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HYDROLOGICAL INFLUENCES ON ECOLOGICAL ZONATION IN A SALT MARSH TIDAL CREEK BASIN: CRAB HAUL CREEK, SOUTH CAROLINA, USA

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by

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ABSTRACT

Ecological zones in a salt marsh are controlled by many factors, including hydroperiod, elevation, soil salinity, groundwater flow, competition, and nutrient/oxygen availability. The primary driving factor(s) are still debated, but most models of zonation consider elevation or hydroperiod as the key factor. This project is designed to gather high-resolution aerial images from a helium balloon kite (Helikite) to improve our understanding of the influence of hydroperiod on zonation. The Helikite was used to capture aerial photographs of Crab Haul Creek Basin, the most landward salt marsh basin in North Inlet, South Carolina. Near-IR photographs were taken from 75-100m altitude to resolve the waterline during rising tide from the headwaters to a tide gauge located 150m north.

We used Helikite visual light images and automated classification to identify ecological zones. Photographs taken during peak primary production have distinct pixel RGB values for the main groundcover types. After creating a signature file based on each groundcovers distinct pixel signature, maximum likelihood pixel-based computerized classification was applied. By quantifying the hydroperiod and comparing it to ecological zones we found that elevation and hydroperiod do not solely explain zonation. Other factors must be considered important, particularly groundwater flow and evapotranspiration.

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LIST OF ABBREVIATIONS

ADUDEM .... Australian National University Digital Elevation Model

DGPS .... Differential Global Positioning System

DTM .... Digital Terrain Model

GCP .... Ground Control Point

GPS .... Global Positioning System

MHW .... Mean High Water

MSL .... Mean Sea Level

NERR .... National Estuarine Research Reserve

NOAA .... National Oceanic and Atmospheric Administration

NW .... Northwest

OL .... Oyster Landing

PVC .... Polyvinyl Chloride Pipe

RGB .... Red Green Blue

RMSE .... Root-Mean-Squared-Error

RSLR .... Relative Sea Level Rise

SE .... Southeast

SLR .... Sea Level Rise

TFS .... Total Field Station

TLS .... Terrestrial Laser Scanner

CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

Salt marshes play an important role in coastal ecosystems, serving as a protective buffer from wind and ocean tides (King and Lester, 1995), as a nursery to marine life (Warlen and Burke, 1990; Wasserman and Strydom, 2011), and as a nutrient and pollutant filter between the marine and terrestrial realms (Nixon, 1995; Kadlec and Knight, 1996; Comín et al., 1997). Problems like sea level rise and marsh restoration require a better understanding of the spatial and temporal movement of water within these systems.

Ecological zones within a salt marsh are marked by low plant species diversity and simple community structure. Each species of marsh plant occupies a marsh zone (low, middle and high) influenced by physical stresses and tolerance (Chapman, 1974). The driving factors affecting ecological zonation include elevation, hydroperiod, soil salinity, groundwater flow, adaptability, competition, and nutrient and oxygen availability. The primary driving factor(s) of zonation remains debated. Zones are often modeled by correlating only either elevation or hydroperiod to specific plant species (Kirwan and Mudd, 2012; Kirwan and Murray, 2007; Mariani et al., 2013) suggesting only these surficial processes control zonation. However, in Venice Lagoon (Italy) Silvestri et al., 2005 concluded that though tidal regime and soil salinity are factors of ecological zonation they do not explain the distribution of halophytic species. Thibodeau

et al., 1998 used observations from groundwater monitoring wells to conclude that groundwater flow is a more accurate predictor of zonation than elevation.

The hydroperiod is the period of flooding influenced by the wetlands storage capacity, water budget, and landscape contours (Manomaipiboon, 2007; Welsch et al., 1995). Mitsch and Gosselink, 2007 describe four types of hydroperiod relating to marsh zones: irregularly flooded (High marsh), regularly flooded (Mid and low marsh), irregularly exposed (high creek), and subtidal (creek thalweg). Hydroperiod is a key factor in wetland structure and function (Odum et al., 1995), but despite its role it remains poorly understood due to lack of data at relevant spatial scales.

Understanding the hydroperiod will become increasingly important as sea level continues to rise because it directly impacts ecological zonation, erosion, accretion, and marsh evolution. The stability of a salt marsh in response to relative sea level rise (RSLR) requires maintaining elevations suitable for growth by accumulating and trapping both organic and inorganic sediment (Cahoon and Reed, 1994; Morris et al., 2002). Equilibrium of a salt marsh is affected by the rate of RSLR, tidal range, and the productivity of marsh plants. Marshes are considered stable when marsh elevation is greater than the optimal elevation for primary production (Morris et al., 2002).

The purpose of this study is to quantify the hydroperiod at Crab Haul Creek Basin and look for correlations to ecological zonation and elevation. If hydroperiod is the main driving factor of zonation, symmetry will be seen between the northwestern and southeastern sections of the basins, separated by the creek drainage divide. Zone boundaries will correlate with hydroperiods, and highly salt-tolerant plants will be seen throughout the basin, without influence from fresh groundwater flow. If elevation is a

proxy for hydroperiod (Kirwan and Murray, 2007) they will have a linear relationship across the low, middle, and high marsh. It has been previously noted that over large distances elevation correlates only weakly to inundation frequency as tidal water is not distributed equally over elevations but influenced by changing winds and watersheds (Bockelmann et al., 2002).

1.2 ECOLOGICAL ZONES

Spartina alterniflora is the dominant species in salt marshes of the southeastern United States. *Spartina* occurs in tall form on the low marsh near the creek (irregularly exposed hydroperiod) then short form across the middle marsh (regularly flooded hydroperiod) (Valiela et al., 1978; Mendelssohn et al., 1981; King et al., 1982; Gallagher et al., 1988). When *Spartina* dies its fallen stalks, *Spartina* wrack, are washed up and deposited on the middle and high marsh by spring tides and storm surges (Pennings and Richards, 1998). Wrack can lead to marsh shadowing preventing sun penetration resulting in the die off of the vegetation it covers leaving mud patches when washed away (Bertness and Ellison, 1987; Valiela and Rietsma, 1995). *Spartina's* lower boundaries are set by physical stress like flooding and salinity (Pennings et al., 2005) and *Spartina's* upper limits are set by competition from *Juncus roemarianus*.

Juncus grows on the high marsh (irregularly flooded hydroperiod) and is highly competitive (Redfield, 1972). *Juncus* has a low physical tolerance and performs poorly when transplanted at lower elevations with frequent inundation (Pennings et al., 2005). However, small populations have been reported on levees and sand deposits on the low and middle marsh (Redfield, 1972; Wiegert and Freeman, 1990). *Juncus* also increases

the performance of coexisting plants outside of the high marsh (Pennings et al., 2005). *Spartina* performs better in fresher waters when *Juncus* is present (Pennings et al., 2005).

Salicornia virginica grow in areas of high salinity on the high marsh (irregularly flooded hydroperiod) in salt flats between *Spartina* and *Juncus* zones (Weigert and Freeman, 1990; Pennings et al., 2005). Groundwater flow direction below *Salicornia* zones oscillates upward during neap tides and downward during spring tides (Thibodeau et al., 1998). This oscillation combined with proximity to a small freshwater lens allows evapotranspiration to dominate and hypersaline conditions to develop (Thibodeau et al., 1998).

1.3 SALINITY AND GROUNDWATER

Across the marsh basin the hydroperiod influences soil salinity and ecological zones (Mendelssohn et al., 1981). Highest soil salinities occur in the mid marsh (at mean high sea level) due to a peak in evaporation and shorter duration of inundation than the low marsh (Silvestri et al., 2005; Pennings and Callaway, 1992). Water salinity is influenced by freshwater from rain and groundwater, evaporation, and sediment properties (Lindberg and Harriss, 1973).

Groundwater flow patterns and rates are also controlled by precipitation, evapotranspiration, tidal fluctuations, discharge from freshwater adjacent uplands, hydraulic properties, and the geometry of marsh sediment (Wilson and Morris, 2012). Groundwater flow also plays an important role in soil salinity because large areas of freshwater discharge can inhibit salt water infiltration (Thibodeau et al., 1998).

Salt marshes and adjacent estuaries experience nutrient exchange from groundwater flow influenced by variations in tidal signal because porewater discharge

carries significant nutrients (Wilson and Morris, 2012). Hypersaline conditions can also develop in salt marshes depending on the tidal range and the size of the freshwater lens below the adjacent high marsh (Thibodeau et al., 1998). These hypersaline conditions produce *Salicornia* zones.

CHAPTER 2

STUDY SITE

2.1 NORTH INLET

Crab Haul Creek basin is located in North Inlet, South Carolina (Figure 2.1A) near Georgetown on the marsh lands of North Inlet NERR (National Estuarine Research Reserve). North Inlet is a bar-built barrier beach estuary (NOAA, 2006) dominated by tidal channels and is largely covered by Spartina alterniflora (Gardner and Porter, 2001). The inlet is flushed by tides twice a day, with more than 50% of its water discharging into the ocean (NOAA, 2006).

Crab Haul Creek Basin is the most inland creek system of North Inlet (2,000m long by 200m wide) and has a boundary adjacent to forest-marsh upland with a large freshwater lens. Crab Haul Creek has a mean tidal range of 1.2m, measured from the NOAA tide gauging station at Oyster Landing (OL) (Figure 2.1B) 2.8km upstream established in 1982. This study focuses on the headwaters region of the creek, an area reaching 200m east-west and 150m north-south. The average channel width in the headwaters tributary network is 1.5m. The main channel increases in average width from 4.5m widening to 7m at the edge of the study area. The study area is bordered to the north and south by previously established piezometer transects (Thibodeau, 1998). A local meter stick tide gauge station (Crab Haul Gauge) was positioned 150m north of the headwaters (Figure 2.1C). This study focuses on the

headwaters region of the basin because this area experiences marsh propagation (landward migration of creek, distinct ecological zones, and is small enough for the cameras to completely capture the spread of water during a half tidal cycle.

2.2 GEOLOGY

The oldest marsh deposits date from 3,500 years before present and transgressed over beach sand eroded by meandering channels. Since the Holocene, slow sea level rise (SLR) has governed the evolution of this marsh. Finger-shaped basins formed between the ridges when swales invaded by saltwater transformed forest into marsh. Crab Haul Basin is one of these intertidal salt marsh systems. The basin is closed to the south by a causeway (> 400m from the headwaters). It is flanked on the east by a Pleistocene beach ridge, and is flanked on the west by the forest-marsh boundary. The bottom of the creek is mostly comprised of detritus, fine sediment, and oyster shell hash. The creek drains the forested uplands and is considered to be fairly pristine (NOAA, 2006). Historic tide gauge records form Charleston Harbor indicate a RSLR of 0.361cm/yr over 50 years (1922-1972) (Kjerfve et al., 1978; Hicks and Crosby, 1974) and 210Pb profiles from North Inlet show a sediment accumulation rate of 0.14-0.45cm/yr which agreed with 137CS rates of 0.13-0.25cm/yr (Sharma et al., 1987). This indicates that North Inlet is keeping pace with RSLR, + 0.3cm/yr.

