FINAL REPORT

Integrative Approach to Understanding the Causes of Salt Marsh Dieback: Coupled Hydrologic/Ecological Models of Marsh Dieback Processes (II.6)

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In Partial Fulfillment of :
DNR Interagency Agreement No.

30 December 2005

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DESCRIPTION OF INTEGRATED PROGRAM

Restoration ecology includes the development of diagnostic capabilities for ecological systems that are based on ecological theory of succession and ecosystem development. These diagnostic capabilities are presently limited by the ability of scientists and managers to: 1) anticipate ecological responses of ecosystems to specific manipulations or site conditions; 2) monitor responses of ecosystems at sufficient space and time scales to validate these responses; and 3) modify operations of rehabilitation projects according to the response of ecosystems to obtain specific goals. One of the most difficult tasks in restoring ecological systems is to first perform diagnostics as to what factors are responsible for deteriorating conditions (or health) of the ecosystem. Better early diagnostics would allow managers to select the proper set of conditions for site manipulations necessary to rehabilitate habitats toward a specifically defined goal. Thus, a fundamental need of restoration ecology is cause and effect research leading to development of diagnostic tools that can be used to predict, monitor, and validate the response of ecosystems to rehabilitation criteria. The proposed project will focus on what caused the dieback of salt marsh communities in the Barataria-Terrebonne estuary known as 'brown marsh' phenomenon.

There has been widespread dieback of salt marsh in coastal Louisiana in spring and summer of 2000 with estimations of nearly 100,000 acres of severely damaged area. In this integrated project, we propose that restoration objectives and goals, with the purpose of promoting marsh stabilization, represent tests of the mechanisms that have been proposed as responsible for the brown marsh phenomenon. Marsh damage during the severe drought of 2000 suggests that water levels were below average in the coastal zone of Louisiana. Land use changes may have altered regional and local hydrology leading to significant changes in flooding patterns (waterlogging stress), freshwater/saltwater imbalances (saltwater intrusion), and soil biogeochemical processes (regulator toxicity). These drivers negatively affect plant vigor and organic matter accumulation, leading to reduced soil formation in coastal wetlands. There are limited data available to evaluate the impact of water deficits brought about by a combination of drought and low river flow to changes in hydroperiod and biogeochemistry of coastal wetlands. It is not understood how these types of dry conditions associated with La Niña climate disturbances can cause plant stress and wetland loss. This is somewhat due to our lack of basic information on the tolerance of salt marsh plants to a combination of potential stressors. Salt-water intrusion associated with the inland movement of isohalines to locations that seldom experience even low salinity conditions can explain diebacks in fresh water and intermediate marshes. But the unique trend in the brown marsh condition observed in summer 2000 was the stress to higher salinity vegetation in the salt marsh zone suggesting additional mechanisms beyond salinity stress. Brown marsh was unexpectedly most evident in Fourleague Bay, which is connected to discharge from the Atchafalaya River. And the most prominent trend is for the damage to first appear in more inland areas of the marsh, with less damage observed to fringe salt marsh zone.

Ecological modeling is a powerful tool that can be used to describe, quantify, and forecast the response of wetland ecosystems to different coastal management strategies (Twilley et al. 1999). While there are a few ecological models that describe vegetation patterns in wetland ecosystems, there are very few that describe their hydrology, particularly subsurface water budgets. Coupled

models of both vegetation dynamics and hydrology are critically needed given the increasing pressure of human activities and land use changes on distribution of freshwater resources. In addition, models must be at the appropriate scale to capture the drivers that are responsible for specific patterns of ecosystem damage. We report on an effort to develop and apply coupled ecological/hydrologic models to help understand the scenarios that could produce conditions associated with the brown marsh event in coastal Louisiana during summer of 2000.

This report describes an effort to integrate existing modeling platforms with existing landscape monitoring plots of water levels and elevation in marshes of the Mississippi River Deltaic Plain (Figure 1) . Field monitoring and manipulative greenhouse experiments were available to develop parameters that are needed to develop the HYMAR model that describes hydrology in coastal marsh wetlands to simulate the impacts of changes in river flow and precipitation on marsh die back. The idea of this modeling platform is to combine models of marsh hydrology with patterns of soil biogeochemical processes to link with marsh response (Figure 1).

Conceptual Model of Brown Marsh Event

The challenge in this modeling effort was to capture the mechanisms that were proposed to be responsible for the occurrence of marsh dieback in summer 2000. It is important to try and include these mechanisms so that different scenarios can be tested within the integrated modeling domain. In 1995/1996 water levels along the Louisiana Gulf Coast were lower for longer periods than in 1999/2000. No widespread dieback of the salt marsh was noted. This suggests that low coastal water levels by themselves did not contribute to the dieback during the summer of 2000. Similarly, the absolute (cumulative deficit) amount of rainfall from October of one year to mid-summer of the next did not appear to contribute by itself to the die-back, again as evidenced by comparing 1995/1996 with 1999/2000. The most pronounced difference between the two time frames in terms of rain was that most rain during the dieback year occurred in a few, large events. In 1995/1996 there were more frequent rain events of shorter duration. Precipitation was lower than average for both 1995/1996 and 1999/2000. While the cumulative rainfall through June was comparable for the two water years, the pattern of rainfall was not. In 1999/2000 more than 80% of the rain between October and June fell in three major episodes, with almost no rain in the intervening time period. In 1995/1996 rain fell intermittently, and in small amounts through the similar timeframe. This pattern shows up in the soil moisture deficit, calculated as the difference between Potential Evaporation and Actual Evaporation. When there is not enough soil moisture to meet demands of the potential evaporation, a soil moisture deficit can occur. Taken as indicators of moisture stress only, and not as actual numbers, the deficit is greater in May, July and August of 2000 than in 1996.

Hydrology data measured in Old Oyster Bayou provided insights to better understand water levels in an interior marsh site during summer 2000 (Figure 2). Through this effort, we observed that marsh water levels since May 2000 were highly correlated with prolonged drawdowns occurring in response to westerly and northerly winds. The most extreme drawdown instance measured (-18 cm) lasted for several weeks, contributing to the stress of marsh vegetation due to lack of easily extractable water (Figure 2). Preliminary analysis of the marsh water level data also suggest that water level decreases are in large part due to high rates of evapotranspiration (ET) with a slight recharge of groundwater during the nighttime hours.

Based on these observations, the following proposed scenarios were proposed as hypotheses for each research group to test using a variety of field, experimental and modeling techniques:

1. Unusually high salinity water flooded the marsh. In the soil this salinity was concentrated/amplified to levels that were toxic because there were only three rainfall events of any significance. Without higher than average surface water salinities dieback would not have occurred even with the observed pattern of precipitation. The higher than usual salinities could have come from low river discharge, overall lack of rain and/or coastal upwelling.

2. Rainfall events in 1999/2000 were too far apart to sustain normal soil moisture or to provide recharge of water deficits associated with evapotranspiration. The lack of water may have caused plant stress, regardless whether soil salinities increased; and/or the lack of infiltrating rainwater allowed soil salinities to build up. The latter would have occurred even if surface water salinities had not been unusually high this year.

