TASK V.5: FACTORS CONTROLLING THE RESTORATION OF BROWN MARSH SITES WITH SMALL DREDGE SEDIMENT ENRICHMENT

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In Partial Fulfillment of:
DNR Interagency Agreement No. 2512-03-12

March 2006

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EXECUTIVE SUMMARY

Introduction

Projects that effectively lengthen the life expectancy of existing wetlands until a more natural hydrologic and sedimentation regime is re-established have an important place in Louisiana's coastal restoration strategy. Using sediment in combination with vegetation has proven to be a cost-effective technique, capable of preserving and restoring significant portions of Louisiana's coastal marshes. Currently, there is little information available on building, managing, and vegetative restoration of highly-disturbed dredged soils. Because of the high cost associated with hydraulic dredging, this study, Subtask II.1 – *Factors Controlling the Restoration of Brown Marsh Sites With Small Dredge Sediment Enrichment*, was conducted in association with a larger construction study, Task V.5 (*Brown Marsh Small-Dredge Demonstration Project (4351BRM)*) under the direction of the Louisiana Department of Natural Resources Coastal Restoration Division (LDNR). Working in collaboration with the Louisiana Department of Natural Resources Division of Coastal Restoration, we were able to conduct a large-scale, manipulative, and multi-year study to assess the affects of dredge sediments on marsh recovery following a catastrophic event. The three areas that this segment of the study addressed were: (1) an assessment of pre- and post-treatment spatial changes across treatment and control sites; (2) construction of hydrologic models to assess the distribution, frequency, and duration of the hydrologic regime effecting treatments and controls; and (3) a determination of the effects of artificial plantings and supplemental nutrients on vegetative recovery, recruitment, succession, and above-ground productivity.

Study Site and Experimental Design

The initial project design, as prepared by LDNR, consisted of constructing replicated sediment enriched sites with fixed, but varying depths of sediment at two locations within brown marsh impacted saline marshes. The two selected sites are located adjacent to, and on the interior side of the west bank of Bayou Lafourche, latitude 29° 11.17' N and longitude 90° 14.23' W, or approximately 3.5 miles southwest of Leeville, La.

The selected research site was constructed into eight sediment cells; five were discrete contained cells that received hydraulic sediment as treatments, and three were open un-confined control cells that did not receive sediment treatments. Treatment cells varied slightly in area, and were ~ 6 acres in size. The five sediment treatment cells were divided into groups, varying by the amount of sediment each group would receive; two treatment cells were designed to receive ~ 6" of sediments, two cells ~ 9" of sediments, and one cell was designed to receive ~ 12" of sediments. In addition to the five confined cells, the original design included three un-confined control cells that received no sediments.

Spatial Change

We compiled and georeferenced five aerial photographs that span six years. The aerial dataset consisted of one year pre-dieback normal marsh coverage (1998), one year post-dieback brown marsh event coverage (2001), and two years post-sediment treatment coverage (April 2003, Dec. 2003, Dec. 2004). We found that in 1998 (pre-dieback), both the study and control sites were healthy and moderately robust saline marshes that contained only two salient features, vegetated marsh and permanent water bodies. Both sites were predominately *Spartina alterniflora* emergent marsh with the treatment site containing 91% vegetation and 9% water, while the control sites contained 97% vegetation and 3% water.

Within a year following the 2000 brown marsh event, there was significant loss of emergent marsh within both the treatment and control sites. The relative impact of the brown marsh event was proportionally equal in both the treatment and control areas, with 82% and 78% emergent marsh loss respectively.

We defined marsh loss as a net reduction in vegetated area by conversion to exposed soil or open water, coupled with any net increases in open water from its original baseline value. We found that by the end of the study period, the treatment sites had a net loss of 1.6 acres (or 5.7% of the total area) and the control sites had a net loss of 1.1 acres (or 13.1% of the total area) compared to their respective pre-brown marsh values. From a recovery perspective, we found that by the end of the study period, the vegetative component of the treated sites had recover to 95% (24.5 of 25.8 acres) of its pre-brown marsh condition, while the control sites recovered to 90% (7.5 of 8.3 acres) of its pre-brown marsh conditions. Both the treatment and control sites had small net increases in water area (0.3 acres) over their pre-brown marsh conditions.

Hydrology

To assess water and salinity effects we established a continuous recorder and monitored water level and salinity for a 15-month period. We found the study sites to be a strong saline marsh with average salinity of 21.1 ppt (±4.1) and fluctuating water levels of -6.9" below and 19.8" above normal marsh. The average water level for the 15-month period was -0.13" (±5.83), or just slightly below normal marsh surface. In addition, we found both water level and salinity varied seasonally with the highest water levels during the summer months and the highest water salinity levels during the fall months. In addition, we found that there was no correlation between water level and salinity (r= -0.1, n= 20,920), but a moderately strong negative relationship between rainfall and salinity (r= -0.54).

When we analyzed the frequency of flooding relative to key treatment elevations, we found the greatest occurrence of flooding frequency was at normal marsh elevation (85.7% of total) followed by elevations found within the control sites (78.4% of total). Within the treatment cells, flooding frequency declined with increased elevation, flooding 53.8% of the time at 6" above normal marsh and declined to only 11.7% of the time at 12" above normal marsh. We found that there were no frequency of occurrence at or above 19" above normal marsh.

In addition to frequency, we determined the percent of time that key treatment elevations were flooded. At normal marsh (0" elevation), we found almost equal periods of surface flooding (49% of total) and drying (51% of total). This nearly 1:1 ratio of wetting and drying is optimal for plant growth by providing a balanced oxidation-to-flooding regime, that is critically important to intertidal plant species such as *Spartina alterniflora*. Within the control site, there was a disproportionate ratio (7.3:1) of flooding- (88%) to-drying (12%), producing wetter and potentially greater reduction in soils.

Vegetative and Nutrient Treatments

The primary objectives of the vegetative field trials were to assess main and interaction effects of artificial planting and supplemental nutrients on the rate of vegetative recovery and species composition, following sediment enhancement at different depths. The experimental design incorporates a multi-factorial design with multiple levels within each factorial. Treatment variables include sediment depth (0", 6", 9" and 12"); plant species (*Spartina alterniflora, Juncus roemerianus, Distichlis spicata, Spartina patens, Avicennia germinans*, and unplanted); and nutrients (fertilized and unfertilized). Treatment effects were measured as survival, frequency, total cover, and above-ground biomass production.

We found no significant difference in survival within either nutrient or elevation, but a statistical difference among plant species treatments. In terms of survival, *Avicennia germinans* (black mangrove) was the only species with 100% survival, followed by *Distichlis spicata* (saltgrass) with 93%, and *Spartina alterniflora* (smooth cordgrass) with 92% survival. *Juncus roemerianus* (black needlerush) performed very poorly with less than 1% survival.

When we combined elevation and species as treatments, we found that species segregated along elevation. For example, *S. alterniflora,* which is typically an intertidal species, performed better at lower elevations than at higher elevations. While *D. spicata*, which prefers a less saturated soil, increased with increases in elevation. *Avicennia germinans* was the only species that performed equally well across all elevations. The control sites, which were considerably lower

(~ -6” below normal marsh) than the lowest treatment site elevation (+6” above normal marsh) had total mortality across all plant treatments.

We use the relative frequency of species occurrence to determine plot composition (species richness) and relative abundance. Both measures are indicators of habitat suitability, species aggressiveness, and vegetative-site sustainability. We found that in almost all plant-elevation combinations (94%), that the vegetative treatments had formed mixed communities of three to five species. The one consistent exception to this determination was the three reference marshes, which were monospecific communities dominated by *S. alterniflora*.

In comparing biomass production of *S. alterniflora* across elevations and nutrient, we found no significant difference (p= 0.93) in biomass production among elevations. In addition, there was no statistical difference (p= 0.54) in *S. alterniflora* biomass between planted treatments, the normal marsh reference plots, and the unplanted plots, as they all came to be dominated by *S. alterniflora* in less than two complete growing seasons. In addition, although *Spartina alterniflora* was only one of six species established as plant treatments, it was clear by the conclusion of the study, that *S. alterniflora* was the dominate and primary colonizer within the study area and reference marshes. The only non-treatment species collected over the course of the study was *Salicornia virginica,* which appears to provide early pioneering vegetative cover with preferential trends towards open and sparsely vegetated sites.

SECTION II
SPATIAL, HYDROLOGIC, AND VEGETATIVE ASSESSMENT

INTRODUCTION

Wetland deterioration is a significant environmental problem in coastal Louisiana with average rates of wetland loss at 65 $km^2 y^{-1}$. Although natural and human-induced factors have both been cited as causing wetland loss, many of their effects are mediated through one common agent: sediment availability (Boesch, 1982, Mendelssohn et al., 1983). Therefore, a sound approach for reducing wetland loss and restoring deteriorated wetlands is the addition of sediment to increase marsh elevations to a level that will support wetland plants (Mendelssohn and McKee, 1988, Delaune et al., 1990, Wilsey et al., 1992).

Although a number of innovative ideas (e.g., spray dredging, sediment transport through abandoned oil and gas pipelines, hovercraft dispersal, as well as the introduction of novel sediment sources such as drill cuttings and spent bauxite) appear promising in this regard. However, a major limitation to the beneficial-use of dredged material, either natural or artificial, for the rehabilitation and restoration of wetland habitats is our limited understanding of how different depths of added sediment affect the structure and function of wetlands (Kuhn and Mendelssohn, 1999). Too little sediment may have no beneficial effect while too much sediment may detrimentally modify the vegetative dynamics and ecosystem processes essential for the maintenance and self-regulation of these systems. Thus, there is a need to integrate biotic and physical elements into dredge-sediment engineering to maximize the successful and beneficial use of dredge material for both the large scale restoration of brown marsh sites, as well as other degrading wetlands in coastal Louisiana.

Because of the high cost associated with hydraulic dredging, this study, Subtask II.1 – *Factors Controlling the Restoration of Brown Marsh Sites With Small Dredge Sediment Enrichment*, was coordinated with the Louisiana Department of Natural Resources' Task V.5 – *Remediation Through the Application of Sediment Utilizing Small Dredge Technology*, to provide a cost-efficient opportunity to study marsh nourishment on a landscape-scale not normally available through traditional research funding. Task V.5 provided a large-scale, manipulative experiment that allowed us to conduct a multi-year investigation to determine temporal changes in both species composition, vegetative establishment and wetland function at a scale generally too cost prohibitive.

GOALS AND OBJECTIVES

Projects that effectively lengthen the life expectancy of existing wetlands until a more natural hydrologic and sedimentation regime is re-established have an important place in Louisiana's coastal restoration strategy. Using sediment in combination with vegetation has proven to be a cost-effective technique, capable of preserving and restoring significant portions of Louisiana's coastal marshes. Currently, there is little information available on building, managing, and vegetative restoration of highly-disturbed dredged soils. Consequently, the goal of this study is to identify the physical, chemical, and biological factors which control the success or failure of dredge sediments as a restoration technique applicable in intertidal salt marshes. The objectives of the study are: (1) to assess the hydrologic-elevation effects on vegetative recovery resulting from sediment enhancement; (2) to assay the physico-chemical nature of dredge sediments at varying sediment loads; (3) to quantitatively assess vegetation recruitment and temporal changes; and (4) to determine the effects of artificial plant establishment and nutrient introduction on plant recruitment and establishment at varying sediment depths.

Specific research questions that address these objectives are:

1. What is the effect of sediment enrichment on vegetation recovery at brown marsh sites; and/or, would brown marsh impacted areas naturally recover without sediment enrichment?
2. What are the soil-plant factors that control successful recovery?
3. At what surface elevation and hydroperiod is recovery of *Spartina alterniflora* and other applicable salt marsh vegetation maximal?
4. Does artificial planting, with and without supplemental nutrients, accelerate brown marsh recovery?
5. How is vegetative succession affected by varying amounts of sediment addition, and what are the succession effects of varying sediment depth?

This section, *Spatial, Hydrologic, and Vegetative Assessment,* addresses three of these five study questions by: (1) assessing spatial changes across treatment and controls throughout the life of the study; (2) constructing a hydrologic model to assess the hydrologic effect on treatments and controls; and (3) determining the effects of artificial planting and supplemental nutrients on vegetative recovery, recruitment, succession, and above-ground productivity.

STUDY SITES AND EXPERIMENTAL DESIGN

This study, Subtask II.1 – *Factors Controlling The Restoration of Brown Marsh Sites With Small Dredge Sediment Enrichment* was conducted in association with a larger construction study, Task V.5 – *Brown Marsh Small-Dredge Demonstration Project (4351BRM)* under the direction of the Louisiana Department of Natural Resources Coastal Restoration Division (LDNR). The LDNR's stated goal for Task V.5 (demonstration project) was to assist the research efforts in the recovery of severely impacted marshes resulting from brown marsh events. The objectives of LDNR's Task V.5 were to demonstrate the effectiveness and applicability of "small dredge" equipment to hydraulically move sediments from an inland waterway and deposit materials within interior marshes, and to nourish and/or rebuild impacted marshes.

The initial project design, as prepared by LDNR, consisted of constructing replicated sediment enriched sites with fixed, but varying depths of sediment, at two locations within brown marsh impacted saline marshes. The two sites selected by LDNR are located adjacent to, and on the interior side of the west bank of Bayou Lafourche, latitude 29° 11.17' N and longitude 90° 14.23' W, or approximately 3.5 miles southwest of Leeville, LA. See Figure 1 *Vicinity Map*, for additional location information.

The two constructed sites were designated as Sites I and II, with Site II being the larger of the two sites and the selected area for this research study. Site II was designed and constructed into eight sediment cells; five were discrete contained cells that received hydraulic sediment as treatments, and three were open unconfined control cells that did not receive sediment treatments. Cell size was variable, with the five sediment treatment cells (2B, C, D, E, and F) ~ 6 acres in size, and the three control cells (2A, G, and H) varied in size from ~3.5 to ~ 6 acres.

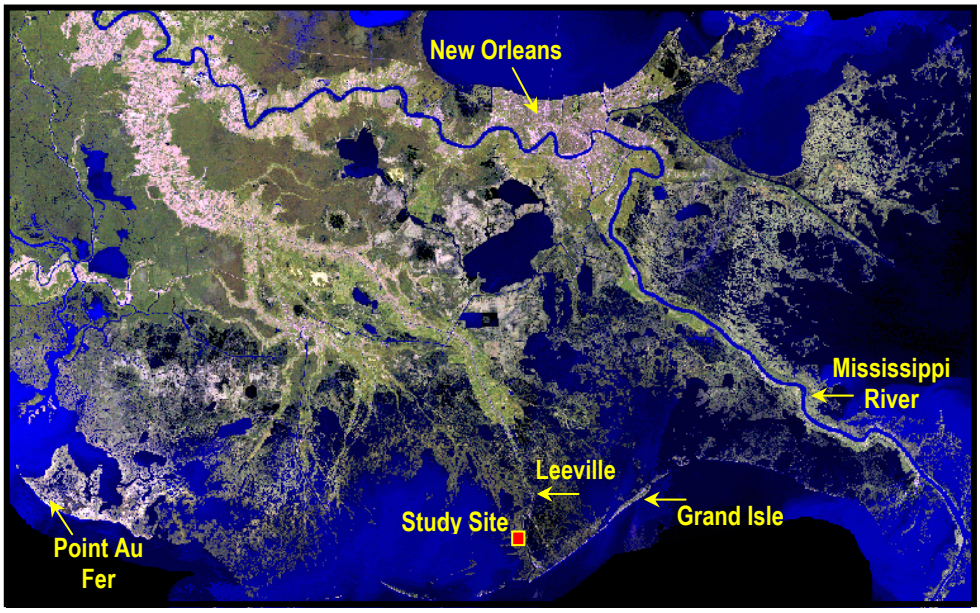


FIGURE 1 – Vicinity map and study site location.

Treatment cells 2B and 2F were designed for and intended to receive ~ 6" of sediments, 2C and 2E were designed for and intended to receive ~ 9" of sediments, and 2D was designed for and

intended to receive ~12" of sediments. Cells 2A, 2G, and 2H were designed as unconfined control cells and received no supplemental sediment. When filled, it was expected that the pumped sediments would compact up to 50% of the original "as built" elevation; consequently, all of the treatment cells were allowed an overage of ±3" tolerance according to the design specifications. Figures 2 and 3 are construction design schematics for both Sites I and II showing location, cell designation, and sediment placement as designed by LDNR.

Site II was selected for this study, consequently, we will limit the design, implementation, and results discussion of this report to Site II.

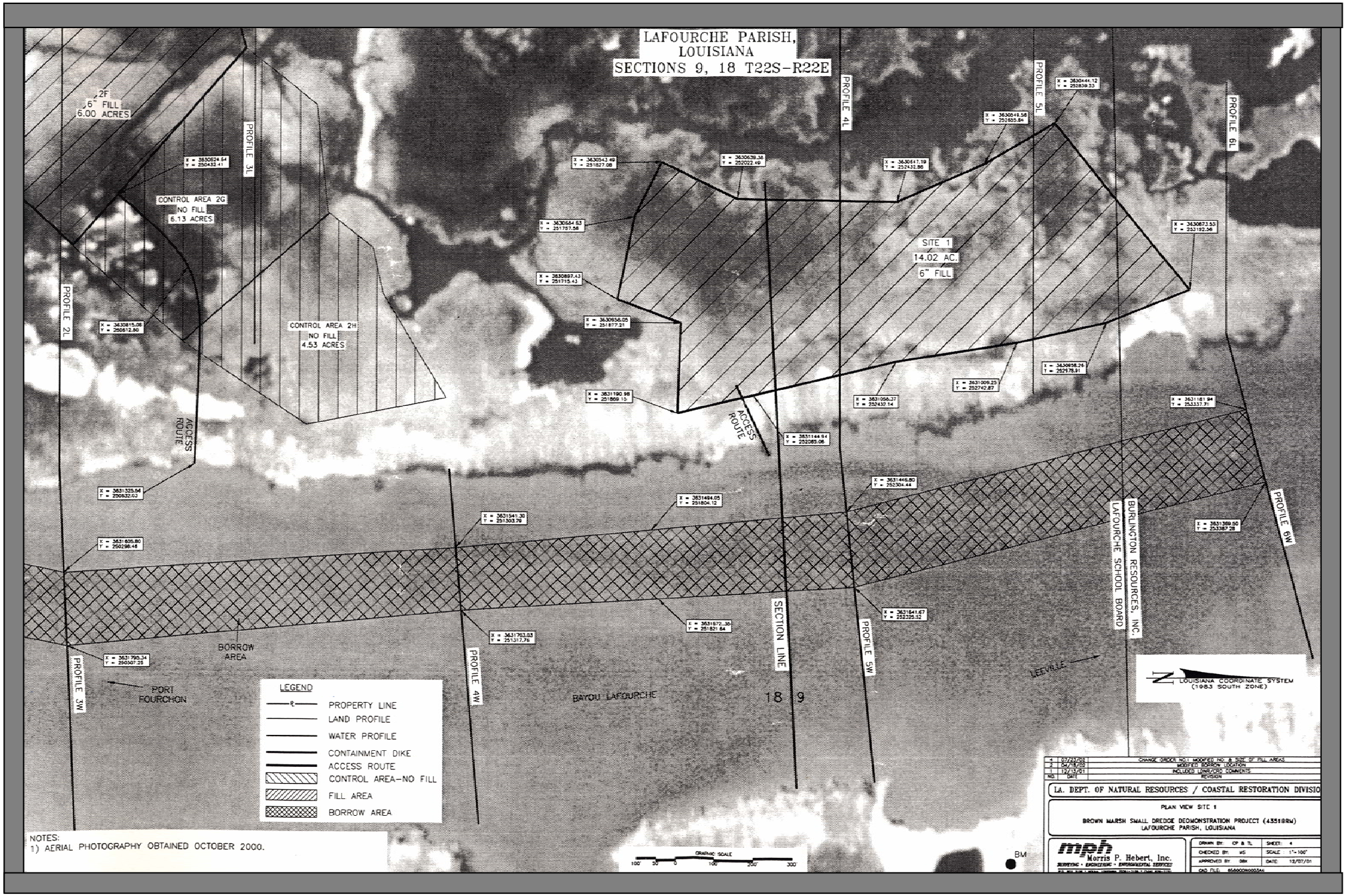


FIGURE 2 – Site 1, design and construction schematic as built by LDNR. Site 1 is one of two sediment treatment areas constructed by LDNR. Site 1 is approximately a quarter mile north-northeast of sediment treatment site 2.

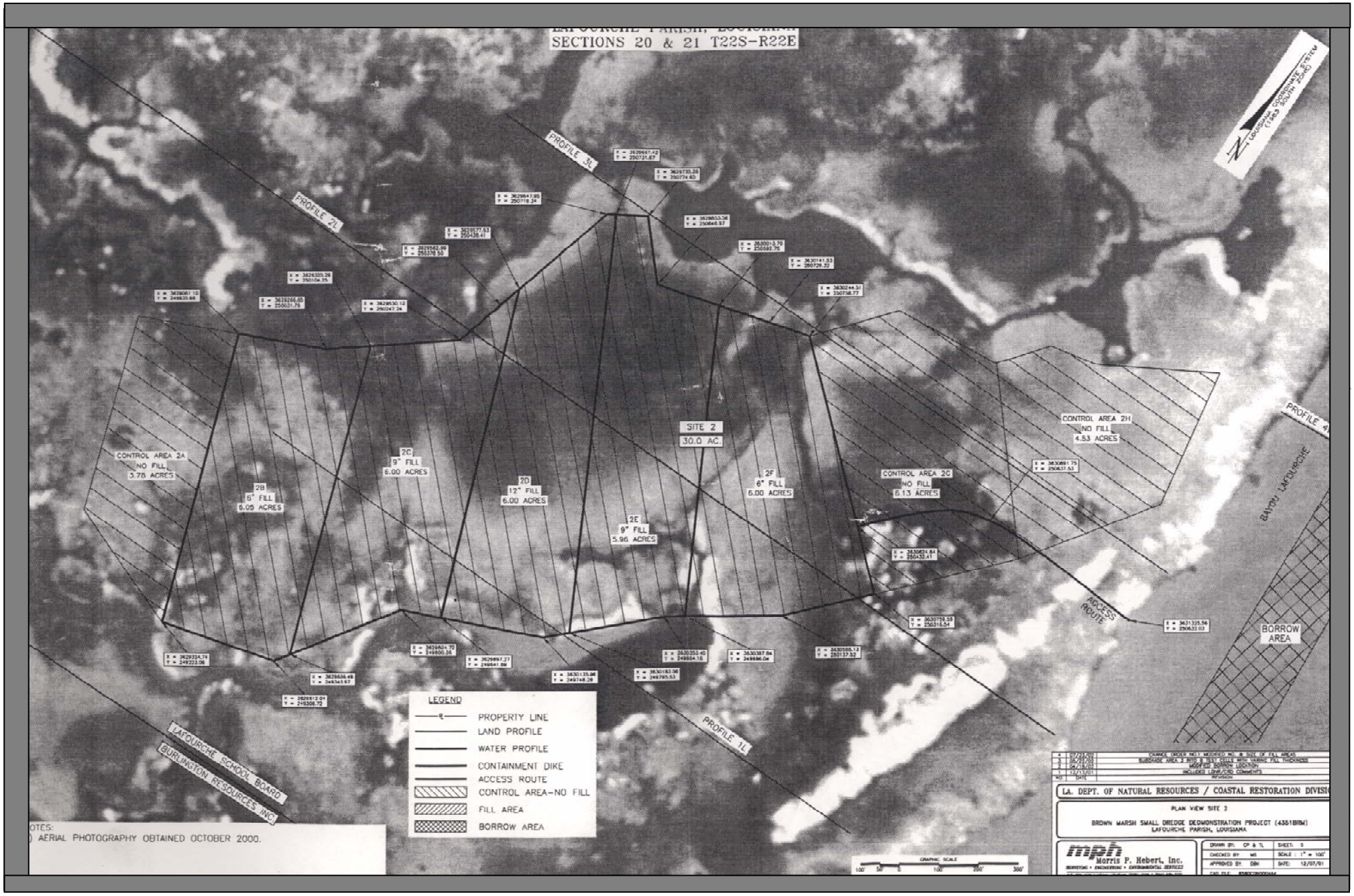


FIGURE 3 – Site 2, design and construction schematic as built by LDNR. Site 2 is one of two sediment treatment areas constructed by LDNR. Site 2 is approximately a quarter mile south-southwest of sediment treatment site 1. Site 2 was selected as the study area.

METHODS

Subtask II.1 was conducted over a thirty-month period beginning in the spring of 2003 and completed in the fall of 2005. This section, *Spatial, Hydrologic, and Vegetative Assessment* was divided into three study elements that include: (1) an assessment of pre- and post-treatment spatial changes across treatment and control sites; (2) construction of a hydrologic model to assess the distribution, frequency, and duration of the hydrologic regime effecting treatments and controls; and (3) a determination of the effects of artificial planting and supplemental nutrients on vegetative recovery, recruitment, succession, and above-ground productivity.

Table 1 is a timeline in quarter year increments that summarizes the three study elements, selected subtasks within elements, and their respective implementation timeframe. Element I (spatial assessment) was begun within the construction year (2003); however, field work on elements II (hydrology) and III (vegetative field studies) were postponed until the second year. The delay resulted in extending the study eight additional months to provide a full growing season for the vegetative components associated with element III. Each of the study elements are further defined and discussed in their respective methods section that follows.

TABLE 1 – STUDY ELEMENTS AND TIMELINE

Year/Month	2003			2004				2005			
	A-J	J-S	O-D	J-M	A-J	J-S	O-D	J-M	A-J	J-S	O-D
I Aerial Imagery Compilation											
(a) Pre-Construction and 2000 Brown Marsh Conditions											
(b) Post-Construction 2003 and 04											
(c) Database Development and Interpretation											
II Hydrologic Model											
(a) Site Selection and Installation											
(b) Data Collection and Maintenance											
(c) Data Analyses											
III Vegetative/Nutrient Field Study											
(a) Plant Material Collection and Expansion											
(b) Field Study Implementation											
(c) Data Collection											
(d) Data Analyses											

I. Aerial Image Compilation

Subtask Ia and b: Pre- and post-study image

A geographical information system (GIS) project was created by integrating five time-period base maps using Environmental Systems Research Institute's (ESRI) ArcView 3.2a software. The objective of the GIS project was to assemble a series of high resolution georeferenced maps from which a geospatial dataset could be developed, and subsequent change could be accurately measured. Five base maps were used to develop the geospatial project, two of the aerial images were flown and prepared by a third party, and three were flown under personal services contract specifically for this study.

The two existing maps were the 1998 Leeville SW digital orthophoto quadrangle (DOQ) map and the 2001 Brown Marsh Re-flight Infrared Photography maps, both prepared by the U.S. Geological Survey (USGS). The Leeville DOQ is an infra-red aerial photograph flown at 1:12,000-scale, is quarter-quadrangle centered, and has a 1-meter pixel ground resolution. The 2001 Brown Marsh imagery was a dataset consisting of approximately 300 scanned 9"x 9" color-infrared aerial photographic frames. The dataset covers the extent of 12 USGS quadrangles that encompasses the most prominent areas affected by brown marsh between the Mississippi and Atchafalaya Rivers in 2000. Selected images were scanned at 300 dpi and converted into JPEG or TIFF compression file formats and were available on-line through the LaCoast website. The Leeville SW quadrangle was included as part of the 2001 Brown Marsh Re-flight dataset, and was used as one of the five base maps.

The remaining three base maps were flown specifically for this study under a personal services contract issued to AeroData, Inc. AeroData flew imagery for this study in early spring (April 2003), four months post-sediment placement; late fall (December 2003), 12-months post-sediment placement; and again in late fall (December 2004), 24 months post-sediment placement. One additional flight was made in late December of 2005; however, the data derived from that flight has not been processed and is not included in this report.

Aerial images provided by AeroData were flown at a low altitude (2,000 feet), are 1:4,000-scale, and are color-infrared photography. Images were scanned at a high resolution (2032 dpi) and have a 0.076-meter pixel ground resolution. All of the base maps were georegistered to the North American Datum of 1983 (NAD83) and to identifiable ground control-positions with coordinates acquired from ground survey using Erdas Imagine 8.7. See Figure 4 for an example of the five base maps.

Subtask Ic: Database Development and Interpretation

The geospatial measurements needed for area comparison were computed using ArcView 3.2a. To create these data, a set of geographical attributes were created for each time-series map and a "control" polygon was placed on each map. Attributes are simply habitat descriptors that represent site variability that can be measured spatially and then used in a GIS assisted comparison. For example, the 1998 DOQ maps were pre-brown marsh and used as a reference map, representing undisturbed and relatively healthy marsh. Consequently, there were only two habitat variables, healthy emergent marsh and permanent water bodies. However, within the same control area of the 2001 imagery (post-brown marsh), the attribute set was expanded to include dead emergent marsh and intermittent water bodies, two additional attributes that represent a degree of areal change, resulting from brown marsh effect between 1998 and 2001.

The control polygon placed over each base map was a geo-referenced overlay used to restrict attribute delineations to a fixed constant. Since all base maps were geo-referenced one to the other, the control layer also provided a summary check to ensure accuracy across multiple base maps. We created two control polygon layers, one to delineate the boundaries of the sediment treatment site and the other to delineate two treatment controls adjacent the dredge-sediment sites. The sediment retention levees are clearly visible on the spring 2003 aerial imagery and provided an excellent template to establish the treatment control layer boundaries. The untreated brown marsh controls were created by following the interface between tidal creeks and vegetated marsh where they existed, then arbitrarily squared-off to complete the polygon where no natural separation existed. Figures 5 is an example of the methodology and placement of the control boundaries for both the sediment treatment cells and the control sites. In Figure 5, we partially overlaid the control lines around the sediment cells showing both the created boundary and the underlining retention levees that were used as guidelines. Within the two control sites (yellow boundary), note that we followed water-vegetation boundaries where they existed, then simply connected the polygon where no natural boundaries existed. We created a single, geo-referenced digital outer boundary layer that was used over each individual base map.