Vibracores were collected along Transects D and C in 1993 to evaluate the stratigraphy (Thibodeau, 1997) (Figure 2.1C). On the high marsh typically a sandy A soil horizon (10-15cm thick) is overlain by organic litter and underlain by a sandy, leached E soil horizon (10-20cm thick). Below the E horizon lies 60-150cm of a spodic horizon (Bh) of fine to medium-grained sand cemented by humus. Below this lie sand deposits

and a basal mud at least 50cm thick. Surface sediments near the headwaters on the low and mid marsh are characterized as mixed mud and sand. Low-permeability marsh mud thickness increases towards Transect D. Below this there is a unit of sand and mud modified from forest soil. Near transect D more silt and clays have been deposited yielding a thicker, broader mud layer than near the headwaters (Thibodeau, 1997).

2.3 HYDROLOGY

Piezometers were installed along transects D and C (Figure 2.1C) from 1994-1996, creating a detailed picture of groundwater flow patterns in a forest-marsh system. Three processes control groundwater flow in Crab Haul Creek: tidal forcing, precipitation, and evapotranspiration (Thibodeau, 1997). The importance and influence of these processes change with location in the basin. In the high marsh, precipitation and evapotranspiration control variation of the water table. In the low marsh tides control water table variation and mask the impact of precipitation and evapotranspiration. The mid marsh does not experience as large of a range of water level variation as the low marsh (Thibodeau, 1997).

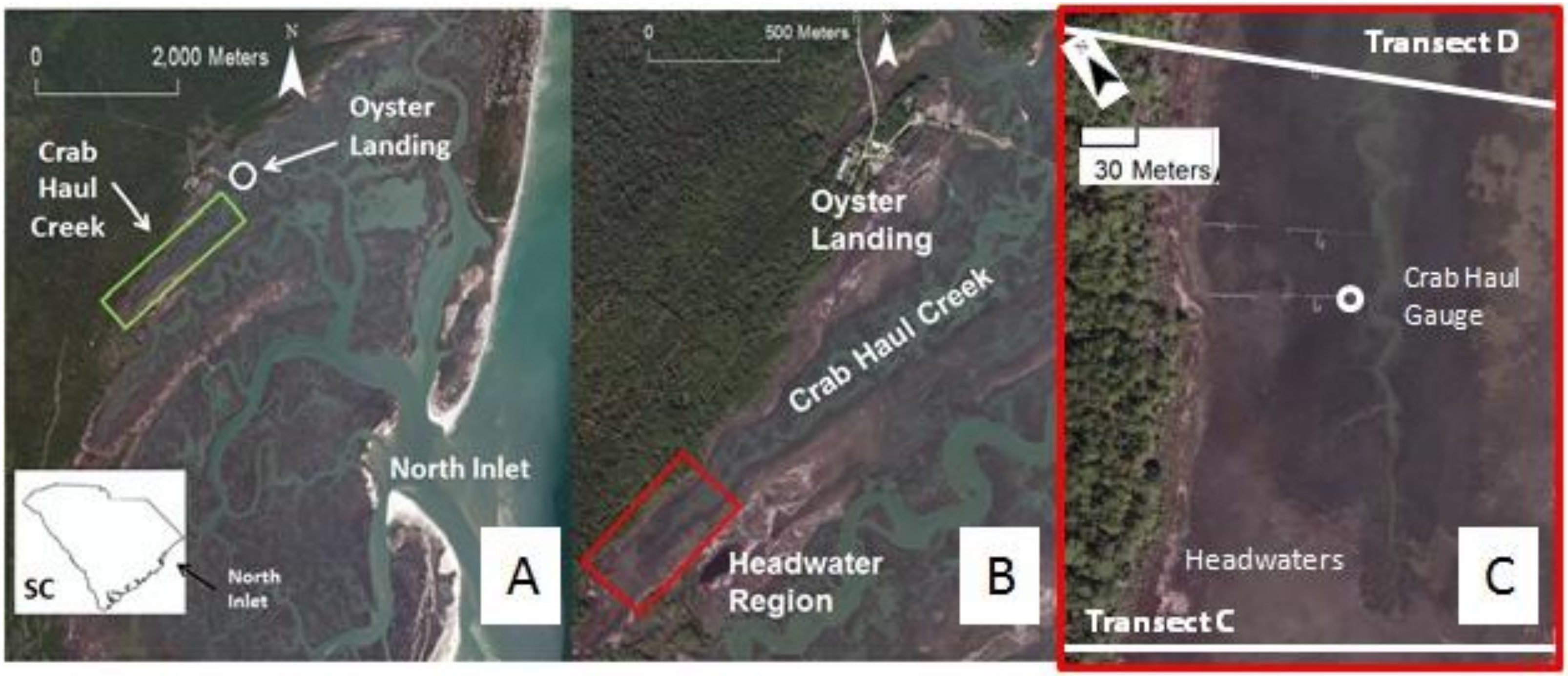


Figure 2.1: A: Map of North Inlet in South Carolina, Crab Haul Creek (green box) and NOAA tidal gauging station at Oyster Landing (white circle). B: Crab Haul Creek with the study area outlined in red. C: Study area of Crab Haul Creek Basin. Transects D and C were established by Thibodeau in 1997, Crab Haul tide gauge is located off the first boardwalk (white circle).

CHAPTER 3

METHODS

3.1 FIELD EQUIPMENT

3.1.1 HELIKITE

Aerial photographs were captured using a 1.6m^3 helium balloon mounted to a kite, Helikite (e.g.Vericat et al., 2009) (Figure 3.1). The Helikite allows for frequent, inexpensive deployment for gathering high-resolution, low-altitude aerial images. Other advantages include maneuverability, the ability to stay aloft in one position for long periods of time, and rapid deployment. The Helikite can operate in winds up to 30mph, carry 250grams, and reach altitudes of 300m.

In this study the Helikite was operated from the ground using a standard rectangular reel and attached with braided Dacron Kite line, 500’ of 100 pound line. The balloon was typically flown in low wind speeds (5mph) and altitudes averaging between 60 to 100m. The Helikite is ideal to capture the waterline (wet vs. dry ground), delineate between ecological zones, and even image small crab burrows with centimeter sized diameters.

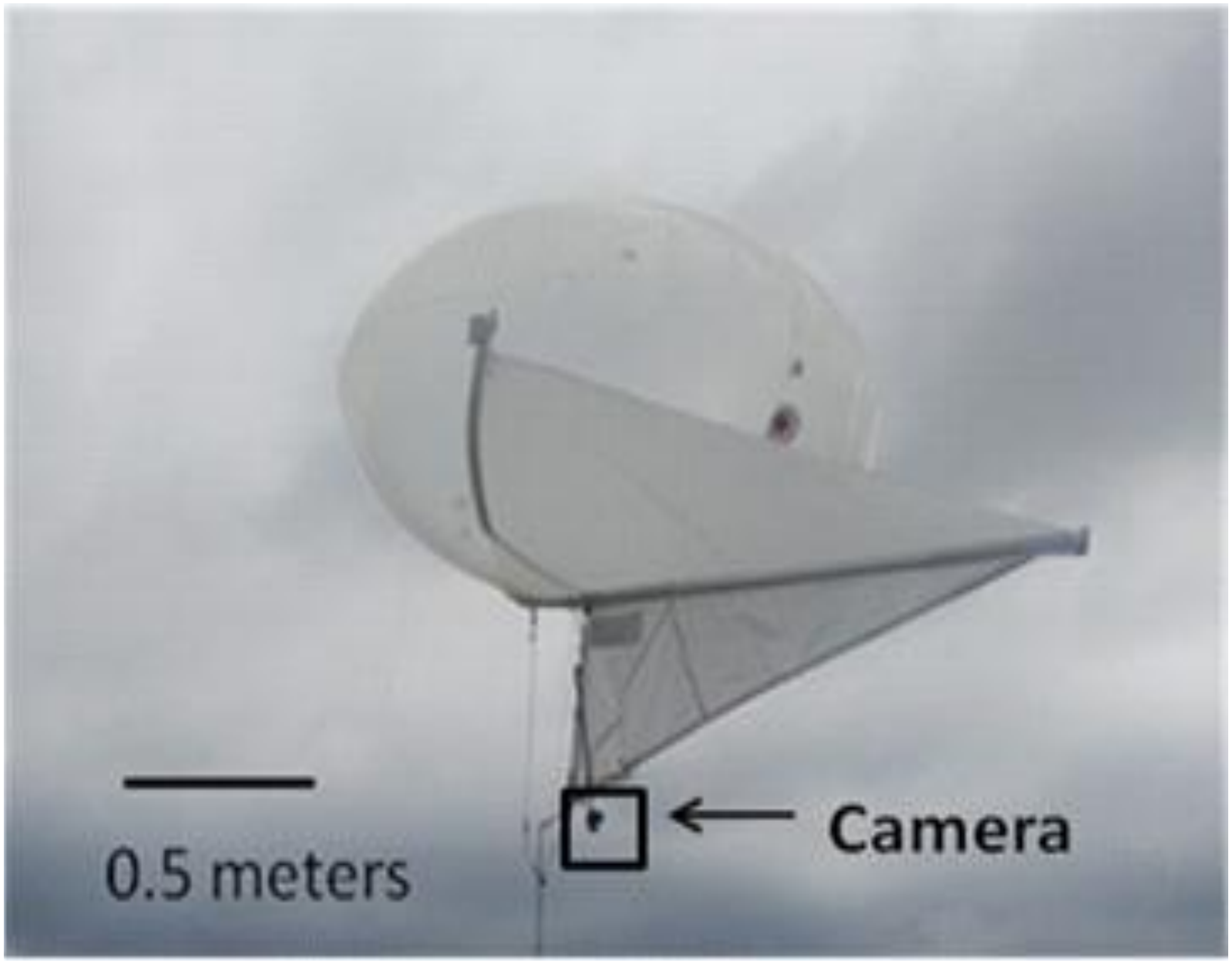


Figure 3.1: The Helikite fully inflated.

3.1.2 DIGITAL CAMERAS

Cameras used were a Canon Powershot ELPH 300 HS (12 megapixel resolution) and Canon S95 (10 megapixel resolution). The S95 was converted into a near infrared camera by replacing the internal low-pass filter over the image sensor with an infrared filter. We then used an amplified color IR filter (665nm) and ultraviolet filter (0-400nm). These filters made it is easier to delineate between wet and dry ground, because water absorbs light and appears darker in images while vegetation has a high reflectance and appears lighter. Memory cards were uploaded with extra scripting parameters, including an intervalometer, for continuous shooting at designated time intervals, using Canon Hack Development Kit.

3.1.3 GROUND CONTROL POINTS AND GPS

Ground control points (GCP) with known GPS location were photographed to georeference the photographs. Thirty-two GCP were constructed by mounting 25cm diameter bucket lids to PVC pipes (Figure 3.2) then distributing them across the marsh so each photograph contained 8-10 GCP. Accuracy of balloon-kite based remote sensing is dependent on spatial distribution of GCP and orthorectification (Eulie et al., 2013). Uncertainty includes errors in GPS positioning of GCP, root-mean-squared-error (RMSE) from georeferencing and rectifying images, and manual errors in digitization. We used a Trimble GeoXH DGPS with an accuracy of $\pm$10cm through post-processed differential correction.

Figure 3.2: Ground control points (GCP) 25 cm diameter bucket lids mounted to PVC pipes.

3.1.4 TIDE GAUGING STATIONS

A NOAA tide gauging station is located at OL 2.8km north of Crab Haul Creek's headwaters (Figure 2.1A) 2.031m below MSL. Local tide data was gathered from Crab Haul Gauge (Figure 2.1C). Water depth was recorded every 5 minutes by photographing Crab Haul Gauge and reading the depth of water photographed on the meter stick (Figure 3.3). The image time was then assigned to a tide height. Local data was compared to NOAA data from OL to establish vertical difference, 1.8m, between the stations and create a more complete tidal record. The creek bed at Crab Haul Gauge is 0.231m below MSL.