3. Drought induced changes in marsh hydrology caused normally anaerobic and reduced soils to become aerobic and oxidizing. Oxidation of pyrite (FeS_2) and other reduced metal sulfides lowers pH (increased acidity) and elevates levels of soluble metals especially Fe, Mn, and Al. These changes in soil biogeochemistry may have been significant enough to cause plant mortality.

This report will describe the development of a modeling platform to integrate hydrologic and biogeochemical processes that could potentially affect marsh productivity, and are likely to be associated with the drought of 2000 to cause the brown marsh phenomenon. The modeling platform is also a component of the coastal ecosystem forecasting system to assist restoration efforts referred to as the Coastal Louisiana Ecosystem Assessment and Restoration program (CLEAR: www.clear.lsu.edu). Restoring geophysical processes is a key factor associated with site criteria to rehabilitate marsh ecosystems in coastal environments. Geophysical processes were identified with regional drought and low river flow as key site criteria responsible for the brown marsh phenomenon. Thus the key drivers that will formulate the hypotheses of how biogeochemical processes control marsh productivity include soil water deficits (change in hydroperiod), in concert with abiotic stressors (e.g. salinity, pH, metals, etc.). This report describe an effort to use coupled hydrologic/ecologic models to simulate hypotheses as to what factors may have contributed to the brown marsh event; and provide guidance on future monitoring and remediation programs.

Modeling Approaches

Data on soil characteristics, water quality and water levels were assembled and where necessary measured to use coupled hydrologic/ecological models to predict water levels and selected soil parameters for salt marshes at specific sites in Terrebonne basin given the hydrologic and climatologic conditions preceding and continuing during summer 2000 die-back. Model simulations included comparisons with previous years, variability according to soil type and

variability of surface water salinities**.** We looked at the most recent 20-year record of freshwater discharge and rain along Louisiana's coast, the long-term water levels from the available gauging stations that were tied in with GPS to local hydrology. From these data we attempted to infer how different the year 2000 was from previous years in terms of flooding, and compare how the marshes were impacted in the different types of water shortage. There is evidence that 1981 was similar in terms of rain and low discharge, but did not have a prior year deficit of rain water as occurred in 1999 prior to the drought of 2000. In addition, 1986 was a drought year, followed by the summer of 1987 and winter 1988 that both had exceptionally low water levels. The difference is that all of these low river flow years had more local precipitation. What was unique in 2000 was both low river flow and local drought conditions. Questions to be addressed include how long were water levels below the marsh surface in both the recent drought and previous low-water years; and to define what was the relative contribution of tidal or rainfall events in recharging those soil water deficits. Where possible, the actual year identified as unusual were compared to the long-term mean, and the current year.

Modeling Objectives:

1) Combine the best features of the individual unit models (HYMAN and PORSAM) into a single architecture (HYMAR);

2) Link the unit hydrology-biogeochemistry models into a spatially explicit segment model capable of 1D transport across a gradient from interior marsh to tidal creek;

3) Use output from landscape models of the Barataria region during different climate , wind and river flow conditions as boundary conditions for both the segment and unit models;

4) Simulate the effects on pore water salinity of water deficits resulting from different drought scenarios.

5) Use the model to hindcast pore water salinity from 1995 through year 2000.

MODELING PLATFORMS

The modeling platform developed for the brown marsh project is referred to as the HYMAR model that integrates subsurface model of HYMAN, the surface hydrodynamic model of H3D, and the ecological saltmarsh model of PORSAM. Each of these model platforms are described below.

HYMAN model

The HYMAN model consists of a set of simultaneous differential equations that are numerically integrated to simulate soil salinity in coastal wetlands (Twilley and Chen 1998). Water levels in a inland wetland are described by the following equation:

$$dL/dt = Rn + Si - Sp - ET - So \pm \Delta T \qquad (1)$$

where L is water level (above mean sea level, cm); Rn is net precipitation (cm/day); Si is surface inflow (cm/day); Sp is seepage (cm/day); ET is evapotranspiration (cm/day); So is

surface outflow (cm/day); ΔT is tide exchange (cm/day); and t is time (day). The equation to describe the balance of salt in the soil of a basin wetland is based on conservation of mass per unit area as follows:

$$d(SL)/dt = (Ti \times St) - (To \times Ss) - (Sp \times Sw) - (So \times Ss) \qquad (2)$$

where S is the concentration of salt (‰); L is water level (above mean sea level, cm); Ti is water input by flood tide (cm/day); St is the salinity of slack flood tide (‰); To is water output by ebb tide (cm/day); Sp is seepage (cm/day); Sw is the salinity of pore water (‰); So is runoff (cm/day); Ss is the salinity of surface water (‰). The model solves for water levels and salinity based on equations (2) and (3) using measurements of hydrological processes in wetlands described above.

Three forcing functions, precipitation, tidal flood frequency, and evapotranspiration, are used as inputs to the model based on actual field data. HYMAN is used to simulate water and salt movement in a vertical layer of sediment of unit area extending from full bank stage to 0 msl. Tide frequencies in a specific site depend on tidal height in adjacent bay and distance inland of marsh. The main program of the model includes four alternative functions, which depend on water level within the marsh and height of slack flood tide relative to wetland topography. Initial water level, bank full stage of surface water, and specific yields for surface and ground water control the amount of water that occurs per unit area of marsh after accounting for the daily water flux events. To evaluate the terms in this mass balance equation, we must know the volume of water moving at specific time intervals. While this may seen obvious, most climatological data are available only on a daily basis. Therefore the time step for the simulation is daily while the model allows for updating water level and salinity after each hydrologic event. The relative timing of a tide and precipitation occur in time steps less than a day compared to surface flow, evapotranspiration, and seepage that are daily integrated. In the model we programmed the sequence of events as tide, precipitation, surface flow, evapotranspiration, and seepage. Simulations of water levels, including degree of water level deficits in the soil, are shown in Figure 3. These simulations demonstrate the similarity to the types of conditions observed in Old Oyster Bayou during summer 2000 (Figure 2).

The algorithms developed for the HYMAN model were used to modify code in the H3D models to generate projected variations in soil salinity in spatially explicit marshes under different scenarios of tidal frequency and freshwater input. These soil salinities were then used to parameterize the HYMAR model to understand influence of changes in water levels to wetland productivity and development.

PORSAM Model:

The PORSAM model (Morris 1995) also accounts for mass balances of water and solutes (Figure 4), and was adapted to the marshes in the Louisiana delta. Losses of water from the sediment occur through drainage and evapotranspiration (ET). Potential ET is calculated using Thornthwaite's model (Sellers, 1965) and then scaled to derive actual ET according to the calculated water potential. Water potential is calculated from the soil matrix potential (an empirical input that depends on the texture) and pore water salinity. Drainage occurs at low tide until the sediment has reached field capacity (typically >90%). Empirical measurements of field capacity and porosity were generated from the integrated biogeochemical studies that performed in other parts of the program (see Figure 1).

