kinetics in *Spartina alterniflora*. Ecology 71(1):282-287.

Burdick, D.M., M. Dionne, R.M. Boumans, and F.T. Short. 1997. Ecological responses to tidal restrictions of two northern New England salt marshes. Wetlands Ecology and Management 4(2):129-144.

Cahoon, D.R. 1994. Recent accretion in two managed marsh impoundments in coastal Louisiana. Ecological applications 4(1):166-176.

DeLaune, R.D., and W.H. Patrick, Jr. 1979. Rate of sedimentation and its role in nutrient cycling in a Louisiana salt marsh. *In*: Estuarine and Wetland Processes with Emphasis on Modeling. pp. 401-412.

DeLaune, R.D., R.J. Buresh, and W.H. Patrick, Jr. 1979. Relationship of soil properties to standing crop biomass of Spartina alterniflora in a Louisiana marsh. Est. Coastal Mar. Sci. 8:477-487.

Fallon, R.D., S.Y. Newell and L.C. Groene. 1985. Phyllophane algae of standing dead Spartina alterniflora. Marine Biology 90:121-127

Fleeger, J.W. 2007. Louisiana State University. Personal Communication.

Flynn, K.M., I.A. Mendelssohn, and B.J. Wilsey. 1999. The effects of water level management on the soils and vegetation of two coastal Louisiana marshes. Wetlands Ecology and Management 7:193-218.

Gambrell, R.P., and W.H. Patrick, Jr. 1978. Chemical and microbiological properties of anaerobic soils and sediments. In: Plant Life in Anaerobic Environments. Ann Arbor Science Publishers, Inc., Ann Arbor, MI, pp. 375-423.

Gornitz, V., S. Lebedeff, and J. Hansen. 1982. Global sea level trend in the past century. Science 215(4540):1611-1614.

Hoffpauir, B. 2007. McNeese State University. Personal communication.

Hoese, H.D. and M. Konikoff. 1995. Effects of marsh management on fisheries organisms: the compensatory adjustment hypothesis. Estuaries 18: 180–197.

Hood, W.G. 2004. Indirect environmental effects of dikes on estuarine tidal channels: thinning outside of the dike for habitat restoration and monitoring. Estuaries 27(2):273-282.

Jackson, G., R. Zingmark, A.J. Lewitus, R. G. Tymowski, and J. Stuckey. 2006. Spatial and temporal dynamics of epiphytic microalgae on the cordgrass *Spartina alterniflora* in North Inlet Estuary. Estuaries and Coasts 29(6B):1212-1221.

Jones, R.C. 1980. Productivity of algal ephiphytes in a Georgia salt marsh: effect of inundation and frequency and implications of total marsh productivity. Estuaries 3(4):315-317.

Koch, M.S., I.A. Mendelssohn and K.L. McKee. 1990. Mechanism for the hydrogen sulfide-induced growth limitation in wetland macrophytes. Limnol. Oceanogr. 35(2):399-408.

Kuhn, N.L., I.A. Mendelssohn, and D.J. Reed. 1999. Altered hydrology effects on Louisiana salt marsh function. Wetlands 19(3):617-626.

Mendelssohn, I. A. and K. L. McKee. 1988. Spartina alterniflora die-back in Louisiana: Time course investigation of soil waterlogging effects. Journal of Ecology 76:509-521.

Mendelssohn, I.A., K.L. McKee, and W.H. Patrick, Jr. 1981. Oxygen deficiency in Spartina alterniflora roots: Metabolic adaptation to anoxia. Science. 214:439-441.

Mendelssohn, I.A. and J.T. Morris. 2000. Ecophysiological controls on the productivity of Spartina alterniflora Loisel. In: Concepts and Controversies in Tidal Marsh Ecology. Eds. M.P. Weinstein and D.A. Kreeger. pp 59-80.

Minello, T. J. 1993. Chronographic tethering: a technique for measuring prey survival time and testing predation pressure in aquatic habitats. Marine Ecology Progress Series 101:99-104.

Minello, T.J. and L.P. Rozas. 2002. Nekton in gulf coast wetlands: fine-scale distributions, landscape patterns, and restoration implications. Ecological Applications 12(2): 441-455

Minello, T.J. and J.W. Webb. 1997. Use of natural and created *Spartina alterniflora* salt marshes by fishery species and other aquatic fauna in Galveston Bay, Texas, USA. Marine Ecology Progress Series 151:165–179.

Minello, T.J. and R.J. Zimmerman. 1983. Fish predation on juvenile brown shrimp, *Penaeus aztecus* Ives: the effect of simulated *Spartina* structure on predation rates. Journal of Marine Biology and Ecology 72:211–231.

Minello, T.J. and R.J. Zimmerman. 1985. Differential selection for vegetative structure between juvenile brown shrimp (*Penaeus aztecus*) and white shrimp (*P. setiferus*), and implications in predator-prey relationships. Estuarine, Coastal and Shelf Science 20:707- 716.

Minello, T.J. and R.J. Zimmerman. 1991. The role of estuarine habitats in regulating growth and survival of juvenile penaeid shrimp. p. 1–16. *In* P. DeLoach, W. J. Dougherty, and M. A. Davidson (eds.) Frontiers in Shrimp Research. Elsevier, Amsterdam, The Netherlands.

Minello, T. J., R. J. Zimmerman, and E. X. Martinez. 1989. Mortality of young brown shrimp Penaeus aztecus in estuarine nurseries. Transactions of the American Fisheries Society 118:693-708.

Minello, T. J., R. J. Zimmerman, and R. Medina. 1994. The importance of edge in the use of a created salt marsh by natant macrofauna. Wetlands 14:184-198.

