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Comparing Newly Built Wetlands in the Atchafalaya Bay, Louisiana and Sacramento-San Joaquin Delta, California

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Abstract

This research investigated patterns in elevation change in newly built wetlands in the Atchafalaya delta, and newly restored wetlands in the Sacramento-San Joaquin River delta. RSETs were used to measure small changes in elevation, and soil cores were processed to examine mineral and organic contributions.

Elevation change was highly variable, responding to influences from water level, river discharge, storms and vegetation. Mineral matter consistently added more to the marsh soil through volumetric and gravimetric contributions. Organic contributions were not significantly different across sites, suggesting the type of emergent vegetation at a site may not be the most important factor.

Sites with the lowest elevations had the highest rates of positive elevation change. Higher elevation sites were more exposed and had negative rates of elevation change. The findings suggest ideal sites for marsh building are in areas that receive sediment input, are protected from high-energy events, and can support emergent vegetation.

Keywords: freshwater tidal marsh, marsh elevation change, soil organic and mineral contributions

Chapter 1: Introduction
1.1: Background

An estimated 890,000 km^2 of wetlands existed in the United States in the 1600s and since then there have been extensive wetland losses in the lower 48 states as these lands are drained and converted for other uses (EPA, 2003). Although there were wetland gains from the late nineties into the early millennium because of factors such as public education and outreach, enforcement of wetland protection, and coastal monitoring programs, the overall trend shows losses have outpaced gains (Figure 1.1; Dahl, 2009). Net loss estimates of 252 km^2 for the recent period of 2004 through 2009 have resulted in the nation's total wetlands acreage equaling just over 445,000 km^2 (Dahl, 2009), a number half of the 1600s estimate. Both human actions and natural threats compromise wetlands and now factors associated with global climate change must be factored in as well (Table 1.1).

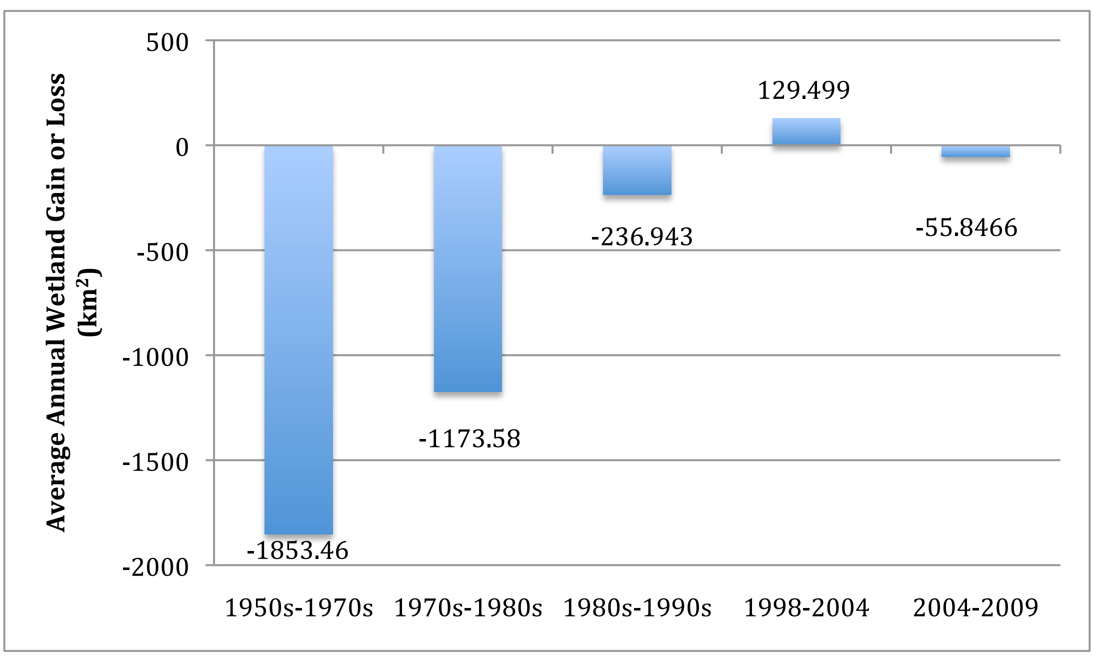

Figure 1.1 Average annual net gain or loss estimates for the lower 48 states for time periods during 1954-2009 (adapted from Dahl, 2009).

Human Actions	**Natural Threats**	**Global Climate Change**
Drainage	Erosion	Increased air temperature
Dredging and deposition of fill material	Subsidence	Precipitation shifts
Diking and damming	Sea level rise	Increased storm frequency
Tilling for crops	Droughts	Droughts
Levees	Hurricanes and storms	Floods
Logging		Increased atmospheric CO_2
Mining		Sea level rise
Runoff		
Air and water pollutants		
Nonnative species		
Grazing		

Table 1.1 Factors contributing to wetland loss in the lower 48 states (adapted from EPA, 2003).

The state of Louisiana contains about 40 percent of the coastal salt marshes in the United States and has one of the highest rates of wetland loss in the country. Over the past approximately 7000 years Louisiana was built by the Mississippi River and its complex system of overlapping delta lobes, which cycle through periods of building and deterioration (Baumann et al., 1984; Roberts, 1997). Historically the river was a source not only of delta building but also of freshwater, nutrients, organic matter and sediments that would spill over and nourish the adjacent wetlands (Day et al., 2007). However, with the construction of flood and river control structures much of this nourishment has been curtailed and marshes no longer receive the mineral and organic matter deposits they need in order to promote positive vertical accretion and new land building (DeLaune et al., 2003; DeLaune and Pezeshki, 2002; Hatton et al., 1983; Neubauer, 2008; Nyman et al., 1990; Nyman and Delaune, 1991; Nyman et al., 1993a, 1993b).

Areas in northern California have also been struggling with high rates of wetland loss. The Sacramento-San Joaquin Delta, found east of the San Francisco Bay Estuary, was at one time a 1400 km^2 tidal wetland area (Drexler et al., 2007) but beginning in the mid-1800s much of

this area was drained for agriculture leading to extensive subsidence of this land (Drexler et al., 2009a, 2009b). Along with the direct dewatering effects, the main cause of this subsidence was the oxidation of organic carbon, where carbon from the soil was converted into carbon dioxide (Deverel and Leighton, 2008). Subsidence has continued into the present and has resulted in delta "islands" being between 3 and 8 meters below sea level (California Department of Water Resources, 1980; Ingebritsen and Ikehara, 1999).

When the effects of subsidence are combined with eustatic sea level rise, measures of relative sea level rise can be obtained. Eustatic sea level rise, which has been estimated to be between 1.0 and 2.4 mm yr^{-1}, is a result of ocean thermal expansion and the melting of glaciers and ice caps in the past two centuries (Church and White, 2006; Douglas and Peltier, 2002). Even higher values of eustatic sea level rise, 3.1 mm yr^{-1}, are more recently recommended by the Army Corps of Engineers (USACE, 2011). Together, high rates of local subsidence, 2.4-13 mm yr^{-1} for the Louisiana coast (Coastal Protection and Restoration Authority of Louisiana, 2012) and 5-30 mm yr^{-1} in California (Deverel and Leighton, 2008), combine with the high eustatic sea level rise measures and result in high rates of relative sea level rise for marshes in these areas.

If coastal marshes are unable to maintain accretion rates because they are cut off from the rivers that historically provided sediment and nutrients, and are faced with rising amounts of relative sea level, they are in danger of being converted to open water. From 1985 to 2010 Louisiana has experienced wetland loss at a rate of 42.9 km^2 per year (Couvillion et al., 2011). There has been a total net loss of coastal land from 1932 to 2010 of 4876.9 km^2 (Couvillion et al., 2011). Predictions for the next 50 years estimate an additional 4548.0 km^2 will be lost if serious action is not taken (Figure 1.2; Coastal Protection and Restoration Authority of

Louisiana, 2012). Wetland restoration in Louisiana has therefore become a main focus in order to combat impending future loss.

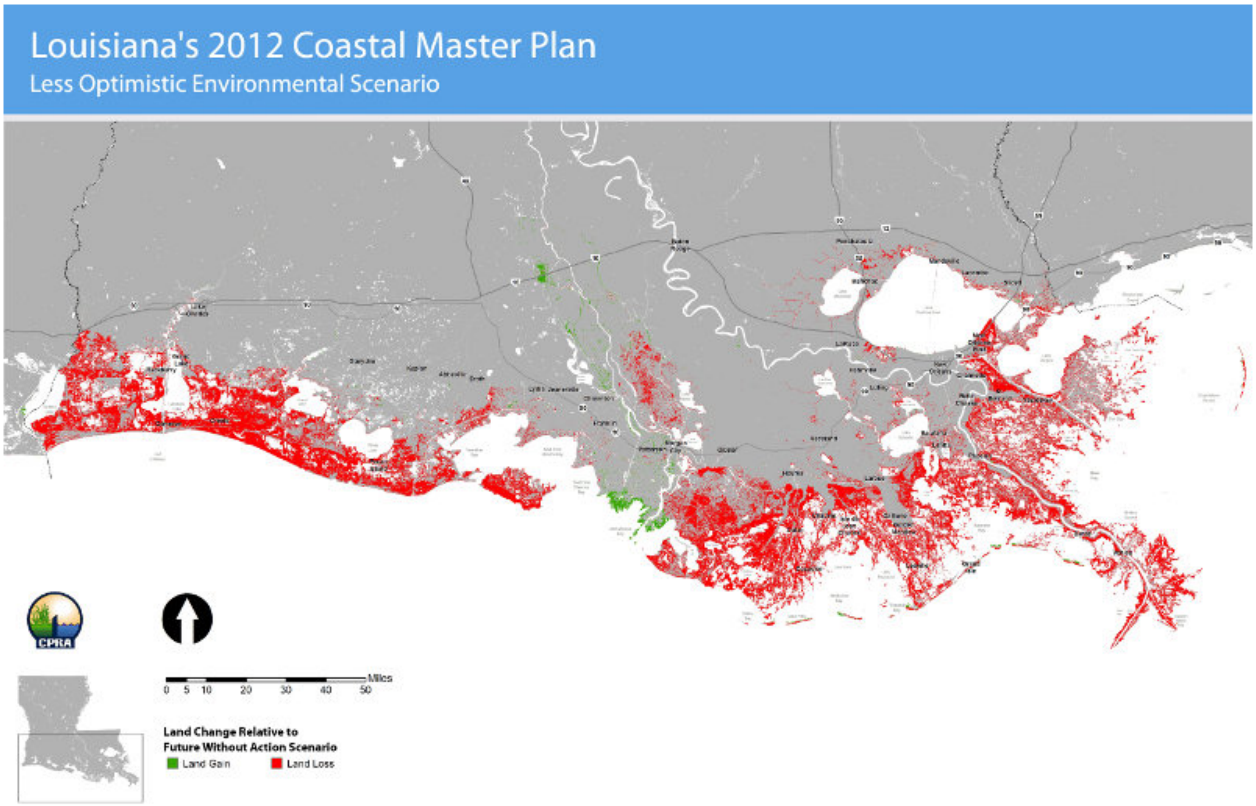

Figure 1.2 Coastal Louisiana land loss predictions for the next 50 years. Areas of red represent land loss while areas of green represent land building (Coastal Protection and Restoration Authority of Louisiana, 2012).

Wetland restoration has been a main focus for the Sacramento-San Joaquin delta of California as well. The Sacramento River, which flows from the north, and the San Joaquin River, which flows from the south, define this delta. The two rivers meet and flow out through the San Francisco Bay. After so much of the wetland area in this delta was converted for other uses (Figure 1.3), public concern grew and in 1966 the first wetlands protection legislation was passed in the United States that called for “no net loss of wetlands” for the San Francisco Bay (Williams and Faber, 2001; Williams and Orr, 2002). The first restoration project began in 1972 (Williams and Faber, 2001) and most recently, in May of 2012, a preliminary draft of a new

Delta Plan was presented to the Delta Stewardship Council, a group created by legislature in 2009 that includes a diverse group of members from all over California and all different fields of expertise. The 2012 plan has two primary goals: restore Delta ecosystems and provide a more consistent California water supply (Delta Stewardship Council, 2010).

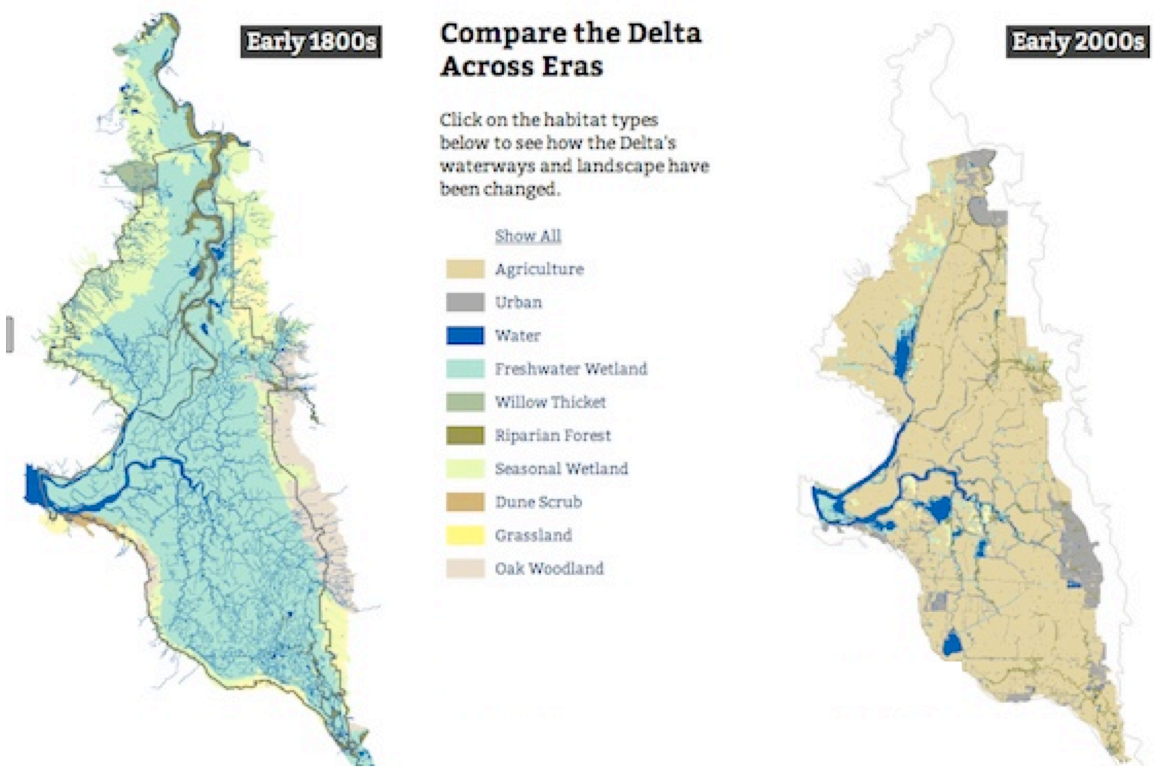

Figure 1.3 Historic marsh changes in Sacramento-San Joaquin Delta (Christensen, http://science.kqed.org/quest/delta-map/).

1.2: Coastal Land Building

Though the future outlook for coastal wetlands looks bleak, there are some areas where natural wetland building is occurring through the creation of new wetlands prograding into open water areas. River systems everywhere transport sediment from erosional areas of the watershed to depositional areas like deltas and estuaries (Wright and Schoellhamer, 2004). Over long-term geomorphic time scales, equilibrium is found between the processes of erosion, deposition, and sea-level change, and landforms such as tidal wetlands are created (Wright and Schoellhamer, 2004).

Once sediment in a delta or estuary builds up enough to become subaerial, plants are able to colonize and stabilize the created mudflat (Williams and Orr, 2002). This helps combat potential erosion and increases future sedimentation by trapping new sediment brought in with flood events (Roberts, 1998; Williams and Orr, 2002). The combination of high loads of mineral sediments and nutrients promotes vigorous vegetation growth (Mitsch and Gosselink 2000; Morris et al. 2002; Williams and Orr, 2002). That vegetative growth then initiates a positive feedback of organic matter accumulation and more mineral sediment deposition (Mitsch and Gosselink 2000; Morris et al. 2002), which furthers the vertical building process. Suspended sediment deposition is especially key in restoring wetland areas that have subsided significantly (Wright and Schoellhamer, 2005). A marsh will continue building until it reaches equilibrium with the mean high water level of the area and becomes a mature marshplain (Figure 1.4; Allen, 1990; Williams and Orr, 2002). The long-term sustainability of a marsh is maintained by the interactions of relative sea level rise, plant productivity, sediment deposition, and subsidence; all of these processes maintain a marsh at any given site in a dynamic equilibrium with the local tide levels (Mitsch and Gosselink, 1986; Morris et al., 2002).

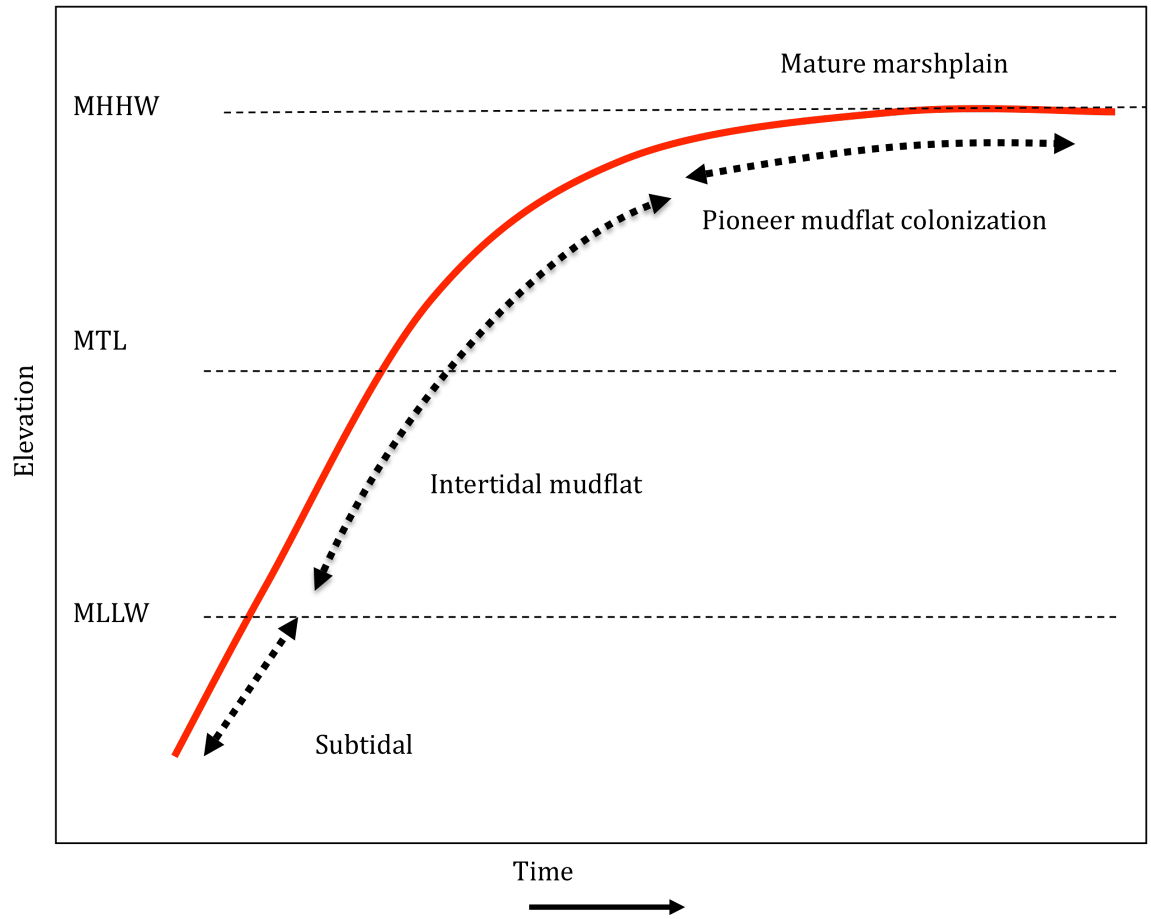

Figure1.4 Conceptual model of marsh evolution through time. When the marsh begins building in the subtidal zone it is flooded by mean lower low water, MLLW, due to its low elevation. As more sediment is deposited and there is positive elevation change it becomes an intertidal mudflat and is closer to mean tide level, MTL. With continued building it surpasses MTL, reaches an elevation high enough for vegetation to colonize and then continues building until it reaches the mean higher high water level, MHHW, where it becomes a mature marshplain (adapted from Williams and Orr, 2002).

Although wetland loss has been the dominant trend in both Louisiana and California, there are areas in both states where wetland building is now occurring. With an understanding of the processes associated with this building, managers can be better equipped to plan the restoration projects that are needed to assuage the trends of high wetland loss.

1.2.1 Louisiana

Along the coast of Louisiana the most recent delta-switching event for the Mississippi River is the attempt to abandon the current bird foot delta for the new delta forming in the

Atchafalaya Bay (Figure 1.5; Roberts, 1998). In order to prevent the Mississippi River from switching its course fully into the Atchafalaya River, the Old River control structure was built in 1963 to limit the flow into the Atchafalaya River to 30% of the Mississippi River flow (Roberts, 1998). Two bayhead deltas, one at the mouth of the Atchafalaya River, and another at the Wax Lake Outlet (Figure 1.5), formed and became subaerial after an unusually high flood year in 1973 (Roberts, 1998).

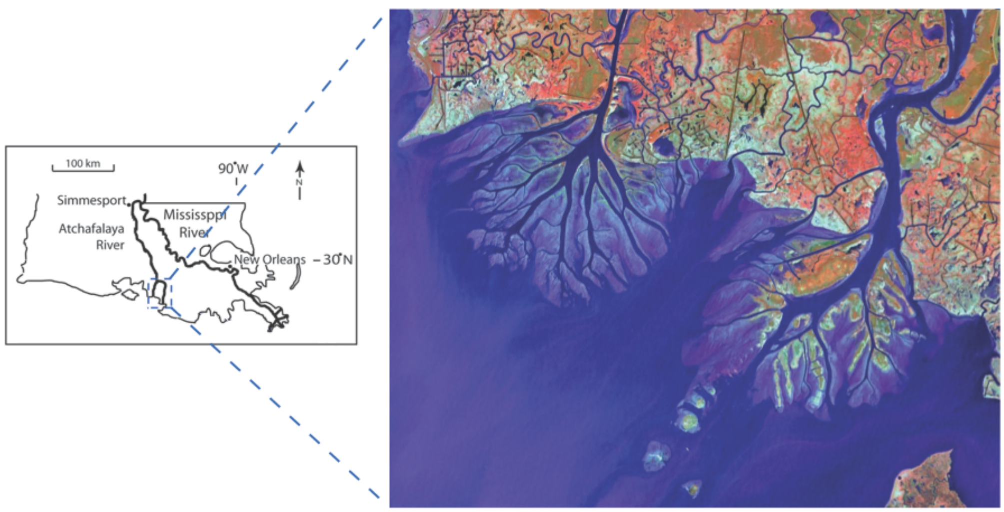

Figure 1.5 Wax Lake (left) and Atchafalaya (right) deltas (Landsat 5 Thematic Mapper Satellite Image, 11/17/2005. Image provided by Barras, J., USGS, www.ngi.lsu.edu).

The suspended load of the Atchafalaya River near the delta is composed primarily of finer silt and clay particles (Dumars, 2002). In early sedimentation reports for the Atchafalaya Bay Thompson (1951) described the upper layers of sedimentation to be “mud with a jelly-like consistency,” and a later study by Roberts (1998) reports the sediments filling the basin were mostly fine-grained swamp deposits. A recent study published by Allison et al., (2012) found that from Simmesport to Morgan City and to the Wax Lake outlet there is net sediment storage of 23 million tons yr-1, with only 30% of that total comprised of sand (Figure 1.6).

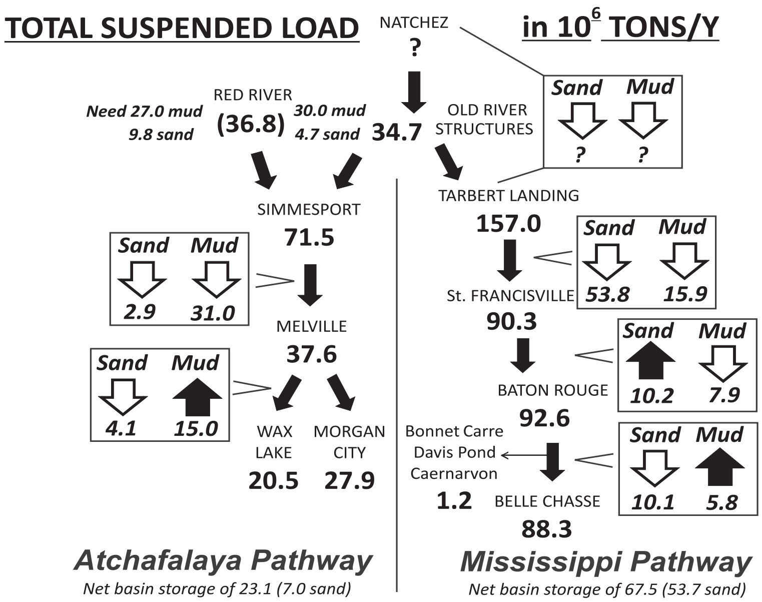

Figure 1.6 Average annual total suspended load in the Atchafalaya and Mississippi Rivers for 2008-2010 flood years. Data collected from USGS and US Army Corps of Engineers monitoring stations. White arrows represent losses from the suspended load and black up arrows represent additions to the suspended load (Allison et al., 2012).

Maintenance dredging for shipping traffic in the Atchafalaya Delta has caused it to evolve differently than the Wax Lake Delta. Material that is dredged is deposited along the banks of the delta creating a proficient channel, which carries sediment from the river directly to the Gulf of Mexico (Coastal Protection and Restoration Authority of Louisiana, 2011). This curtails some of the natural delta building process, a process which is taking place in the Wax Lake Delta since dredging there was stopped in 1980 (Coastal Protection and Restoration Authority of Louisiana, 2011).

Succession of plant communities is dynamic in the Atchafalaya Delta – some species increase over time, some are relatively stable with time, and some are present initially and then die off (Sasser and Fuller, 1988). The islands of the delta are covered by 3 dominant species with the most extensive coverage by the *Sagittaria* community (Sasser and Fuller, 1988). These species usually occur in the lowest elevations (CPRA, 2011) and have been known to be an early

colonizing species (Evers et al., 1998; Holm and Sasser, 2001; Johnson et al., 1985; Shaffer et al., 1992).

Some studies of vegetation in the Atchafalaya and Wax Lake Deltas have hypothesized that communities have shifted due to differences in periodic saltwater intrusions within the two deltas (Shaffer et al., 1992; Swenson and Sasser, 1992). These salinity incursions are expected during late summer and autumn months when discharge from the Atchafalaya River is lower and there is an increase in frontal and storm activity (Swenson and Sasser, 1992). Historically the average annual sediment supply of the Atchafalaya River was estimated to be 68 million tons (Roberts, 1997), with peak spring discharge often exceeding 11,0000 m^3 s^{-1} (van Heerden, 1983). Between 1980 and 1996 the lowest discharge figures were found to be during the months of September and October (Holm and Sasser, 2001). Holm and Sasser (2001) collected yearly salinity and water level data to investigate salinity patterns in the two deltas and found there was a consistent pattern of salinity pulses in the Atchafalaya Delta, but no salinity pulses in the Wax Lake Delta during the same years. Salinity pulses in the Atchafalaya Delta were brought in by cold fronts and tropical disturbances, and could be due to the relatively deep (8 m) and wide (135 m) navigation channel that is dredged through the Atchafalaya Delta (Holm and Sasser, 2001). Also, since the Wax Lake Delta is located within the freshwater plume of the Atchafalaya River this has been suggested as a reason why salinity levels do not rise in this delta (Holm and Sasser, 2001).