The infiltration of salt water supplies an estimated 44.6 g m^{-2} day^{-1} of salt to the marsh sediment (Figure 4). This is nearly balanced by the drainage, excretion, and diffusion. Drainage accounts for the greatest loss (38 g m^{-2} day^{-1}) of salt from the sediment. Salt diffusion occurs at a rate that depends on the gradient in salinity between surface water and pore water and was empirically measured in marsh mesocosms (Morris 1995). Secretion of salt from *Spartina* leaves is calculated in the model as a function of the transpiration rate and pore water salinity (Bradley and Morris 1991).

Marsh pore water salinity is sensitive to the relative elevation of the salt marsh (Morris 1995). Marshes that are situated high in the intertidal zone have more variable salinities than marshes situated at lower elevations. A marsh at a high elevation that is flooded infrequently by seawater tends to have higher pore water salinities due to evapotranspiration. Simulations of marshes in Old Oyster Bayou indicate that ET is the major pathway for water loss. Losses of water are balanced by infiltration by flooding, which is the major input, and by precipitation. Infiltration can supply water until the pore space is fully saturated.

In the Mississippi River Delta marshes the elevation of the marshes relative to mean sea level was unknown. However, the marsh surface reaches an equilibrium with mean sea level, depending on the rate of sea level rise (Morris et al. 2002). In simulations reported here, we simulated the relative marsh elevation using a sedimentation model reported previously (Morris et al. 2002) and sea level data reported from Grand Isle (Fig 5). Simulations were started in the year 1996 with three alternative scenarios that differed only in the elevations assumed for the beginning of each simulation. One alternative was to start the simulation with the marsh surface was 5 cm below the mean high tide (MHT) level; a second was started with the elevation equal to MHT, and a third with the elevation at 5 cm above MHT. In every case, the marsh surface converged on the same equilibrium by the year 2000 (Fig. 5). Thus, by 2000, the elevation of the marsh was 21 –5 = 16 cm above MSL, which places it somewhat below MHT.

Marsh pore water salinity is also sensitive to flood water salinity. Flood water salinity in the simulations (Fig. 6) were taken from Grand Isle. Note that the 'normal pattern' of salinity in the MR Delta shows salinities declining from about 30 ppt in the late summer to about 10 ppt in the spring. This decline did not occur during the summer of 2000 and flood water salinity remained about 30 ppt during the spring and summer due to low flow conditions in the Mississippi River.

Simulated marsh pore water salinity demonstrated a number of spikes during 1996 (Fig. 6), which were probably due to the fact that the simulated marsh elevations had not equilibrated with MSL and were unrealistically high. Pore water salinity was generally well below 50 ppt during 1997 and 1998, a level that is stressful for marsh cordgrass (*Spartina alterniflora*) (Nestler, 1977, Parrondo et al. 1978, Hwang and Morris 1991, Bradley and Morris 1991). During 1999, simulated pore water salinity climbed to 50-60 ppt. There was a marked departure from the pattern during the summer of 2000 when pore water salinity climbed above 90 ppt (Fig. 6). This level of salinity would have been lethal to the vegetation (Fig. 6 bottom).

The simulations of Spartina biomass (Fig. 6 bottom) were based on a response curve that was derived from a complication of published studies. In lab studies, salinities greater than 45 ppt (Woodhouse et al. 1974) or 50 ppt (Shiflet 1963) cause death of *Spartina alterniflora*. In one

field study, soil water salinity >45 ppt occurred only at the 45-60 cm elevation. The hypersalinity of this zone was thought to have cased a dieback and stunted growth of *S. alterniflora* (Webb 1983). In another field study, growth of *Spartina alterniflora* was inversely related to the interstitial salinity along these clines. Growth is robust in low saline areas and weak in areas of high porewater salinity

H3D Hydrodynamic Models:

A three-dimensional hydrodynamic and salinity model was used to assist in determining the cause of the brown marsh phenomenon. Hydrodynamics in the water bodies surrounding specific marsh sites under investigation are a combination of estuarine processes, such as saltwater intrusion and response to water level fluctuations at the open boundaries, and lake dynamics, such as strong response to wind forcing, particularly water level setup and the development of high-velocity currents in near-shore shallow regions. A robust, flexible and efficient numerical model such as H3D was used to incorporate all of these processes in an operational program. H3D computes the three components of velocity as well as scalar quantities, such as temperature and contaminant concentrations, on a Cartesian three-dimensional grid. The current version of the model is described in detail in Stronach *et al*. (1993) and Meselhe and Noshi (2001).

The H3D modeling system solves the Reynolds equations of motion, with the turbulent fluxes expressed in an eddy viscosity/diffusivity formulation. It uses a shear-dependent turbulence formulation in the horizontal, and a shear and stratification dependent formulation in the vertical. The numerical model includes provision for wetting and drying, which is the component that was modified with the HYMAN model described above to include subsurface hydrology and forecast water deficits in marsh soils. Flooding and drying is implemented in a straightforward manner, and care is taken to ensure that scalar quantities, such as salinity or contaminants, are conserved in the wetting and drying processes. The model is semi-implicit, so that relatively large time steps can be used, which is also important for this model.

This model is currently in use by the Louisiana Department of Natural Resources (LaDNR) to evaluate marsh management strategies and assess the impact of human intervention on the salinity and water level fluctuations of the surrounding areas.

The following list summarizes the research tasks that were implemented to utilize the H3D modeling system to test the scenarios for brown marsh phenomenon:

- Collected and compiled bathymetry data and marsh elevations for each site;
- Located monitoring stations and identified the type and frequency of the data collected. These data were used for boundary conditions (forcing parameters) and for model calibration;
- Designed and established the model layout and the computational grid with the adequate resolution needed in each site;

- Calibrated the model against field measurements. Parameter adjustments made during the calibration process were physically based;

- Used the model to provide detailed information about the water level and salinity fluctuations using modifications in code from the HYMAN model to generate the HYMAR version.

Coupling H3D with the other modeling components provided a comprehensive approach to analyze and investigate the brown marsh phenomenon. Calibration of the HYMAR model used hydrology and marsh structure data. The hydrology data for this site was used to calibrate the HYMAR model and to run sensitivity analyses of water levels and soil salinity. The HYMAR model can then be extrapolated to other marsh sites along Terrebonne basin given information on water levels and tidal flooding frequency. Monte carlo simulations of the HYMAR model was used to test whether the model can accurately track differences in soil salinity between extremes in hydroperiod of the estuarine gradient. This model may also track the amount of oxidation of wetland soil by using porosity and water levels to calculate the amount of soil exposed to the atmosphere.

Figure 7 (Left) shows the general layout of Lake Felicity site. This site was selected as it contains a pair of healthy and stressed marsh. Figure 7 (Right) shows the computational grid used to model the site. The grid resolution was 10 m in the horizontal direction. Since this site is quite shallow and there is no salinity stratification, the H3D model was used in a two-dimensional mode. There are some field measurements available for this site. The field data were used to setup and partially calibrate the numerical model. Figure 8 shows water level time series for the healthy and stressed marsh. It can be observed in the figure that the drawdown is more severe and lasts longer in the stressed marsh than the healthy marsh.