3.2 MOSAICKING AERIAL PHOTOGRAPHS

Images captured in the field were cropped and corrected for contrast, sharpening, and exposure. First sun spots, blurs, and vignetting were removed by cropping. Next image contrast increased by 100% (IR photographs) to further delineate between wet and dry ground. Contrast was not changed in visible light photographs used for ecological classification. Image sharpness was increased 150% in order to identify the waterline between individual stalks of *Spartina* and GCP's. Exposure varied significantly with sun and cloud cover. Exposure was corrected until short form *Spartina's* red pixel values were between 20-60, green 40-60, and blue 20-50, based on *Spartina's* brightness (0-255) RGB values during primary production for visible light photographs.

Corrected images were georeferenced by matching the photographed GCP to their GPS location. Each image contained at least 8 GCP to reduce the number of extreme errors and improve the transformation of the image onto the coordinate plane (Hughes et al., 2006). GCP were spread out throughout the entire image, spaced around borders and the center, to provide a stable warp (digital manipulation). Two types of GCP were used:

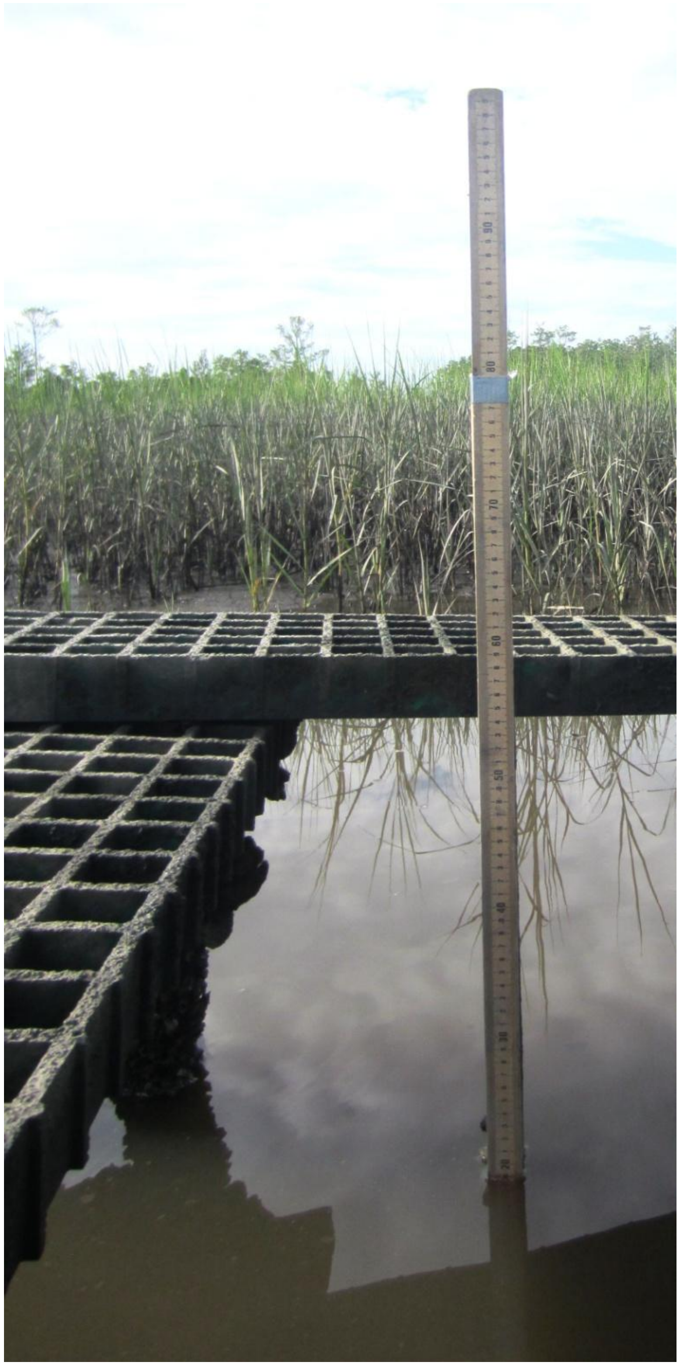


Figure 3.3: Meter stick tide gauge (Crab Haul Gauge) located at the northern end of the study site. Photograph was taken every 5 minutes and time was assigned to water levels. hard (boardwalks and bucket lids) and soft (*Spartina* stalks and crab burrows).

Hard points were favored (>8 per image) because they were easier to locate Soft points were used for georeferencing lower altitude images with fewer GCP onto previously orthorectified images.

A second-order transformation was applied to warp the image onto the coordinate plane. Second-order was used because it did not excessively distort the image, common in third and higher order transformations (Hughes et al., 2006). GCP were assigned new coordinates. The difference between the original GCP location and position after the transformation was represented by the RMSE. The average RMSE of the GCP was 3.4 X 10^{-9}m, effectively zero.

Photographs of the same tide heights were combined into a single mosaic raster. Pixels were removed by selecting only the topmost layer of each overlapping zone to be represented in the final mosaic. Mosaics maintained the same number of bands (3) and bit depth (brightness, 0-255) as the original. Multiple mosaics were created from low to high tide of different tide heights (Figure 3.4).

3.3 CREATING A DIGITAL TERRAIN MODEL

We created a cm-level Digital Terrain Model (DTM) to determine the hydroperiod spatially. Waterlines, representing a single tide height, acted as elevation contours. We used two types of waterlines, hand digitized from photomosaics and manually walked with a GPS. Additional elevation points were provided by a Sokkia 30R Total Field Station (TFS) and a Leica Terrestrial Laser Scanner (TLS) in areas that were inundated only during spring tides, above tides captured by Helikite imagery.

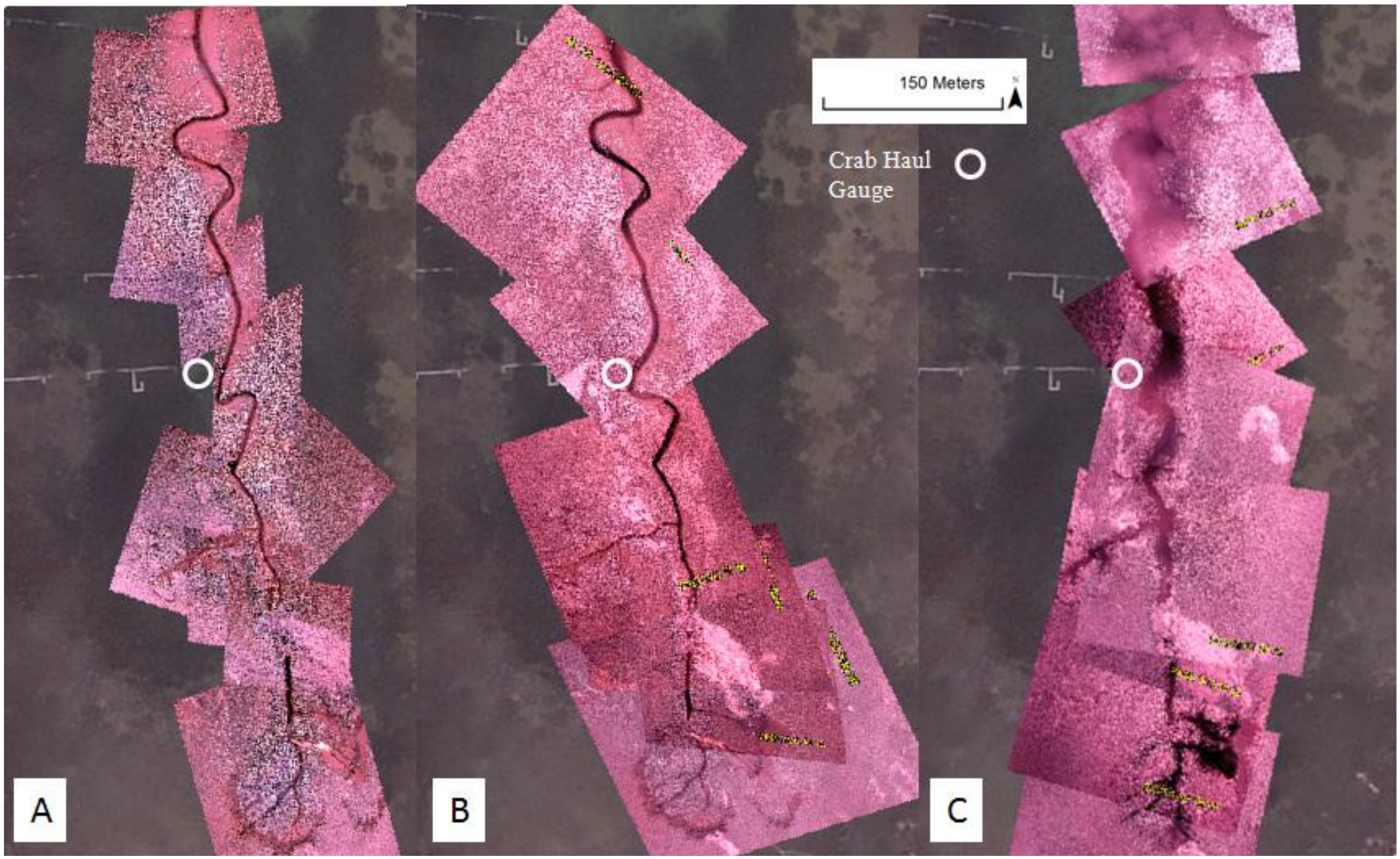


Figure 3.4: Photo mosaic of IR images of 3 tide heights. Panel A is low tide, Panel B mid tide, and Panel C high tide (neap tide).

3.3.1 DIGITIZED WATERLINES

We digitized waterlines from photo mosaics of different tidal heights (Figure 3.4) and individual images (Figure 3.5) by flying the balloon 90-105 m altitude while walking up and down the creek during rising tide (Figure 2.1C). It was important to capture a single tide height so the depth of water at the end of the creek was the same as the headwaters in each photomosaic. Typically it took 5-7 minutes to walk the 150m distance of the study area with tide rising 0.5m/minute, approximately 3 hours before high tide. Direction and path of walking the balloon was dictated by wind speed and direction. Ideal conditions were low wind speeds, 3-5mph, though the Helikite was flown in up to 15-20mph winds. Using the photo mosaics of tide elevations, waterlines were digitized manually along the contrast edge in photographs (Figure 3.5). Photograph time was then compared to Crab Haul Gauge to determine tide height.

The Helikite remained aloft and stationary, photographing the spread of water every minute, above the headwaters and a large tributary on the northwestern side of the basin. These images were georeferenced and image time was compared to Crab Haul Gauge to determine tide height/elevation. Waterlines were digitized every 5-7 cm increase in tide height. Eighty-one waterlines ranging from -21 to 32 cm MSL were drawn. Accuracy of digitized waterlines depended on the RMSE of the photo mosaic and changes in water level between images taken at the headwaters and Crab Haul Gauge. Tide rose an average of 0.5cm/minute in the latter half of rising tide, therefore waterlines in images taken minutes apart had an error of $\pm$3cm in tide height.