In addition to studying salinity patterns, Holm and Sasser (2001) found through a greenhouse study that *Sagittaria latifolia*, a dominant species in the Atchafalaya Delta, is negatively impacted by prolonged exposure to salinities above 6ppt. This is in agreement with a study conducted by Martin and Shaffer (2005), which found that *Sagittaria latifolia* growth is

depressed at 3ppt and there is plant die off at levels above 6ppt. *Sagittaria lancifolia*, a similar species, has also been found to be negatively impacted by elevated levels of salinity (McKee and Mendelssohn, 1989). The findings on the detrimental impacts of salinity to *Sagittaria spp*. along with the findings that have shown salinity incursions are more common in the Atchafalaya Delta in comparison to the Wax Lake Delta could have impacts on plant community succession and marsh building in this delta.

Research into *Colocasia esculenta,* a dominant wetland species that colonizes much of the Wax Lake Delta, has not been as extensive as the *Sagittaria spp*. research. Historically this plant has been used for agricultural purposes and so more is known about its properties as a food source. However, in a 1993 study White found that as splays developed in the Mississippi River Delta three different species colonized, one of which was *Colocasia esculenta*. The species was found to colonize areas of quiet water just downstream of areas dominated by *Salix nigra*, which offered protection to the emergent *Colocasia* (White, 1993). *Colocasia* was also found to colonize areas with large amounts of silt and clay that exist at elevations below mean sea level and so are usually covered by water (White, 1993). In the Wax Lake Delta monospecific stands of *Colocasia esculenta* have developed, which is not typical of most freshwater tidal marsh communities, which have much higher plant diversity. Due to its dominance in the Wax Lake, and the fact that it is known to be a slightly later colonizing species in comparison to *Sagittaria latifolia* (Johnson et al., 1985; Shaffer et al., 1992) focusing on this species for this study could prove to be insightful for understanding if contributions to elevation change from earlier and later colonizing species are any different.

The Wax Lake outlet was constructed in 1941 in order to provide a more efficient path for the Atchafalaya River to the Gulf of Mexico (DuMars, 2002). The route to the Atchafalaya

basin via the Wax Lake outlet is 21km shorter in comparison to the route the lower river follows (Roberts, 1998). Although subaerial building in the Wax Lake Delta was slower to happen in comparison to the Atchafalaya Delta due to a small inland basin that required filling (Roberts, 1998), by 2005 this outlet had created 100 square kilometers of new land (Kim and Mohrig, 2009). While it was not designed as a sediment diversion, the Wax Lake outlet has proven the land building capacity of the Atchafalaya River and counters the argument that riverine sediment supply is inadequate for building land in the face of current subsidence and sea level rise (Kim and Mohrig, 2009; Kim et al., 2008). The wetland systems currently being built in the Wax Lake and Atchafalaya deltas provide evidence that new land can be built in the Mississippi Delta (Kim et al., 2008).

Since it is known that rivers can build new land, many of the wetlands restoration projects in Louisiana include river diversions, which allow water to flow from the Mississippi and Atchafalaya Rivers into adjacent estuaries (Swarenski et al., 2008). Adding freshwater, nutrients, clays and silts from the river is assumed to help nourish and promote vertical accretion (Day et al., 2007). However, in some cases diversions that add just freshwater to adjacent estuaries have led to further damage of wetlands through weakening of the marsh soil. Swarenski et al. (2008) has shown that river water input into organic rich freshwater marshes in regions of the Mississippi River deltaic plain can create weaker soils by generating a more soil reducing environment that degrades the root mat (Swarenski et al., 2008). In a study on the effects of nutrient loading to saltwater marshes Turner (2011) concluded that freshwater diversions could lead to increased soil metabolism, lower root and rhizome biomass, and therefore compromise soil strength. However both of these studies focus on marshes dominated by organic matter, and diversions dominated by freshwater. It is also important to understand the impacts of sediment

diversions, and their effects on mineral dominated freshwater marshes. This study aims to help understand the contributions that rivers make to the natural marsh building processes so that we can design these diversions more effectively for restoration goals.

1.2 2 California

The largest estuary on the west coast of the United States, sustaining the largest system of tidal wetlands in California (Conomos, 1979; Grewell et al., 2007), is the San Francisco Estuary (Conomos et al., 1985), which includes the Sacramento-San Joaquin Delta. The annual inflow into the Delta comes from runoff of 40% of the land area of California, and outflow heads predominantly into the San Francisco Bay. Wetlands in the Delta are nourished through a combination of the river input from the watershed and tidal input coming up from the ocean (Wright and Schoellhammer, 2005).

While the Sacramento-San Joaquin Delta is similar to other river deltas around the world in that it formed at the mouth of river systems, it is different because it was not built by the deposition of sediment from upstream (Lund et al., 2007). This delta was created in a low-lying area where sediment from the watershed mixed with large amounts of organic matter from marsh plants, and accumulation of this mineral and organic matter kept pace with the slow rise in sea level (Lund et al., 2007). Marshes were created on top of thick layers of peat that had accumulated, and then were prone to high rates of subsidence creating delta islands that exist below sea level (Lund et al., 2007).

Although the Sacramento River did not originally build the delta through deposition of suspended sediment, its supply of sediment to the delta is important. A decreasing trend in the suspended sediment discharge of the Sacramento River has been documented (Wright and Schoellhammer, 2004). As of 1990 the sediment supply being carried to the estuary dropped by 30% of the peak in the late 1800s (Gilbert 1917; Beeman and Krone 1992), and there was a

significant drop in suspended sediment concentration for the water years 1991-1998 to 1999-2007 (Schoellhamer, 2011). The sediment supply to the delta has been severely disturbed by human action since the late 1800s, beginning with hydraulic mining for gold during that time (Schoellhamer, 2011), which washed large amounts of sediment into the rivers and bays (Gilbert 1917). Following this, in the 1900s dams and bank stabilization projects began trapping sediment, which decreased the suspended load in the Sacramento River (Wright and Schoellhamer, 2004). With the end of hydraulic mining and the trapping of sediments behind dams and flood control structures the suspended sediment supply of the Sacramento River decreased by one half from 1957 to 2001 (Wright and Schoellhamer, 2004).

By the end of the 1900s the sediment supplied to the delta from the Sacramento River was almost equal to that supplied by other small local tributaries (Schoellhamer et al., 2005). Most material is transported to the San Francisco Bay during large winter floods (Orr et al., 2003) when coarser sediments are deposited upstream of floodplains and the fine clays and silts settle in the bays closer to the San Francisco Bay (Buchanan and Ruhl, 2001).

Salinity in the Delta is controlled by tides, water management programs, and the climate; times of the year with lower freshwater flows lead to higher salinity waters moving into the Delta (Ingebritsen and Ikehara, 1999). Although the system is dominated by freshwater, there are times where salinity levels increase due to inflow from the Bay. Summer salinity levels in the Delta historically were moderated by freshwater inflows during melting periods but these levels are now rising due to higher spring temperatures causing the peaks in water runoff to happen earlier in the year (Knowles and Cayan, 2002). Salinity ranges fall with increased distance from the San Francisco Bay resulting in the Sacramento-San Joaquin Delta with salinity levels less than 2% (Uncles and Peterson, 1995).

The Sacramento River drains approximately 68 million km^2 of the northern half of California's Central Valley and during the past 200 years large areas within the Sacramento-San Joaquin Delta have been leveed and turned into highly productive agricultural lands (Wright and Schoellhamer, 2004). Restoration projects since 1972 in the San Francisco Bay have been wide ranging but since the late 1990s the emphasis has shifted to large scale tidal wetland restoration as tidal flows and river connections are reintroduced to historical wetland areas (Williams and Faber, 2001). Because one of the two main goals of the Delta Stewardship Council is to protect and enhance ecosystems in the Delta, the breaching of agricultural levees in order to restore tidal action to historic tidal marsh areas is supported, whether it happens naturally or with restoration management.

Since the Sacramento River is a primary pathway for sediment transport in the Delta it has been concluded that wetland restoration projects that are directly connected to this river will have the greatest probability of success due to the high sediment supply (Wright and Schoellhamer, 2005). Two recent levee BREACH studies in the San Francisco Bay estuary (Figure 1.7) developed restored marsh evolution models that follow the Williams and Orr (2002) model described in Figure 1.4. A third BREACH project is now underway, focusing on Liberty Island (Figure 1.7), an area north of previous study sites.

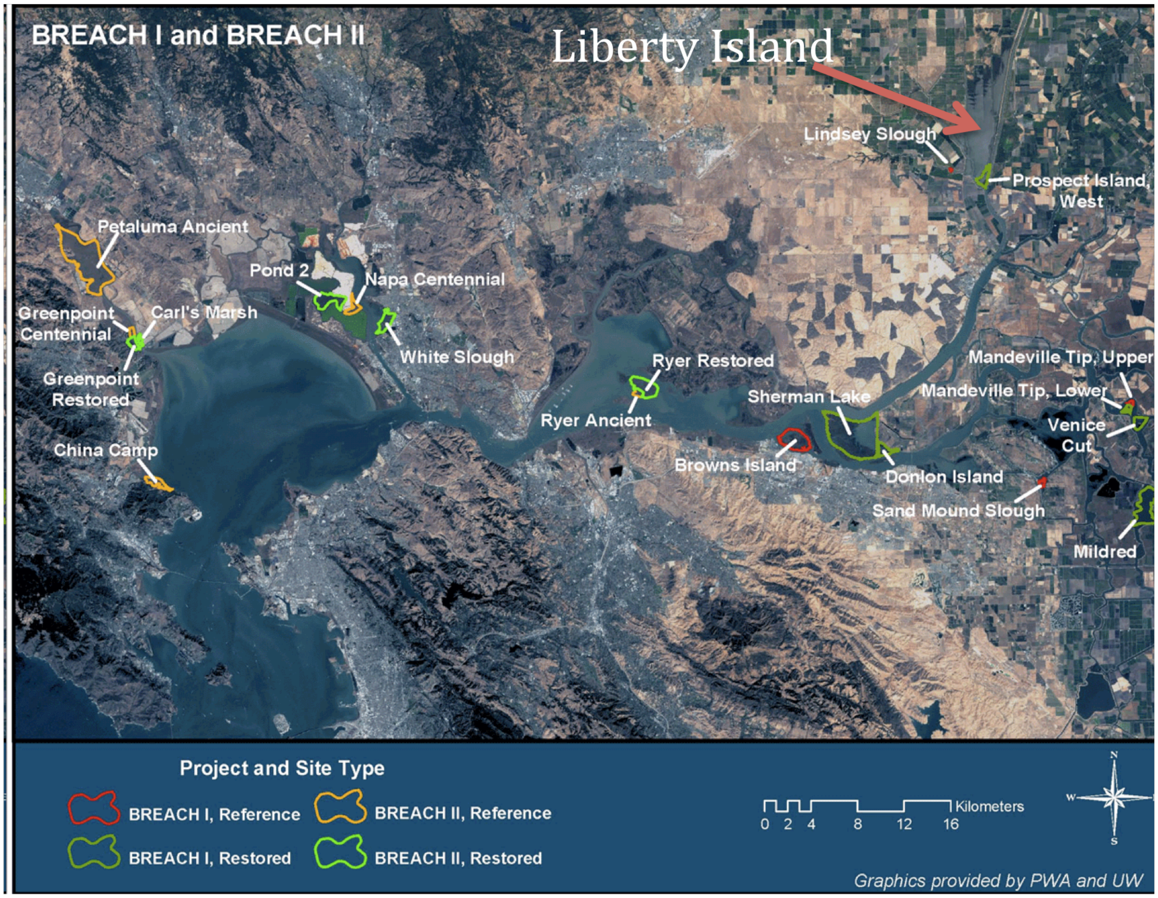

Figure 1.7 Site locations for BREACH I and II studies, with Liberty Island, site of the current BREACH III study, highlighted (www.depts.washington.edu/calfed/breachii.htm).

Since the early 1900s Liberty Island (Figure 1.8), a delta island in the Sacramento-San-Joaquin Delta, has been enclosed by levees, drained, and used for farmland. In 1997 the levees breached during a major flood, the island was flooded, and since then the area has been left to mature through natural restoration processes (Mager, 2004). As floodwaters brought in and deposited sediment, mudflats began to emerge, and in some areas sediment deposition was high enough that the mudflats reached an elevation where tule vegetation (*Schoenoplectus spp.)* began to colonize. Areas in the northern part of the island (Figure 1.8) have had more *Schoenoplectus spp*. colonization, likely because there was not as much subsidence in comparison to the southern

half of the island. This results in higher elevations in the northern half of the island and therefore more vegetation colonization.

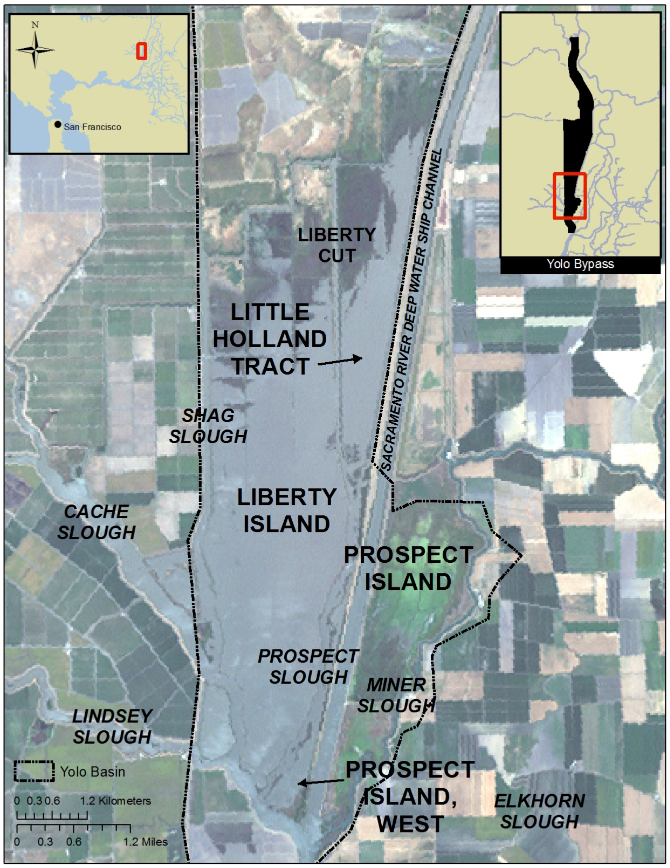

Figure 1.8 Liberty Island, CA (https://sites.google.com/a/uw.edu/breach-iii/study-site).

In a study in the Parana River Delta in South America *Schoenoplectus californicus* was found to be one of the only vegetative colonizers of bare sediments (Pratolongo et al., 2008). Once it colonized the early bars and islands of the delta it aided in the sedimentation process allowing the areas to become more mature marsh islands (Kandus and Malvarez, 2004). It was also found that while the *Schoenoplectus* stands came in and colonized early bars and incipient islands since it was the only species able to tolerate the physical stress of these high energy environments, the stands tended to be replaced by later colonizing species such as the tree *Erythrina crista-galli* and *Scirpus giganteus* as the islands matured (Kandus and Malvarez,

2004). *Schoenoplectus californicus* can reduce water velocity during times of high sedimentation and high water flows, and therefore facilitates further sediment deposition and the colonization of other species (Kandus and Malvarez, 2004). In the Sacramento-San Joaquin Delta and down into the San Francisco Bay estuary *Schoenoplectus californicus* was noticed to be rooting below local mean sea level, and was found to be partially submerged during the lowest tides of the year (Watson and Byrne, 2009). While this species appears to be playing a critical role in the natural restoration processes taking place in this area of California, perhaps it will eventually be replaced as it was in the Parana Delta in South America.

1.3 Marsh Building Processes

Measuring surface elevation change in a marsh is critical in order to tell the story of how the marsh is building. With ancillary data other important processes that contribute to this building can be revealed as well. The elevation of a marsh changes due to a combination of several processes including sedimentation, erosion, organic matter accumulation, subsurface compaction/expansion and groundwater discharge/recharge (Cahoon et al. 1995a; Cahoon, 2006). The impacts of these processes on the marsh surface can be measured using a surface elevation table (SET), which was designed to measure small changes in marsh surface elevation relative to an installed benchmark (Boumans and Day, 1993).

Wetland soils are composed primarily of organic and inorganic matter, water, and pore space (Turner et al., 2007), so all of these components add to marsh building. Accretion is the combination of mineral sedimentation on the marsh surface and above and belowground organic matter accumulation, and is therefore defined as the vertical measurement of marsh soil development (Reed and Cahoon, 1993). Mineral sediments are deposited on the marsh surface during flooding and so are limited by the amount of suspended sediment and the flooding

duration (Reed, 1995). Mineral matter is dense, relatively stable, and therefore not as prone to compaction in comparison to organic material. It therefore provides important volumetric contributions to the soil (Turner et al., 2007).

Bulk density is the measure of the amount of mass of a unit volume of dry soil, and unlike particle density, which only accounts for the solid particles in a unit volume, bulk density is impacted by the amount of pore space as well (Brady, 1974). Finer textured soils can have more pore space than coarser soils because the individual particles do not rest as close together as the particles in sandy soils (Brady, 1974). With an increase in pore space there is a resultant decrease in bulk density (Brady, 1974). In terms of building new marshes, having sediment with lower bulk densities would be important because soils with lower bulk densities can build the same volume of land with less mass than soils with higher bulk densities. Measurements of soil bulk density are therefore important to consider when investigating sediment supply sources to use for marsh building.

Plants also add to soil volume through their belowground biomass (roots and rhizomes) (Turner et al., 2007), and in some cases only negligibly through aboveground biomass (Nyman et al., 2006). In addition to mineral sediments, floodwaters can also bring in nutrients, which aid in both above and belowground plant production (Cahoon et al., 1999). Because elevation change takes into account the vertical building of the marsh, it is important to determine the volumetric contributions of the soil mineral and organic matter when investigating marsh elevation change.

The contributions of mineral and organic matter to marsh soils has been widely studied (Atwater and Belknap, 1980; Callway et al., 1997; Chmura and Hung, 2004; DeLaune et al., 2003; Hatton et al., 1983; McCaffrey and Thompson, 1980; Nyman et al., 1990, 1993b, 2006; Nyman and DeLaune, 1991; Nyman et al. 1995; Orr et al., 2003; Reed, 1995, 2002; Turner et al.,

2000, 2004), but there have been few studies that focus on the importance of these contributions in tidal freshwater marshes (Neubauer, 2008; Pasternack and Brush, 2001). Recently however, Neubauer (2008) conducted a study that did examine tidal freshwater marshes along the Atlantic and Gulf of Mexico coasts, as well as marshes along the Scheldt River in Europe. He found that both mineral and organic inputs were important in influencing marsh accretion at all sites, however, accretion in freshwater marshes along the Gulf of Mexico was driven by inorganic accumulation (Neubauer, 2008). Volumetric contributions for these marshes ranged between 1.4 and 10.8% for organic matter, and between 0.5 and 32.0% for mineral matter (Neubauer, 2008). When considering elevation change it is the volumetric contributions that are important so it is obvious here that the mineral matter added more to the marsh elevation change at these sites.

Similarly, a study in the San Francisco Bay Delta found mineral inputs to be more important for surface accretion. The study, which took place at sites not far south of Liberty Island, found that on a percent weight basis inorganic matter dominated the surface soil contributions, most likely because of high sediment inputs from the Sacramento River and Yolo Bypass discharges (Reed, 2002). Historically the northern Delta was dominated by organic-rich soils, with limited mineral sedimentation only available during flood events of the Sacramento River (Atwater 1982). However, it is now suggested that marsh soil accretion in this delta is no longer dominated by organic matter accumulation (Reed, 2002).

Many recent studies have been conducted to elucidate factors and processes contributing to marsh building. Changes in hydrology have been one major theme of study, with a recent focus on groundwater levels and their effects on shrink and swell soil responses (Cahoon et al., 2011). Everglade studies have found a significant relationship between surface water stage and marsh elevation (Cahoon et al., 2003; Smith and Cahoon, 2003), and Whelan et al. (2005) found

shrink-swell variations in soil profiles, also in the Everglades, led to elevation changes. Salt marsh studies in Europe and Australia have connected summer drought reductions in the water table to lower surface elevations (Van Wijnen and Bakker, 2001; Rogers and Saintilan, 2008), and high precipitation amounts have been linked to extended soil swelling in mangrove soils leading to increased surface elevations (Cahoon and Lynch, 1997). Evapotranspiration leading to water loss in the soil is another process that has been shown to alter surface elevation (Paquette et al., 2004; Cahoon, 2006).

Organic matter accumulation impacts on marsh building have been another focus of recent marsh elevation studies. Authors have published data demonstrating that increases and decreases in organic matter correspond positively and negatively with surface elevation changes (Cahoon et al., 2003, 2006; McKee et al., 2007; McKee, 2011). Mangrove studies have shown that with the addition of certain nutrients there has been an increase in root accumulation and a concurrent positive impact on the rate of elevation change (McKee et al., 2007). Morris et al. (2002) also attributed changes in elevation to seasonal changes in vegetation growth and decomposition in a South Carolina salt marsh.

Marsh building can also be affected by hurricanes and tropical storms. Storms can re-suspend and deposit mineral matter (Baumann et al., 1984, Turner et al., 2006), in addition to organic matter through litter and re-suspended organic substrate (Guntenspergen et al., 1995). Storms have also been shown to cause erosion and scouring due to increased wind and wave action (Guntenspergen et al. 1995). Salinity intrusions due to storm surge can also play a role in elevation change as increased salinity levels can lead to plant mortality from salt-burning (e.g., Howard and Mendelssohn 1999, Cahoon et al. 2003). But, if vegetation recovers quickly the sediment, nutrient and freshwater inputs from the storm can all increase organic matter

production, causing positive elevation change (McKee and Cherry, 2009). McKee and Cherry (2009) found that Hurricane Katrina contributed to soil volume directly through deposition and also through stimulating root matter accumulation at a site in Big Branch Marsh National Wildlife Refuge. They concluded that one of the factors that contributed to increased belowground biomass was the increase in space for root and rhizome growth from the additional sediment deposition (McKee and Cherry, 2009).

Though global sea level has been rising, tidal marshes have been able to keep pace and maintain equilibrium by continually building soil volume (Nyman, 1993a; Reed, 1990, 1995). In a South Carolina salt marsh Morris et al., (2002) found that the ideal elevation for the marsh with respect to mean sea level and mean high tide can be described by Figure 1.9 below. The study concluded that the vegetation in a salt marsh is constantly working to modify its habitat elevation to be in equilibrium with sea level (Morris et al., 2002). This model is similar to that presented in Figure 1.4, which demonstrated that marshes build through time in order to reach a mature marshplain that has an elevation close to that of the mean high water level of that area (Williams and Orr, 2002).

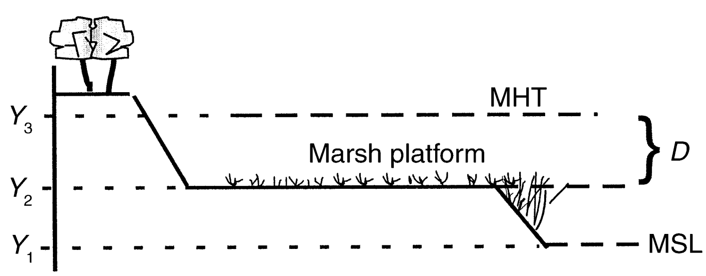

Figure 1.9 Relationships between mean sea level (MSL), mean high tide (MHT), and the equilibrium position of the marsh platform at depth (D) relative to MHT (Morris et al., 2002).

Elevation change in a marsh is a crucial process; once a marsh is built it needs positive elevation change in order to survive relative sea level rise. Also, the vertical building processes

that occur will dictate which type of marsh, i.e. subtidal, intertidal mudflat, pioneer mudflat, mature marshplain the site will become (Williams and Orr, 2002). In order to understand how a marsh is building vertically the volumetric contributions must be considered. It is the volume of the marsh soil, not the weight, which determines whether or not the marsh is keeping pace with relative sea level rise. With a better understanding of the processes that contribute to elevation change, we can be better equipped to plan restoration projects that can create the marsh conditions necessary for local sea level conditions.

1.4 Research Needs

Studies of newly building river deltas thus far have done little to explain the story of elevation change. At the mouth of the Yangtze River in China, Yang (1999) reported on grain size deposition and accretion patterns, as well as organic matter accumulation and plant trapping abilities, but had no report on overall elevation change. In the lower delta of the Parana River in South America, where new wetlands are building, Kandus and Malverez (2004) produced a conceptual model of plant succession and Pratalongo et al. (2008) discussed tidal influences on the dominant plant species, but again no work has been published on surface elevation change. Work has also been done in tidal freshwater wetlands of the Chesapeake Bay on sedimentation processes, seasonal patterns, and resultant geomorphology of delta islands (Pasternack et al., 2000; Pasternack and Brush, 1998, 2001, 2002). In the San Francisco Bay Delta Culberson et al. (2004) also studied sedimentation rates using sediment traps and Drexler et al. (2009 a, b) looked at historical peat accretion to determine vertical accretion rates. Again, these last studies focused just on accretion patterns, which is not synonymous with elevation change. While all of these studies are adding to our knowledge of the processes involved in deltaic wetland building, there are no connections drawn for how they contribute to marsh elevation change.

Studies on marsh building that have been conducted thus far have been wide ranging in their goals but have focused primarily on salt and brackish marshes in areas that are not newly building. This study aims to help close this gap by understanding the factors that contribute to marsh surface building in newly built deltaic wetlands in Louisiana and newly restored wetland areas in the northern San Francisco Bay Delta. Due to the fact that restored marshes can be lower in the tidal range because in many cases they were drained to become farmland and then had high rates of subsidence from compaction, they may respond differently to the natural building processes (Orr et al., 2003). By exploring this comparison the hope is that more will be learned about the processes of freshwater marsh building in order to better plan for ongoing restoration.

1.5 Hypotheses

To prevent marsh loss when facing sea level rise increasing marsh surface elevation is critical for preventing submergence (Nyman et al., 1994; Reed, 1995, 2002; Rybczyk and Cahoon, 2002) and marshes will adjust elevation to maintain equilibrium relative to new conditions (Allen, 2000). It is therefore hypothesized that since the sites in this study are newly building and newly restoring they are all building to reach the mature marsh plain stage, and sites with the lowest marsh surface elevation will have the highest rates of positive surface elevation change.

Hypothesis 1: Sites in this study with the lowest marsh surface elevation will have the highest rates of positive surface elevation change in their respective deltaic areas.

Recent literature leads me to believe mineral matter will contribute more at the sites in my study both through weight and through volume. Also, since the Atchafalaya and Wax Lake Deltas became subaerial only after the high flood year of 1973, and Liberty Island began its natural wetland building after levees were breached and the Island was flooded in 1997, these wetlands can be considered relatively “young.” The relative youth of these sites also leads me to

believe mineral matter will account for more of the soil matter in comparison to soil organic matter. If this is true then surface elevation change at these sites will be more dependent on mineral matter.

Hypothesis 2: Mineral matter volumetric and gravimetric contributions will be higher than organic matter contributions for all sites studied.

Although it is hypothesized that mineral matter will contribute more to elevation change at the sites in this study, it is still important to examine organic contributions to the soil. Organic sediments accumulate primarily through root growth and other in situ processes such as the accumulation of decomposing plant matter; unlike mineral matter, the majority of soil organic matter is not transported from other locations (McCaffrey and Thompson, 1980; Neubauer, 2008; Nyman and DeLaune, 1991). *Schoenoplectus spp*. is the dominant species at Liberty Island and as judged by eye it seems to have both greater stem density and stem height than the *Sagittaria latifolia* and *Colocasia esculenta* at the Atchafalaya and Wax Lake Delta sites. Due to this, it is hypothesized that soil organic matter values will be higher for the Liberty Island sites in comparison to the Atchafalaya and Wax Lake Delta sites. This additional soil matter could result in the sites at Liberty Island having higher rates of positive elevation change.

