Abstract

Evaluations of salt marsh surface elevation and stability have generated much attention in the past few decades due to predicted sea-level rise of 4.8mm yr^{-1}. Semi-annual elevation data were collected at Upper Philips Creek Salt Marsh (UPCM) using Surface Elevation Tables (SETs) from August 1997 to September 2004. Monthly and hourly data were collected using SETs and Root zone Surface Elevation Tables (RSETs) from June 2003 to September 2004. UPCM was divided into three areas (low, mid, and high marsh) determined by elevation above mean sea-level and type of vegetation. Elevation data were correlated with tidal inundations, meteorological data, and ground water levels for 6 months prior to semi-annual readings and 1 month prior to monthly data collection. Hourly SET and RSET data were correlated with the daily tidal cycle.

Low marsh elevation increased over the course of the 7 year study by 5.2cm, increasing at a rate of 5.8mm yr^{-1}. Expansion below the surface accounted for 2.6cm of the total increase. Mid-marsh elevation increased by 2.9cm, increasing at a rate of 3.6mm yr^{-1}. Expansion below the surface accounted for 5.3cm of the total increase in elevation. High marsh elevation increased by 1.5cm at a rate of 1.5mm yr^{-1}. The high marsh experienced compaction of 1.7cm below the surface during the 7 year study. Root zone increases occurred in the low and mid-marsh zones, 0.3cm and 0.7cm respectively, while the high marsh experienced root decay and compaction losing 0.3cm during the study from June 2003 to September 2004.

Mean high-high tide (MHHT) decreased relative to mean sea-level by 5.08cm yr^{-1}, an order of magnitude higher than the predicted rise in sea-level of 4.8mm yr^{-1}.

Surface elevation at the low, mid, and high marsh were inversely correlated to MHHT for both the semi-annual and monthly data collections. Hourly data collection was not correlated with the daily tidal cycle. Marsh surface elevations were not correlated with precipitation and ground water level over the study period.

Shorter duration studies of UPCM did not reveal significant correlation to short term meteorological data such as drought or hurricane impact or daily tide cycles. Decades long records incorporating short term phenomenon are necessary to determine surface elevation response to sea-level rise.

Acknowledgements

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Chapter 1

Introduction and Background

1.1 Introduction

Evaluations of salt marsh stability and surface elevation changes have received much attention over the past few decades largely due to predicted sea-level rise related to global warming (Hoffman et al., 1983; Leonard et al., 1995). Coastal wetlands are among the most productive ecosystems in the world. These wetlands at the land-ocean margin provide many direct benefits to humans, including habitat for commercially important fisheries and wild life; storm protection; improved water quality through sediment, nutrient and pollution removal; recreation; and aesthetic values. The question whether salt marshes survive present and future sea-level rise has been studied extensively (Kaye and Barghoorn, 1964; Hoffman et al., 1983; Baumann et al., 1984; Cahoon, 1994; Cahoon and Reed, 1995; Dubois, 1997; Leonard et al., 1995; McKee and Mendelssohn, 1989; Reed, 1992; Roman et al., 1997; Stevenson et al., 1985; White and Morton, 1997; White and Tremblay, 1995; Wijnen and Bakker, 2001). Results of these studies suggest that accelerated rates of sea-level rise could cause substantial loss of coastal salt marshes (Stevenson et al., 1985). In fact, there are extensive areas of the Mississippi delta region (Baumann et al., 1984), coastal Louisiana (Cahoon, 1994), and some brackish-water marshes of the Chesapeake Bay (Stevenson et al., 1985) where relative rates of sea-level rise presently exceed vertical marsh accretion. Similar losses may be occurring all along mainland salt marshes.

The long term stability of a subsiding coastal wetland may be responsive to climatic, geologic, hydrologic, and biologic forces of natural and man-made origin (Ranwell, 1972). Although coastal marshes can deteriorate for many reasons, the fundamental mechanism driving marsh deterioration is loss of marsh elevation below the mean level of the local tides resulting in state changes or transformation of marshes into subtidal systems. For a marsh to maintain its surface elevation for long periods of time, the rate of addition of organic and mineral material must be equal to or greater than the rate of settlement or autocompaction of the sediments (Kaye and Barghoorn, 1964). The sustainability of marsh ecosystems also depends upon the balance between the physical factors of tidal flooding frequency and duration which affects soil sedimentation, erosion, and the shrink- swell characteristics of soil material. Likewise, organic sediment deposition, soil salinity, soil permeability, nutrient fluxes, and biological factors such as root production and above ground production have been identified as important factors in wetland surface elevation (McMillan, 1971). Therefore, the ecological stability of a salt marsh depends upon its sensitivity to marsh surface elevation relative to mean sea level and sensitivity to biological processes controlled by tidal inundations.

1.2 Surface and subsurface processes

There are two processes responsible for the control of surface elevation of salt marshes: surface sediment accretion and subsurface accumulation of live and dead plant material (Mitsch and Gosselink, 2000). These processes contribute to soil volume, which may control and is controlled by hydrology or the flooding of the marsh surface (Figure 1.1).

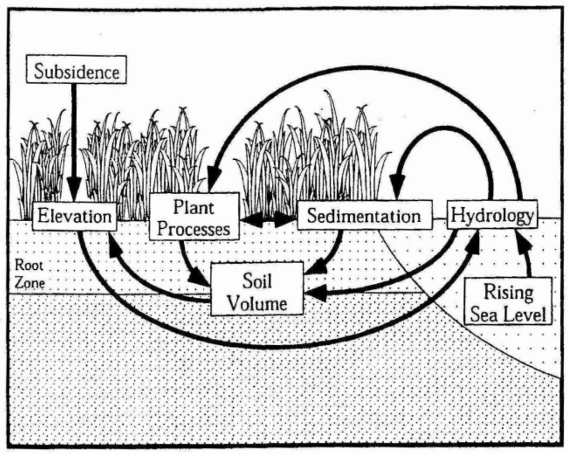

Figure 1.1. Conceptual drawing showing the relationship between hydrologic, biologic, and geologic processes of salt marsh surfaces. (Adapted from Cahoon et al. 2002).

Flooding frequency and duration impact the oxygen content of the soil, which, in turn, influences the primary production and organic matter decay (Mendelssohn and Morris, 2000). Sedimentation enhances plant growth and root production by delivering nutrients to the soil. More dense vegetation or larger plants enhance sedimentation by trapping greater amounts of sediment suspended in tidal flows on the surface of the marsh (Cahoon et al., 1999). When sea-level rise is moderate, a healthy marsh increases its surface elevation at the same rate as the increase in sea-level. In a deteriorating marsh or areas where an accelerated rate of sea-level rise occurs, plant growth is reduced because of increased flooding. As a result, the soil volume decreases and accretion of the marsh surface cannot keep pace with sea-level rise. Eventually plant stress reaches a point where the plants die, the plant roots collapse and decay and the marsh becomes submerged (Hoffman et al., 1983).

Previous investigations at the Virginia Coastal Reserve-Long Term Ecological Research (VCR-LTER) site attempted to predict how marshes responded to sea level rise based on geomorphic setting and sediment supply (Brinson et al., 1995). Marshes may migrate landward or prograde into the lagoon in the presence of a shallow upland slope depending on adequate sediment supply. In the absence of sufficient sediment, the marshes migrate landward and erode at the lagoon margin. However, deterioration or erosion of the marsh is not limited to the lagoon edge but can occur throughout the marsh (Stevenson et al., 1985). When salt marshes are bounded by steeper slopes adequate sediment supply results in a stalled transgression of the marsh at the landward margin and a prograding marsh surface at the lagoon margin (Brinson et al., 1995). Similarly, steep slopes and low sediment supply result in a stalled transgression of the marsh and an eroding lagoonal margin. According to Brinson et al., (1995), the two most common scenarios along the seaside of the lower Delmarva Peninsula where the VCR-LTER is located (Figure 2.1), are landward migration and stalled conditions, both with eroding seaward edges, due to the lack of terrigenous sediments.

Many salt marsh hydrologic studies ignore the impact of below-ground water dynamics, often using tidal inputs and precipitation to make inferences about wetland processes (Carter, 1986; Hutchinson et al., 1995). Even the currently accepted definition of hydroperiod excludes below-ground dynamics: “the depth, duration, frequency, and seasonality of flooding" (Mitsch and Gosselink, 2000). Ignoring the below-ground dynamics discounts ecologically important parameters such as the oxidation/reduction state of soils. When the water table is at ground level, anoxic conditions may exist at and below the water table exerting stress on plants. Root production during the growing season may be inhibited, in turn, impacting organic matter accumulation and surface elevation rise (Stasavich, 1998). Likewise, the physical structure of the clay soil in the marsh may change with the rise and fall of the water table. Water absorbed between crystal layers of 1:1 clay may cause the layers to move apart, making the clay more plastic, swelling its volume. If shrink/swell clay particles are present, they may also control water and nutrient availability by holding a large amount of the polar water molecules and the nutrients found in the water (Robinson, 1994; Brady and Weil, 2002).

Cahoon et al. (1999) suggests several other possible factors that affect the surface elevation of wetlands and salt marshes. Episodic events such as hurricanes, extra-tropical storms (nor'easters), or droughts may change the rates at which surface erosion or accretion occurs. These events alter salinity, in turn affecting plant production both above and below ground. As stated previously, vegetation type and density alter deposition and erosion of sediments on the marsh surface. The effects of plants on sediment deposition and erosion differ widely over a marsh (Leonard, 1997; Leonard et al., 2002). Topography also influences surface water velocity and thereby sediment entrainment in water draining the marsh (Christiansen, 1998; Mwamba and Torres, 2003).

The findings of these investigations do not present a clear representation of the dynamics of the marsh surface as a whole and suggest that marsh surface elevation responds to a combination of interrelated processes involving climate impacts, hydrology, sedimentation, plant processes, and deep and shallow subsidence. Often neglected in these studies are the time periods at which these processes occur, which may affect the methods and time tables used to measure salt marsh surfaces.

1.3 Surface Elevation Tables

Surface Elevation Tables (SETs) have been the scientific standard for measuring surface elevation since their development in 1984 (Boumann and Day, 1984). There are currently more than 12 major studies (Cahoon, et al., 1999) using SETs with more sites coming online since 1999. SETs have been used successfully in macro, meso, and micro tidal regimes; in salt marshes and mangroves and in surface and subsurface regimes with consistent results (Winjen and Bakker, 2001; Cahoon, et al., 1995; Erwin, 2006; and Whelan et.al 2005). Recent improvements in SET design allow for the measurement of accretion or subsidence throughout the entire profile enabling discernment of elevation changes in the root zone, peat zone, and the entire soil profile from the bedrock to the surface of the marsh. This segregation of the profile enables researchers to distinguish between tidal effects on the surface vegetation processes and water level effects on subsurface dynamics. Storm and high tide inundations may be compared to surface dynamics with root zone

SETs, while water table elevations during droughts and wet periods may be compared to peat zone SET measurements (Murphy and Voulgaris, 2006).

1.4 Objectives

Initial data suggests possible seasonality of marsh accretion with the winter seasons collecting more material on the surface of the marsh possibly due to larger storms; hence more sediment delivered to the marsh surface. In this thesis, seasonality, geomorphological position, hydroperiod, precipitation, and ground water level are considered to be important mechanisms determining the elevation change of salt marshes. To address the issues discussed above, the following questions were developed for this study:

- Because initial data readings were compiled on a semi-annual basis, will more frequent data collection result in different rates of erosion or sedimentation?
- How do tidal inundations correlate with rates of salt marsh erosion or sedimentation?
- How do droughts and periods of high precipitation affect shallow subsidence?
- What affect does elevation above mean sea level and corresponding vegetation have on marsh surface elevation changes?
- Is the type of clay present in the salt marsh soil profile a type with shrink swell characteristics?

Chapter 2

Methods and Materials

2.1 Study Site

The VCR-LTER megasite is a coastal lagoon complex of temperate salt marshes and barrier islands on the Atlantic coast of the Virginia Eastern Shore. The specific study area within the megasite focuses on marsh surface elevations in Upper Philips Creek (UPCM) Salt Marsh located at 37°45' N latitude, 75°50'W longitude (Figure 2.1). UPCM salt marsh soils are very poorly drained Chincoteague and Magotha soils (Cobb and Smith, 1982). Soils generally consist of 20% organic material, 45.8% sand, 42.1 % silt and 13% clay particles (Thomas, 2004). Diurnal, meso-tidal conditions exist in Philips Creek with an average daily tidal range of 1.5 to 2m (Turaski, 2002). Human impacts such as agriculture, petroleum mining, excavation of drainage ditches, and burning of vegetation (Cahoon, 1994; White and Morton, 1997; White and Tremblay, 1995) are minimal on Upper Philips Creek Marsh. UPCM is typical of many on the lower Delmarva Peninsula mainland and is an example of a shallowly sloped marsh (Hmieleski, 1994) that is transgressing into upland ecosystems (Kastler and Wiberg, 1996). UPCM is located in an area where historical sea level rise was measured at approximately 3 to 3.5 mm yr^{-1} (Emory and Aubrey, 1991; Hayden et al., 1995), but the rise has been recently updated to reflect an increase of 3.8 to 4.0 mm yr^{-1} (Erwin et al., 2006). More recent measurements indicate an increased rate of sea level rise of 4.8 cm per year (Erwin et al., 2006).

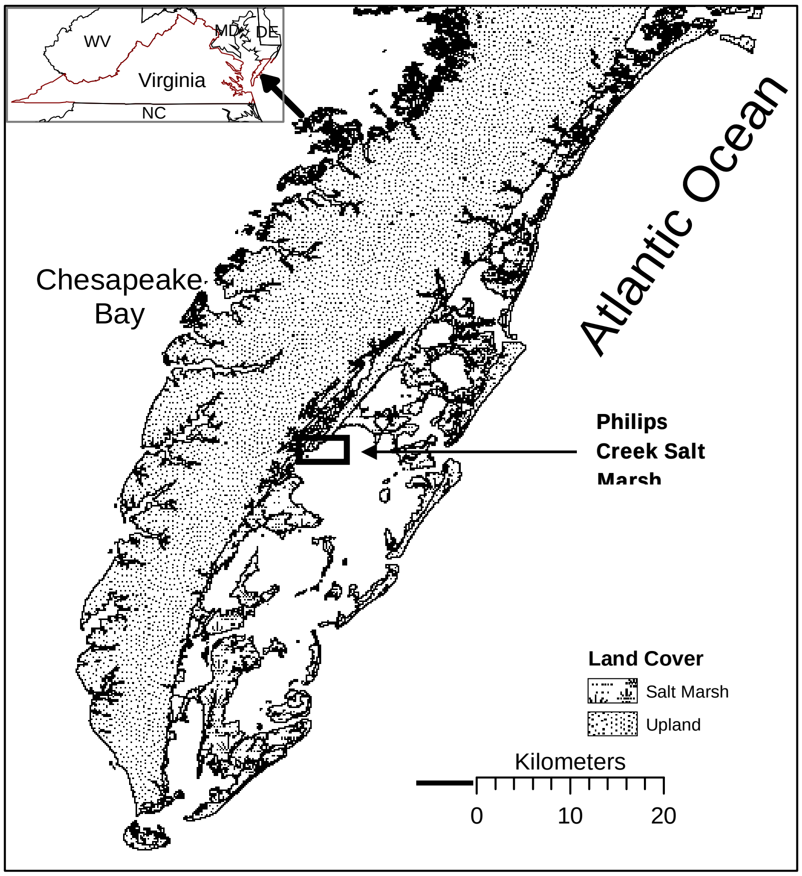

Figure 2.1: Location of Study Site on the Delmarva Peninsula, Eastern shore of Virginia, U.S.A. From VCR-LTER image library.

2.2 SET and RSET Installation

SET Installations

The three SET (Surface Elevation Tables) sites used in this study were previously established in Philips Creek salt marsh in 1997 and have been monitored semi-annually since August, 1997 (http://www.vcrlter.virginia.edu/). These sites were located in the low, mid, and high marsh zones 2, 3, and 4 respectively (Figure 2.2). The sites were chosen to represent areas of the marsh delineated by typical tidal inundation frequency and vegetation type. Site 2A, 2B, and 2C were placed in the low marsh where short-form *Spartina alterniflora* is the predominant species. Short form *S. alterniflora* dominates the regularly flooded low marsh surfaces (Brinson et.al., in review). Sites 3A, 3B, and 3C were placed in the mid marsh where *Juncus roemerianus* and *Spartina patens* are the dominant marsh grasses. *Juncus roemerianus* appears on UPCM marsh surfaces in patchy areas above Pleistocene ridges where peat and soil accumulations are less than the low or high marsh surfaces. Sites 4A, 4B, and 4C were placed in the high marsh where *Spartina patens* and *Distichlis spicata* are dominant though *J. roemerianus* and *S. alterniflora* have been slowly migrating into this area (Brinson et al., 1995). High marsh vegetation is notable for its lack of trees and shrubs due to higher soil salinities. In the high marsh, precipitation is the main source of water though storm surges occur frequently enough to contribute to soil and water salinity. At each site, boardwalks were constructed to minimize impact on the marsh surface.

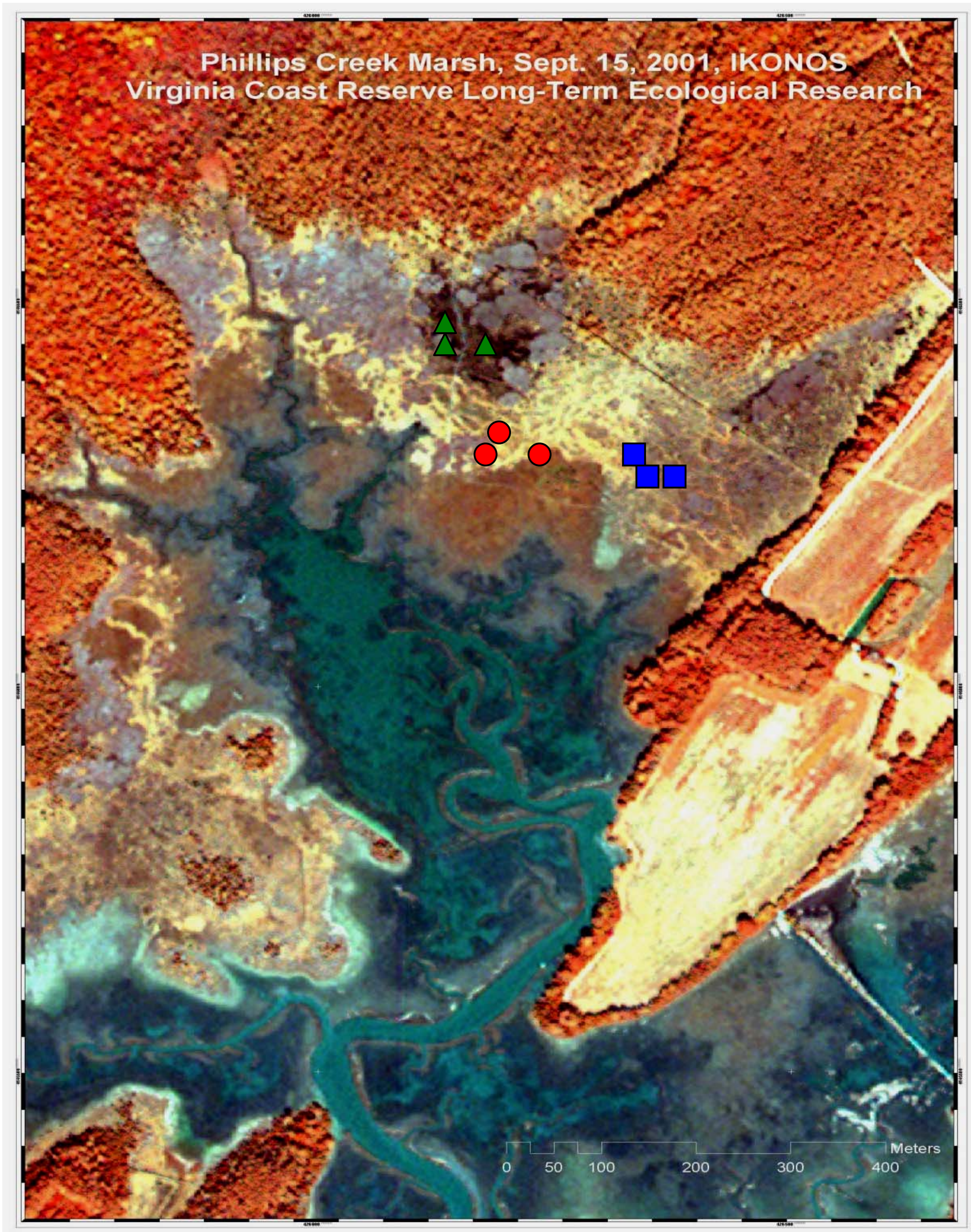

Figure 2.2: Aerial photo of Upper Philips Creek Salt marsh with north at the top of the photo. SET sites consist of 3 benchmarks indicated by circles at low marsh zone 2, squares at mid marsh zone 3, and triangles at the high marsh, zone 4.

Each of the three SET benchmarks in zones 2, 3 and 4 were surveyed and related to the benchmark established by the National Geodetic Survey (Hayden et al., 1995) and related to mean sea level (Table 2.1).

SET Site	Latitude	Longitude	Relative Elevation	Elevation above Mean Sea Level
S2A	37.4596862220	-75.8338939739	-35.771	1.000
S2B	37.4597296919	-75.8344354901	-35.748	1.014
S2C	37.4595934801	-75.8345797855	-35.747	1.002
S3A	37.4596623689	-75.8324733371	-35.574	1.061
S3B	37.4597153091	-75.8325133939	-35.617	1.076
S3C	37.4599302033	-75.8324784624	-35.567	1.086
S4A	37.4614136792	-758354299450	-35.651	1.119
S4B	37.4616347699	-75.8352838637	-35.641	1.098
S4C	37.4613118247	-75.8348333510	-35.955	1.095

Table 2.1: Latitude and Longitude of SET site benchmarks and elevation (m) above mean sea level. (http://www.vcrleter.cirginia.edu/~crd7m/brnv/wl.txt)

To establish the SET benchmark, 3-inch diameter aluminum irrigation pipes were driven into the marsh surface until refusal. Site 2A, 2B, and 2C were driven into a depth of 2.3 m, 1.24 m, and 1.36 m respectively. Site 3A, 3B, and 3C benchmark pipes were driven into the marsh 1.3 m, 1.3 m, and 1.09 m respectively. Site 4A, 4B, and 4C pipes were driven into the marsh 1.24 m, 1.24 m, and 1.18 m respectively. These measurements represent the depth to the sandy Pleistocene surface below the recent marsh horizons formed in the Holocene. The original SET benchmark pipes driven to refusal encompass the entire marsh soil profile.