Once both treated and untreated control boundaries were in place, we created a single multi-attribute layer by drawing polygons around each discrete habitat within the treated

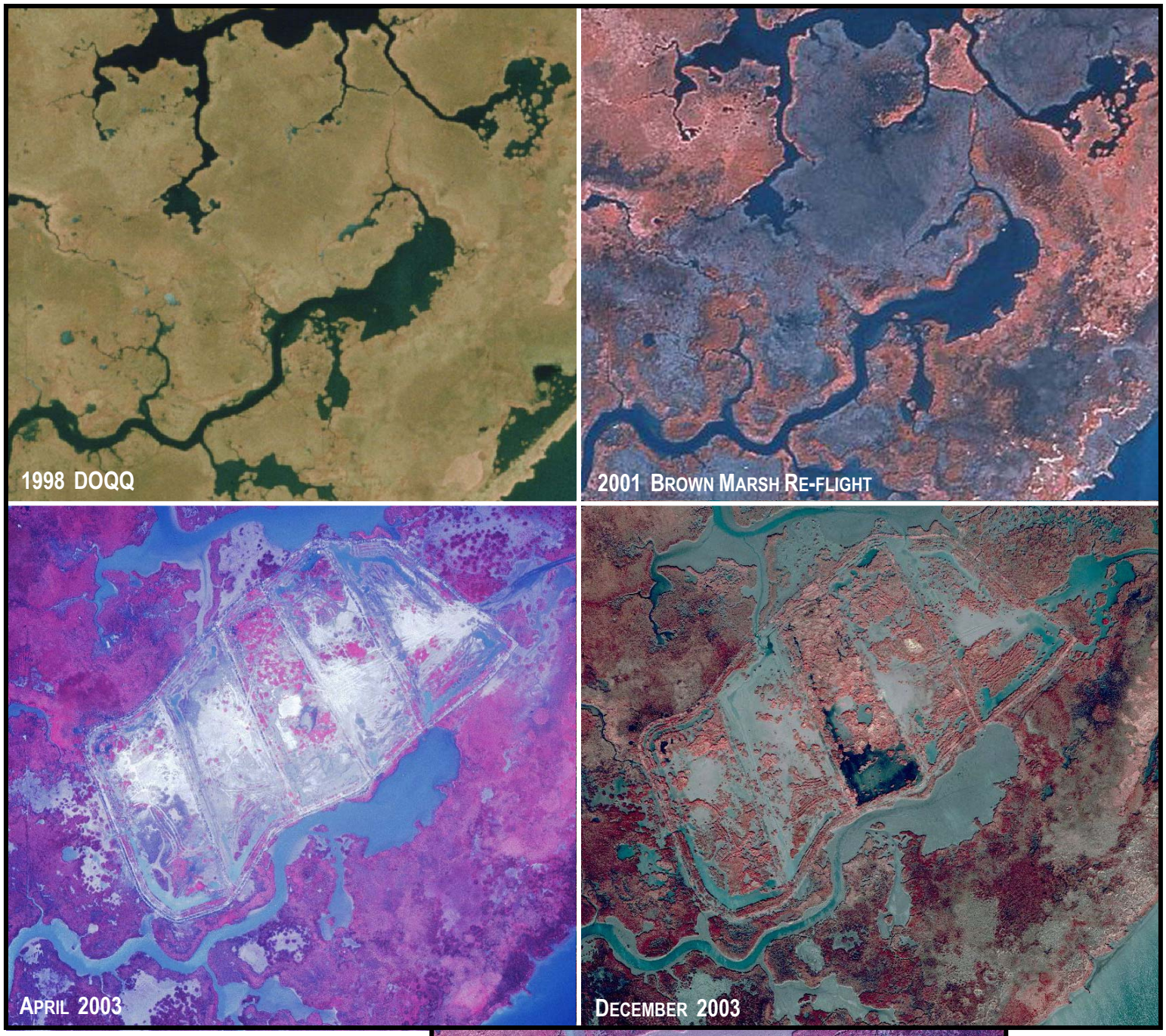


FIGURE 4 – Five base maps used in the GIS assisted land-use change analysis: two maps, the 1998 DOQQ and the 2001 brown marsh re-flight aerials were produced by the USGS, and three maps, Spring 2003, Fall 2003, and Fall 2004 were produced under personal services contract for this study. All five aerials were georegistered to the North American Datum 1983 and to ground control positions.

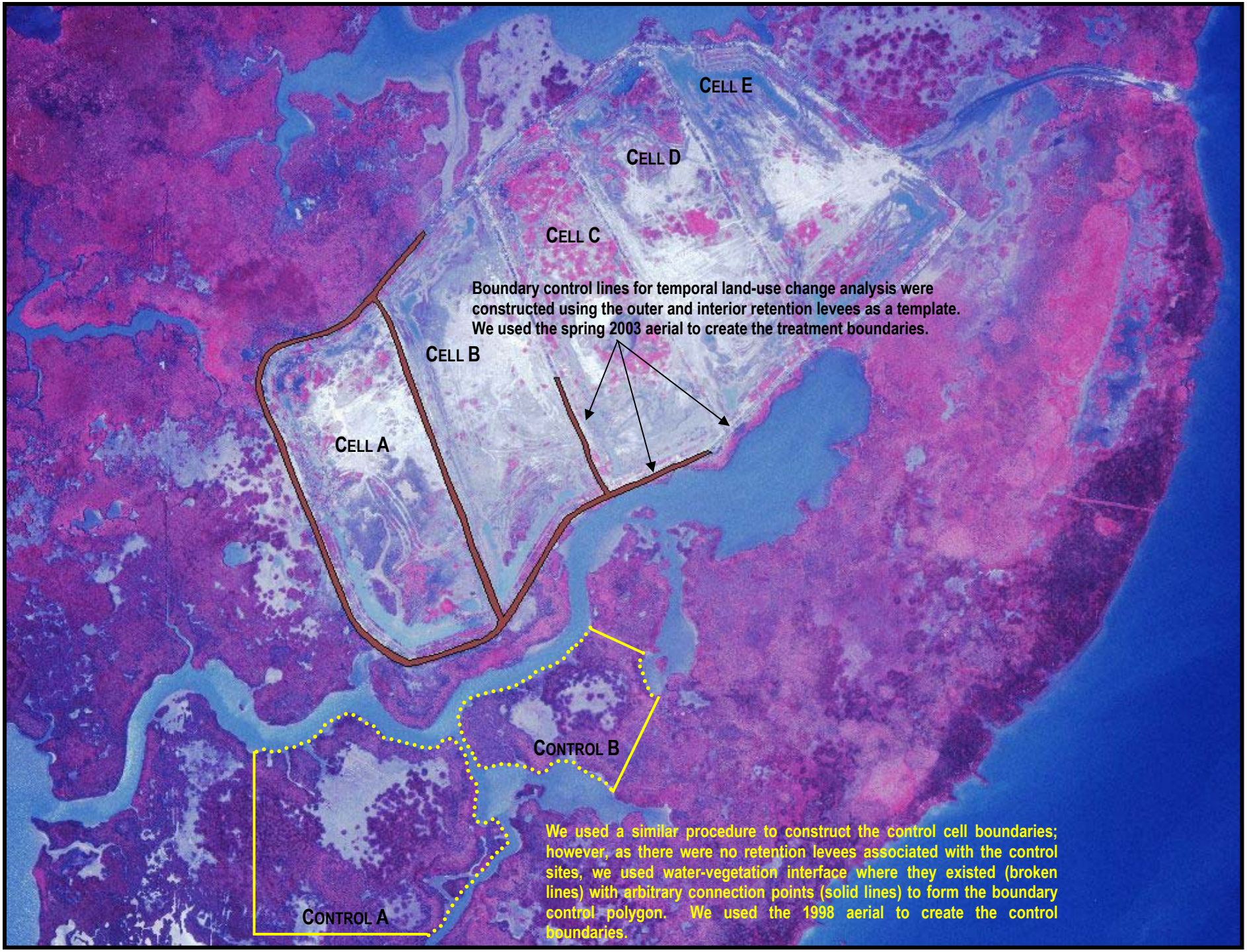


FIGURE 5 – Methodology and placement of sediment treatment and control site boundaries.

and untreated controls for each base map. We used a single layer to initially delineate attributes so that adjacent polygons would share common boundaries, thus eliminating overlap and area error. Using Edit Tools 3.6 Extension for ArcView, each single multi-attribute map layer was electronically clipped, and like-polygons (attributes) were transferred to separate individual layers. Using XTools Extension for ArcView, we created a index and metrics table for each attribute layer per map. The individual tables were exported into MSExcel, compiled, and formatted such that data could be analyzed using descriptive statistics in combinations, or as separate units.

II. HYDROLOGY

Subtask IIa: Site Selection and Installation

One of the objectives of this study was to assess the hydrologic-elevation effects on vegetative recovery resulting from sediment enhancement. To accomplish this we installed a YSI model 600LS sonde, equipped with multi-sensors and a vented level system, to record changes in both water level and salinity values. We measured water temperature (°C), specific conductance (µS/cm), salinity (ppt), and water levels (in) on a continuous basis (half-hour intervals) for 15 months.

The sonde was installed in an unobstructed tidal creek on the north-northwest side of the study site. The sonde was positioned in the center of the intersection between a tidal creek and a constructed opening in the north boundary levee of sediment cell 2B. This site was selected as it represented the largest and more centrally located tidal conveyance channel within the study area. In addition, the tidal creek appeared to provide the greatest watershed within the treatments cells and had the least amount of obstructions after sediment placement. See Figure 6 for sonde location.

To facilitate installation and quarterly data collection we built a boardwalk that projected from the east end of the retention levee that intersects the tidal creek. The sonde was housed in a vertical structure consisting of a 16' treated 4"x 4" post driven into the marsh to resistance. The sonde was attached to a 2" PVC pipe that was then placed within a 3" perforated PVC pipe mounted to the 4"x 4" post with lag bolts. The bottom of the sonde rested on a 6" hitch-pin that was inserted through the 3" PVC and positioned approximately 2" off the tidal creek floor. The 10' vented data cable was threaded through the top of the 2" PVC and secured in a covered hard-plastic electrical box, mounted by a flange on top of the 3" PVC. See Figure 7 for a schematic of the sonde field structure.

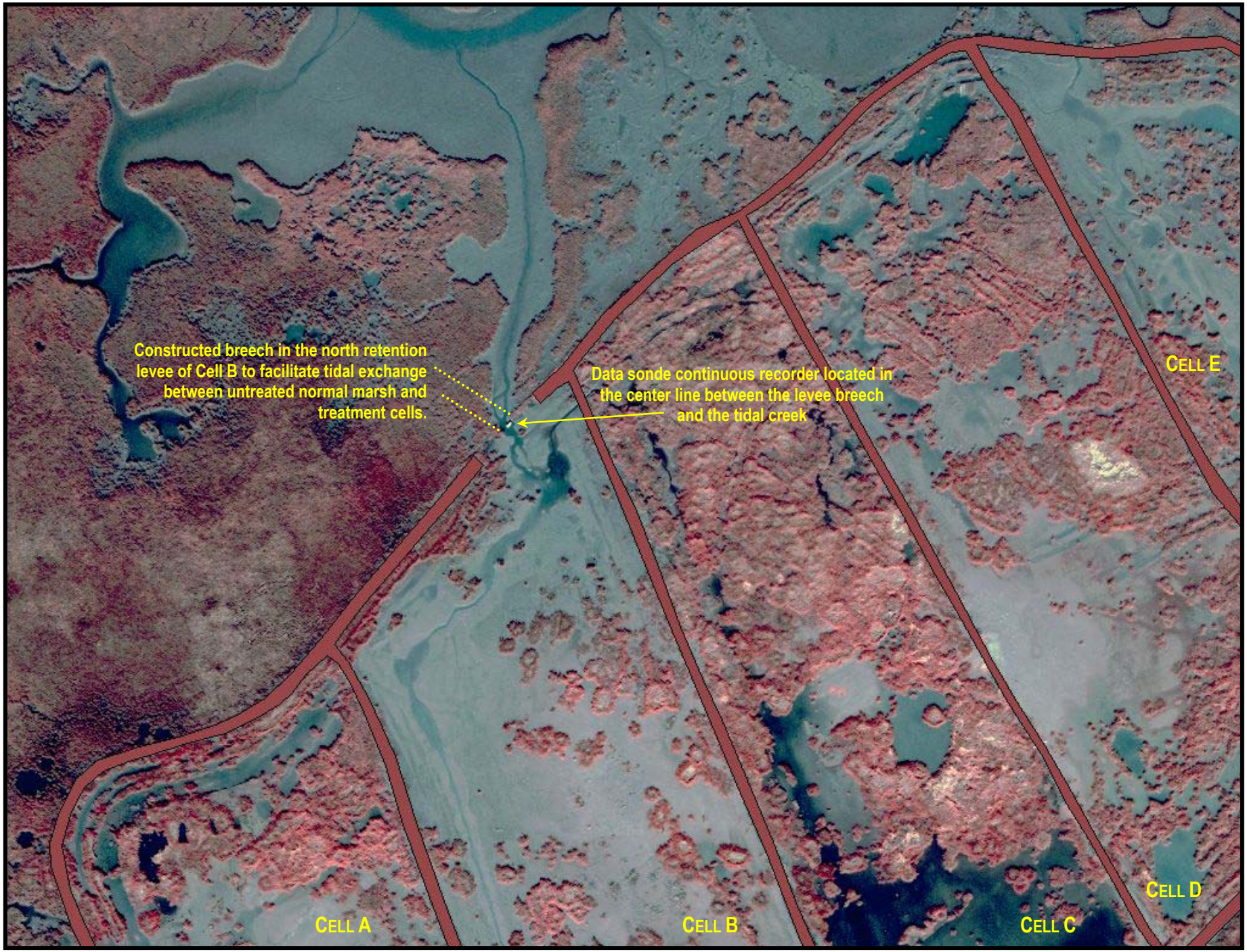


FIGURE 6 – Location of data sonde: December 2003 image.

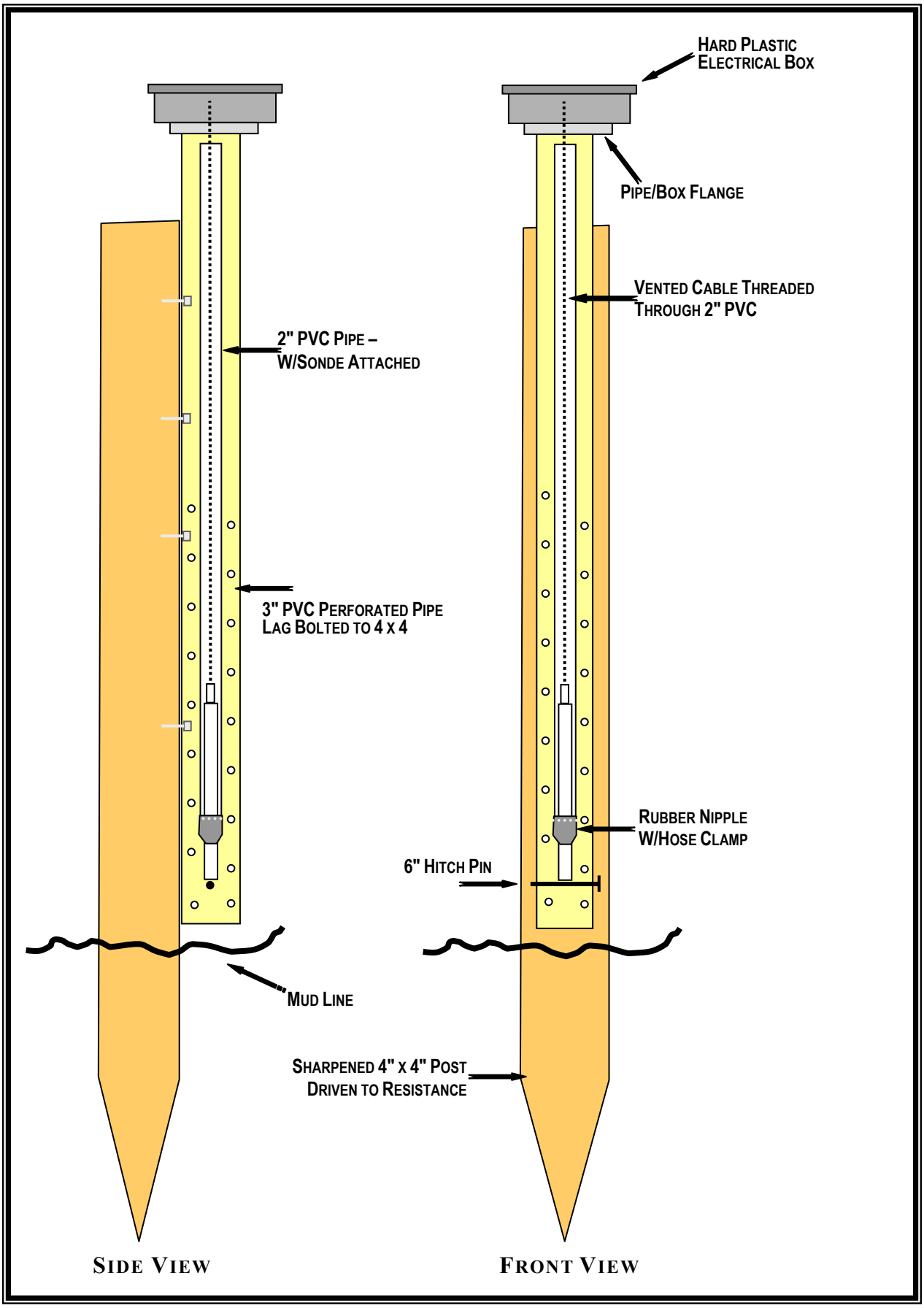


Figure 7 – Data sonde field structure schematic: structure weathered one tropical storm and two category three hurricanes without service interruption.

The boardwalk provided easy access to the sonde without disturbing or damaging the tidal creek or adjacent marsh. The sonde structure provided a relatively water-tight, protective housing that allowed for removing and replacing the sonde with minimal tools. Since the bottom of the sonde could not be positioned any lower than the top of the fixed 6" hitch-pin (located at the bottom of the 3" PVC), we were confident that the sonde was repositioned at the same elevation after each quarterly data collection, cleaning, and calibration check.

Subtask IIb: Data Collection and Maintenance

Water depth values were measured using a vented level sensor system, as opposed to depth sensors. Both systems employ differential strain-gauge transducers to measure pressure on the water column. Depth sensors are sensitive to atmospheric fluctuations and where changes in barometric pressure are significant, long-term monitoring errors of ± 0.6 feet are common. Consequently, we employed a vented system in which one side of the transducer is exposed to the water column and the other side is vented to the atmosphere. In this system, the transducer measures only the pressure exerted by the water column and atmospheric pressure is ignored; consequently, barometric changes have no affect on level readings. Water level accuracy using a vented level system in shallow (0-10') water is estimated at ± 0.3 cm.

Field data was downloaded quarterly from the sonde. We used a YSI microcomputer based datalogger (YSI 650 Multiparameter Display System) for field collection and subsequent data transfer for analyses. In addition to downloading data quarterly, the sonde was cleaned and sensors were recalibrated. For quality control/quality assurance checks, a set of real-time measurements were taken at the end of each quarterly redeployment and checked against applicable standards prior to leaving the sonde unattended. In addition, a water sample was taken and analyzed under laboratory conditions as an additional check. The data sonde logged almost 21,000 data entries continuously and uninterrupted over the 15-month sampling period, including through both Hurricanes Katrina (August 29, 2005) and Rita (September 24, 2005).

Subtask IIc: Data Correction and Analysis

The sonde was attached to a stationary structure installed in the center of an unobstructed tidal creek, as described earlier in this section. The bottom of the sonde was fixed approximately 2" off the creek bottom, and well below "normal" marsh surface. Since we established normal marsh as our baseline elevation (assumed as zero), it was also necessary to standardize water level measurements to normal marsh elevation, that is, to

correct water level measurements to actual plus or minus levels above or below the marsh surface. This was accomplished by determining the elevation of the water level sensors relative to an average elevation of three reference marshes and subtracting the difference from each water level measurement. Reference marshes were defined as healthy emergent marshes unimpacted by either brown marsh effect, project construction, or sediment overflow. See Figure 8 for reference marsh locations.

Field data was downloaded quarterly from the sonde. Quarterly files were imported into MSExcel and compiled into one dataset organized by date and by time within date. Measured parameters were temperature (°C), specific conductance (µS/cm), salinity (ppt), and water level (in). Measurements were taken every 30 minutes, providing 83,684 data points over the life of the study. We used a number of the descriptive statistics to construct several hydrograph models to assess flooding distribution, frequency, duration, and depth across key elevations, as well as to determine possible correlations between flooding, salinity, and elevation.

III. Vegetative/Nutrient Field Study

The primary objectives of the vegetative field trials were to assess main and interaction effects of artificial planting and supplemental nutrients on the rate of vegetative recovery and species composition following sediment enhancement at different depths. The experimental design was constructed to test three main-effect hypotheses, that is, in sediment enriched marsh: (1) is there any difference in vegetative response at different sediment depths (elevations); (2) is there any difference in vegetative response between plant species typically used in vegetative restoration; and (3) does the addition of supplemental nutrients effect vegetative response and species composition?

In addition to the main-effect treatments, the experimental design tested for three interaction effects: (1) is there an interaction between sediment depth (elevation) and species; (2) is there an interaction between species and supplemental nutrients; and (3) is there an interaction between elevation, species, and nutrients. The experimental design incorporates a multi-factorial design with multiple levels within each factorial. Treatment variables include sediment depth (0”, 6”, 9” and 12”); plant species (*Spartina alterniflora, Juncus roemerianus, Distichlis spicata, Spartina patens, Avicennia germinans*, and unplanted); and nutrients (fertilized and unfertilized).

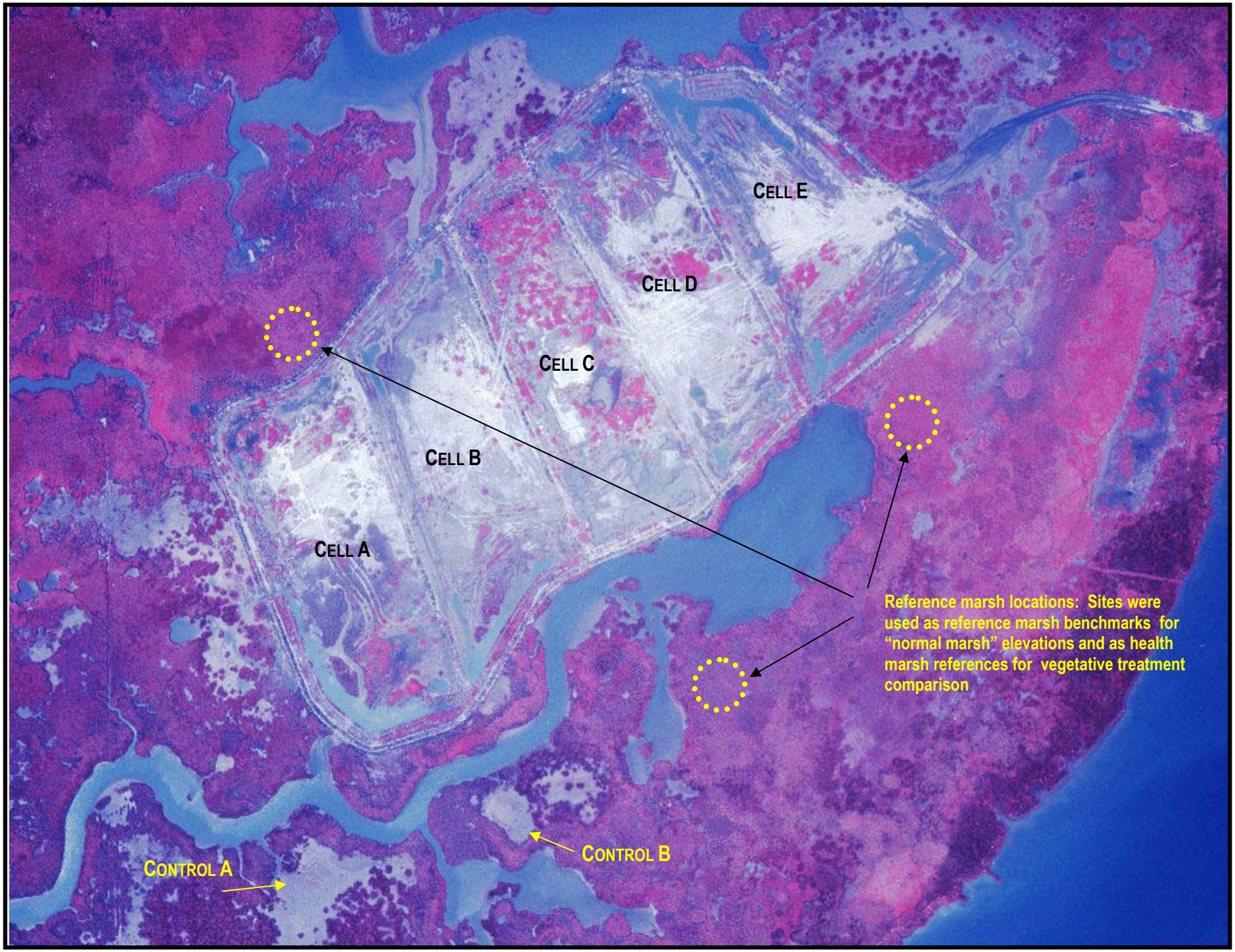


FIGURE 8 – Reference marsh location sites: Sites use for determining reference elevations and normal marsh vegetative comparisons.

We employed a split-plot design using sediment depth (4 levels) as main plots. Nested within the sediment main plots were subplot factors of plant species (6 levels) and fertilization (2 levels). The combination of treatment variables produced 48 treatment combinations (4 x 6 x 2 = 48). Each subplot factor was replicated 3 times within the main plot, and each main plot was replicated twice across the experimental area.

Subtask IIIa: Plant Material Collection and Expansion

Plant material used as plant species treatments were initially collected from a native marsh south southwest of Port Fourchon, La., near West Belle Pass. Individual species were collected from within a small community structure, and were clonally propagated to minimize genetic variability within replicates. *Avicennia germinans* (black mangrove), the only non-herbaceous species used in the study was also collected from West Belle Pass; however, treatment replicates of *A. germinans* were propagated from seeds (propagules) and were not clonally replicated.

Plant materials were collected in the fall of 2003, and expanded under greenhouse culture through the winter of 2003 and spring of 2004. All species were container grown (5" rectangular pots) and were of like size and condition when field planted. We used 10 replicates per treatment combination which required 240 containers per species. We used 5 species as treatment variables, which provided a total sample number of 1,200 plants. Figures 9A through 9D are examples of plant size and condition at the time of plantings.

Subtask IIIb: Field Study Implementation

Plants were transported to the study site on May 10, 2004, and planting was completed over a three-day period. The planting design consisted of blocking main plots into 12 equal subplots within 4 elevations. We established one plant treatment, with and without supplemental nutrients, per subplot. Species-nutrient treatments within subplot were replicated 10 times and planted in a row/column configuration. Including the unplanted subplots (with and without nutrients), we established 1,320 species-nutrient cells. Supplemental nutrients were added in the form of an 18-gram high density, slow release tablet. Elemental composition of the fertilizer tablet was 20% nitrogen, 10% phosphorus, and 5% potassium, with some trace elements. Nutrients were added at the time of planting by placing two tablets in the upper 2" of the soil surface above the plant root-ball.

FIGURE 9 – Examples of plant treatment species. All treatment plants were container grown and of like size.

To facilitate monitoring and data collection, the 4 outside corners of the nested plots within elevation were marked with ½"x 5' PVC and GPS coordinates were taken. In addition, each plant-nutrient replicate within subplots was marked with a ½"x 3' bamboo marker.

Subtask IIIc: Data Collection and Analysis

Dependent variables for the vegetative-nutrient experiments were: (1) survival, (2) cover value, (3) species composition, and (4) relative abundance – measured as standing crop biomass. Because *A. germinans'* growth form (woody) differs significantly from that of all other test species (herbaceous), three additional measurements (basal diameter, height, and secondary branching) were taken for *A. germinans* plots.

Survival measurements were taken at 30 and 90 days post-planting intervals, i.e., mid June and August 2004, respectively. Replicates within each individual subplot were scored as living or dead based on the presence or absence of living, above-ground culms, and expressed as percent survival. We surveyed every plant across all treatments, at both 30 and 90 day intervals, for a 100% sample.

Percent cover, species composition, and relative abundance were all taken over a three day period in early November 2005. Percent cover was visually estimated using a ½m^2 quadrat divided into quarter quads for visual separation. Three samples were randomly taken within the plant row/column matrix from each subplot and averaged to determine percent cover. Average cover values were determined for all 144 subplots across the main plot.

To assess species composition and relative abundance, we used a clip-plot method (Mueller-Dombois and Ellenburg, 1974) to obtain species frequency and above-ground biomass. Standing crop was harvested by clipping plant materials within a ½m^2 quadrat at approximately 1 cm above the soil surface. Each clip-plot was replicated 3 times within each subplot for a sample size of 432. Clipped material was placed in plastic bags, labeled, and transported back to the lab for separation. Under laboratory conditions, individual samples were separated by species and recorded for frequency of occurrence. Metrics for basal diameter, height, and secondary branching were also recorded for *A. germinans*. Individual species from each clipped-plot sample were placed in labeled brown kraft bags, weighed, dried at 75°C to a constant weight, and re-weighed.

RESULTS AND DISCUSSION

Subtask II.1 – *Factors Controlling the Restoration of Brown Marsh Sites With Small Dredge Sediment Enrichment*, was coordinated with the Louisiana Department of Natural Resources' Task V.5 – *Remediation Through the Application of Sediment Utilizing Small Dredge Technology* to provide a cost-efficient opportunity to study marsh nourishment on a landscape-scale not normally available through traditional research funding.

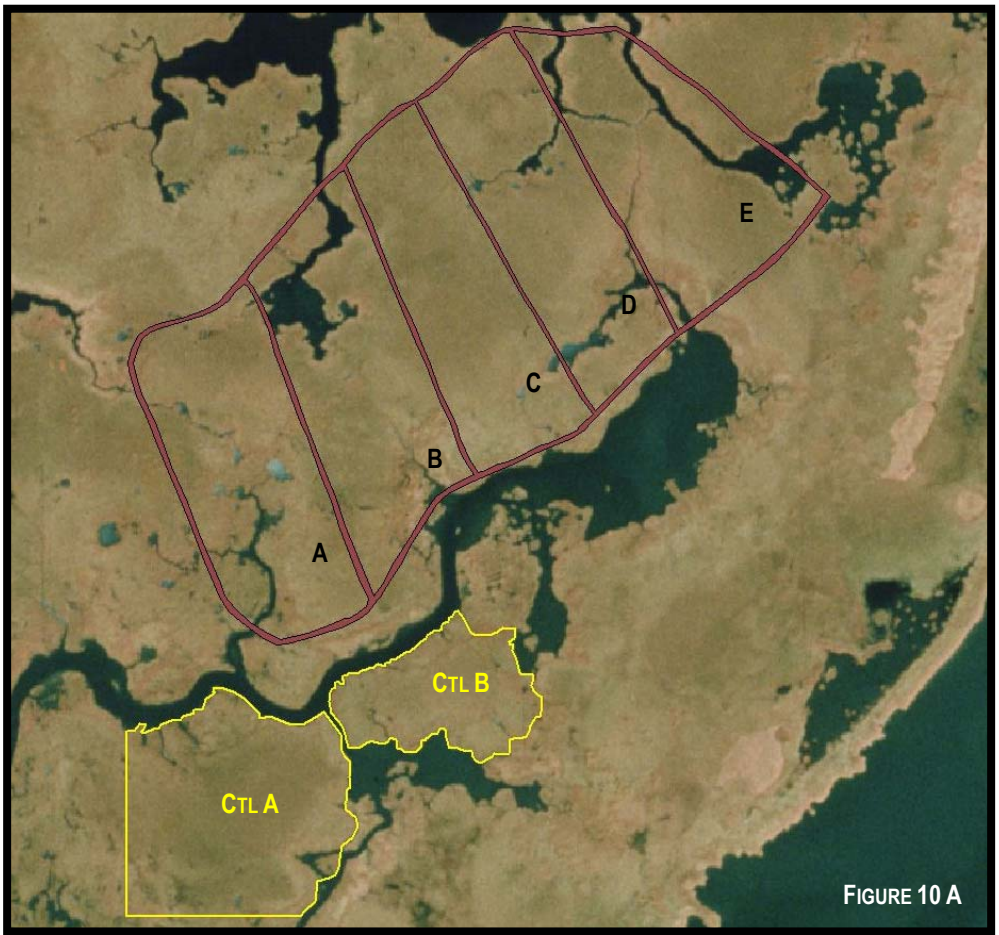
This section, *Spatial, Hydrologic, and Vegetative Assessment* is divided into three study elements that assess the effects of sediment enrichment on (1) spatial change, (2) hydrology, and (3) vegetative recovery in a deteriorating marsh. We will present our results and observations by the three study elements as outlined in the Methods sections.