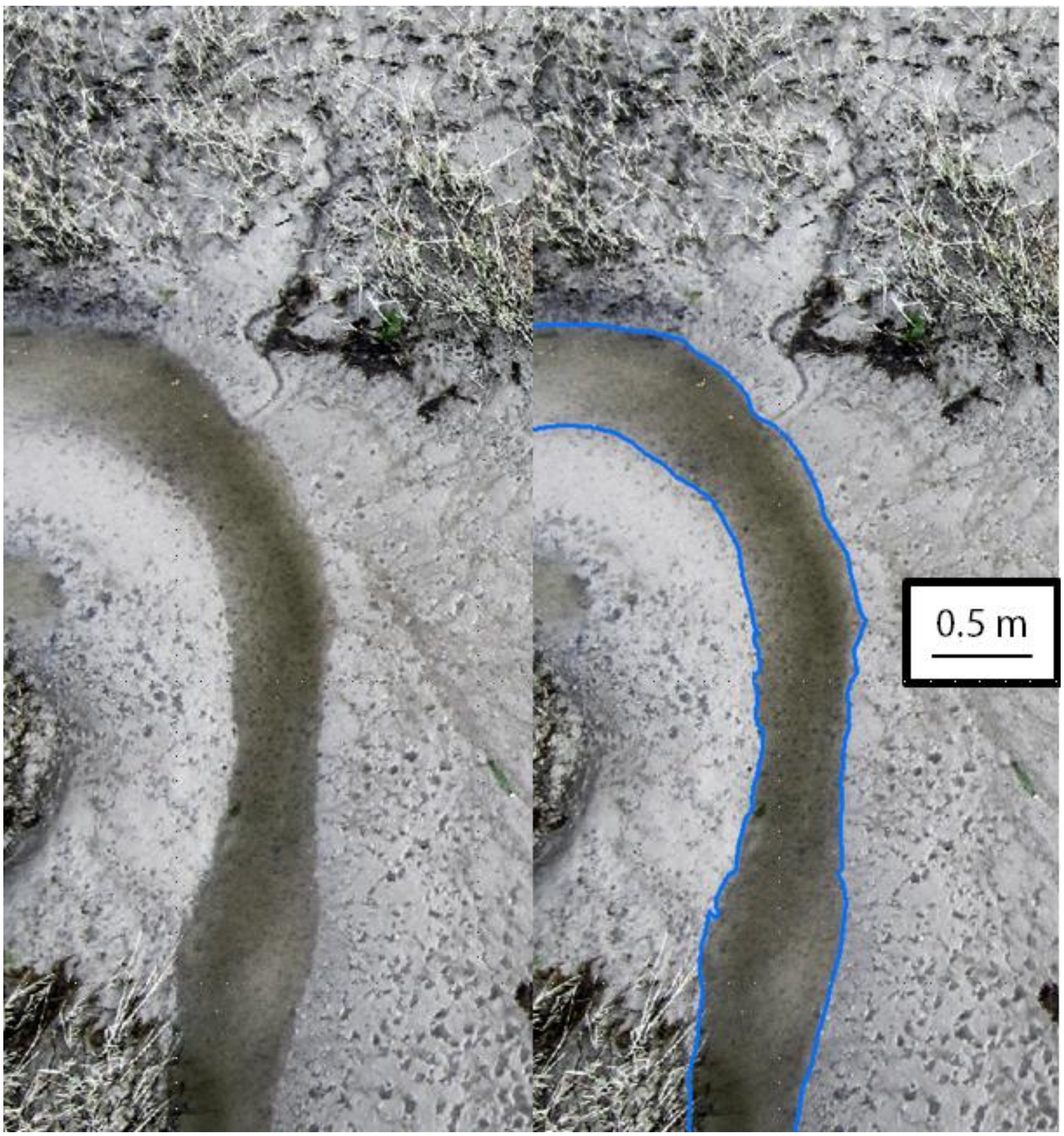


Figure 3.5: Digitizing the waterline by manually drawing the boundary between wet and dry ground.

3.3.2 GPS WATERLINES

At high tides it was difficult to capture the spread of water with aerial photography as patches of vegetation and Spartina wrack became denser and the Helikite was challenging to fly near the forest. To overcome this difficulty, waterlines were manually recorded by walking the waterline with GPS. TerraSync software on the GPS recorded one differentially corrected position every two seconds resulting in 150-200 position records during the 5-7 minute walk, or 1point/meter.

3.3.3 TOTAL FIELD STATION

The TFS gathered additional elevation data where waterlines were not recorded. PVC pipes were positioned as targets along the high marsh. The Locations of PVC targets were recorded using the Trimble GPS. TFS points were referenced to Crab Haul Gauge by back sight shots. The TFS had a distance accuracy of ±3mm for less than 100m from the station using white reflectorless mode. Additional error was associated with the size of the target and sinking in marsh mud (±2cm).

3.3.4 TERRESTRIAL LASER SCANNER

We shot the TLS in three locations around the headwaters using 4 GCP with GPS locations. Point clouds with X, Y, Z, red, green, blue, and intensity values were extracted and georeferenced using GPS locations from the stations and GCP. The TLS was shot with 12.5mm resolution at 10m and scan quality of 2pulses/second. The point clouds had a RMSE of ±0.047 m after georeferencing.

The TLS was shot in November, not during primary production, so brightness 0-255 RGB values were not different enough between bare earth and dead vegetation to act as a filter. To differentiate the returns and reference TLS to the other elevation data TFS

points located in known bare earth were given a 0.25 m buffer. TLS points that intersected the TFS buffers were selected and the lowest z value, bare earth, was determined. The TFS and TLS elevations (cm) were plotted against each other and a linear regression was fit with a R^2 value of 0.8227. The average difference in elevation between TLS and TFS in bare earth was $\pm$2cm. The TLS elevation data was correlated to the waterline and TFS data and vegetation returns were removed by selecting points within $\pm$10 cm of the waterline/TFS data. The point cloud was down sampled to 200 random points 4m apart.

3.3.5 COMBINING ELEVATION DATA

All 4 methods of elevation measurements were combined (points and lines) and interpolated to create a DTM (Figure 3.6). This interpolation method used an algorithm, ADUDEM (Hutchinson, 1988, 1989, 1996, 2000; Hutchinson et al., 2011), which created a surface representing a natural drainage. The algorithm created a general drainage model of the surface based off the curvature of the contours and inputs point elevation. This method of interpolation combined both local interpolations (inverse distance weighted) with global methods (spline and kriging) and imposed constraints that resulted in a connected drainage pattern with correct ridge and stream representations (Wahba, 1990). DTM error was estimated by comparing recorded data points to their position on the interpolated model. All elevation data fell in their correct interpolated surface of the DTM. Overall GCP GPS error was $\pm$10cm. Additionally, waterlines had an error of $\pm$3cm, TFS error of $\pm$2cm, and TLS error of $\pm$5cm from georeferencing and $\pm$12cm from TFS correlation.

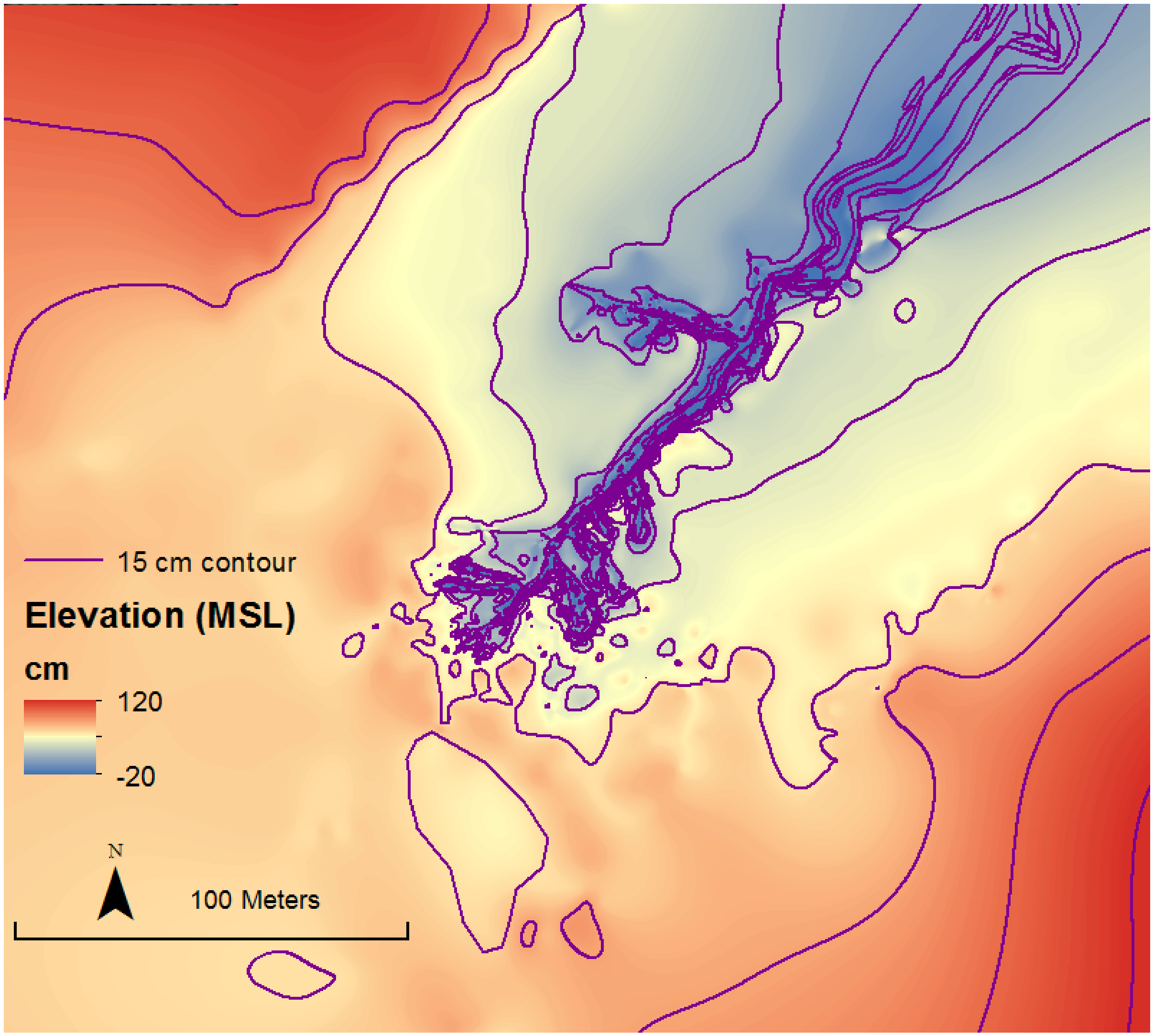


Figure 3.6: DTM of Crab Haul Creek using waterline contours and elevation points from TFS and TLS with contours every 15 cm.

3.4 ECOLOGICAL ZONES

Zones were determined from visible light photomosaic taken from the Helikite on June 28, 2013. The zones classified in this study include tall and short form *Spartina alterniflora, Spartina* wrack, bare earth (sand and mud), *Juncus roemarianus,* and *Salicornia virginica*. Maximum likelihood classification was applied to the photomosaic by creating a signature file from locations of known ecological zones and back tested using a different set of field observations. The signature file was created from training sample groups of each ecological zone. Training samples were created by selecting ten groups of ~300 pixels (0.5m^2) of each zone from different sections of the photomosaic.

Because zones had overlap in spectral signatures and certain zones occupied larger areas of the marsh we created an *a priori* file of the probability of each zone existing in the study site. This was done by taking the output of the first maximum likelihood classification and the original photomosaic to digitize polygons over general zone areas. Polygons were then divided by the total study area and produced the following probabilities: short *Spartina* 0.40, tall *Spartina* 0.21, mud 0.12, *Salicornia* 0.09, sand 0.04, *Spartina* wrack 0.05, and *Juncus* 0.09. The a prior file does produce a bias in the classifier as pixels who's spectral signatures are between two classes will be designated to the class with the highest probability.