RSET Installations

Shallow-rod surface elevation tables (RSET) were installed July 2003 adjacent to the original SET sites and related to the SET benchmarks (Table 2.2). The RSET benchmarks were allowed to settle on the marsh surface before the first readings were accomplished in September 2003.

RSET Site	Latitude	Longitude	SET Elevation AMSL	RSET Elevation AMSL
S2A	37.4596862220	-75.8338939739	1.000	1.018
S2B	37.4597296919	-75.8344354901	1.014	1.019
S2C	37.4595934801	-75.8345797855	1.002	1.013
S3A	37.4596623689	-75.8324733371	1.061	1.071 (*Jun*)
				1.066 (*pat*)
S3B	37.4597153091	-75.8325133939	1.076	1.056 (*Jun*)
				1.086 (*pat*)
S3C	37.4599302033	-75.8324784624	1.086	1.066 (*Jun)*
				1.056 (*pat*)
S4A	37.4614136792	-758354299450	1.119	1.089
S4B	37.4616347699	-75.8352838637	1.098	1.113
S4C	37.4613118247	-75.8348333510	1.095	1.075

Table 2.2. Latitude and Longitude of SET and RSET site benchmarks and elevation (m) above mean sea level. Two separate RSET benchmarks were established at site 3 in *J. roemerianus, S. Patens* vegetation. Elevations of SET and RSET benchmarks taken 9/11/04.

Each RSET benchmark was driven 20 cm into the marsh surface to include the actively growing root zone. Zones 2 and 4 had one RSET benchmark installed adjacent to each SET benchmark. Zone 3 had 2 RSET benchmarks installed, one in each plant community type *J. roemerianus* and *S. patens*, adjacent to the SET benchmark. Elevations were recorded for each RSET benchmark and related to the same benchmark as the SET sites (Hayden et al., 1995). Using the Hayden benchmark, and the adjacent SET benchmark, the ground surface at each RSET benchmark was related to mean sea-level. Where possible, the original boardwalk was used to protect the marsh from human disturbance, although some construction was necessary to facilitate data collection at the new RSET sites. There may have been some compaction during construction at the RSET sites; however, after the initial relative elevation reading, compaction due to human disturbance has been minimal.

Feldspar marker horizons were originally laid down on the marsh surface adjacent to the SET plots in August, 1997 with the first reading taken in February, 1998. Placement of new feldspar plots were not necessary due to the proximity of the RSET benchmarks to the SET benchmarks, the long record of accretion, and the feldspar layer being intact and clearly visible. Depth of sediment accumulation readings from the feldspar marker horizons were done simultaneously with each SET data collection on a semi-annual basis. During this study, RSET and SET data were collected each month beginning in June, 2003 and ending September, 2004 (Appendix B).

2.3 SET and RSET Data Collection

The SET and RSET devices consist of a mechanical leveling arm and table that is attached to a benchmark with prepositioned holes and pegs and leveled establishing a fixed measuring point (Figure 2.3). Nine brass pins arranged in a 3 x 3 grid on the SET leveling arm table, and nine fiberglass pins in a row are lined up on the RSET leveling arm (Figure 2.4).

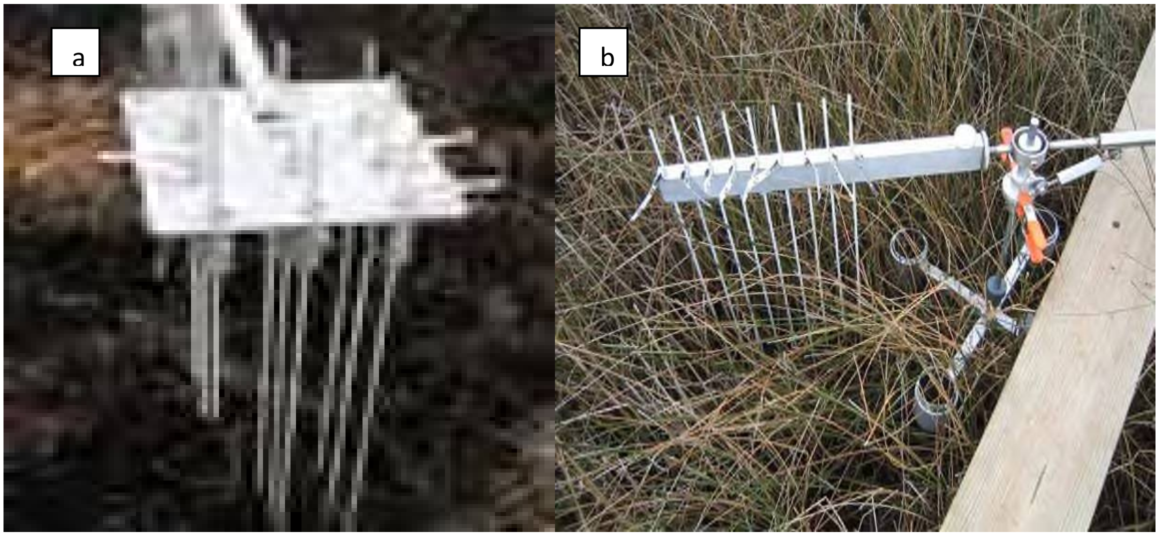

Figure 2.3: Original SET design (a), RSET design (b) showing measuring pins lowered to the marsh surface. (Adapted from Cahoon et.al. 2002b).

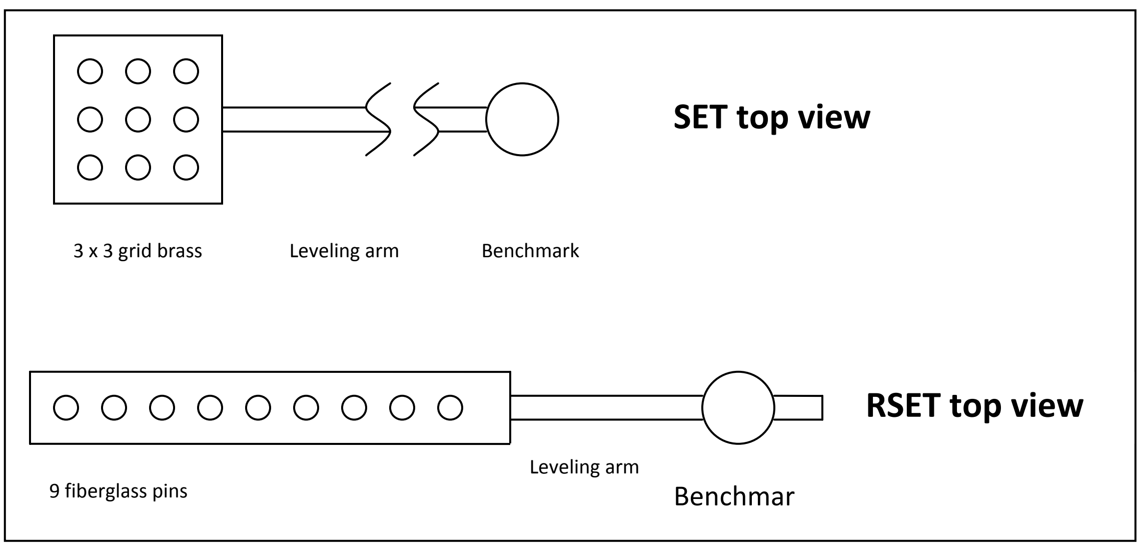

Figure 2.4: Top view of the SET and RSET leveling arms. The SET brass pins are arranged in a 3 x 3 grid with the 1 pin located on the lower left side of the table closest to the leveling arm. The RSET pins are numbered sequentially 1 through 9 starting with pin 1 next to the leveling arm. (Adapted from Cahoon et.al. 2002b). Drawing not to scale.

Each of the pins were lowered onto the marsh surface one at a time and fixed at the leveling table or leveling arm with badge clips. The marsh surface was determined by visually sighting the surface when the depth of the water above the surface did not obstruct the view. When water was present on the marsh surface, feeling for the resistance of a solid surface below the pin was necessary. Care was taken to place the pin on the surface to prevent a depression in the soil. Resistance by the surface of the marsh to the lowered pin was the only means available to determine when a pin came into contact with the surface due to the opaque quality of the water. If a pin was lowered onto standing vegetation, the pin was placed on the marsh surface to the side of the standing stalk. Detritus incorporated into the marsh surface was left in place when lowering pins. However, after Hurricane Isabel in September, 2003, an excess amount of forest wrack was deposited on SET site 3 above the boardwalk and benchmark, and was manually removed in order to place the pins on the surface of the marsh (Figure 2.5). Care was taken to leave detritus already incorporated on the marsh surface.

Figure 2.5: SET zone 3 illustrating salt marsh cord grass leaves (*S. alterniflora*) and forest pine needles and cones (*Pinus taeda*) deposited above the marsh surface. The wrack was partially removed prior to taking the elevation reading on Sept. 27, 2003. Care was taken not to remove detritus already incorporated into the marsh surface.

To determine relative elevation, pin length was measured in cm from the top of the pin collar located on the table of the leveling arm (Cahoon et al., 2002b; Cahoon et al., 2002a).

At each benchmark measurements were taken at multiple positions. For zone 2, in the low marsh, and zone 4, in the transitional high marsh, measurements were made in four compass directions. Site 3 required 6 directions, 3 taken in *J. romerianus*, and 3 taken in *S. patens* vegetation type. The position or direction of the leveling arm corresponded to notches cut in the benchmark pipe to allow repeated measures in exactly the same location. The mean relative elevation of each site was calculated by the total number of pin measurements at zone 2 and 4, n = 36, and zone

3, n = 54. RSET measurements were obtained in the same way as the SET measurement. RSET relative elevation means were determined by averaging the pin lengths in four directions at zones 2 and 4 benchmarks n = 36. Zone 3 RSET benchmarks were determined by averaging individual pin readings acquired from 2 RSET benchmarks in each vegetation type *J. roemerianus and S. Patens*, n = 72. Each SET and RSET benchmark was considered to be an independent estimate of elevation within each marsh zone (i.e. site 2A, 2B, 2C) so that each zone had n = 3 data points for each reading date.

SET data were collected semi-annually, summer and winter, beginning in August of 1997. Beginning in June 2003, SET data were collected monthly for 15 months ending in September, 2004. RSET data were collected for 12 months simultaneously with SET data collection beginning in September 2003 and ending in September 2004 (Appendix B). Daily readings were accomplished by the same means as the semi-annual and monthly readings and were collected from June 28, 2004 to July 3, 2004 (Appendix B).

2.4 Hydrological Data

The hydrological variables investigated in this study were ground-water level, and daily tide maxima. Ground-water levels were recorded by Stevens type A water level recorders, serial number, BC021408D, located near a creek bank in the low marsh at 1.303m AMSL. Water level recorder number BM0213EF8 was located in the mid marsh at 1.481m AMSL, and water level recorder number BH0213FFA was located in the high marsh at 1.427 m AMSL. Ground water recorders were located in close proximity to zone 2, in the low marsh, and zone 4, in the high marsh. The ground water recorder was located adjacent to SET zone 3, in the mid marsh. Water level data were collected at 45-minute intervals. During the early course of the study mechanical difficulty with the water level data recorders left periods of time from 2000 to 2002 with no readings. It was determined that the semi-annual readings could not be correlated with the ground water data set as it contained gaps. However, the monthly readings contained small gaps during January 2004 but were determined to be sufficiently complete. Water levels recorded were corrected to the SET surface elevations by the following equations:

Low Marsh: $WL_{in} \times 0.0254 + 1.821$ (1)

Mid Marsh: $WL_{in} \times 0.0254 + 1.698$ (2)

High Marsh $WL_{in} \times 0.0254 + 1.624$ (3)

Semi-annual, monthly, and daily tide measurements for the day of data collection were obtained from a NOAA tide gauge in Wachapreague, 20 km north of the study site (http://tidesandcurrents.noaa.gov/data_menu). The tide gauge at Redbank, Virginia is closer to the study site, however, gaps in the Redbank data record made these data unsuitable for this study. Although the tidal range is smaller at Wachapreague than at Redbank, (1.75 m compared to 2.25 m respectively), and the timing of high tide is approximately one hour later at Redbank than at Wachapreague, a strong correlation exists between the two sites. The tide levels for Phillips Creek can be determined by the following equation (Christiansen, 1998; Turaski, 2002):

$$Tide,_{\,Phillips\ Creek}\,(cm, MSL) = [Tide,_{\,Wachapreague}\,(m) + 1.85m] * 1.08(cm\ m^{-1}) - 1.89 \quad (4)$$

To investigate the effect of tides on surface elevation of the marsh, the number of times the daily mean high high tide (MHHT) exceeded the surface elevation at each benchmark in the 6 months prior to the semi-annual data collection was used. The number of tidal inundations compared to the monthly data were those MHHTs occurring 1 month prior to the data collection.

Hourly precipitation measurements were obtained from the NOAA Climate Data Center located at the Accomack County Airport (MFV) Melfa, Virginia (37° 39'N and 75° 46'W) (*http://cdo.ncdc.noaa.gov/ulcd/ULCD)*. The meteorological station located at UPCM and operated by the VCR-LTER was destroyed by Hurricane Isabel in September, 2003 and meteorological data directly relating to Philips Creek marsh were not available after that date. The station at Painter Virginia was approximately 8 miles north of UPCM. It was determined that the occasional afternoon thunderstorm may have been missed by precipitation measurements at Melfa, Virginia. However, average monthly rainfall at Accomack County Airport (MFV), VA, was consistent with historical records from Philips Creek marsh (Figure 2.6).

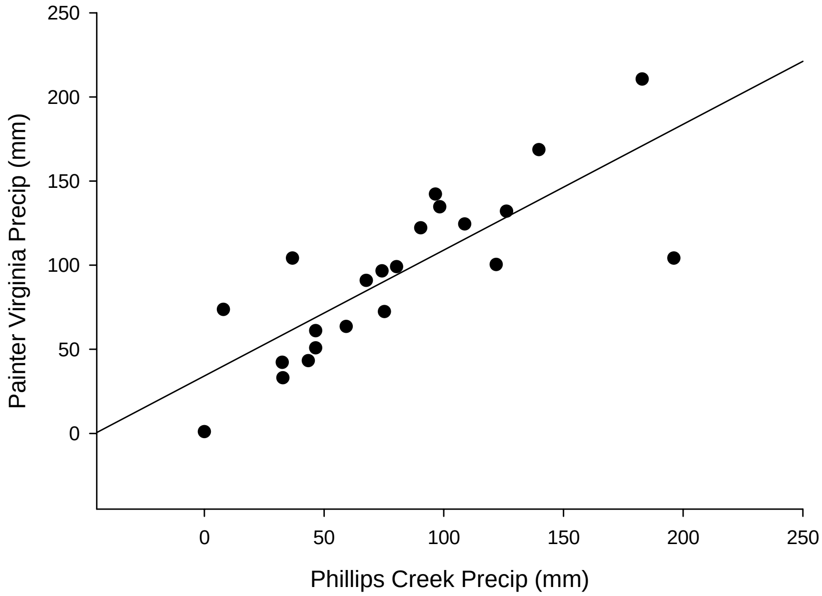

Figure 2.6: Comparison between Philips Creek precipitation and NOAA station, Painter, Virginia. Only months with complete data were used from Aug 1998 to Sept 2003 (n=22), $r^2 = 0.632$.

Figure 2.7 illustrates the elevation above mean sea level of the SET benchmarks, RSET benchmarks, and water level recorders. RSET benchmarks were placed within ± 5% of the elevation of the original SET benchmarks.

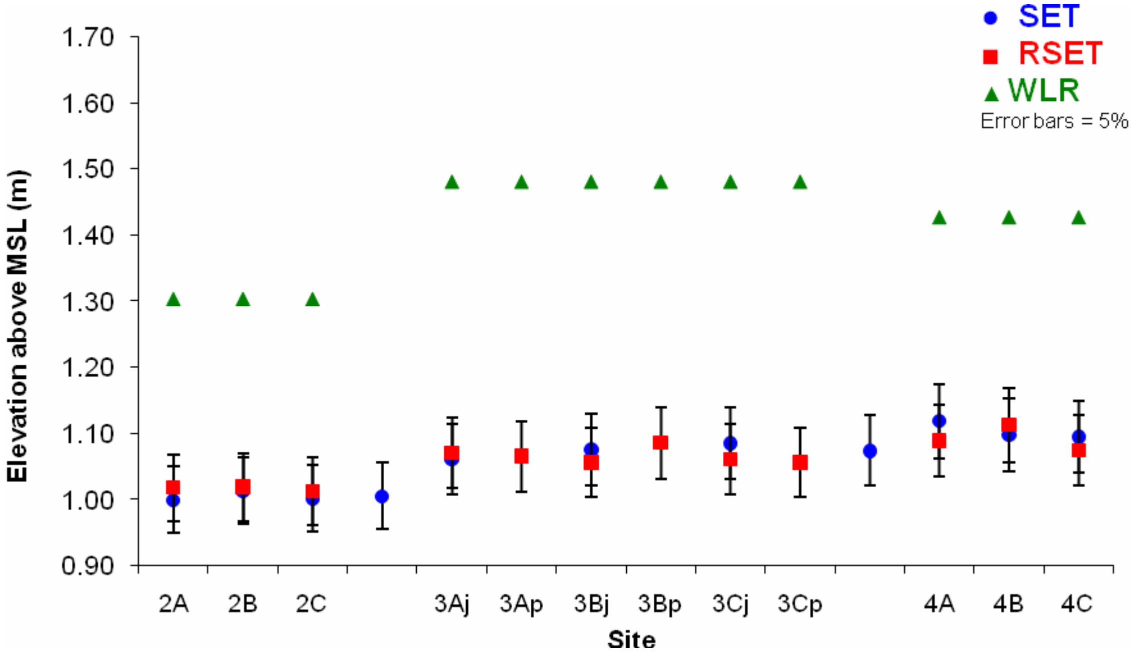

Figure 2.7. Elevations of SET and RSET benchmarks and water level recorders for each site within the marsh zone. SET benchmarks are denoted by circles. RSET benchmarks are denoted by squares. Water level recorders are denoted by triangles. The error bars represent a 5% increase or decrease in elevation. Zone 2 water level recorder was located adjacent to a migrating creek bank near the upland forest. Zone 3and 4 benchmarks were located within different vegetated areas. Benchmarks located in areas dominated by *S. patens* are denoted with the letter p, while benchmarks located in primarily *J. roemerianus* are denoted by the letter j.

2.5 Data Analysis

Marsh surface elevation at each SET benchmark was averaged across all measuring pins in 4 directions at zone 2 and 4 (n = 36), whereas, zone 3 used 6 directions (n = 54). To determine the rate of relative elevation change (REC) between semi-annual (s-a), monthly (mon), and daily (d) sampling events the following formula was used:

$$REC_{\text{semi-annual or monthly}} = \frac{\text{average soil elevation } (X_{t+1} - X_t)_{cm}}{(\text{number of s-a, mon, or daily reading})_{\text{yr, mon, or day}}} \quad (5)$$

where X_t is the average elevation at time t, and X_{t+1} is the average elevation at time t + 1.

If the slopes of elevation change within each zone, low marsh, mid marsh and high marsh, site ABC within each zone, differed significantly, that would indicate that marsh elevation did not respond the same within each zone. A student *t* -test was used to compute the test statistic for slope of elevation change (Kleinbaum and Kupper, 1997):

$$T = \frac{\beta site\ A - \beta site\ B}{S\ \beta site\ A - \beta site\ B} \quad (6)$$

Where β site A is the least-squares estimate of the slope of site A using the number of observations at site A and β site B is the least-squares estimate of the slope of site B using the number of observations of site B. β site A – β site B is the estimate of the standard deviation of the estimated difference between the slopes and is based on combining residual mean-square errors for Site A and B. This equation was used to compare Site A and B, B and C, and A and C within each zone (Appendix A).

Shallow subsidence or expansion in the soil profile as a whole and within the active root zone was determined by the difference between SET relative elevation change and RSET relative elevation change and is an indication of root production, decomposition, or autocompaction within the entire soil profile. The following formula was used to determine shallow subsidence or expansion (SS or E) in the total profile:

$$SS\ or\ E_{total} = SET - Accretion \tag{7}$$

Subsidence or expansion of the root zone was determined by the following formula:

$$SS\ or\ E_{root\ zone} = SET - Accretion - (RSET - Accretion) \tag{8}$$

The thickness of the entire soil profile was defined as the sum of surface accretion and changes in the thickness of the active root zone and autocompaction or expansion below the active root zone.

2.6 Sediment Clay Analysis

A 3-inch diameter aluminum pipe corer was used to remove the clay samples from the marsh. The pipe was rotated and pushed into the marsh to a depth of approximately 50 cm. A shovel was used to break the bottom of the core from the marsh. The samples were removed from the pipe by making 2 longitudinal cuts down the length of the pipe on opposite sides. One side of the pipe was removed and the core was allowed to drop from the pipe onto a table where each core was photographed and measured. One sample was cut from the core with a 2.54 cm thickness from the active root zone, and one sample 2.54 cm thick was cut from below the active root zone. The depth of the samples below the top of the core was not similar due to the difference in the depth of the active root zone in each core.

Clay samples from the root zone of site 2A and 2C, 3A and 3C, and 4A and 4C were soaked in de-ionized water overnight. The samples were treated with a sonic dismembrator (Model 550, Fisher Scientific, Pittsburg Pa.) for 15 to 20 minutes to free the clay particles from the roots. The water was decanted, and centrifuged to recover the sediment portion.

To remove organic material from the samples, the sediment was treated with warm, 34% - 37% Fisher Technical Grade H_2O_2 in 5-ml aliquots until reaction stopped. The reaction was determined to have stopped when the sample stopped bubbling. Sediment samples were centrifuged (Precision Universal Centrifuge; Precision Scientific Company, Chicago, Ill.) again to recover the sediment and the hydrogen peroxide solution was poured off. The samples were then chemically treated to remove colloidal iron (oxide/hydroxide) using 0.3 M sodium citrate, sodium bicarbonate, and sodium dithionite in a hot water bath at 75^{o} C. Sodium chloride (saturated at room temperature) and acetone (pure Fisher Scientific reagent) were used to flocculate particles following treatment, leaving all clay samples Na-saturated.

Following the removal of colloidal iron, the samples were placed in a centrifuge, spun down and washed twice with de-ionized water. Samples were spun in a calibrated centrifuge to separate the less than 2 μ size fraction (clay) for X-Ray Difraction (XRD) analysis.