I. SPATIAL CHANGE ASSESSMENT

A geographical information system (GIS) project was created to assess spatial changes across treatment and control sites between 1998 and 2004. Five time-period, high resolution, and georeferenced maps were integrated using Environmental Systems Research Institute (ESRI) software. The objective of the GIS project was to assemble a series of maps from which a geographical attribute dataset could be developed, and subsequent changes could be accurately measured. Common control polygons were placed over each base map to restrict attribute delineations to a fixed constant and to provide a summary check to ensure accuracy across multiple base maps. Summary tables, indexed by attributes and areal measurements, were created for each map series, compiled, and used for comparison analyses.

1998 DOQ Map

We used the 1998 digital orthophoto quadrangle (DOQ) map to establish pre-brown marsh and pre-treatment baseline habitat measurements. As described earlier in the Methods section, a fixed constant boundary was placed over the sediment treatment areas, as well as over the two non-sediment control sites. We used the outline of the retention levees as a template for the sediment treatment boundary, and an arbitrary delineation boundary for the control treatment boundary. Using the delineation control boundaries as guides, we found only two salient habitat features found on the 1998 map, healthy emergent marsh and open intertidal water bodies. We delineated and highlighted both features within study cells A through E and control cells (Ctl-A and Ctl-B) for visual separation and to create a metrics table for numeric comparisons (Figure 10).



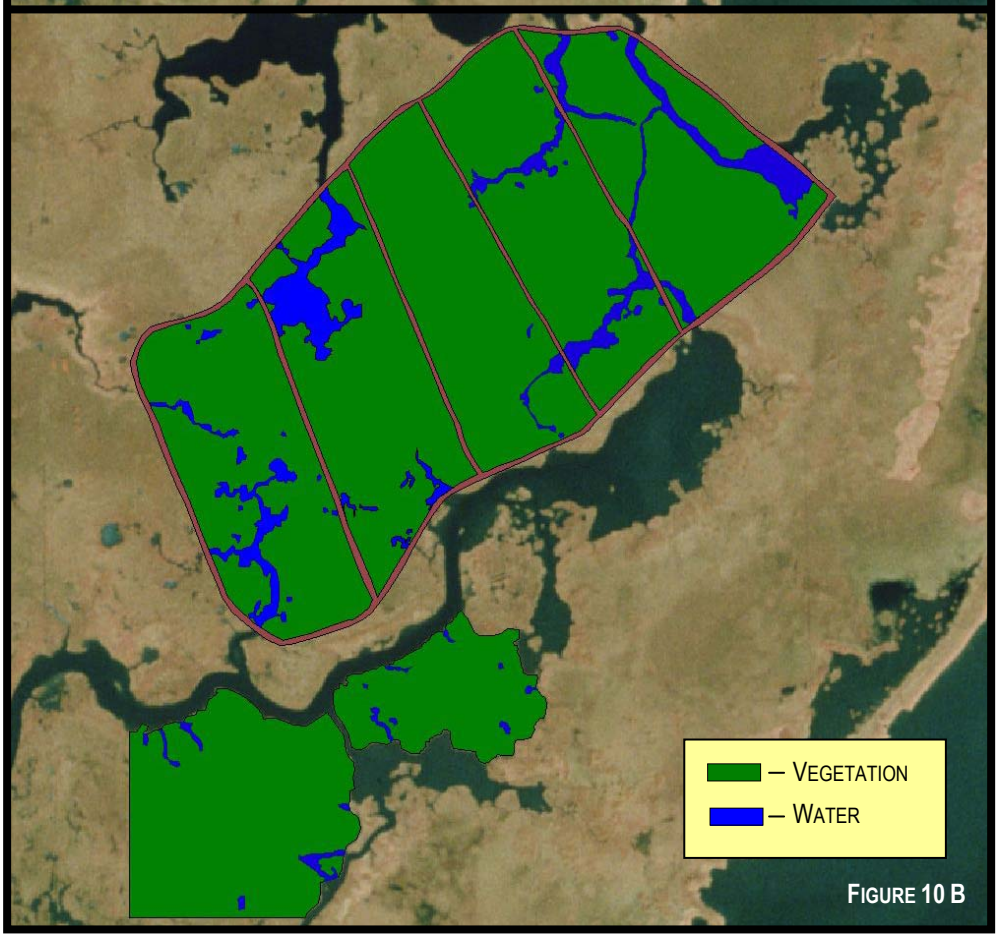


FIGURE 10 – 1998 habitat land-use map: Fig. 10A shows both the sediment treatment and the control sites with the control boundary overlay, but without the habitat attribute layer. Fig. 10B is the same area for both the treatment and control sites but with the habitat attribute layers highlighted for comparison.

We found in 1998 a robust cover of emergent vegetation within both the sediment treatment and control areas of the study sites. Vegetation within the sediment treatment boundaries was the dominant feature with 91% cover followed by permanent open water at 9%. The control areas also contained vegetation-to-water in approximately the same proportion as that of the treatment area, with 98% and 2% vegetation and water respectively. Table 2 is a summary detailing 1998 attributes calculations across treatments and sites.

TABLE 2 – 1998 HABITAT SUMMARY

YEAR	TREATMENT	ATTRIBUTE	CELL	FT²	ACRE(S)
1998	Sediment Cells	Vegetation	A	241,829.72	5.55
			B	222,243.11	5.10
			C	225,338.72	5.17
			D	219,198.34	5.03
			E	215,685.58	4.95
		SubTotal Vegetated	**A-E**	**1,124,295.47**	**25.80**
1998	Sediment Cells	Water	A	21,946.53	0.50
			B	36,994.32	0.85
			C	3,135.71	0.07
			D	20,225.07	0.47
			E	34,657.36	0.80
		SubTotal Water	**A-E**	**116,959.0**	**2.69**
		Total Treatment Cells	**A-E**	**1,241,254.47**	**28.50**
1998	Control Cells	Vegetation	Ctl. A	249,974.67	5.74
			Ctl. B	112,711.23	2.59
		SubTotal Vegetated	**Ctl. A-B**	**362,685.90**	**8.33**
1998	Control Cells	Water	Ctl. A	5,875.71	0.14
			Ctl. B	2,976.94	0.07
		SubTotal Water	**Ctl. A-B**	**8,852.65**	**0.21**
		Total Control Cells	**A-B**	**371,538.55**	**8.54**

2001 Brown Marsh Re-flight Map

The large scale die-back that occurred in 2000 was termed "brown marsh" due to its unique reddish-brown signature. Figure 11A and 11B are low altitude photographs of an impacted marsh in mid-summer of 2000. The color gradient from high-bank (reddish-green) to the interior (deep rust) was characteristic of brown marsh sites in the Barataria-Terrebonne Basin and is indicative of relative vegetative health. In the interior of most impacted sites mortality was uniformly high, characterized by leafless standing dead culms; note the total absence of any green stems in Figure 11B. By late winter of 2000, (Figure 11C) all of the above-ground biomass had deteriorated and was exported out of

FIGURE 1 1 – Brown Marsh impacted marsh

The large scale die-back that occurred in 2000 was termed "brown marsh" due to its unique reddish-brown signature. Figure 11A is a low altitude photograph of an impacted marsh in mid-summer 2000; the color gradient from high-bank (reddish-greenish) to the interior (deep rust) was characteristic of brown marsh sites in the Barataria-Terrebonne Basin and is indicative of the relative vegetative health. Figure 11B is a ground-level photo taken in the interior of an impacted marsh. Site characteristics were uniformly high mortality distinguished by leafless standing dead culms; note the total absence of any green stems. By late winter 2000 (Figure 11C) all the above-ground biomass had deteriorated and exported out of the marsh, leaving a large expansion of bare, loose, and unconsolidated mudflats. Standing-dead stems in mid-summer (fig.11B) provided some physical protection from sediment loss, but were reduced to surface stubble (Figure 11D) by late winter providing little, if any protection from surface erosion.

the marsh, leaving large expansions of bare, loose, and unconsolidated mudflats. The standing-dead stems present in mid-summer 2000 were reduced to surface stubble by late winter (Figure 11D).

In the November 2001 aerial map, we used the dark gray signature of the reduced stubble and exposed mud to delineate habitat loss resulting from brown marsh effect within the study area (Figure 12). We used the same boundaries and delineation methods as previously described for the 1998 base map. In addition to healthy emergent marsh and open water bodies, we added a third attribute to the 2001 dataset to account for impacted (dead) marsh as affected by the brown marsh events.

We found a significantly large amount of marsh loss in both the sediment treatment and the control sites of the study area. Marsh loss within the study area followed the same uniform pattern seen throughout the Barataria-Terrebonne Basin; that is, the greatest mortality occurring in the marsh interior with lesser degrees of mortality along shorelines and tidal creek banks, suggested a correlation with tidal flushing (McKee, Mendelssohn, Materne, 2003). Although this pattern is evident in the 2001 map, it is not entirely consistent. For example, marsh on the north bank of the tidal creek located on the north end of cell B (Figure 13), appears to be relatively unimpacted; where as the marsh directly across from it on the south bank, is virtually dead. This same pattern of healthy-and-dead marsh on opposing banks, can also be seen along the tidal creek located on the north end of cell E. For a more complete discussion of brown marsh effects, see the final report *Salt Marsh Dieback in Coastal Louisiana: Survey of Plant and Soil Conditions at 23 Sites in Barataria and Terrebonne Basins, June 2000-September 2001*, submitted to the Louisiana Department of Natural Resources in 2003.

As with the 1998 map, we delineated and highlighted all the features within the study cells (A-E) and control cells (Ctl-A and Ctl-B) for visual separation (Figure 12) and to create a 2001metrics table for numeric comparisons. We found a high, but varying degree of marsh loss across the treatment areas in 2001. Cell A, for example, had the smallest amount of marsh loss (65%) when compared to the same area in 1998, and cell C the greatest amount (96%). Marsh losses within the control sites were also high, with 84% and 91% loss in control cells A and B, respectively. Across the entire sediment treatment area, there was a net loss of 21.1 acres (81.7%) in emergent marsh and a net gain of 0.27 acres (9.9%) in open water compared to the same area in 1998. Losses and gains were similar across the control treatments, with a net loss of 6.5 acres (77.8%) in

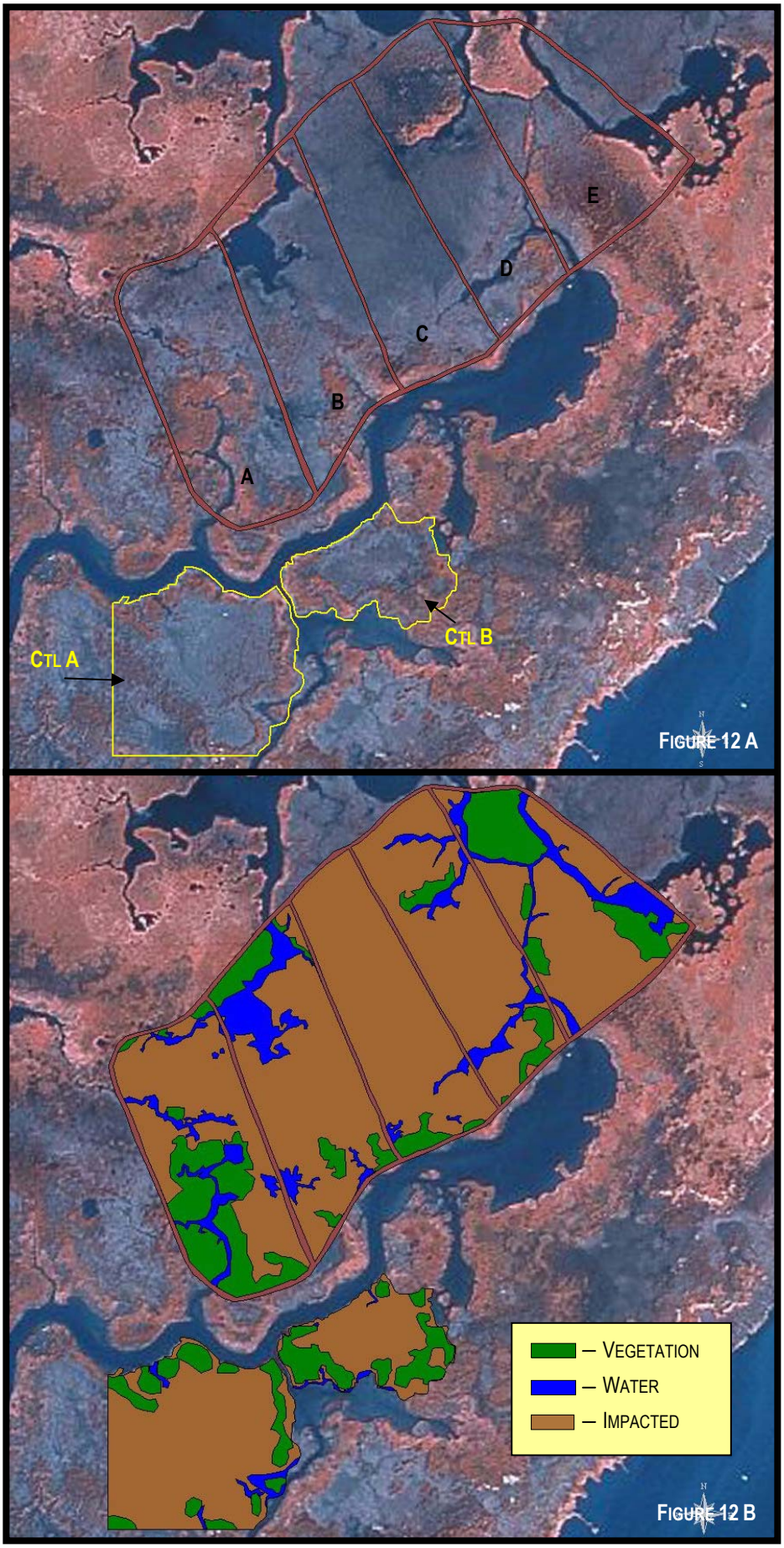


FIGURE 12 – 2001 habitat land-use map: Fig. 12A shows both the sediment treatment and the control sites with the control boundary overlay, but without the habitat attribute layer. Fig. 12B is the same area for both the treatment and control sites but with the habitat attribute layers highlighted for comparison.

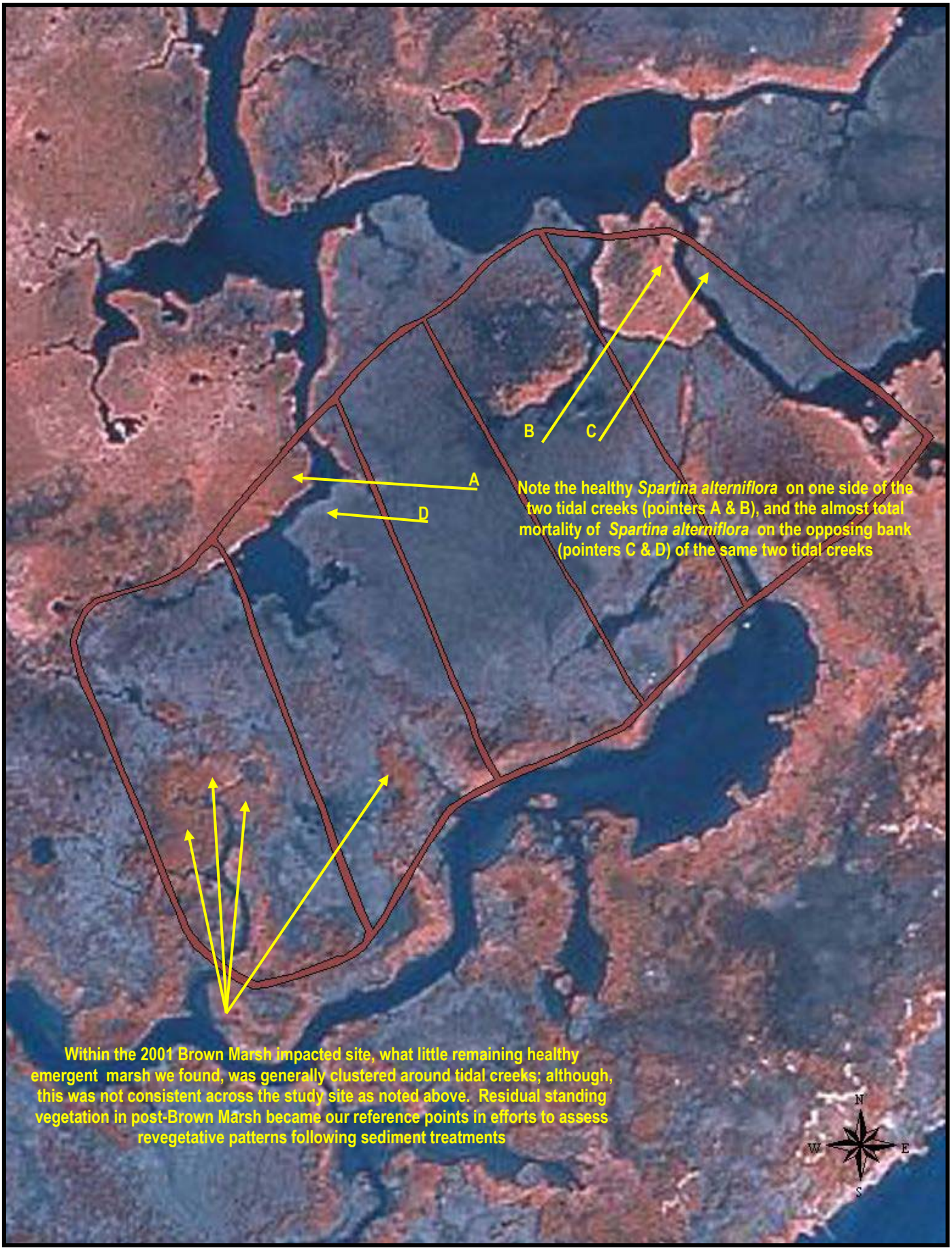


FIGURE 13 – 2001 Brown Marsh image with standing emergent vegetation and dead stubble.

emergent marsh and a net gain of 0.04 acres (20.9%) in water. Although there were net gains in water bodies in both the sediment treatment and control sites, gains were statistically small, and could be attributed to differences in water levels at the time of photography. Table 3 is a summary of spring 2001 study figures across treatments and sites. Table 3 also includes like-area comparisons with a calculated difference (gain or loss) from the 1998 pre-brown marsh imagery.

TABLE 3 2001 HABITAT CHANGE SUMMARY

YEAR	TREATMENT	ATTRIBUTE	CELL	FT²	ACRE(S)	CHANGES FROM 1998 ACRE(S)	CHANGES FROM 1998 %
2001	Sediment Cells	Vegetation	A	84,505.1	1.94	-3.61	-65.0
			B	28,803.2	0.66	-4.44	-87.0
			C	9,736.9	0.22	-4.95	-95.6
			D	18,579.2	0.43	-4.61	-91.5
			E	64,155.4	1.47	-3.48	-70.2
		SubTotal Vegetated	**A-E**	**205,779.8**	**4.72**	**-21.09**	**-81.6**
2001	Sediment Cells	Impacted	A	151,787.8	3.49	+3.49	+100
			B	189,544.2	4.35	+4.35	+100
			C	214,528.7	4.92	+4.92	+100
			D	200,858.3	4.61	+4.61	+100
			E	150,542.1	3.46	+3.46	+100
		SubTotal Impacted	**A-E**	**907,261.1**	**20.83**	**+20.83**	**+100**
2001	Sediment Cells	Water	A	27,463.5	0.63	+0.13	+25.5
			B	40,875.9	0.94	+0.09	+10.4
			C	4,336.6	0.10	+0.03	+37.5
			D	19,913.1	0.46	-0.01	-1.7
			E	35,951.1	0.83	+0.03	+3.7
		SubTotal Water	**A-E**	**128,540.2**	**2.96**	**0.27**	**9.9**
		Total Treatment Cells	**A-E**	**1,241,581.2**	**28.51**		
2001	Control Cells	Vegetation	Ctl. A	40,887.7	0.94	-4.80	-83.6
			Ctl. B	39,642.3	0.91	-1.67	-64.8
		SubTotal Vegetated	**Ctl. A-B**	**80,530.0**	**1.85**	**-6.47**	**-77.8**
2001	Control Cells	Impacted	Ctl. A	207,145.3	4.76	+4.76	+100
			Ctl. B	73,063.2	1.68	+1.68	+100
		SubTotal Impacted	**Ctl. A-B**	**280,208.5**	**6.44**	**+6.44**	**+100**
2001	Control Cells	Water	Ctl. A	7,783..2	0.18	+0.04	+31.6
			Ctl. B	2,978.6	0.07	+0.0	+0.0
		SubTotal Water	**Ctl. A-B**	**10,761.7**	**0.25**	**0.04**	**20.9**
		Total Control Cells	**A-B**	**371,500.2**	**8.54**		

2003 Imagery – 4 and 12 months post-treatment

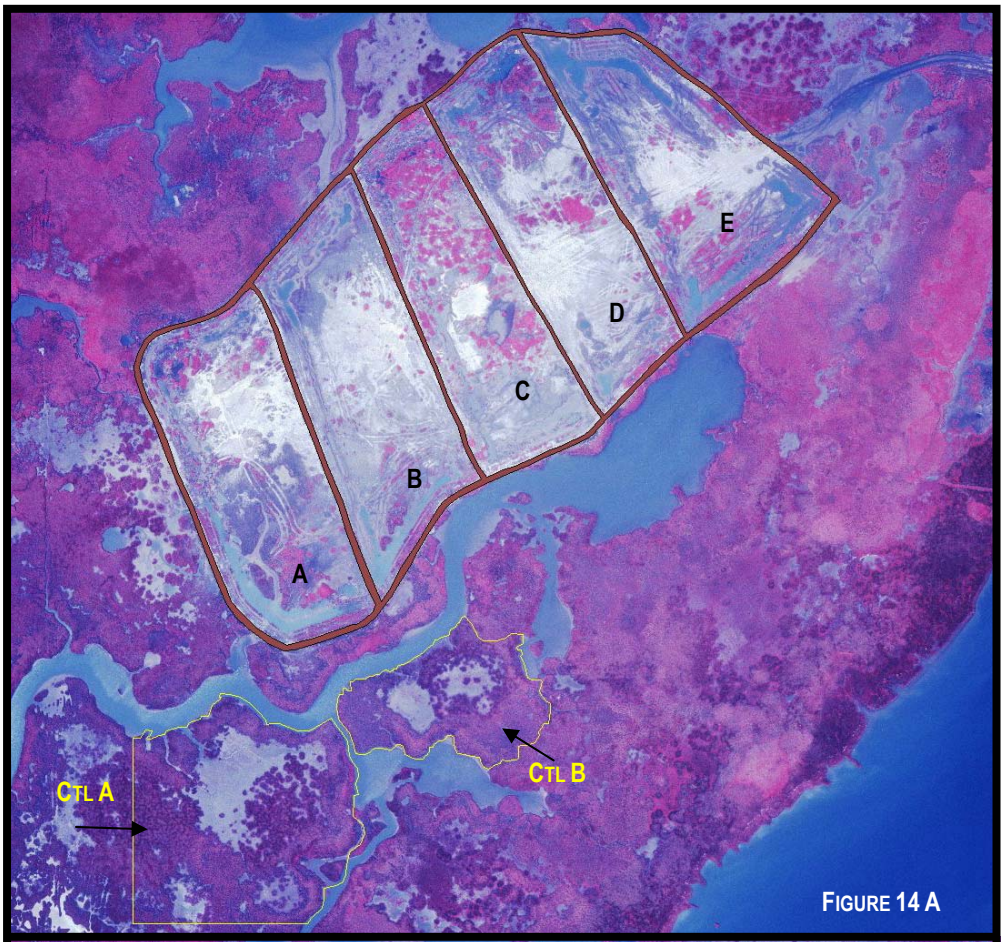
The next set of aerial photography that we used in the spatial analysis were flown in April 2003 (4-months post-treatment) and December 2003 (12-months post-treatment). These

dates were selected to establish an initial baseline shortly after deposition and prior to the first growing season, and for subsequent comparison at the end of the first and second full growing seasons. As with earlier maps used in the analyses, we fixed common boundary controls to their respective maps prior to separating treatment and control attributes to restrict delineations to a fixed constant and to provide a summary check to ensure accuracy across multiple base maps.

Sediments used in the study area were hydraulically dredged from the bottom of Bayou Lafourche, were mixed with water at an indeterminate ratio, and pumped as a slurry onto the marsh surface. Sediment depths within individual sediment cells varied, with the greatest depth of sediments created closest to the outlet end of the slurry conveyance pipe. Sediment distribution was a function of sediment-water ratio, hydraulic pressure, sediment particle size, and the frequency at which the conveyance pipe was moved. Marsh topography (surface features), such as standing vegetation or surface depressions also had an effect on the degree of deposition. Deep depressions, such as barrow-pits were filled to the same level as the surrounding marsh, but settled disproportionally because of the greater volume of saturated sediments within the barrow area. Deep barrow pits, ponds, and tidal channels collected higher concentrations of fluid soils, resulting in longer hydro-periods than surrounding marsh, and generally become permanent water features within the study area. Areas of dense vegetation also had a sediment reducing effect by obstructing and deflected slurry-flow through standing stems, resulting in thinner deposits within vegetative stands. Although there were a number of mechanical, physical, and biological interactions that influenced the overall distribution pattern and sediment depth, all of the cells within the study area received some level of sediment enrichment.

In the previous evaluation year (2001 brown marsh), we created an attribute termed "impacted" to describe standing dead marsh affected by brown marsh events. Although there were some isolated pockets of relatively healthy marsh found within the 2001 study area (4.7 acres or 18%), virtually the entire area was affected to some degree by brown marsh. In assessing land use changes found on the spring 2003 aerial map (4 months post-treatment), we continued using the term "impacted", but now in reference to disturbed soils lacking vegetative cover as a result of sediment placement (Figure 14)

We compared habitat change from 2001 (brown marsh) to spring 2003 (4-months post-sediment treatment) across three habitat variables; vegetative cover, impacted soils, and permanent open water. At the end of 2001, there were 4.72 acres of vegetation (16.6% of



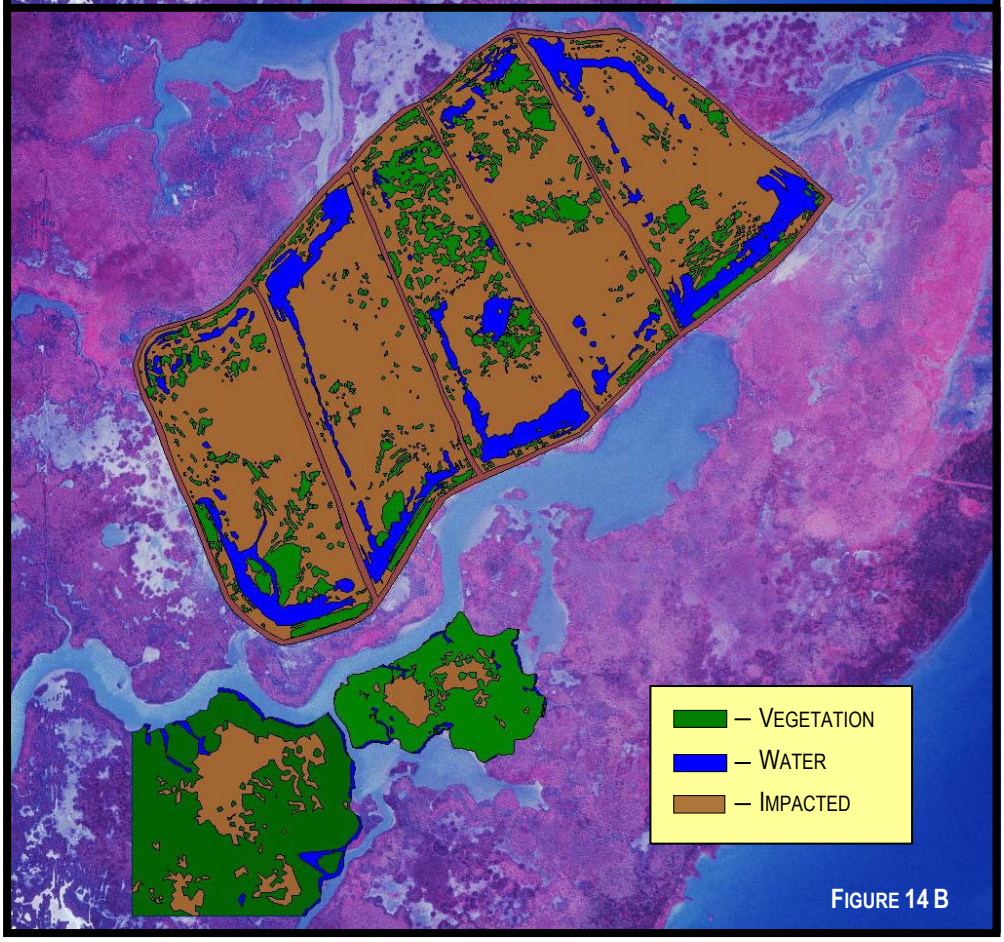


FIGURE 14 – Spring 2003 habitat land-use map: Fig. 14A shows both the sediment treatment and the control sites with the control boundary overlay, but without the habitat attribute layer. Fig. 14B is the same area for both the treatment and control sites but with the habitat attribute layers highlighted for comparison.

the total area), 20.83 acres of impacted area (73% of total), and 2.96 acres of water (10.3% of total). Four months after treating the area with additional sediments, there was little statistical change across the sediment cells. By spring of 2003, there was a 10% reduction in vegetative cover from that found in 2001 (4.25 acres down from 4.72 acres), impacted acres remained static with a 0.43% increase (20.92 acres up from 20.83 acres), and open water increased 17.8% (3.48 acres up from 2.96 acres).