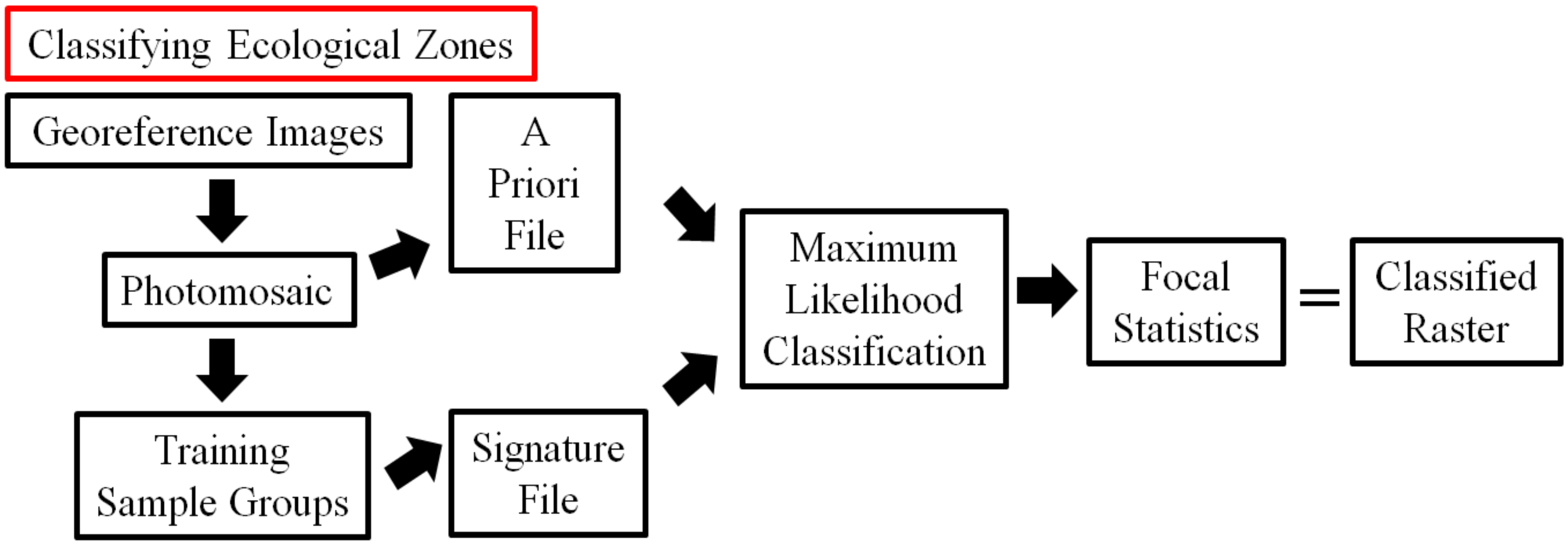
Maximum likelihood classification was applied to the photomosaic and assigned each cell to a class (Figure 3.7). The a priori file assigned cells that fell in overlap between spectral signatures. To reduce speckle and further define ecological zones, a majority filter replaced cells using a circular neighborhood with 0.25m radius (Figure 3.7).

3.4.1 CLASSIFICATION ACCURACY

Accuracy was tested by comparing field observations to the classification raster. The ecological zone for each GCP and TFS point was recorded during the six months of data collection, totally 250 points. GCP and TFS points did not distinguish between sand and mud, so they were combined into a single bare earth class. An error matrix was created by comparing the number of times a zone was classified correctly to the total number of observations in that class (Table 3.1). The maximum likelihood classification had an overall accuracy of 84%.

The Landis and Koch 1977 scale indicates that values less than 0 have no agreement, 0-0.20 have slight, 0.21-0.40 are fair, 0.41-0.60 are moderate, 0.61-0.80 are substantial, and 0.81-1 are almost perfect. Another by Fleiss 1981 indicates values under 0.40 as poor, between 0.40-0.75 as fair to good, and above 0.75 as excellent. In either case the overall accuracy of this raster is almost perfect to excellent.

Some individual categories have lower accuracies. Tall *Spartina* has a producer accuracy of 0.64 and short *Spartina* has a user's accuracy of 0.67 falling into Landis and Koch's substantial category and Fleiss' fair to good. All other individual categories are within the excellent to almost perfect portion of the scales. Error is more likely to be found between tall and short *Spartina* since they are the same species with similar spectral signatures. If short and tall *Spartina* are combined into a single classification overall accuracy increases to 91%.



1. Georeference images: Visible light photographs were georeferenced by attaching photographed GCP to their GPS location and transforming the image onto the coordinate plane.
2. Photomosaic: Georeferenced images are combined into a single raster layer to get rid of overlap between images, removing pixels below the topmost image in overlapped areas.
3. Training Sample Groups: Ten groups of 300 pixels ($0.5m^2$) of a single ecological zone gathered across the photomosaic.
4. Signature File: These ten groups are then averaged to create a single spectral signature of each ecological zone with unique RGB values.
5. A Priori File: Because overlap between spectral signatures was observed between ecological zones an a priori file was created to designate probabilities of ecological zones by digitizing polygons of known ecological zones in the photomosaic and dividing polygons by the total basin area.
6. Maximum Likelihood Classification: Assigns each cell to a class based on the signature file and assign cells in overlapping signature files using the probability from the a priori file.

7. Focal Statistics: To reduce speckle a majority filter with a circle neighborhood (0.25m radius) was applied to reassign cells based on the majority class in each neighborhood.

Figure 3.7: Flow chart of ecological zone classification.

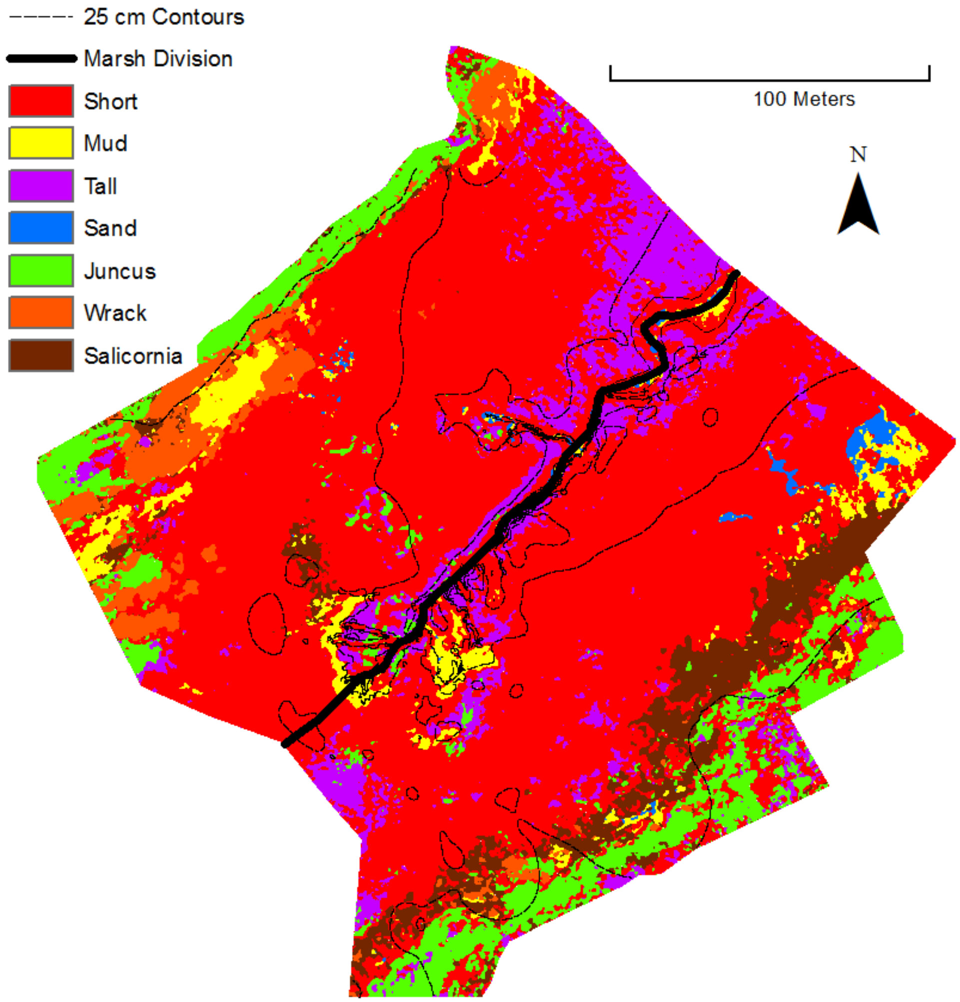


Figure 3.8: Maximum likelihood classification of ecological zones in the study area with a majority filter. The creek division is shown in black to separating the northwestern from the southeastern sections.

Table 3.1: Error matrix of the maximum likelihood classification application.

	Bare earth	Short	Tall	Juncus	Wrack	Salicornia	User Accuracy
Bare earth	30	0	0	0	0	2	94%
Short	3	64	17	5	0	6	67%
Tall	0	4	32	2	0	0	84%
Juncus	0	0	1	33	0	0	97%
Wrack	1	1	0	0	27	1	90%
Salicornia	1	0	0	1	0	43	96%
Producer Accuracy	86%	93%	64%	80%	100%	83%	

Overall accuracy = major diagonal/row sum → 229/274 = 84%

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3.5 CALCULATING HYDROPERIODS

Hydroperiods were calculated using 5 years (January 2008-2012) of tide data from OL. Average vertical distance between OL and Crab Haul Gauge was ±1.8m (Figure 3.9). Tidal cycles from Crab Haul Creek were recorded during low wind speed, <2.2m/s, so wind was not considered as a factor of tide height.

Hydroperiods were calculated for 10cm intervals of tide height from -20-130cm MSL by adding the number of minutes an interval was recorded as high to the time greater tide heights were recorded. For example in February 2009 the 0-9cm interval experienced inundation for the time 0-9cm was recorded as high tide from OL (3,120 minutes) and all minutes of tide height >9cm (9,930 minutes). This resulted in a total inundation time of 13,050 minutes of 40,302 minutes, or 32% of the month of February. The highest water level recorded in the 5 year record was 1.38 m in August of 2011 during Hurricane Irene (Figure 3.10).

3.6 COMBINING ELEVATION, HYDROPERIOD, AND ECOLOGICAL ZONATION

Elevation and hydroperiod were compared by calculating hydroperiods per 10 cm elevation intervals and fitting a line to the points (Figure 3.10). The relationship between ecological zonation and hydroperiod and elevation was determined by calculating the percent of each ecological zones in 10cm intervals for elevation and 5% intervals for hydroperiod. The percentage of each zone in 10 cm intervals was determined by extracting the elevation interval from the DTM and calculating the ecological zones in that area from the maximum likelihood classification. Areas of ecological zones per 5% hydroperiod intervals were determined by using the linear regression equation (Figure

3.10). We then extracted the hydroperiod interval from the DTM and calculated the percentage ecological zones within each hydroperiod.