Hypothesis 3: Due to the observed higher Schoenoplectus spp. stem density and stem height Liberty Island sites will have higher soil organic matter percent by weight values than the Atchafalaya and Wax Lake Delta sites.

While the Atchafalaya and Wax Lake Deltas are receiving higher percentages of fine sediments (Figure 1.6) sites at Liberty Island receive coarser deposits from the Sacramento River. Since Liberty Island is further upstream in its river system (Figure 1.10), coarser sediments are deposited there while the finer sediments settle out in the bays closer to San Francisco Bay (Buchanan and Ruhl, 2001). It is therefore hypothesized that due to smaller grain

size of the sediment deposited at the Atchafalaya and Wax Lake Delta sites, these sites will have lower bulk density values than the Liberty Island sites.

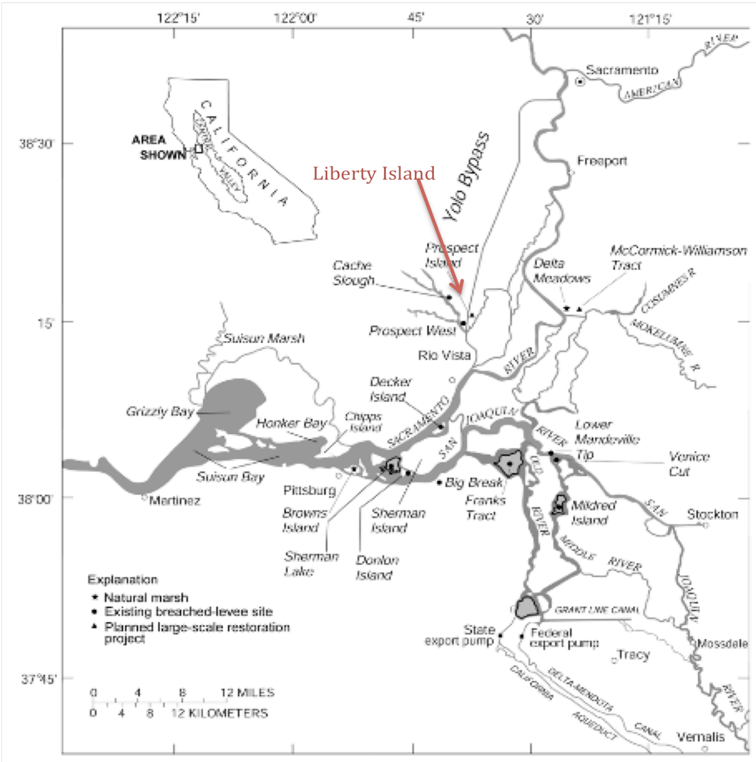

Figure1.10 Sacramento-San Joaquin Delta map with location of Liberty Island study site (adapted from Orr et al., 2003).

Hypothesis 4: Due to its location further upstream in the Sacramento-San Joaquin River delta system, Liberty Island sites will have higher median grain size and bulk density values than the Atchafalaya and Wax Lake Delta sites.

Chapter 2: Methodology

2.1: Study Sites

As discussed above, the freshwater wetland areas that have been chosen for this study are found in the Wax Lake Delta, the Atchafalaya River Delta and the Sacramento-San Joaquin Delta. The first two deltas, found along the coast of Louisiana (Figure 1.5), are being built by the Atchafalaya River and natural wetland building process. The Louisiana Coastal Reference Monitoring System (CRMS) has a monitoring site in each of these deltas where there is ongoing collection of soil, water, and vegetation data (http://www.lacoast.gov/crms_viewer/). Liberty Island (Figure 1.8) is a restored tidal wetland area found in the Sacramento-San Joaquin River delta plain in California that has been flooded and reconnected to tidal action. The research conducted at Liberty Island is part of a larger interdisciplinary study, BREACH III, which seeks to provide predictive tools to evaluate the risks and advantages of any future restoration in the San Francisco Bay Delta area, and understand the thresholds of new marsh development (https://sites.google.com/a/uw.edu/breach-iii/home).

Despite the fact that the study sites exist in different states and are connected to different coastal systems, comparatively studying these systems can provide a better understanding of how natural wetlands develop.

2.1.1 Atchafalaya River and Wax Lake Deltas

Four sites in the Atchafalaya River Delta and 4 sites in the Wax Lake Delta were selected for this study (Figure 2.1). There is one set of measured marsh surface elevation data for each of these 2 deltas, collected by the Coastal Reference Monitoring System (CRMS). Average marsh elevation readings were collected by the CRMS staff in July 2009 for site 6304 in the Atchafalaya Delta using a Thales Z-Max base station with a Thales Z- Max rover unit, and in

April 2009 CRMS site 0479 in the Wax Lake Delta using a Trimble 5700 RTK base station and a Trimble 5800 rover unit (http://www.lacoast.gov/crms_viewer/). The average marsh elevation at Atchafalaya site 6304 was recorded to be 0.599 m (NAVD88), and site 0479 in the Wax Lake Delta had an average marsh elevation of 0.492 m (NAVD88; http://www.lacoast.gov/crms_viewer/).

The suspended load of the Atchafalaya River is made up mostly of fine silt and clay particles (DuMars, 2002). As these sediments were deposited they created seaward-thinning lobes that extended towards the Atchafalaya bay (van Heerden and Roberts, 1988). Study sites in the Atchafalaya Delta were chosen on 4 separate delta islands, with 2 located to the east of the main river channel and 2 located to the west of the main river channel (Figure 2.1). These four sites were chosen because they were all in areas dominated by *Sagittaria latifolia*, which is one of the dominant species at the CRMS RSET site, and as mentioned earlier is considered an early colonizing species. Also, by choosing sites on four different delta islands the hope was that no one set of environmental conditions would dominate the field sampling.

As in the Atchafalaya Delta, sites in the Wax Lake Delta were chosen along 4 different delta islands in order to avoid one set of environmental conditions dominating the data. These 4 sites were chosen in areas dominated by *Colocasia esculenta*, which is known to be a later colonizing species (Johnson et al., 1985; Shaffer et al., 1992), and is a dominant species at the CRMS RSET site. This species usually colonizes downstream of larger forests in areas with fine sediments and below mean sea level (White, 1993). Sites in both deltas are influenced by river and tidal flows. Tides in the bay are mixed micro tides, usually around 30 cm (Holm and Sasser, 2001).

Figure 2.1 Study sites in Atchafalaya River Delta ("AR" sites to the east) and Wax Lake Delta ("WL" sites to the west). CRMS site 6304 is closest to AR-B site, and CRMS site 0479 is closest to WL-A site (Google earth).Figure 2.11 Study sites in Atchafalaya River Delta ("AR" sites to the east) and Wax Lake Delta ("WL" sites to the west). CRMS site 6304 is closest to AR-B site, and CRMS site 0479 is closest to WL-A site (Google earth).

2.1.2 Sacramento-San Joaquin Delta

Liberty Island is located in the Yolo Bypass, which is a leveed, 59,000-acre floodplain that is in Yolo and Solano counties to the west of the Sacramento River (www.delta.ca.gov). The Bypass was constructed in the early 1900's to keep the cities of Sacramento and Davis, and surrounding communities from flooding during high flows in the Sacramento River (DFG, 2008). The Bypass was designed to have a capacity for flows between 14,000 to 15,000 m^3 s^{-1} (Schemel et al., 2002). Though the Yolo Bypass is flooded inconsistently, most major inundations have happened during the winter months (Schemel et al., 2002) and when with flooding the size of the Sacramento-San Joaquin Delta is doubled. Floodwaters usually move through and drain to the south and east relatively quickly (Lund et al., 2007). A system of levees and other flood control structures now surround the Bypass, and the Department of Water Resources controls water inflows. The levee breaches at Liberty Island have facilitated the

restoration of some historical marsh areas, and therefore altered the conveyance of floodwaters through the Bypass. This is therefore an area of investigation for the BREACH III team.

The 3 sites studied at Liberty Island can be considered restored marsh sites (Figure 2.2) because prior to being converted to farmland they were tidal marsh areas. All 3 sites are dominated by *Schoenoplectus spp*. and receive input from the Sacramento River, which drains the watershed north of the Delta, and input from tides coming in through the San Francisco Bay. Since the Delta as a whole has no one large open body of water, unlike the Bay, wind waves are less likely to build up (Orr et al., 2003). However, it has been found that wind waves can be a source of erosion for flooded islands similar to Liberty Island (Orr et al., 2003).

The most Northern study site at Liberty Island (Figure 2.2) is an exposed site on the west side of the island. It is considered exposed because it is more prone to wind, wave and tidal action as it faces the open water area of the island. Its interior (~4m in from the edge of the marsh) elevation was measured to be 1.098m (NAVD88) using RTK measurements taken in September of 2011 by members of the BREACH III team.

A second site on the west side of the island is considered a protected site, as it is located on the west side of the marsh facing the levee. Because it is protected it does not receive direct wind wave action from the open water area in the middle of the island. Interior marsh elevation at this site was measured to be 0.979m (NAVD88) by the RTK measurements, so this site was referred to as the high protected site.

The third site is located on the eastern side of the island where the tules seem to be colonizing more slowly than in the west side marshes. This site is the lowest in elevation of the 3, measured to be 0.499m (NAVD88) by RTK measurements, and so is subject to the longest flooding duration. This is considered a protected site as well because like the protected site on

the west side of the island, there is marsh area separating this site and the open water in the central region of the island. This site is also the closest of the 3 Liberty Island sites to a levee and was referred to as the low protected site.

Figure 2.2 Study sites at Liberty Island (Google earth).

2.2 Field Methods

2.2.1 Marsh Elevation Change

The original surface elevation table (SET; Boumans and Day, 1993) that was used to measure marsh elevation change was improved by Cahoon et al. (2002a, 2002b) to increase precision and allow for measurements in vegetated wetlands in addition to the shallow water areas the SET was originally designed for. The new rod surface elevation table (RSET) was designed to measure changes in sediment elevation and in conjunction with other measurements could partition out contributions from shallower and deeper substrate zones than the original SET (Figure 2.3).

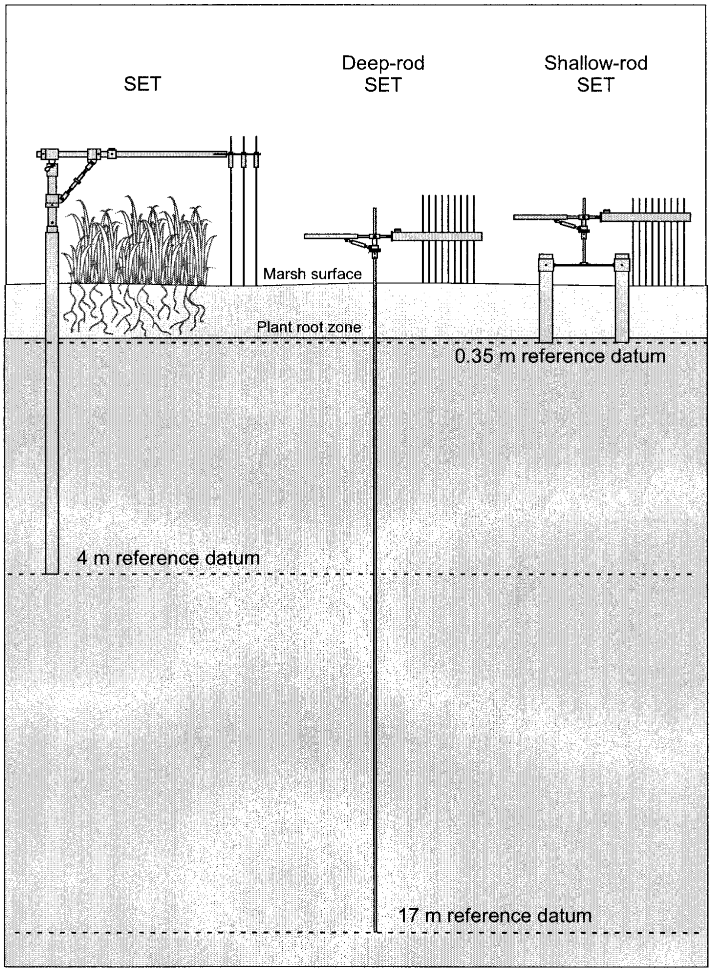

Figure 0.3 Substrate profile diagram for Old Oyster Bayou salt marsh site showing original SET, RSET and shallow RSET with relative depths (Cahoon et al., 2002b).

RSETs were used to measure marsh elevation change at the 3 study sites at Liberty Island, and at 1 site each in the Atchafalaya and Wax Lake Delta. RSETs were installed by the Louisiana Coastal Reference Monitoring System (CRMS) in the Atchafalaya and Wax Lake Deltas in 2009 so elevation measurements for these two sites were obtained from their website. At Liberty Island, we installed benchmark rods and receivers at the three sites. Installation methods that have been developed by the USGS were followed (Cahoon and Lynch, http://www.pwrc.usgs.gov/set/).

The RSET method measures elevation change over time relative to a fixed subsurface datum (Cahoon et al., 2002a, 2002b). Stainless steel rods are driven into the ground until refusal

and are used as the benchmark rod (Figure 2.4). Each time measurements are taken the SET is attached to the benchmark rod, which keeps the reference plane and orientation of the device fixed (Cahoon et al., 2002a, 2002b). This creates a highly precise way of measuring surface elevation change due to the ability to measure the same location each time (Cahoon et al., 2002b). Four measurement directions are established and each time nine pins are lowered to the marsh surface; the height of the pins relative to the RSET arm is measure and recorded (n = 36 per RSET and measurement interval; Cahoon et al., 2002b).

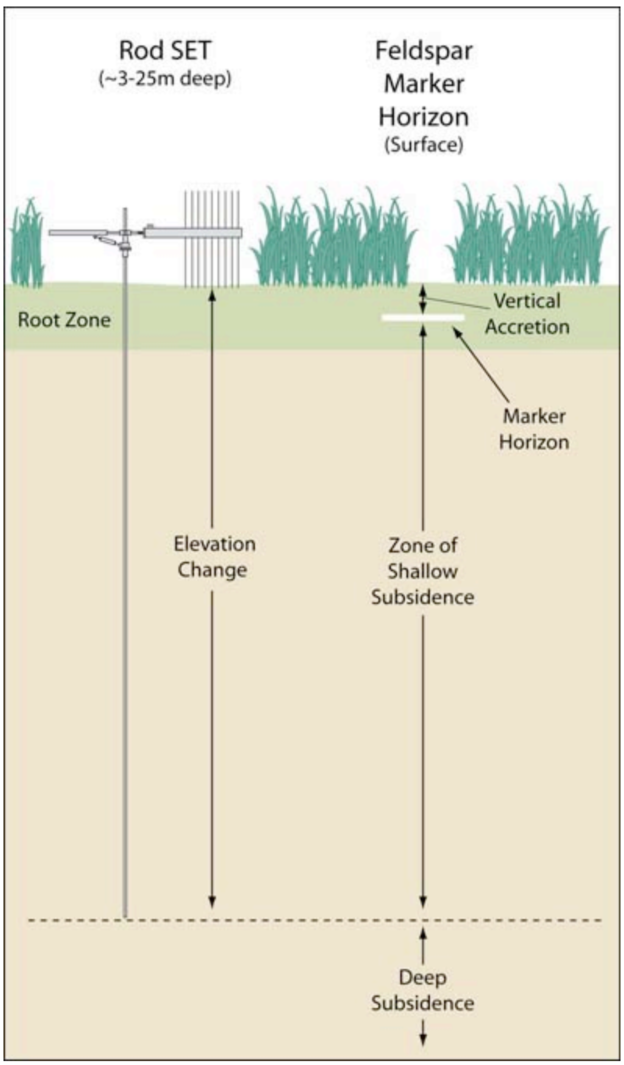

Figure 0.4 Diagram of rod SET (www.pwrc.usgs.gov).

In the Wax Lake and Atchafalaya Deltas, elevation measurements at the CRMS sites were collected bi-annually since 2009. At Liberty Island, CA, RSETs were installed about 4m in from the edge of the vegetation at the three sites described above (Figure 2.2). Elevation readings were taken every 4 months at these sites starting in February 2011 and ending in June 2012.

In order to calculate how the marsh surface elevation was changing calculations had to be made in reference to some starting elevation, and a specific datum. RTK measurements at the CRMS sites were collected in April 2009 for the Wax Lake site and July 2009 for the Atchafalaya site. Additionally, RTK readings were taken at the Liberty Island sites in September 2011. Measurements were recorded relative to the NAVD88 datum, and standard error for RTK measurements is 2 cm. These initial elevation readings were used in order to calculate mean elevation and mean elevation change relative to NAVD88 at each site. Differences between subsequent pin heights were calculated and added to the initial RTK elevation.

Example Equation: June elevation (mm NAVD88) = (June 2011 pin height – Feb 2011 pin height) + initial RTK elevation reading (mm NAVD88)

Once converted to NAVD88 the 36 pin readings for each site were averaged to calculate the mean elevation. The amount of elevation change was also averaged to get mean elevation change for each time period sampled (i.e. June – Feb 2011, Feb – Oct 2011, Oct - Feb 2012, Feb - June 2012 for Liberty Island).

In order to calculate the rate of elevation change for the entire measurement period, mean change in elevation for each site was graphed and a linear trend line with a zero y-intercept was added. The slope of this line represents the change in mm per day, or the rate of elevation change.

2.2.2 Transects and Plots

At each site within the three deltas transects were set up, each around 14 meters long with four 0.25 m^2 plots spaced along the transect (Figure 2.5). Choosing sites for these transects was dictated by the existence of homogenous stands of the vegetation that dominates at the corresponding RSET site, i.e. *Sagittaria latifolia* in the Atchafalaya Delta, *Colocasia esculenta* in the Wax Lake Delta, and *Schoenoplectus spp*. at Liberty Island. Transects were set in an area of mostly homogenous vegetation as judged by eye (Figure 2.6) and along each transect four plots were sampled for aboveground biomass and soil properties.

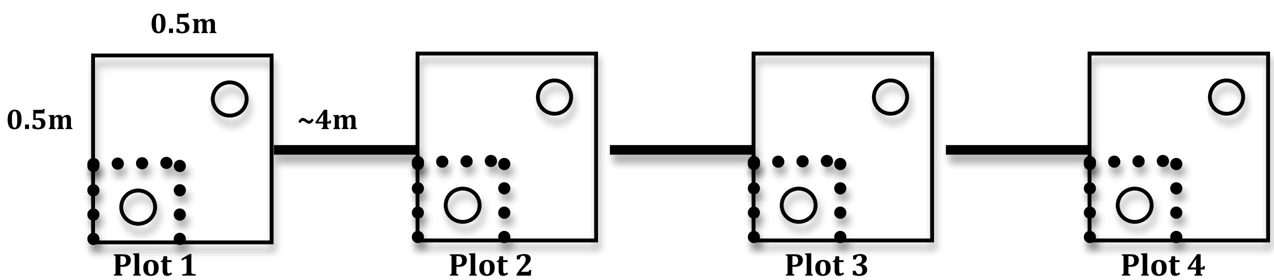

Figure 0.5 Diagram of sampling transects. Circles represent the 2 cores taken in each plot and dotted line in bottom corner represents quadrat for harvesting aboveground biomass.

In each 0.25 m^2 plot two cores were taken (Figure 2.7), the first in one corner for measuring root specific gravity and one in the opposite corner for evaluating organic matter and bulk density content. Before coring, aboveground biomass was harvested with shears from a 0.0625 m^2 quadrat in the bottom corner of the plot.

Figure 2.6 Transect set up in *Sagittaria latifolia* patch in Atchafalaya River delta. Flags mark 4 plot locations.

Figure 0.7 0.25 m^2 PVC plot with 2 core tubes inside.

2.2.3 Coring

For each of the root specific gravity cores 35 cm long, 5 cm diameter aluminum core tubes (Figure 2.8) were pressed into the soil from the marsh surface with a rotating motion to allow the sharpened end of the tube to cut through any roots. Once the tube was pushed to about

a 30 cm depth they were extracted. A sharp shooter shovel was used to dig out the area around the tube, which could then be extracted by sliding a hand under the bottom and pulling up. Cores were then wrapped and kept on ice for transportation back to the lab. In the lab cores were stored in a refrigerator to maintain the integrity of the roots until further processing. Cores for bulk density and organic matter processing were transferred and stored in the lab in the same way.

Figure 0.8 Aluminum core tube after extraction.

2.2.4 Live Aboveground Biomass

Live aboveground biomass was collected using a 625 cm^2 quadrat set down in the bottom left hand corner of each plot (Figure 2.5). All live aboveground biomass within the quadrat was harvested with hand shears, placed into labeled trash bags and stored at about 4ºC until further processing. Back in the lab the biomass was placed in the oven at 60°C until all moisture was removed and a constant weight obtained, about a week. Once dried, the sample was removed and weighed on a scale to one tenth of a gram. The sample bag was then emptied and reweighed. The live aboveground biomass values were calculated by subtracting the bag weight from the total weight and then units were converted to g/m^2.

2.3 Lab Methods

2.3.1 Bulk Density, Organic and Mineral Matter Gravimetric Contributions

To process the cores taken from the plots for bulk density and organic matter, the cores were extruded from the metal tubes and cut into 5 cm segments. In order to remove all moisture,

each segment was placed in a beaker of known mass, put into an oven at 60°C and dried overnight. After removing and cooling, the sample was weighed and the weight of the beaker was subtracted from this total weight to obtain the dry weight. The bulk density can then be calculated using equation 2.1.

Equation 2.1: Bulk Density (g/cm^3) = (dry weight of sample / volume of sample)

After calculating bulk density a mortar and pestle was used to crush the sample into a fine powder and steps were used following the loss on ignition (LOI) procedure developed by Heiri et al. (2001) to calculate organic matter content. Crucibles were cleaned, dried and weighed. The ground up powder was divided equally into crucibles and weighed. These were placed back into the oven at 60°C for 4-6 hours to remove any moisture collected during the grinding process, and then reweighed. They were then placed into a furnace at 400°C for 16 hours. Once samples were removed and cooled, they were again reweighed. The gravimetric organic matter percent of the sample could then be determined using the following equation:

Equation 2.2: % OM = [(Dry weight of sample before combustion – weight of sample after combustion) / dry weight before combustion] *100

To calculate organic and mineral matter gravimetric accumulation rates Equation 2.3 was used.

Equation 2.3: Accumulation rate (g/cm2/yr) = OM (g/cm3) * rate of elevation change (cm/yr)

OR Accumulation rate (g/cm2/yr) = MM (g/cm3) * rate of elevation change (cm/yr)

2.3.2 Root Specific Gravity, Organic and Mineral Matter Volumetric Contributions

To calculate the specific gravity of collected roots, cores were extruded and segmented into 5 cm sections. Roots in each segment were gently rinsed of all sediment with a light stream of water. Live and dead roots were separated; live roots are more translucent, white or opaque, where as dead roots are more flaccid and dull and can have a deeper yellow to brown color

(Schubauer and Hopkinson, 1984; Rodgers et al., 2004). Between 0.3 and 0.4 grams of roots were gently patted dry and weighed. A clean and dry 25 mL pycnometer (Figure 2.9), which is a glass flask of standardized volume with a glass stopper, is used to calculate the specific gravity of the roots according to the method described by Burdick (1989). The pycnometer was weighed when empty and dry, and then again when filled with distilled water. The roots were added to the pycnometer displacing a certain amount of water. The pycnometer with water and roots was then weighed again.

Figure 0.9 Pycnometer used for determining specific gravity of root material (labplanet.com).

Since the volume of the pycnometer remains constant, and the density of water is known (1 g cm^{-3}) the specific gravity of the roots can be calculated using equation 2.3.

Equation 2.3: $SG = M_r / (M_p + M_r - M_{pr})$

In this equation, M_r = mass of roots, M_p = mass of pycnometer with water, M_{pr} = mass of pycnometer with water and roots. The denominator in this formula ($M_p + M_r - M_{pr}$) represents the mass of the volume of water that was displaced.

It is assumed that the majority of the organic matter in the soil is derived from root and rhizome matter, and so the volumetric contributions of organic matter can determined by dividing the average mass of organic matter in a soil segment by the average specific gravity of roots obtained using the pycnometer.

Equation 2.4: OM volume (cm^3) = OM Mass (g) / Root Specific Gravity (g/cm^3)

The volume of mineral matter can be calculated using a similar method. The average mineral matter mass for a core was divided by the specific gravity of mineral matter, which for mineral soils falls in the accepted range of 2.60 – 2.7 g/cm^3 (Brady, 1974). The value of 2.6 g/cm^3 was used for all calculations for consistency.

Equation 2.5: MM volume (cm^3) = MM Mass (g) / 2.60 g/cm^3

2.3.3 Mineral, Organic and Pore Space Volume Percentages

Once the volumetric contributions of the mineral and organic matter was known, pore space contributions could be deduced as well.

Equation 2.6: PS volume (cm^3) = Total segment volume (cm^3) - MM volume (cm^3) - OM volume (cm^3)

From here the percent contributions for mineral matter, organic matter and pore space to the soil could be calculated.

Equation 2.7: MM % = (Volume MM (cm^3) / Segment Volume (cm^3)) *100%

The same formula was used to calculate organic matter and pore space volumetric percent contribution.

2.3.4 Particle Size Analysis

Sieve Analysis

In order to construct a grain size distribution curve and calculate percent sand, silt and clay values a sieve analysis followed by a hydrometer analysis were used following ASTM

procedure D422-63. To complete the sieve analysis around 500g of a dried soil sample was weighed and then poured into the top of a stack of sieves. Any large organic matter or large shell matter in the sample was removed prior to sieving. The sieves were stacked so their mesh diameters got progressively smaller. The stack was shaken in a mechanical sieve shaker for 20 minutes and the weight of the soil left in each sieve was measured. The percent of soil left on each was calculated using formula 2.8.

Equation 2.8: % sediment left on sieve =

(mass of sample on sieve / total starting mass) *100

Sediment that passed through the bottom sieve, which has a mesh diameter of 0.075mm, was collected and kept for hydrometer analysis.

Hydrometer Analysis

Again ASTM procedure D422-63 procedure was followed to perform the hydrometer analysis. The portion of sediment that passed through the bottom sieve in the sieve analysis was kept for the hydrometer analysis. 50.0g of this soil was added to a 4% solution of the dispersing agent sodium hexametaphosphate and soaked for 16 hours. After soaking the solution was added to a mixing cup, mixed for 2 minutes with a high-speed mechanical mixer, and then transferred to a 1000mL graduated cylinder. To ensure the solution was thoroughly mixed the cylinder was capped and inverted 60 times in one minute. When the inversions were complete the time was noted as time 0, and hydrometer (see Figure 2.10) and temperature readings were taken from this point following the ASTM 422-63 procedure.

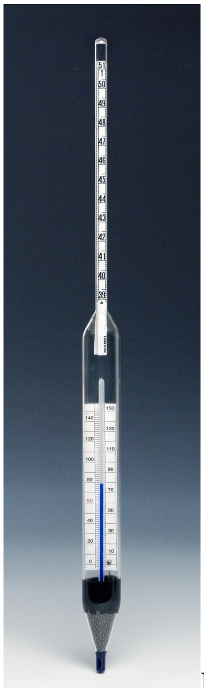
Figure 2.10: Standard hydrometer used for measuring the grams per liter of sediment still in suspension with passing time (icllabs.com).

Hydrometer readings measure the amount of sediment (grams per liter) in suspension at different settling times. The settling times vary depending on the diameter of the particles. With these readings, and meniscus, zero, and temperature correction factors, diameter values were then calculated (ASTM D422-63). By combining the results of the sieve and hydrometer analyses a grain size distribution curve (Figure 2.11) can be constructed, and median grain size (D50), sand, silt and clay percentages can be read from the graph. 50% of particles in a sample are finer than the D50 value.