Topographic surveys were conducted at the site. The data was used to set up the bathymetry data file needed for the computational grid. Additional surveys for the channel and the transition from the channel to the marsh were also collected (see Figure 9).

Water level and salinity data were collected in the channel and in the marsh. Some of the data were used to setup the model boundary conditions, while the interior stations were used for calibration and validation purposes. Sample of the model results are shown in Figures 10, 11, and 12. Overall, the model performance was fairly reasonable. To further improve the model performance, field data (water level and salinity) need to be collected at numerous locations to capture the spatial variability. The data must also be collected for a time long enough to capture seasonal variations.

Figures 13 and 14 show a series of images during an inundation event by high-salinity water, and how it was retained in the lower topographic portions of the marsh areas. To track the water level for every image, a tide chart was included in the right hand side of every image. The images indicate that due to micro topographic differences, the stressed marsh retained more saline water for longer period of time. It should be emphasized that this is not conclusive evidence. As discussed above, considerable more field data is needed to refine and validate the numerical model. Finally, Figure 15 shows results from the coupled surface-ground water model

(HYMAR). The figure shows the water level fluctuations above and below (draw-down) the marsh level. This model is a useful and comprehensive tool for this study. It provided detailed information spatially and temporally that can assist in analyzing and understanding the system response to changes in the hydrology and or meteorology of the sites of interest.

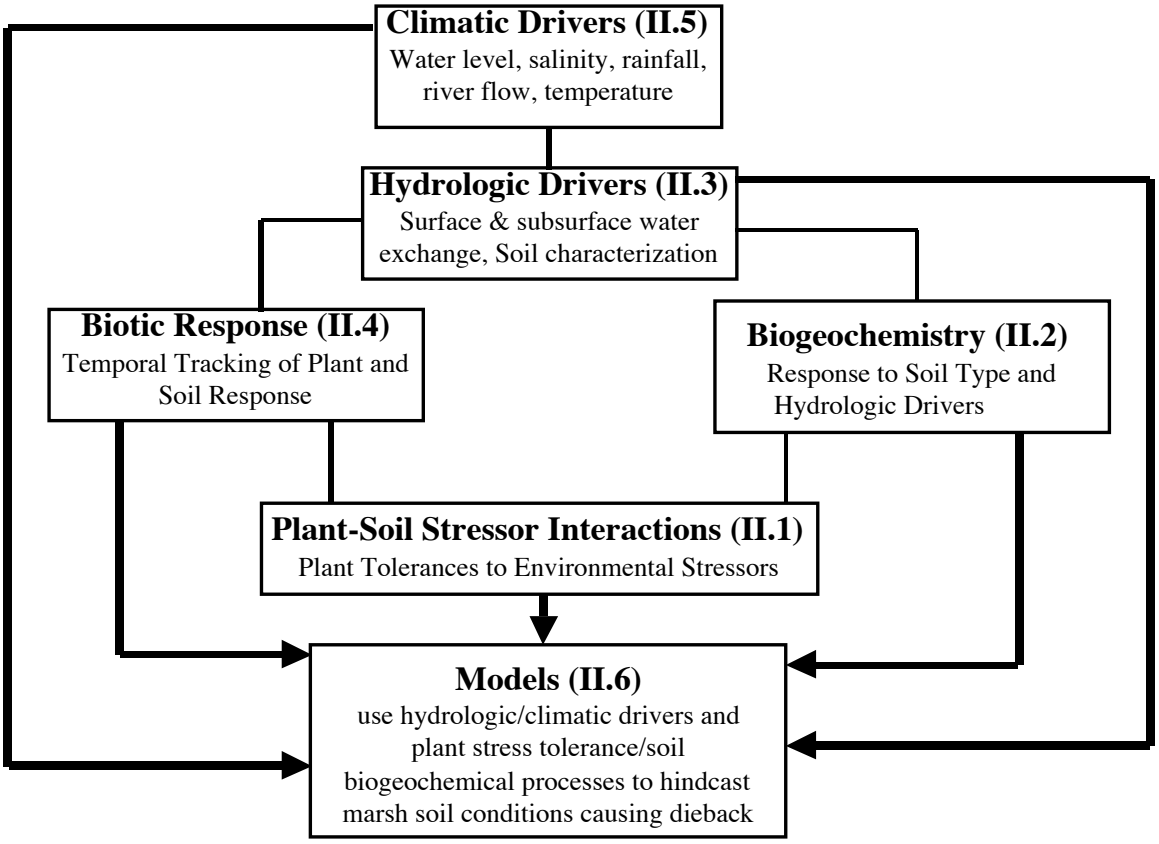


Figure 1. Conceptual diagram of the integrated research program to study the brown marsh phenomemn.

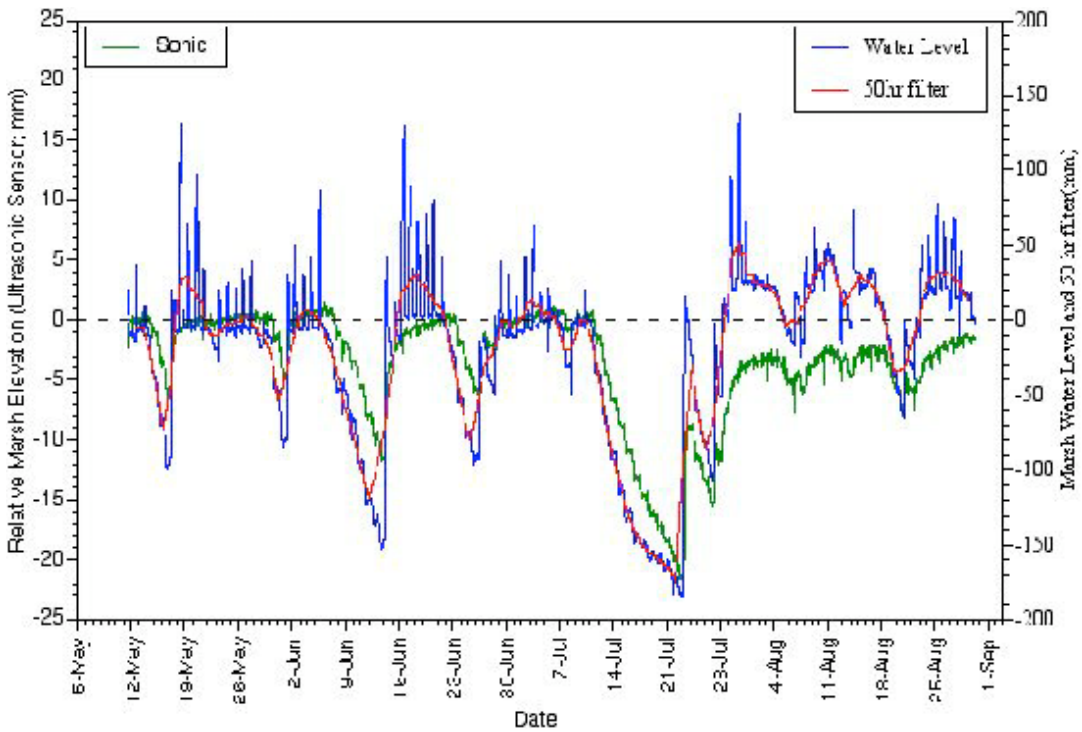


Figure 2. Field measurements of water and surface elevations at Old Oyster Bayou from May to August 2000.