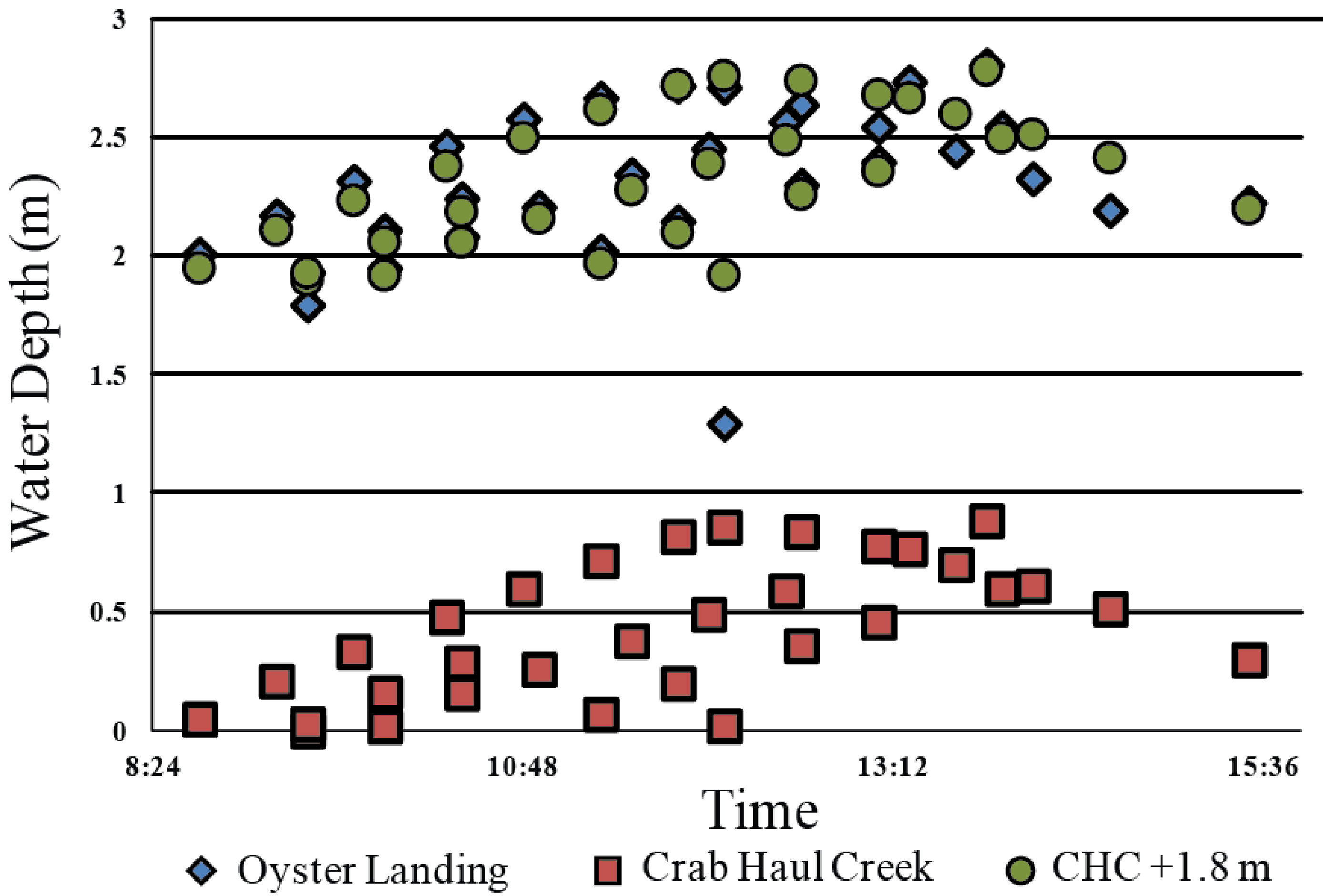

Figure 3.9: Vertical difference between Oyster Landing and Crab Haul gauges.

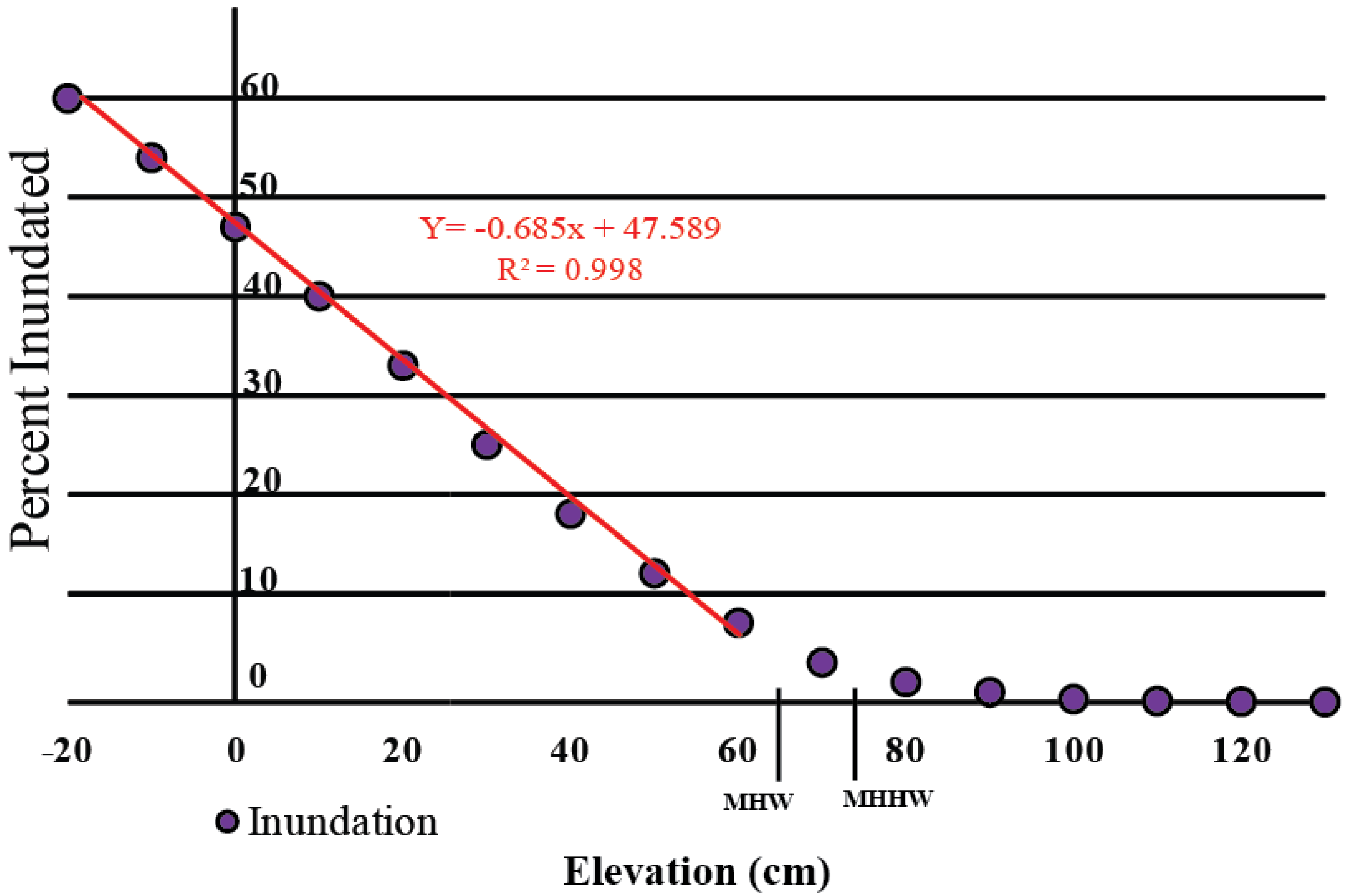

Figure 3.10: The annual inundation (hydroperiod) of 10 cm elevation intervals. Elevation and hydroperiod have a linear relationship on the middle and low marsh below MHW, after which the relationship falls apart.

CHAPTER 4

RESULTS

4.1 RELATIONSHIOP BETWEEN HYDROPERIOD AND ELEVATION

Hydroperiod was calculated for 10cm intervals from OL data converted to the Crab Haul Gauge datum (Figure 3.10). Our local observations demonstrate a linear relationship between elevation and hydroperiod for elevations below 64cm, mean high water (MHW). There is an apparent break near the high marsh when inundation becomes infrequent, <5% a year. On the high marsh inundation decayed in a roughly exponential manner until reaching elevations not recorded as flooded in the years of 2008-2012. Elevations above MHW are influenced by wind, which was not accounted for in this study.

4.2 PERCENTAGES OF ECOLOGICAL ZONES

Percentages and areas of each ecological zone were calculated for the total basin area, the northwest (NW), and the southeast (SE) (Table 4.1). Each hydroperiod and elevation interval contained several types of ecological zones. Mud, Short *Spartina*, Tall *Spartina*, and sand were found in the creek (-20-20cm inundated annually 60-40%). Tall and short *Spartina* were prominent on the low marsh (20-40cm inundated annually 35-20%). On the mid marsh (40-80cm inundated annually 15-5%) short *Spartina* alone dominated. On the high marsh (elevations >80cm inundated <5% annually) *Juncus*, *Salicornia*, and *Spartina* wrack were the main ecological zones.

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4.3 ASYMMETRICAL ECOLOGICAL ZONES

The basin was divided by the creek to assess symmetry between the NW and SE. If hydroperiod or elevation were the primary controlling factors of zonation, symmetry of ecological zones would be seen across the basin. Symmetry however was not seen in terms of elevation, hydroperiod, or ecological zonation (Table 4.2 and 4.3) (Figure 4.1 and 4.2). Short *Spartina* was the prevailing ecological zone and occupied approximately the same area in the NW as the SE. It was most prominent on the mid marsh (Figure 4.2) with a hydroperiod between 5-15% (Figure 4.3). Tall *Spartina* dominated near the creek bank and was the most abundant ecological zone on the low marsh, particularly in the NW which had a large tributary network (Figure 4.2). Tall *Spartina* was additionally found on the middle marsh and was more prominent in the SE where the hydroperiod was between 10-20% (Figure 4.3).

Spartina wrack was found on the high marsh in the NE (Figure 4.2). The prevailing wind direction is to the southwest from the mouth of the basin to the headwaters with speeds averaging 3-4m/s (Kjerfve, 1978). Mud was found in high concentration with sand in the creek channel but also in the NE on the high marsh (Figure 4.2). Sand was also found in the SE on the middle marsh and may be salt pans, or areas of high salinity where plants are unable to grow (Figure 4.2).

The high marsh was primarily occupied by *Juncus* and inundated <2% annually (Figure 4.3). This area was twice as large (from middle marsh to upland forest) in the SE. We observed *Juncus* sporadically in clusters around the headwaters on the middle and low marsh (Figure 4.2). The small lower elevation clusters do not overlay elevation uplifts and levees on the DTM (Figure 3.6) as previously reported. This suggests another

source is allowing *Juncus* to flourish on the lower marsh while maintaining its physical limitations in salinity. Eighty-six percent of all *Salicornia* identified was in the SE (Figure 4.2). *Salicornia* is almost absent in the NW on the middle-high marsh.