Although there were relatively small statistical changes within test variables, there were significant physical changes in habitat distribution, particularly with vegetation and water bodies. For example, in comparing the location of healthy vegetation between 2001 and spring 2003, note that what remaining relatively healthy marsh can be seen in the 2001 aerial (Figure 13) is clustered around tidal creeks and contained in fairly discrete stands of vegetation. However, in spring 2003, all of the larger stands had disappeared and vegetation reappears as small randomly distributed clumps, not particularly associated with any apparent surface features, such as water or pre-treatment standing crop. It would have been reasonable to assume that post-treatment vegetative recovery would have been concentrated in areas where pre-treatment vegetative communities existed. Historically, standing crops have proven to be a nursery-rich source for above- and below-ground propagules, as well as for seed-based recovery.

However, what we observed early in the study was a complete redistribution of plant materials with no apparent correlation to pre-treatment standing crop. For example, in 2001 vegetative cover found in sediment cells C and D was only 0.65 acres (see Figure 12 for location and Table 3 for calculations), but it had increased to 1.97 acres by spring 2003 (Figure 14 and Table 4). In contrast, cells A, B, and E which had the largest concentration of plants in 2001, showed reduced vegetative cover by 24% to 53% in spring 2003.

Water distribution changes paralleled that of vegetation, but resulting from different mechanisms. For comparison, we delineated the location of tidal channels (red outline) on the pre-treatment 1998 imagery (Figure 15A) and overlaid these channels on the post-treatment spring 2003 image (Figure 15B). For contrast, we delineated and colored existing water (dark blue) and vegetation (dark green) on the 2003 image. Note that only in the immediate area, where the retention levees were intentionally breeched (marked by a yellow circle), was there some minimal return to the original watershed pattern. For the most part, water bodies within the treatment cells did not return to their original patterns, but re-established primarily along barrow-site excavation lines.

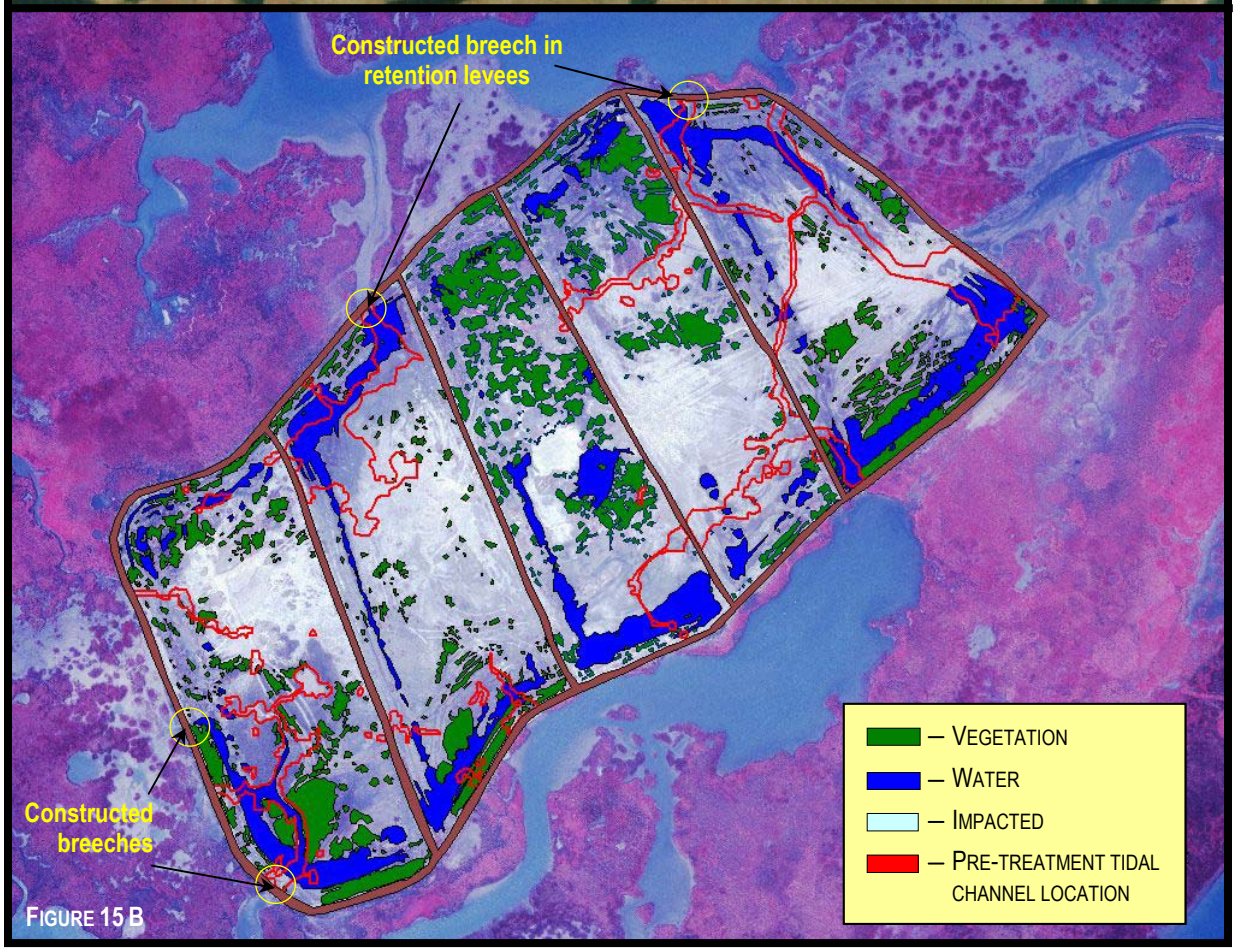


Figure 15 – Fig. 15A is the 1998 image with the pre-sediment treatment locations of tidal channels outlined in red; Fig. 15B is a post-sediment treatment image (spring 2003) with the 1998 channel overlay. Note that virtually all of the original site hydrology has been changed and for the most part has been replaced with isolated discrete shallow water bodies.

Non-treatment control sites A and B both showed significant recovery from 2001, increasing plant cover by 358% and 132% respectively. Unlike the sediment treatment cells where foundation plants appeared random, there was an obvious regrowth pattern within impacted control cells. Plant growth advanced from the outer-edge towards the center, indicating that most (if not all) of the new growth is clonal, originating from old-growth rhizomes.

Table 4 is a summary of spring 2003 study figures across treatments and sites. Table 4 also includes like-area comparisons with a calculated difference (gain or loss) from 2001.

TABLE 4 SPRING 2003 HABITAT CHANGE SUMMARY

YEAR	TREATMENT	ATTRIBUTE	CELL	FT²	ACRE(S)	CHANGE FROM 2001 ACRE(S)	CHANGE FROM 2001 %
Spring 2003	Sediment Cells	Vegetation	A	47,773.3	1.10	-0.85	-43.53
			B	21,244.6	0.50	-0.16	-24.66
			C	52,596.1	1.21	+0.99	+444.8
			D	32,916.8	0.76	+0.33	+77.9
			E	29,311.7	0.68	-0.79	-53.7
		SubTotal Vegetated	**A-E**	**183,842.5**	**4.25**	**-0.48**	**-10.0**
Spring 2003	Sediment Cells	Impacted	A	192,262.8	4.42	+0.93	+26.7
			B	204,311.6	4.69	+0.34	+7.9
			C	145,832.0	3.35	-1.58	-31.9
			D	193,602.7	4.45	-0.17	-3.62
			E	174,992.8	4.02	+0.56	+16.2
		SubTotal Impacted	**A-E**	**911,001.9**	**20.93**	**+0.08**	**+0.43**
Spring 2003	Sediment Cells	Water	A	27,515.3	0.63	+0.00	+0.32
			B	36,083.6	0.83	-0.11	-11.7
			C	29,889.9	0.69	+0.59	+592.9
			D	12,555.1	0.29	-0.17	-37.4
			E	45,441.5	1.04	+0.22	+26.4
		SubTotal Water	**A-E**	**151,485.4**	**3.48**	**+0.53**	**+17.83**
		Total Treatment Cells	**A-E**	**1,246,329.8**	**28.66**		
Spring 2003	Control Cells	Vegetation	Ctl. A	187,154.4	4.30	+3.36	+358.0
			Ctl. B	91,682.5	2.11	+1.20	+131.7
		SubTotal Vegetated	**Ctl. A-B**	**278,836.9**	**6.41**	**+4.56**	**+246.6**
Spring 2003	Control Cells	Impacted	Ctl. A	57,867.8	1.33	-3.43	-72.1
			Ctl. B	19,138.8	0.44	-1.24	-73.8
		SubTotal Impacted	**Ctl. A-B**	**77,006.6**	**1.77**	**-4.67**	**-72.5**
Spring 2003	Control Cells	Water	Ctl. A	10,768.8	0.25	+0.07	+37.4
			Ctl. B	4,848.9	0.11	+0.04	+60.9
		SubTotal Water	**Ctl. A-B**	**15,617.7**	**0.36**	**+0.11**	**+44.0**
		Total Control Cells	**A-B**	**371,461.2**	**8.54**		

Fall 2003 and 2004 Imagery – 12 and 24 months post-treatment

As with previous maps used in the project, we delineated and highlighted all the features within the study cells (A-E) and control cells (Ctl-A and Ctl-B) for fall 2003 and fall 2004 (Figures 16 and 17). As before, we attached common boundary controls to both maps to restrict delineations to a fixed constant and to provide a summary check to ensure accuracy across all project maps. The fall 2003 and fall 2004 aerial images were taken at the end of the first and the second year growing seasons, 12 and 24 months post-treatment, respectively.

Within the sediment treatment cells we found that vegetative recovery by fall 2003 had increased significantly in nine months. Vegetative cover across the four sediment cells increased 237.7% from the previous spring, an increase of 10.1 acres (14.3 acres up from 4.3 acres). Vegetative gains were greatest in cells B, D, and E which were primarily bare soils going into the summer months of 2003. Bare or impacted soils were decreased by 207.6% (14.12 acres), a reduction from 20.9 acres to 6.8 acres, and water increased by 112.9% (3.9 acres) up from 3.4 acres to 7.4 acres. The greatest water body gains were in cells C, D, and E. The largest single water body was found at the low end of cell C, and appeared to be trapped water resulting from lack of an outlet.

Both control sites in the fall of 2003 also showed positive habitat changes, but at a more reduced rate than that of the sediment treatment cells. The vegetated areas within the control sites increased very little, from 6.4 acres to 6.7 acres, a scant 0.35 acre increase in nine months. Concurrently, there was a 0.36 acre decrease from the impacted area (1.8 acres down to 1.4 acres). Water areas within the control sites stayed virtually static, 0.36 acres to 0.37 acres. Overall, the control sites appeared to have stabilized, with little habitat change within the nine month evaluation period.

By December 2004, the vast majority of the sediment cells had re-vegetated, with the exception of the extreme high and the extreme low elevations within each cell (Figure 17). Within the sediment cells a total of 24.6 acres were vegetated, up from 14.3 acres in December 2003. Of primary significance was that the impacted areas had been reduced by 5.9 acres over 12 months, leaving less than one acre (0.95) of bare soil remaining across the entire study site. In addition, water bodies had been reduced by 60.2% (4.5 acres), down from 7.4 acres to 3.0 acres. Within the control sites, as was the case in the previous 12 months, only slight changes occurred. Vegetated areas increased by 0.67 acres (6.8 acres to 7.4 acres), the impacted areas decreased by 0.82 acres (1.4

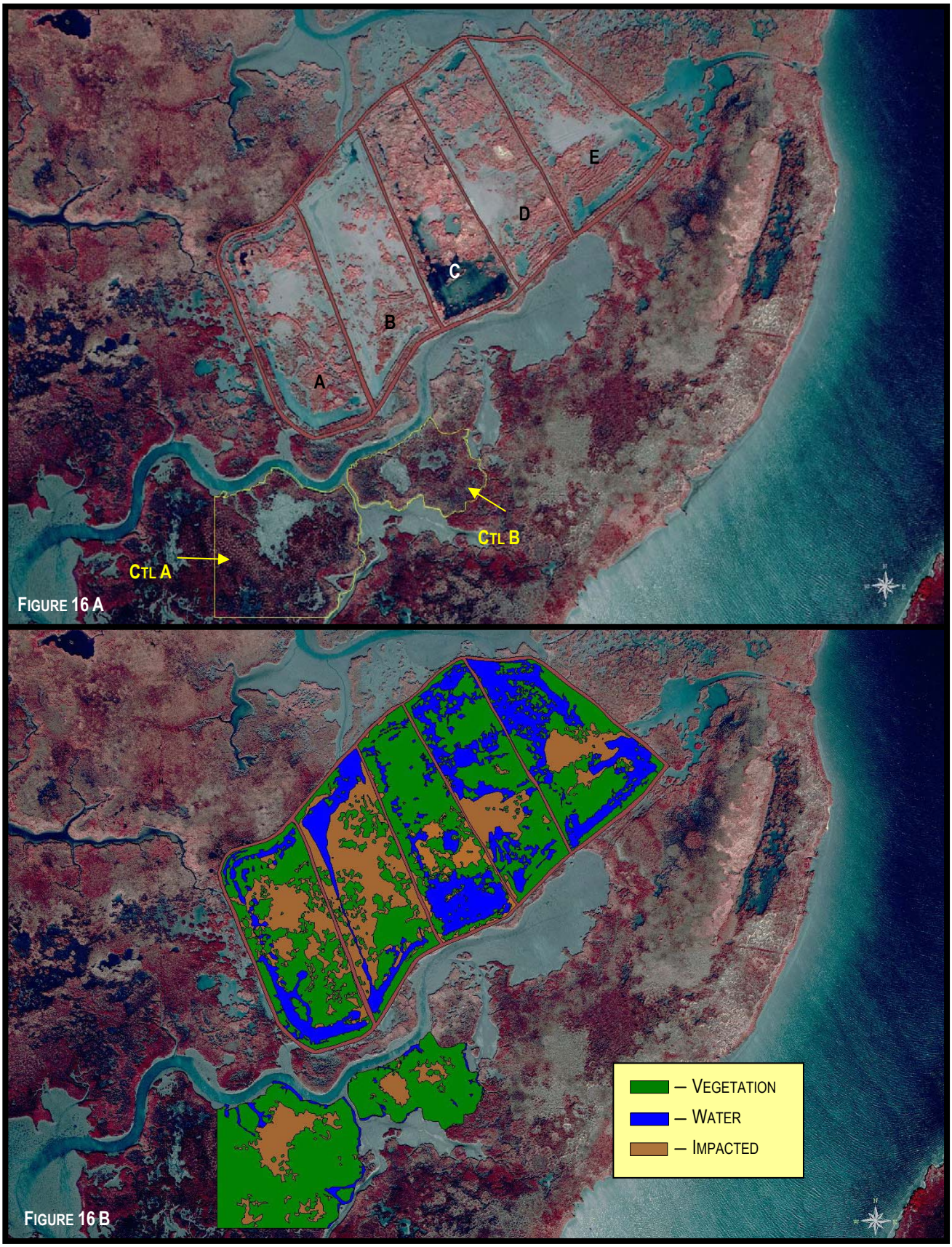


FIGURE 16 – Fall 2003 habitat land-use map: Fig. 16A shows both the sediment treatment and the control sites with the control boundary overlay, but without the habitat attribute layer. Fig. 16B is the same area for both the treatment and control sites but with the habitat attribute layers highlighted for comparison.

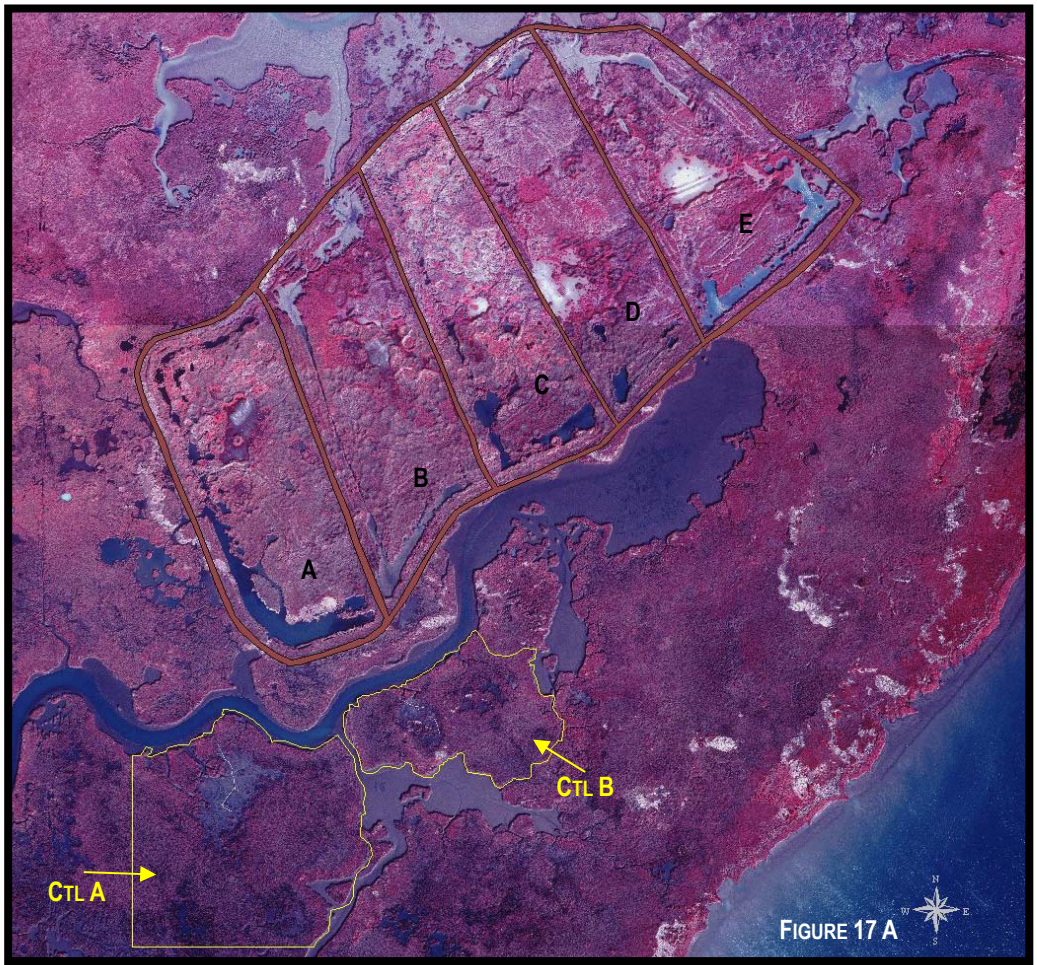


FIGURE 17 – Fall 2004 habitat land-use map: Fig. 17A shows both the sediment treatment and the control sites with the control boundary overlay, but without the habitat attribute layer. Fig. 17B is the same area for both the treatment and control sites but with the habitat attribute layers highlighted for comparison.

acres to 0.59 acres) leaving less than one acre (0.59) of bare, or unvegetated area. In addition, water bodies remained fairly constant with a 0.15 acre increase (0.37 acres to 0.52 acres). Table 5 is a summary of the fall 2003 and 2004 study data across treatments and sites. Table 5 also includes like-area comparisons with a calculated difference (gain or loss) between spring 2003 and fall 2003, and fall 2003 and fall 2004.

A complete set of aerial photograph enlargements without overlays are include in Appendices 1 through 5. We include this additional set of maps to provide greater detail and a less obstructed views of the study sites and control areas.

TABLE 5 FALL 2003 AND 2004 HABITAT CHANGE SUMMARY

TREATMENT	ATTRIBUTE	CELL	FALL 2003		CHANGE BETWEEN SPRING & FALL 2003		FALL 2004		CHANGE BETWEEN FALL 03 & FALL 04	
			FT²	ACRE(S)	ACRE(S)	%	FT²	ACRE(S)	ACRE(S)	%
Sediment Cells	Vegetation	A	148,121.4	3.4	2.3	210.4	218,246.1	5.0	1.6	47.3
		B	90,538.1	2.1	1.6	317.9	224,749.5	5.2	3.1	147.9
		C	135,635.3	3.1	1.9	156.6	210,819.8	4.8	1.7	55.2
		D	134,926.3	3.1	2.3	307.8	217,127.5	4.9	1.9	60.8
		E	115,599.4	2.7	2.0	289.3	200,470.1	4.6	1.9	73.3
		SubTotal Vegetated	**624,820.5**	**14.4**	**10.1**	**237.7**	**1,071,413.0**	**24.5**	**10.2**	**71.3**
Sediment Cells	Impacted	A	71,693.3	1.7	-2.8	-62.7	9,049.5	0.2	-1.4	-87.4
		B	123,345.5	2.8	-1.9	-39.7	6,158.3	0.1	-2.7	-95.0
		C	31,836.9	0.7	-2.6	-78.1	1,369.3	0.0	-0.7	-95.8
		D	34,881.1	0.8	-3.6	-81.9	10,846.5	0.3	-0.6	-68.9
		E	34,241.9	0.8	-3.2	-80.4	13,800.2	0.3	-0.5	-59.8
		SubTotal Impacted	**295,998.7**	**6.8**	**-14.1**	**-67.5**	**41,223.8**	**0.9**	**-5.9**	**-86.1**
Sediment Cells	Water	A	44,489.6	1.0	0.4	61.4	36,505.9	0.8	-0.2	-17.9
		B	45,235.9	1.0	0.2	25.4	28,349.4	0.7	-0.4	-37.4
		C	63,330.4	1.5	0.8	112.2	16,220.6	0.4	-1.1	-74.6
		D	69,472.9	1.6	1.3	458.4	11,295.3	0.3	-1.3	-83.7
		E	99,794.6	2.3	1.3	119.5	36,057.6	0.8	-1.5	-63.9
		SubTotal Water	**322,323.4**	**7.4**	**4.0**	**112.9**	**128,428.8**	**3.0**	**-4.5**	**-60.2**
		Total Treatment Cells	**1,243,142.6**	**28.6**			**1,241,065.6**	**28.4**		
Control Cells	Vegetation	Ctl. A	199,244.8	4.6	0.3	6.5	219,689.1	5.1	0.5	10.3
		Ctl. B	94,545.6	2.2	0.1	3.0	103,420.5	2.4	0.2	9.4
		SubTotal Vegetated	**293,790.4**	**6.8**	**0.4**	**5.4**	**323,109.6**	**7.5**	**0.7**	**10.0**
Control Cells	Impacted	Ctl. A	45,048.0	1.0	-0.3	-22.2	21,822.3	0.5	-0.5	-51.6
		Ctl. B	16,290.1	0.4	-0.1	-15.0	4,006.9	0.1	-0.3	-75.3
		SubTotal Impacted	**61,338.1**	**1.4**	**-0.4**	**-20.4**	**25,829.2**	**0.6**	**-0.8**	**-57.9**
Control Cells	Water	Ctl. A	11,469.7	0.3	0.0	6.5	14,606.4	0.3	-0.1	27.9
		Ctl. B	4,845.4	0.1	0.0	0.0	8,295.7	0.2	0.1	69.4
		SubTotal Water	**16,315.1**	**0.4**	**0.0**	**4.5**	**22,902.1**	**0.5**	**0.0**	**40.2**
		Total Control Cells	**371,443.6**	**8.6**			**371,840.9**	**8.6**		

II. Hydrology

To assess water and salinity effects for the study area, we constructed a number of hydro-graphs to determine flooding frequency, distribution, duration, and depth across selected elevations, as well as to determine possible correlations between salinity, flooding, and rainfall. Over the 15-month study period, we found tidal cycling to follow a diurnal (one high and one low tide per ~24 hours) cycle, modified by over-riding weather effects, such as rainfall and storm surge. Minimum and maximum water elevations within the study area were -6.98" below– and +19.82" above normal marsh, with an average elevation of -0.13" (± 5.83) below normal marsh. Figure 18 is a complete dataset with daily minimum, maximum, and average water levels plotted across the entire sample period. We plotted water levels from tropical storm Matthew (September 04) and hurricanes Katrina and Rita (August and September 05) for reference, but excluded their statistics as outliers to reduce skewness in the descriptive statistics.

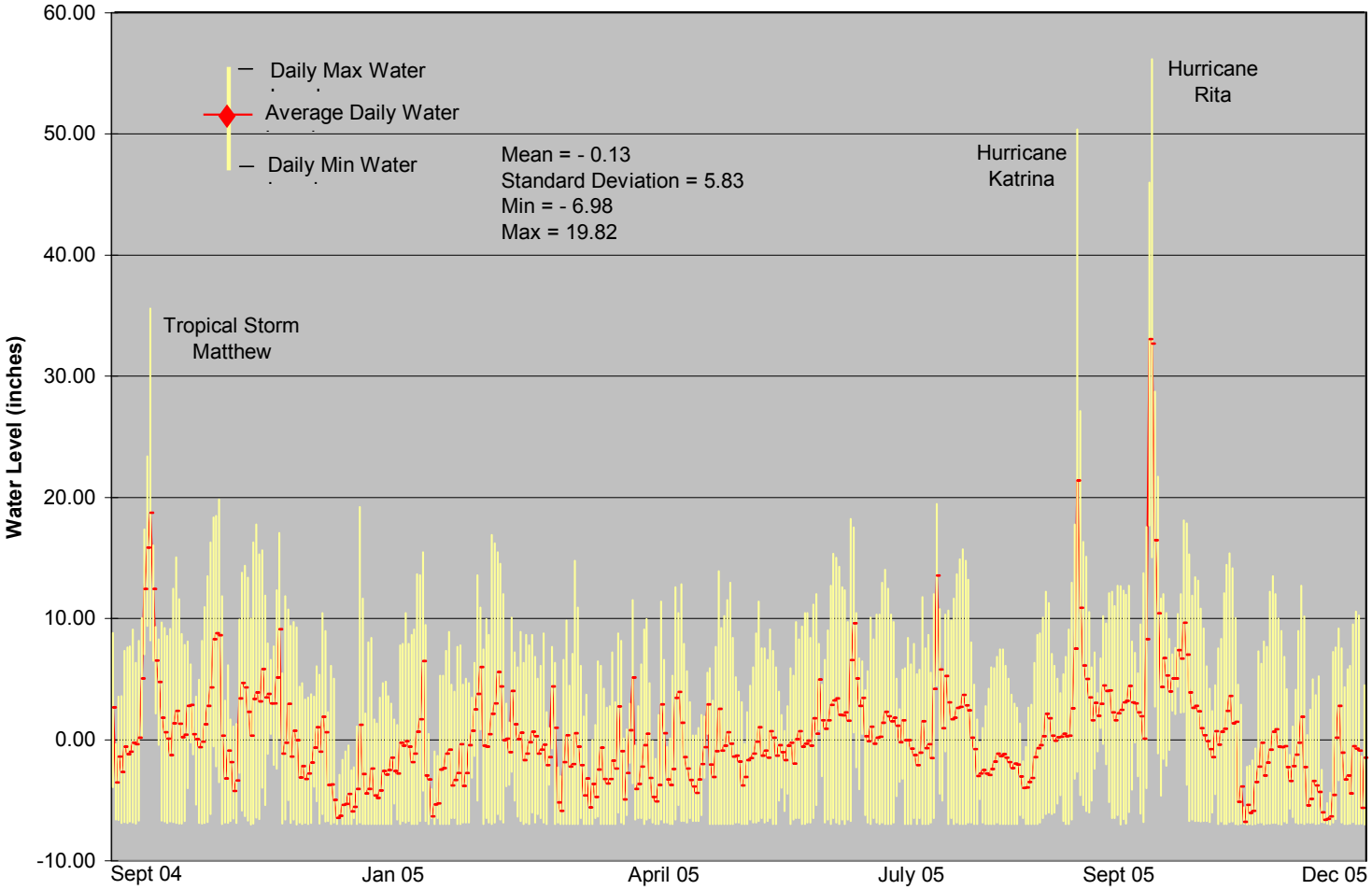


Figure 18 – Summary of water level readings taken over a 15 month sample period. Individual data lines represent the minimum, maximum, and means. Daily average is plotted across the data set in red.

We combined water level data into quarters, grouping them into a seasonal year: December to February represents winter, March to May – spring, June to August – summer, and September to November – fall. Using an analysis of variance to compare seasonal means for differences, we found a significant difference between seasonal water levels (p=0.53). A pairwise comparison showed that winter and spring differed from summer and fall, but were not significantly different from each other, and that summer and fall, although having different averages, were not statistically significantly different from each other. Seasonally, spring and winter had the lowest water levels, both averaged -1.34" (±5.32 and ±5.05) below normal marsh, while summer and fall levels were higher with averages of +0.83"(±6.09) and +0.39" (±6.11) above normal marsh. Using normal marsh as a reference elevation, we found that the marsh was flooded 40% at- or above- normal marsh elevation during low water periods (winter-spring) and an average of 49% at- or above- normal marsh elevation during high water periods (summer-fall). Quarterly water level plots are included in Appendix 6.

Flooding Frequency

There were a number of questions regarding the impact that increasing sediment depth (deposition over normal marsh) would have on flood frequency, duration, and distribution. To compare flood values across treatment elevations, we first defined flooding frequency as the number of flood events (expressed as percent of total) that flooding occurred, at- or above- a reference elevation of interest. A flood event is defined as a rising and falling water cycle, that begins with water level below a reference elevation, rises to- or exceeds- the reference elevation, and ends when water falls below the initial elevation; one full cycle (regardless of the length of timeframe) would constitute one flood event or frequency. For example, if 2" above normal marsh is the reference elevation and the sample period is four days, we would count two flooding frequencies if – on day one, water rises from less than 2" to ≥2" and stays at that level for two days. On the third day the water level falls to less than 2" and rises again to ≥2" on day four. Because water levels rose from below, equaled or exceeded, and fell below the target elevation twice within the sample period, two flooding events (or frequencies) had occurred. Using the four sediment treatment depths as reference points, (0", +6", +9", and +12" above normal marsh), we determined the frequency of flooding, and found that there was an 86% frequency of flooding at 0" (normal marsh), a 54% frequency at +6", a 29% frequency at +9", and only a 12% occurrence at +12" above normal marsh. In the higher elevations, water reached +18" less than 1% of the time, and never exceeded +19", except under tropical storm conditions (Figure 19).