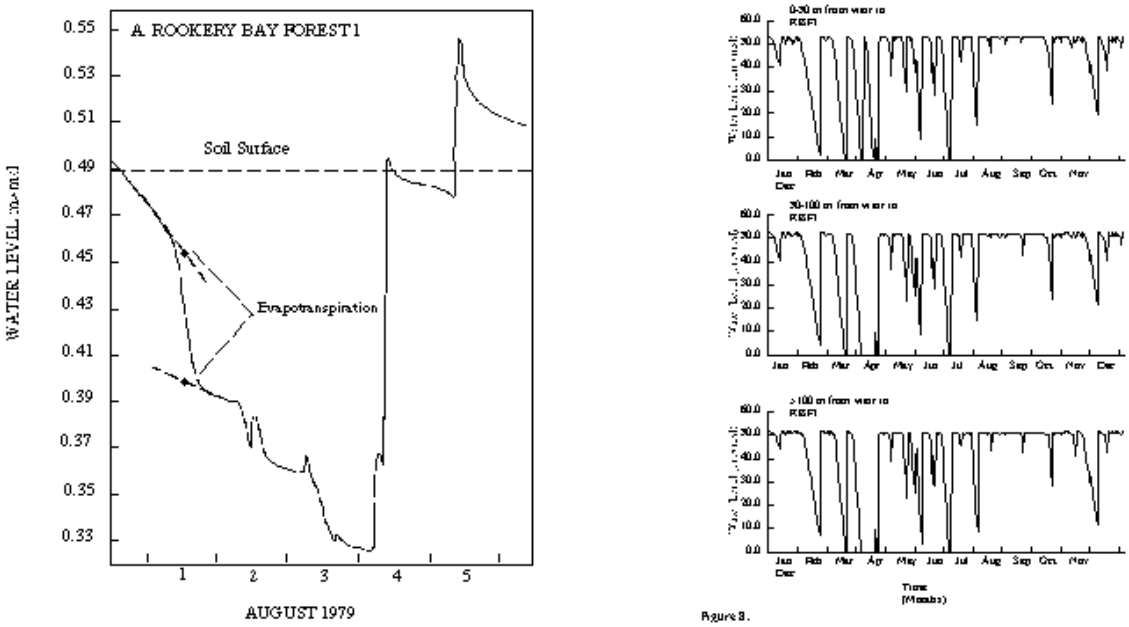
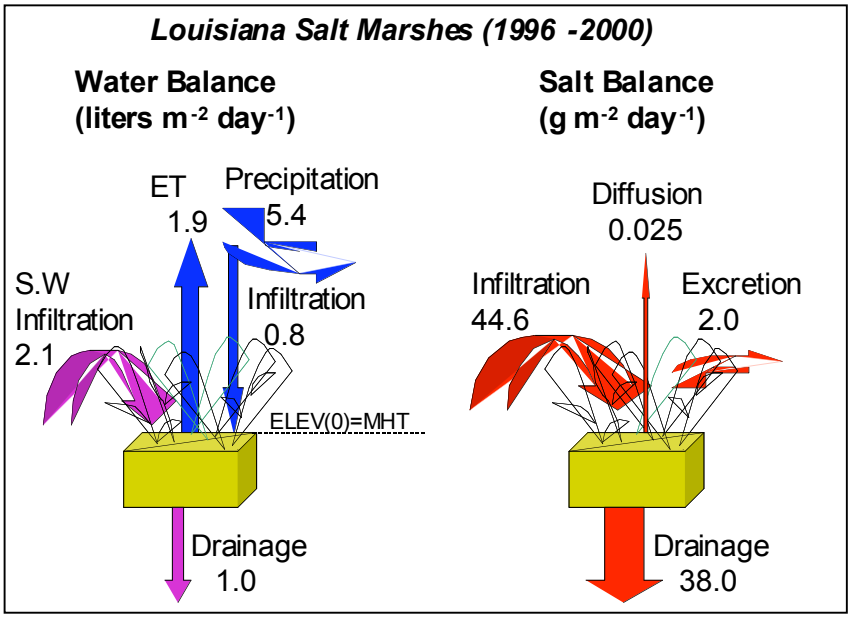


Figure 3. Field measurements of water deficits in mangroves of south Florida; and simulations of water levels during the year at three locations using the HYMAN model (Twilley and Chen 1998).



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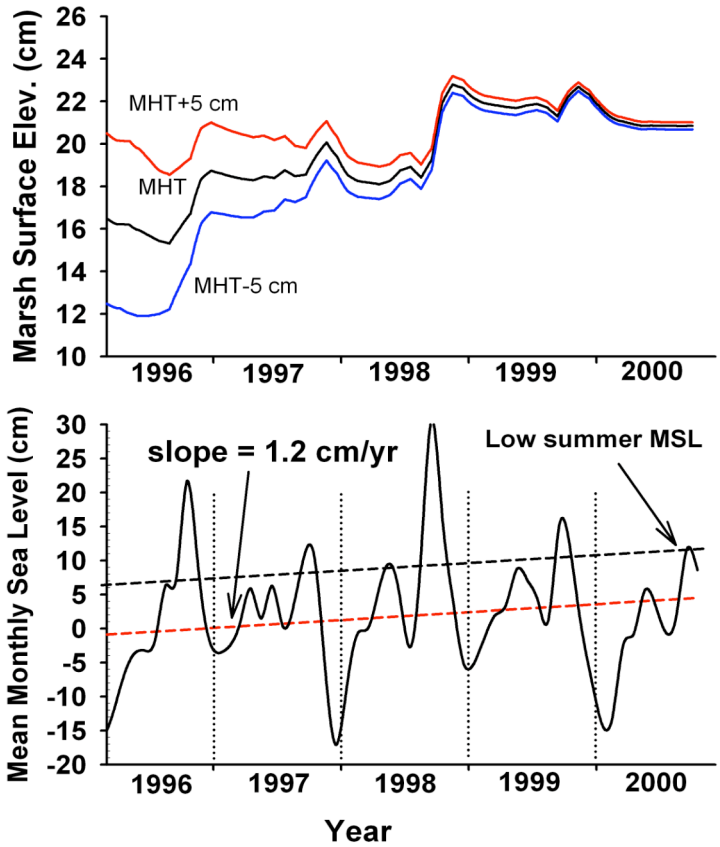


Figure 5 Top: Simulated marsh elevations. The marsh surface elevation at time zero (1996) was assumed to be at -5 cm below the current mean high tide (MHT) elevation, at MHT, or 5 cm above MHT. Bottom: Mean monthly sea level from Grand Isle (solid line), mean sea level (red dashed line), and reference line (black dashed) documenting the low water level that characterized the Delta during the summer of 2000.