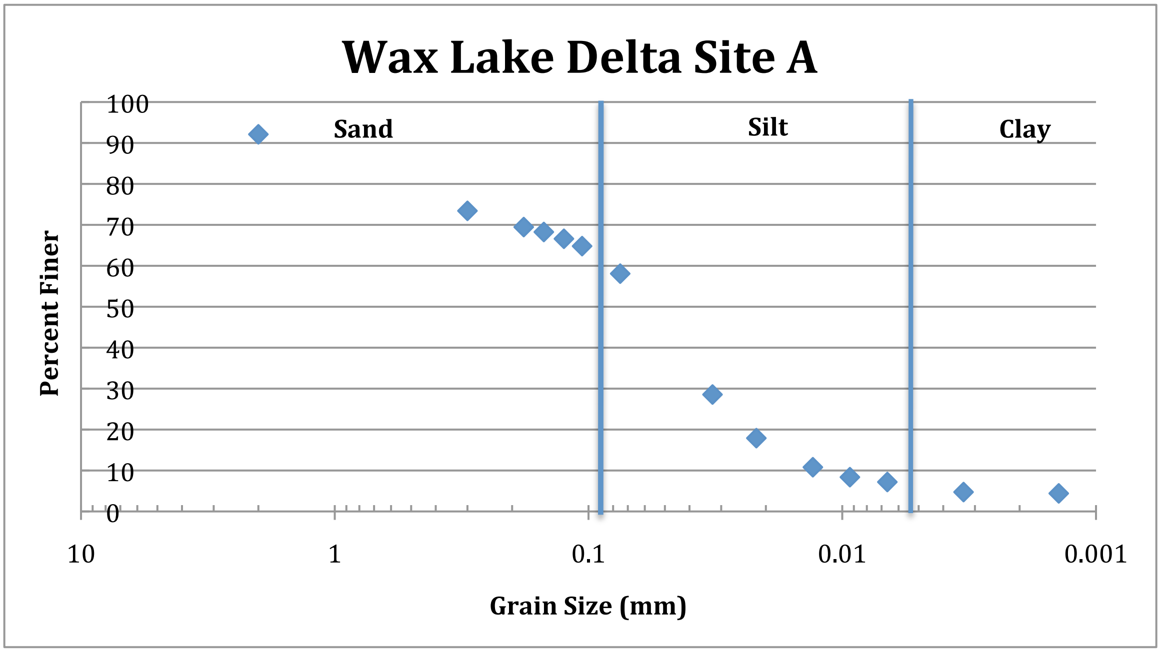

Figure 2.11: Example grain size distribution curve that can be constructed with results from the sieve and hydrometer analysis.

2.4 Statistical Analysis

Significance of differences for data collected was determined using one-way analysis of variance (ANOVA) with a 95% confidence interval ($\propto$ =0.05) and the Tukey post-hoc test. Where applicable mean results are reported as mean change ±1 standard deviation. Statistics were calculated using Excel 2008 and IBM SPSS Data Collection.

2.5 Ancillary Data

In addition to data collected and measured in the field, this research was supported with ancillary data. Water salinity, floristic quality index, vegetation percent cover, and water level data for the Atchafalaya and Wax Lake Delta sites was obtained from the Coastal Reference Monitoring Systems (CRMS) website (www.lacoast.gov). These data were used to explore factors contributing to elevation change at the sites. River discharge for the Atchafalaya River at Morgan City and Calumet was also downloaded to use in the examination of elevation change patterns. These data were obtained from the USGS website (wdr.water.usgs.gov). Sacramento

River discharge was also obtained from the USGS website for the Rio Vista station, which is approximately 15 miles south of Liberty Island (see Figure 1.10). Sacramento River stage at the Rio Vista station, monitored by the California Department of Water Resources (cdec.water.ca.gov), was obtained as well.

Chapter 3: Results

3.1 Marsh Surface Elevation

Marsh surface elevation was significantly higher at the Atchafalaya Delta site in comparison to the Wax Lake Delta site when all pin height measurements were compared ($p<0.001$, Figure 3.1). When comparing pin height readings for the first and last sampling periods at the Atchafalaya site (Oct 2009-Sept 2011) there was not a statistically significant difference ($p=0.989$), and the net elevation change was -2.30 mm (Table 3.1). During the same sampling period at the Wax Lake site there was also not a statistically significant difference between pin height readings taken during the first and last sampling period (Figure 3.1) and the net change in marsh surface elevation was -2.39 mm (Table 3.1). However, measurements at the Wax Lake did begin 8 months earlier than at the Atchafalaya Delta site (Figure 3.1) and if that entire sampling period is considered, from February 2009 to September 2011, there was a net increase in marsh surface elevation of 46.89 mm, which was a significant increase from the starting elevation ($p<0.001$).

Rates of elevation change were also calculated in mm yr^{-1} for the same sampling period at these two sites, between October 2009 and September 2011. The overall rate of change for the Atchafalaya Delta site during that time period was -1.6 mm yr^{-1}, and 12.3 mm yr^{-1} for the Wax Lake Delta site (Table 3.1).

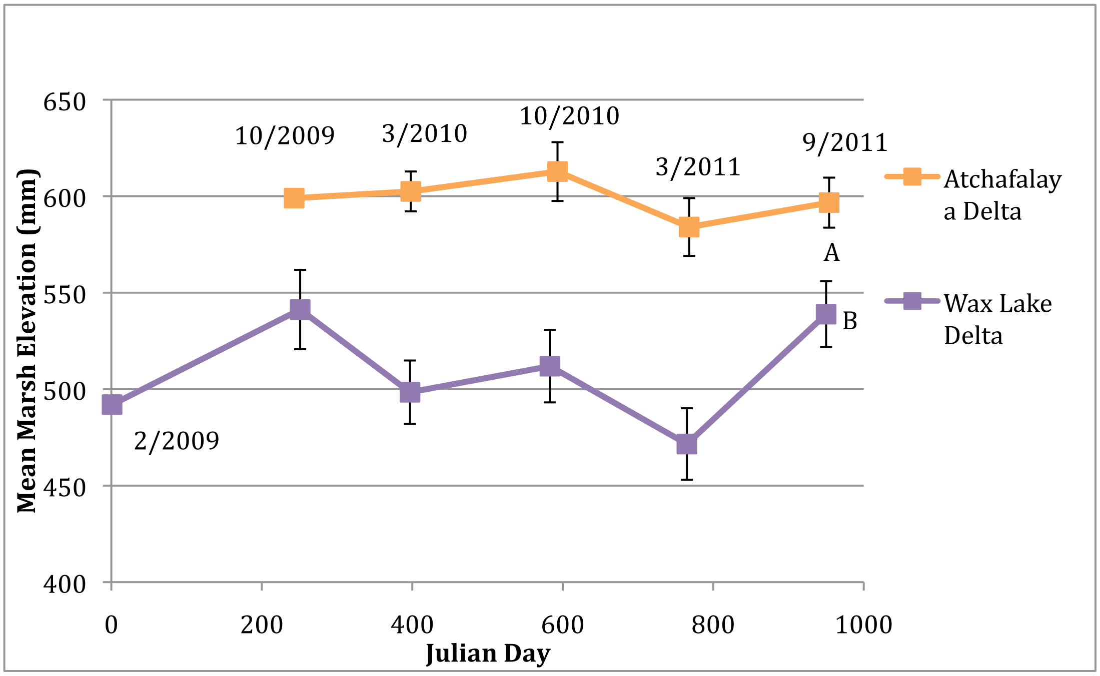

Figure 3.1: Mean marsh surface elevation (NAVD 88) measurements (n=4 for each sampling time, +/- 1 std dev.) for Atchafalaya and Wax Lake Delta sites (Data download http://www.lacoast.gov/crms_viewer/). Different letters represent significant differences of mean pin height measurements (ANOVA, ∝=0.05 confidence interval).

	Mean Elevation (mm)	Rate of Elevation Change (mm/yr)	Overall net elevation change (mm)
Atchafalaya Delta	598.99[a] (±6.29)	-1.6	-2.30
Wax Lake Delta	509.01[b] (±7.60)	12.30	-2.39 *
			46.89**

Table 3.1: Mean elevation (NAVD 88, +/- std. dev.), rate of change and net change for Atchafalaya and Wax Lake Delta sites. *Represents net change for the same measurement period as Atchafalaya Delta Site. ** Represents net change including the 8 months marsh elevation readings were taken at the Wax Lake Delta CRMS site prior to the start of measurements at the Atchafalaya Delta Site.

When pin height measurements for the three Liberty Island sites were compared they were significantly different ($p<0.001$, Figure 3.2). Also, the beginning and end elevations for each of the sites were significantly different as well. The two protected sites had greater net change, as well as higher rates of positive elevation change in comparison to the exposed site (Table 3.2), which had the most negative rate of elevation change, -10.26 mm yr^{-1}. Rates of elevation change at these sites were calculated for the time period between June 2011 and June

2012. The low protected site had the lowest elevation of the three sites, and a high rate of positive elevation change, however, the high protected site showed the greatest positive elevation change for the sampling period (Table 3.2).

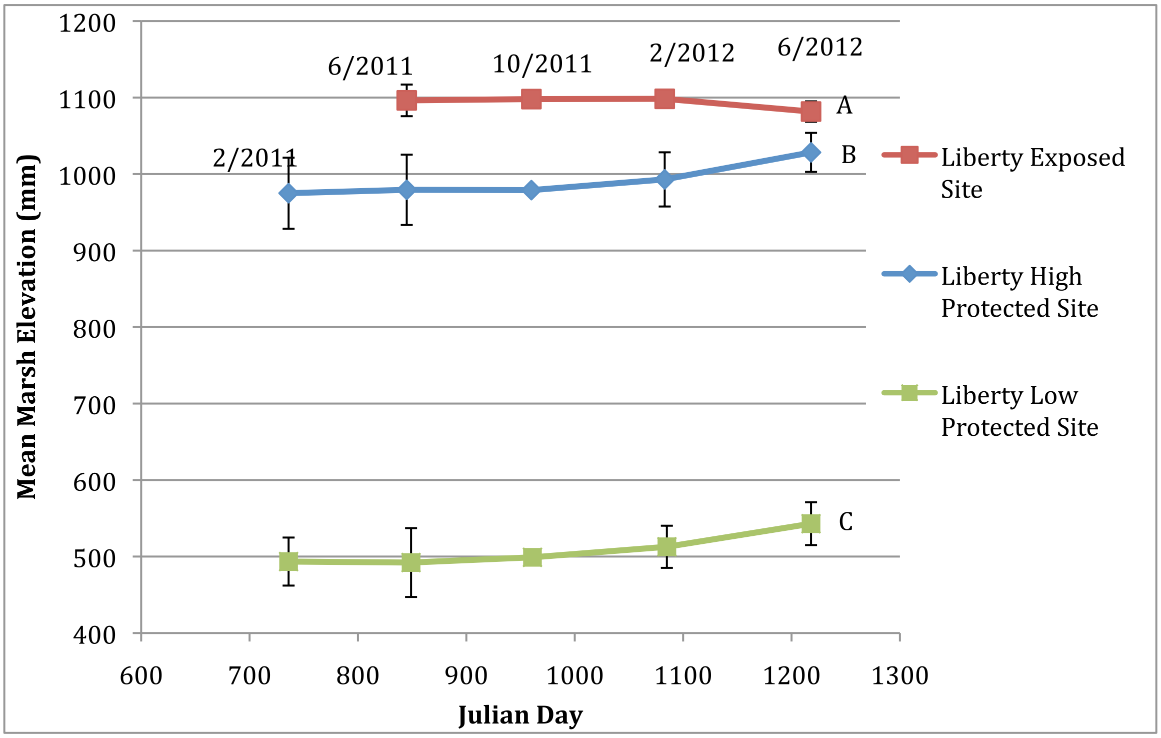

Figure 3.2: Mean marsh surface elevation (NAVD 88) measurements (n=4, +/- 1 std. dev.) for the February 2011-February 2012 sampling period at Liberty Island. Different letters represent significant differences of mean pin height measurements (ANOVA, ∝=0.05 confidence interval).

	Mean Elevation (mm)	Rate of Elevation Change (mm/yr)	Net elevation change (mm)
High protected	991.00[a] (±19.2)	28.03	53.3
Exposed	1093.6[b] (±8.58)	-10.26	-14.6
Low Protected	508.01[c] (± 16.36)	26.94	49.5

Table 3.2: Mean elevation (+/- std. dev.), rate of change and net change for Liberty Island sites.

When comparing pin heights for all 5 sites studied there were significant differences between all sites (Figure 3.3) except for the low protected site at Liberty Island and the Wax

Lake Delta site (p=0.715). The high protected and exposed sites at Liberty Island show significantly higher marsh surface elevations ($p<0.001$) than the Atchafalaya, Wax Lake, and low protected sites (Figure 3.3).

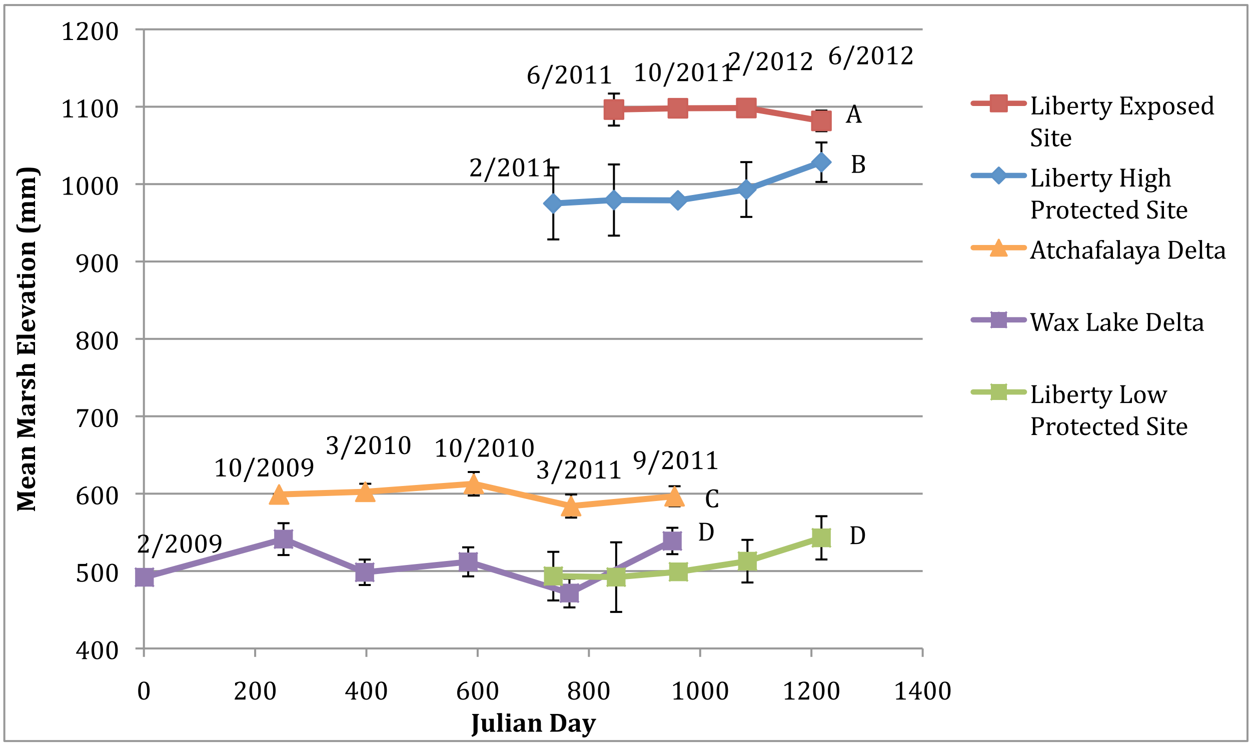

Figure 3.3: Mean marsh surface elevation (NAVD 88; n=4, +/- std. dev.) for all study sites. Different letters indicate significant difference of mean pin height measurements (ANOVA, $\propto$=0.05 confidence interval).

3.2 Gravimetric Accumulation Rates

For sites with calculated accumulation rates (accumulation rates for sites with negative elevation change could not be calculated) mineral matter rates were significantly higher ($p<0.001$) than organic matter accumulation rates (Table 3.3). There were also significant differences between sites for both mineral and organic matter accumulation rates ($p<0.001$; Table 3.3). The two lowest sites, the low protected site at Liberty and the Wax Lake Delta site had high mineral matter accumulation rates and corresponding high rates of positive elevation change for their respective delta areas. However, while the low protected site did have a high rate of positive elevation change, the high protected site at Liberty had the highest rate of positive

elevation change, and the highest rate of organic matter accumulation (Table 3.3). The Liberty exposed and Atchafalaya Delta sites both had negative rates of elevation change, which prevented the calculation of accumulation rates for these sites (Table 3.3).

	Mean Elevation (mm)	Rate of Elevation Change (mm/yr)	Elevation Measurement Period (yrs)	Organic Matter Accumulation ($g/cm^2/yr$)	Mineral Matter Accumulation ($g/cm^2/yr$)
Exposed	1093.6^{b} (±8.58)	-10.26	0.7	NA	NA
High Protected	991.00^{a} (±19.2)	28.03	1.0	0.22 ± 0.06^{a}	1.69 ± 0.76^{a}
Atchafalaya Delta	598.99^{c} (±6.29)	-1.60	1.9	NA	NA
Wax Lake Delta	509.01^{d} (±7.60)	12.30	2.6	0.05 ± 0.95^{c}	1.16 ± 0.26^{c}
Low Protected	508.0^{d} (± 16.36)	26.94	1.0	0.16 ± 0.05^{b}	$2.59 \pm 0.1.14^{b}$

Table 3.3: Mean elevation, rate of elevation change, and accumulation rates for all sites studied. Accumulation rates are based on periods of measured elevation change. Different letters in superscripts represent statistically significant differences (ANOVA, ∝=0.05 confidence interval).

<u>Hypothesis 1</u>

The collected elevation change data does not fully support hypothesis 1, which stated in order to keep up with sea level rise and build towards mature marsh plain status, sites with the lowest marsh surface elevation will have the highest rates of positive surface elevation change. The two lowest sites in this study were the Wax Lake Delta and the low protected site at Liberty Island. These sites did have two of the highest rates of positive elevation change, 12.30 and 26.94 mm yr^{-1} respectively. In addition the low protected site had the highest rate of mineral matter accumulation and one of the highest rates of organic matter accumulation. However the high protected site at Liberty Island had the highest rate of positive elevation change, 28.03 mm yr^{-1}. Therefore hypothesis 1 is not accepted.

3.3 Organic and Mineral Matter Volumetric Contributions

There were no statistically significant differences ($p>0.05$) between organic, mineral and pore space volumetric contributions between the Atchafalaya and the Wax Lake Delta sites. Pore space consistently occupied more volume than mineral matter, which occupied more volume than organic matter (Figure 3.4 and 3.5). This relationship was statistically significant ($p<0.001$) except for the mineral and pore space volume measurements for the Atchafalaya site ($p=0.055$).

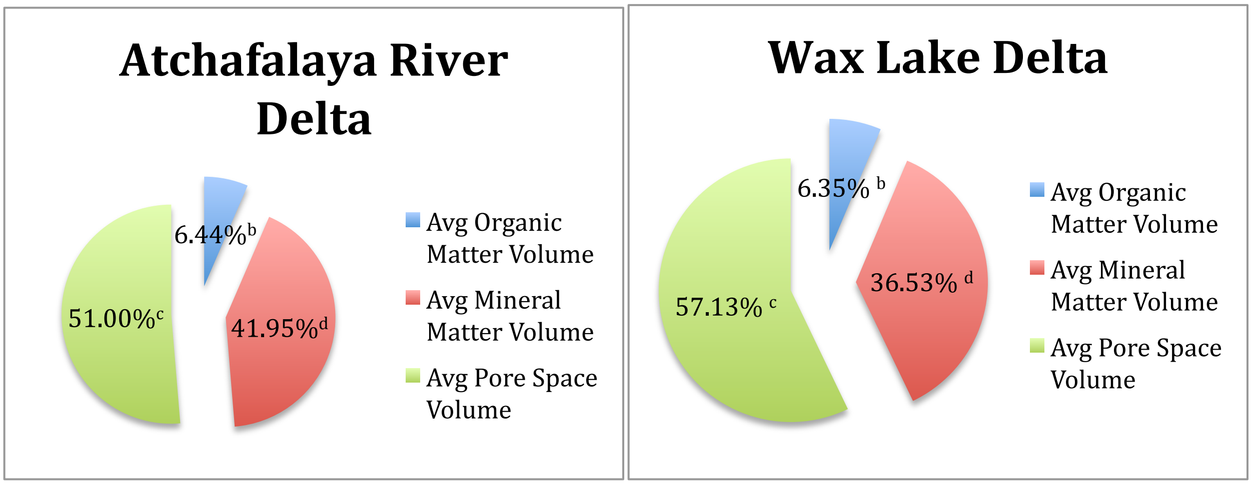

Figure 3.4: Average soil volumetric contributions for Atchafalaya and Wax Lake Delta sites. Different letters represent significant differences between sites (ANOVA, $\propto$=0.05 confidence interval).

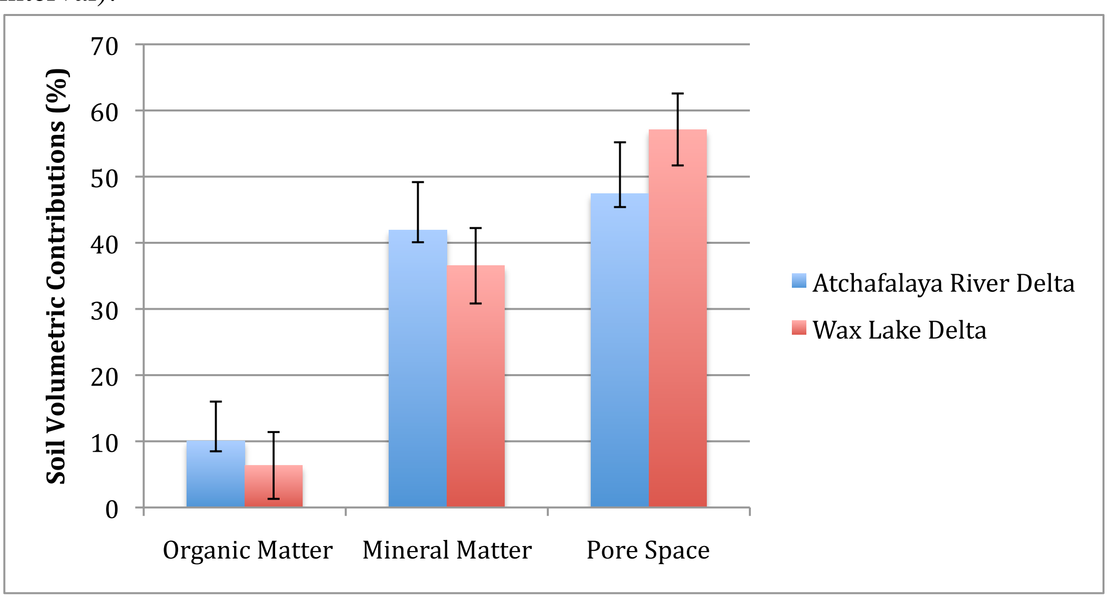

Figure 3.5: Atchafalaya and Wax Lake Delta soil volumetric contributions. Bar graph depicted as mean ± 1 std. dev. There are no significant differences between volumetric contributions at the 2 sites. P values > 0.05, ANOVA $\propto$=0.05 confidence interval.

For the three Liberty Island sites pore space volume was also found to be greater than mineral matter volume, which was greater than organic matter volume in the soil (Figure 3.6 and 3.7). This relationship was statistically significant for the exposed and high protected sites ($p=0.026$ for high protected mineral and organic matter volume, $p<0.001$ for all others), but there was only a statistically significant difference between the organic matter and pore space volume ($p=0.035$) for the low protected site (mineral and organic matter volume $p=0.146$, mineral and pore space volume $p=0.642$). When comparing values across sites there were no statistically significant differences between the pore space, mineral matter, or organic matter volume values ($p>0.05$).

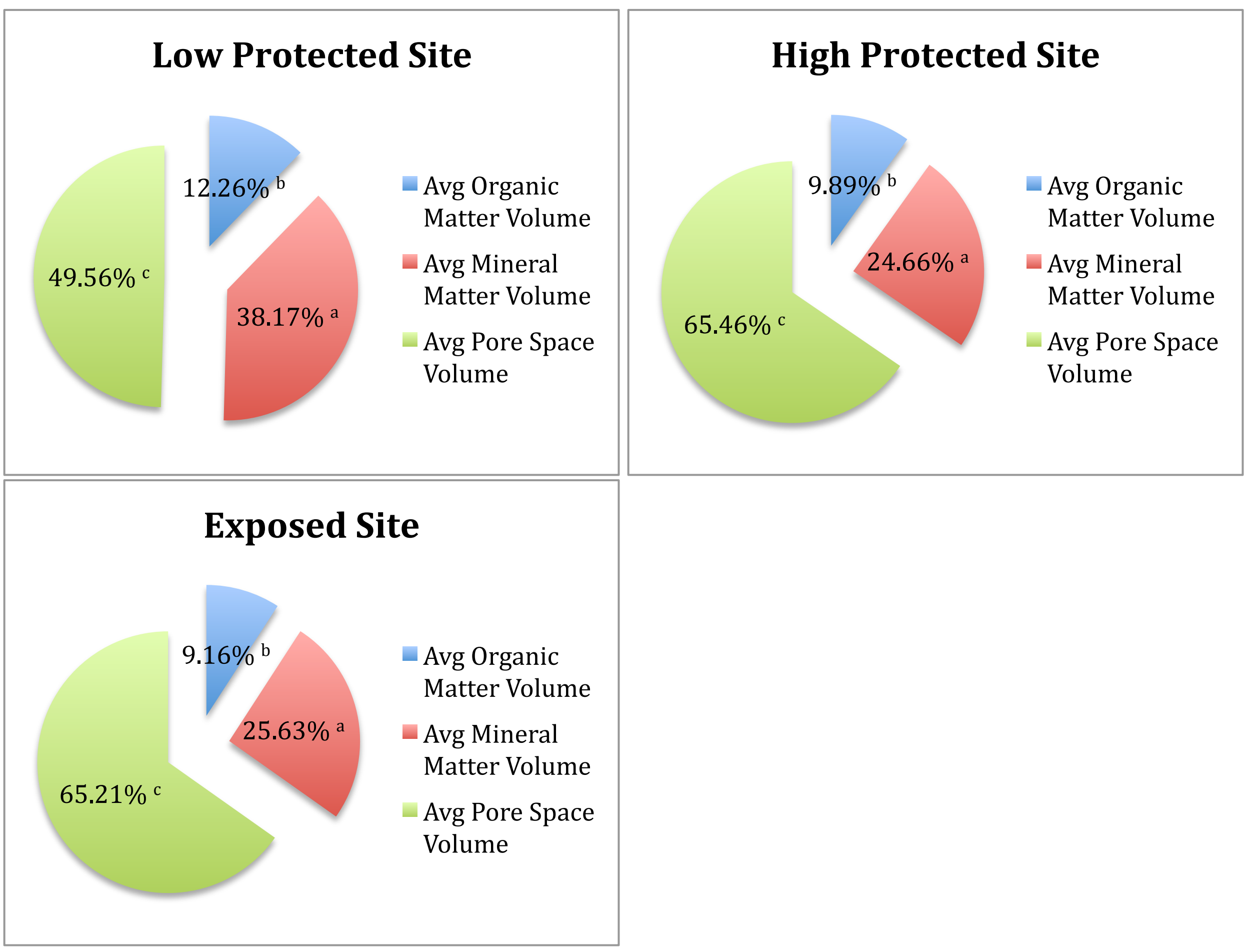

Figure 3.6: Average soil volumetric contributions for Liberty Island sites. Different letters represent significant differences between sites (ANOVA, $\propto=0.05$ confidence interval).