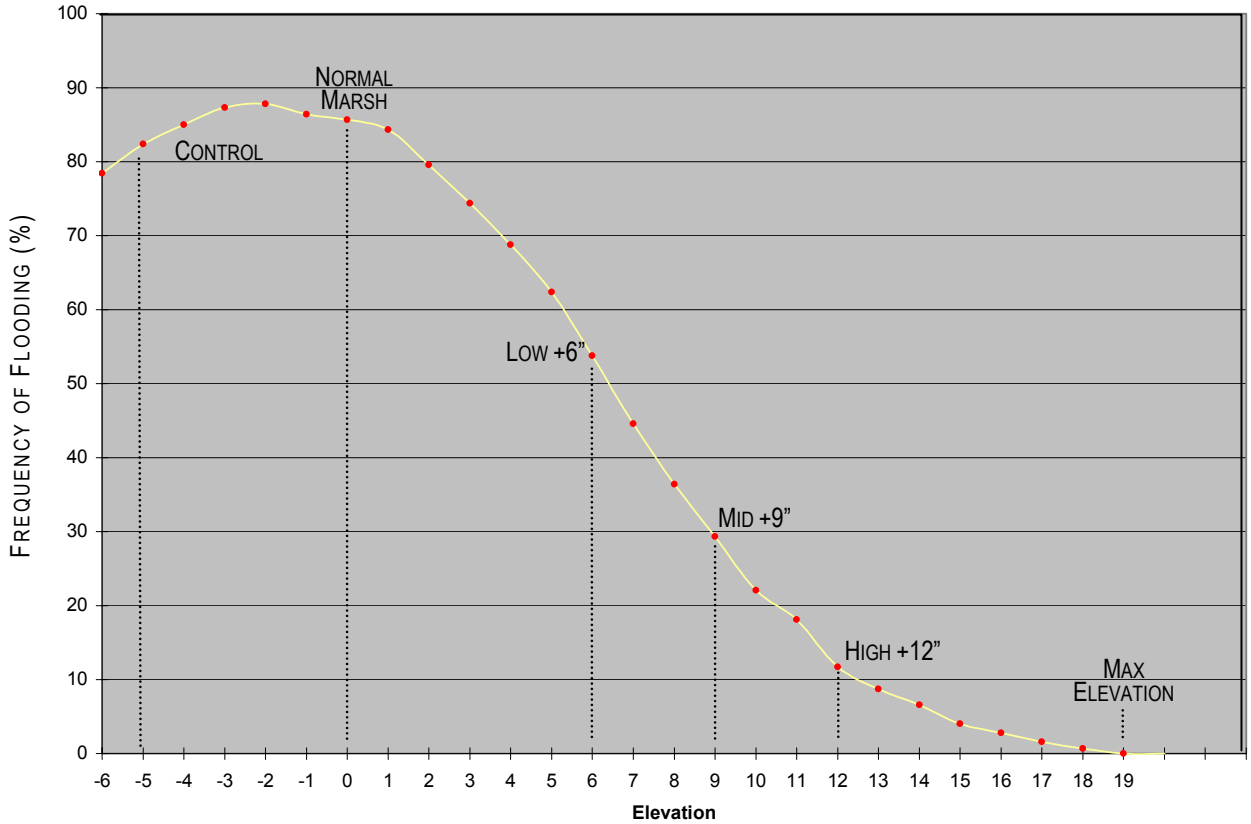


FIGURE 19 – Flooding frequency over a 15-month period. Key treatment site and control elevations are noted.

Table 6 is a summary of flood frequency events for the study period (426 days) and is summarized by elevation, occurrence, and percent of total. Target sediment treatment elevations are highlighted for reference.

TABLE 6 – Summary of Frequency

Elevation	Frequency	% of Total		Elevation	Frequency	% of Total
-6	334	78.4		+7	190	44.6
-5	351	82.4		+8	155	36.4
-4	362	85.0		+9	125	29.3
-3	372	87.3		+10	94	22.1
-2	374	87.8		+11	77	18.1
-1	368	86.4		+12	50	11.7
0	365	85.7		+13	37	8.7
+1	359	84.3		+14	28	6.6
+2	339	79.6		+15	17	4.0
+3	317	74.4		+16	12	2.8
+4	293	68.8		+17	7	1.6
+5	266	62.4		+18	3	0.7
+6	229	53.8		+19	0	0.00

To determine the elevational relationship between the control plots and normal marsh, we completed two elevation transects (profiles). We began each profile at the inside slope of the tidal creek, crossed the adjacent emergent vegetated marsh, traversed across the impacted brown marsh area, and ended the survey line approximately 30 feet into the vegetated marsh on the opposing side of the dieback mudflat.

Figure 20 is schematic of the transect location and elevation profile for control site A. Within the control plots, we found that the adjacent vegetated marsh, both at the leading and tailing ends of the transect line were at 0" elevation, equivalent to normal marsh. However, immediately outside of the vegetative marsh there was an immediate drop (~ 4") and a continuous decline in elevation within the open dieback area. Marsh elevation dropped from 0" at the vegetative-open marsh edge to -6.72", approximately mid way within the dieback area and returned to 0" within a few feet after re-entering vegetated marsh. Elevations within the vegetated high marsh equaled that of normal marsh (0") and the average elevation within the non-vegetated control was -5.8" below normal marsh. Using -5.8" as an elevation reference, we determined that the control sites had a 78% frequency of flooding.

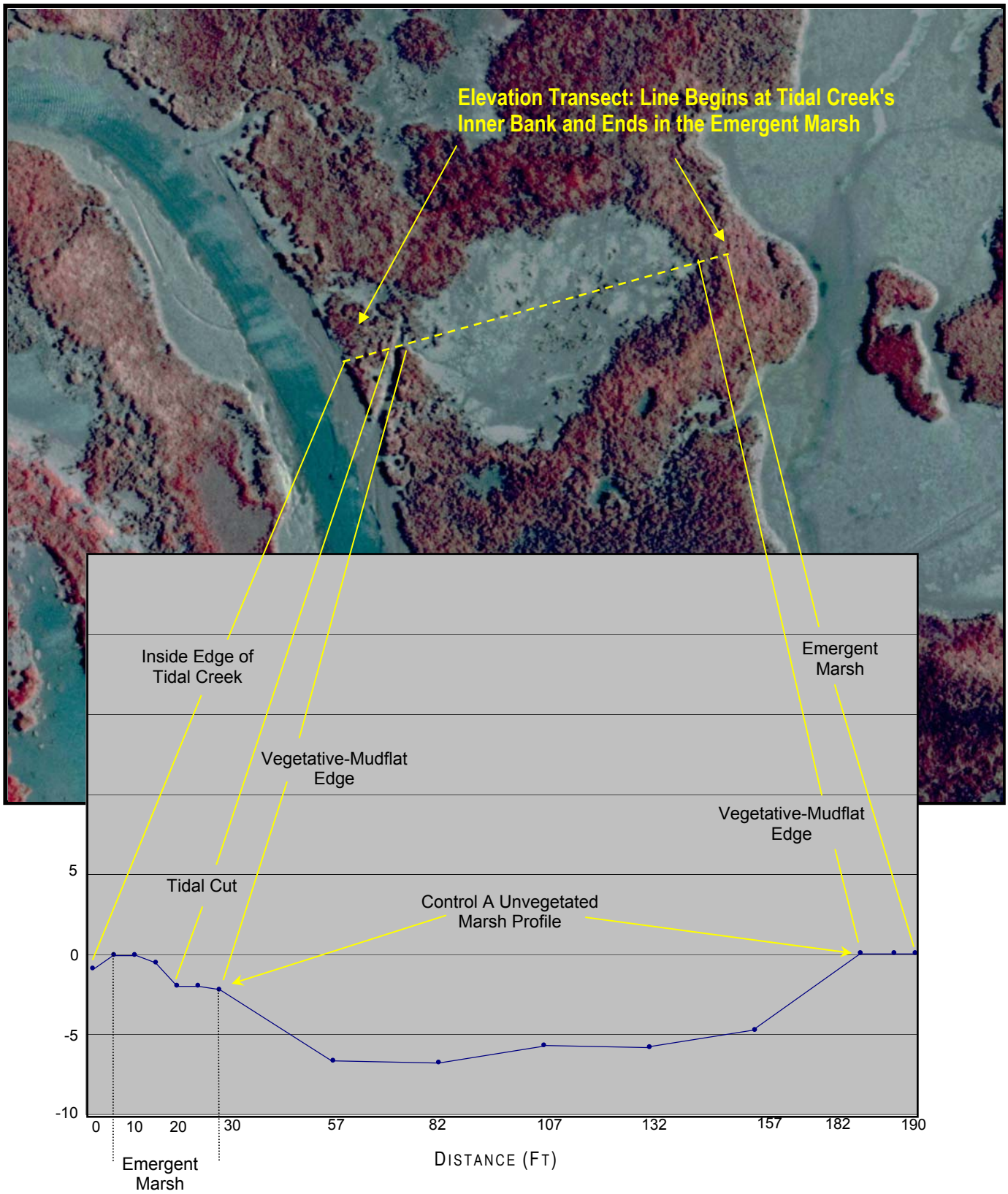


FIGURE 20– Elevational transect surveyed across Control site A and adjacent marsh. The submerged marsh surface in Control A demonstrates the instability of high organic marsh soils and the degree of soil loss when vegetation is impacted by high mortality and plant recovery is slow or non-existent.

Percent Time Flooding (Duration)

We defined flooding duration as the cumulative amount of time (expressed as percent of total) that standing water remained at- or above- a specific elevation. Since each recorded occurrence is equivalent to a 30-minute duration, the cumulative sum of each occurrence at- or above- a specific elevation would equal to the total time (or percent) that the marsh was flooded.

Using the same reference elevation dataset that we used for frequency, that is, 0", +6", +9", and +12" above normal marsh, we found that at 0", the marsh was flooded 49% of the time within the 15-month monitoring period. As elevations increase above normal marsh, the percent of flooding falls off sharply, with +6" and +9" marsh elevations flooding 19% and 8.9% of time respectively. Flooding at the upper elevations (+12") was minimal and occurring only 3.4% of the time, and less than 0.1% of the total time at +19" above normal marsh. In the untreated control sites, using an average elevation of -5.8" below normal marsh, we found the control sites flooded 88% of the time within the study period. Conversely, that means the surface area of the control sites did not have standing water over them for only 12% of the time. Figure 21 is the cumulative percent time flooded plotted in 1" elevation increments, and Table 7 is a summary of the amount of time flooded within the study period (426 days) summarized by elevation, occurrence, and percent of total.

TABLE 7 – SUMMARY OF % TIME FLOODED BY ELEVATION

ELEVATION	TIMES IN HOURS	% OF TOTAL		ELEVATION	TIMES IN HOURS	% OF TOTAL
-6	8977.5	88.0		+7	1522.0	14.9
-5	7217.0	70.8		+8	1191	11.7
-4	6793.5	66.6		+9	904.0	8.9
-3	6372.9	62.5		+10	662.5	6.5
-2	5909.5	58.0		+11	479.5	4.7
-1	5454.5	53.5		+12	351.5	3.4
0	4994.5	49.0		+13	230.5	2.3
+1	4447.5	43.6		+14	159.0	1.6
+2	3934.0	38.6		+15	113.0	1.1
+3	3413.5	33.5		+16	65.0	0.6
+4	2832.5	27.8		+17	42.0	0.4
+5	2342.0	23.0		+18	21.5	0.2
+6	1925.0	18.9		+19	7.5	0.1

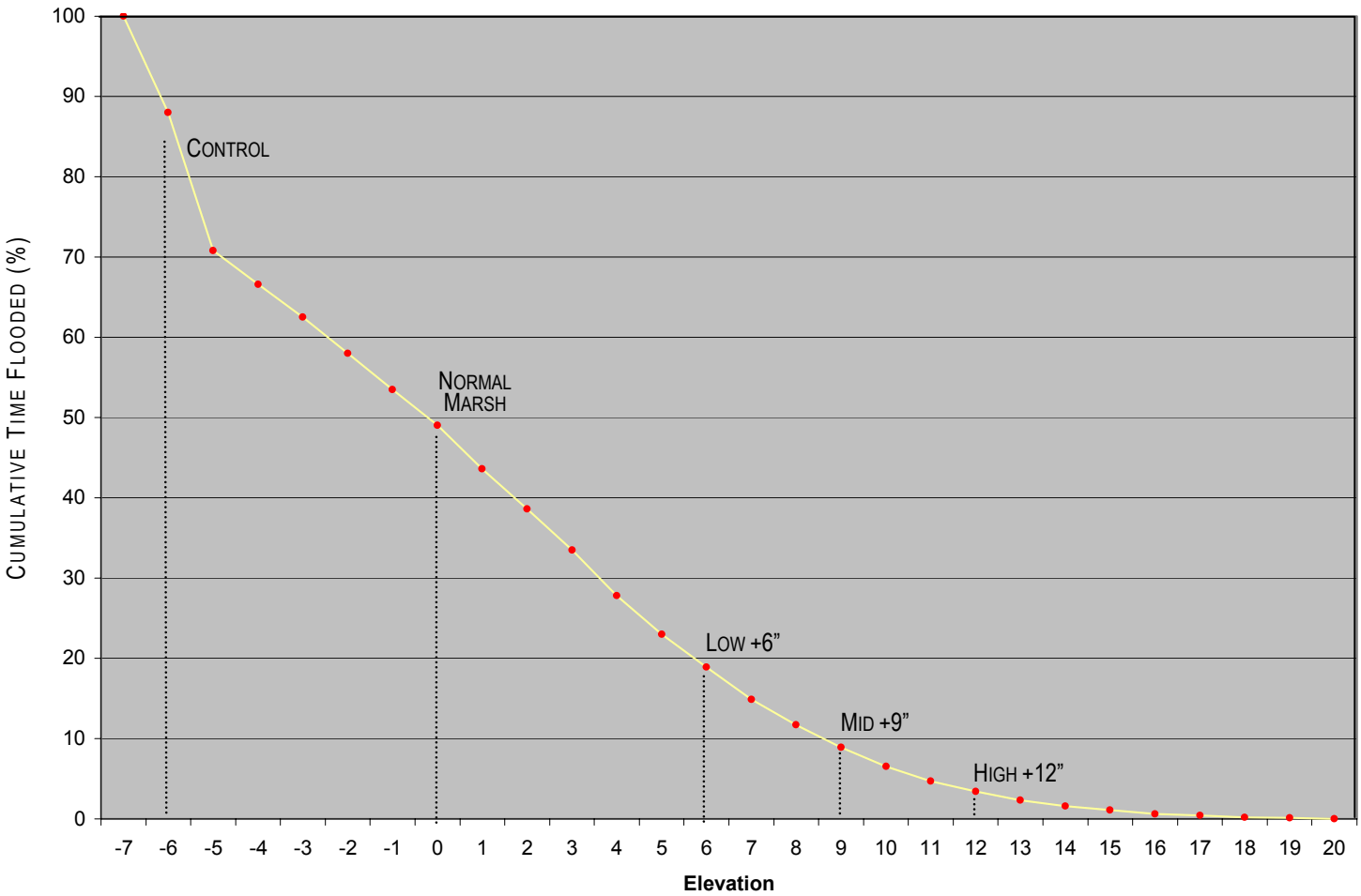


Figure 21 – Flooding duration, expressed as cumulative percent time flooded over the entire study period. At normal marsh elevation (0"), the marsh had approximately equal periods (49% and 51%) of wet - dry periods respectively.

Figure 22 is a composite of the percent flooding amounts plotted by season. We found that flooding duration varies seasonally, with shorter flooding periods in the winter-spring months (40% at normal marsh) and longer durations in the summer-fall (54% at normal marsh). For contrast, we plotted percent time flooded (duration) over flooding frequency, and is included as Appendix 7.

Salinity

Salinity was taken using a continuous recorder and read at 30-minute intervals, thus, providing a moderately large dataset to work with. Daily salinity varied significantly (Figure 23) throughout the study period, with a minimum of 1.2 ppt, a maximum of 30.9 ppt, and a 15-month average of 21.1 ppt (±4.1). Given the tidal ranges discussed earlier and an average salinity in the twenties, the study site would be defined as an intertidal saline marsh. As with flooding, we combined salinity data into quarters, grouping them

into a seasonal year: December to February represents winter, March to May – spring, June to August – summer, and September to November – fall (Figure 24). Using an analysis of variance to compare seasonal means for differences, we found a significant difference among seasonal salinities (p=0.49). A pairwise comparison, showed winter, spring, and summer differed from fall, but were not significantly different from each other. Winter and spring had the lowest salinity with averages of 19 ppt (±3.8), followed by summer (20.4 ±3.3), and fall with the highest (24.5 ±3.6). Individual seasonal salinity plots and their respective description statistics are included as Appendix 8.

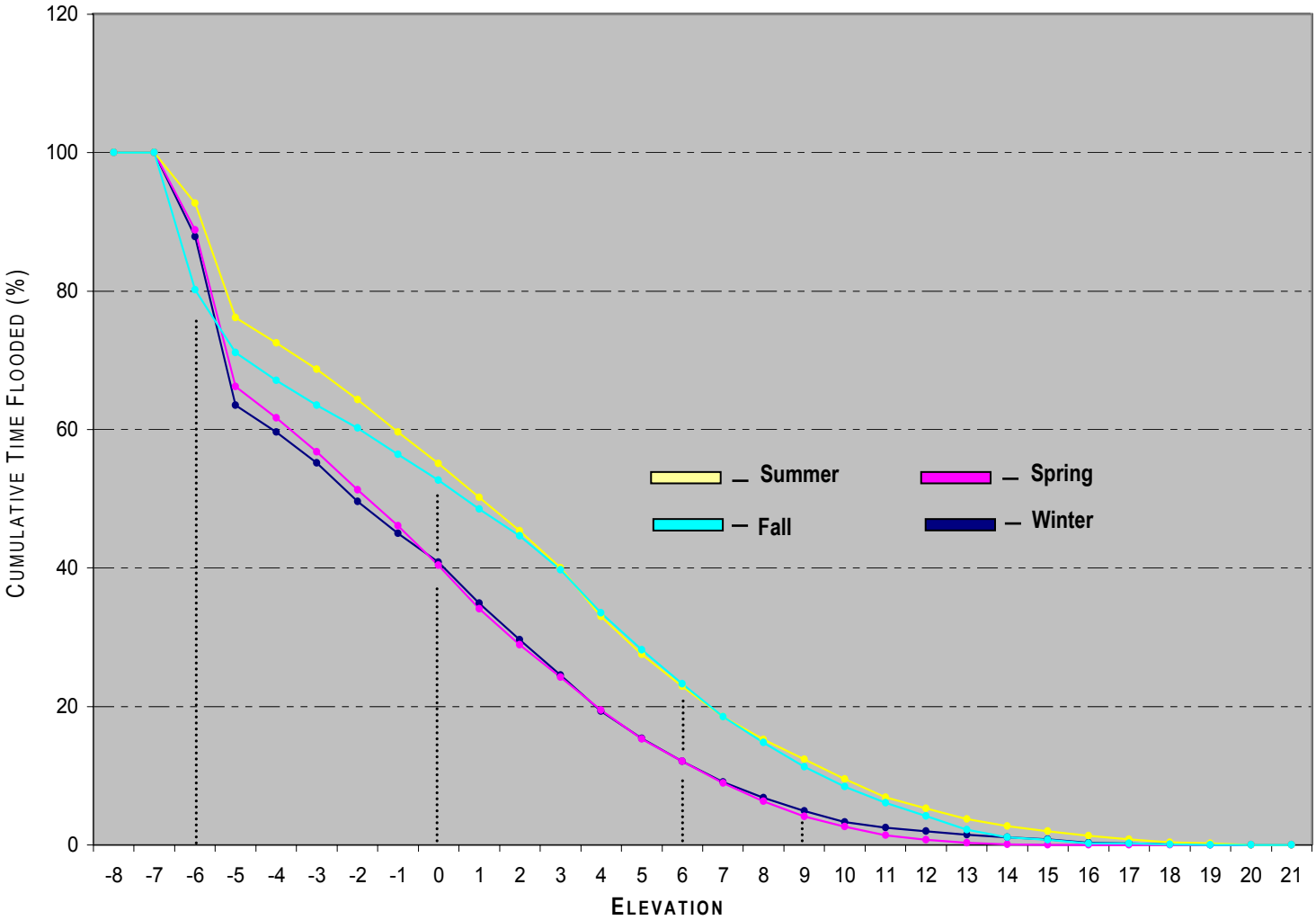


FIGURE 22 – Seasonal flooding duration by elevation. Summer and fall had the greatest length of flooding periods while spring and winter were statically equal and lower.

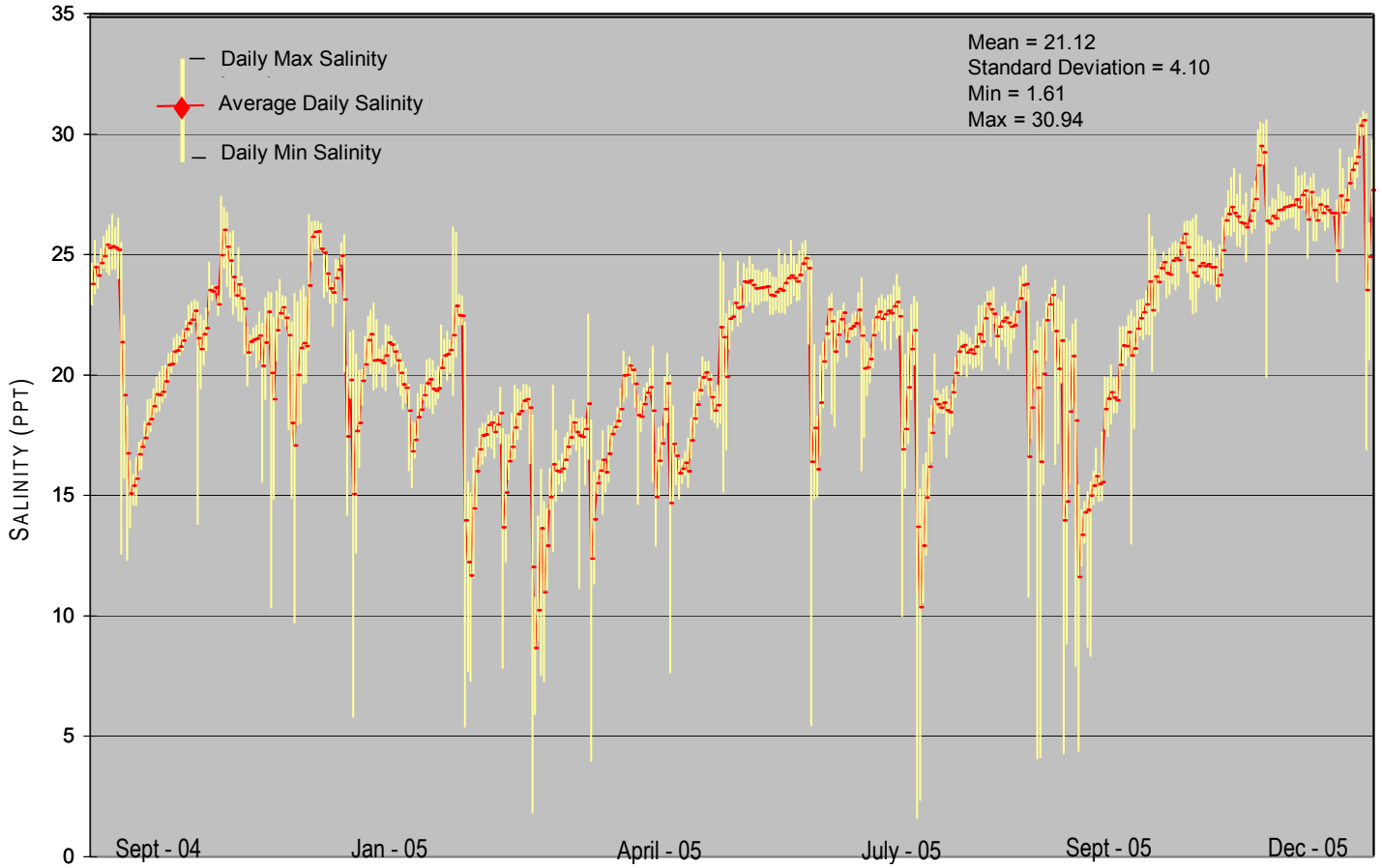


FIGURE 23 – Daily minimum and maximum salinity for the 15-month monitoring period. Daily average is indicated in red.

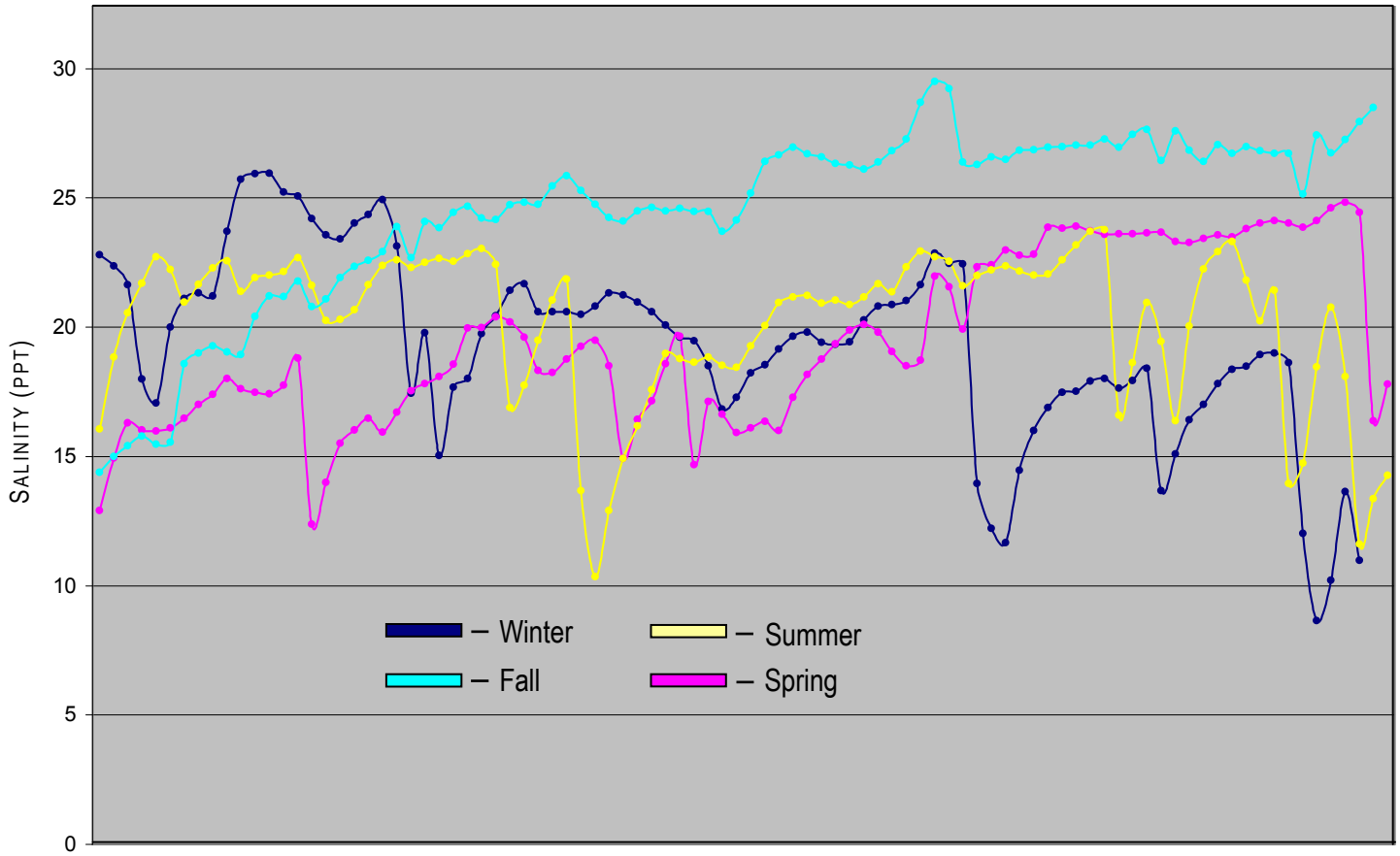


FIGURE 24 – Daily average salinity plotted by seasonal quarters.

Since there appeared to be some similarities in the high-low seasonal patterns between salinity and water levels, we looked at both tidal and rainfall influence relative to salinity change. We found there was virtually no relationship (r= -0.1, sample size= 20,920) between water levels and salinity, but found a moderately strong negative relationship (r = -0.54) between rainfall and salinity. Figure 25 is rainfall plotted over salinity for a 12-month period. For greater detail, we plotted rainfall over salinity for two three-month periods, winter (December through February) and fall (September through November) (Figures 26A and 26B). Note in the winter sequence, lower levels of salinity ($\overline{x}$= 19.3 ppt) and higher occurrence of rainfall (17.58”); also note that there is an immediate drop in salinity following a rainfall event. In the fall sequence, however, note that salinity is elevated ($\overline{x}$= 24.5 ppt), rainfall is down (6.05”), and that there is a steady increase in salinity during a prolonged period of little-to-no rainfall. Consequently, it is reasonable to assume that rainfall has an immediate but short-term effect on marsh salinities as opposed to water level, either from normal tidal cycles or wind driven surge.