Table 4.1: Percentages and area of ecological zones in Crab Haul Creek Basin produced from the maximum likelihood raster

	Total Study Area ($46,700\ m^2$)		Northwestern Section ($22,410\ m^2$)		Southeastern Section ($23,780\ m^2$)	
	Percentage	Area m^2	Percentage	Area m^2	Percentage	Area m^2
Short	66%	30,620	67%	15,000	65%	15,440
Mud	4%	1,900	4%	960	4%	960
Tall	10%	4,500	11%	2,400	8%	1,950
Sand	<1%	370	<1%	95	<1%	270
Juncus	9%	4,300	7%	1660	11%	2,500
Wrack	4%	2,060	8%	1840	1%	190
Salicornia	6%	3,000	2%	400	10%	2,470

Table 4.2: Percentage of each ecological zone at a given 10 cm elevation interval rounded to the nearest whole number. T= total basin area, S = southeastern section, N = northwestern section. Highest ecological percentages are highlighted in red. Yellow boxes indicate creek, green boxes low marsh, orange mid marsh, and blue high marsh

Elevation MSL (cm)	% total area	Short			Mud			Tall			Sand			Juncus			Wrack			Salicornia		
		T	S	N	T	S	N	T	S	N	T	S	N	T	S	N	T	S	N	T	S	N
(-21)-(-11)	0	38	25	64	31	35	22	24	33	6	7	7	8	0	0	0	0	0	0	0	0	0
(-10)-(-1)	0	50	45	56	31	33	28	9	15	2	10	7	14	0	0	0	0	0	0	0	0	0
0-9	1	62	52	73	14	21	7	13	22	2	11	5	17	0	0	1	0	0	0	0	0	0
10-19	3	63	63	62	12	23	5	19	10	25	5	4	6	1	0	2	0	0	0	0	0	0
20-29	4	43	54	39	5	15	1	51	31	59	0	0	0	1	0	1	0	0	0	0	0	0
30-39	5	58	52	59	3	12	1	38	35	38	0	0	0	1	1	2	0	0	0	0	0	0
40-49	9	84	74	87	2	6	0	14	19	12	0	0	0	0	1	1	0	0	0	0	0	0
50-59	20	90	89	92	2	2	1	5	6	4	2	3	0	1	0	2	0	0	1	0	0	0
60-69	21	73	73	71	7	5	10	5	7	1	1	1	1	3	1	6	2	0	10	9	13	1
70-79	27	56	52	59	4	2	6	4	6	3	0	0	0	13	16	12	10	2	16	13	22	4
80-89	8	34	33	37	3	2	4	4	5	0	0	0	0	42	46	27	7	2	26	10	12	6
90-99	2	25	37	0	0	0	1	14	22	0	0	0	0	54	40	82	5	0	14	2	1	3
100-109	0	29	56	0	1	3	0	9	18	0	0	0	0	52	13	93	0	0	0	9	10	7

Table 4.3: Percentage of each ecological zone at 5% hydroperiod interval rounded to the nearest whole number. T= total basin area, S = southeastern section, N = northwestern section. Yellow boxes indicate creek, green boxes low marsh, orange mid marsh and high marsh (less than 5% inundation)

Hydroperiod	% total area	Short			Mud			Tall			Sand			Juncus			Wrack			Salicornia		
		T	S	N	T	S	N	T	S	N	T	S	N	T	S	N	T	S	N	T	S	N
60	0	40	27	62	32	36	25	21	30	5	7	7	8	0	0	0	0	0	0	0	0	0
55	0	48	42	56	33	35	30	10	16	2	9	7	12	0	0	0	0	0	0	0	0	0
50	0	56	50	61	18	23	14	11	18	3	15	9	22	0	0	0	0	0	0	0	0	0
45	0	65	53	76	14	22	7	13	23	4	7	2	12	1	0	1	0	0	0	0	0	0
40	2	64	61	67	14	26	6	14	8	17	6	5	7	1	0	2	0	0	0	1	0	1
35	3	46	60	39	6	15	1	46	25	58	1	0	1	1	0	1	0	0	0	0	0	0
30	3	41	48	40	3	11	1	55	41	58	0	0	0	1	0	1	0	0	0	0	0	0
25	4	62	55	64	3	12	0	33	32	34	0	0	0	2	1	2	0	0	0	0	0	0
20	7	82	70	86	2	8	0	15	21	13	0	0	0	1	1	1	0	0	0	0	0	0
15	13	92	90	93	1	2	1	6	8	4	0	0	0	1	0	1	0	0	1	0	0	0
10	16	86	85	88	4	4	4	4	5	3	3	5	1	1	1	3	1	0	1	1	0	0
5	52	55	54	57	4	2	7	5	7	2	0	0	0	17	18	14	7	1	16	12	18	4

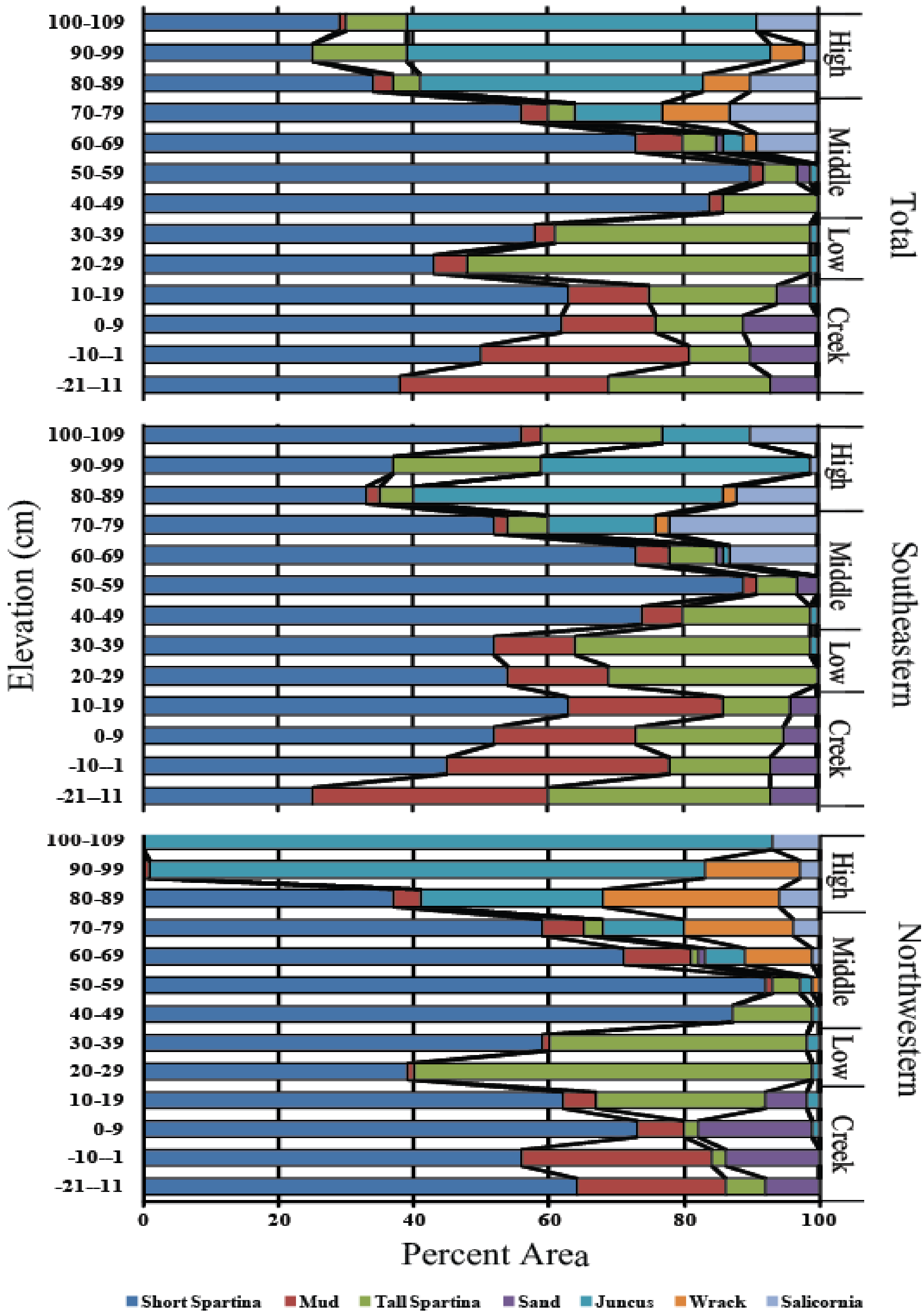

Figure 4.1: Graphical representation of percentages of ecological zones at elevation intervals for the total basin, northeastern section, and southeastern section.

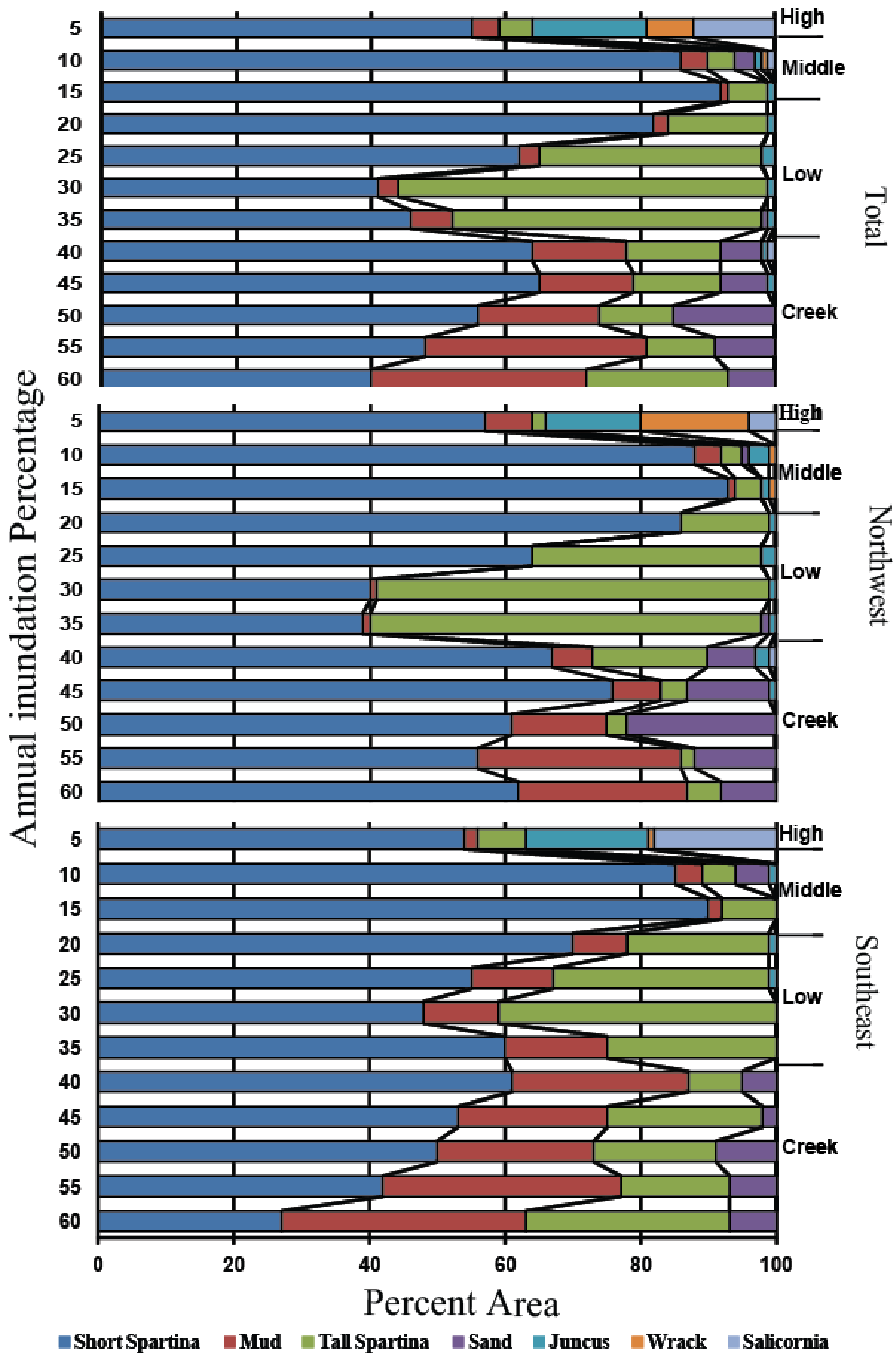

Figure 4.2: Graphical representation of percentages of ecological zones at hydroperiod intervals for the total basin, northeastern section, and southeastern section.