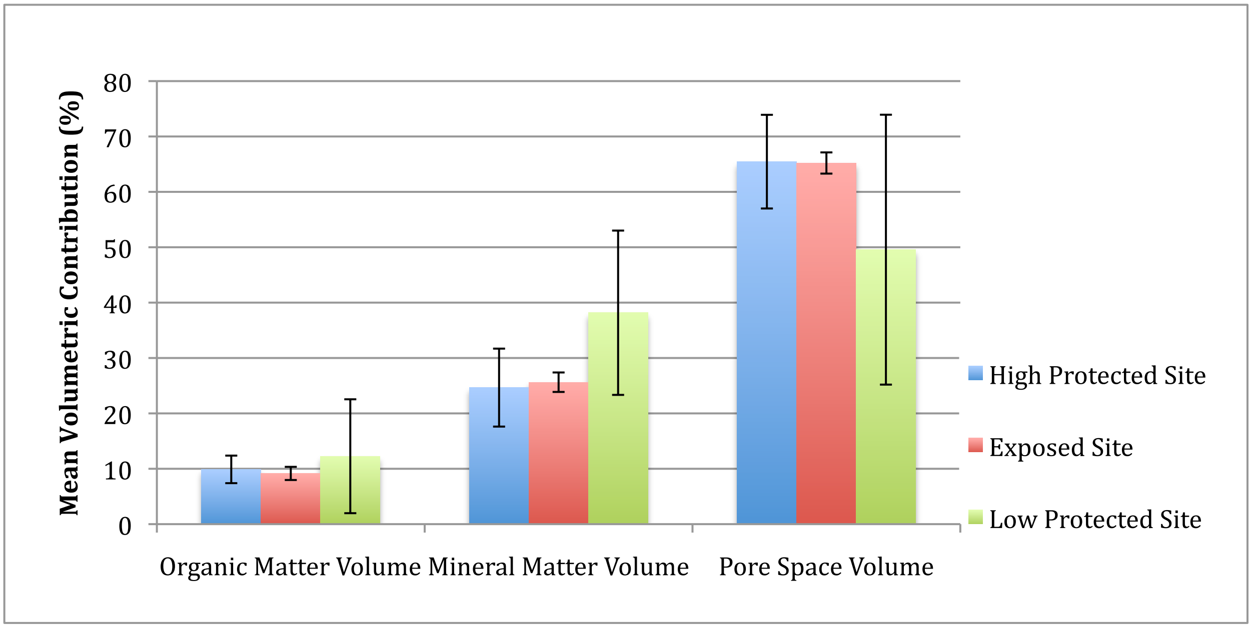

Figure 3.7: Liberty Island soil volumetric contributions. Bar graph depicted as mean ± 1 std. dev. There are no significant differences between volumetric contributions at the 3 sites. P values > 0.05, ANOVA ∝=0.05 confidence interval.

When comparing the Atchafalaya and Wax Lake deltas with the Liberty Island sites mineral matter volume was significantly different between a few sites (Figure 3.8 and 3.9). Mineral matter volume was significantly different between the Atchafalaya Delta and Liberty exposed sites (p=0.002), and the Atchafalaya Delta and Liberty high protected site (p=0.001). However, mineral mater volume at the low protected site at Liberty Island was not significantly different than the Atchafalaya Delta site (p=0.887).

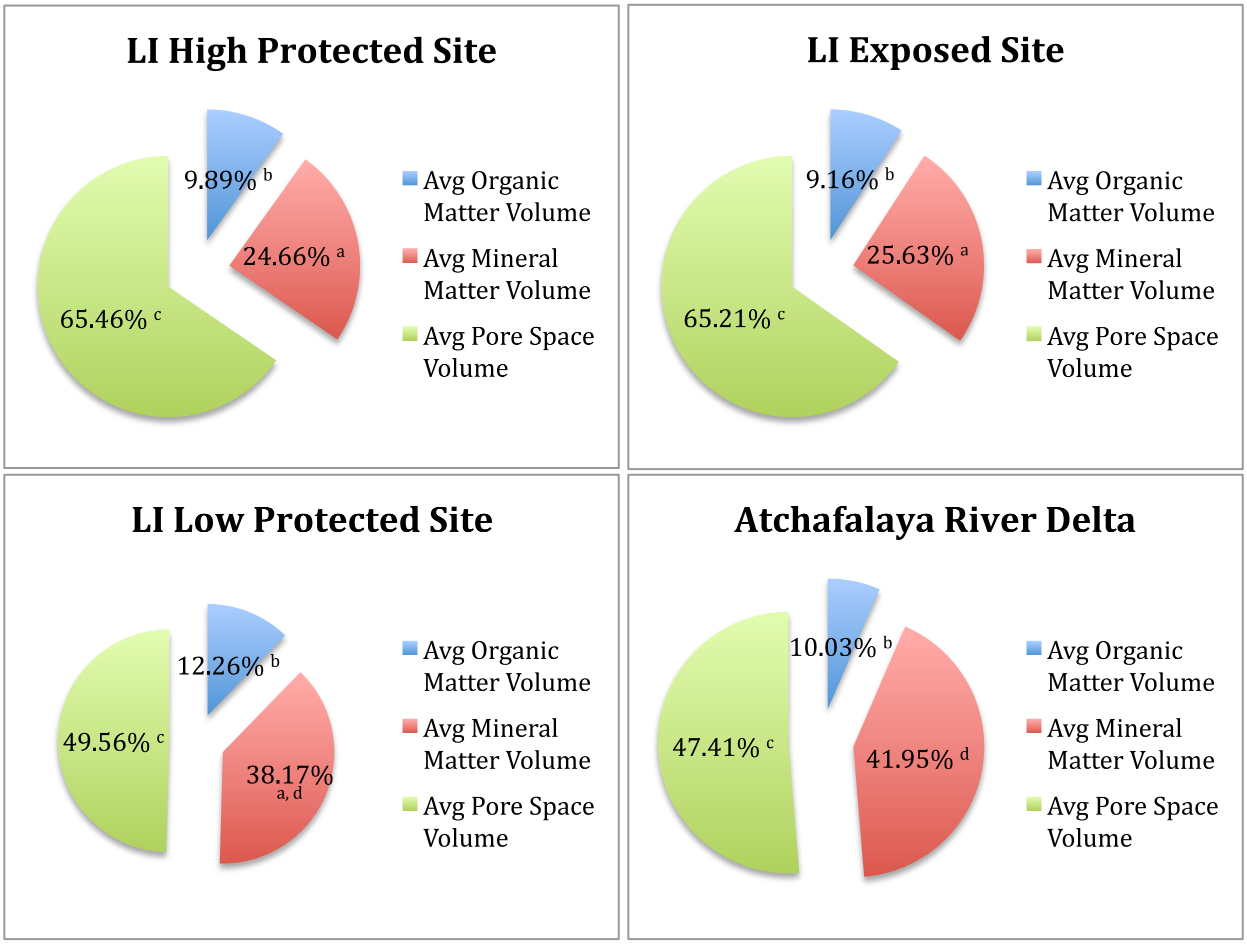

Figure 3.8: Average soil volumetric contributions for Liberty Island and Atchafalaya Delta sites. Different letters represent significant differences between sites (ANOVA, ∝=0.05 confidence interval).

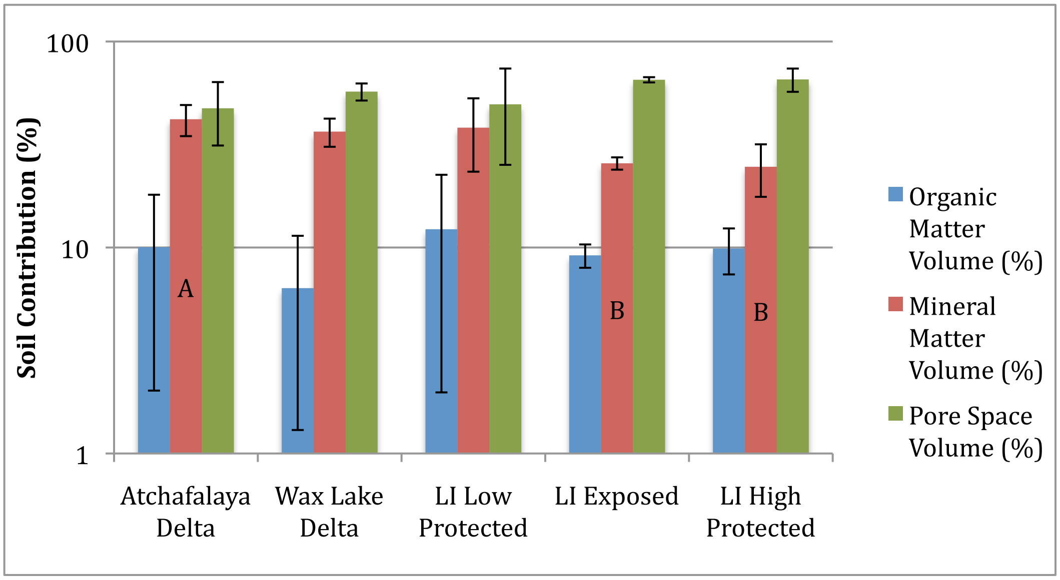

Figure 3.9: Volumetric soil contributions for all sites studied. Bar graph depicted as mean ± 1 std. dev. Different letters represent significant differences (ANOVA ∝=0.05 confidence interval). Bars without letters represent sites without significant differences (p>0.05).

3.4 Organic and Mineral Matter Weight Contributions

Mineral matter weight was significantly greater than organic matter weight for all segments in the cores (p<0.001; Figure 3.10). There were not significant mineral matter weight differences between the Atchafalaya, Wax Lake and low protected sites (p>0.05). However, there were significant differences between the low and high protected sites at Liberty, and between the low protected and exposed sites at Liberty (p=0.001). For organic matter weight, the Liberty Island sites had significantly higher values than the Atchafalaya and Wax Lake Delta sites (p<0.004) (Figure 3.10).

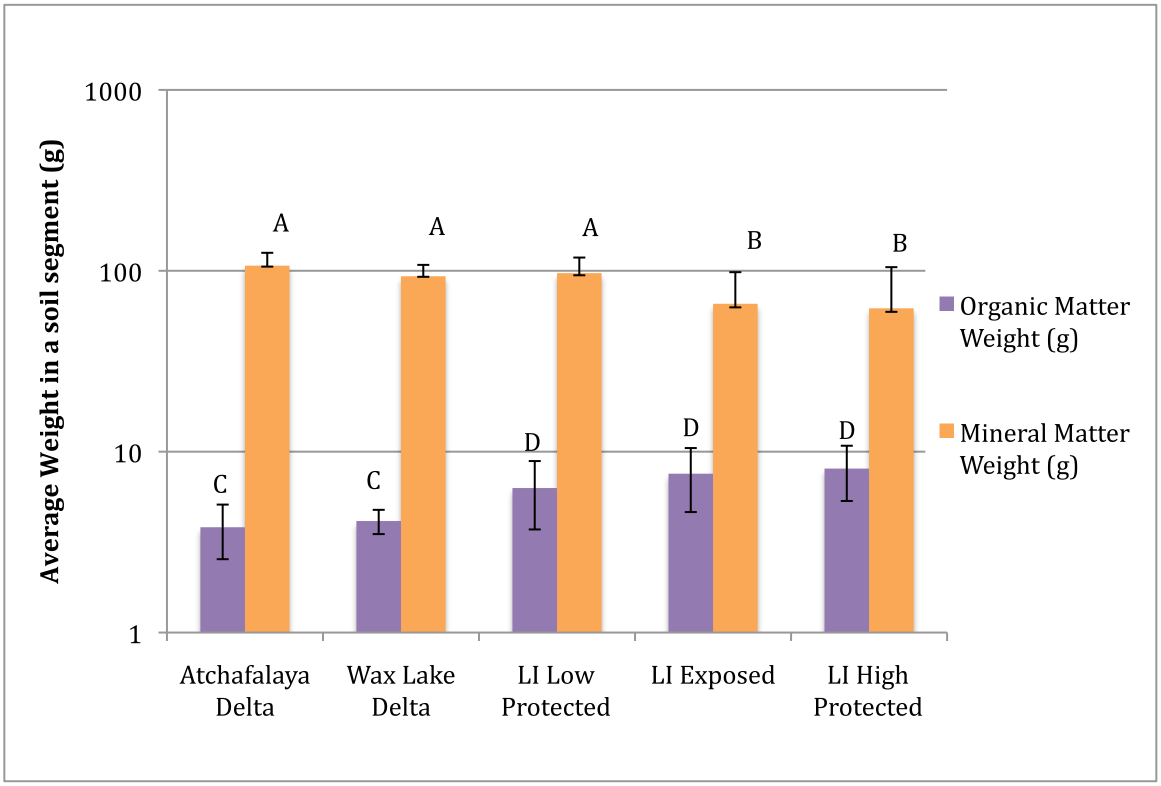

Figure 3.10: Organic and mineral matter weight contributions to the soil for all sites studied. Bar graph depicted as the mean soil weight of all 5 cm core segments ± 1 std. dev. The different letters represent significant differences (ANOVA ∝=0.05 confidence interval).

<u>Hypothesis 2</u>

Results for organic and mineral matter volume and weight contributions support hypothesis 2, which stated mineral matter volume and weight contributions will be higher than organic matter contributions at all sites. The low protected site is the only site where the mineral matter volume, though still higher, wasn't significantly higher than the organic matter volume ($p=0.146$). Hypothesis 2 is therefore accepted for all sites except the low protected site at Liberty Island.

3.5 Aboveground Biomass and Soil Organic Matter Percent

Collected live aboveground biomass (g/m^2) was only significantly different for the Atchafalaya Delta sites (Figure 3.11). The *Sagittaria latifolia* (mean 424.47 ± 356.8 g/m^2) at the Atchfalaya sites had significantly lower aboveground biomass in comparison to both *Colocasia*

esculenta (mean 1137.64 ± 765.7 g/m^2) and *Schoenoplectus spp*. (mean 1935.35 ± 863.37 g/m^2) collected at the Wax Lake and Liberty Island sites respectively.

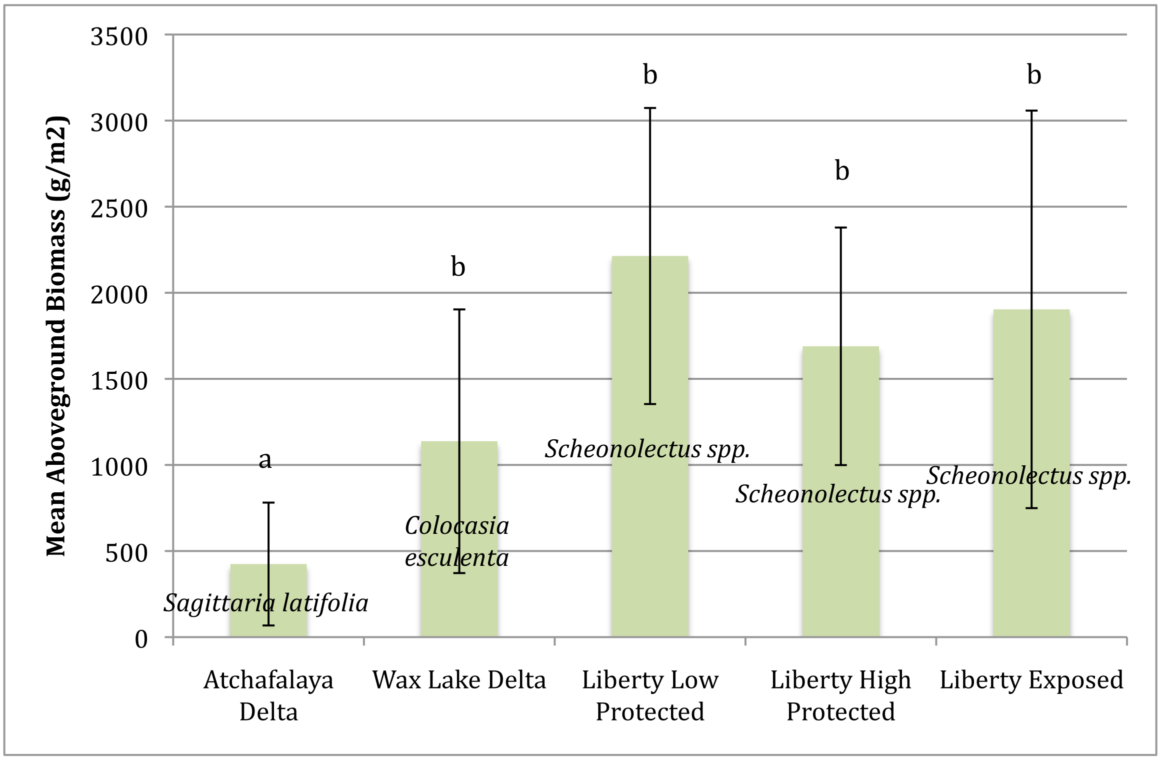

Figure 3.11: Collected live aboveground biomass. Bar graph depicted as mean +/- std. dev. Atchafalaya Delta and Wax Lake delta sites n=16; Liberty sites n=4. The different letters represent significant differences (ANOVA, $\propto$=0.05 confidence interval).

Percent organic matter values were not statistically different between the Atchafalaya and Wax Lake sites ($p=0.318$; Figure 3.12). There was a significant difference among the Liberty Island sites (exposed and high protected $p=0.02$; exposed and low protected $p=0.01$; high and low protected: $p<0.001$). Liberty Island sites had significantly higher organic matter percent values in comparison to the Louisiana Deltas ($p<0.001$).

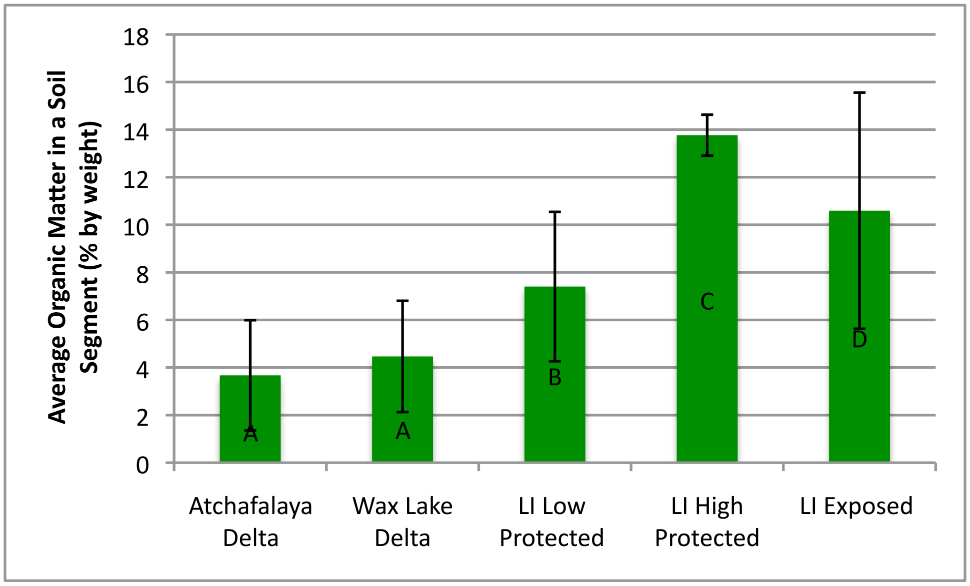

Figure 3.12: Average Soil Organic Matter percent by weight. Bar graph depicted as mean ± 1 std. dev. The different letters represent significant differences (ANOVA ∝=0.05 confidence interval).

Hypothesis 3

Schoenoplectus spp. aboveground biomass at the Liberty sites was significantly higher than *Sagittaria latifolia* aboveground biomass at the Atchafalaya Delta sites, but it was not significantly higher than *Colocasia esculenta* aboveground biomass at the Was Lake Delta sites. Despite this, soil organic matter values (percent by weight) were significantly higher at Liberty Island in comparison to both the Atchafalaya and Wax Lake Delta sites as was hypothesized. Hypothesis 3 is supported.

3.6 Bulk Density

Bulk density values were significantly greater for the Atchafalaya, Wax Lake, and low protected sites in comparison to the exposed and high protected sites at Liberty Island (Figure 3.13). There was a significant difference in bulk density between the Atchafalaya and Wax Lake sites ($p=0.008$), but not a significant difference between the Atchafalaya and low protected site ($p=0.559$). There was also not a significant difference between the Wax Lake and low protected

sites (p=0.975). At Liberty there was not a statistically significant difference between the two higher sites (p=0.973).

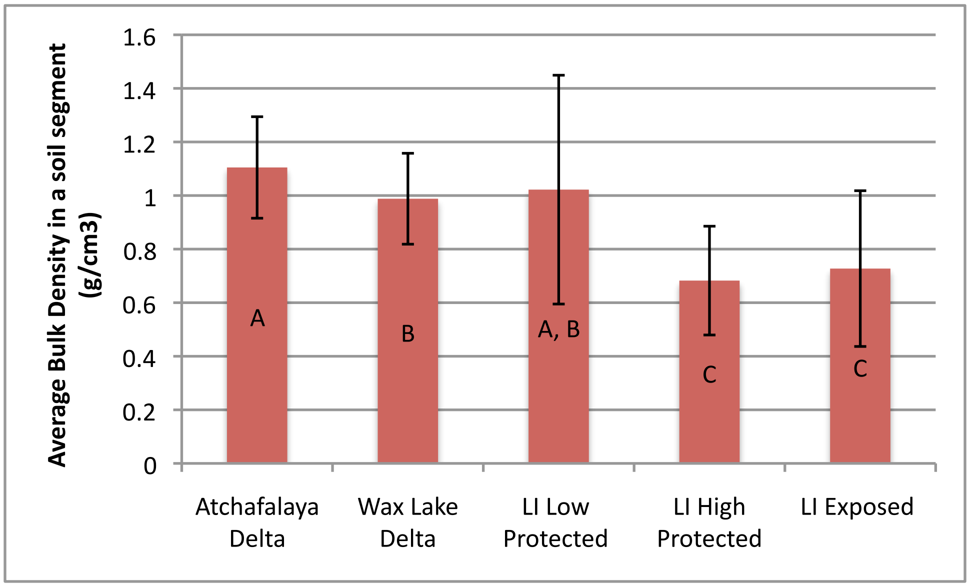

Figure 3.13: Bulk density values for all sites studied. Bar graph depicted as mean ± 1 std. dev. The different letters represent significant differences (ANOVA ∝=0.05 confidence interval).

3.7 Median Grain Size and Sand, Silt, Clay Percentages

Median grain size (D50) was calculated for the Atchafalaya and Wax Lake Deltas (n=4), and for each of the sites at Liberty Island (n=1). Due to the low number of samples analyzed for grain size statistics could not be run for this data. However, it is clear that median grain size at Liberty Island was higher than the median grain size for the Wax Lake and Atchafalaya Deltas (Figure 3.14).

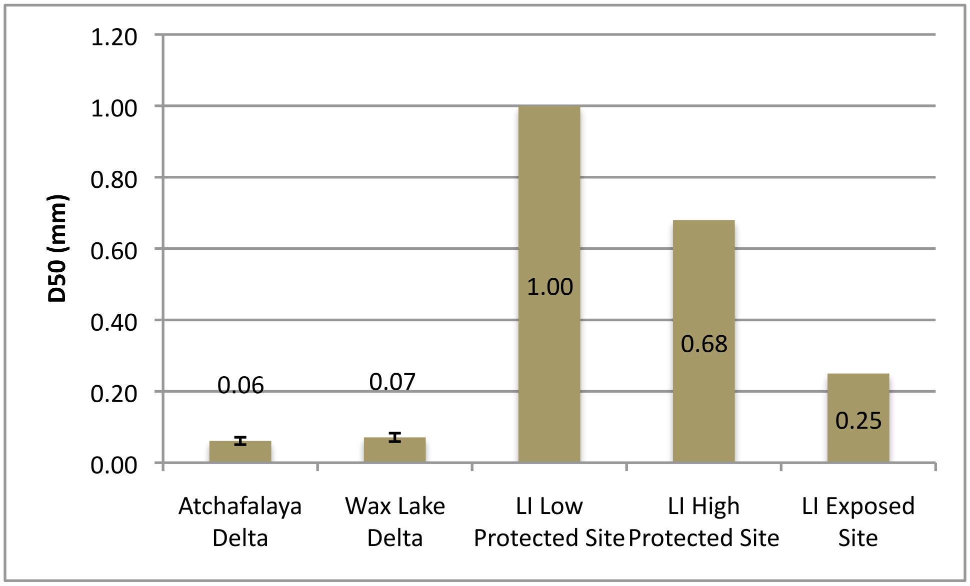

Figure 3.14: Median grain size for all sites studied. Grain size analysis was conducted for 1 sample at each Liberty Island site, but for 4 sites each in the Atchafalaya and Wax Lake Deltas so bars are depicted as mean ± std. dev.

Statistics also were not run for sand, silt and clay percentages. However, it was observed that sand percentages were higher for Liberty sites, and accounted for more of the samples than silt and clay (Figure 3.15). At the Atchafalaya and Wax Lake delta sites there was much less of a difference between sand and silt percentages at each site. The Atchafalaya sites showed a 13% higher silt percentage in comparison to the sand percentage, whereas the Wax Lake sites showed a sand percentage that was just 2% higher than the silt percentage. At all sites clay percentages were the lowest of the three.

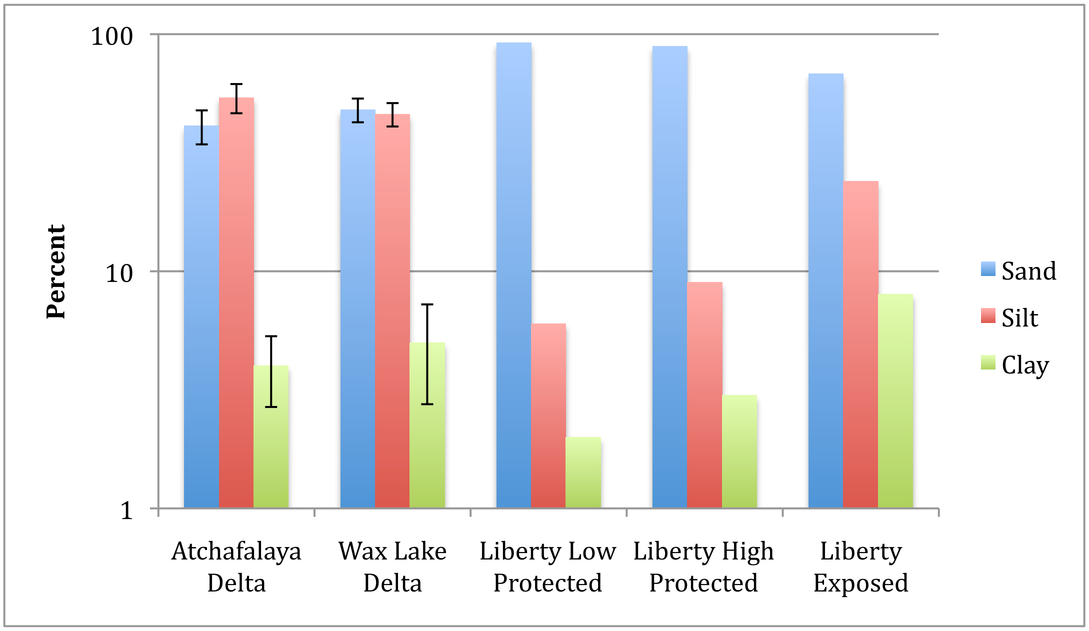

Figure 3.15: Sand, silt and clay percentages. Bar graph depicted as mean +/- std. dev. For Atchafalaya and Wax Lake sites (n=4). No error bars are shown for Liberty sites since grain size analysis was conducted on only 1 sample for each site.