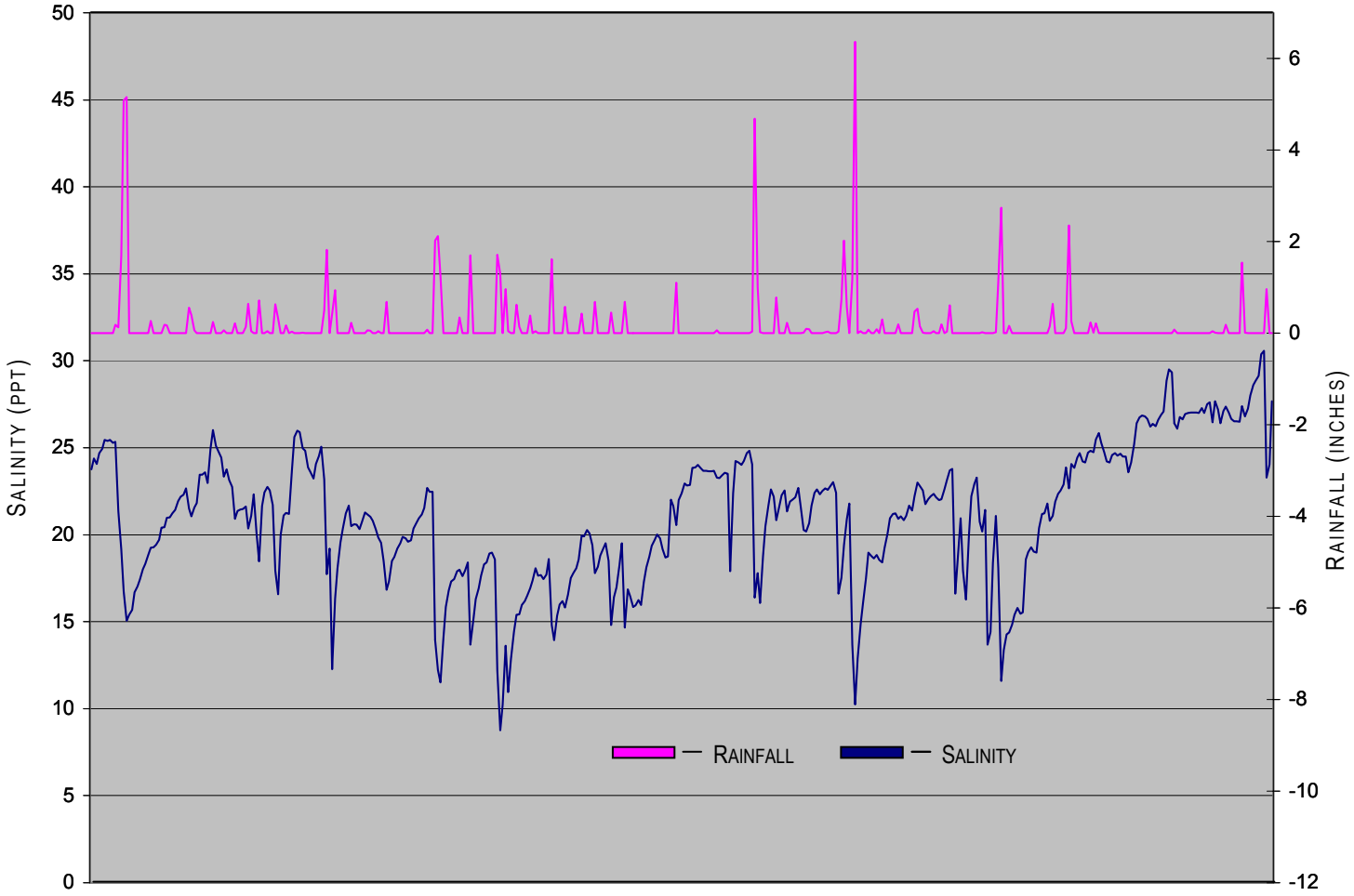
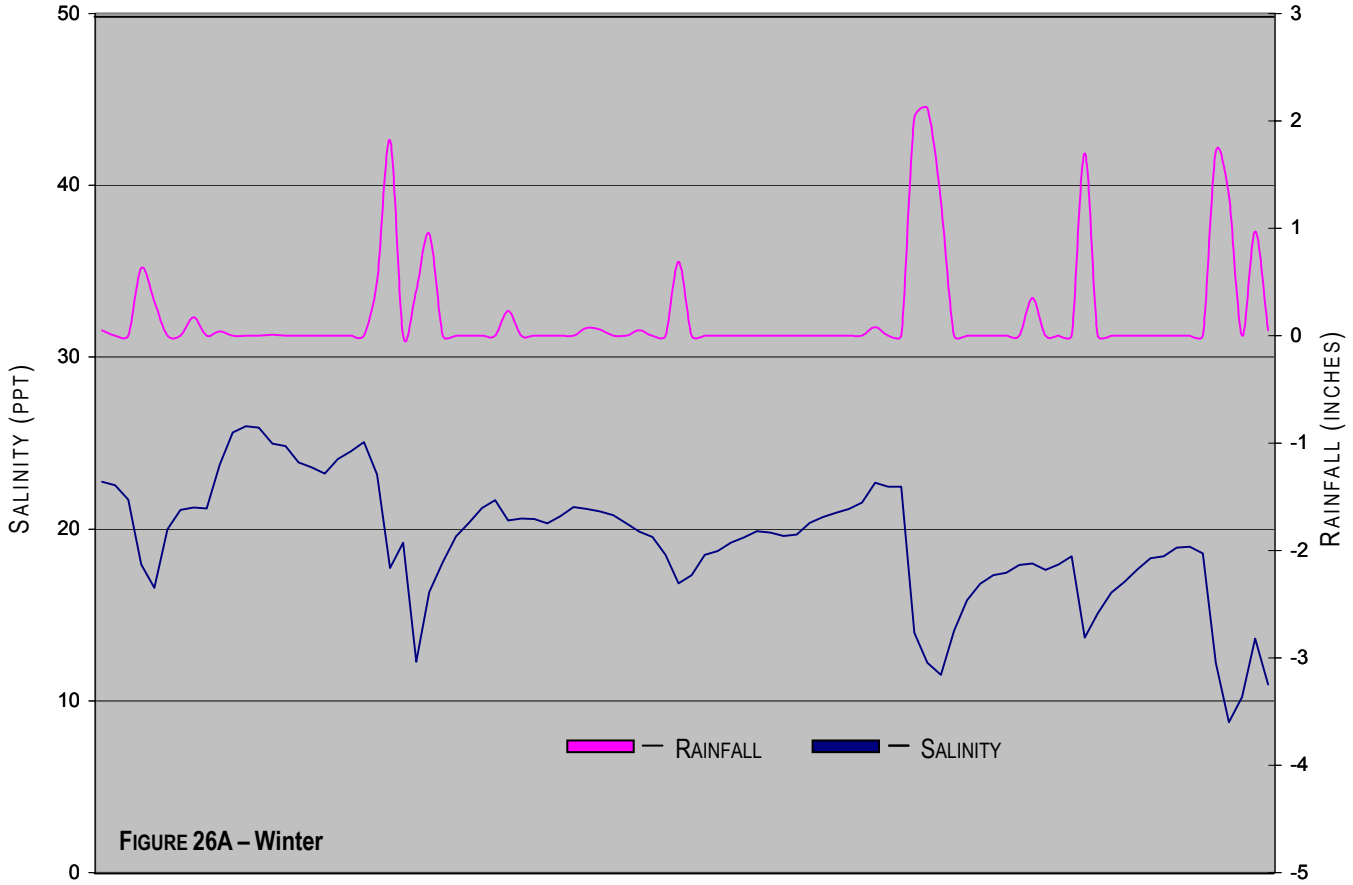


FIGURE 25 – Rainfall plotted over salinity for a twelve month period beginning December 2004 through November 2005.



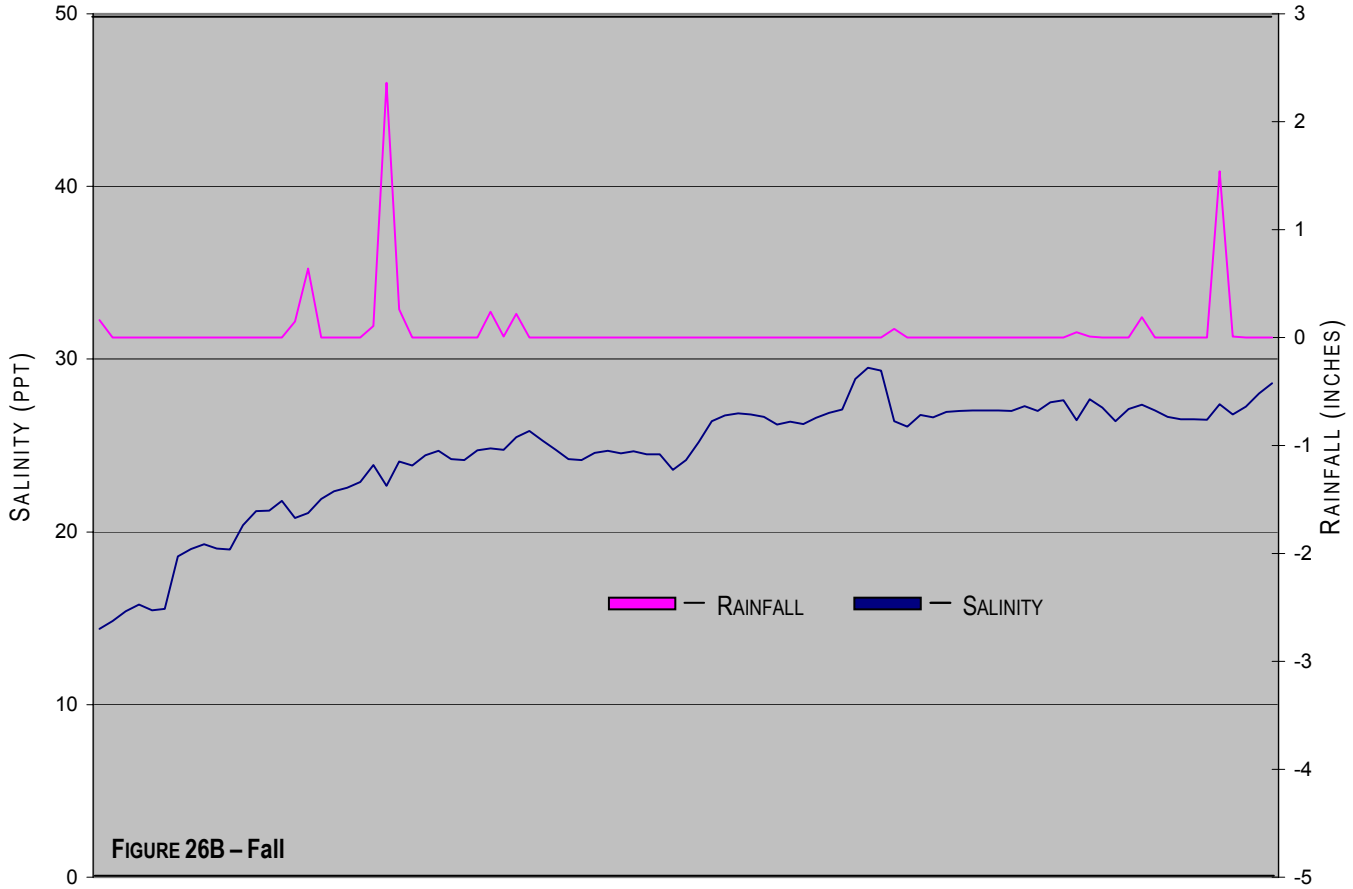


FIGURE 26 – Rainfall plotted over salinity for a three month period. Fig. 24A is a winter (Dec.-Feb.) rainfall/salinity period and Fig. 24B for fall (Sept.-Nov.). Note the steady increase in salinity in the fall during a prolonged period of low rainfall.

III. VEGETATIVE/NUTRIENT

The primary objectives of the vegetative field trials were to assess main and interaction effects of artificial planting and supplemental nutrients on the rate of vegetative recovery and species composition following sediment enhancement at different depths. The experimental design was constructed to test three main-effect hypotheses, that is, in sediment enriched marsh: (1) is there any difference in vegetative response at different sediment depths (elevations); (2) is there any difference in vegetative response between plant species; and (3) does the addition of supplemental nutrients effect vegetative response and species composition?

In addition to the main-effect treatments, the experimental design tested for three interaction effects: (1) is there an interaction between sediment depth (elevation) and species; (2) is there an interaction between species and supplemental nutrients; and (3) is there an interaction between elevation, species, and nutrients. The experimental design incorporates a multi-factorial design with multiple levels within each factorial. Treatment variables include sediment depth (0", 6", 9" and 12"); plant species (*Spartina alterniflora, Juncus roemerianus, Distichlis spicata, Spartina patens, Avicennia germinans*, and unplanted); and nutrients (fertilized and unfertilized). Treatment effects were measured as survival, frequency, percent cover, and above-ground biomass production. Not surprisingly, our results showed large differences among species ($p=0.001$) in regard to nearly all dependant variables (survival, frequency, cover, biomass). Therefore, we chose to analyze species response to elevation and to fertilization individually.

Survival

Survival measurements were taken at 30 and 90 days post-planting intervals, that is, mid June and August 2004, respectively. Replicates within each individual subplot were scored as living or dead based on the presence or absence of living above-ground culms, and expressed as percent survival.

Survival across all treatments, ranged from excellent to extremely poor within the sediment treatment site. However, there were no surviving plants at the control sites, indicating that sediment addition was the critical factor in species survival. *Avicenna germinans* (black mangrove) had the highest survival rate, with 100% survival across all sediment elevations and nutrient levels (Figure 27). *Distichlis spicata* (saltgrass) and *Spartina alterniflora* (smooth cordgrass) produced 92.8% and 92.2% survival,

respectively. *Spartina patens* (marshhay cordgrass) was fourth in survival at 75%, with *Juncus roemerianus* (black needlerush) having the lowest rate of survival at 0.6%.

When assessing nutrients and elevation as main treatment effects, we found no significant difference across treatments for either of the two variables for most of the plant species. Survival within the fertilized plantings averaged 72.7% compared to 71.6% in the unfertilized plantings. Within elevation, the average survival rate for the high (12") elevation was 71.3%, the mid (9") elevation with 73.3%, and the low (6") elevation had 71.7% survival. There were no plant species differences within the two control sites, as there was 100% mortality across all species at both control sites. Main treatment effects are plotted on Figure 27 which compares percent survival within respective treatments.

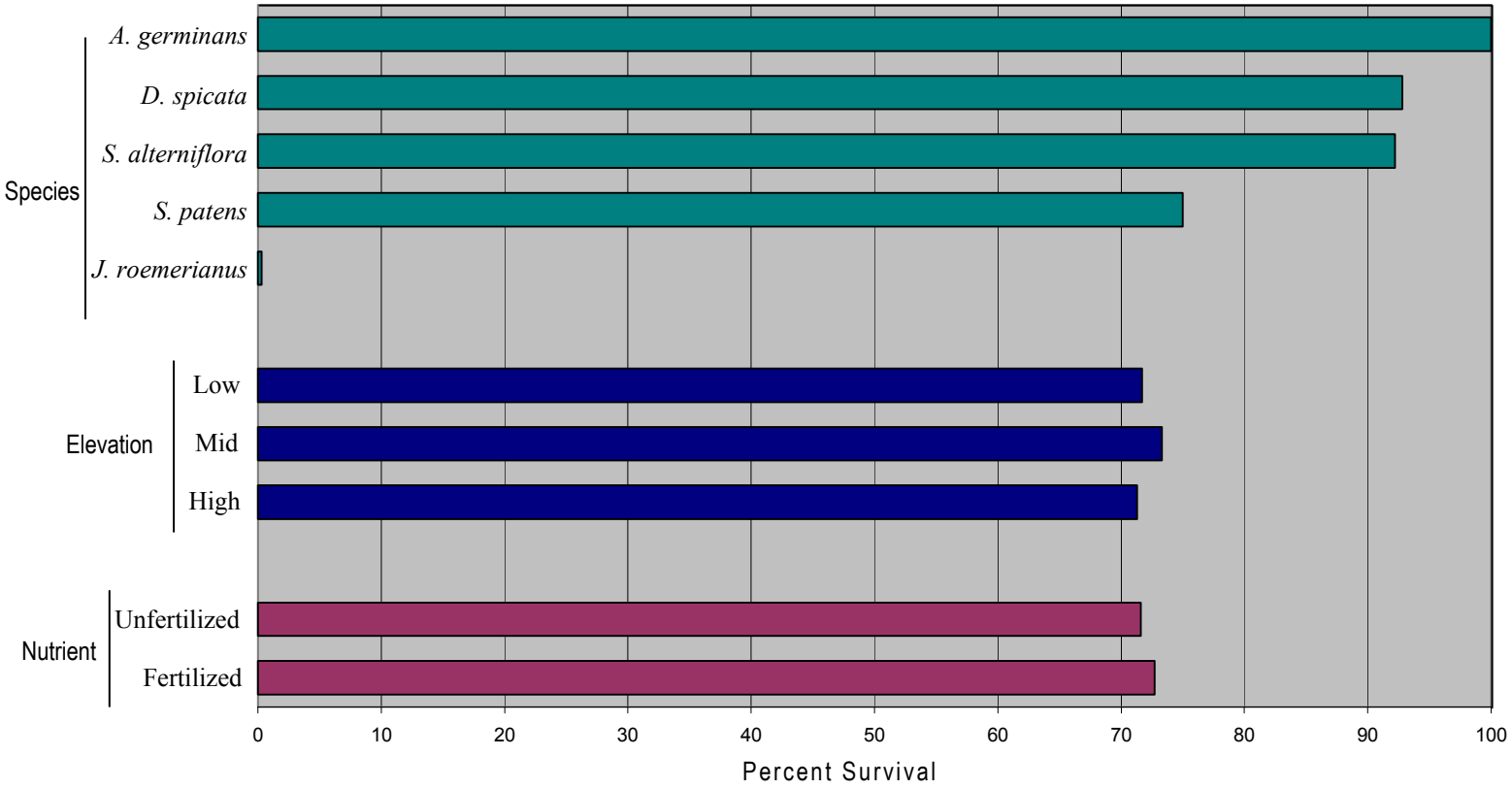


FIGURE 27 –Three main effect treatment results expressed as percent survival. As shown above, there were no statistical differences within the nutrient and elevation treatments, but some differences within the plant species treatments. *Avicennia germinans* and *Juncus roemerianus* were at opposite ends of the performance scale, with 100% survival and near 0% respectively.

Spartina alterniflora – In assessing plant species-elevation effect, we found varying degrees of strength between elevation and plant survival. For example, there was a slight trend for survival to increase as elevation decreased within the *S. alterniflora* plantings. The average survival rate for *S. alterniflora* at the high (12") sediment treatment was 80%, followed by the mid (9") elevation with 96.6% survival (Figure 28). The highest survival rate was at the lowest (6") elevation treatment with 100% survival. *S. alterniflora* plantings in both control sites failed completely with 100% mortality at both sites. There was no significant interaction between *S. alterniflora* and nutrient levels (p= 0.57); average plant survival was 93.3% with fertilization and 91.1% survival without fertilization. Figure 28 shows the five plant treatments plotted across elevation.

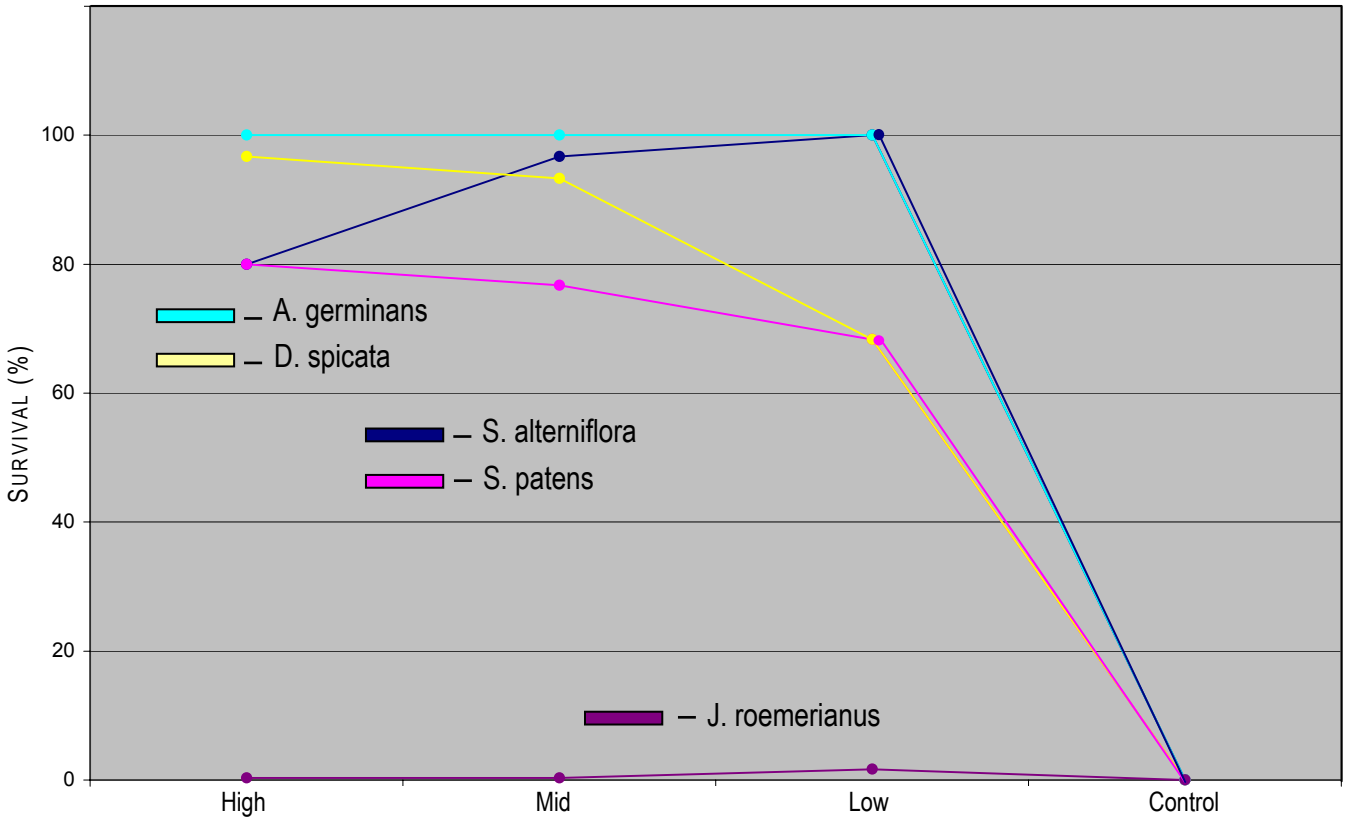


FIGURE 28 – Plant species treatment plotted across elevation. There were varying trends of survival by species within elevation within the sediment treatment cells; however, there was total mortality of all plant treatments within both control sites.

Spartina patens – Survival relative to elevation was the inverse of that of *S. alterniflora:* That is, the highest survival rates were on the high elevations ($\bar{x}$= 80%), followed by the mid elevations ($\bar{x}$= 76%), and the lowest survival at the low elevations ($\bar{x}$= 68%) (Figure 28). There was total loss of *S. patens* plantings in both controls, with 100% mortality. As with *S. alterniflora*, there was no significant difference (p= 0.84) between nutrient

treatments with a 75.5% average survival with fertilization and a 74.4% survival without fertilization.

Distichlis spicata – Survival within the *D. spicata* plantings followed the same pattern as that of *S. patens*; that is, survival increased with increases in elevation (Figure 28). The highest survival rates were found at the high elevation with 97% survival, followed by 93% at the mid elevations, and lowest at the low elevation with 88% survival. There was total loss of *D. spicata* plantings in both controls, with 100% mortality. There was no significant difference ($p= 0.71$) in *D. spicata* survival with fertilization ($\overline{x}= 93.3\%$) and without fertilization ($\overline{x}= 92.2\%$).

Avicenna germinans – The *A. germinans* plantings did extremely well across all elevational treatments, with the exception of the controls (Figure 28). There was a 100% survival at all three elevational treatments and total mortality (100%) at both control sites. There was 100% survival within both nutrient level tests as well.

Juncus roemerianus – The *J. roemerianus* plantings did extremely poor across all of the elevational sites including the controls. There was 100% mortality within the high and mid elevations, as well as at both control sites. At the low elevation only 1 of 54 plants survived (1.7%), and no additional nutrient analyses were conducted because of the extreme mortality within species.

Frequency, Cover, and Species Composition

We used three additional assessments; (1) frequency of plant species occurrence; (2) canopy cover; and (3) plant species composition as additional measurements in assessing the sediment treatment and the control site plant-habitat suitability. Frequency of occurrence, percent cover, and species composition are good indictors (individually and collectively) of plant species suitability, invasiveness, and the compatibility of individual species to form sustainable vegetative communities at specific elevations. Percent cover, species composition, and relative abundance were all taken over a three-day period in early November 2005. Percent cover was visually estimated using a ½m^2 quadrat. Three samples were randomly taken within the plant row/column matrix from each subplot and averaged to determine percent cover. Average cover values were determined for all 132 subplots across the main plot. To assess species composition and relative abundance, we used a clip-plot method (Mueller-Dombois and Ellenburg, 1974) to obtain species frequency and above-ground biomass. Standing crop was harvested by clipping plant materials within a ½m^2 quadrat at approximately 1 cm above the soil surface.

We found *Spartina alterniflora* to occur more frequently than any of the other five plant species when compared across all treatments, and far exceeded the second ranked species

(*Distichlis spicata)* by over 350%. *Spartina alterniflora* occurred in 284 of 324 samples (87.7% of total), while *D. spicata* occurred in 63 of 324 samples (19.4% of total). Only one non-treatment species, *Salicornia virginica* (woody glasswort) was collected within the planted plots and ranked third (17.3%) in frequency across treatments. *Salicornia virginica* is a highly specialized species generally associated with high-saline soils, is an early colonizer, and often found in association with disturbed soils. Within the sediment treatment site, *S. virginica* was predominately found (37%) in the low elevations, second in frequency only to *S. alterniflora*. In addition, there was a noticeable trend for *S. virginica* to be found more often in sparsely vegetated plots where there was a high ratio of open-to-vegetated soils. Based on our frequency sample (n= 324), it is reasonable to characterize *S. virginica* as a sympatric, opportunistic and slightly aggressive saline species, that provides moderate to poor cover on spare to bare disturbed soils, and primarily found in lower intertidal zones. Within our planting plots, *S. virginica* most often competed with *S. alterniflora* for habitat.

When we combined species frequency with elevation, there was little change in individual species ranking between elevations (Table 8). However, more notable were the relative changes in frequency within species across elevation. Across all treatment variables, *Spartina alterniflora* was the most aggressive species found and had formed a significant presence in virtually every other plant treatment plot. We recorded S. *alterniflora* in 57% of samples collected within the high elevation, 97% within the mid elevation, and 100% (108 of 108) within the low elevation. *Spartina alterniflora* was followed by *Distichlis spicata* and then by *Salicornia virginica*, the only non-treatment (volunteer) species collected. Another indicator of habitat preference (or suitability) is the occurrence of open samples (bare soil) within the planting plots. At the high elevation there was a 19.4% occurrence of bare soil samples, reduced to 2.8% at the mid elevation, and no occurrence (0%) at the low elevation. Table 8 is a summary of plant species grouped by elevation in descending order of frequency. We also included the percent of total within elevation (n= 108 within each elevation).

TABLE 8 – SUMMARY OF PLANT SPECIES FREQUENCY

ELEVATION	SPECIES	RANK ORDER	FREQUENCY	% TOTAL WITHIN ELEVATION
High (12")	*Spartina alterniflora*	1	62	57.4
	Distichlis spicata	2	26	24.1
	Unplanted	3	21	19.4
	Avicennia germinans	4	18	16.7
	Spartina patens	5	15	13.9
	Salicornia virginica	6	8	7.4
	Juncus roemerianus	7	0	0.0
Mid (9")	*Spartina alterniflora*	1	105	97.2
	Distichlis spicata	2	19	17.6
	Avicennia germinans	3	18	16.7
	Spartina patens	4	12	11.1
	Salicornia virginica	5	8	7.4
	Unplanted	6	3	2.8
	Juncus roemerianus	7	0	0.0
Low (6")	*Spartina alterniflora*	1	108	100.0
	Salicornia virginica	2	40	37.0
	Avicennia germinans	3	18	16.7
	Distichlis spicata	3	18	1.7
	Spartina patens	4	14	13.0
	Juncus roemerianus	5	1	0.9
	Unplanted	7	0	0.0

In addition, we determined relative frequency by species and elevation, that is, each species percent was divided by the sum of all species percents for a given species and elevation. Those relative frequencies, shown in Figure 29, demonstrate that both within and across elevations that the majority (94%) of the treatment species resulted in mixed communities (3 to 5 species) dominated by the original species planted. The exception was *Juncus roemerianus,* which suffered high mortality early in the study period. In contrast, we found that within the reference sites (at normal marsh elevation), no mixed communities were found, but rather monospecific stands of *S. alterniflora.*

In addition, we plotted the percent of change (gain or loss) of individual species over their initial planting frequency (Figure 30). Species were grouped by elevation and plotted against their initial planting frequency and expressed as zero. The percent values assigned to each species represent the net gain (positive value), or net loss (negative value) from its original planting frequency. A zero value represents a no-net gain or loss of species from its original establishment plot; that is, the species had a 100% frequency

within it's original planting plots, but was not collected outside of its respective plots. We included *Salicornia virginica,* although not one of the original treatment species, but because of its consistence in occurrence within samples. Since *S. virginica* was not one of the original plant treatment species, we had no baseline value to compare against. As such, its values found in Figure 30, represent the actual frequency of colonization within each of the 108 samples taken at each elevation.

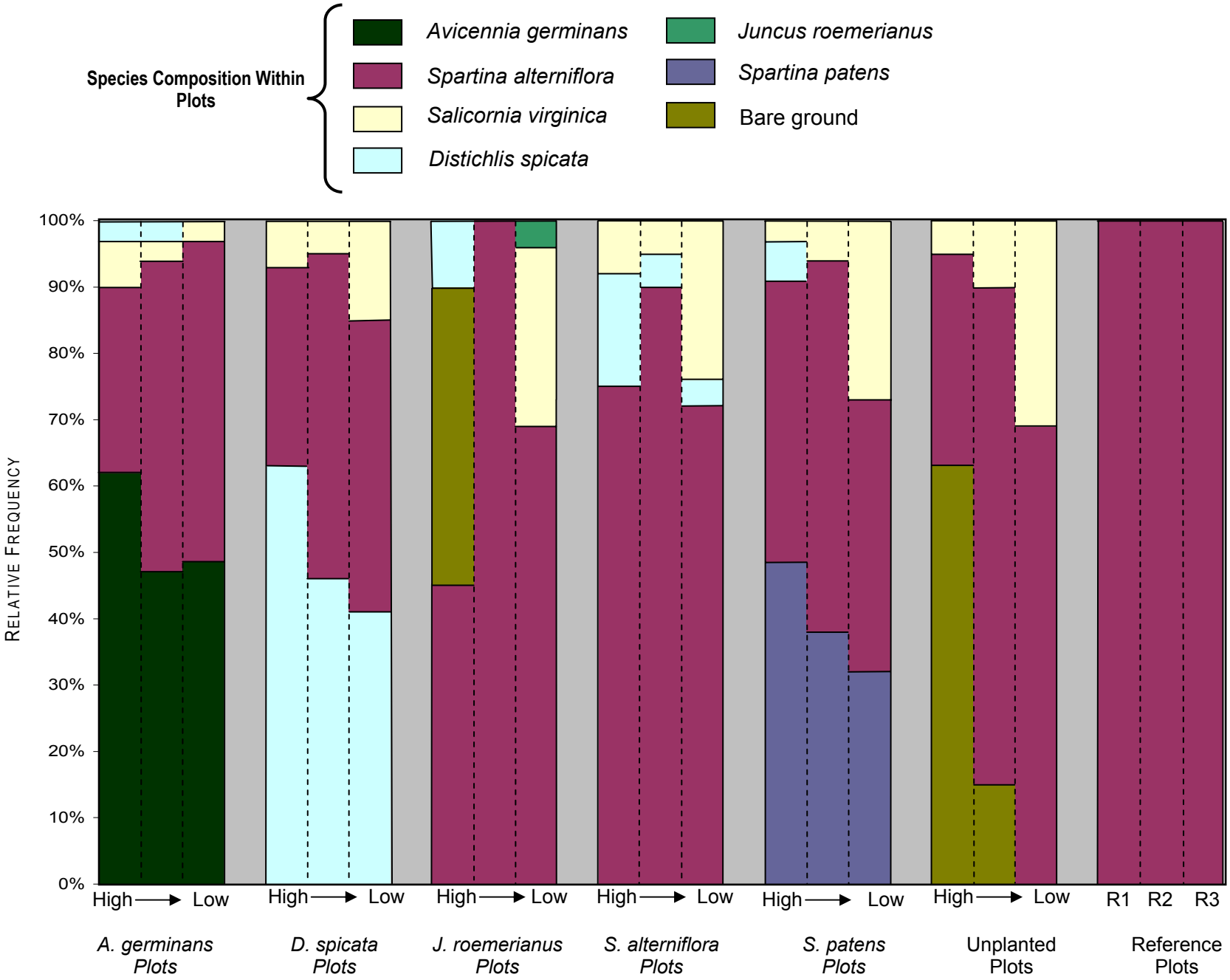


FIGURE 29 –Plant species frequency by elevation and species treatment (x axis). Species are color coded and provide an indication of individual species invasiveness outside of its original planting plot, and the successional change (species richness) that is evolving across plots and elevation.

As shown in Figure 30, *S. alterniflora* was the one species which widely colonized outside of its original treatment plot and far exceeds the second ranked *Distichlis spicata*. The rate and direction of spread by individual species was influenced by elevation (water levels). Note that *S. alterniflora* and *Salicornia virginica* increased significantly (encroached into other plots) as elevation decreased, where as *Distichlis spicata* encroachment was reduced with a decrease in elevation. The unplanted plots (bare-areas) increased at the high elevations (there were 16% more bare-area samples than originally established), but were reduced to 17% of the original number at the mid elevation, and were completely eliminated at the low elevation.