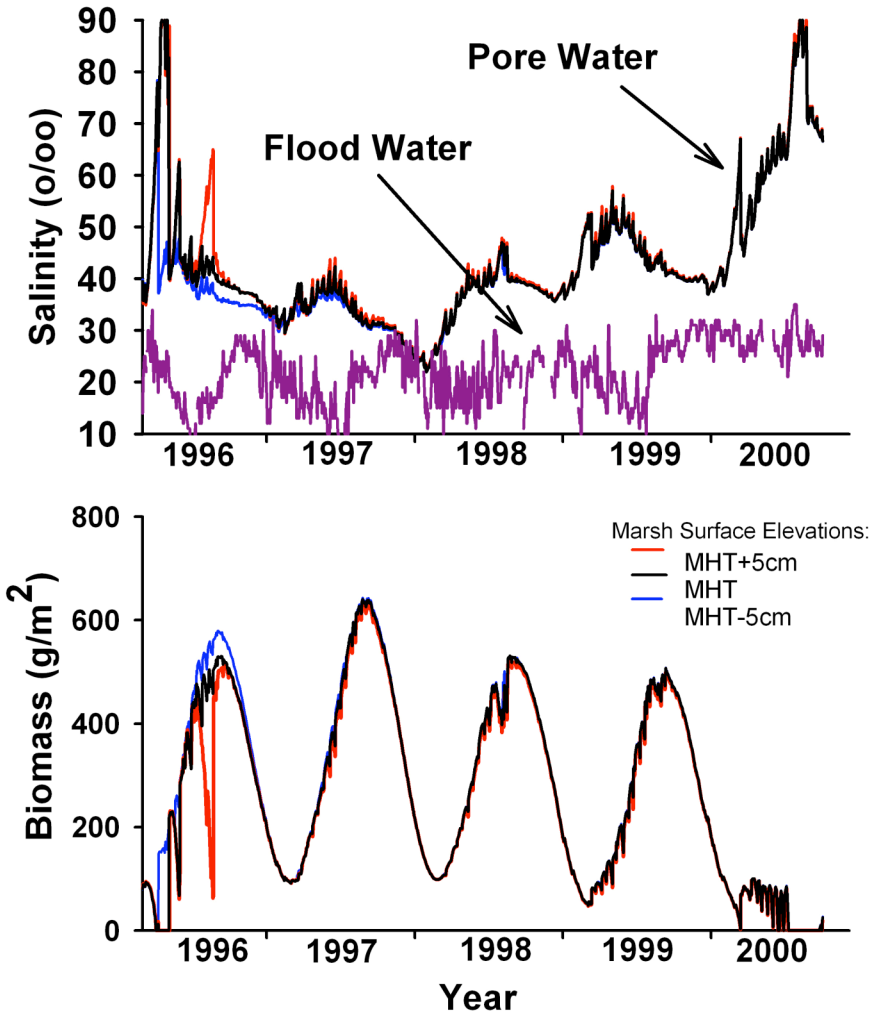
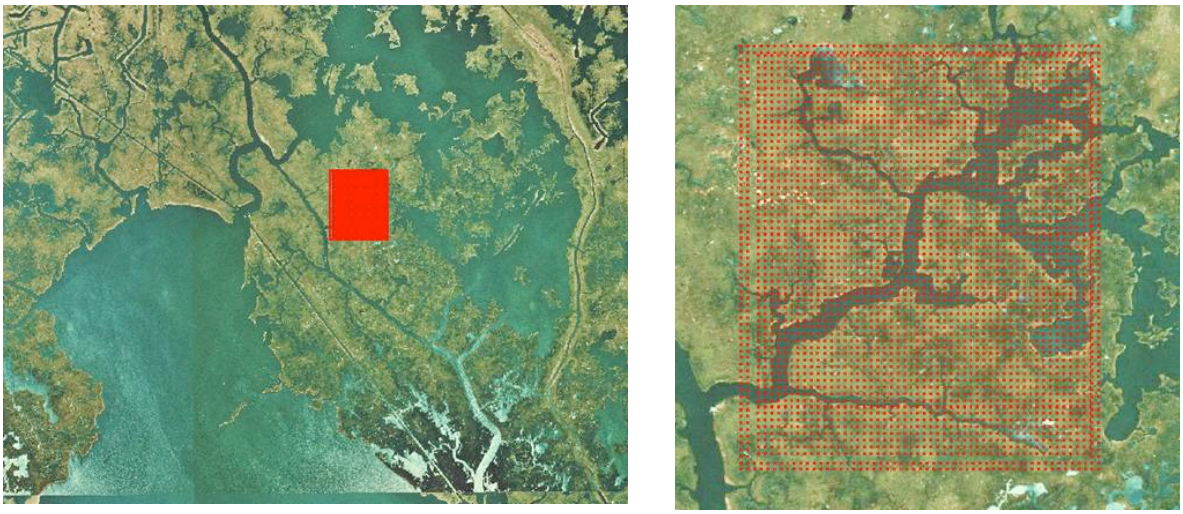


Figure 6. Top: Observed flood water salinity at Grand Isle and simulated pore water salinities from each of the three simulations. Bottom: Simulated biomass density of *Spartina alterniflora*.



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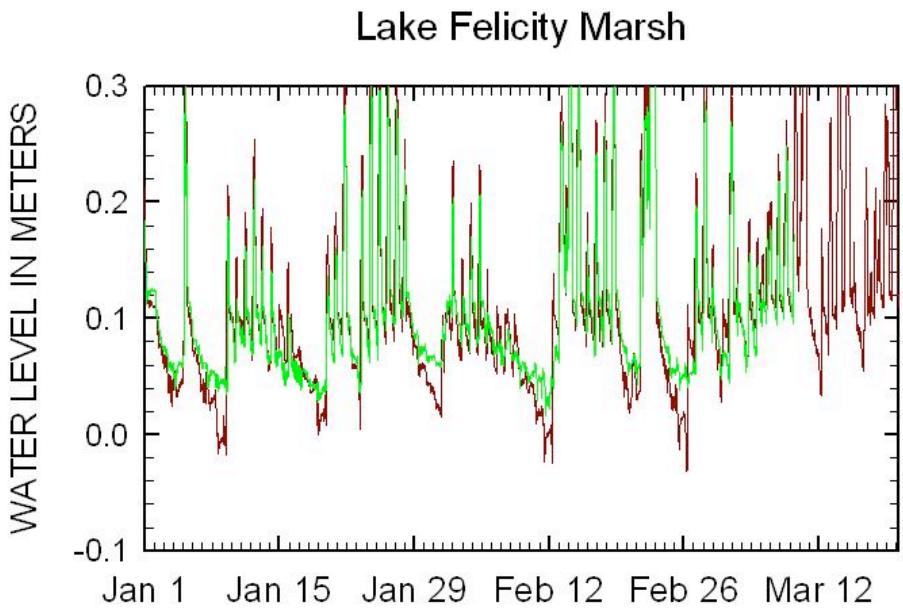