Less than 2 micron clay fraction was vacuum filtered onto a 0.45 micron Metricel filter (Gelman Scientific, Ann Arbor, MI.). The layer of clay was transferred to a glass slide and dried for XRD analysis. All samples were air dried at room temperature for 24 hours and x-rayed from 4 to 37 degrees two-theta. Then all samples were placed in a closed desiccator with Ethylene Glycol for 24 hours and were x-rayed a second time from 4 to 37 degrees two-theta.

Chapter 3

Results/Discussion

3.1 Semi-annual Marsh Surface Elevation Changes

This study determined that each of the three benchmarks within a geomorphologic zone behaved similarly so that each zone in an area determined by predominant vegetation and elevation above mean sea level could be considered as a single unit (Appendix A). Semi-annual data used in this study were collected between August 1997 and September 2004. Monthly readings began in June 2003 and were completed in September 2004 (Appendix B). Low marsh, zone 2, gained 5.2 cm in total elevation of which marker horizon accumulation contributed 52% of the elevation gain or 2.7 cm (Table 3.1). In the mid-marsh, zone 3, marker horizon accretion of 2.5 cm contributed 86% of the 2.9 cm of total elevation change. The high marsh, zone 4, marker horizon accreted 3.2 cm, 2 times greater than the total increase in elevation, 1.5 cm. For this to occur, zone 4 had to experience subsidence or compaction of 1.7 cm below the marker horizon.

During the monthly data collection, accumulation above the marker horizon contributed 0.0 cm of the 2.5 cm of total elevation change in zone 2 and the root zone contributed 12% or 0.3 cm of the 2.5 cm expansion. This indicates 88% of the increase in elevation occurred below the root zone. The mid-marsh, zone 3, gained 0.8 cm of total elevation. The marker horizon eroded by 0.4 cm indicating increase of elevation was due to healthy root growth and soil expansion below the surface. An increase of 1.2 cm occurred below the marker horizon of which the root zone contributed 0.7 cm or greater than half of the elevation increase. The high marsh, zone 4, gained 0.9 cm of total elevation of which accretion above the marker horizon accounted for 0.1 cm. Nearly all of the increase in zone 4 occurred below the root zone as this area lost 0.3 cm of elevation. This loss of volume might be a result of root death and decomposition.

Semi-Annual Data Collection	Zone 2 Low Marsh	Zone 3 Mid-Marsh	Zone 4 High Marsh
Total Elevation Change	5.2 cm	2.9 cm	1.5 cm
Marker Horizon Accumulation	2.7 cm	2.5 cm	3.2 cm
Shallow Subsidence or Expansion	2.5 cm	0.4 cm	-1.7 cm
Monthly Data Collection			
Total Elevation Change	2.5 cm	0.8 cm	0.9 cm
Marker Horizon Accumulation	0.0 cm	-0.4 cm	0.1 cm
Shallow Subsidence or Expansion	2.5 cm	1.2 cm	0.8 cm
Root Zone SS	0.3 cm	0.7 cm	-0.3 cm

Table 3.1. Distribution of marsh surface accretion or subsidence as a portion of the surface (marker horizon), root zone, and below root zone profile of the three marsh zones.

The elevation change was positive over all three zones over the course of the seven year study. The low marsh, had the highest rate of elevation change at 5.8 mm yr^{-1} ($r^2 = 0.89$) (Figure 3.1). A large increase occurred between 6 months and one year after Hurricane Isabel made landfall on the Delmarva Peninsula, September 18th, 2003. The mid-marsh gained elevation at the rate of 3.6 mm yr^{-1} ($r^2 = 0.92$). The high marsh gained elevation at the rate of 2.1 mm yr^{-1} ($r^2 = 0.76$). During the course of the seven year study, a severe drought began at the end of 1999 and ended with the landfall of hurricane Isabel in 2003 (Appendix C). Although the changes in elevation were small, the mid marsh and high marsh gained elevation possibly due to the deposition and incorporation of marsh and forest wrack on the data collection site by hurricane Isabel (Figure 2.5). Gains or losses of elevation do not show a definite pattern of seasonality that could be attributed to data collection during summer/fall or winter months.

Semi-annual marsh surface elevation measurements with respect to mean high high tide (MHHT) show an inverse relationship to 6 month tidal elevation means (Fig. 3.2). MHHT decreased relative to mean sea level 5.08 cm per year as predicted by the 18.6 year nodal lunar and ecliptic tidal cycle (Pugh, 1987). This is an order of magnitude greater than the mean predicted sea level rise of 4.8 mm (Erwin, 2006). MHHT ranged from 0.889 m AMSL in winter of 1998 to a low of 0.546 m AMSL in the winter of 2004. This decrease in MHHT decreased the number of inundations occurring each year from a high of 88 inundations in the low marsh in the 6 months prior to the February 1998 reading to a low of 5 inundations in the 6 months prior to

August 2002 (Table 3.2). Increases in tidal inundations from October 2003 to February 2004 correspond to an active Atlantic hurricane season, with the highest and longest tidal inundations occurring during Hurricane Isabel, 2003 (http://www.hpdrc.fiu.edu/rac/storms/) (http://www.nhc.noaa.gov/). Tidal inundations decreased again in the 6 months prior to September 2004 largely due to an inactive storm season up to that point with only tropical storm Alex affecting coastal Virginia in July of 2004.

Marsh surface elevation gains did not correlate with precipitation over the course of the seven year period (Figure 3.3). The period between August 2000 and February 2002 experienced an extended severe drought. Coupled with a lower number of tidal inundations during that time frame, all marsh surfaces experienced extended periods of dryness. This may have contributed to large areas of die-off of *S. alterniflora* in the low marsh (Figure 3.4) in the spring and summer of 2004 (Marsh, 2007). The drought ended with an increase in precipitation beginning with hurricane Isabel in September 2003.

Contrary to findings stating that greater than 43,000 ha of salt marsh were greatly affected by drought in Louisiana (McKee et al., 2004), salt marsh elevation continued to increase in UPC throughout the months of drought and showed no correlation with the increased precipitation during and after Hurricane Isabel. Further long term study should indicate whether or not the salt marsh will continue to gain elevation or experience a delayed negative response to drought conditions.

Tidal Inundations	Low Marsh A	B	C	Mid Marsh A	B	C	High Marsh A	B	C
Aug-97	74	69	74	41	37	33	21	29	31
Feb-98	88	81	88	64	61	58	53	56	57
Sep-98	87	76	87	59	52	48	36	44	45
Feb-99	56	50	55	33	30	28	22	27	28
Aug-99	57	53	57	39	35	34	29	33	33
Feb-00	37	34	36	26	25	21	14	19	20
Aug-00	31	29	31	22	21	19	18	19	19
Feb-01	27	23	27	18	17	15	9	12	13
Sep-01	14	13	14	10	9	9	8	8	8
Feb-02	11	10	11	7	7	7	6	7	7
Aug-02	5	5	5	2	2	2	2	2	2
Feb-03	21	19	20	13	10	10	8	8	8[a]
Sep-03	14	14	14	12	11	11	9	9	10
Feb-04	24	23	24	19	17	16	14	14	14[b]
Sep-04	7	6	7	3	4	3	2	3	3

Table 3.2 Number of tidal inundations occurring at each site over the course of the study. Differences in the number of inundations in each zone are a result of the slightly different elevations AMSL of each benchmark and the distance of the BM from the distributary. [a] Tidal inundations increased in the six months prior to the Sep 03 reading, with an average of 20 inundations occurring in the low marsh between Oct 7th to Oct 16th 2002 which corresponds to tropical storm Kyle, Oct 2002 . [b]An average of 24 tidal inundations occurred in the low marsh corresponding to Hurricane Isabel with an average of 20 occurring before and after the hurricane.

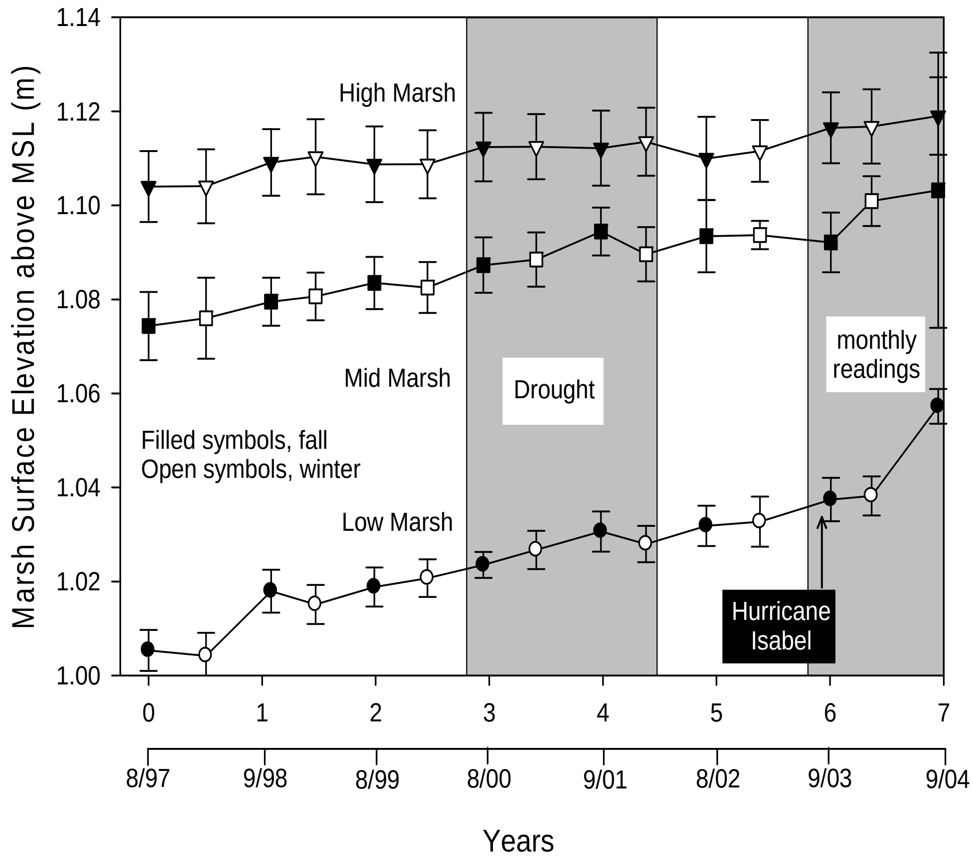

Figure 3.1. Semi-annual SET measurements of marsh surface elevation (relative to mean sea level) at the low (circles), mid (squares) and high (triangles) marsh sites. The SETs measure elevation relative to a datum roughly corresponding to the Pleistocene surface. Measurements were made over a 7-year period beginning in August 1997 by Mark Brinson, Linda Blum, and Robert Christian with assistance from the author for a portion of the record. See methods for details describing SET design and installation. Filled symbols represent data collected in August or September; open symbols represent data collected in February or early March (see Appendix B for measurement dates). Error bars represent standard error for n=3. Shaded areas indicate when an extended drought occurred or when monthly measurements of marsh surface elevation were made. The arrow indicates when Hurricane Isabel made land-fall in Virginia on September 13, 2003. The rate of elevation change was 5.8 mm yr^{-1} ($r^2 = 0.89$), 3.6 mm yr^{-1} ($r^2 = 0.92$), 2.1 mm yr^{-1} (r^2=0.76); low, mid, and high marsh respectively.

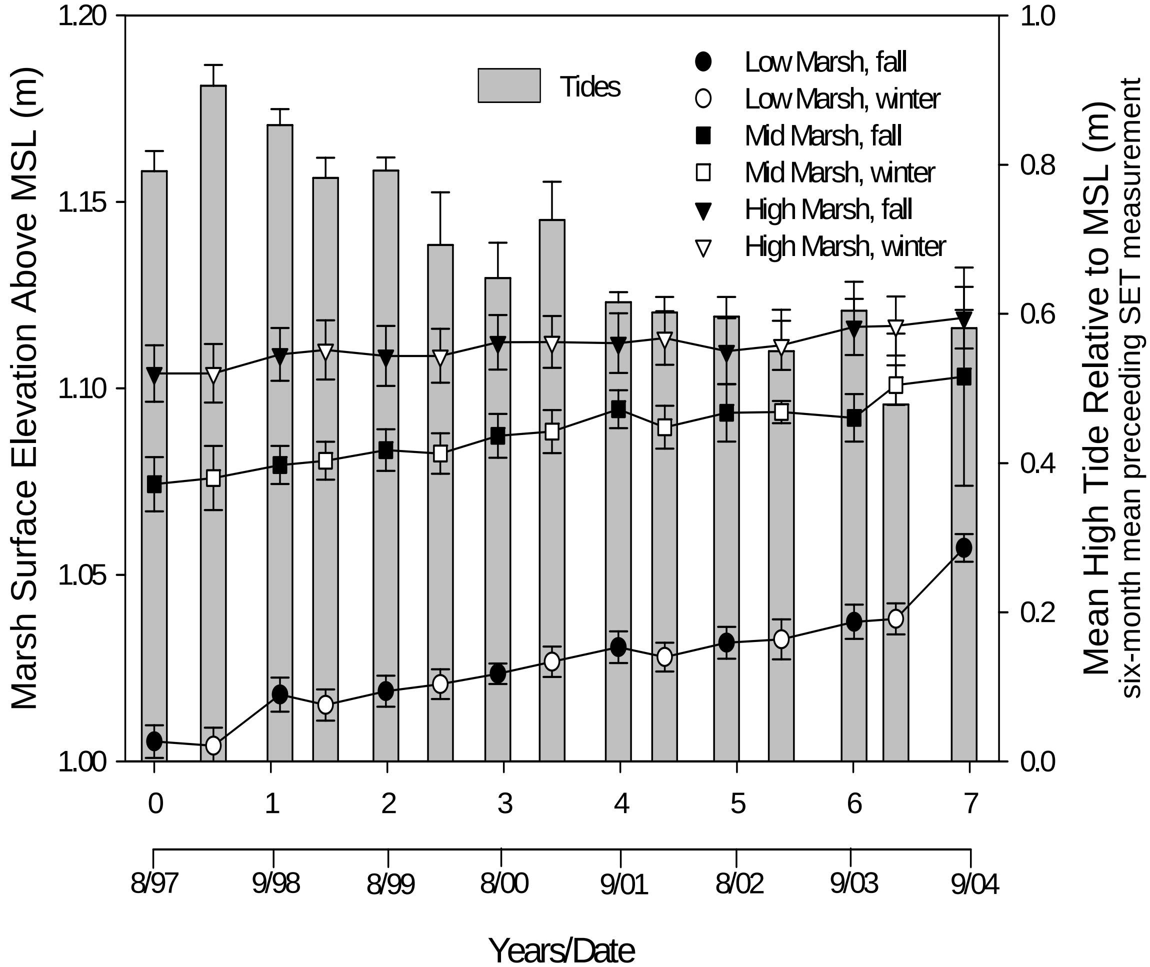

Figure 3.2. Semi-annual SET measurements (as in Fig. 3.) plotted with mean high tide water elevation (bars) relative to mean sea level during the interval between SET measurements. Errors bars are one standard error; n depends on the number of high tides during the preceding interval. Surface elevation and mean high-tide water level are inversely and significantly correlated over the course of the measurement for low (correlation coefficient = 0.81, $r^2 = 0.65$, P = 0.0005), mid (correlation coefficient = 0.90, $r^2 = 0.81$, P < 0.0001), and high (correlation coefficient = 0.77, $r^2 = 0.0.60$, P = 0.0012) marsh zones. The magnitude of the change in mean high tide elevation (5.08 cm per year) is an order of magnitude greater than the average rate of mean sea-level rise during this period.

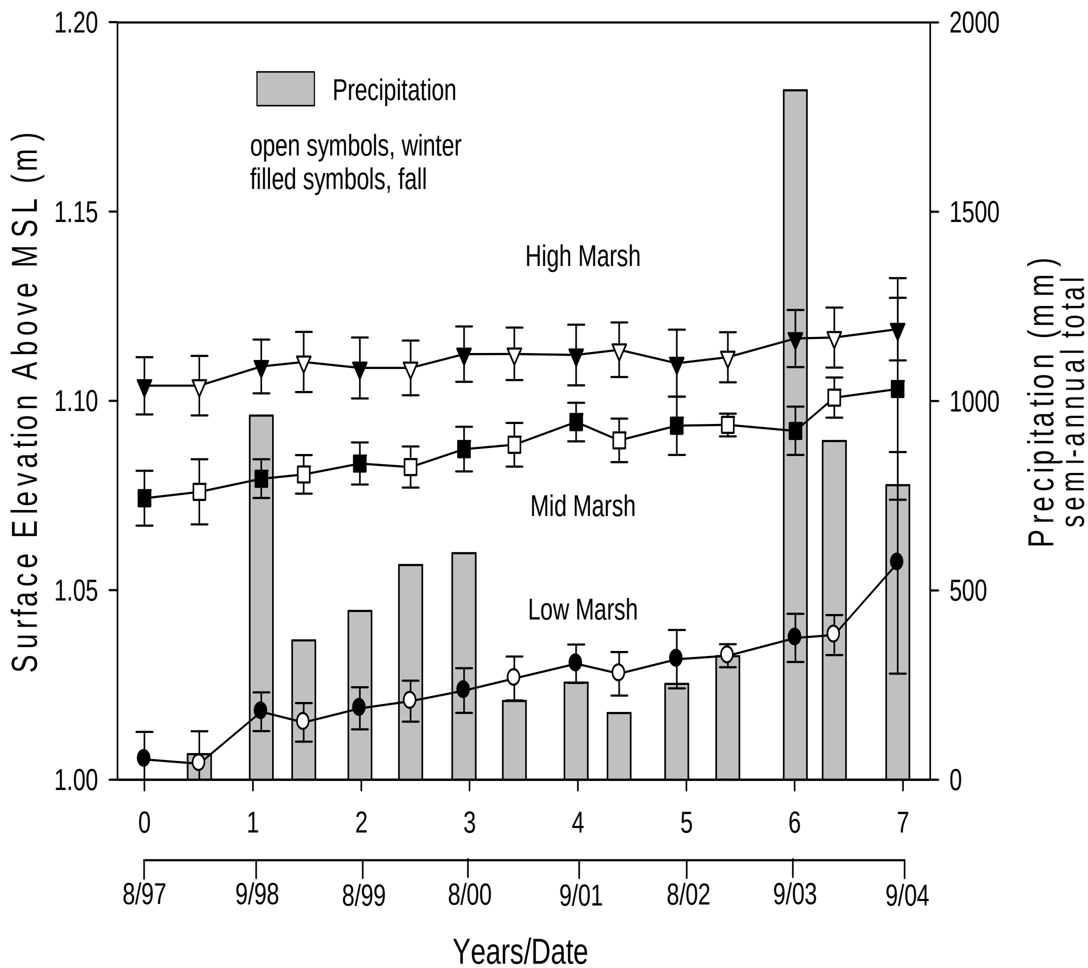

Figure 3.3. Semi-annual SET measurements (as in Fig. 3.2) plotted with total precipitation (bars) during the interval between SET measurements. Marsh surface elevation and total precipitation are not significantly correlated. The interval from August 2000 to February 2002 was an extended period of very low precipitation. Precipitation associated with Hurricane Isabel in September 2003, accounted for the very large amount of rainfall observed prior to the SET measurement made in that month. The SET measurements were made 13 days after the hurricane made landfall in the Virginia.

Figure 3.4. Low marsh, Zone 2. Large areas of the low marsh experienced a die-off of *S. Alternaflora* in the spring and summer of 2004, possibly a result of the extended drought beginning in August of 2000 and ending in September 2003.

Accretion of material over the marker horizon in the low marsh increased 2.7 cm over the 7-year study resulting in an accretion rate of 4.9 mm yr^{-1} ($r^2 = 0.85$), (figure 3.5). Accretion in the mid-marsh increased 2.5 cm for a rate of 5.2 mm yr^{-1} ($r^2 = 0.82$) whereas the high marsh accreted the greatest amount of material, 3.2 cm for a rate of 3.8 mm yr^{-1} ($r^2 = 0.86$). There was no significant difference between accretion occurring during winter or summer months. However, the mid marsh gained a large amount of accreted material after the arrival of Hurricane Isabel in September 2003 due to the amount of salt marsh and forest wrack deposited on the marsh surface

(Figure 2.5). The amount of accretion decreased from the marsh surface over the next two data collections (Figure 3.5) indicating erosion or root decay and/or compaction onto the marsh surface.

Marker horizon accretion with respect to MHHT shows a similar inverse relationship with low marsh correlation coefficient = 0.79, $r^2 = 0.69$, P = 0.0002, mid marsh correlation coefficient = 0.83, $r^2 = 0.69$, P = 0.0002, and high marsh correlation coefficient = 0.79, $r^2 = 0.62$, P = 0.0008 (Figure 3.6). Drought, decreasing tidal inundations and smaller high tides may all have contributed to less erosion of the marsh surface or greater root production due to lower soil moisture content during the study period. Marker horizon accretion was not significantly correlated with precipitation during the 7-year study (Figure 3.7).

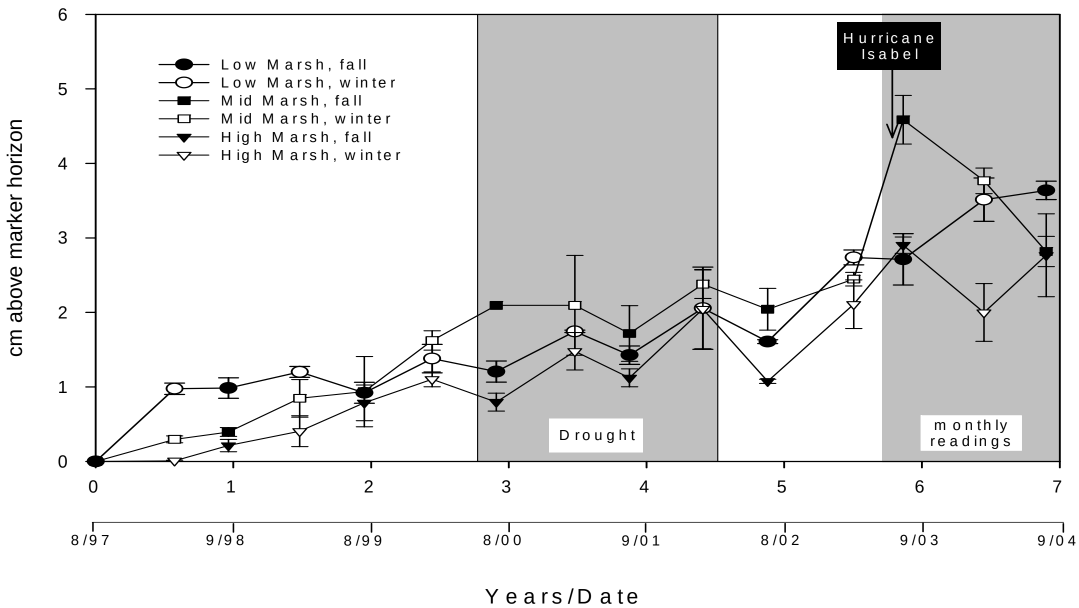

Figure 3.5. Semi-annual accretion measured as depth of material over a marker horizon at the low, mid and high marsh sites. Measurements were made over a 7-year period beginning in August 1997 by Robert Christian, Linda Blum, and Mark Brinson with assistance from the author for a portion of the record. Filled symbols represent data collected in August or September; open symbols represent data collected in February or early March (see Appendix B for measurement dates). Error bars represent standard error for n=3. Shaded areas indicate when an extended drought occurred or when monthly measurements of marsh surface elevation were made. The arrow indicates when Hurricane Isabel made land-fall in Virginia on September 13, 2003. The rate of accretion was 4.85 mm yr^{-1} ($r^2 = 0.85$), 5.24 mm yr^{-1} ($r^2 = 0.82$), 3.97 mm yr^{-1} (r^2=0.86); low, mid, and high marsh respectively.