<u>Hypothesis 4:</u>

Though there were not enough samples analyzed to make any statistically significant observations, it does seem that grain size at the Atchafalaya and Wax Lake deltas is smaller than grain size at Liberty Island, most likely due to the higher percentages of sand in the soil at Liberty. However, bulk density values were significantly lower at two of the Liberty Island sites in comparison to the Louisiana sites so hypothesis 4, which stated bulk density values would be higher at Liberty Island, is not accepted.

Chapter 4: Discussion

4.1 Surface Elevation Change

In addition to investigating mean elevation, accumulation rates and rates of change at each of the sites, elevation change through the measurement periods was explored to see if any patterns could be discerned that might assist with understanding the processes resulting in the observed changes. A better understanding of the factors that contribute to elevation change in newly building marshes can be used to guide restoration planning.

4.1.1 Atchafalaya River Delta

Though the net overall change for the Atchafalaya Delta RSET site was minimal (-2.3 mm, Table 3.1), there were changes in the elevation throughout the measurement period that were larger than the net overall change (Figure: 4.1). As can be seen (Figure 4.1) changes in elevation reflect patterns in mean water level, which is measured at the same site as the same site as the marsh elevation. With increases in water level there are associated increases in elevation change, and with decreases in water level there are decreases in elevation change. This is expected since sediment deposition requires the opportunity for sediment to be transported to the marsh surface by floodwaters, and an increase in hydroperiod results in an increase in the opportunity for sediment deposition (Reed and Cahoon, 1992; Reed, 1995; Cahoon et al., 1995). In a Louisiana study Cahoon et al., (1995) concluded that seasonal trends in elevation could be attributed to higher mean water levels in the Gulf of Mexico in the summer, which led to increased water storage and increased positive elevation change.

While these patterns are evident, they are not consistent for the entire measurement period. Measurements taken at the Atchafalaya site during summer seasons showed positive change during the first summer season, but then negative elevation change during the second

measured summer. This is unexpected since the mean water level increases during this second summer season. The negative elevation change during this time could be the result of Tropical Storm Lee, which passed through Louisiana in September 2011. The effects of this storm will be discussed later.

In addition to water level, elevation change at the Atchafalaya Delta site also seemed to follow patterns of river discharge, measured for the Atchafalaya River at Morgan City (Figure 4.2). It is assumed that higher levels of river discharge would be associated with higher amounts of suspended sediment. However, the suspension of fine sediments can be limited by availability if the flow is high enough to transport the sediment, but the material is not available. Sediment can also be transport limited when it is available, but the flow is not high enough; in this situation deposition occurs (Naden, 2010). If fine sediments were not limited by availability or flow then there would be a strong relationship between fine sediment concentration and river discharge. However, there is actually a high amount of scatter in flow and suspended sediment data. This variability has been attributed to variations in season, sediment source availability and local hydrologic conditions (Naden, 2010).

Despite the variability that can exist in discharge and suspended sediment measurements, for this study it is assumed that in general increases in river discharge have associated increases in suspended sediment availability. Therefore it is expected that with increases in river discharge there could be corresponding increases in positive elevation change, and the opposite would be true for decreases in river discharge. Early studies have found that the decrease in suspended load and discharge in the Mississippi River contributed to the high rates of wetland loss in coastal Louisiana (Kesel, 1989). In the marshes of coastal Louisiana the highest concentrations of total suspended solids occur in conjunction with high water levels associated with frontal

passages and hurricanes (Reed, 1989; Cahoon, 1994), and during high Mississippi and Atchafalaya discharge events between January and May (Allison et al., 2012). In a study of coastal salt marshes in Louisiana, Day et al. (2011) also found that both Hurricane Andrew and the marshes proximity to the Atchafalaya River had influence on sediment deposition.

Though elevation change at the Atchafalaya Delta site mostly follows the river discharge levels (Figure 4.2), this pattern is not consistent for the whole period of measurement. During the second measurement period, while mean discharge decreases there is a significant increase in elevation change. This increase in elevation change could be more related to the increase in vegetative percent cover during the 2010 year (Figure 4.3). The increase in percent cover could have resulted in an increase in belowground biomass. Since the majority of organic matter in Louisiana marsh soil is made up of root material (Reed, 1995), the increase in belowground biomass could have resulted in an increase in positive elevation change.

Additionally, while there was a decrease in mean river discharge for the March-October 2010 period, there was an increase in mean water level. An increase of marsh flooding can slow soil organic matter decomposition (Nyman and DeLaune, 1991). So, while there may have been less sediment available during this time period due to decreased discharge, the organic contributions may have facilitated the positive elevation change.

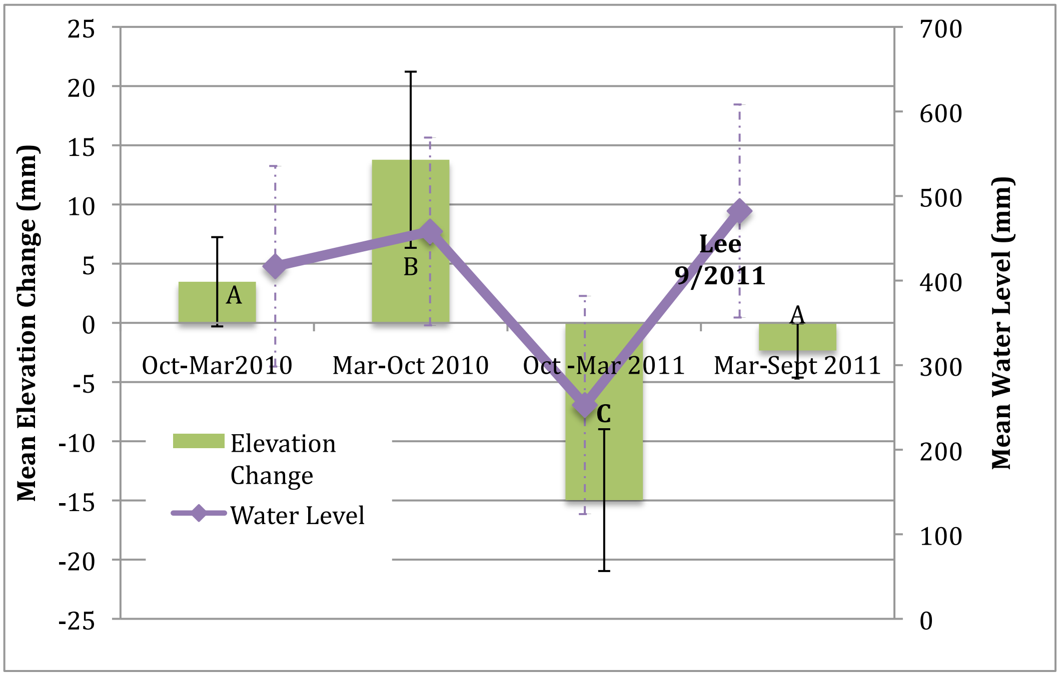

Figure 4.1: Atchafalaya Delta site mean elevation change and mean water level (NAVD88) for same measurement periods (± std. dev.; data download http://www.lacoast.gov/crms_viewer/). Different letters represent significant differences in amount of elevation change (ANOVA ∝=0.05 confidence interval).

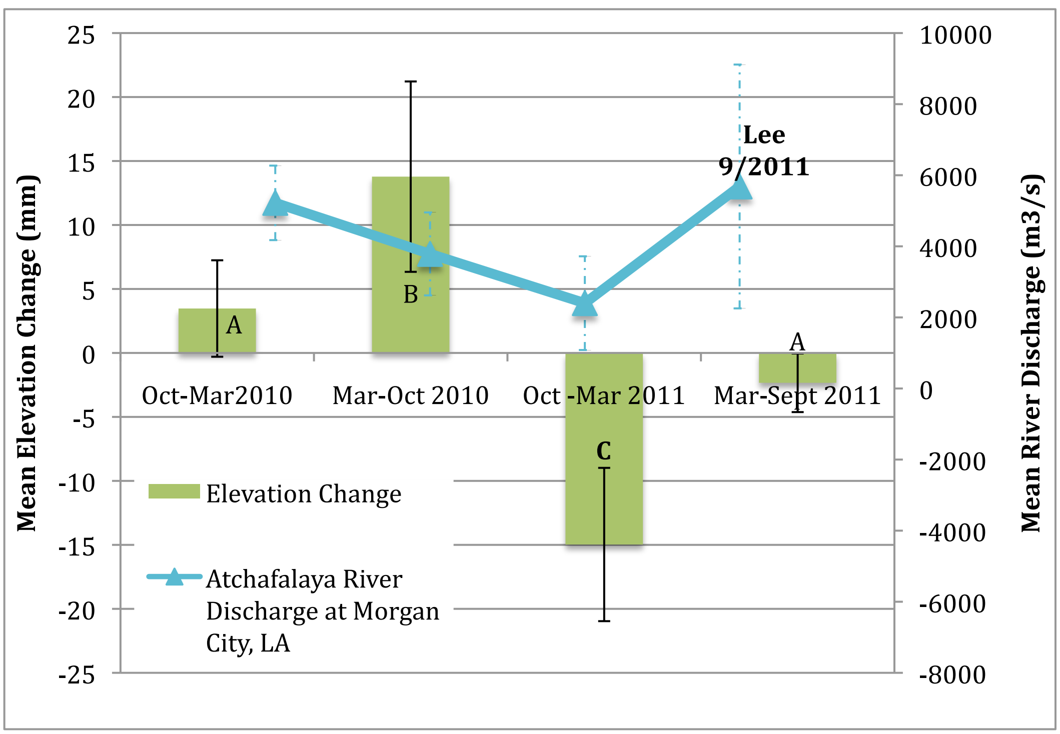

Figure 4.2: Atchafalaya Delta site mean elevation change and mean river discharge (± std. dev.; data download http://wdr.water.usgs.gov/nwisgmap/). Different letters represent significant differences in amount of elevation change (ANOVA ∝=0.05 confidence interval).

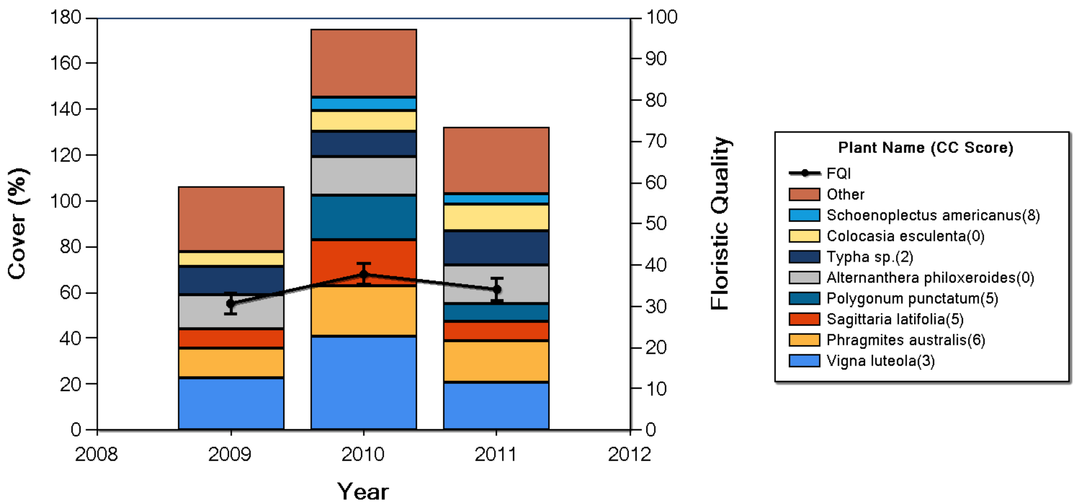

Figure 4.3: Atchafalaya Delta site vegetation percent cover and floristic quality index based on CRMS standards. (Figure from Coastwide Reference Monitoring System, CRMS site 6304, http://www.lacoast.gov/crms_viewer/).

While both mean water level and mean river discharge increased during the last measurement period at the Atchafalaya Delta site, there was negative elevation change, which could have been caused by the passing of Tropical Storm Lee. The storm brought a wide area of low pressure to the central Gulf of Mexico on September 1, 2011 and became a tropical depression on September 2, 190 nautical miles southwest of the mouth of the Mississippi River (Brown, 2011). On September 3 Lee reached a maximum intensity around 60 nautical miles southwest of Morgan City, and then made landfall on September 4 about 60 miles northwest of the Atchafalaya Basin near Intracoastal city, Louisiana (Figure 4.4; Brown, 2011).

At Louisiana Universities Marine Consortium (LUMCON) in Cocodrie, LA, sustained winds were measured to be 26-kt. Lee maintained subtropical storm strength into September 4 with 35-kt winds sustaining over the northern Gulf of Mexico (Brown, 2011). These strong winds created elevated water levels along the Louisiana coast for several days and heavy rainfall was measured to be between 10-15 inches along the Gulf Coast moving west from southeastern Louisiana to Alabama (Brown, 2011).

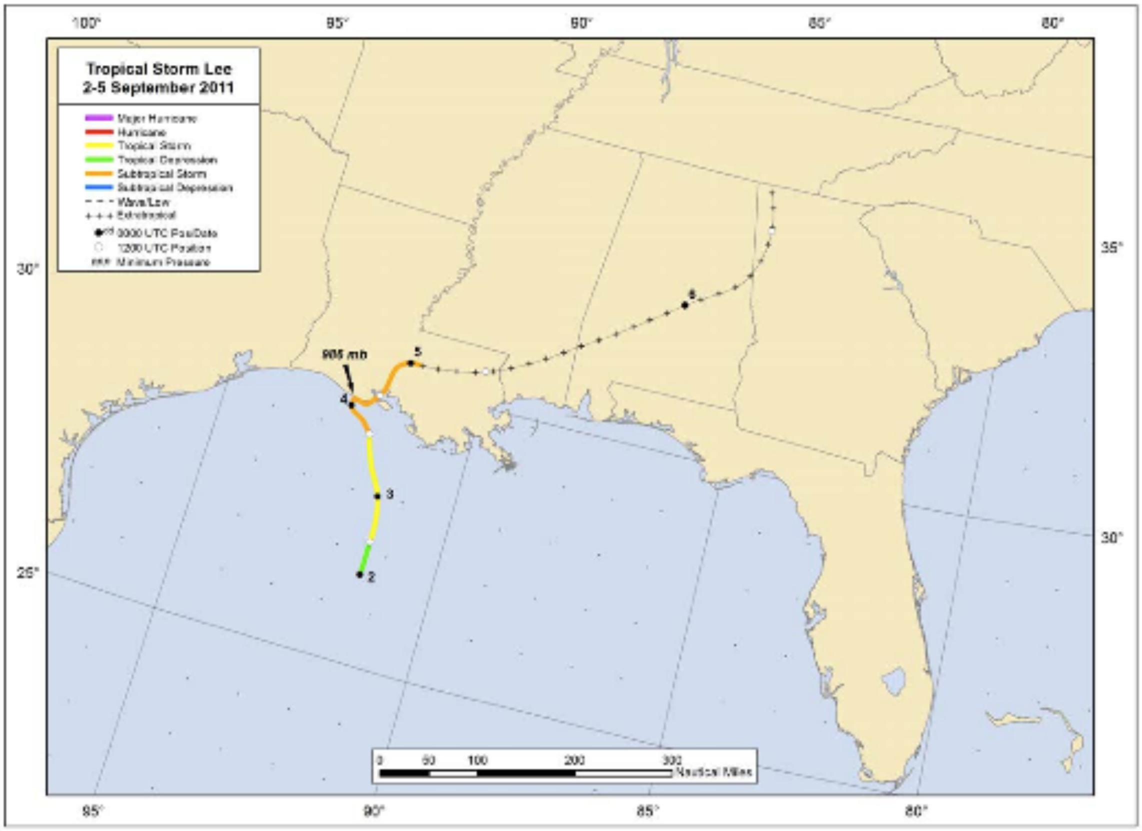

Figure 4.4: "Best Track" of Tropical Storm Lee, September 2-5, 2011 (Brown, D.P., 2011, Tropical Cyclone Report Tropical Storm Lee: National Hurricane Center).

With the increased water levels from the storm pushing up through the Gulf of Mexico, there was a measured increase in salinity at the Atchafalaya Delta site. The increase of salinity jumped to over 10 ppt, a large increase from the usual 0-2 ppt range measured at this site (Figure 4.5). At the two most southern sites the jump in salinity seemed to have caused dieback in the *Sagittaria latifolia* population, the dominant plant species being studied in the Atchafalaya Delta (Figure 4.6). Martin and Shaffer (2005) found that at 3ppt growth of *S. latifolia* is depressed and at 6ppt the species becomes "extinct." Their study also found that with increasing salinity there is a decreasing trend in above and belowground biomass for *S. latifolia*, and at 6ppt the species produced no belowground biomass (Martin and Shaffer, 2005). Spalding and Hester (2007) also found lowered growth and death in *Sagittaria lancifolia,* a similar freshwater wetland species.

The dieback from increased salinity levels can explain the drop in positive elevation change measured at the Atchafalaya site at the end of September 2011 (Figure 4.1). Salinity intrusions from storms have been shown to create impacts on marsh surface elevation change as salt burning can lead to plant mortality (Howard and Mendelssohn, 1999; Cahoon et al., 2003) The plant die-back can then lead to decreases in soil organic matter and corresponding lower surface elevation (Guntenspergen et al., 1995).

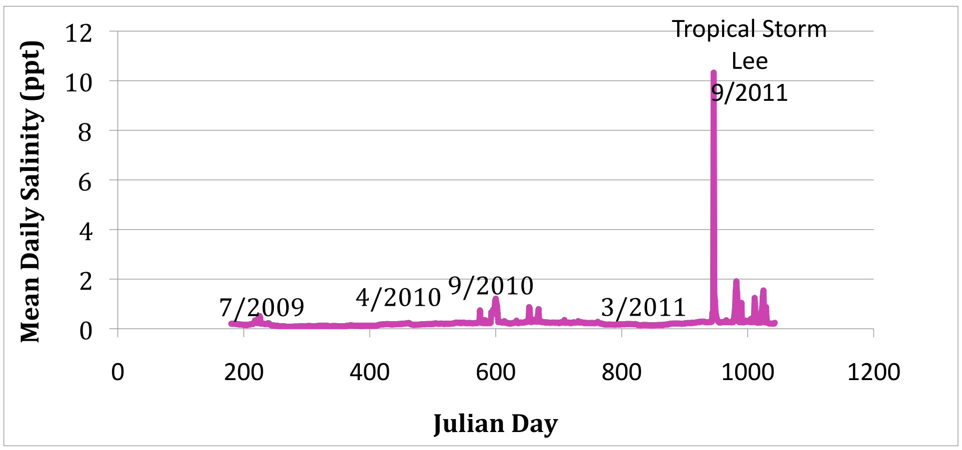

Figure 4.5: Atchafalaya Delta site mean daily salinity (Data download http://www.lacoast.gov/crms_viewer/).

Figure 4.6: Atchafalaya Delta sites A and B showing *Sagittaria latifolia* dieback from salinity incursion due to Tropical Storm Lee.

In summary, changes in surface elevation at the Atchafalaya Delta site were significant during the measurement period and seemed to follow patterns of water level, discharge and

vegetation changes. In addition, effects from Tropical Storm Lee resulted in negative elevation change at this site.

4.1.2 Wax Lake Delta

Similar to the Atchafalaya site the Wax Lake Delta site also showed an overall net negative elevation change of -2.39 mm for the same time period measured. Elevation change at this site seemed to also be impacted by water level, river discharge, and vegetation growth patterns (Figure 4.7 and 4.8). As can be seen in Figure 4.7, higher values of mean water level correspond to positive elevation change and the same is true for river discharge, which for the Wax Lake site was obtained from the Calumet, LA discharge gauge (Figure 4.8).

When links between vegetation seasons and elevation change patterns were investigated, there was positive elevation change during summer growing seasons (Figure 4.8). However, the amount of positive elevation change during the 2010 growing season was significantly lower in comparison to the 2009 and 2011 growing seasons, which could be a result of the lower percent vegetative cover measured during that year at this site (Figure 4.9).

While elevation change was positive during the summer seasons, it was negative, or significantly lower during the winter seasons. Lower elevation change during the winter seasons can be due to the decomposition of vegetation in the winter (Cahoon et al., 1995). During the winter months of their study Graneli et al. (1992), found rhizome mortality of about 30% for *Phragmites australis*, an invasive freshwater wetland plant. They documented formation of new rhizomes starting in June, and less belowground biomass towards the end of the growing season (Graneli et al., 1992). Additionally, studies of *Spartina alterniflora* in salt marshes have found a decline in belowground biomass in the winter season (Darby and Turner, 2008; Ellison et al., 1986). However, it is interesting to note that there have been some *Spartina alterniflora* studies

that have shown peaks in aboveground biomass just before the winter as substantial amounts of reserves built up and stored for the spring growing season (Gallagher, 1983; Gallagher et al., 1984).

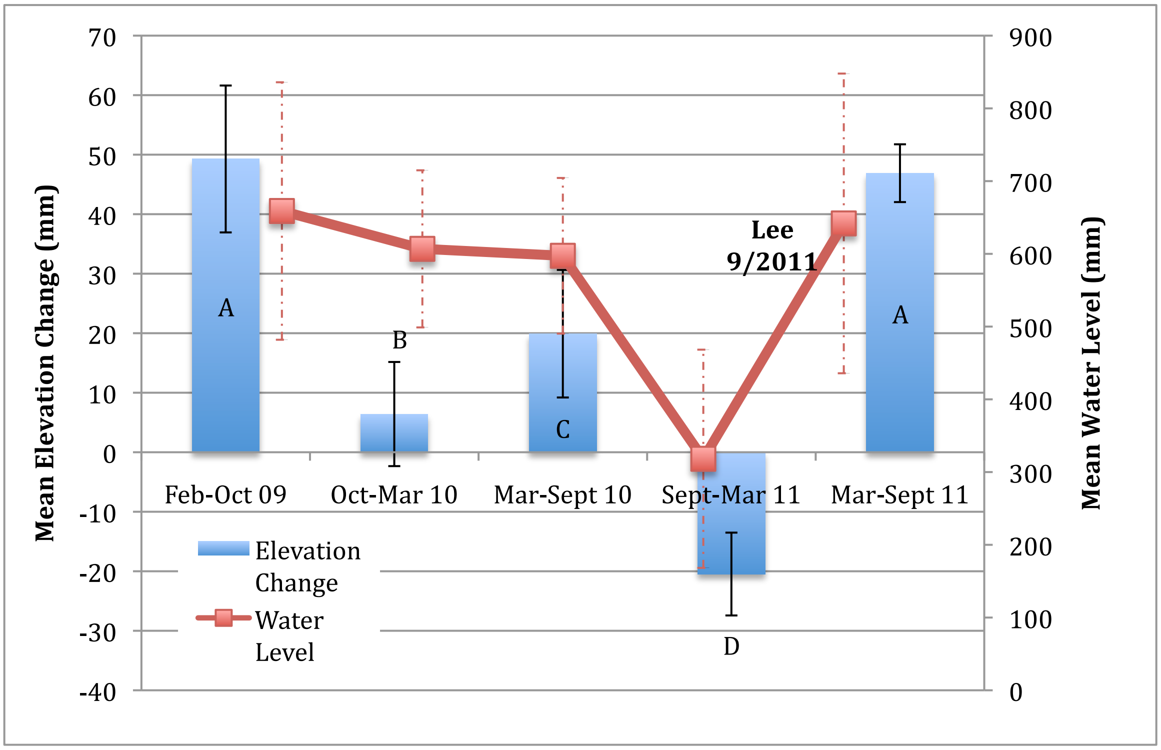

Figure 4.7: Wax Lake Delta site surface elevation change and mean daily water level (NAVD88) for same measurement periods (± std. dev.; data download http://www.lacoast.gov/crms_viewer/). Different letters represent significant differences (ANOVA ∝=0.05 confidence interval).

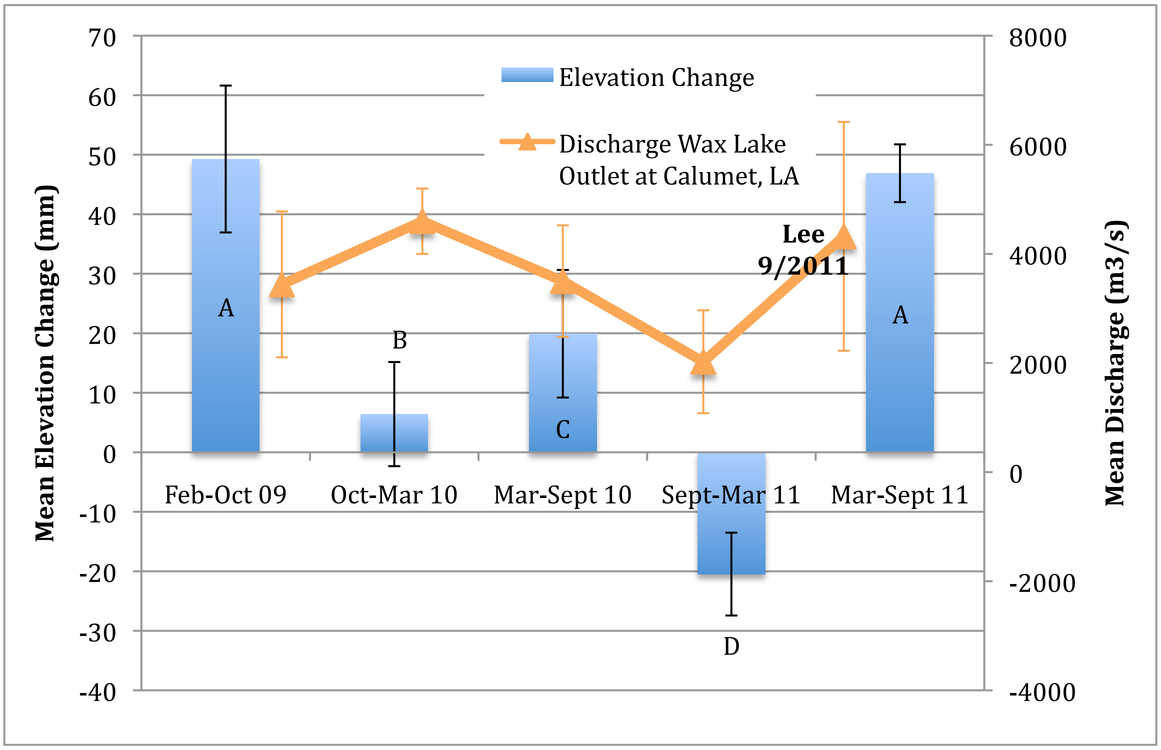

Figure 4.8: Wax Lake Delta site surface elevation change and mean daily river discharge for same measurement periods (± std. dev.; data download http://wdr.water.usgs.gov/nwisgmap/).

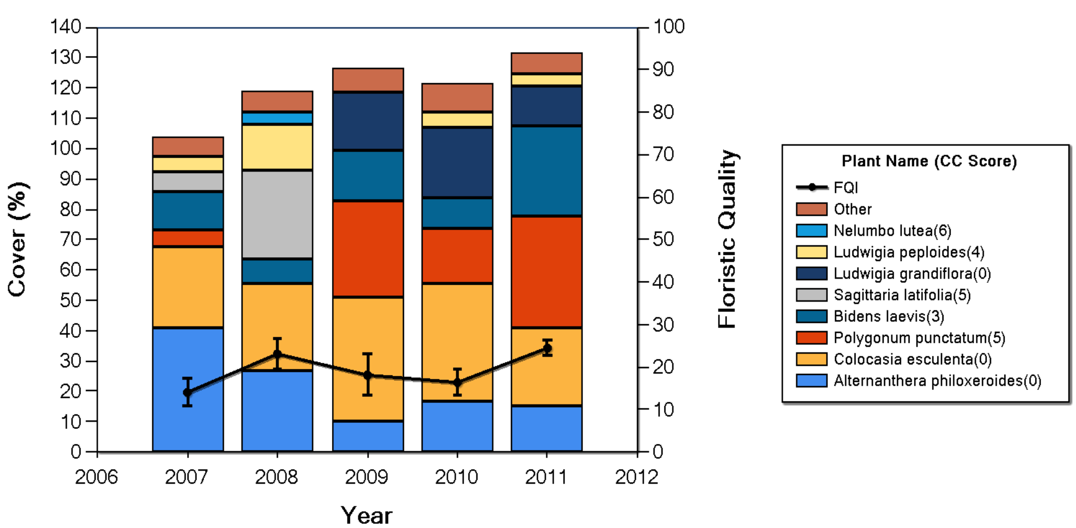

Figure 4.9: Wax Lake Delta site vegetation percent cover and floristic quality index based on CRMS standards (Figure from Coastwide Reference Monitoring System, CRMS site 0479, http://www.lacoast.gov/crms_viewer/).