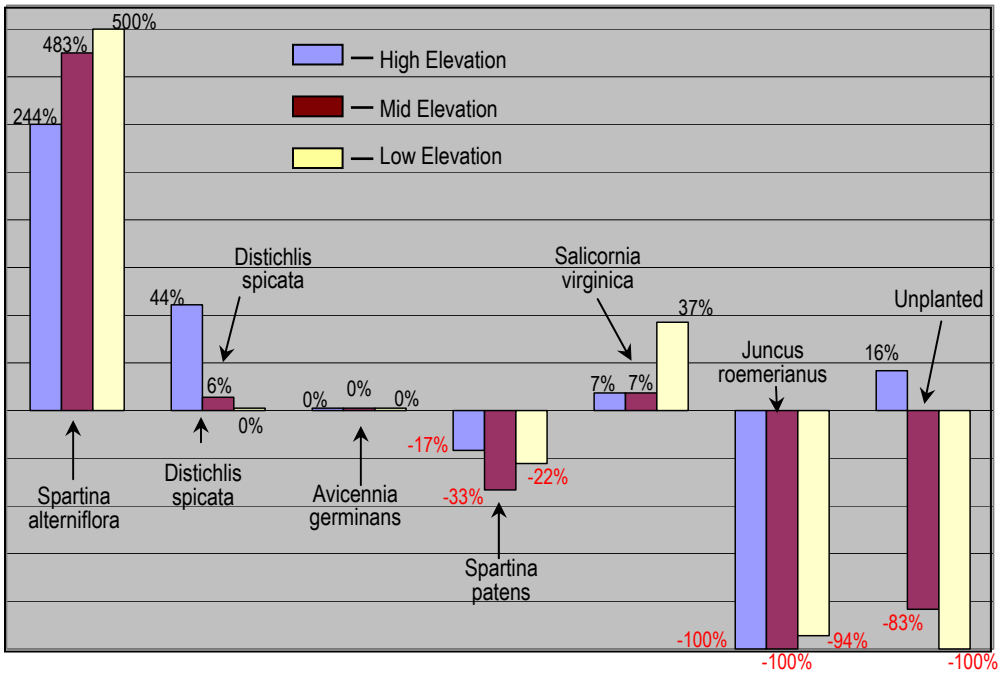


FIGURE 30 – Plant species occurrence (expressed as percent) collected outside of their original plots. Frequency of occurrence provides some indication of habitat preference and species aggressiveness to colonize.

The *Avicenna germinans* treatments, even with a 100% survival at all elevations, showed no movement outside of its original plot placement. It is reasonable to assume that because of *A. germinans'* woody growth form, the slowness with which plants mature, and dispersal by seed, *A. germinan*s is a viable, but passive species.

BIOMASS

As another means of assessing plant treatment response, we compared above-ground productivity (expressed as dry biomass) within each planting treatment. We limited our analyses to within species comparisons across elevations and nutrient treatment levels, because of the differences in growth-form among treatment species … *Spartina patens* is a bunch grass with small diameter stems, *S. alterniflora* is a strongly rhizomatous grass with large diameter and leafy stems, and *Avicenna germinans* is a woody shrub.

As was the case throughout the study, we found no significant effect of nutrients on any plant treatment species. For example, the biomass means within the *S. alterniflora* fertilized and unfertilized plots were 155.1 (±79.5) and 169.9 (±68.2) grams per unit measure respectively, with p= 0.91. However, when we combined species and elevation, we found the interaction produced significant differences for some species. For example, we found no differences within *S. alterniflora* (p= 0.56), but a difference within the *A. germinans* treatment (p= 0.04). A *posteriori* test of differences in the least square means, showed that *A. germinans* plots within the mid elevation differed from the high elevation (p= 0.01), but not from the low elevation (p= 0.40).

Figure 31 summarizes dry biomass production by species across elevations, and for the most part, follows a common species-elevation trend demonstrated throughout this study. Of particular interest are the *S. alterniflora* plots, however, as there was no significant difference (p= 0.93) in biomass production among elevations. In addition, there was no statistical difference in *S. alterniflora* biomass between planted treatments, the normal marsh reference plots, and the unplanted plots as they came to be dominated by *S. alterniflora* (p= 0.54).

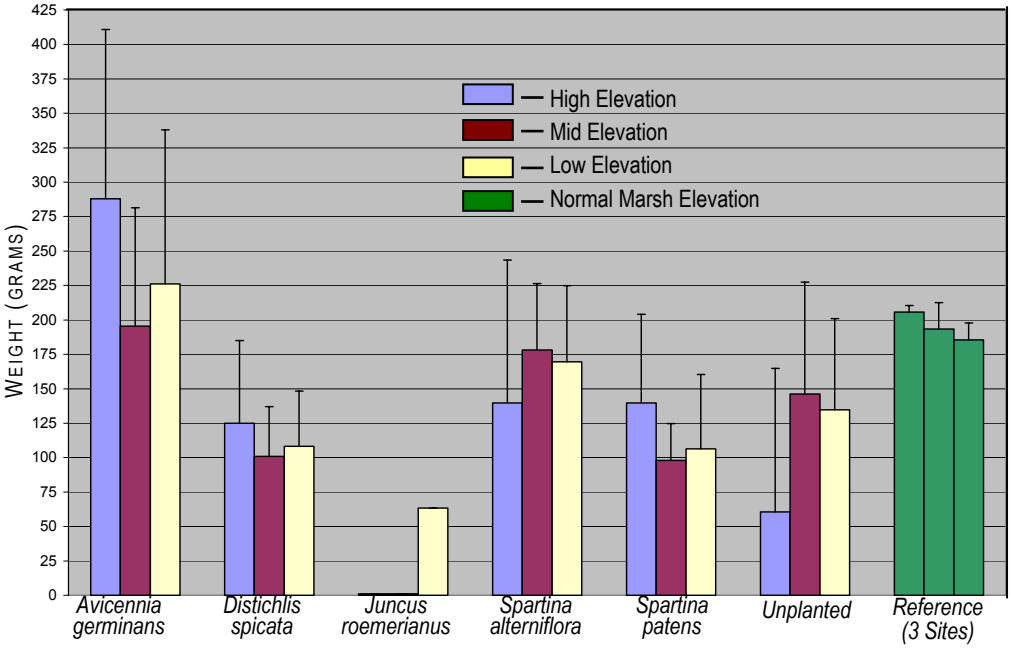


FIGURE 31 – Plant treatment biomass in grams per ½ m²; T-bars are standard deviation.

Consequently, the *S. alterniflora* treated areas (high, mid, and low) all reached vegetative equivalency, statistically equal to that of normal marsh, in less than two complete growing seasons. It should also be noted, that although the high elevation treatments supported the greatest level of plant response in several instances (depending on species), it was also the elevation of greatest variability. Although there were no productivity differences between the high and low elevations within the *S. alterniflora* plots, the standard deviation (±151.3) within the high plots was almost 2½ times higher than that of

the mid elevation (±48.3), and 1¾ times that of the low elevation (±55.2). We excluded the control sites from Figure 31 as there were no surviving plants to compare, but we did include biomass collected at three normal marsh reference sites for comparison.

SUMMARY

Working in collaboration with the Louisiana Department of Natural Resources Division of Coastal Restoration, we were able to conduct a large-scale, manipulative, and multi-year study to assess the affects of dredge sediments on marsh recovery following a catastrophic event. The three areas that this segment of the study addressed were: (1) an assessment of pre- and post-treatment spatial changes across treatment and control sites; (2) construction of hydrologic models to assess the distribution, frequency, and duration of the hydrologic regime effecting treatments and controls; and (3) a determination of the effects of artificial planting and supplemental nutrients on vegetative recovery, recruitment, succession, and above-ground productivity. The following is a summary of each of these elements.

SPATIAL CHANGE

We compiled and georeferenced five aerial photographs that span six years. The aerial dataset consists of one year pre-dieback normal marsh coverage (1998), one year post-dieback brown marsh event coverage (2001), and two years post-sediment treatment coverage (April 2003, Dec. 2003, Dec. 2004). We found that in 1998 (pre-dieback), both the study and control sites were healthy and moderately robust saline marshes that contained only two salient features, vegetated marsh and permanent water bodies. Both sites were predominately emergent marsh with the treatment site containing 91% vegetation and 9% water, while control sites contained 97% vegetation and 3% water. See Table 2, *1998 Habitat Summary* for complete list of habitat area by site.

Within a year following the 2000 brown marsh event, there was significant loss of emergent marsh within both the treatment and control sites. The relative impact of the brown marsh event was proportionally equal in both the designated treatment and control areas, with 82% and 78% emergent marsh loss respectively.

In 2002, a sediment treatment study site was constructed that consisted of five contained sediment cells, each approximately six acres in size. Within each of the five cells, three target sediment treatment depths (6”, 9” and 12”) were completed in December of 2002. When we compared gain and/or loss rates between the sediment treatment and control sites in April of 2003 (four-months post-sediment treatment and 16-months from the 2001 brown marsh analysis), we found a small amount of additional vegetative loss (-0.48 acre) within the sediment treatment cells and a significant vegetative gain (+4.6

acres or 247%) within the control sites. See Tables 3 and 4, *2001 and Spring 2003 Habitat Change Summaries* for a complete list of habitat areas by site and year.

However, by December 2003 (12-months post-sediment treatment and 24-months from the 2001 brown marsh analysis), we saw an equivalent gain within the sediment treatment site (+10.1 acres or 238%) from the previous nine month analysis. Within this same time period, vegetative gains within the control site were very minor (+0.4 acre or 6%). By December 2004 (24-months post-sediment treatment and 36-months from the 2001 brown marsh analysis), the sediment treatment site had gained an additional 10.2 acres (71% from the previous year), while the control site gains continue to be minor (+0.7 acre) or a 10% gain from the previous year.

Figures 32A and 32B track habitat change for both the sediment and control sites beginning with 1998 (pre-brown marsh) through December 2004 (24-months post-treatment and 36-months post-brown marsh). Note that there is virtually no difference in brown marsh impact between the treatment and control areas, both sites losing approximately 75% of their vegetative mass between 1998 and 2001. The habitat effected by brown marsh loss was primarily emergent marsh, as there was little change within the water body area of either the treatment or control sites during that same time period.

By April 2003 (16-months post-brown marsh), the control sites were showing a quicker vegetative recovery than treatment sites, regaining all but 22% of its lost vegetative acres (Figure 32B). Within the same time period, the treated sites continued to lose vegetative area (~ 2% additional loss) (Figure 32A). However, it is reasonable to assume that the continued loss within the treatment sites resulted from burial of standing crop by sediment placement. By the end of 2003 (12-months post-sediment treatment), the treatment sites begin showing signs of increasing vegetative recovery, and by December of 2004 (24-months post-sediment treatment) the sediment treatment site had made significant gains in vegetative recovery.

We defined net marsh loss, within the treatment and control sites, as the combined losses in both emergent marsh and increases in water bodies; that is, emergent marsh that remains unvegetated (bare soil) and an increase in water area from its original baseline value. We found that at the end of the study period, the treatment sites had a net loss of 1.6 acres (or 5.7% of the total) and the control sites had a net loss of 1.1 acres (or 13.1% of the total) compared to its pre-brown marsh values. Conversely, by the end of the study

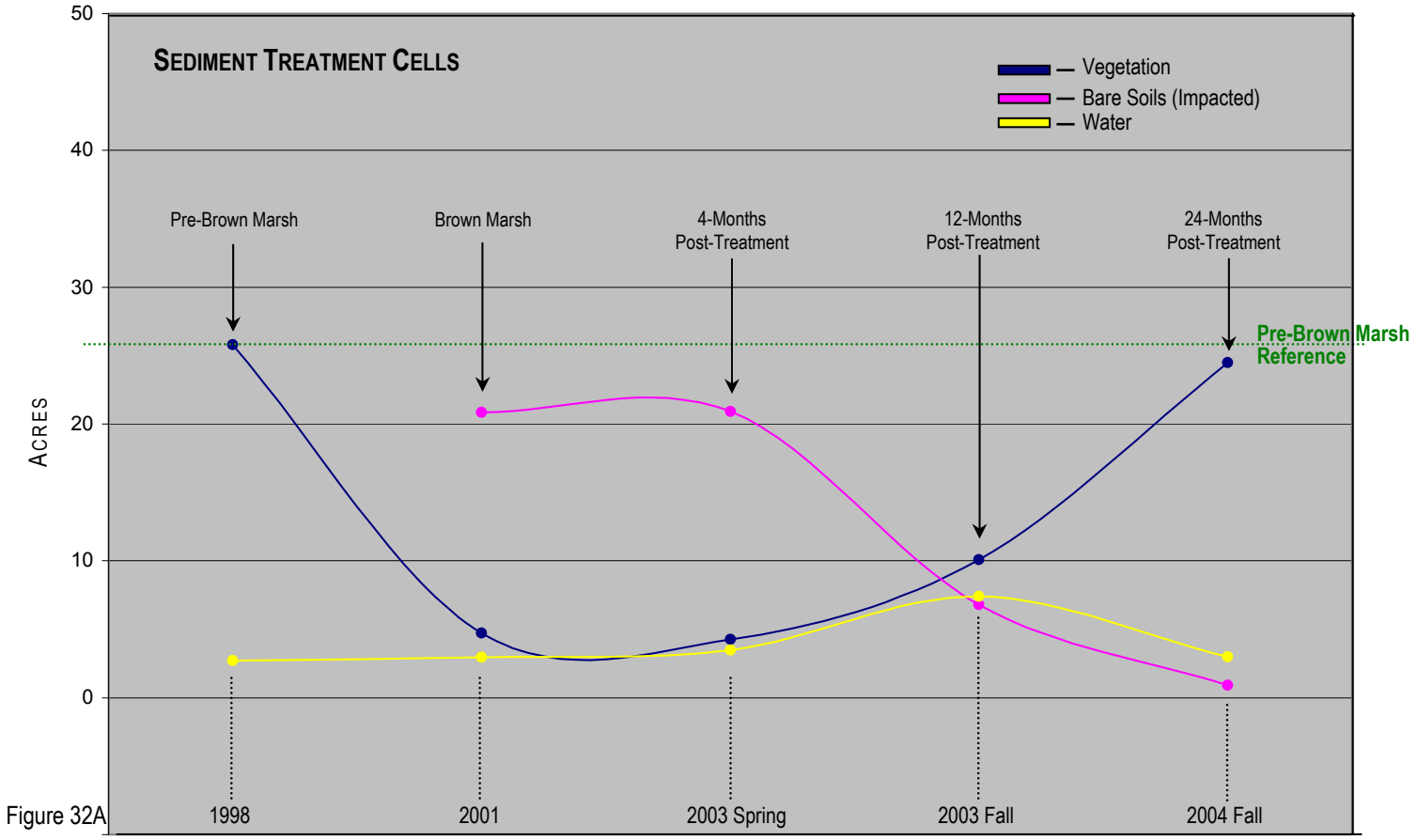


Figure 32A

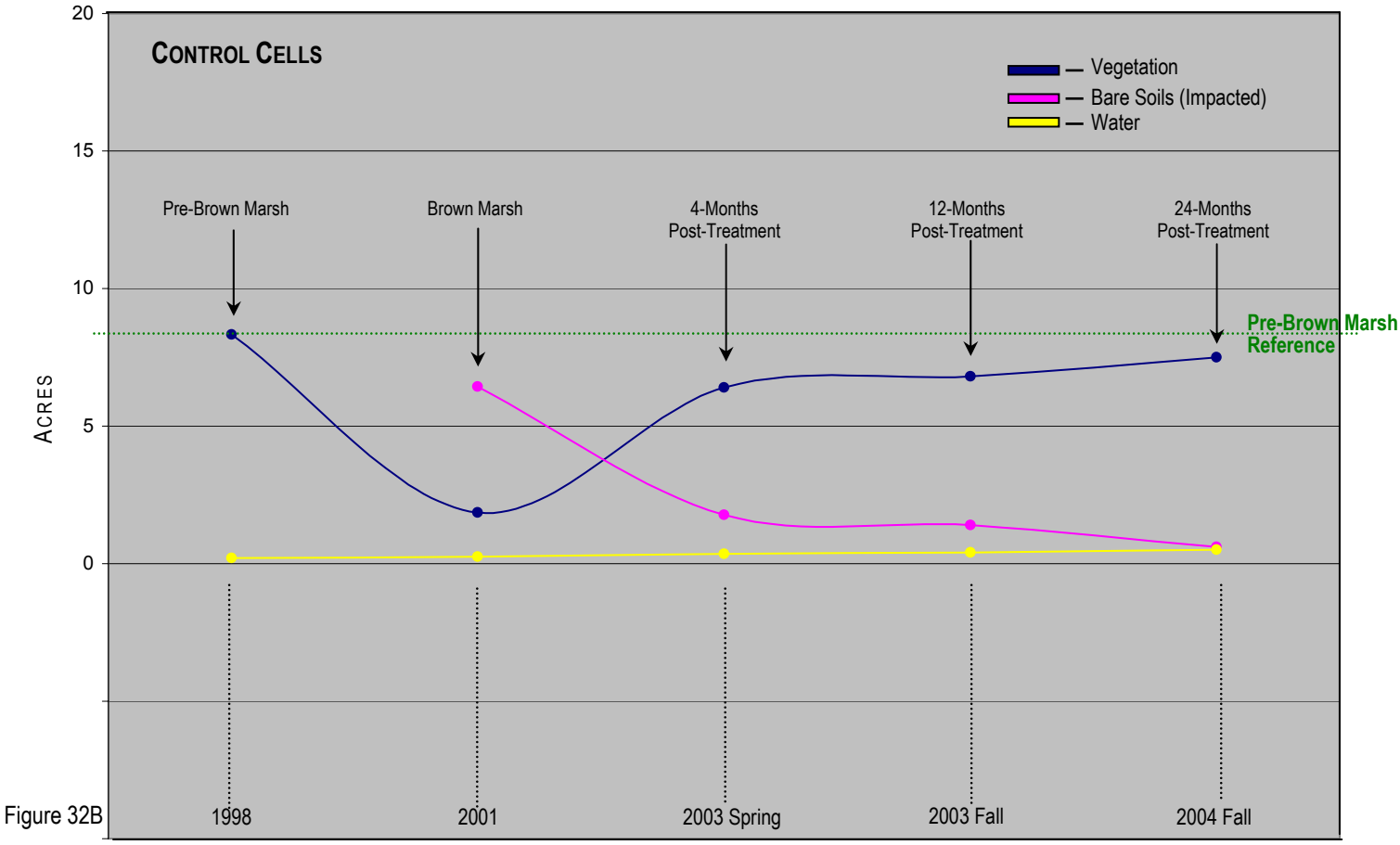


Figure 32B

FIGURE 32 – Six year pre- and post- brown marsh and treatment habitat change for both treatment (Fig. 32A) and control sites (Fig. 32B).

period, the vegetative component of the treated sites had recover to 95% (24.5 of 25.8 acres) of its pre-brown marsh condition, while the control sites recovered to 90% (7.5 of 8.3 acres) of its pre-brown marsh conditions. Both the treatment and control sites had small net increases in water area (0.3 acres) over their pre-brown marsh conditions. See Figures 32A and 32B for habitat change through the study period, and Tables 2-5 for area figures and calculations.

HYDROLOGY

To assess water and salinity effects we established a continuous recorder and monitored water levels and salinity for a 15-month period. We found the study sites to be a strong saline marsh with average salinity of 21.1 ppt (±4.1) and fluctuating water levels of -6.9" below- and 19.8" above-normal marsh. The average water level for the 15 month period was -0.13" (±5.83), or just slightly below the normal marsh surface. In addition, we found both water level and salinity varied seasonally with the highest water levels during the summer months and highest salinity levels during the fall months. In addition, we found that there was no correlation between water level and salinity (r= -0.1, n= 20,920), but a moderately strong negative relationship between rainfall and salinity (r= -0.54).

There were five key elevations across the treatment, control, and reference marshes that were of particular interest. Three of the elevations were formed from sediment deposition (6", 9", and 12" above normal marsh), and found within the treatment site. The average elevations within the untreated control sites at the end of the study was -6" below normal marsh, and we assigned a 0" elevation to the three reference marshes.

When we analyzed the frequency of flooding relative to these key elevations, we found the greatest frequency was at normal marsh (85.7% of total) followed by the control (78.4% of total). Within the treatment cells, flooding frequency declined with increased elevation. Flooding occurring 53.8% of the time at 6" above normal marsh and declined to only 11.7% at 12" above normal marsh. We found that there were no frequency of occurrence at or above 19" above normal marsh. Table 6 summaries frequency of occurrence and percent of total for elevations at one-inch increments.

In addition to frequency, we determined the percent of time key elevations were flooded. At normal marsh (0" elevation), we found that there were almost equal periods of surface flooding (49% of total) and drying (51% of total). This nearly 1:1 ratio of wetting and drying is optimal for plant growth by providing a balance oxidation-to-flooding regime, critically important to intertidal plant species such as *Spartina alterniflora*. Within the

control site elevations, the ratio of flooding (88% of total) to drying (12% of total) was disproportionately skewed towards wet soils. Under these flooding conditions, there is a high probability of significantly reduced soils, resulting in lower plant survival and reduced plant productivity. Plant survival within the control cells, across all species and nutrient levels, was zero. When we compared the presence or absence of vegetation along a continues elevational profile within control site A, we found that the site would not support vegetation when the marsh elevation was approximately 1" below normal marsh (Figure 20). Table 7 summarizes time flooded in hours and percent of total at elevation in one-inch increments.

VEGETATIVE AND NUTRIENT TREATMENTS

The primary objectives of the vegetative field trials were to assess main and interaction effects of artificial planting and supplemental nutrients on the rate of vegetative recovery and species composition following sediment enhancement at different depths. The experimental design incorporates a multi-factorial design with multiple levels within each factorial. Treatment variables include sediment depth (0", 6", 9" and 12"); plant species (*Spartina alterniflora, Juncus roemerianus, Distichlis spicata, Spartina patens, Avicennia germinans*, and unplanted); and nutrients (fertilized and unfertilized). Treatment effects were measured as survival, total cover, and above-ground biomass production.

We found no significant difference in survival within either nutrient or elevation, but a statistical difference among the plant species treatments (Figure 27). In terms of survival, *Avicennia germinans* (black mangrove) was the only species with 100% survival, followed by *Distichlis spicata* (saltgrass) with 93%, and *Spartina alterniflora* (smooth cordgrass) with 92%. *Juncus roemerianus* (black needlerush) performed very poorly with less than 1% survival.

When we combined elevation and species as treatments, we found that species segregated along elevation. For example, *S. alterniflora* which is typical an intertidal species, preformed better at lower elevations than at higher elevations. While *D. spicata*, which prefers a less saturated soil, increased with increases in elevation. *Avicennia germinans* was the only species that preformed equally well across all elevations. The control sites, which were considerably lower (~ -6" below normal marsh) than the lowest treatment site elevation (+6" above normal marsh) had total mortality across all plants (Figure 28).

When we compared plant performance using productivity values, such as frequency of occurrence, cover, and biomass, we found once again that species separated along

elevational lines. We found that *S. alterniflora* was collected more often than any other species regardless of elevation, but varied in value across elevation. See Table 8 for species rank-order by elevation. In addition, we included unplanted plots as a plant treatment variable and found that unplanted plots (measured as bare-soils) moved relative to elevation. For examples, within the high elevation, the frequency of occurrence of bare-soils scored third (19% of the total sample), just under *D. spicata*; however, within the low elevations, bare-soils ranked last (0% of the total), that is, there were no-bare soil samples recorded.

In addition, we used relative frequency to determine plot composition (species richness) and relative abundances. Both measures are indicators of habitat suitability, species aggressiveness, and vegetative-site sustainability. We found that in almost all plant-elevation combinations (94%), that the vegetative treatments had formed mixed communities of three to five species. The exceptions to this determination, however, were the three reference marshes, which formed monospecific communities dominated by *S. alterniflora*. Figure 29 is a summary of species composition by elevation, and grouped by plant treatment. It is clear by comparison (Figure 29), and by data presented in Figure 30, that *S. alterniflora* is the dominant and primary colonizer within the study area and reference marshes. The only non-treatment species collected over the course of the study is *Salicornia virginica,* which appears to provide early pioneering vegetative cover at open and sparsely vegetated sites.

As another means of assessing plant treatment response, we compared above-ground productivity (expressed as dry biomass) within each planting treatment. We limited our analyses to within species comparisons because of the differences in growth-form among treatment species. Because *S. alterniflora* was the dominant species found in both the treatment and control areas of this study prior to the 2000 brown marsh event, we were particularly interested in *S. alterniflora's* response in relation to treatment variables.

In comparing biomass production of *S. alterniflora* across elevations and nutrient, we found no significant difference ($p= 0.93$) in biomass production among elevations. In addition, there was no statistical difference in *S. alterniflora* biomass between planted treatments, the normal marsh reference plots, and the unplanted plots as they came to be dominated by *S. alterniflora* ($p= 0.54$). Consequently, the *S. alterniflora* treated areas (high, mid, and low) all reached vegetative equivalency, statistically equal to that of normal marsh, in less than two complete growing seasons. See Figure 31 for a complete list of species and biomass production by elevation.