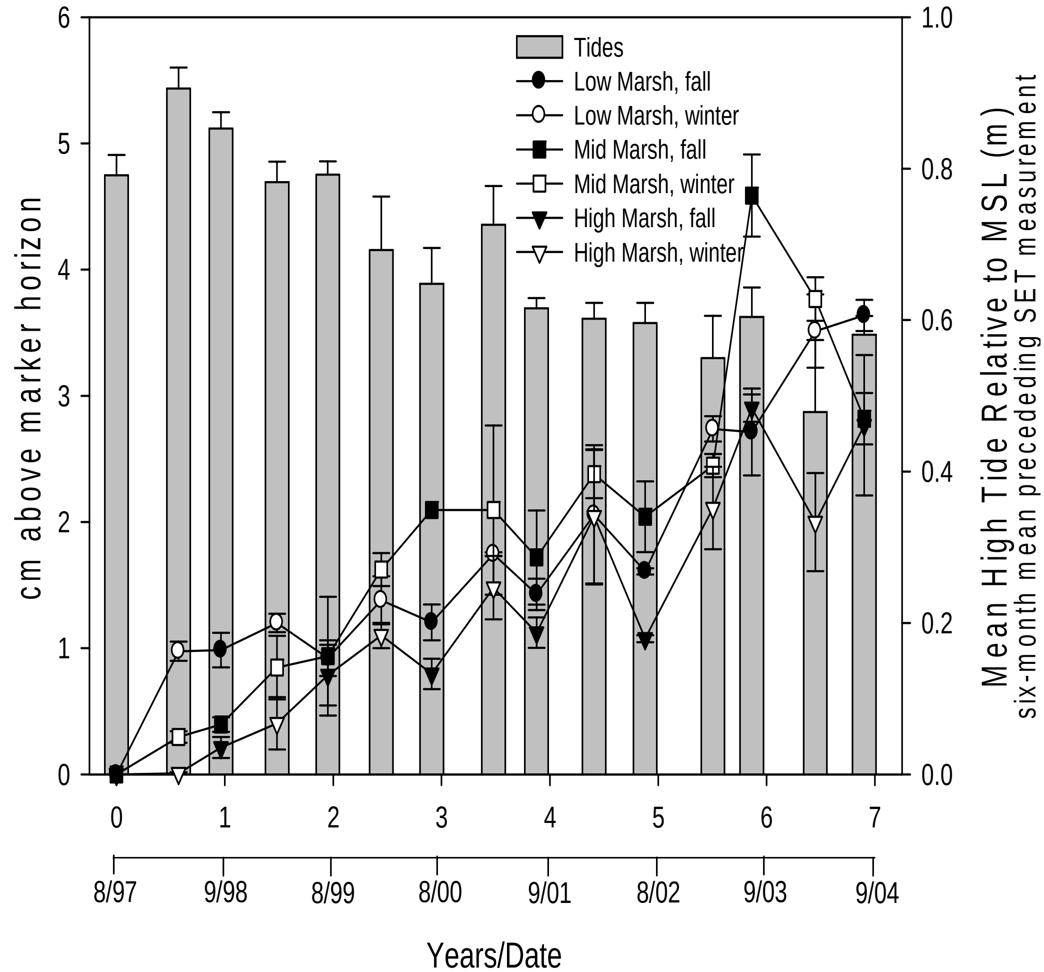

Figure 3.6. Semi-annual accretion (as in Fig.3.5) plotted with mean high tide water elevation (bars) during the interval between accretion measurements. Errors bars are one standard error; n depends on the number of high tides during the interval. Marker horizon depth and mean high-tide water level are inversely and significantly correlated over the course of the measurement in the low (correlation coefficient = 0.79, $r^2 = 0.62$, $P = 0.0009$), mid (correlation coefficient = 0.83, $r^2 = 0.69$, $P = 0.0002$), and high (correlation coefficient = 0.79, $r^2 = 0.62$, $P = 0.0008$) marsh zones. The rate of the change in mean high tide elevation (5.08 cm per year) is an order of magnitude greater than the average rate of mean sea-level rise during this period (4.8mm per year).

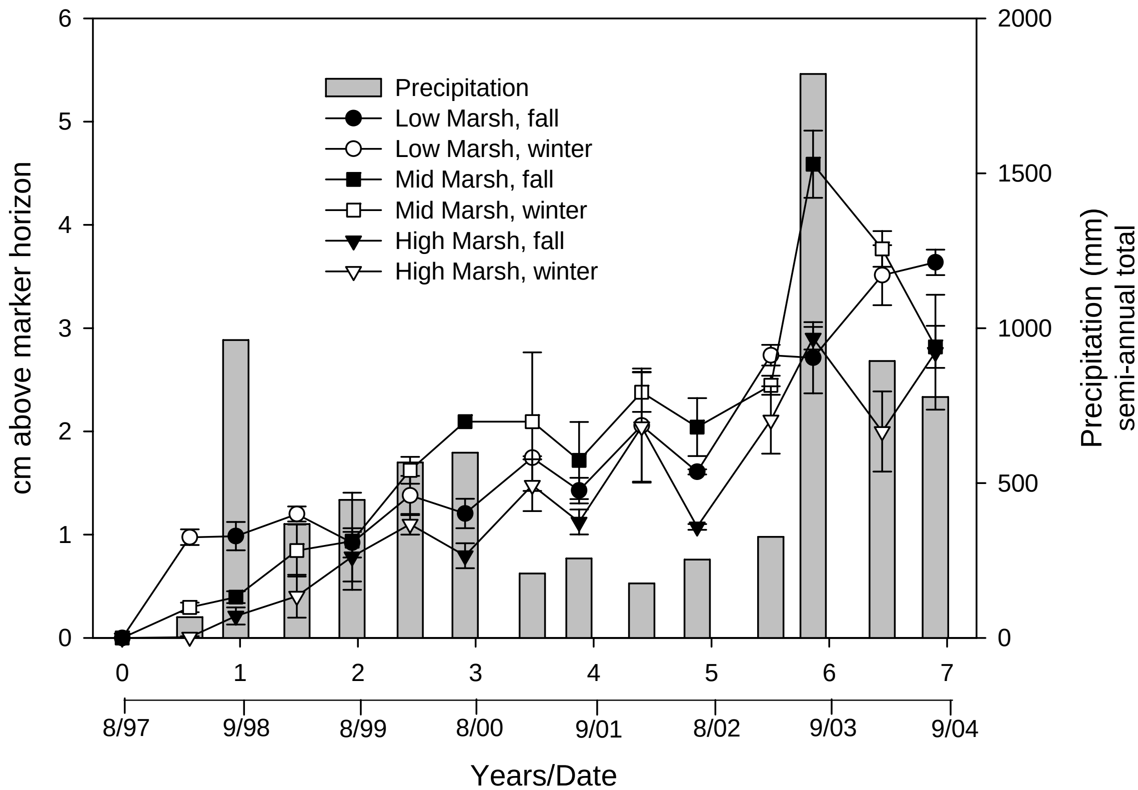

Figure 3.7. Semi-annual accretion (as in Fig. 3.5) plotted with total precipitation (bars) during the interval between accretion measurements. Accretion and precipitation are not significantly correlated.

3.2 Monthly Marsh Surface Elevation Changes

Elevation increased over the course of 15 months or approximately 1.25 years of monthly measurements with the low marsh gaining 2.5 cm or 20.0 mm yr^{-1} ($r^2 = 0.50$). The mid marsh increased in elevation 0.8 cm for a rate of 6.4 mm yr^{-1} ($r^2 = 0.58$), while the high marsh gained 0.9 cm of elevation for a rate of 7.2 mm yr^{-1} ($r^2 = 0.31$) (Figure 3.8). The rate of change per year in the low marsh for the monthly readings, 20.0 mm yr^{-1}, is nearly 3.5 times greater than the semi-annual rate of change at 5.8 mm yr^{-1}. This may reflect a response to Hurricane Isabel as the low marsh elevation increased 1.9 cm after the arrival of the Hurricane. Prior to the arrival of Hurricane Isabel the low marsh only increased 0.6 cm in total elevation since June of 2003 when the monthly data collections began. The mid marsh rate of change, 6.4 mm yr^{-1} for the monthly readings, was nearly 2 times greater than the semi-annual rate of change, 3.6 mm yr^{-1}. This also may reflect the impact of Hurricane Isabel as the mid marsh gained 0.9 cm of elevation after the hurricane made landfall. The high marsh rate of change for the monthly study 7.2 mm yr^{-1} was 3.5 times greater than the 7 year rate of change at 1.5 mm yr^{-1}. The increase in the rates of elevation change during the monthly data collection is reflected in the 7-year study (Figure 3.1) and appears to reflect background differences that may occur over the course of decades (Table 3.3).

Rates of Elevation Change	Low Marsh	Mid Marsh	High Marsh
Semi-Annual Readings	5.8 mm yr^{-1}	3.6 mm yr^{-1}	2.1 mm yr^{-1}
Monthly Readings	20.0 mm yr^{-1}	6.4 mm yr^{-1}	7.2 mm yr^{-1}

Table 3.3. Comparison of rates of elevation between the semi-annual readings and monthly readings. Semi-annual readings were conducted over a 7-year period while the monthly readings were conducted over a 15-month period (1.25 years) within the 7-year period .

The high marsh appeared to have a considerable elevation collapse between September 2003and January 2004 after gaining a high in elevation following hurricane Isabel (Figure 3.8). The surface appears to recover between the January 2004 reading and the September 2004 reading which may correspond to root growth in the spring. The low marsh and mid marsh do not reflect a noteworthy gain or loss of elevation above mean sea-level over the course of the monthly study. Although these changes in the marsh surface may correspond to a one time weather phenomenon, they are not appreciably different than the elevation changes over the course of the seven-year study. Longer study periods need to be conducted in order to determine whether or not the marsh surface experience delayed response to weather phenomenon such as hurricanes.

Monthly SET measurements were not correlated with the monthly MHHT data collected for one month prior to the SET data collection (Figure 3.9). Additionally, monthly SET measurements were not correlated to precipitation measurements taken one month prior to the monthly SET recordings (Figure 3.10). Ground water levels recorded one month prior to monthly SET readings showed no correlation with marsh surface elevations (Figure 3.11).

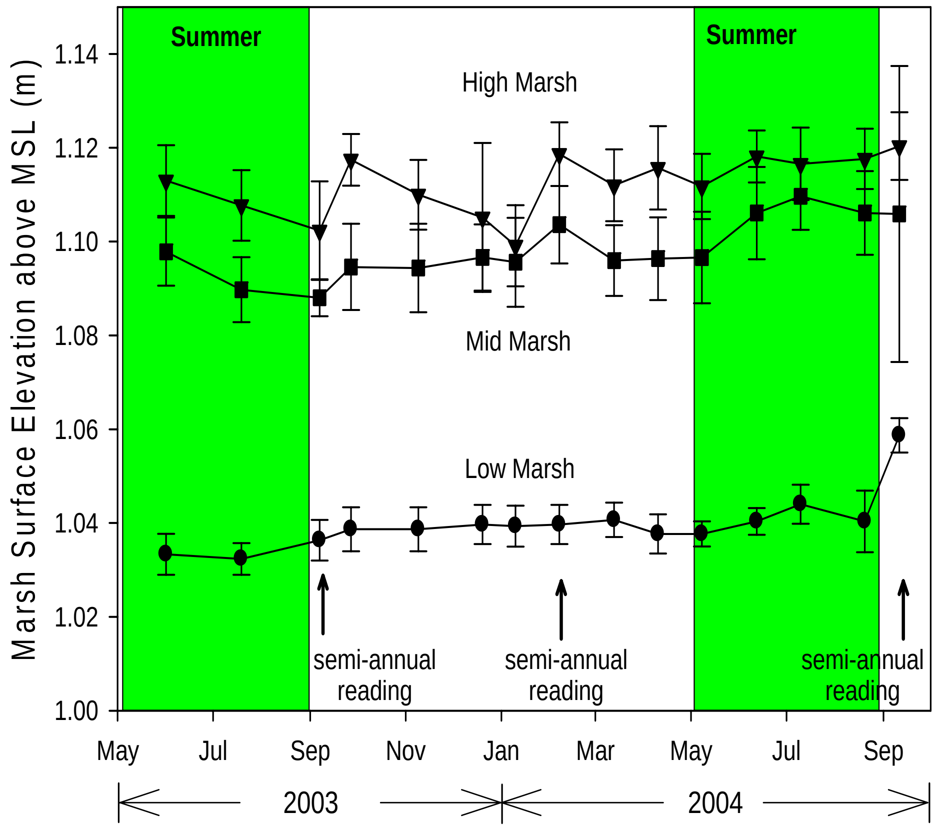

Figure 3.8. Monthly SET measurements of marsh surface elevation (relative to mean sea level) at the low, mid and high marsh sites. The SETs measure elevation relative to a datum roughly corresponding to the Pleistocene surface. Measurements were made over a 15-month period during 2003 – 04 with several gaps during the first half year. Error bars represent standard error for n=3. Arrows indicate the timing of semi-annual measurements that are part of a longer (7-year) record. Shaded areas indicate summer intervals. The rate of elevation change over 15 months (1.25 years) was 20.0 mm yr^{-1} (r^2 = 0.50), 6.4 mm yr^{-1} (r^2 = 0.58), and 7.2 mm yr^{-1} (r^2 = 0.31) low, mid and high marsh respectively.

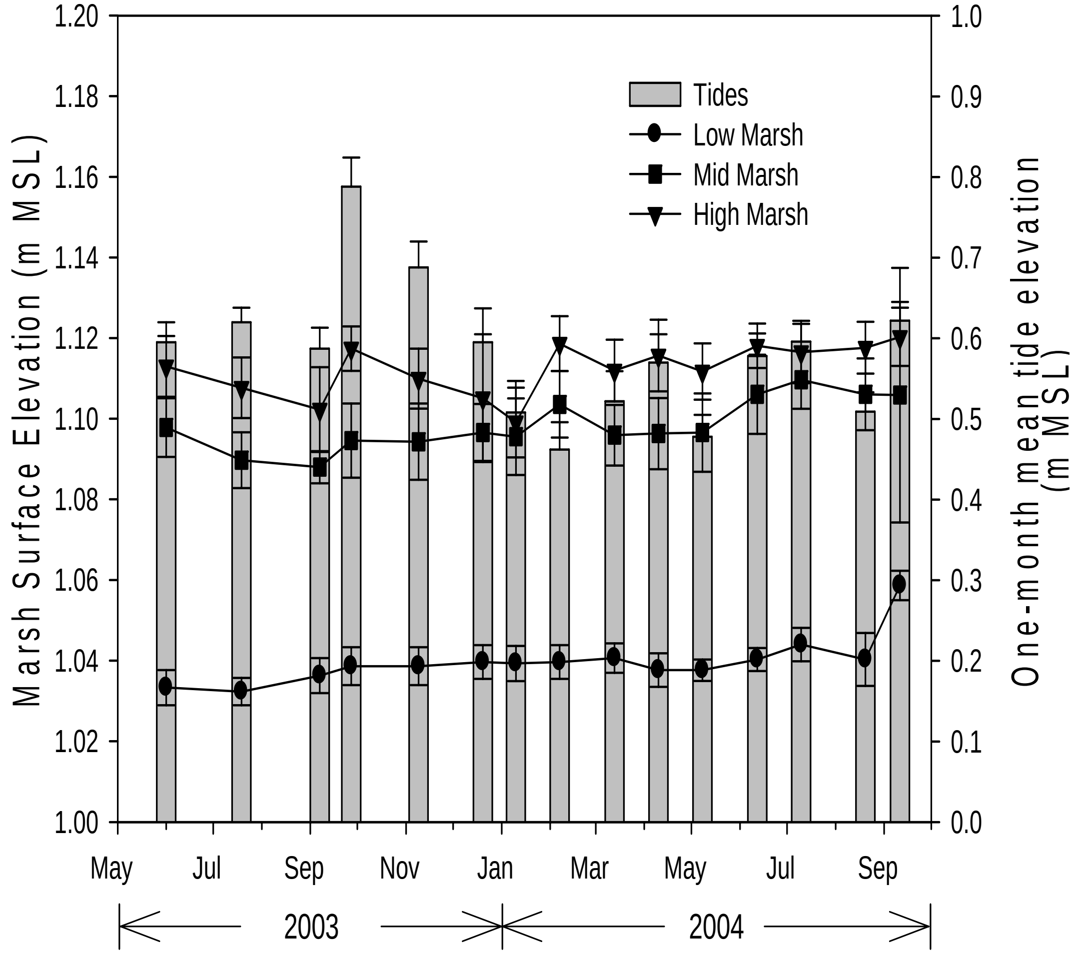

Figure 3.9. Monthly SET measurements (as in Fig. 3.8) plotted with mean high tide water elevation (bars) during the interval between SET measurements. Errors on bars are standard error; n depends on the number of high tides during the preceding interval. Monthly surface elevation and mean high-tide water level are not significantly correlated.

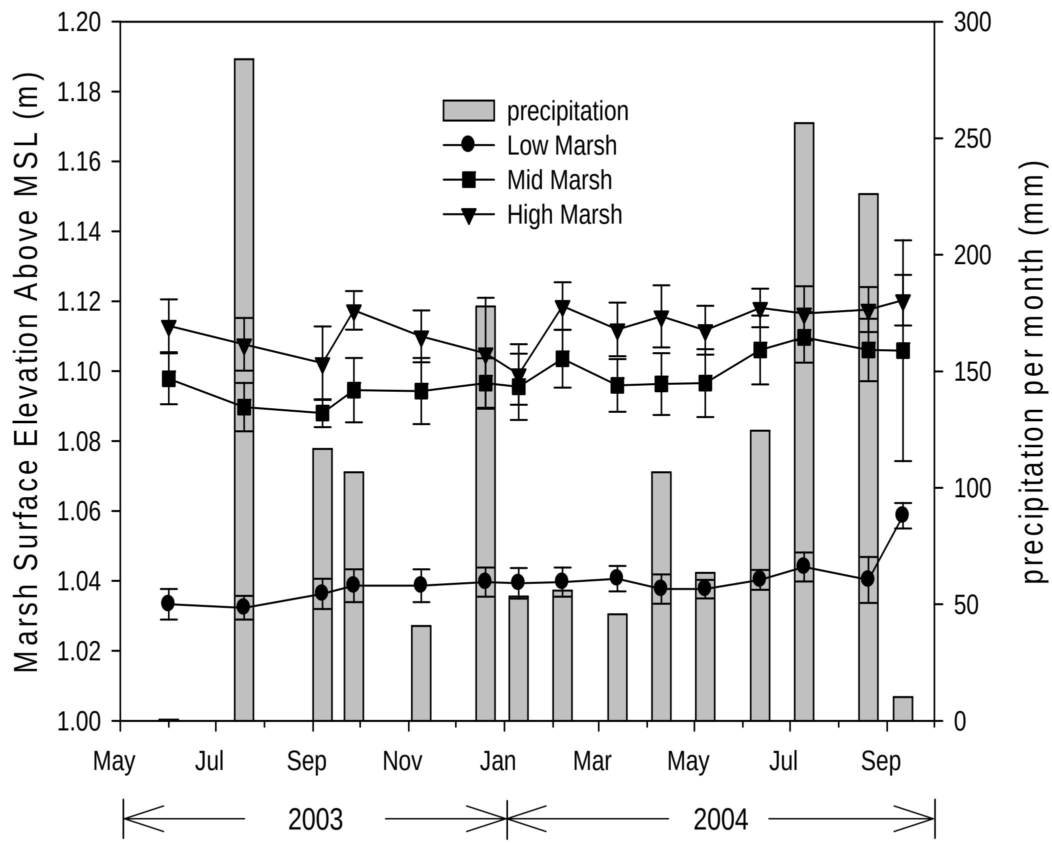

Figure 3.10. Monthly SET measurements (as in Fig.3.8) plotted with total precipitation (bars) during the interval between SET measurements. Monthly marsh surface elevation and total precipitation are not significantly correlated.