In comparison to the negative elevation change at the Atchafalaya Delta site, the Wax Lake Delta had significant positive elevation change during the last measurement period,

between March and September 2011 (Figure 4.7). During this time there was negative elevation change at the Atchafalaya site, which as mentioned earlier may have been due to the salinity spike associated with Tropical Storm Lee. At the Wax Lake site, salinity levels reached just less than 3 ppt (Figure 4.11), much less than the more than 10 ppt at the Atchafalaya site, so salinity did not seem to have a negative impact on elevation change at this site. The significant difference in salinity (p<0.001) at the two sites could be the result of the deep navigation channel in the Atchafalaya Delta, which allows salinity to penetrate further into the delta (Holm and Sasser 2001). The positive elevation change at the Wax Lake site may have been a result of the increased water levels associated with the tropical storm, as well as increased discharge from the spring 2011 flood from the Mississippi River (Figure 4.10). Other reports of elevation increases in coastal wetlands due to storms have shown that this increase can be due to sediment redistribution and deposition (Cahoon et al., 1995b; Nyman et al., 1995), as well as large amounts of sediment delivered from runoff from high precipitation (Cahoon et al., 1996, 2003). One specific study, Cahoon et al. (1995a), found elevated deposition rates for as many as 12 weeks following a storm in some areas of Terrebonne Basin, Louisiana.

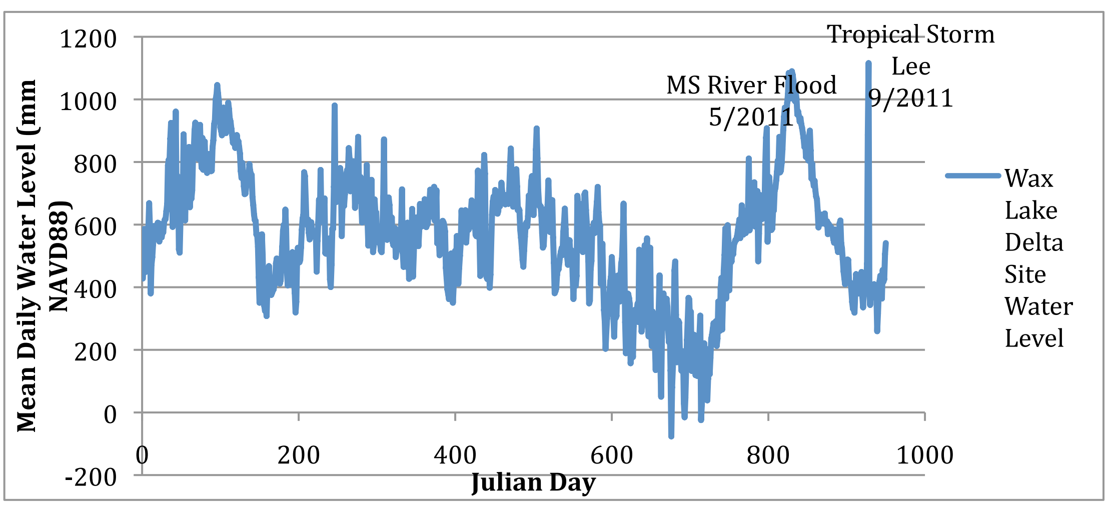

Figure 4.10: Wax Lake Delta site mean daily water level (Data download http://www.lacoast.gov/crms_viewer/).

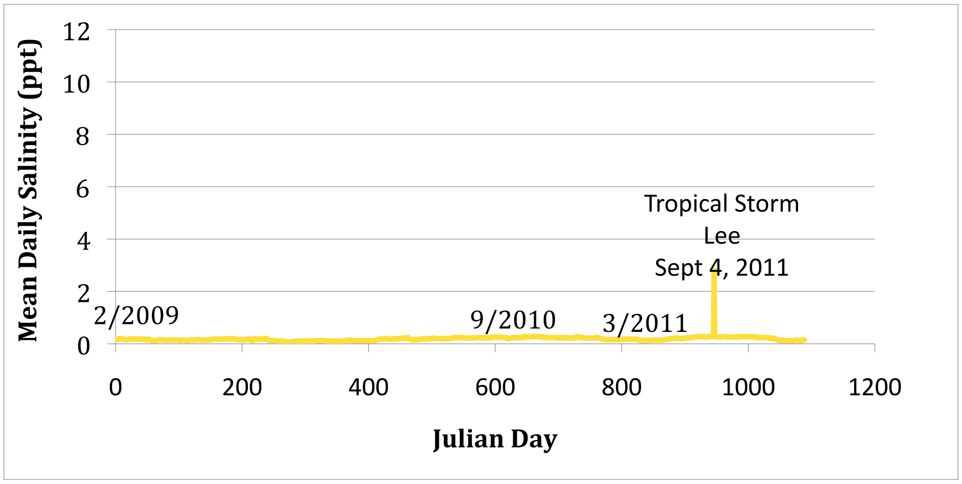

Figure 4.11: Wax Lake Delta site mean daily salinity (http://www.lacoast.gov/crms_viewer/).

Elevation change in both the Atchafalaya and Wax Lake delta sites reflected shifts in vegetation, water level and river discharge. Changes in elevation at these sites were also impacted by individual events , though the two sites do not appear to respond in the same way to the same events.

4.1.3 Liberty Island

The protected sites at Liberty Island had the highest rates of positive surface elevation change (28.03 mm yr^{-1} at the high protected site; 26.94 mm yr^{-1} at the low protected site) when comparing all sites in this study. Significantly higher organic matter percentages (by weight) (Figure 3.12) and lower exposure to wind wave energy, which may have allowed for more settling of suspended sediment at these sites, could have led to the higher rate of positive elevation change. Despite limited fetch in the Sacramento-San Joaquin Delta, it has been found that wind waves can be a source of erosion for some flooded islands in the Delta (Orr et al., 2003). Wind wave action at the exposed site therefore could have facilitated erosion at this site and contributed to the negative rate of elevation change (-10.26 mm yr^{-1}).

As with the Atchafalaya and Wax Lake Delta sites, there were fluctuations in the amount of elevation change throughout the sampling period for the Liberty Island sites. However,

elevation change at Liberty sites was much more variable and did not follow water level, river discharge or vegetation patterns as consistently as the two sites in Louisiana. As discussed above it is expected that elevation change will be positive during vegetation growing seasons and negative during winter decomposition seasons. While a similar study in the Delta showed an increase in marsh accretion during the summer months of June and August, and attributed this to the seasonal accumulation of belowground plant biomass (Reed, 2002), there was no direct pattern in terms of growing season observed at Liberty sites (Figure 4.12a).

When mean water levels were compared to the elevation change, the expectation was that higher water levels would result in positive elevation change, but this was not the case for the Liberty sites. Wright and Schoellhamer et al. (2005) found that 85% of sediment deposited in the Sacramento-San Joaquin Delta occurred during the wet winter season during the 4-year time period from 1998-2002. In contrast to these findings, mean water level measurements from the Rio Vista station show a steady decrease between June 2011 and June 2012 (4.12a). It would be therefore be expected that there would also be a decreasing trend in elevation change. The same is true for Sacramento River discharge, which also showed a pattern of steady decrease for the time period measured in this study. Yet despite the decrease in water level and discharge, there was increasing positive elevation change at the 2 protected sites. Since mean water level and Sacramento River discharge data were obtained from the Rio Vista station south of Liberty Island, the local conditions at the Liberty Island sites may have not been reflected in this data.

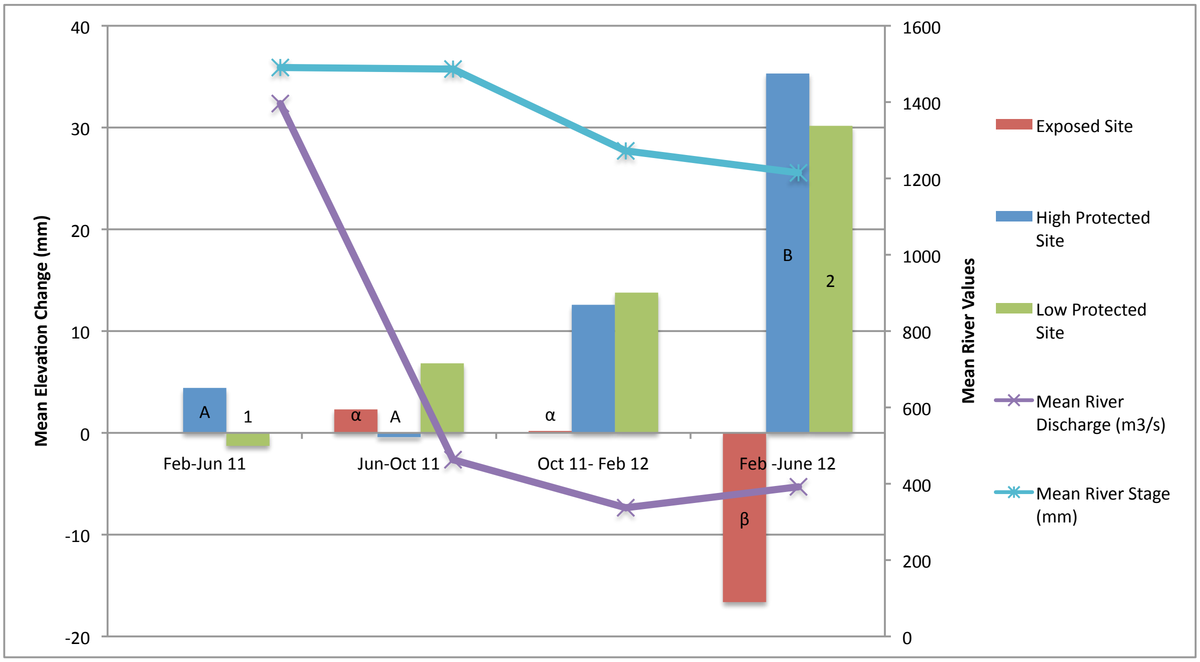

Figure 4.12a: Liberty Island mean surface elevation change, mean river discharge, and mean river stage. Letters, numbers and symbols represent significant differences of elevation change between time periods at each site (ANOVA ∝=0.05 confidence interval). Error bars were left out here for clarity; they can be seen in Figure 4.12b.

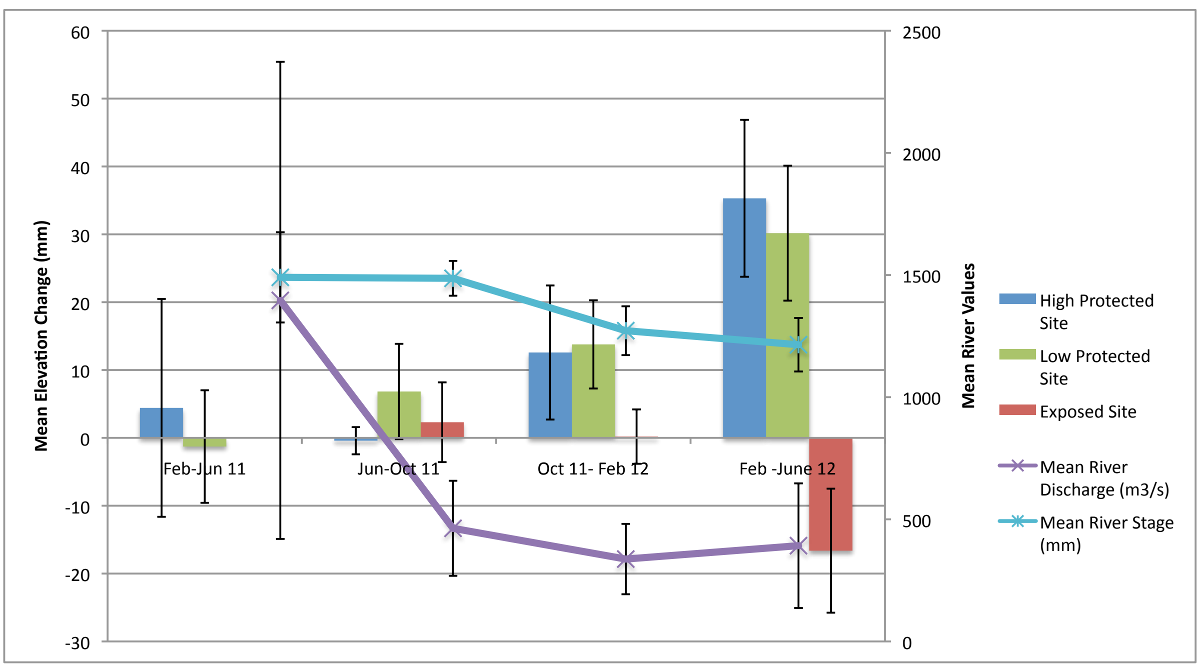

Figure 4.12b: Liberty Island mean marsh surface elevation change, mean river discharge, and mean river stage with error bars (error bars represent ± st. dev.).

Since there was not a direct pattern found between mean water level, river discharge and elevation change, it was thought that tidal inputs possibly had more of a direct impact. When Rio

Vista tide predictions were graphed for 2011 and 2012 (Figure 4.13, 4.14) the graph showed tides were highest in winter and summer, and lowest in spring and autumn. These trends also did not have a strong relationship with the elevation change data. Therefore, it seems that elevation change at the Liberty Island sites may be more impacted by local effects at the sites, not seasonal patterns in vegetation or water levels.

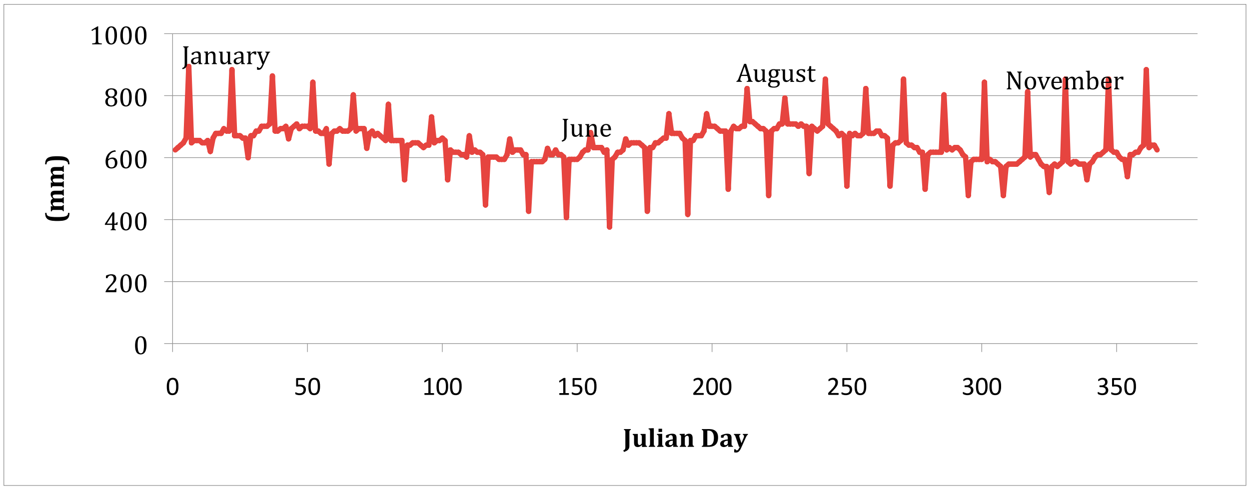

Figure 4.13 Mean daily tide levels 2011, Rio Vista (noaa.gov).

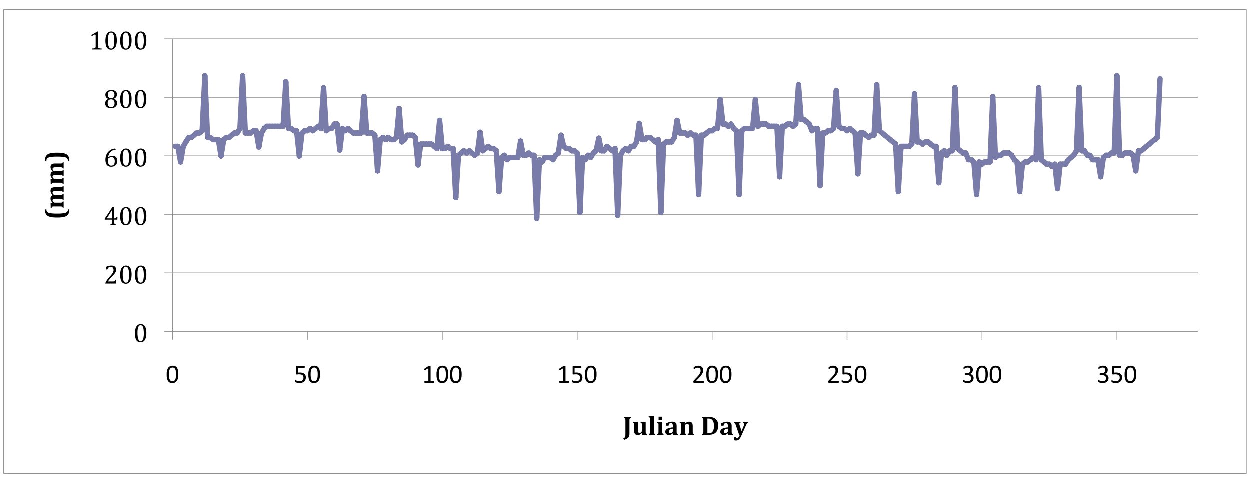

Figure 4.14 Mean daily tide levels 2012, Rio Vista (noaa.gov).

Overall, what can be seen for the sites at Liberty Island is that there was a pattern of increasing elevation change for the two protected sites, and a pattern of decreasing elevation change for the exposed site, including significant negative elevation change during the last

measurement period. It seems that elevation change is most impacted by the protected and exposed nature of these sites.

4.2 Soil Contributions

4.2.1 Mineral and Organic Matter

Since there were no statistically significant differences for soil volumetric contributions between the three Liberty Island sites, or between the two Louisiana sites, volumetric contributions appear to not have directly influenced variations in surface elevation change. However, mineral matter volume did add more to soil volume than organic matter for the sites in this study. Mineral matter weight was also higher than organic matter weight ($p<0.001$; Figure 3.10), and mineral matter accumulation rates were higher than organic matter accumulation rates ($p<0.001$; Table 3.3).On a percent weight basis Reed (2002) also found mineral matter contributions to be higher for freshwater tidal marshes in the Sacramento-San Joaquin Delta. In a study of tidal freshwater marshes along the east coast and the Gulf of Mexico, Neubauer (2008) found soil organic matter weight was on average 25%, with even higher percents for the Gulf of Mexico marshes (53%). These values are higher than the soil organic matter percent by weight values found in this study, which ranged between 4 and 14%. Similar findings to those found here have been reported for marshes in the Yangtze River delta where mineral matter dominates the soil and the low organic content is attributed to the short depositional history of the area, and the high mineral inputs (Yang, 1999). Since the sites in this study are newly built and newly restored marsh areas and there has been a relatively short amount of time since vegetation colonization occurred, mineral matter may dominate at these sites for the same reasons.

In terms of volume, it is clear that mineral matter volumetric contributions were higher than organic matter volumetric contributions. However, there are other freshwater marsh studies, in Louisiana specifically, which have found organic matter adds more to marsh soil through

volume than mineral matter (i.e. DeLaune and Pezeshki, 2002; Neubauer, 2008, 2011). Yet the Neubauer (2008) study found mineral matter volume contributions were higher than organic matter volume contributions. He reported a range of 1-32% mineral volume, and a range of 1-10% organic volume. These numbers are similar to ranges found in this study of 25-42% mineral matter and 6-12% organic matter.

When comparing all five sites, the low protected site had mineral matter weight values that were not significantly different than the Atchafalaya and Wax Lake Delta sites, but were significantly different than the higher two Liberty Island sites. The significantly higher mineral matter values for these sites could be due to their lower elevations, which would allow them to receive more deposition from longer flooding periods. This follows logic since increased hydroperiod increases the opportunity for sediment to deposit on the marsh surface (Reed, 1999).

There were not statistically significant differences between the Atchafalaya, Wax Lake Delta and Liberty Island sites for organic matter volume. Also, despite the different species sampled in the Atchafalaya and Wax Lake deltas there was not a significant difference in soil organic matter weight between the two ($p=0.954$). However, the tule vegetation sampled at the Liberty Island sites did have significantly more organic matter by weight in the soil ($p<0.05$). The roots of *Schoenoplectus spp*. were found to be larger and much more abundant in comparison to both the *Sagittaria latifolia* and *Colocasia esculenta* roots collected, which could account for the significantly higher weight values. Overall the *Schoenoplectus spp*. roots added more weight comparatively, but not more volume to the soil. Therefore, since volumetric contributions are more important for adding positive surface elevation change, when considering freshwater restoration projects this data suggests which plant species is used may not need to be a main consideration. However, it is important to recognize that all three of the species studied

here are emergent wetland species, and the findings should not be generalized for all wetland plant species.

With increasing marsh elevation, the sites at Liberty Island also showed increasing organic matter percent values (Figure 3.12). The high protected site at Liberty also had the highest rate of organic matter accumulation (Table 3.3). The significant increases in organic matter could be a result of the vegetation being able to be more productive at higher elevations due to less flooding stress. Again, for restoration purposes this could imply that higher marsh elevations will promote more organic matter accumulation, as vegetation can be more productive, which can lead to further positive elevation change. The significantly lower bulk density values at the two highest sites could also be a reflection of the higher organic matter contributions.

4.2.2 Grain Size and Bulk Density

Though statistical analysis could not be conducted for grain size due to the low number of samples processed, median grain size at the Atchafalaya and Wax Lake delta sites was noticeably smaller than at the Liberty Island sites (Figure 3.14). This could be due to the Louisiana delta sites being located farther down the river in comparison to Liberty Island, and it could be another reason why rates of elevation change were lower at these two sites in comparison to Liberty Island sites. Median grain size was highest at the low protected site at Liberty Island, which could account for the significantly higher mineral matter weight at this site in comparison to the other two Liberty sites (Figure 3.10).

The low protected site also stood out because it had bulk density values that were not significantly different from bulk density values at the Atchafalaya and Wax Lake sites (Atchafalaya and low protected sites $p=0.559$, Wax Lake and low protected sites $p=0.975$). Bulk density for Louisiana marsh soils is often found to be less than 0.3 g cm^{-3} (Nyman et al., 1990).

In other studies, bulk density values of 0.08 g cm^{-3} (Delaune and Pezeshki, 2002) have been reported for Louisiana brackish marshes. In a study of sites found in the proximity of a freshwater diversion along the Mississippi River, average bulk density values ranged from 0.08 to 0.18 g cm^{-3} (Delaune et al., 2003). After Hurricane Katrina and Rita, bulk density of newly deposited material was found to be 0.37 g cm^{-3}, and values decreased from the coast inland (Turner et al., 2006). Bulk density values found in this study are higher than all of these prior findings, ranging from 0.6 – 1.1g cm^{-3}. It is possible that because these sites are so mineral dominated this has led to the higher bulk density values.

Mineral matter weight values were also not significantly different between the Atchafalaya, Wax Lake and low protected sites. Yet despite the similarities in bulk density and mineral matter weight, median grain size at the low protected site (D_{50}=1mm) was much higher than the median grain size found at the Louisiana sites (Atchafalaya D_{50}=0.06 mm, Wax Lake D_{50}=0.07 mm). This difference could be due to the location of the low protected site at Liberty. Although it is considered "protected," when considering the island as a whole, since this site is located on the east side of the island it may be most exposed to winds coming from the southwest. These winds could create waves that resuspend and transport coarser materials to marshes on the eastern side of the island.

4.3 Study Site Evolution

With the information collected from this study, it is possible to revisit the Williams and Orr (2002) marsh evolution model to determine if their model can be generalized to fit other studies. While the Williams and Orr (2002) diagram represents marsh evolution through time in terms of the tidal frame, it is more appropriate in the case of these sites to consider the elevation of each site in terms of local water levels to obtain an idea of flooding frequency. In the case of the Louisiana sites, the Atchafalaya Delta site seems to have been flooded less frequently in

comparison to the Wax Lake Delta Site, which was flooded for much of the time period measured (Figure 4.15, 4.16).

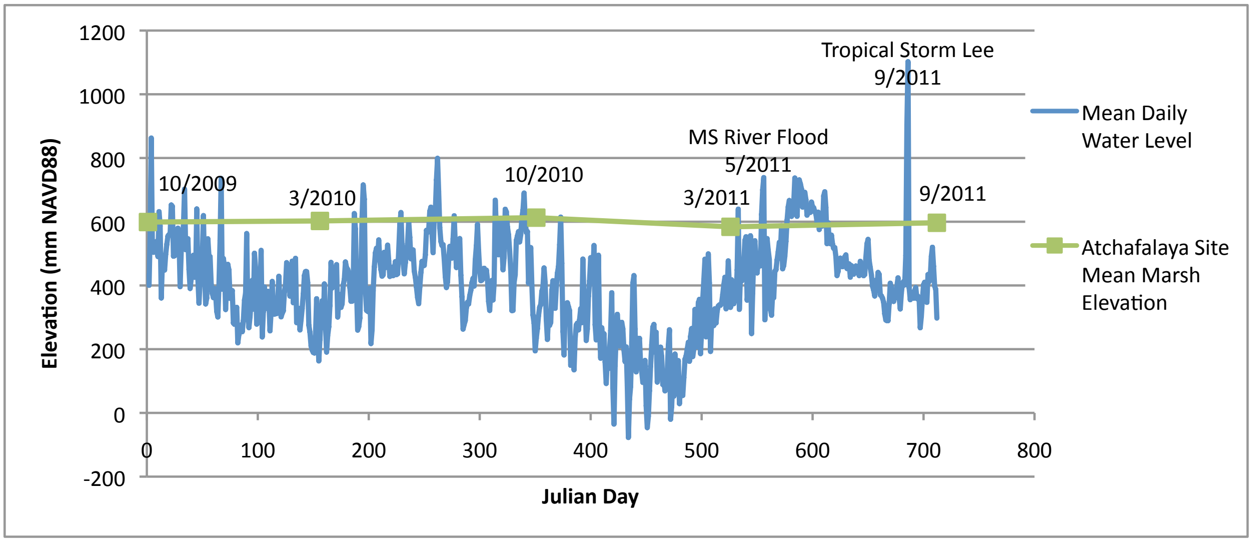

Figure 4.15 Atchafalaya Delta site marsh elevation and daily water level (Data download http://www.lacoast.gov/crms_viewer/).