Mitsch, W.J., and J.G. Gosselink. 2000. Wetlands, 3rd edition: Wiley Publishing, 920 p.

Montague, C.L., A.V., Zale, and H.F. Percival. 1987. Ecological effects of coastal marsh impoundments: a review. Environmental Management 11:743–756.

Pickney, J., and R.G. Zingmark. 1991. Effects of tidal stage and sun angles on intertidal benthic microalgal production. Marine Ecology Progress Series 76:81-89.

Penland, S., K.E. Ramsey, R.A. McBridge, T.F. Moslow, and K.A. Westphal. 1989. Relative sea level rise and subsidence in Louisiana and the Gulf of Mexico. Louisiana Geological Survey, Coastal Geology Technical Report No. 3.

Qiompmes-Rivera and J.W. Fleeger. 2005. The grazing effects of grass shrimp, Palaemonetes pugio, on epiphytic microalgae associated with Spartina alternifloria. Estuaries 28(2):274-285

Reed, D.J., N. De Luca, and A.L. Foote. 1997. Effect of hydrologic management on marsh surface sediment deposition in coastal Louisiana. Estuaries 20(2):301-311.

Reed, D.J., M.S. Peterson, and B.J. Lezina. 2006. Reducing the effects of dredged material levees on coastal marsh function: sediment deposition and nekton utilization. Environmental Management 37(5):671-685.

Rogers, D.R., Rogers, B.D. and W.H. Herke. 1994. Structural marsh management effects on coastal fishes and crustaceans. Environmental Management 18:351–369.

Rogers, B.D., Herke, W.H. and E.E. Knudsen. 1992. Effects of three different water-control structures on the movements and standing stocks of coastal fishes and macrocrustaceans. Wetlands 12:106–120.

Roman, C.T.. Niermg, W.A. and R.S. Warren. 1984. Salt marsh vegetation change in response to tidal restrictions. Environmental Management 8:141-149.

Rozas, L.P. and T.J. Minello. 1998. Nekton use of salt marsh, seagrass, and nonvegetated habitats in a south Texas (USA) estuary. Bulletin of Marine Science 63(3):481-501.

Rozas, L.P., and T. Minello. 1999. Effects of structural marsh Management on fishery species and other nekton before and during spring drawdown. Wetlands Ecology and Management, 7:121-139

Stowe, W.C. 2007. Cleveland Museum of Natural History. Personal Communication.

Sullivan, M.J. 2007. Florida State University Coastal and Marine Laboratory. Personal Communication.

Sullivan, M.J. and C.A. Currin. 2000. Community structure and functional dynamics of benthic microalgae in salt marshes. In: Weinstein, M.P., Kreeger D.A. (eds) Concepts and controversies in tidal marsh ecology. Kluwer Academic Publishers, Dordrecht, p81-106

Sullivan, M.J. and C.A. Moncreiff. 1988. Primary production of edaphic algal communities in a Mississippi Salt Marsh. Journal of Phycology 24:49-58

Sullivan, M.J. and C.A. Moncreiff. 1990. Edaphic algae are an important component of salt marsh food-webs: evidence from multiple stable isotope analysis. Marine Ecology Progress Series 62:149-159.

Thomas, J.L., T.J. Minello, and R.J. Zimmerman. 1990. Abundance patterns of juvenile blue crabs (Callinectes sapidus) in nursery habitats of two Texas bays. Bulletin of Marine Science 46:115-125.

Turner, R.E. 1987. Relationships between canal and levee density and coastal land loss in Louisiana. U.S. Fish and Wildlife Service Biological Report 85(14), 58 pp.

Turner, R.E., E.M. Swenson, and J.M. Lee. 1994. A rationale for coastal wetland restoration through spoil bank management in Louisiana, USA. Environmental Management 18(2):271-282.

Valiela, I. and J.M. Teal. 1974. Nutrient limitations in salt marsh vegetation, pp. 547-563. *In* Reimold, R. J. and Queen, W. H. (eds.), Ecology of Halophytes. Academic Press, New York, NY.

White, W.A., R.A. Morton, and C.W. Holmes. 2002. A comparison of factors controlling sedimentation rates and wetland loss in fluvial-deltaic systems, Texas Gulf coast. Geomorphology 44:47-66.

Whaley, S.D. and T.J. Minello. 2002. The distribution of benthic infauna of a Texas salt marsh in relation to the marsh edge. Wetlands 22(4):753-766.

Wilsey, B.J., K.L. McKee, and I.A. Mendelssohn. 1992. Effects of increased elevation and macro-and micronutrient additions on Spartina alterniflora transplant success in salt-marsh dieback areas in Louisiana. Env. Mgt. 16(4):505-511.

Zimmerman, R.J. and T.J. Minello. 1984. Densities of *Penaeus aztecus*, *P. setiferus* and other natant macrofauna in a Texas salt marsh. Estuaries 7:421–433.

Zimmerman, R.J., T.J. Minello, and G. Zamora, Jr. 1984. Selection of vegetated habitat by brown shrimp, *Penaeus aztecus*, in a Galveston Bay salt marsh. Fishery Bulletin 82:325–336.

Zimmerman R.J., T.J. Minello, M.C. Castiglione, and D.L. Smith. 1990. Utilization of marsh and associated habitats along a salinity gradient in Galveston Bay. NOAA Technical Memorandum, Galveston, TX, USA. NMFS-SEFC-250.

Zimmerman, R.J., Minello, T.J. and Rozas, L.P. 1999. Salt marsh linkages to productivity of penaeid shrimps and blue crabs in the Northern Gulf of Mexico. *In*: Weinstein, M.P. (ed.), Concepts and Controversies in Tidal Marsh Ecology. New Jersey Sea Grant, Fort Hancock.

8. Appendices