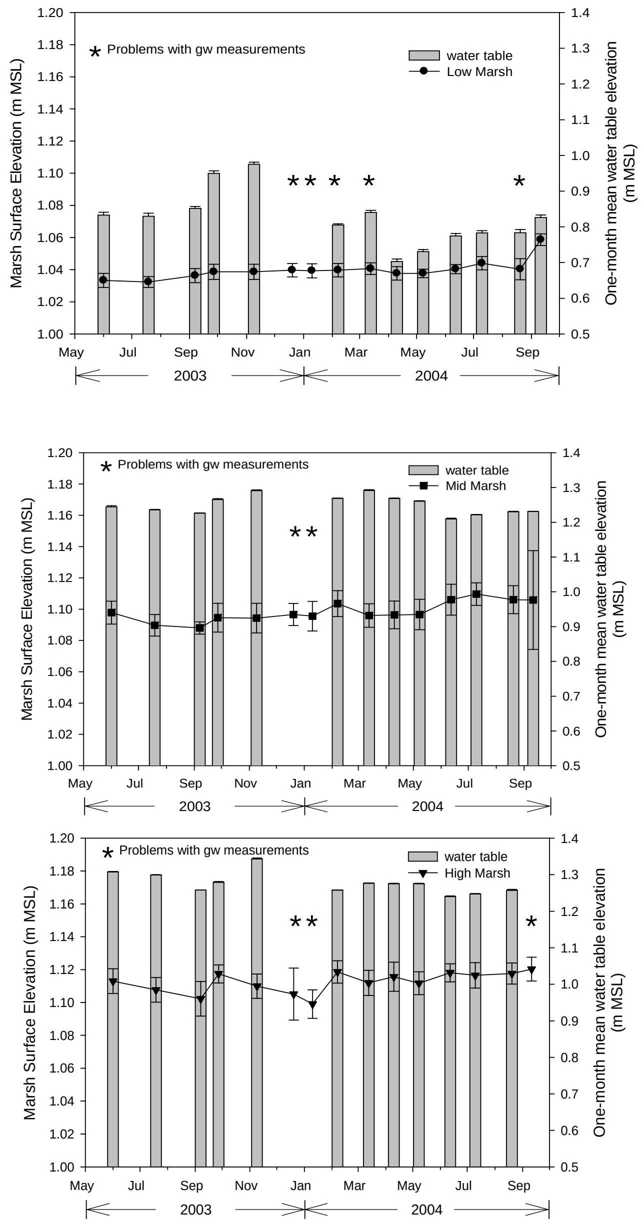

Figure 3.11. Monthly SET measurements (as in Fig. 3.8) plotted with mean ground water elevation (bars), relative to mean sea level, during the interval between SET measurements. Errors on bars are standard error; n depends on the number of records during the interval. The sampling interval for groundwater was 45 min. The stars indicate times when there were problems with the water-level recorder so that the records were incomplete or non-existent. Top Panel) Low marsh. Center Panel) Mid marsh. Bottom Panel) High marsh. No significant correlation exists between monthly marsh surface elevation and ground-water elevation.

Monthly marsh accretion data collection revealed a gain of 4.7 mm in the low marsh (Figure 3.12). The mid marsh experienced a loss of 4.0 mm of accreted material, whereas the high marsh gained 1.5 mm of accreted material. There were no trends evident in the accreted material over the course of 1.25-years of data measurements and revealed no trends between the summer or winter seasons. Similar to the semi-annual readings, monthly marker horizon data and MHHT are not significantly correlated (Figure 3.13). Precipitation occurring during the monthly period was not significantly correlated to marker horizon accretion (Figure 3.14). Marker horizon accretions in the low, mid, and high marsh were not significantly correlated to ground water levels (Figure 3.15). The semi-annual marker horizon data and ground water levels are not correlated, they contrast with studies where peat dominated mangrove soils were strongly influenced by groundwater recharge over short term periods (Whelan et. al, 2005).

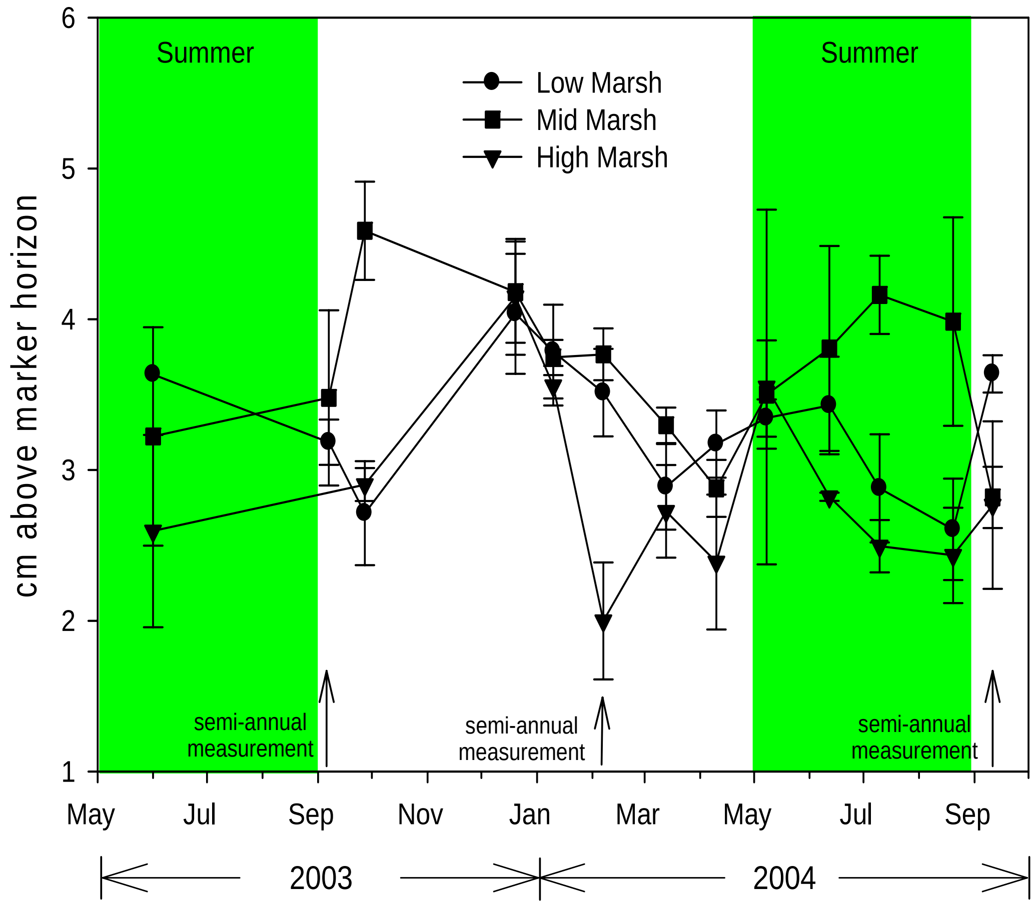

Figure 3.12. Monthly accretion measured as depth of material over a marker horizon at the low, mid and high marsh sites. Measurements were made over a 15-month period during 2003 - 2004 with several gaps during the first half year. Error bars represent standard error for n=3. Arrows indicate the timing of semi-annual measurements that are part of a longer (7-year) record. Shaded areas indicate summer intervals. No trends in accretion or differences among locations are indicated by the data.

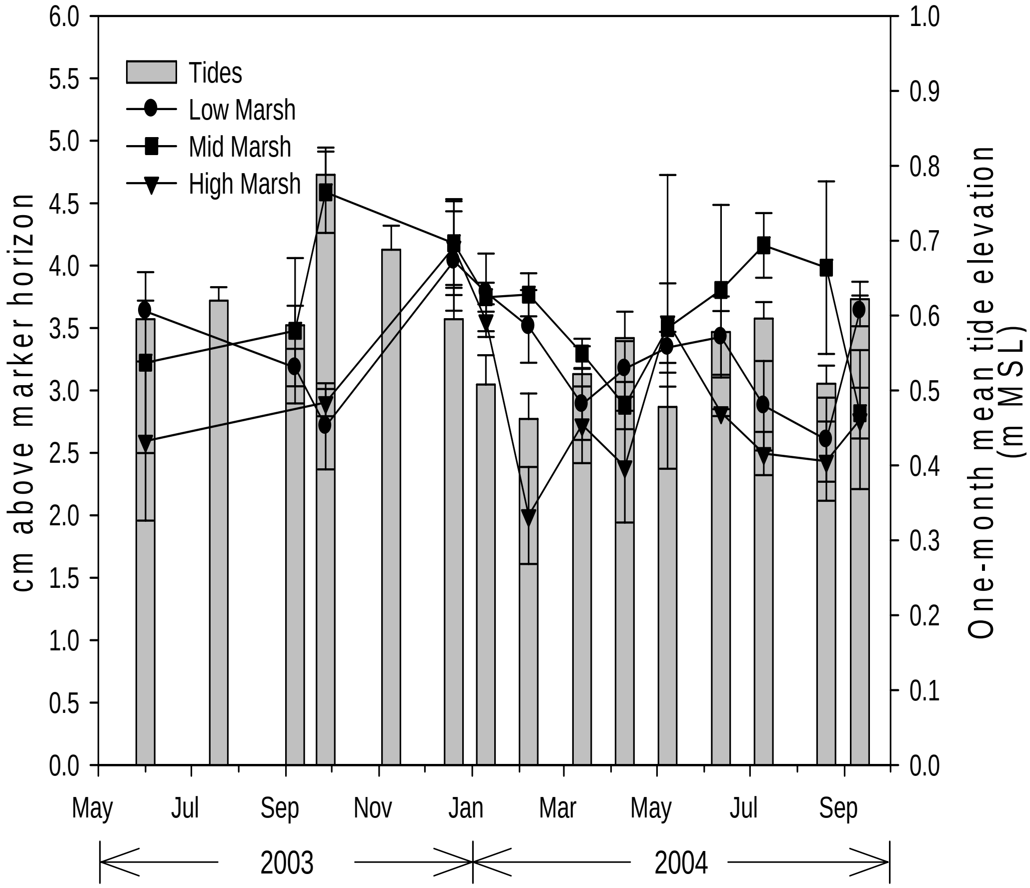

Figure 3.13. Monthly accretion (as in Fig. 3.12) plotted with mean high tide water elevation (bars) during the interval between accretion measurements or during the preceding month when no accretion measurement was made. Errors on bars are standard error; n depends on the number of high tides during the interval. Monthly accretion and mean high-tide water level are not significantly correlated.

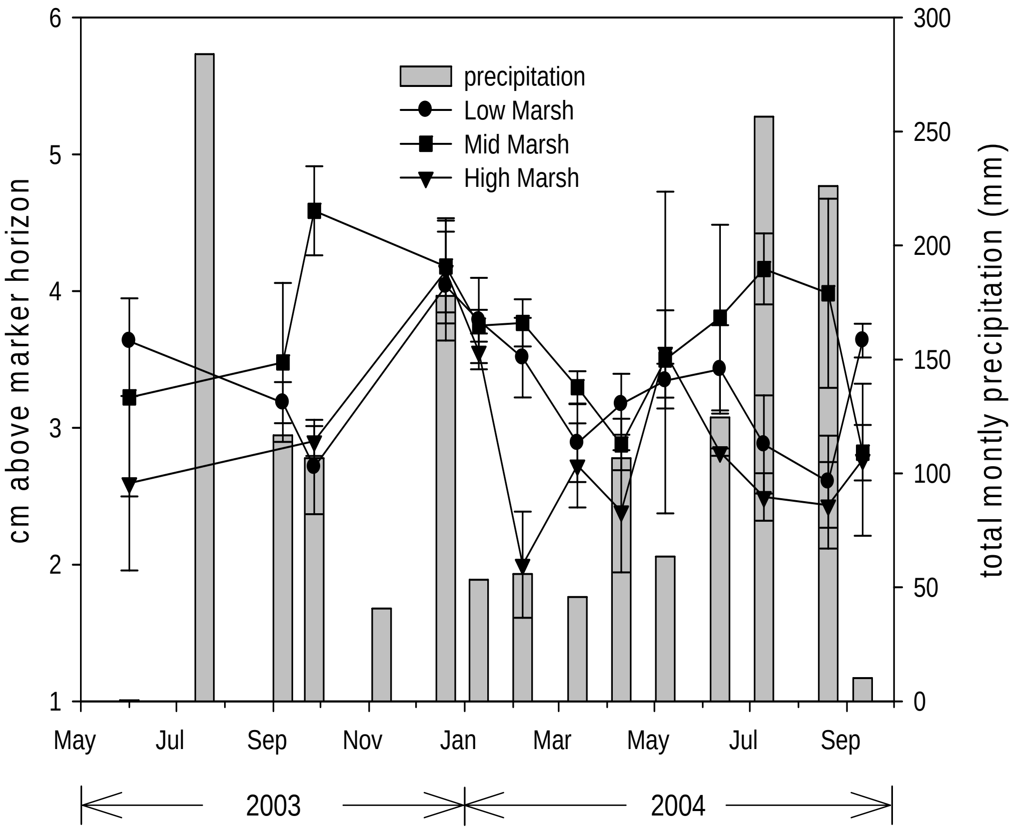

Figure 3.14. Monthly accretion (as in Fig. 3.12) plotted with total precipitation (bars) during the interval between accretion measurements or during the preceding month when no accretion measurement was made. Monthly accretion and precipitation are not significantly correlated.

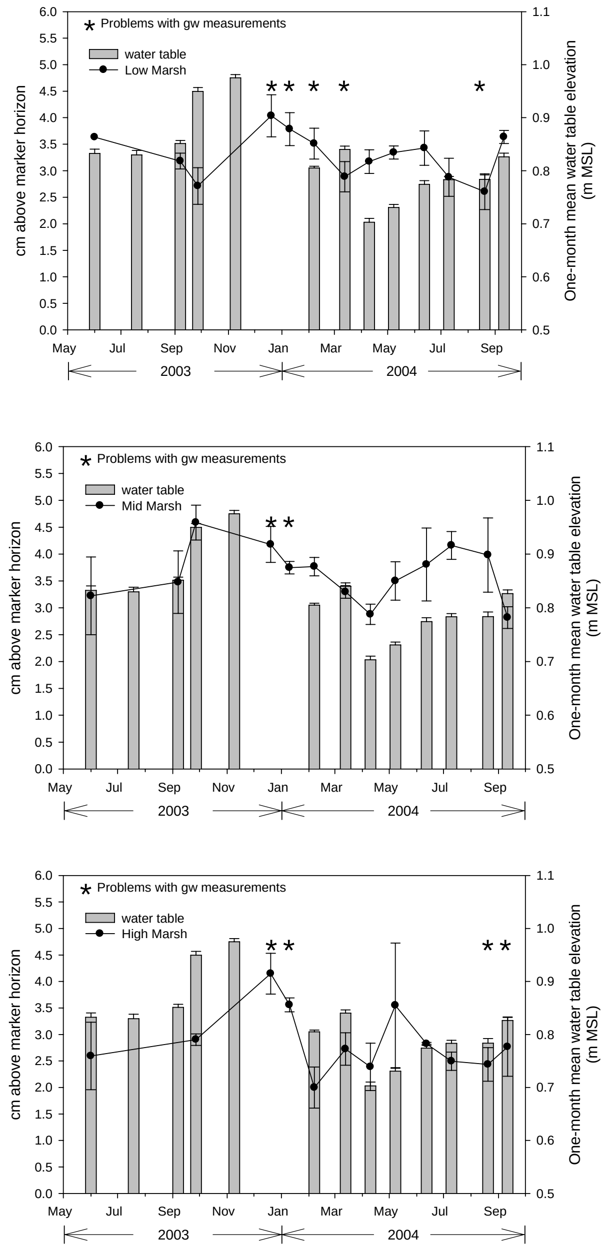

Figure 3.15. Monthly accretion plotted with mean ground water elevation (bars), relative to mean sea level, during the interval between accretion measurements or during the preceding month when no accretion measurement was made. Errors on bars are SEM; n depends on the number of records during the interval. The sampling interval for groundwater was 45 min. The stars indicate measurement problems so that the records were incomplete or non-existent. Top) Low marsh. Center) Mid marsh. Bottom) High marsh. No significant correlation exists between monthly accretion and ground-water elevation. The suggested relationship in the mid-marsh and high-marsh data requires a longer record for confirmation.

Monthly RSET readings were collected over a 12-month period after the RSETS were established in late July 2003 (Figure 3.16). The low marsh surface elevation increased by 5.0 mm during 12 monthly readings. The mid marsh gained 7.0 mm elevation during the study year. High marsh elevation gained 10mm elevation over the course of the one year study. There was no significant trend discernable from these elevation changes.

Mean high tides were not significantly correlated with monthly RSET readings (Figure 3.17). Similarly, precipitation and RSET data are not significantly correlated (Figure 3.18). Ground water levels were not significantly correlated with RSET elevation gains (Figure 3.19).

3.3 Hourly Marsh Surface Elevation Changes

Daily SET and RSET readings were compared to tidal elevations normalized by calculating the time since the high tide prior to beginning the data collection (Figure (3.20). This study attempted to discern if the level of the tide affected marsh surface elevation. The readings were timed to include one high and one low tide per day. No correlation between the tide stage and SET and RSET readings were noted.

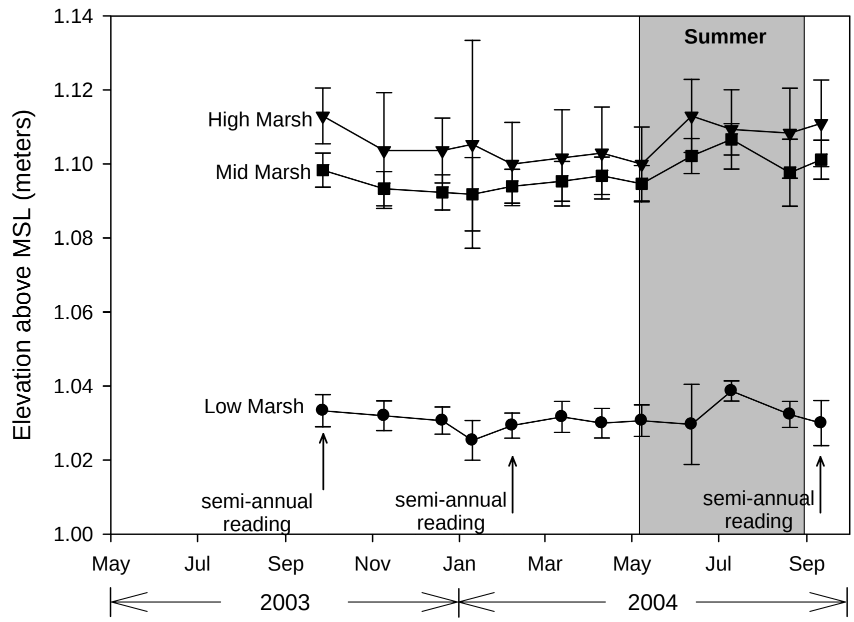

Figure 3.16. Monthly RSET measurements of marsh surface elevation (relative to mean sea level) at the low, mid and high marsh sites. The RSETs measure elevation relative to a datum initially 20 cm below the surface. Measurements were made over a 12-month period during 2003 – 2004. Error bars represent standard error for n=3. Arrows indicate the timing of semi-annual measurements that are part of a longer (7-year) record. Shaded areas indicate summer intervals. No trends in surface elevation are indicated by the data.

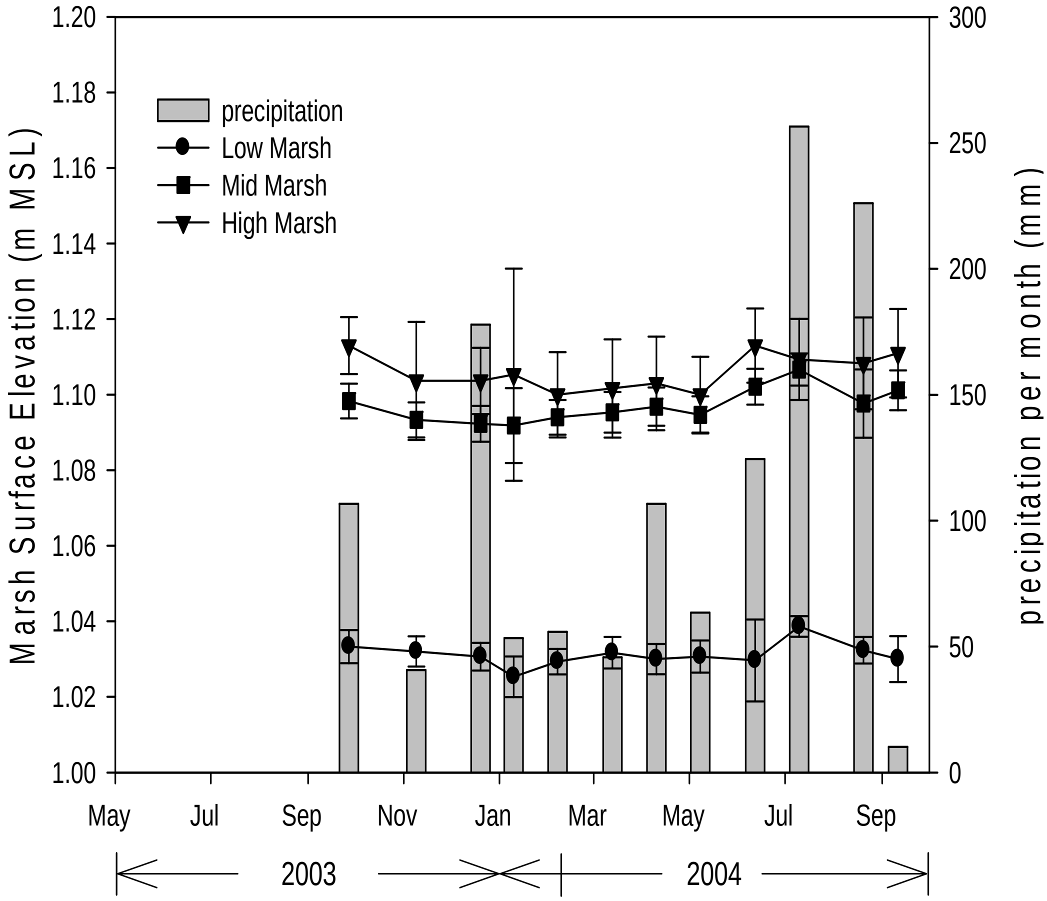

Figure 3.17. Monthly RSET measurements (as in Fig. 3.16) plotted with mean high tide water elevation (bars) during the interval between RSET measurements. Errors on bars are standard error; n depends on the number of high tides during the preceding interval. Monthly RSET marsh surface elevation and mean high-tide water level are not significantly correlated.