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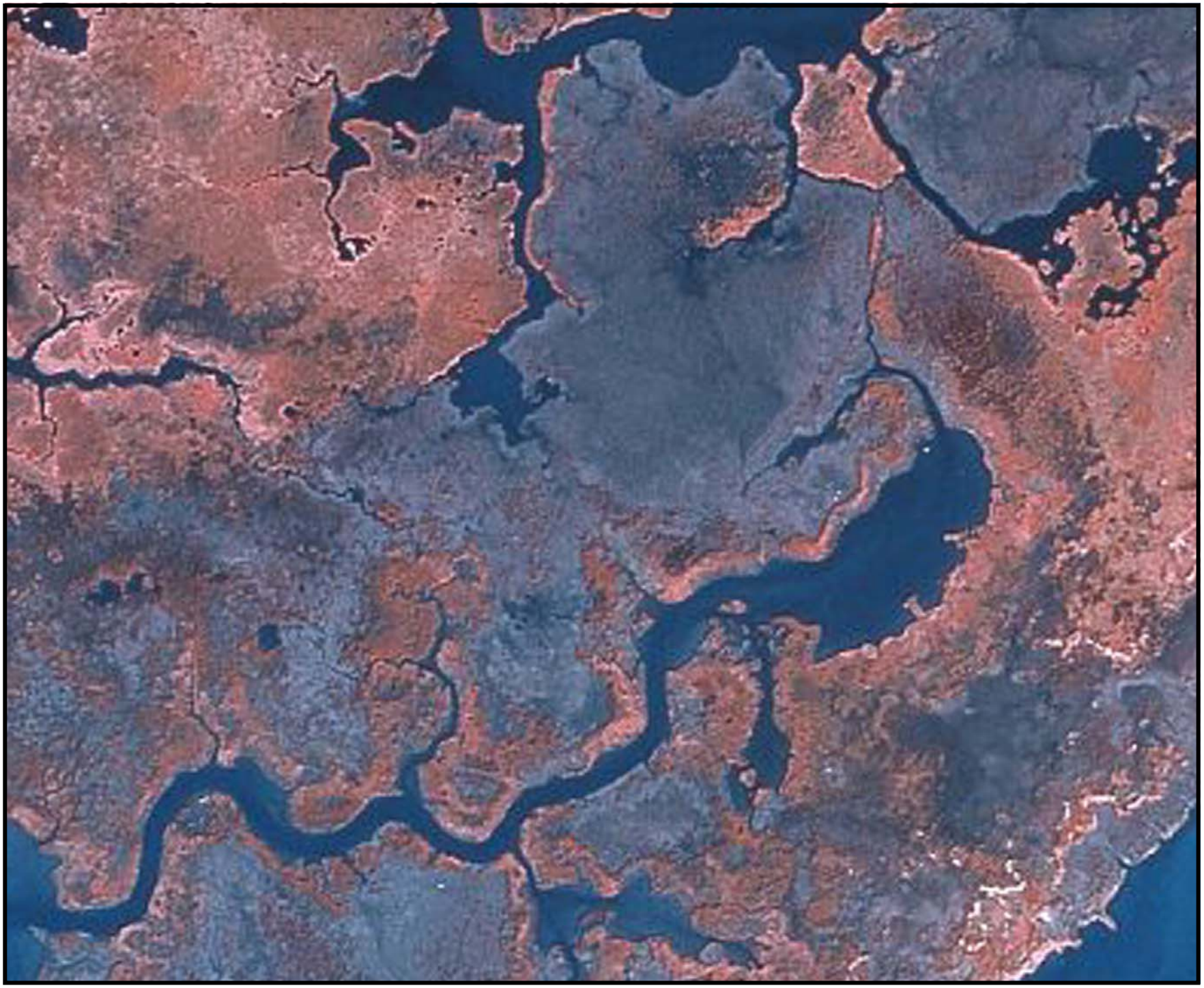
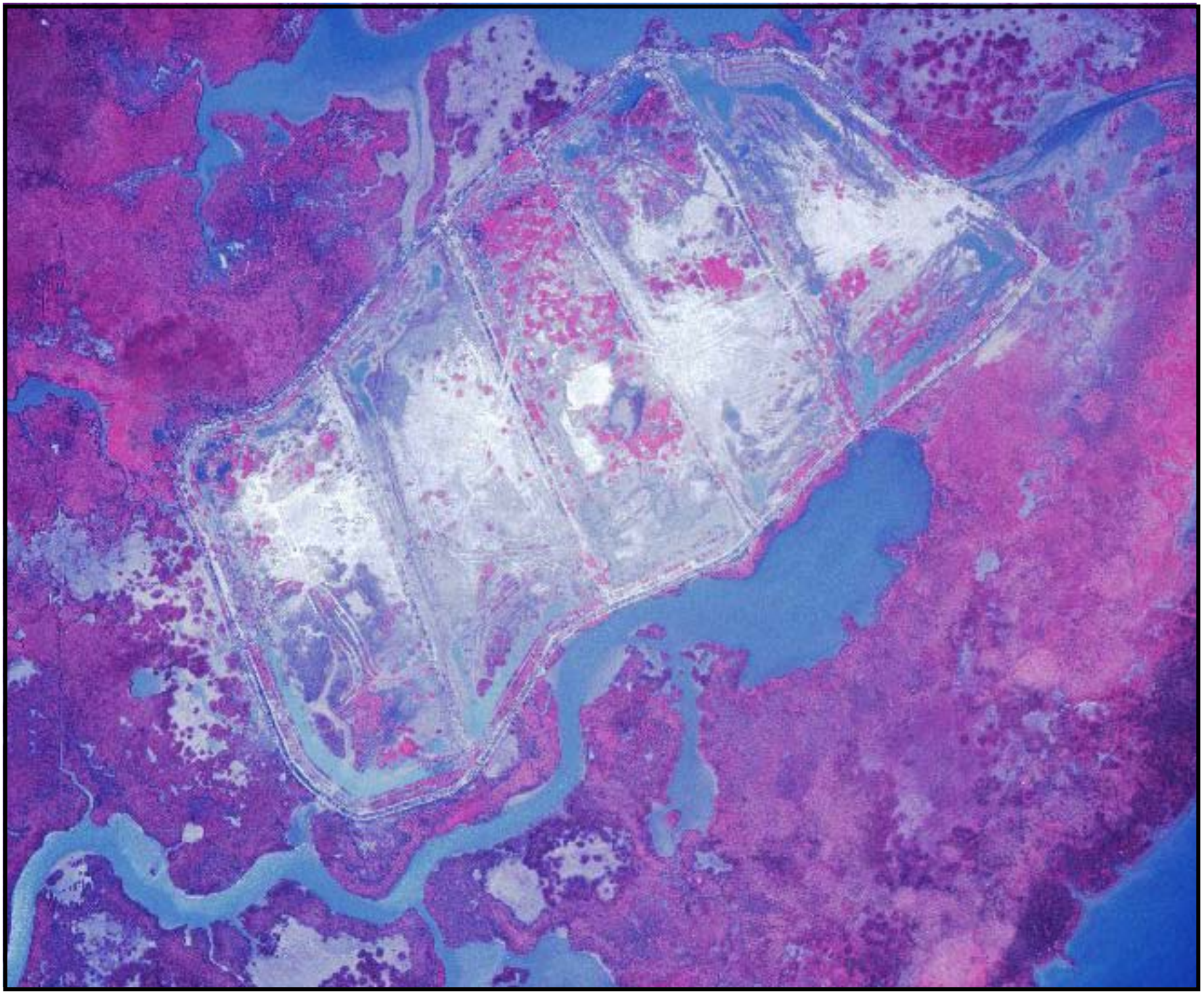
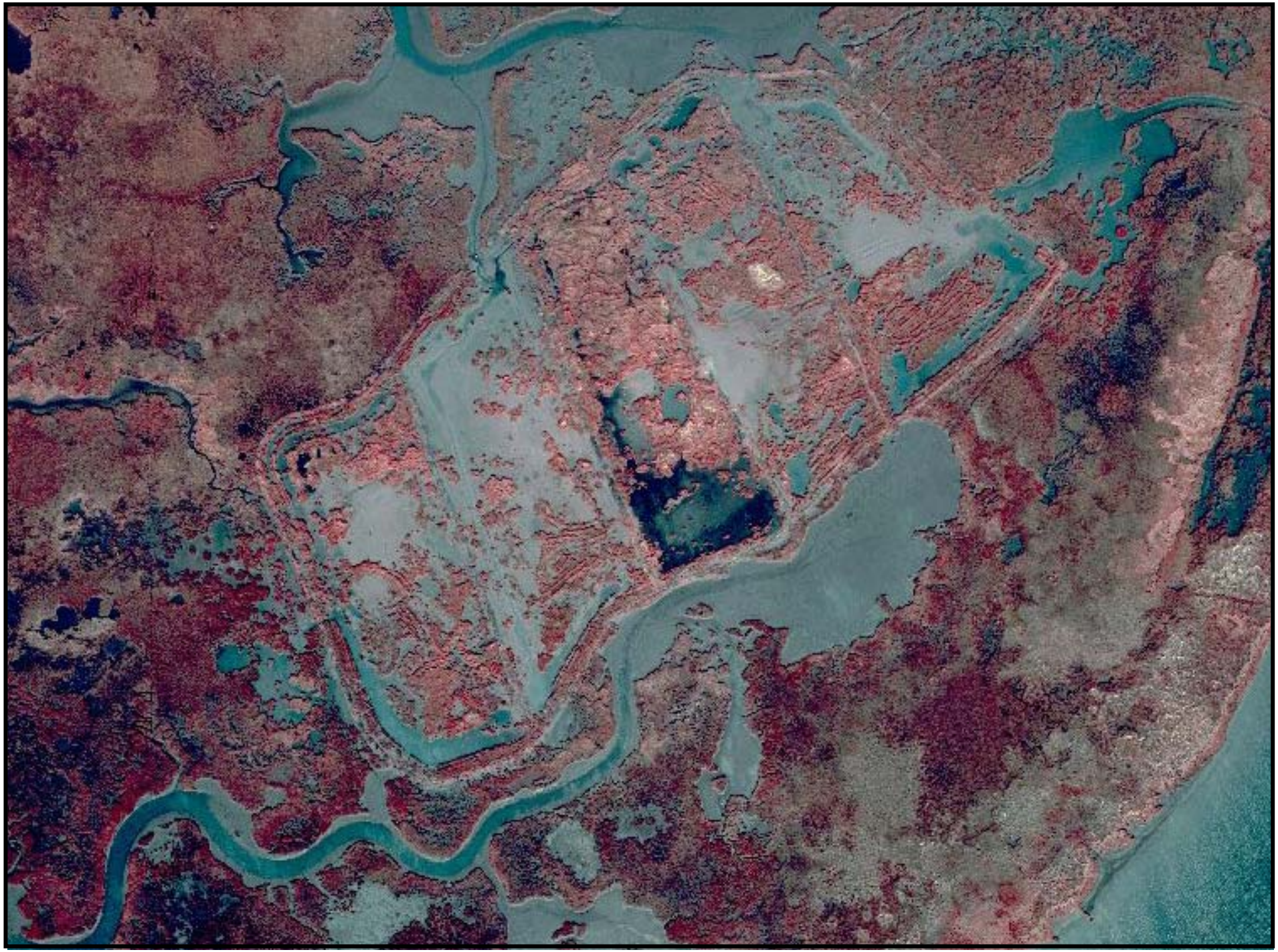
APPENDIX 1 – 1998 AERIAL IMAGE OF TREATMENT AND CONTROL SITES WITHOUT OVERLAYS.



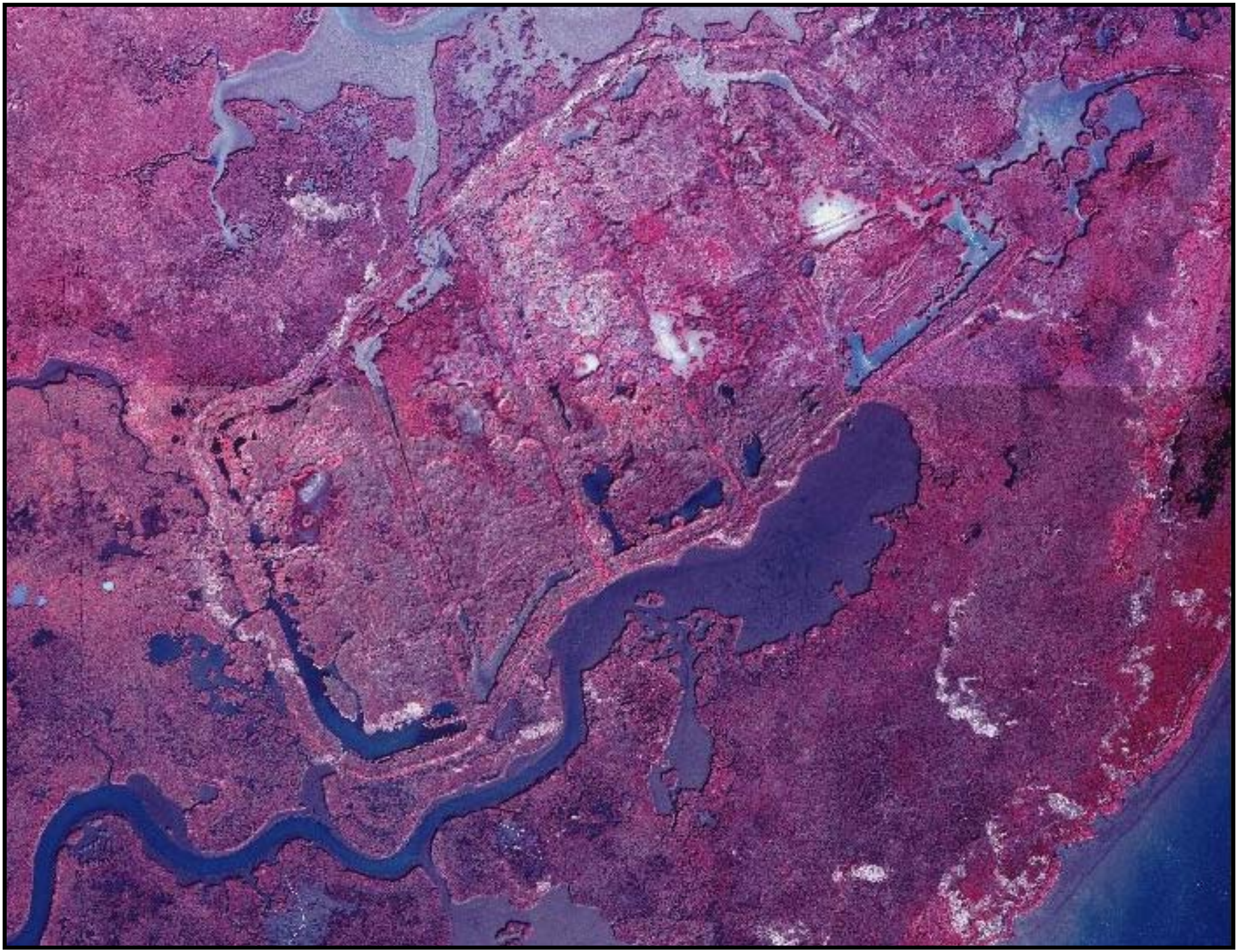
APPENDIX 2 – 2001 AERIAL IMAGE OF TREATMENT AND CONTROL SITES WITHOUT OVERLAYS.



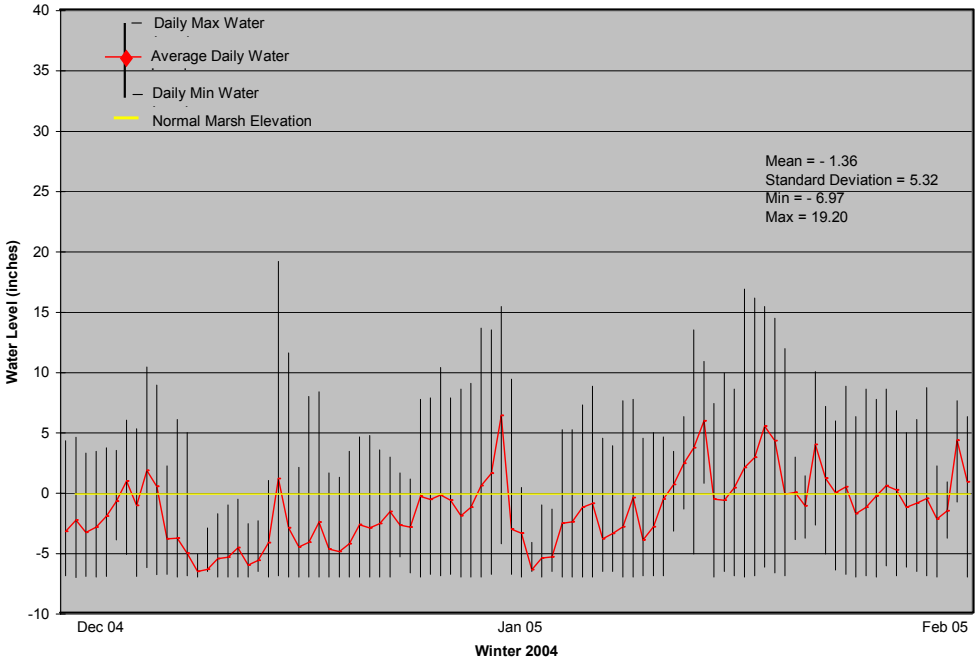
APPENDIX 3 – APRIL 2003 AERIAL IMAGE OF TREATMENT AND CONTROL SITES WITHOUT OVERLAYS.

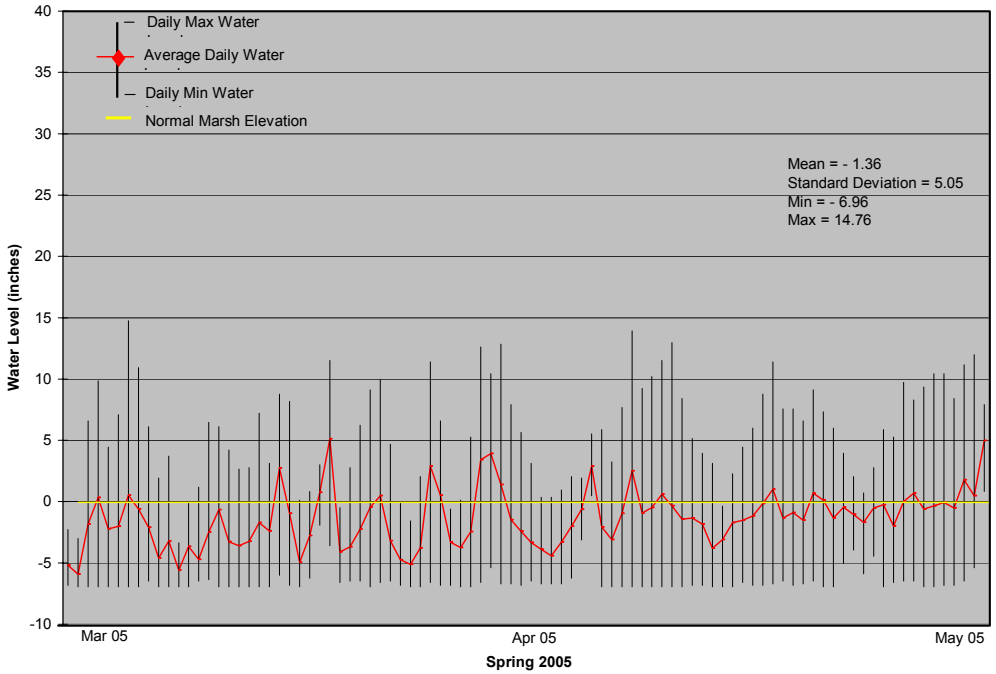


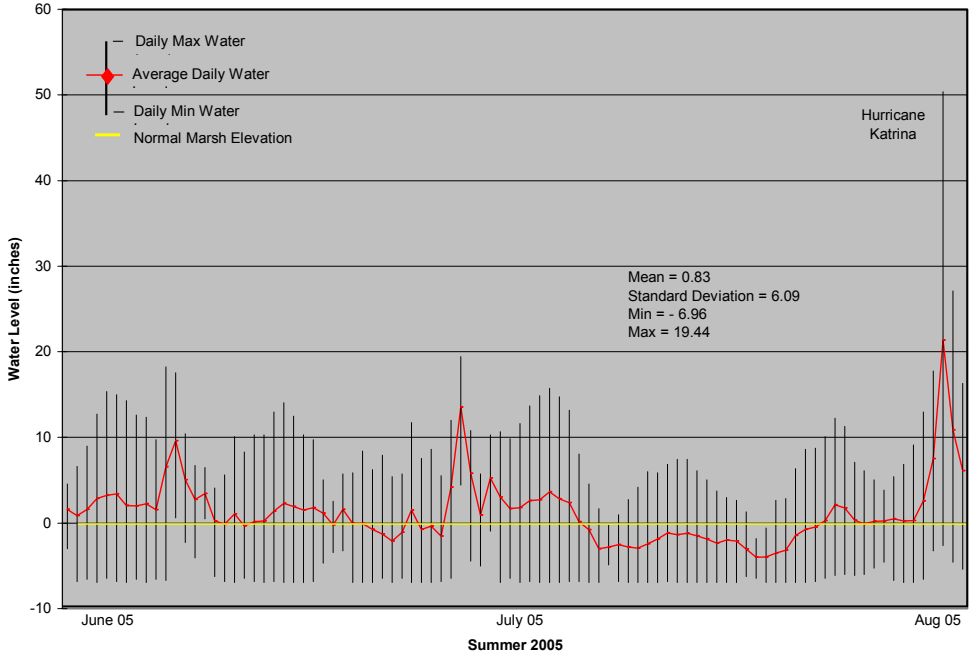
APPENDIX 4 – DECEMBER 2003 AERIAL IMAGE OF TREATMENT AND CONTROL SITES WITHOUT OVERLAYS.

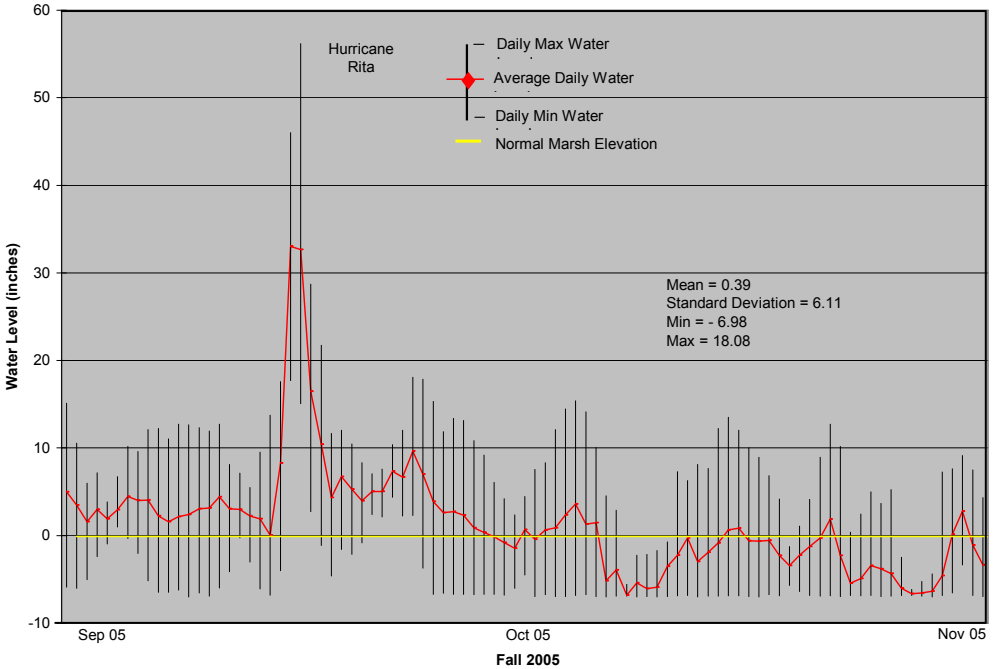


APPENDIX 5 – DECEMBER 2004 AERIAL IMAGE OF TREATMENT AND CONTROL SITES WITHOUT OVERLAYS.

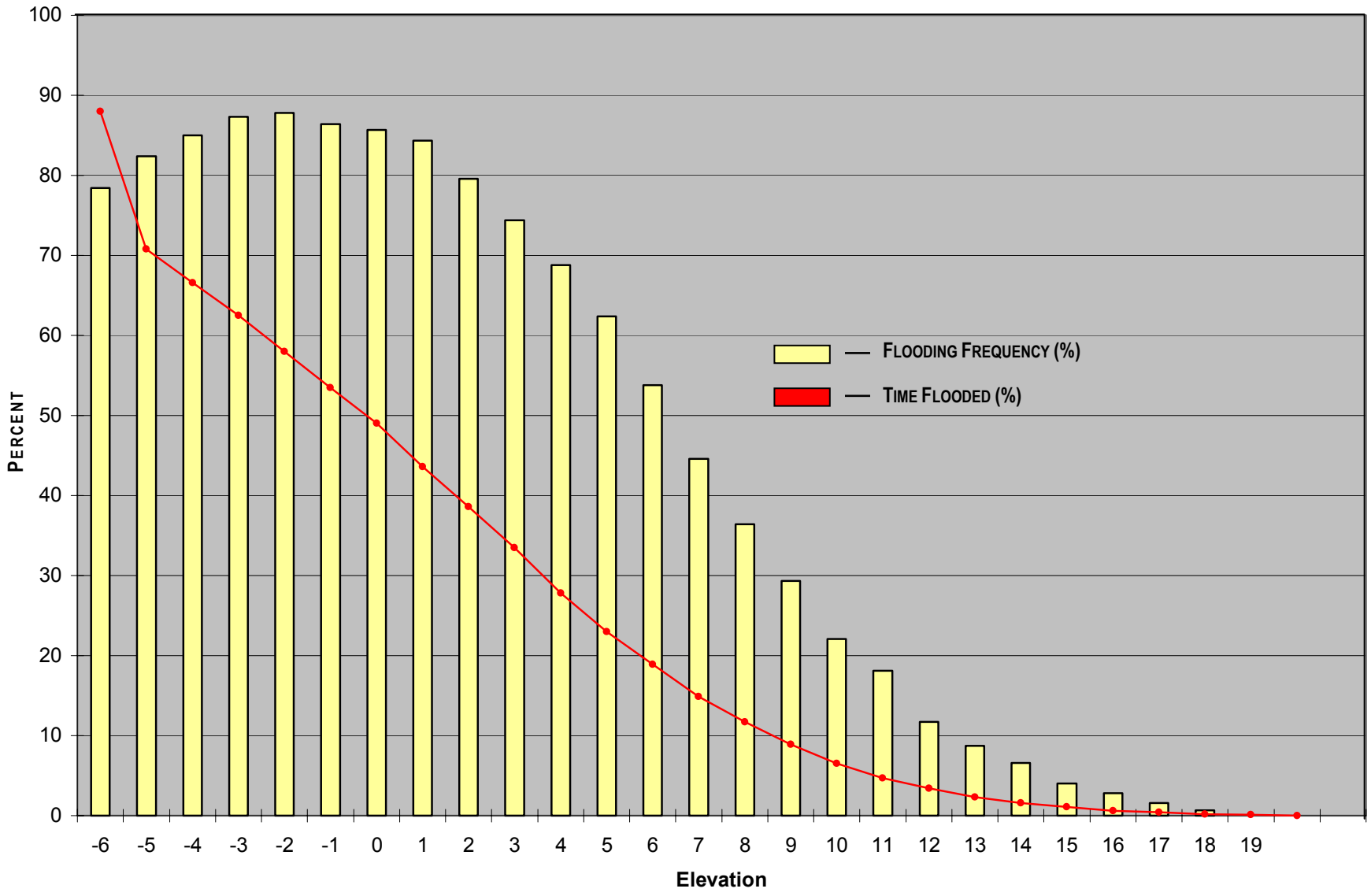




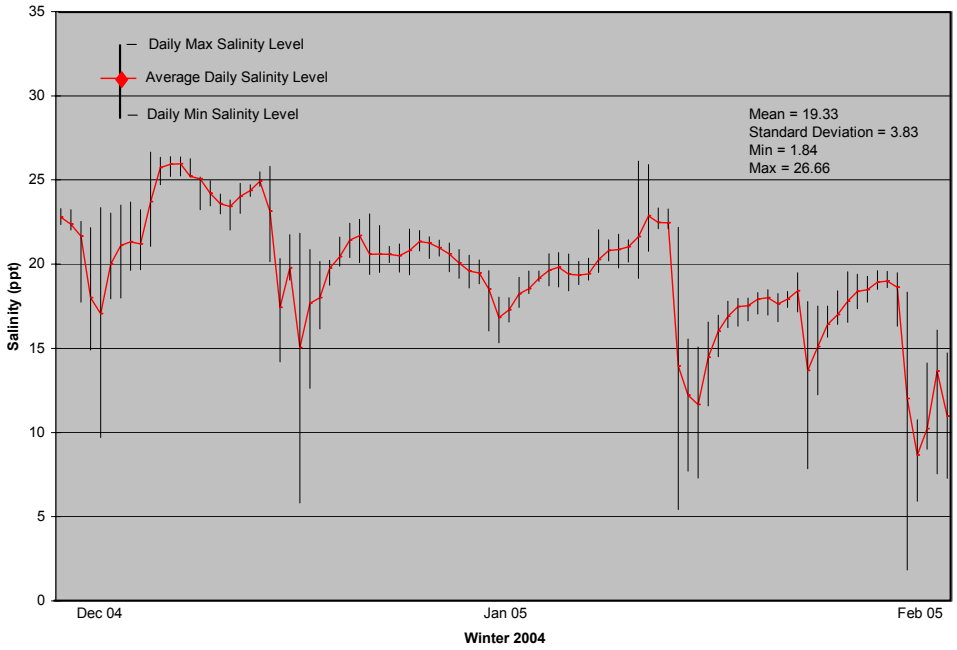


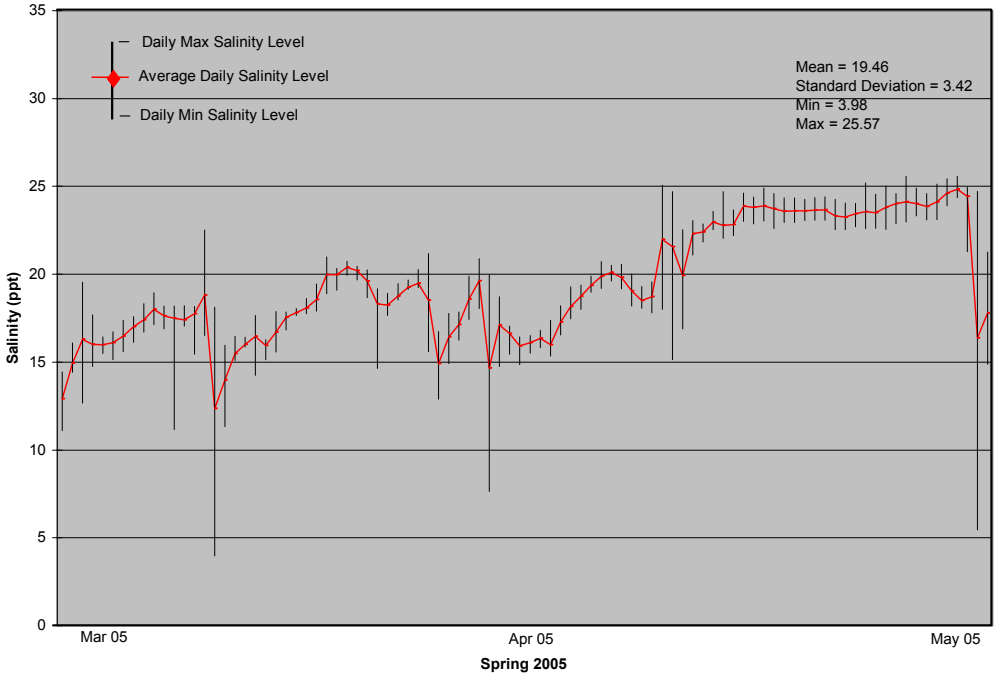


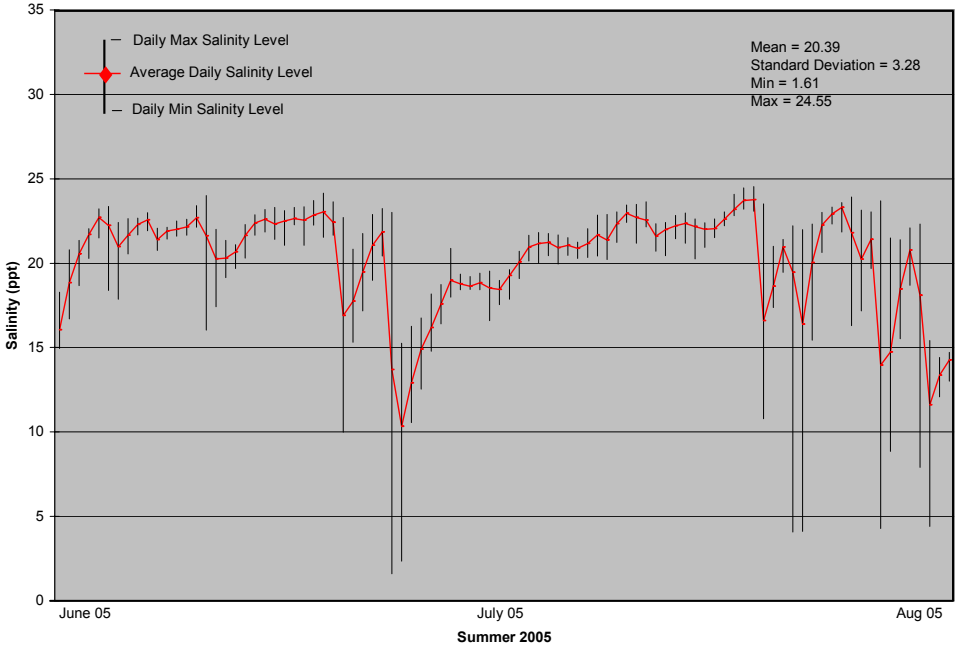
APPENDIX 6 – DAILY MEAN, MAXIMUM, AND MINIMUM WATER LEVELS DIVIDED INTO QUARTER YEAR.

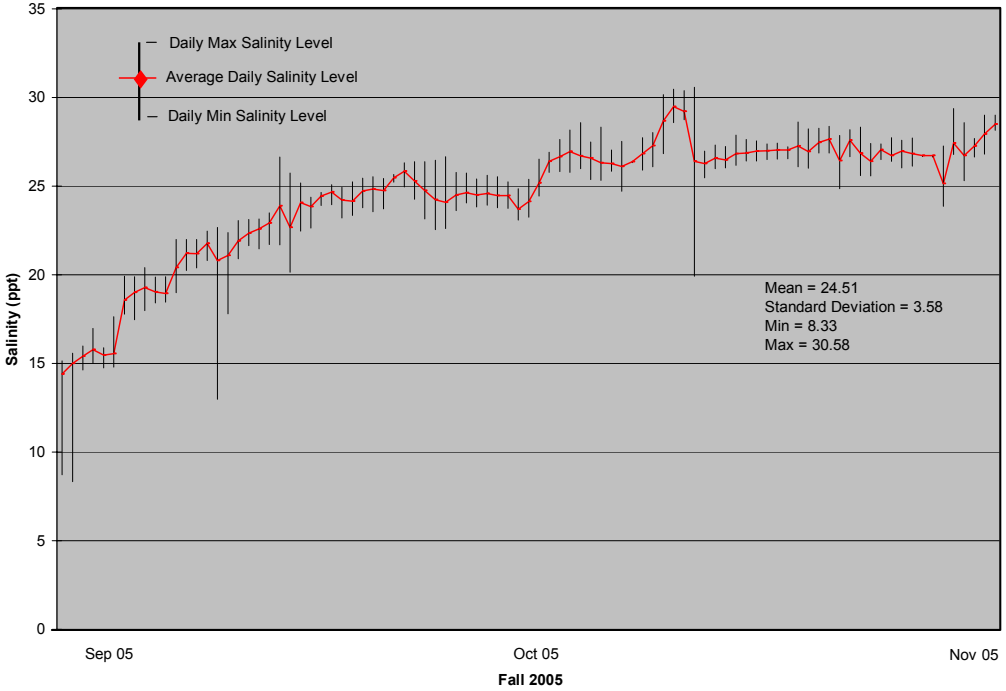


APPENDIX 7 – WATER LEVEL FREQUENCY PLOTTED OVER PERCENT TIME FLOODED.









APPENDIX 8 – DAILY MEAN, MAXIMUM, AND MINIMUM SALINITY LEVELS DIVIDED INTO QUARTER YEAR.