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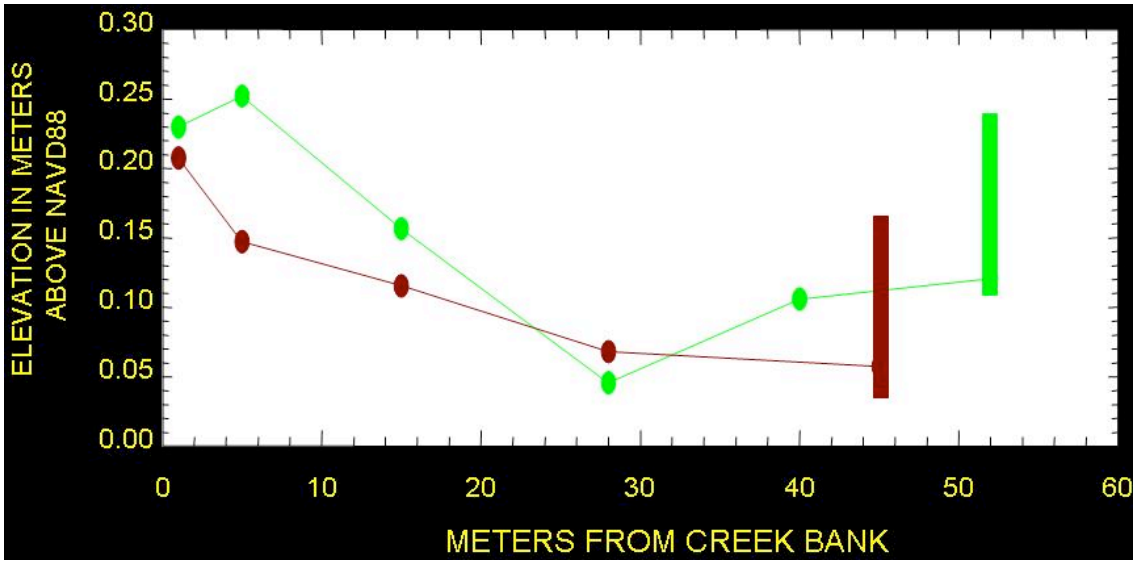


Figure 7. Surface topography of Lake Felicity marshes

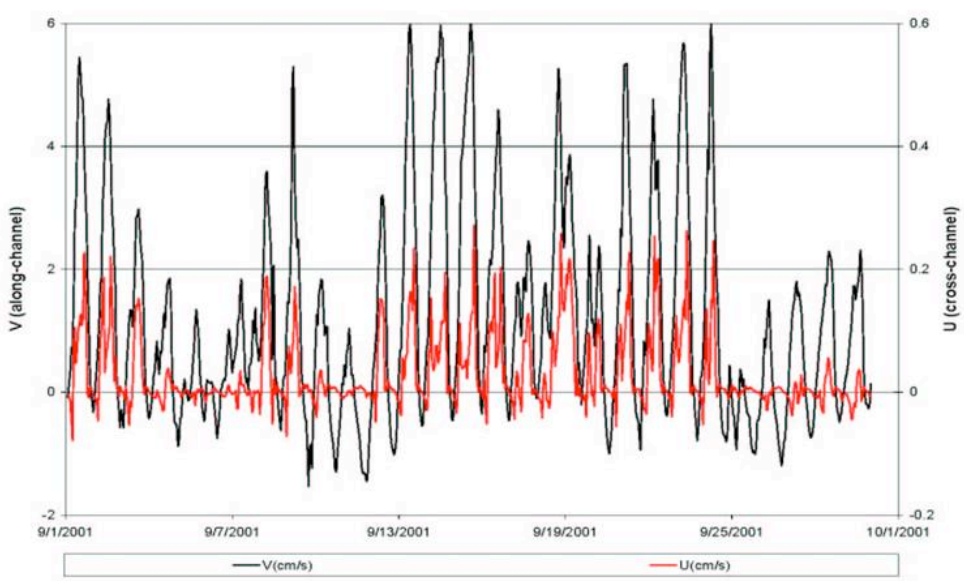


Figure 8. Surface velocities time series in the Channel. Both stream-wise and cross

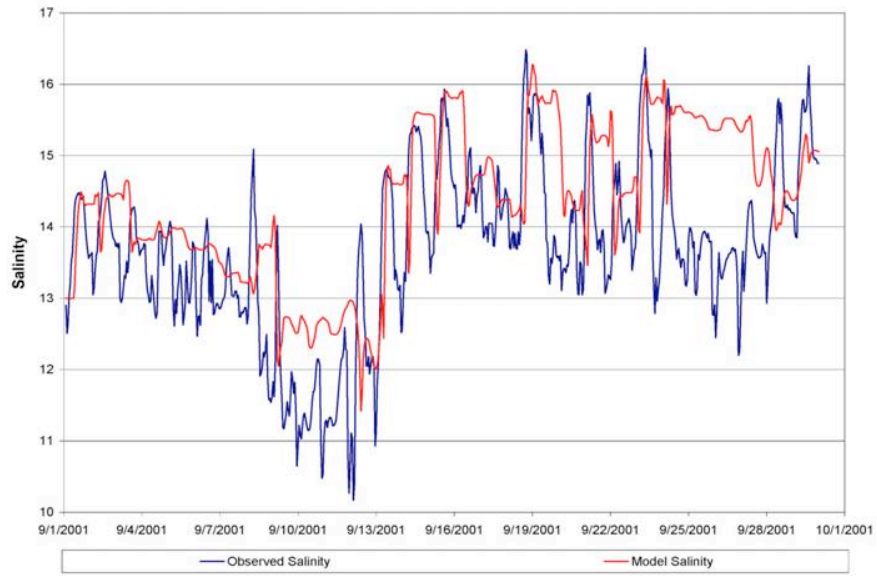


Figure 9. Water surface salinity validation.

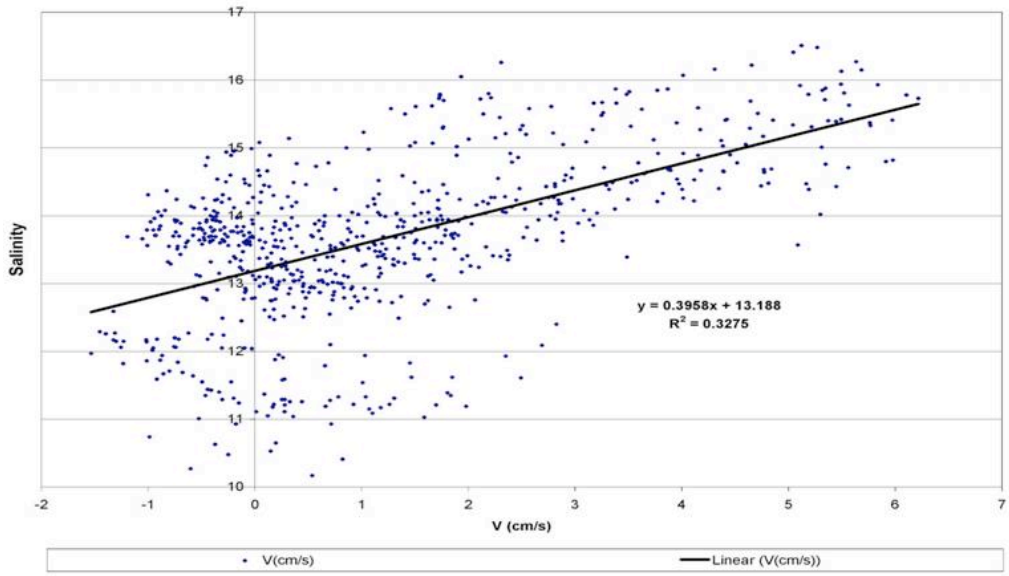


Figure 10. Correlation between flow and salinity: flood tide brings saltier water