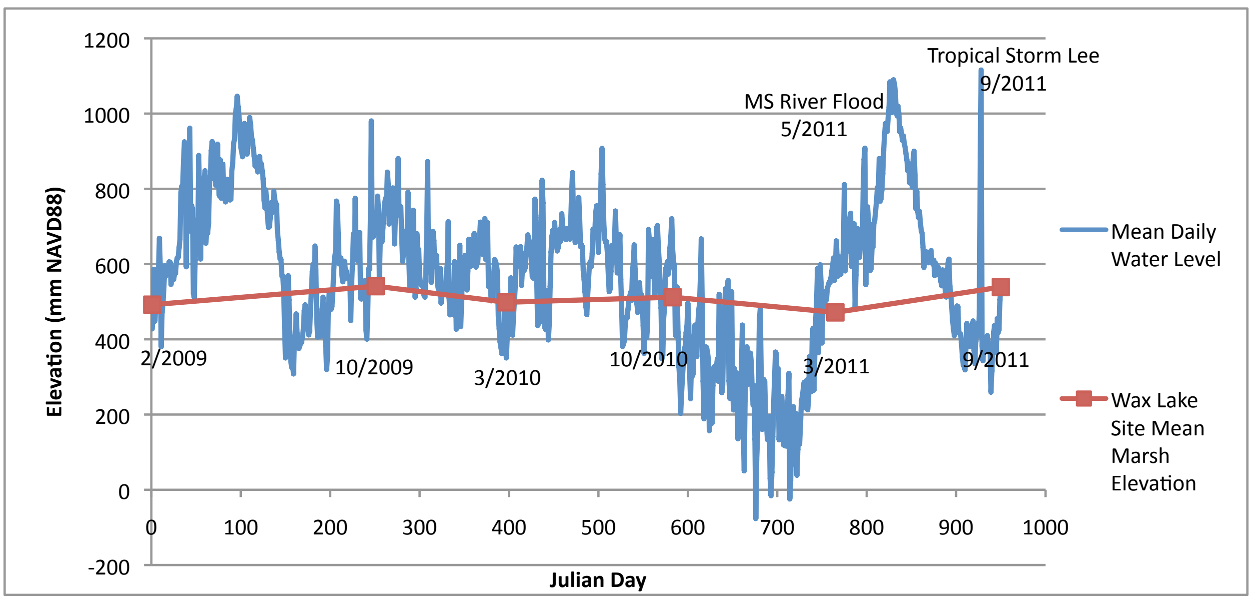

Figure 4.16 Wax Lake Delta site marsh elevation and daily water level (Data download http://www.lacoast.gov/crms_viewer/).

At Liberty Island the two higher sites were flooded less frequently in comparison to the low protected site, which was flooded consistently by high tides and occasionally by low tides as well (Figure 4.17).

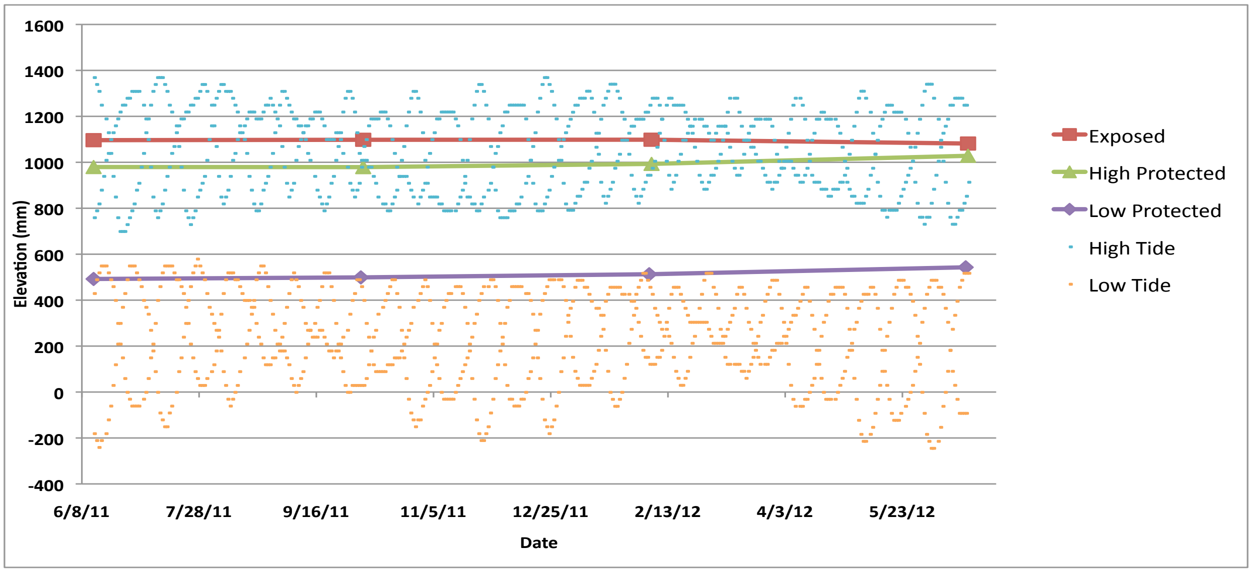

Figure 4.17 Mean elevation for Liberty Island sites with daily tide levels overlaid. Top curves at top of graph represent daily high tides and lower tide curves represent daily low tides (tide predictions from noaa.gov).

By considering the flooding frequency at each site, the sites can then be plotted on a revised marsh evolution model (Figure 4.18). Despite the different inundation regimes at the Liberty Island low protected site and the Wax Lake Delta site, tidally dominated and river dominated respectively, both of these sites have a high frequency of inundation and so are placed lower on the flooding axis (Figure 4.18). While these sites have higher frequency of flooding in comparison to the other sites, and can be considered less mature, it is important to remember that these sites showed two of the highest rates of positive elevation change, which demonstrates they are building towards higher marsh elevations, and thus lower frequency of inundation.

The high protected site at Liberty Island and the Atchafalaya Delta site are also exposed to different inundation regimes, but again seem to be similar in their frequency of inundation. The exposed site at Liberty has the highest elevation and the lowest frequency of inundation and

so is located highest on the flooding axis.

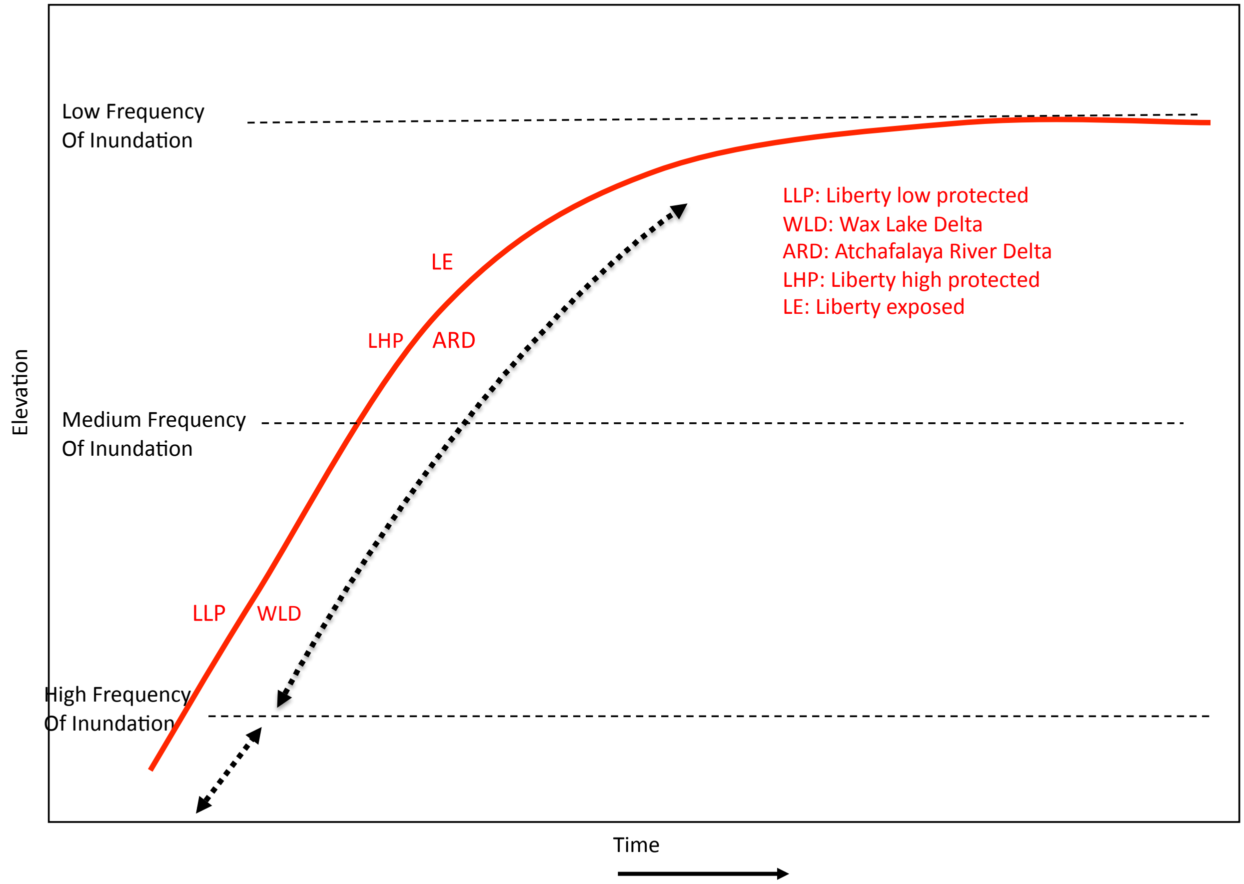

Figure 4.18 Revised marsh evolution model with sites from this study plotted in terms of flooding frequency (adapted from Williams and Orr, 2002).

In terms of marsh restoration, the high protected site at Liberty Island exhibits the most ideal conditions for marsh building. This site had high mineral and organic matter accumulation rates, and the highest rate of positive elevation change. The positive elevation change at this site was most likely facilitated by the protected conditions and the inundation frequency.

Chapter 5: Conclusions

Understanding the factors that contribute to wetland building in coastal marshes is proving to be critically important as large coastal areas in America continue to be converted to other uses and open water. As we gain a better understanding we can plan for better management and restoration in areas most vulnerable. Freshwater deltaic wetlands can be built naturally by receiving inputs from rivers, and with help from the vegetation that colonizes once they have reached a high enough elevation. Mimicking these natural building conditions and processes can prove useful for efficiently meeting restoration and management goals.

Surface elevation change at individual sites in this study was highly variable and seemed dependent on local conditions. No one dominant pattern for changes in elevation was uncovered from this research but, water level, river discharge, vegetation patterns, and storms were main contributing factors. Sites with the lowest marsh elevations had the highest rates of positive surface elevation change within their respective deltas; it is possible that these sites received more mineral matter deposition due to their exposure to more frequent and longer flooding. Since the lower sites had the highest rates of positive elevation change the idea that marshes will keep building in order to maintain elevation relative to sea level rise, and until they reach the level of mature marsh plain, is supported.

While both mineral and organic matter contributed to the marsh soil at all sites, gravimetric and volumetric mineral matter contributions were consistently higher. This suggests these newly building and restoring wetlands are more dependent on sediment delivery than plant growth for building marsh surface elevation. Mineral matter deposits are brought in with marsh

flooding (Reed, 1989), so connections to tidal and riverine inputs must be maintained, and fluctuations in the rivers will have a large impact on these wetlands.

The Mississippi River flood of 2011 seemed to have positively impacted elevation change at the Wax Lake Delta site, and similarly with the significant increase in the Sacramento River stage recorded in May 2012 there was a subsequent significant increase in positive elevation growth at the protected Liberty Island sites. However, there was also significant drop in elevation change during this flood time at the Liberty Island exposed site suggesting sites which are exposed to less energetic conditions may be more optimal for marsh building.

The two Louisiana deltas studied could also be considered exposed as they receive inputs from both the marine and riverine environments. In the case of the Atchafalaya Delta site, this additional exposure to marine forcings prevented positive elevation change due to the salinity incursion from Tropical Storm Lee. Perhaps the lower rates of positive elevation change in these deltas, in comparison to the rates of change at Liberty Island, are due to the exposed nature of these deltas. Therefore, in terms of ideal conditions for marsh building, a site may be more successful if it is able to receive riverine inputs, but has some protection from high-energy events.

In contrast to the findings in this research, there have been other studies of freshwater wetlands, which have found organic matter contributes more to marsh building. However, many of these studies have focused on gravimetric contributions, and there have been few investigations that have focused on volumetric contributions. Yet this is important for understanding the vertical building of marshes. Organic matter volumetric contributions in this study were not significantly different for the three freshwater plant species studied, which suggests restoration projects that aim to promote wetland building may not need to be based on a

certain plant species. However, all three of the species studied here, *Colocasia esculenta, Sagittaria latifolia* and *Scheonoplectus spp.,* grew to heights above the water level and therefore were able to slow flows and trap sediments, so this finding may not hold true for other wetland vegetation species. Research into other dominant freshwater marsh plants would therefore prove interesting to see if organic matter contributions are consistent in a wider variety of plant species that are colonizing newly building marshes.

In addition, since no consistent elevation change patterns emerged from the data collected at these sites, perhaps longer-term measurements would be helpful for discerning any significant trends to inform decision makers. If elevation change measurements could be obtained for longer than a 1-2 years, it is possible that with this long-term data more consistent trends could be discerned. Also, collecting further information on how mineral and organic matter contributions change throughout the year, perhaps during flood and drought seasons, and growth and decomposition seasons, could provide additional insight on seasonal affects of river inputs and vegetation. This knowledge would aid with restoration projects that focus especially on marsh plantings and river diversions.

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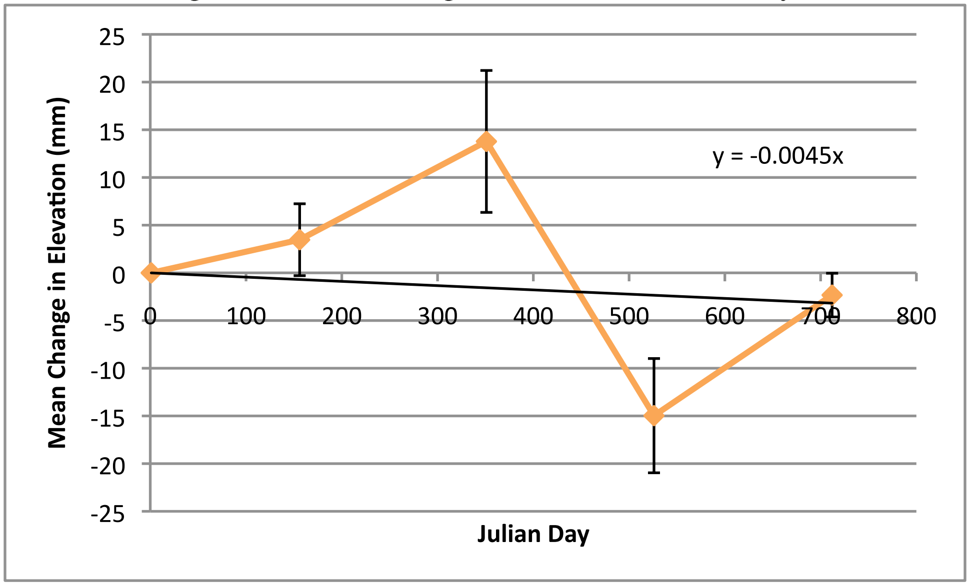
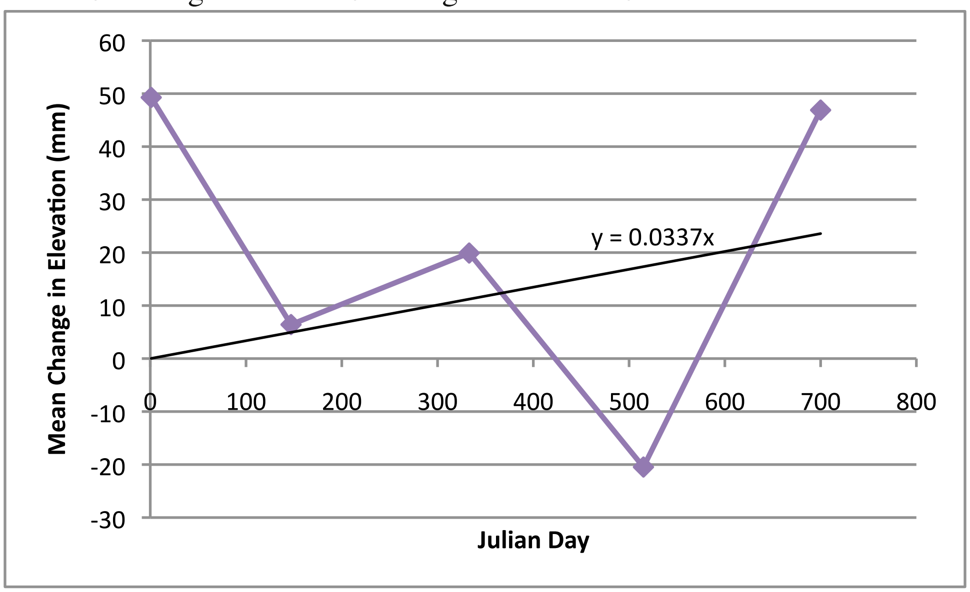
Appendices

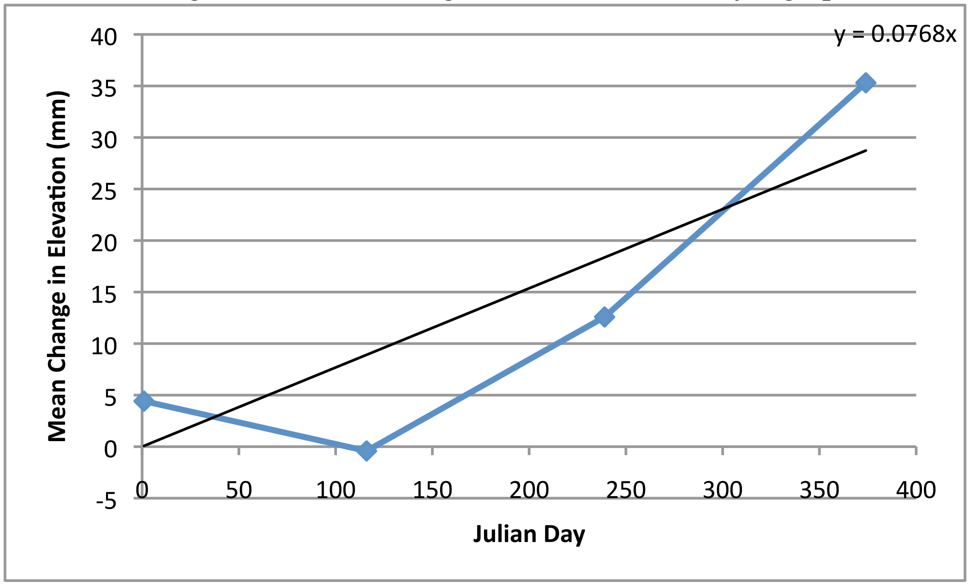
Elevation change with rate of change trend line for Atchafalaya Delta site.



Elevation change with rate of change trend line for Wax Lake Delta site.

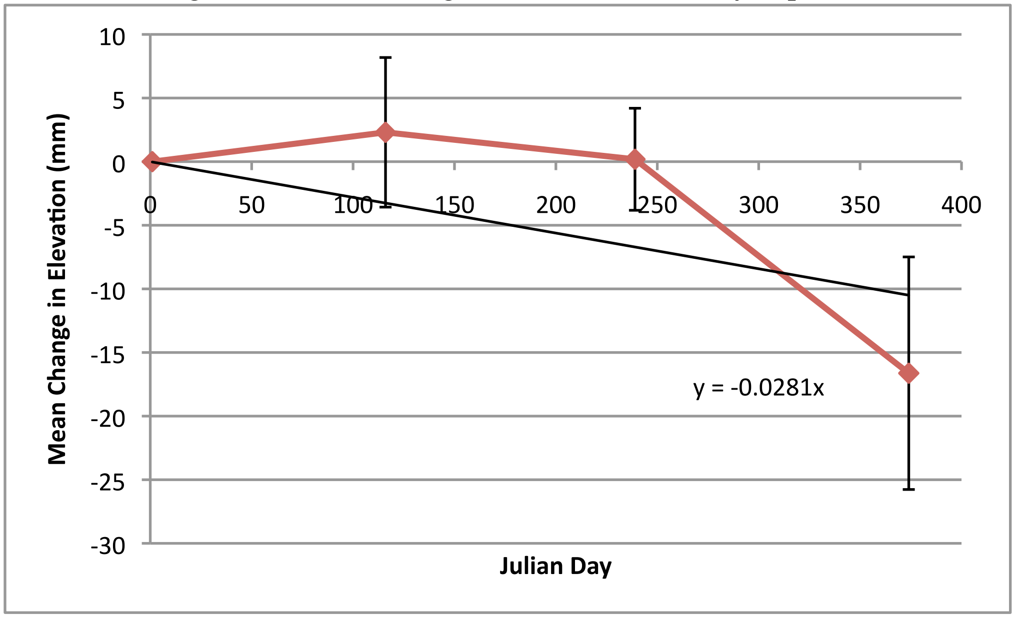


Elevation change with rate of change trend line for Liberty high protected site.

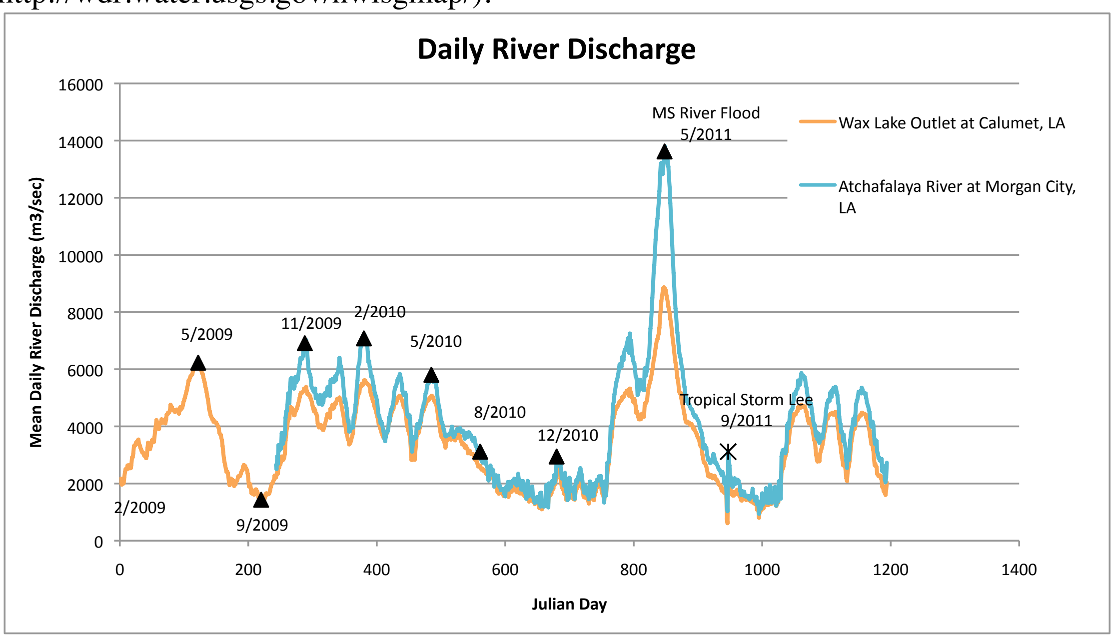


Elevation change with rate of change trend line for Liberty low protected site.

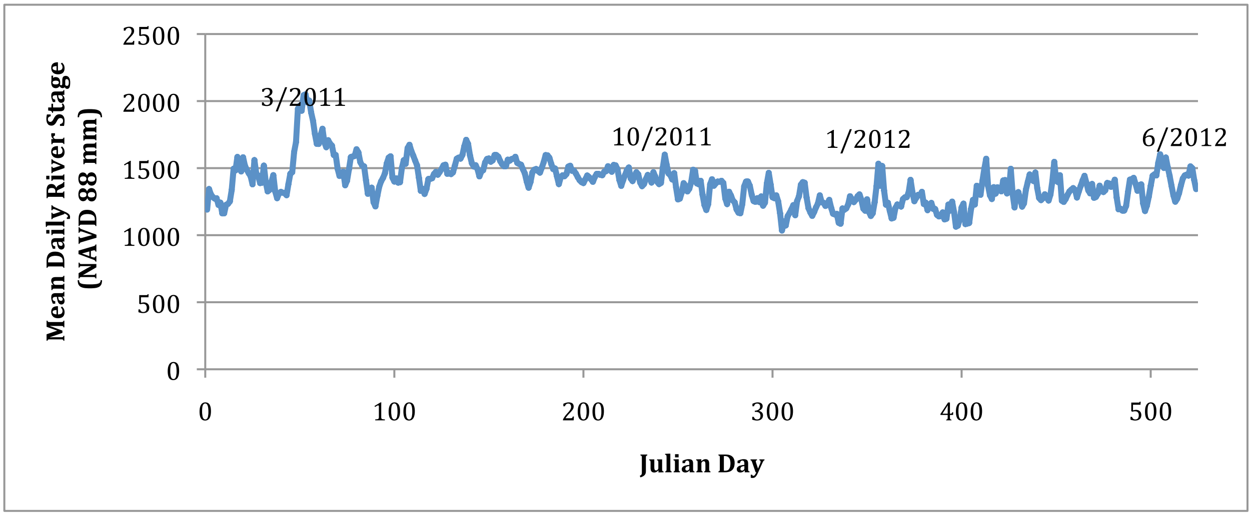
Elevation change with rate of change trend line for Liberty exposed site.



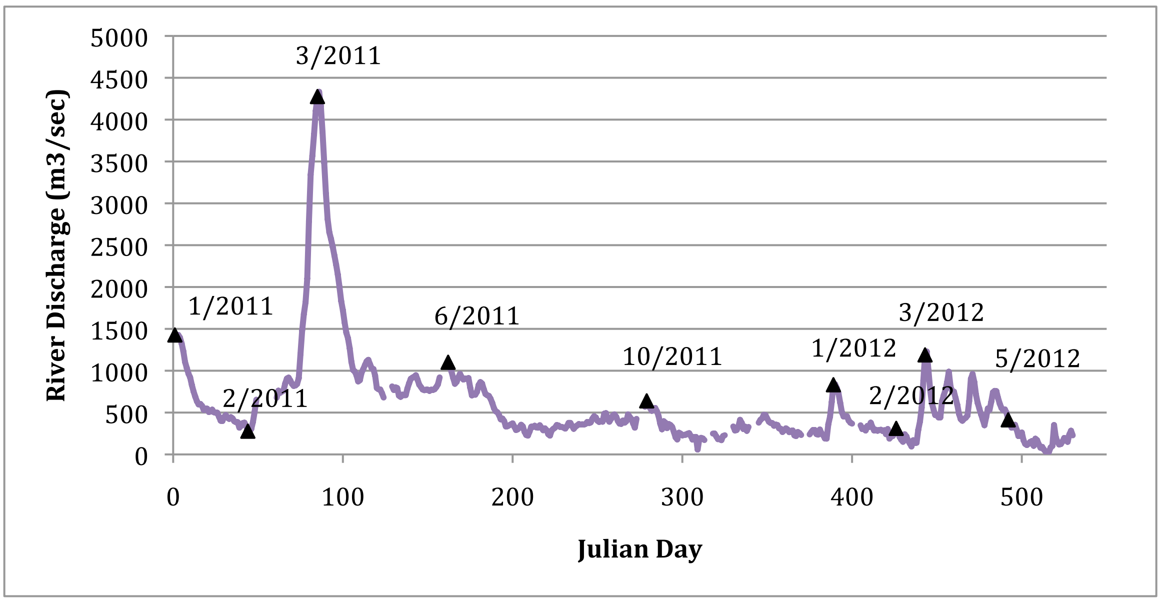
Atchafalaya River mean daily river discharge (Data download http://wdr.water.usgs.gov/nwisgmap/).



Sacramento daily river stage measured at Rio Vista (CDEC station Rio Vista, http://cdec.water.ca.gov).



Sacramento River mean daily river discharge measured at Rio Vista (Data download http://waterdata.usgs.gov).



Vita

Lindsay Dunaj was raised in Springfield, Massachusetts. She received her B.A. in Chemistry from Mount Holyoke College, and her M.S. ed. from Simmons College. She now lives in New Orleans, LA.