CHAPTER 5

DISCUSSION

5.1 ECOLOGICAL ZONATION

This work supports the finding of Thibodeau et al., 1998 that ecological zone distribution in salt marshes is controlled by groundwater flow, expanding findings from Transect D and C to the entire headwater region (Figure 2.1C). Salt marsh models that include ecological zonation as a factor influencing marsh processes (i.e. marsh evolution, accretion, erosion, relationship to SLR) still only attribute specific species to an elevation and/or hydroperiod (Kirwan and Mudd, 2012; Kirwan and Murray, 2007; Mariana et al., 2013). Groundwater flow needs to be included in models and fitness curves as a driving factor of zonation. When multiple species are modeled based on elevation or hydroperiod our observations do not correlate with their results. Ecological zones, particularly *Salicornia*, *Juncus*, and tall *Spartina*, were seen dominating different hydroperiods on opposite sides of the channel, which we suspect to be based on their proximity to uplands and groundwater flow.

The size of the adjacent upland, gradient, and distance to the creek influences the amount of freshwater flowing into the basin. The NW side of Crab Haul Creek is adjacent to a forest-marsh boundary and we believe has a large freshwater lens. The NW also has a steep gradient and short distance to the creek which we speculate could cause more freshwater to flow into the basin. This would prevent salt water

infiltration and evapotranspiration from forming hypersaline zones and the presence of marsh halophyte species. We also hypothesize that the higher upward flow of freshwater reduces soil salinity and allows high marsh plants to be present at lower elevations. The SE portion of the marsh is adjacent to a marsh island and we believe it has a smaller freshwater lens. The SE also has a longer distance to the creek and a shallow gradient. We assume this allows salt water to infiltrate during spring tide and evapotranspiration to occur during neap tide resulting in hypersaline zones on the middle and high marsh. The lack of freshwater flushing the root zone would lead to more saline soils and encourage salt tolerant low marsh plants to grow on the middle marsh (Figure 5.1.)

Crab Haul Creek is the most inland salt marsh basin in North Inlet and is adjacent to both a forest-marsh boundary and a marsh island. Other salt marshes may be located between marsh islands, forested areas, or near the inlet. Predicting groundwater flow patterns could be accounted for in different marsh upland scenarios by measuring the hydraulic distance from the creek to the upland and estimating the size of the freshwater lens. The freshwater lens, distance to the creek, and gradient could be used to predict the upward flow of freshwater and thus the development of hypersaline zones, groundwater flow, and soil salinity.

Elevation has been used as a proxy for hydroperiod in models to distribute ecological zones (Kirwan and Murray, 2007), and our local observations demonstrate a linear relationship between elevation and hydroperiod for elevations below 64cm or MHW (Figure 3.10). We believe that elevation can be used as a proxy for hydroperiod on a local scale, being less reliable on the high marsh. When considering the break at the high marsh it is clear that a small change in elevation would significantly influence the

hydroperiod. It may be appropriate for small, simple, local models to use elevation as a proxy for hydroperiod, but this relationship lessens with larger areas and in the transition from frequent to infrequent inundation.

5.2 IMPACT OF RELATIVE SEA LEVEL RISE

If marsh elevation is below optimal primary production it is unstable and unable to keep pace with RSLR (Morris et al., 2002). At higher rates of RSLR and low marsh elevations marshes cannot vertically accrete in time to compensate the increase in the tidal prism. We speculate that a longer and larger hydroperiod could increase the area with a net downward groundwater flow direction and widen the distribution of tall *Spartina* into the short *Spartina* zone. On the high marsh increased hydroperiod and soil salinity could cause *Juncus* to retreat to higher elevations and allow short *Spartina* to take over.

We hypothesize that the redistribution of zones would influence erosion and accretion on the marsh. Vegetation stalks dissipate wave energy while roots hold soil in place (Environmental Concern, 2012). If the hydroperiod increases past the physical threshold of marsh plants, causing them to die out or relocate, water velocity would increase and erode the creek channel. Sediment deposition is controlled by the hydroperiod, with sediment mobility greatest during storm events and increased hydroperiod (Cahoon and Reed, 1994). More sediment will be distributed onto the marsh surface, but if plants have retreated due to increased flooding there would not be any means to trap the sediment and build up elevation.

In North Inlet most of the marsh is located at elevations higher than optimal primary production (Morris et al., 2002). Maintaining higher elevations increases

productivity and enhances sediment deposition by increasing sediment trapping efficiency, suggesting that North Inlet is keeping pace with RSLR (Morris et al., 2002). Since marsh elevation is already higher than RSLR the marsh has more time to slowly accrete sediment and build vertically with small centimeter level elevation changes. These small changes influence the hydroperiod and the distribution of ecological zones especially when transitioning from frequent to infrequent flooding. We postulate that as RSLR continues it will impact ecological zonation of both marshes in stable and unstable equilibrium.

As sea level rises and marsh elevation increases there should be a landward migration of the marsh (Gardner and Porter, 2001) through headward propagation. Rapid rate of headward erosion suggest that the marsh is unable to keep up with RSLR through accretionary processes. Some marshes in South Carolina, like Cape Romain in the Santee River Delta, are eroding at a rate of 1.9 m/yr (Hughes et al., 2009). However, in Crab Haul Creek Basin no headward propagation was recorded in aerial photographs from January – August 2013 suggesting that Crab Haul Creek is not experiencing headward propagation at a high rate and is keeping pace with RSLR.

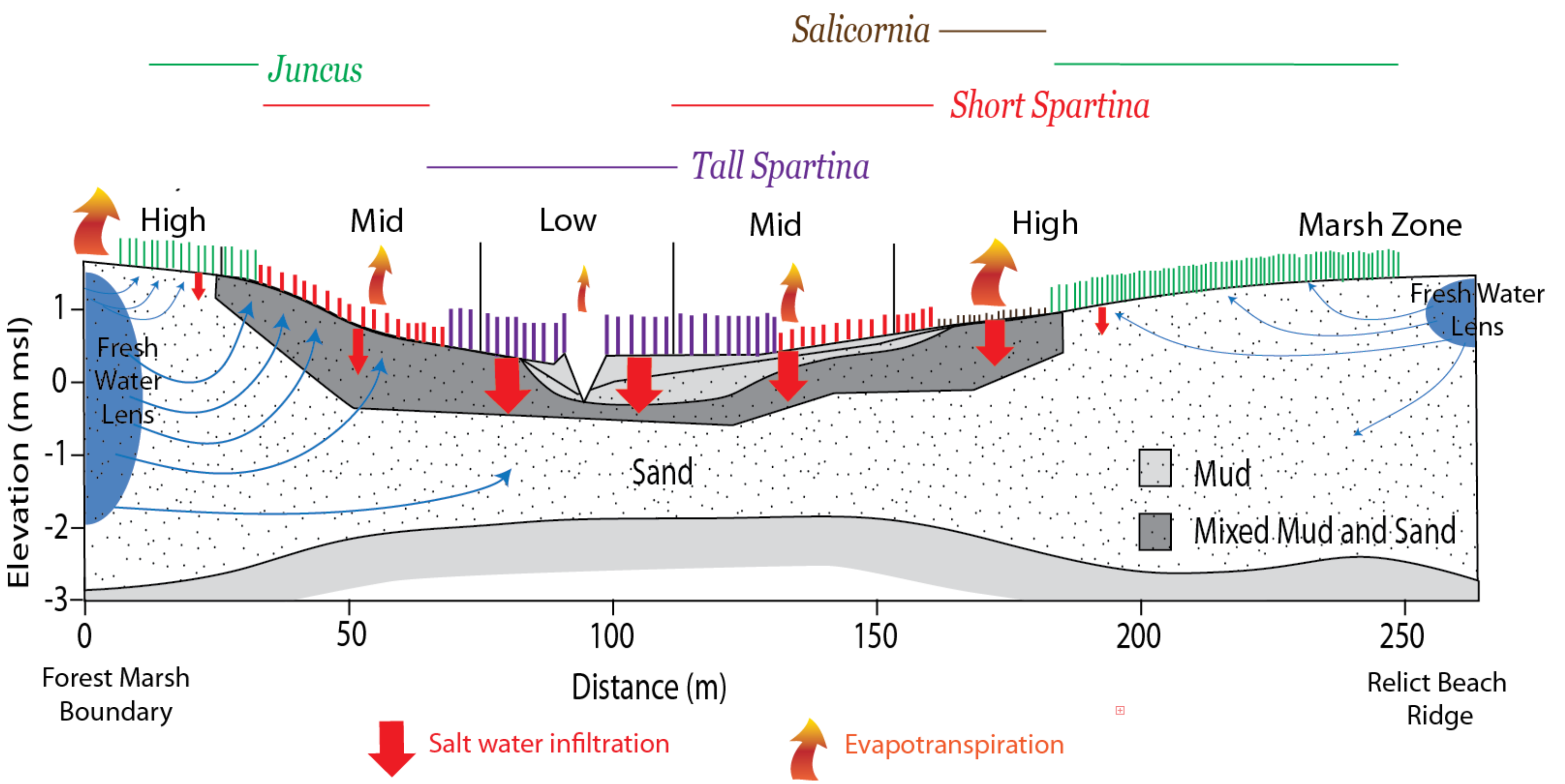

Figure 5.1: General cross-section interpretation of Crab Haul Creek ecological zonation and influence from groundwater. Evapotranspiration is greatest on the high marsh which experiences less inundation. On the western side of the marsh at the forest-marsh boundary there is a large freshwater lens which prevents a large volume of salt water infiltration. On the contrary, the eastern side has a smaller freshwater lens due to the marsh island relict beach ridge. This lack of freshwater leads to the development of hypersaline zones as salt water infiltrates the soil and evapotranspiration occurs during neap tide.

CHAPTER 6

CONCLUSIONS

Using photographs from a Helikite we were able track the spread of water across the marsh surface and classify ecological zones based on their RGB pixel values. We compared elevation and hydroperiod to ecological zones to determine if they alone control. However, the lack of symmetry between either side of the creek suggests this is not the case. In corroboration with the findings of Thibodeau et al., 1998 we propose that groundwater flow is the best explanation of our observed ecological zones. *Salicornia* grew on the middle and high marsh in the SE which we believe to be adjacent to a small freshwater lens that cannot counter saltwater infiltration and evapotranspiration from forming hypersaline zones. *Juncus* grew primarily on the high marsh but was also found on the middle and low marshes in the NW where we believe a large freshwater lens prevents high salinity soils from developing. Short and tall *Spartina* dominated the mid and lower marsh. Tall *Spartina* extended further on the middle marsh in the SE where we believe a small freshwater lens, shallow gradient, and longer distance from upland to creek do not contribute a strong upward flow component and allow for more salt water infiltration.

Though hydroperiod and elevation influence zonation they are not the primary control. Groundwater flow patterns must also be considered in models and fitness curves to more accurately describe the location of marsh plants. Groundwater flow can be

accounted for in models by the hydraulic distance from the creek and estimating the size of upland freshwater lenses.

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