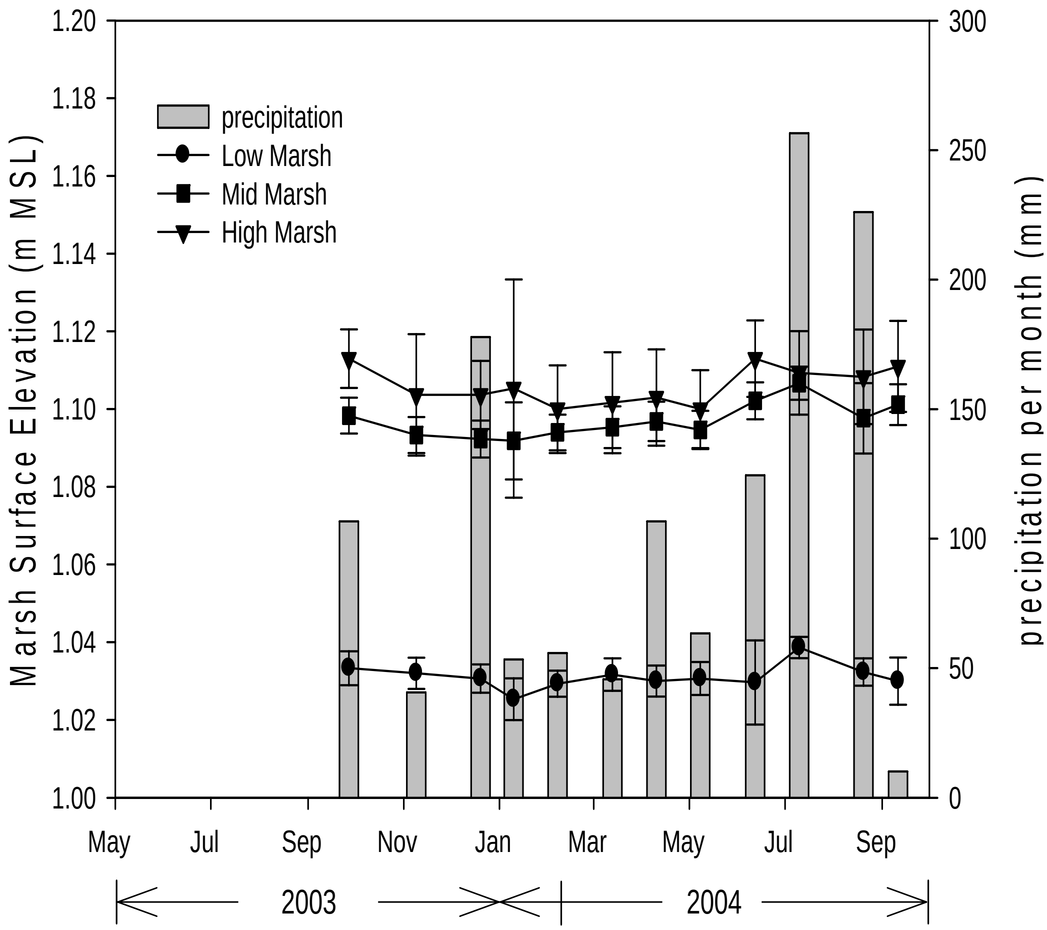

Figure 3.18. Monthly RSET measurements (as in Fig 3.16) plotted with total precipitation (bars) during the interval between RSET measurements. Monthly RSET marsh surface elevation and total precipitation are not significantly correlated.

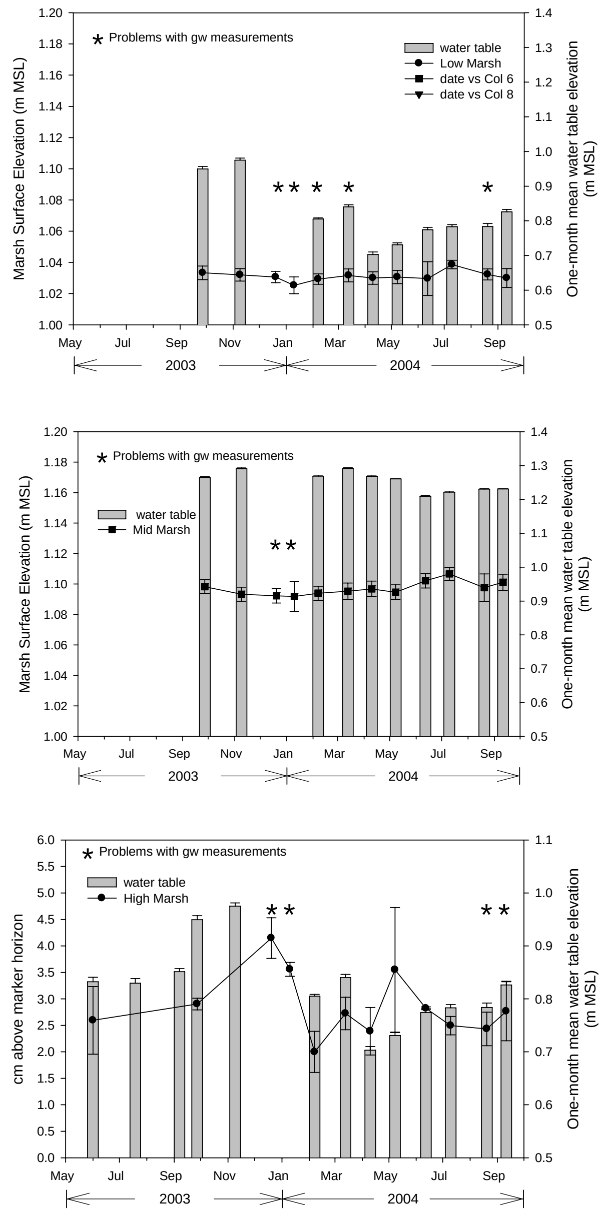

Figure 3.19. Monthly RSET measurements (as in Fig. 3.16) plotted with mean ground water elevation (bars), relative to mean sea level, during the interval between RSET measurements. Errors on bars are standard error; n depends on the number of records during the interval. The sampling interval for groundwater was 45 min. The stars indicate times when there were problems with the water-level recorder so that the records were incomplete or non-existent. Top Panel) Low marsh. Center Panel) Mid marsh. Bottom Panel) High marsh. No significant correlation exists between monthly RSET elevations and ground-water elevation.

3.4 Clay Soil Analysis

Clay minerals were present in very small amounts and analysis interpretations determined that the clay samples in Philips Creek Salt Marsh are composed of Illite, 10, 5, and 3 angstrom reflections (Appendix D). Kaolinite was characterized by 7 and 3.5 angstrom peaks. Small amounts of chlorite and quartz are also present to varying degrees. These findings suggest that the small clay fraction collected from the soil profiles of UPC do not contain montmorillonite type clays. Illite, Kaolinite and Chlorite are not subject to shrink/swell regimes and do not contribute to increases or decreases in soil volume with increase and decrease of moisture content.

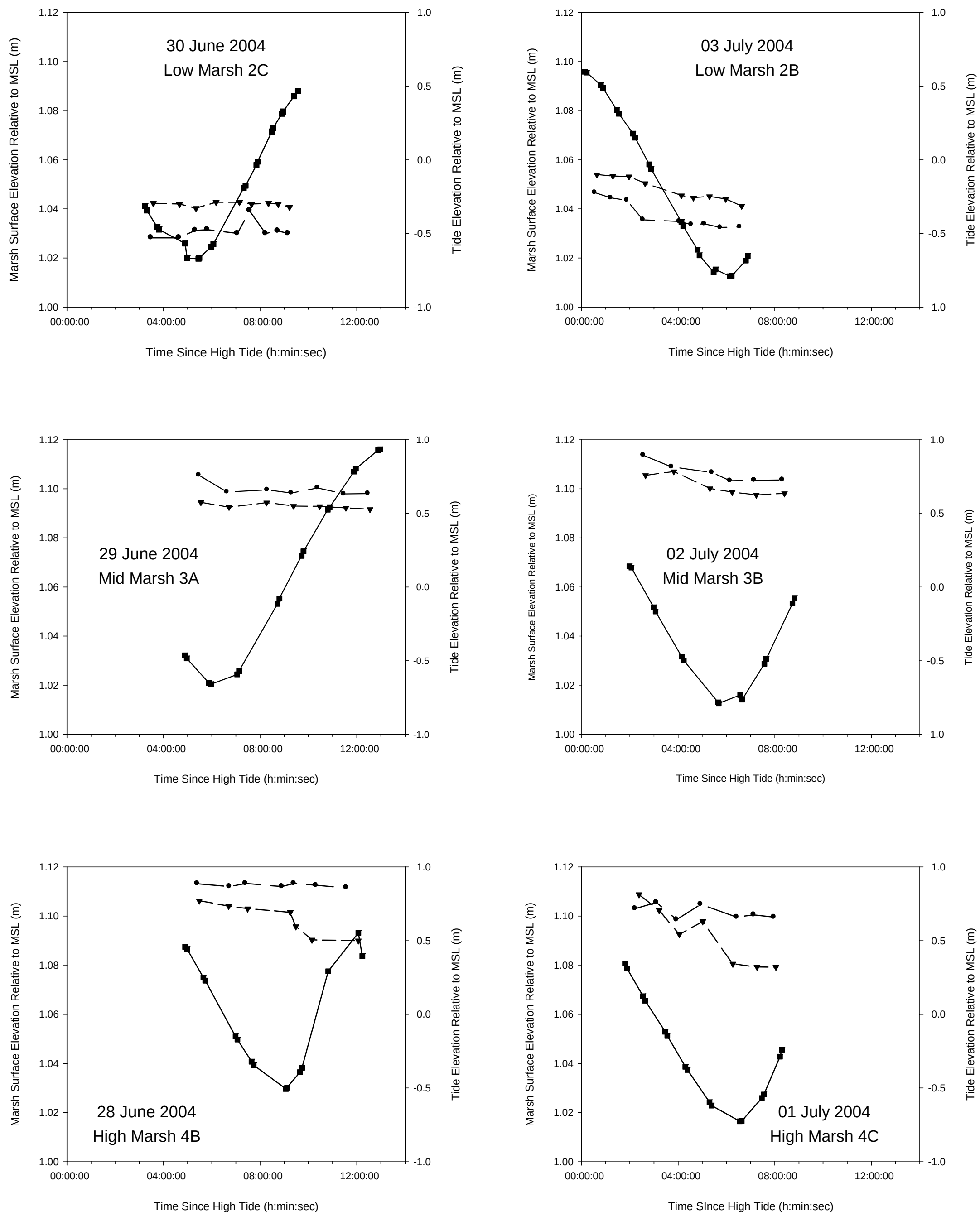

Figure 3.20. Hourly SET (circles) and RSET (triangles) measurements of marsh surface elevation (relative to mean sea level (MSL)) at the low, mid and high marsh sites. Tide elevation (squares) relative to MSL is plotted at the time of SET and RSET measurement. Note the difference in scale between marsh and tide elevation axes and that the tides did not flood any of the sites while elevation measurements were made. Measurements were made over a 4-day period during July 2004 and captured a falling and rising tide. SET and RSET elevations exhibited no detectable response that could be attributed to tides.

Chapter 4

Conclusions

Results of this study indicate that processes operating in Philips Creek Salt Marsh that affect surface elevation occur very slowly over long periods of time. This thesis showed tidal inundations which drive sediment erosion and accretion are inversely correlated. This would strongly indicate that water level on the surface of the marsh affects anoxic conditions and root growth and decay more rapidly than influxes of nutrients brought by tides. Ground water levels and precipitation are not correlated and would likely only have short term affects within the overall change in elevation.

Shorter duration data collection on the monthly and daily tide cycle scale do not reveal any correlation with short term climate such as rainfall and ground water level, and in fact, may show short term changes to surface elevation will eventually even out over the course of longer term study. However, salt marshes with differing soil composition such as with Whelan, 2005, and different hydroperiod regimes, Cahoon, 1999, and different vegetation, i.e. mangroves vs. salt marsh cordgrass may experience rates of elevation change that respond to shorter time phenomenon.

In order to determine the effects of surface elevation in response to sea-level rise at UPCM, a decades long record incorporating the background noise of droughts, excess rainfall, hurricanes and tropical storms would be necessary.

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Appendix A

Site	# observations	Slope	Mean Square Error	Variance of X	Comparison	T-Test
2A	15	0.567	0.272	0.577	2A and 2B	T = 0.0006 < t = 1.706
2B	15	0.562	0.196	0.577	2A and 2C	T = 0.093 < t = 1.706
2C	15	0.543	0.257	0.577	2B and 2C	T= 0.080 < t = 1.706
3A	15	0.421	0.138	0.577	3A and 3B	T = 1.859 > t = 1.706[a]
3B	15	0.962	0.546	0.577	3A and 3C	T = 0.056 < t = 1.706
3C	15	0.556	1.718	0.577	3B and 3C	T = 0.766 < t =
4A	15	0.155	0.051	0.577	4A and 4B	T = 0.047 < t = 1.706
4B	15	0.161	0.083	0.577	4A and 4C	T = 0.116 < t = 1.706
4C	15	0.140	0.083	0.577	4B and 4C	T = 0.146 < t = 1.706

Analysis of benchmark slope within zones show that all three sites in the low marsh and high marsh acted similarly. Site 3A and 3B showed a very small significant difference (a) therefore, the slope of all three sites in this area were considered to be acting similarly.

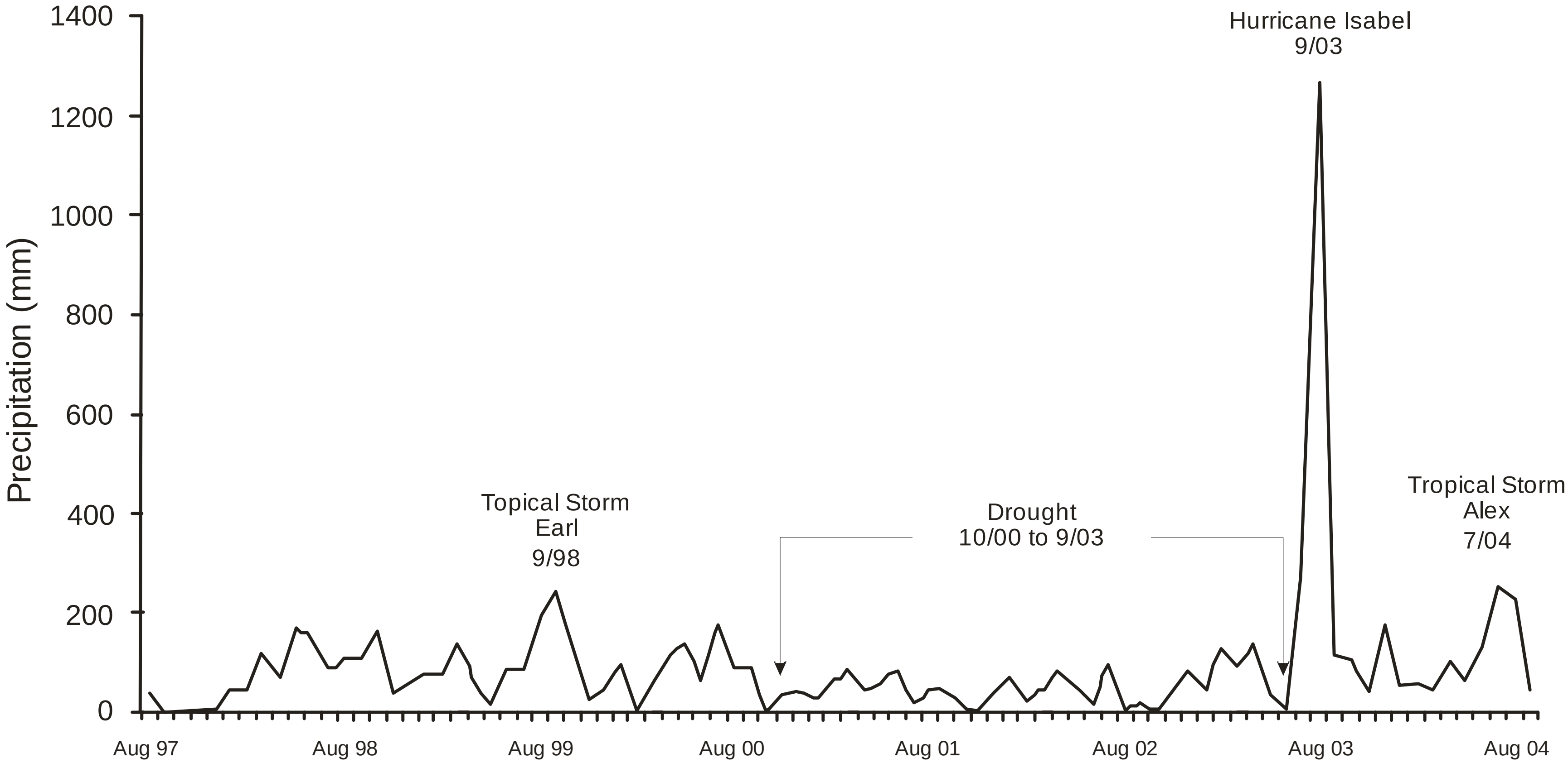
Appendix B

Dates of Data Collection

Semi-Annual	Monthly	Daily
8/22/1997		
2/21/1998		
9/26/1998		
2/19/1999		
8/27/1999		
2/18/2000		
8/18/2000		
2/9/2001		
9/8/2001		
2/1/2002		
8/15/2002		
2/7/2003/		
	6/1/2003	
	7/19/2003	
	9/7/2003	
9/27/2003	9/27/2003	
	11/9/2003	
	12/20/2003	
	1/10/2004	
2/7/2004	2/7/2004	
	3/14/2004	
	4/10/2004	
	5/8/2004	
	6/12/2004	
		6/28/2004
		6/29/2004
		6/30/2004
		7/1/2004
		7/2/2004
		7/3/2004
	7/10/2004	
	8/20/2004	
9/10/2004	9/10/2004	

Appendix C

Monthly Precipitation Data from NOAA Station, Painter Virginia. NOAA Climate Data Center located at the Accomack County Airport (MFV) Melfa, Virginia 37°39'N and 75°46'W (*http://cdo.ncdc.noaa.gov/ulcd/ULCD*).



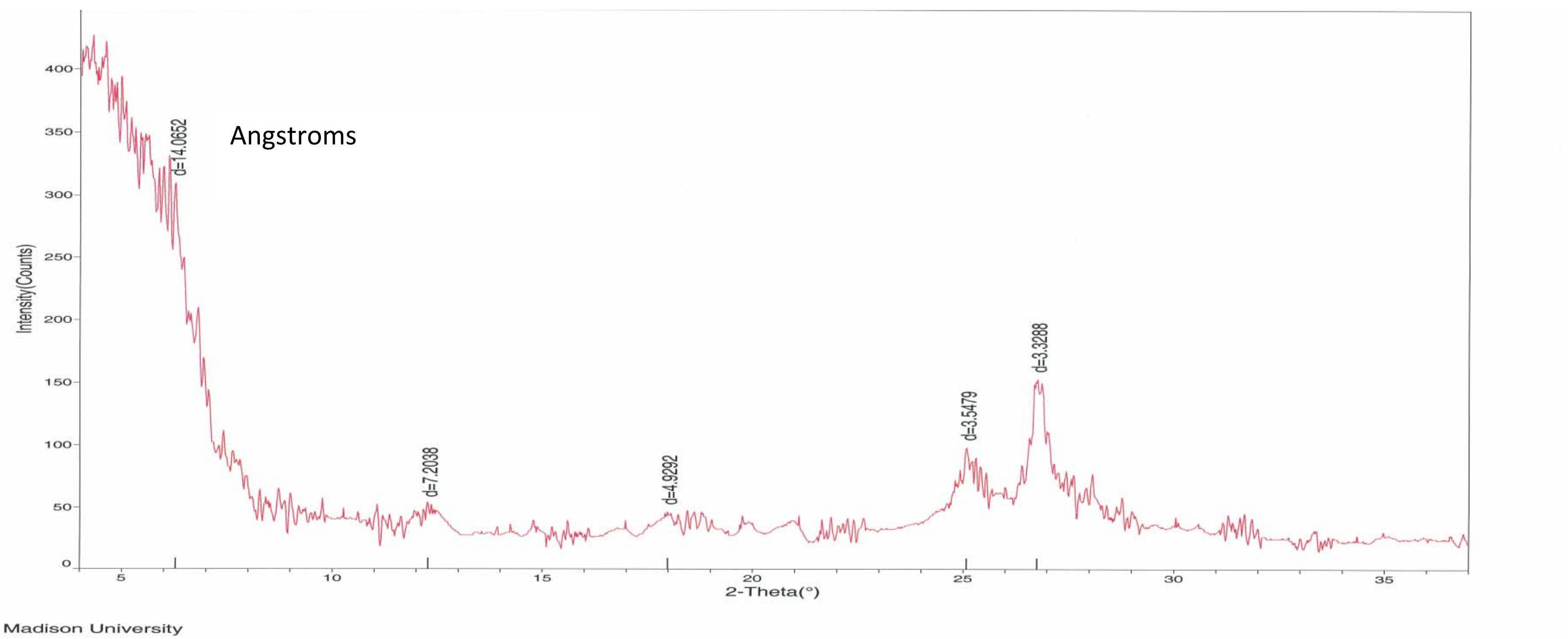
Appendix C continued
Meteorological Data, NOAA Climate Data Center located at the Accomack County Airport (MFV) Melfa, Virginia
Monthly Total Precipitation in mm

Aug 97	37.8	Jan 98	44.4	Jan 99	80.3	Jan 00	99.1
Sep 97	0.0	Feb 98	48.8	Feb 99	72.2	Feb 00	0.3
Oct 97	0.0	Mar 98	117.1	Mar 99	144.5	Mar 00	61.7
Nov 97	7.6	Apr 98	70.9	Apr 99	56.1	Apr 00	121.9
Dec 97	0.0	May 98	164.6	May 99	18.3	May 00	140.2
		Jun 98	156.7	Jun 99	87.6	Jun 00	67.5
		Jul 98	83.3	Jul 99	87.4	Jul 00	182.9
		Aug 98	106.9	Aug-99	196.1	Aug-00	90.2
		Sep 98	108.7	Sep 99	246.6	Sep 00	90.4
		Oct 98	163.1	Oct 99	147.3	Oct 00	0.0
		Nov 98	39.4	Nov 99	29.7	Nov 00	32.5
		Dec 98	52.8	Dec 99	43.7	Dec 00	36.8
Jan 01	32.8	Jan 02	74.2	Jan 03	46.5	Jan 04	53.3
Feb 01	59.2	Feb 02	23.1	Feb 03	126.2	Feb 03	55.9
Mar 01	86.6	Mar 02	47.5	Mar 03	95.5	Mar 04	45.7
Apr 01	50.8	Apr 02	81.8	Apr 03	133.4	Apr 03	106.7
May 01	57.5	May 02	53.3	May 03	39.4	May 04	63.5
Jun 01	84.8	Jun -2	20.1	Jun 03	0.5	Jun 04	124.5
Jul 01	18.8	Jul 02	95.5	Jul 03	283.9	Jul 04	256.5
Aug 01	43.4	Aug- 2	7.9	Aug 03	116.7	Aug 04	226.1
Sep 01	46.5	Sep 02	19.6	Sep 03	1269.1	Sep 04	40.6
Oct 01	11.4	Oct 02	.	Oct 03	106.7		
Nov 01	1.0	Nov 02	41.9	Nov 03	40.6		
Dec 01	43.2	Dec 02	87.6	Dec 03	177.8		

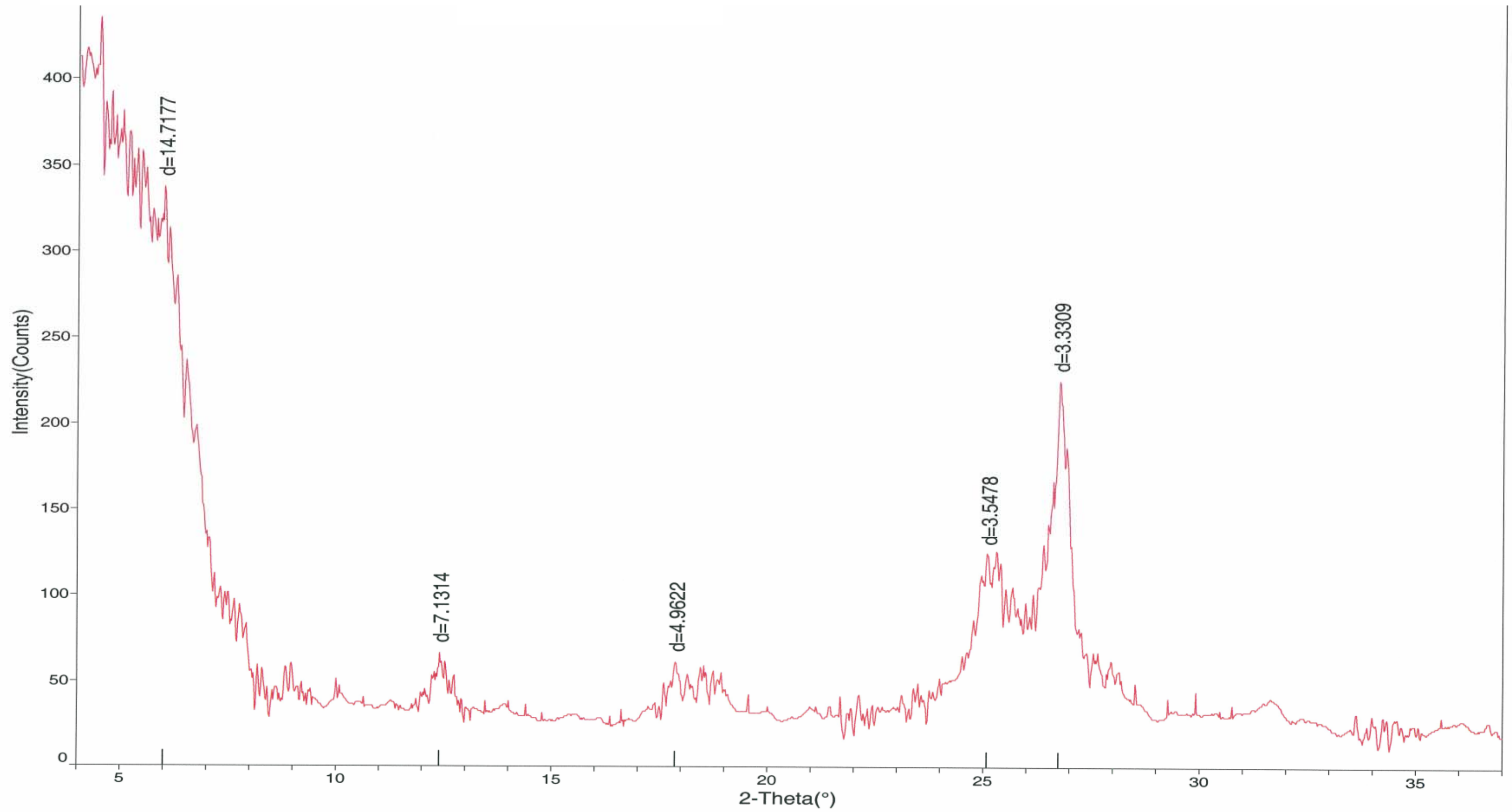
Appendix D

X-ray diffraction diagrams pertaining to the clay particles removed from low marsh, August 2003. Samples were removed from sites 2A and 2C low marsh, 3A and 3C mid marsh, and 4A and 4C high marsh. No expansive clay particles were found in any of the samples.

Site 2A, low marsh air dried sample. Sample contains: Kaolinite at 3.5 and 7.0 angstrom peaks, Illite, at 3.3, 5.0, and 10.0 angstroms

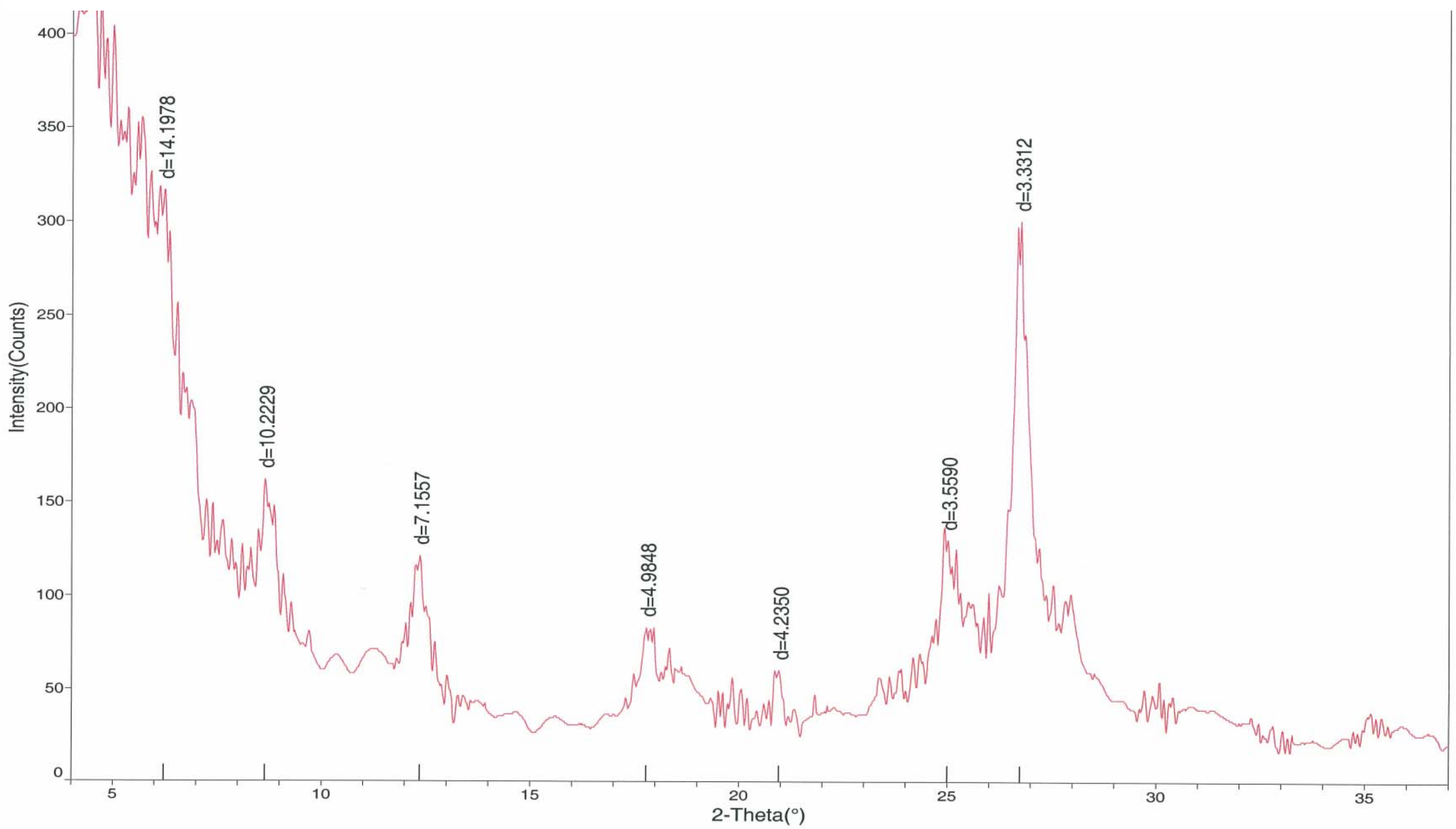


Site 2A low marsh glycol dried sample. . Sample contains: Kaolinite at 3.5 and 7.0 angstrom peaks, Illite, at 3.3, 5.0, and 10.0 angstroms



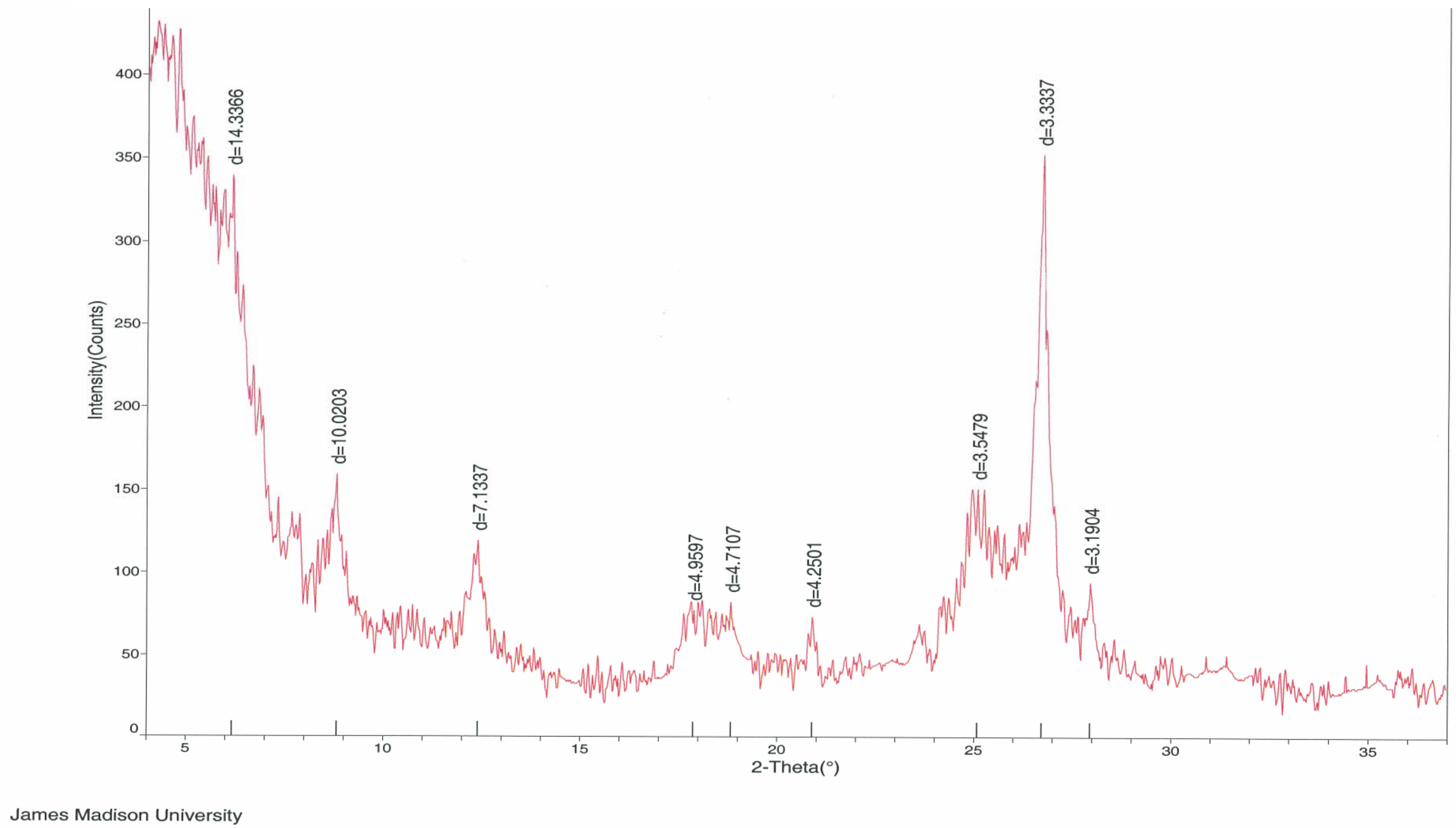
James Madison University

Site 2C, low marsh air dried sample. Sample contains: Kaolinite at 3.5 and 7.0 angstrom peaks, Illite, at 3.3, 5.0, and 10.0 angstroms. A small amount of chlorite is present indicated by the small reflectance at 14.3 angstroms.

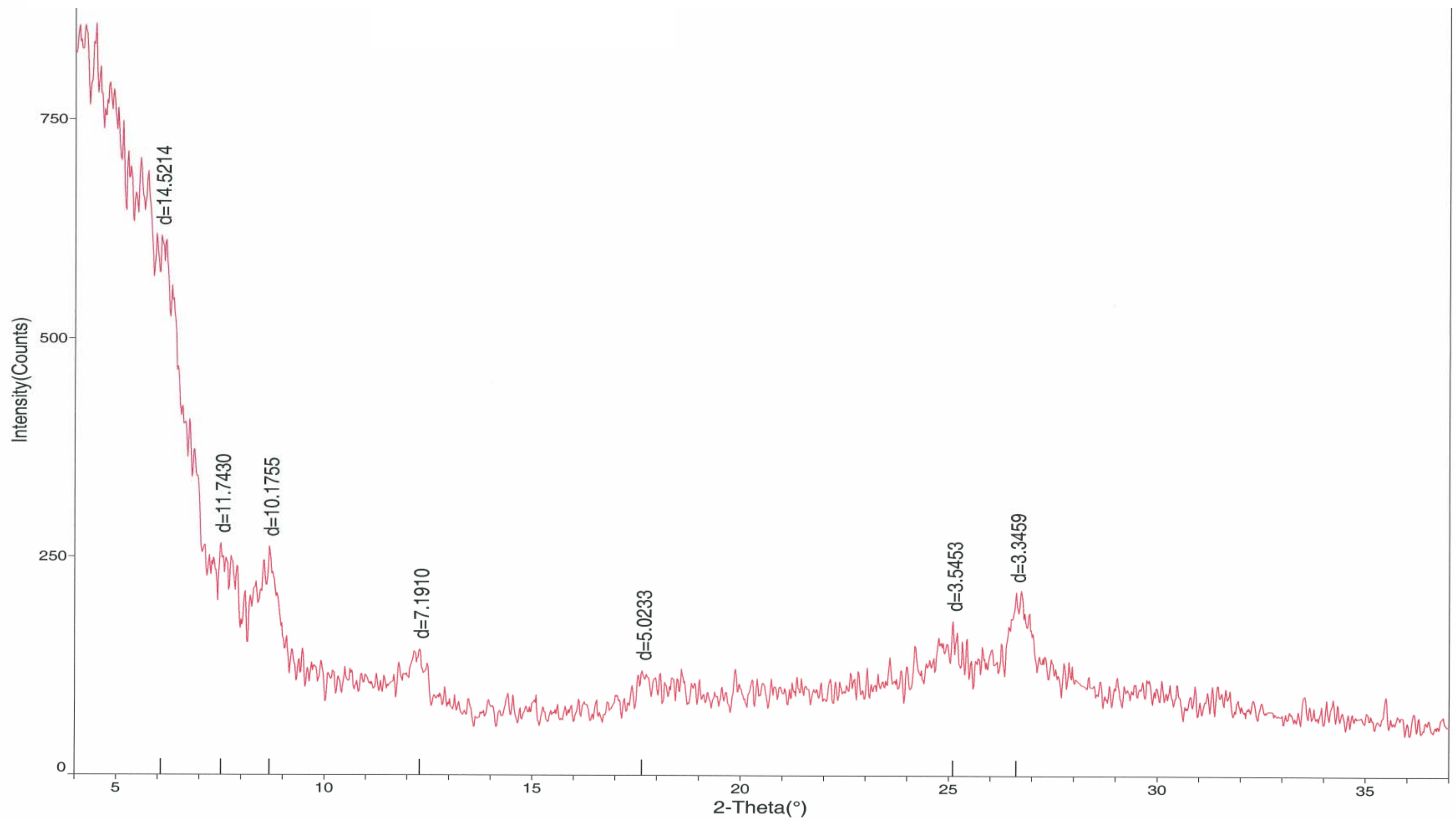


James Madison University

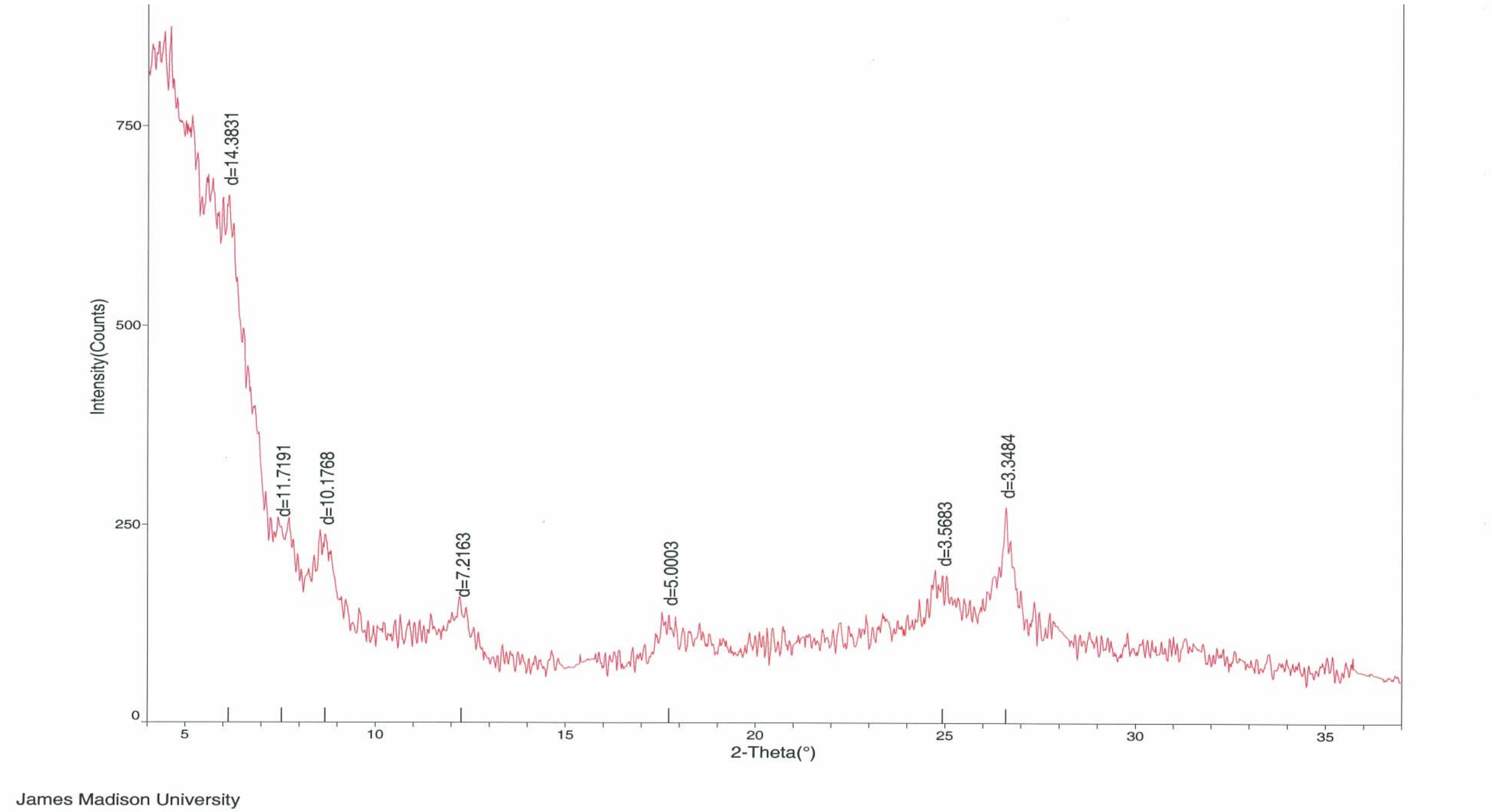
Site 2C low marsh glycol dried sample. . Sample contains: Kaolinite at 3.5 and 7.0 angstrom peaks, Illite, at 3.3, 5.0, and 10.0 angstroms. A slightly stronger Chlorite reflectance is present at 14.3 Angstroms.



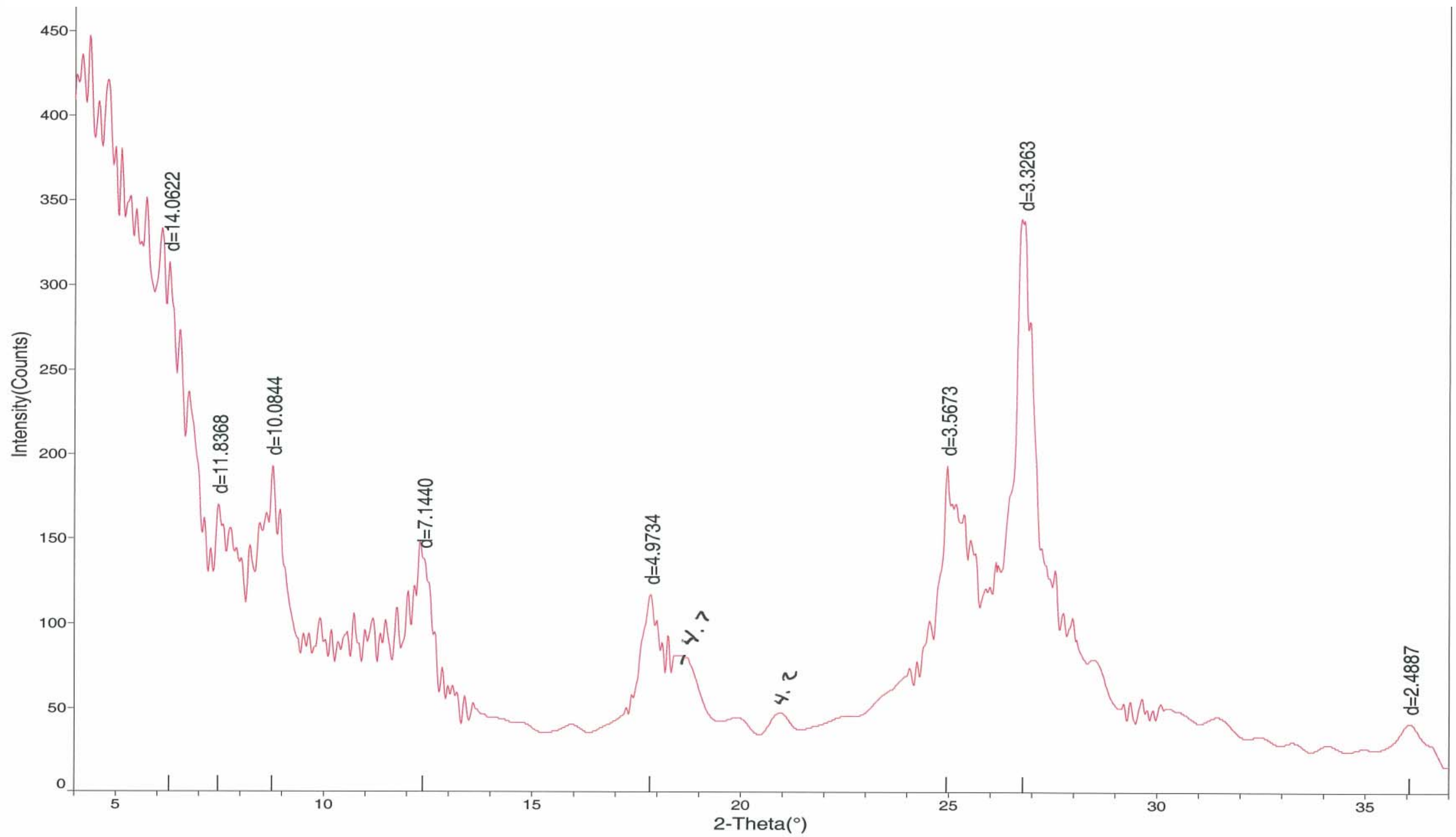
Site 3A, mid marsh air dried sample. Sample contains very small amount of clay particles Sample contains: Kaolinite at 3.5 and 7.0 angstrom peaks, Illite, at 3.3, 5.0, and 10.0 angstroms. A small amount of chlorite is present indicated by the small reflectance at 14.3 angstroms.



Site 3A mid marsh glycol dried sample. X-ray diffraction showed slightly larger amount of clay particles . Sample contains: Kaolinite at 3.5 and 7.0 angstrom peaks, Illite, at 3.3, 5.0, and 10.0 angstroms. A slightly stronger Chlorite reflectance is present at 14.3 Angstroms.

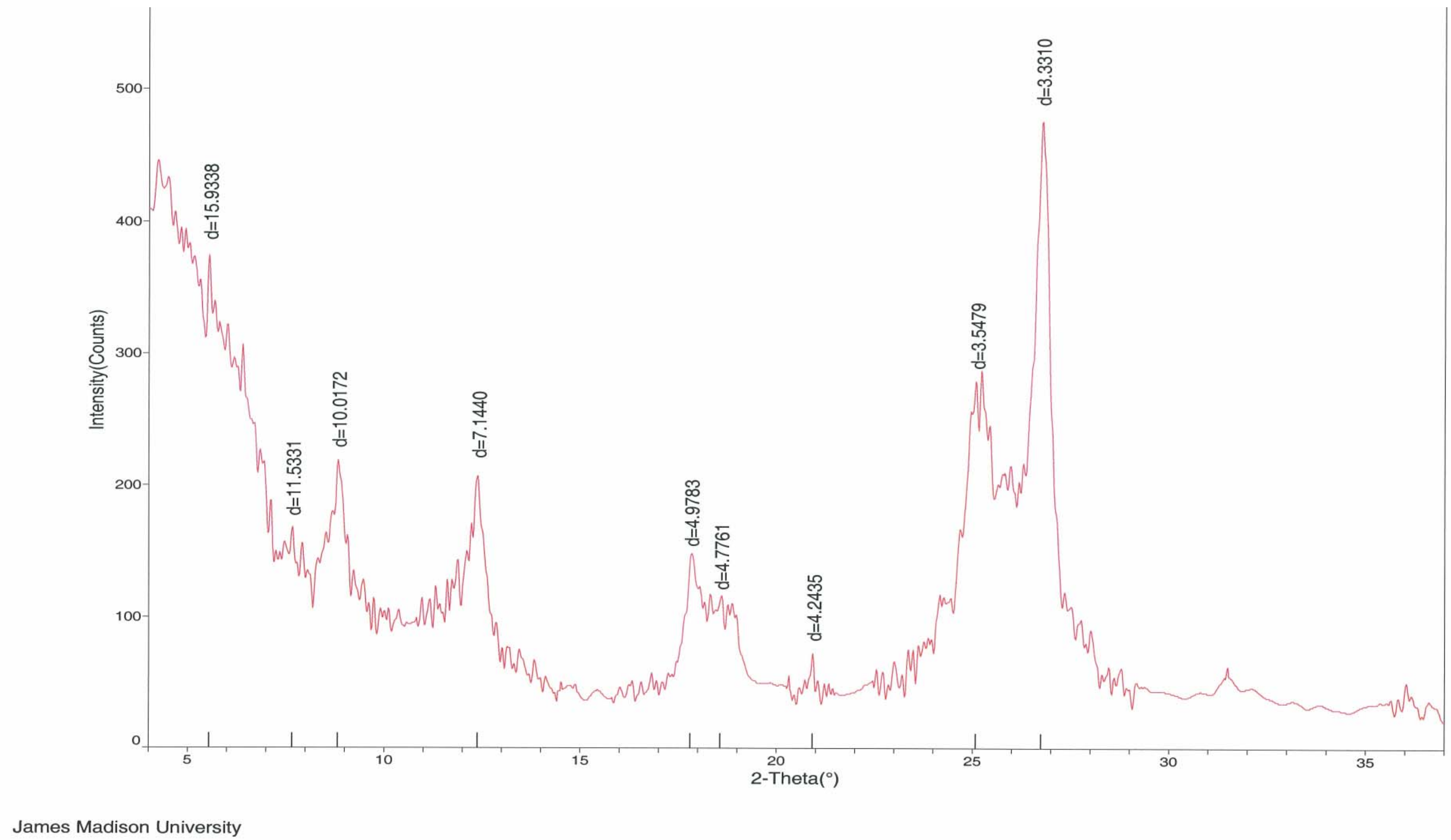


Site 3C, mid marsh air dried sample. Sample contains: Kaolinite at 3.5 and 7.0 angstrom peaks, Illite, at 3.3, 5.0, and 10.0 angstroms. A small amount of chlorite is present indicated by the small reflectance at 14.3 and 4.7 angstroms. Quartz is indicated by a small peak at 4.25 angstroms

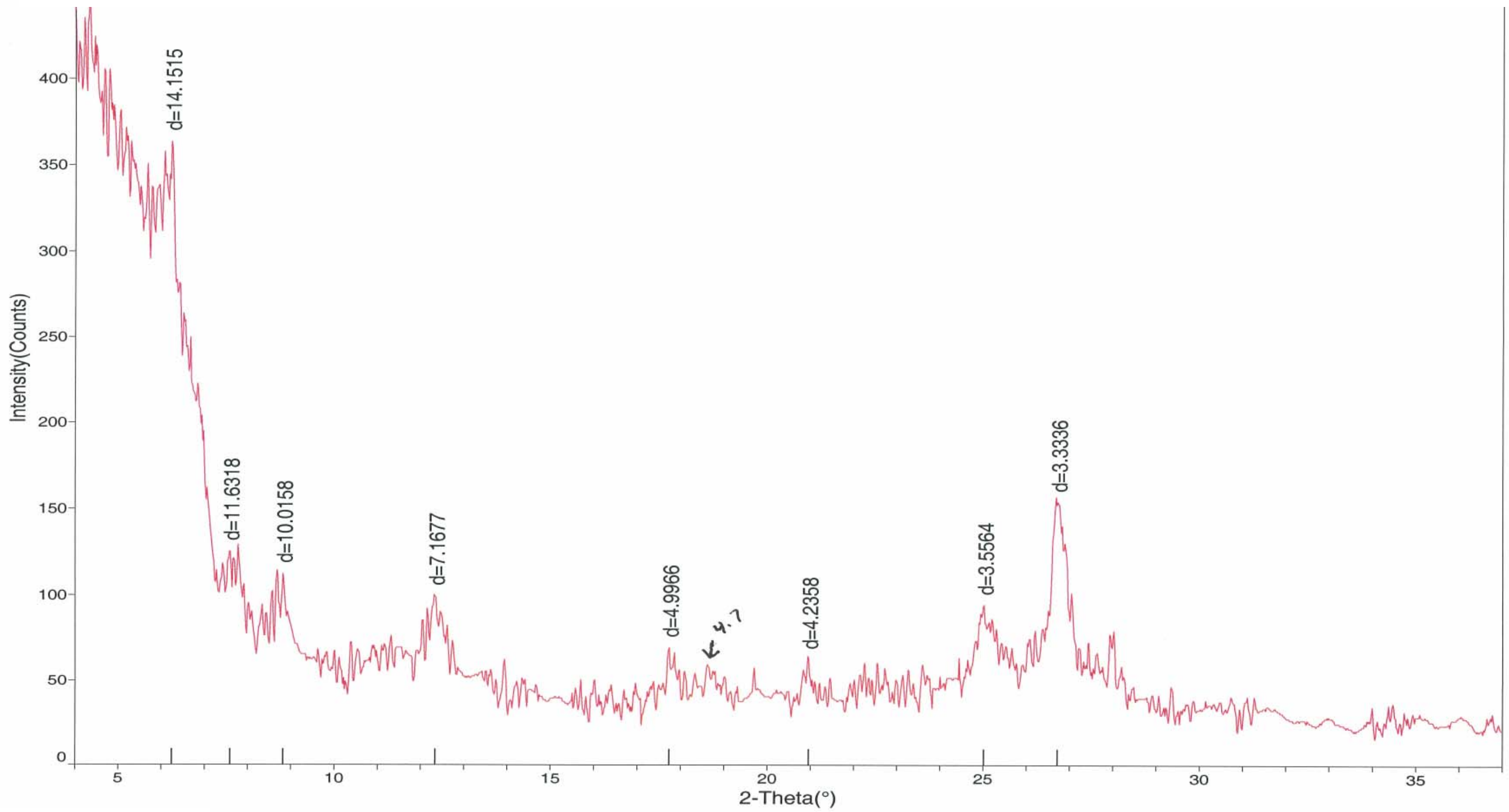


James Madison University

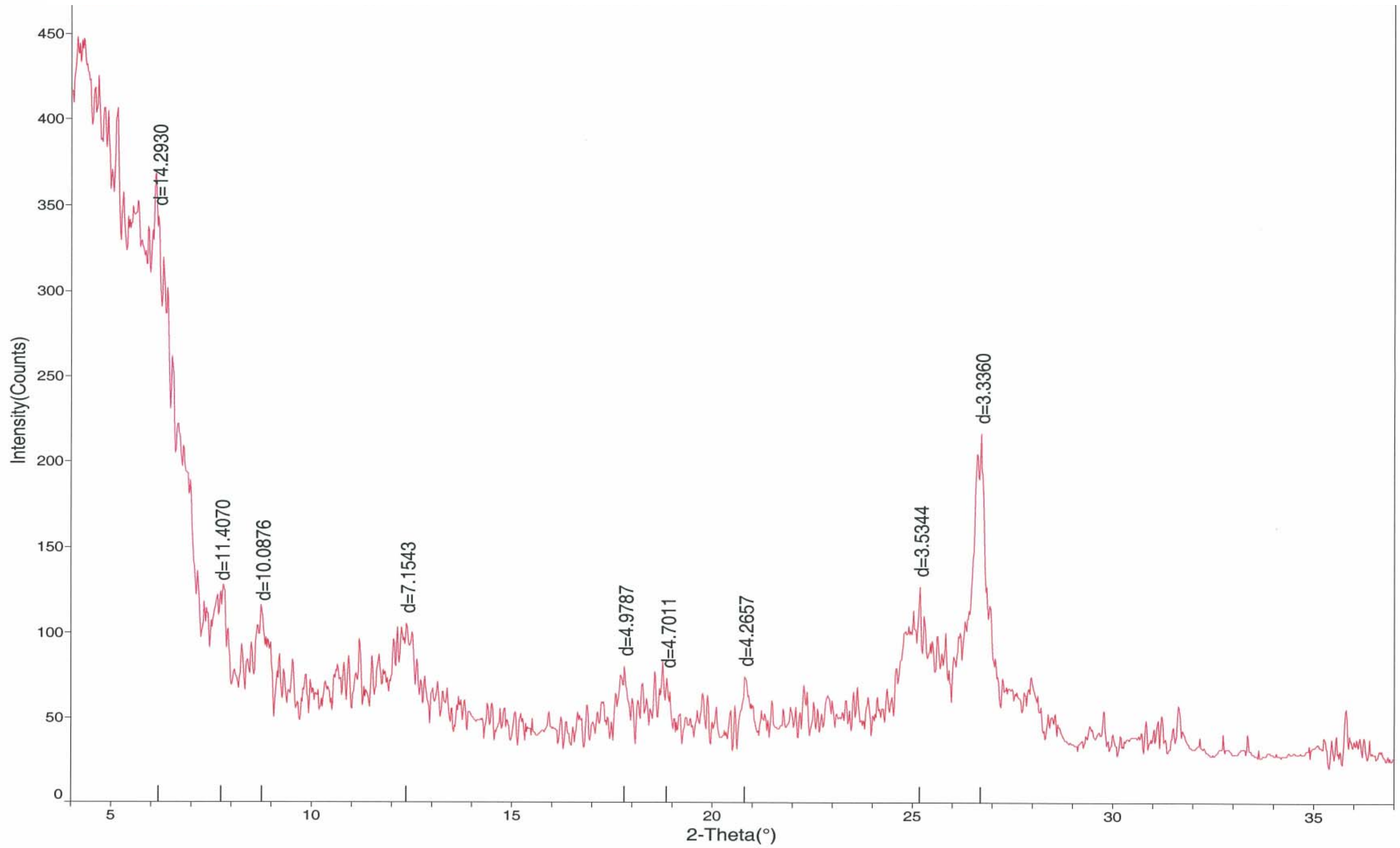
Site 3C mid marsh glycol dried sample. Sample contains: Kaolinite at 3.5 and 7.0 angstrom peaks, Illite, at 3.3, 5.0, and 10.0 angstroms. A slight Chlorite and Quartz reflectance is present at 14.3 and 4.25 Angstroms.



Site 4A,high marsh air dried sample. Sample contains: Kaolinite at 3.5 and 7.0 angstrom peaks, Illite, at 3.3, 5.0, and 10.0 angstroms. A small amount of chlorite is present indicated by the small reflectance at 14.3 and 4.7 angstroms. Quartz is indicated by a small peak at 4.25 angstroms

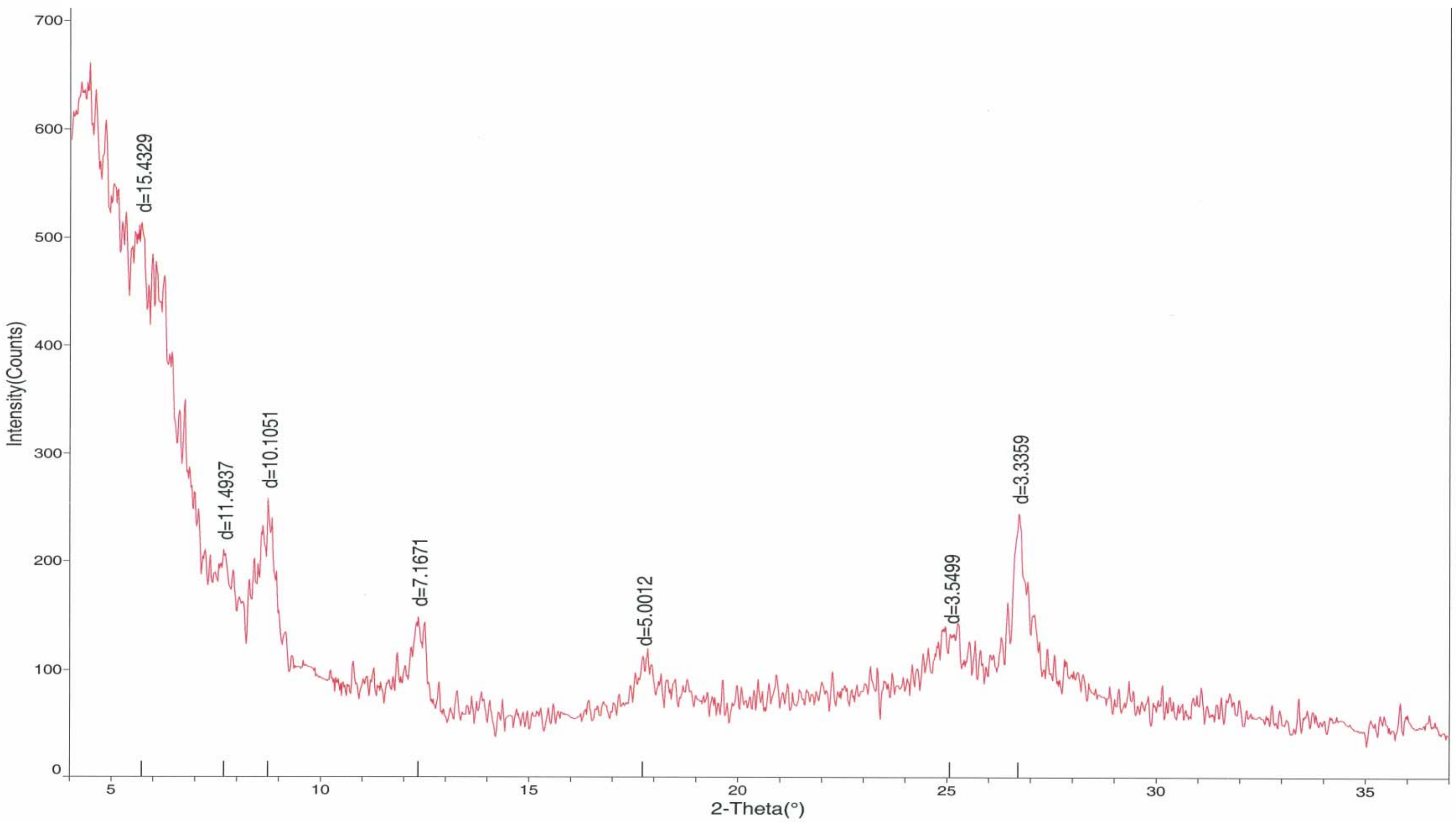


Site 4A high marsh glycol dried sample. Sample contains: Kaolinite at 3.5 and 7.0 angstrom peaks, Illite, at 3.3, 5.0, and 10.0 angstroms. A slight Chlorite and Quartz reflectance is present at 14.3 and 4.25 Angstroms.



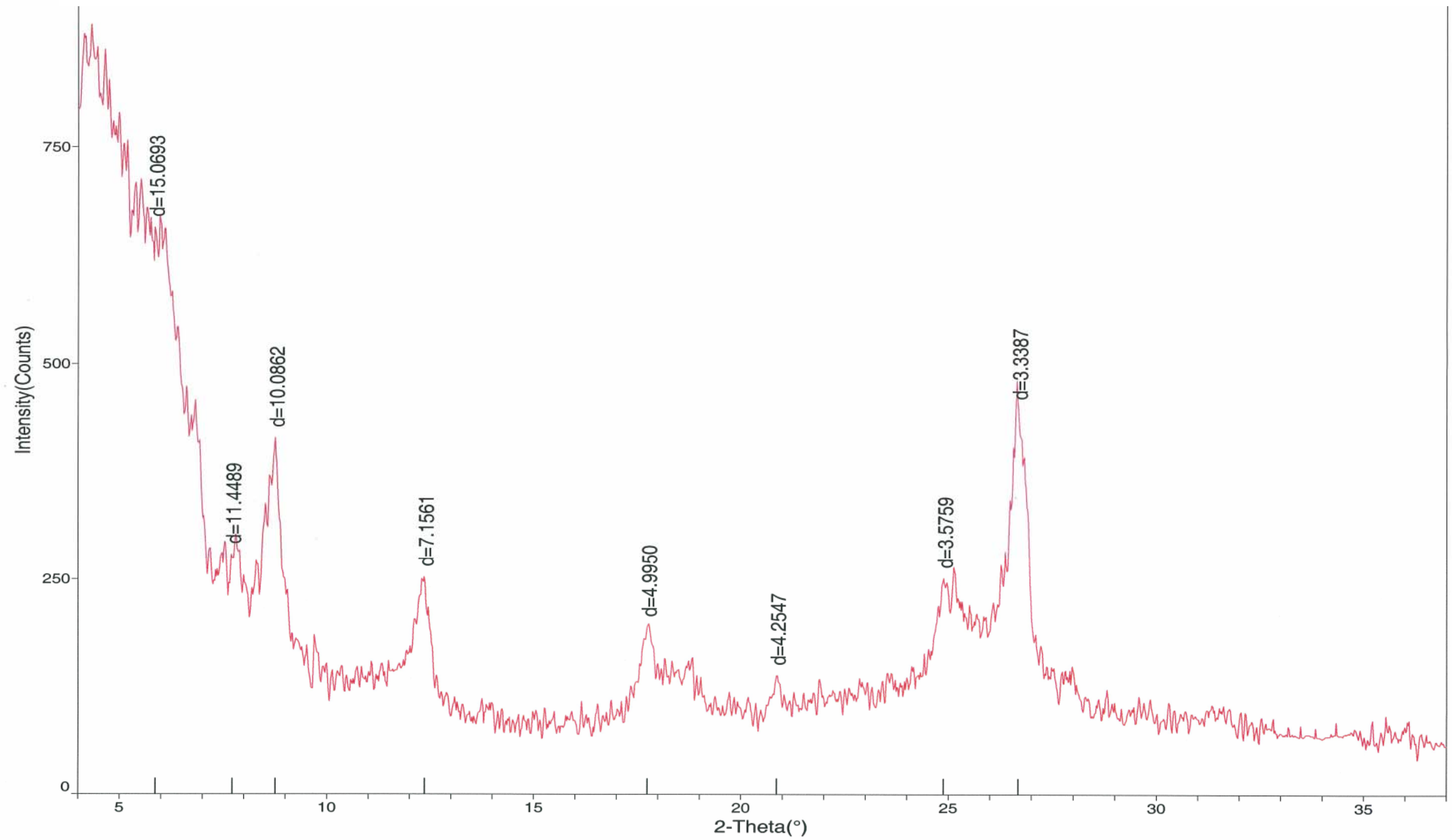
James Madison University

Site 4C, high marsh air dried sample. Sample contains: Kaolinite at 3.5 and 7.0 angstrom peaks, Illite, at 3.3, 5.0, and 10.0 angstroms. A small amount of chlorite is present indicated by the small reflectance at 15.4 angstroms. Quartz is indicated



James Madison University

Site 4A high marsh glycol dried sample.   Sample contains: Kaolinite at 3.5 and 7.1 angstrom peaks, Illite, at 3.3, 5.0, and 10.0 angstroms. A slight Chlorite and Quartz reflectance is present at 15.0 and 4.25 Angstroms.



James Madison University