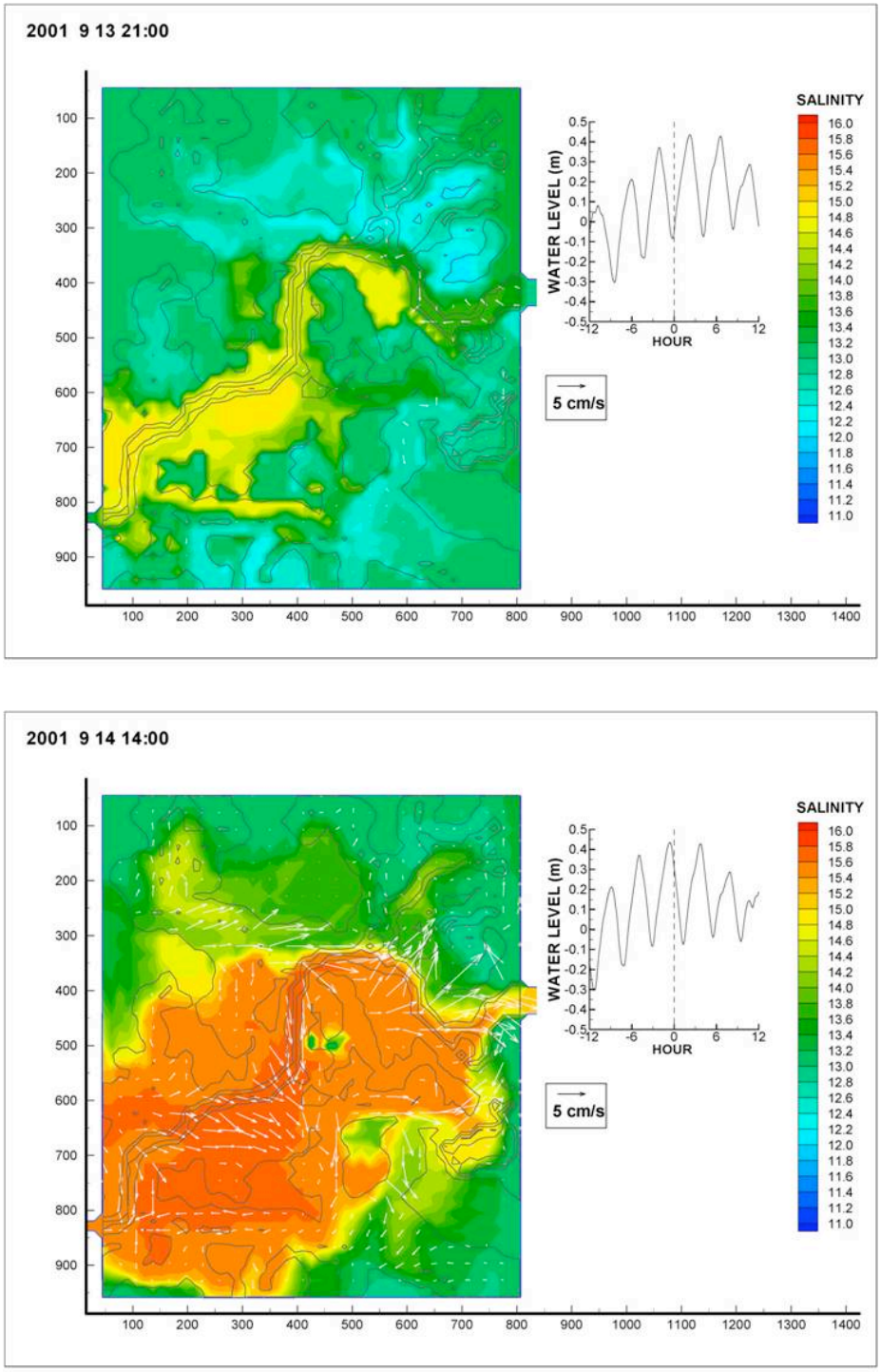
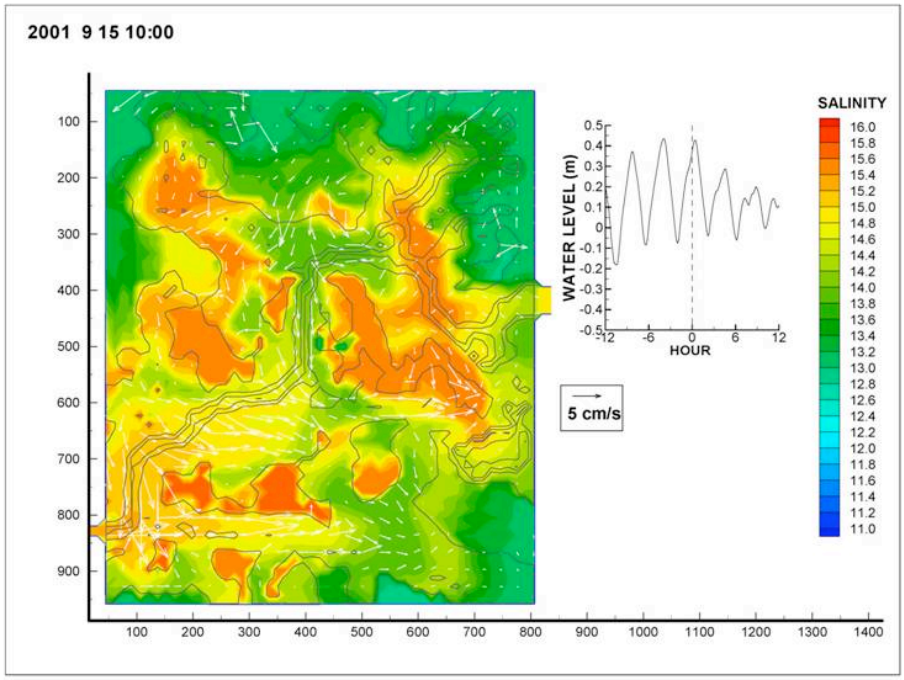


Figure 11. Images (upper and lower) for an inundation event by high–salinity water, and its retention on the lower elevation parts of the marsh



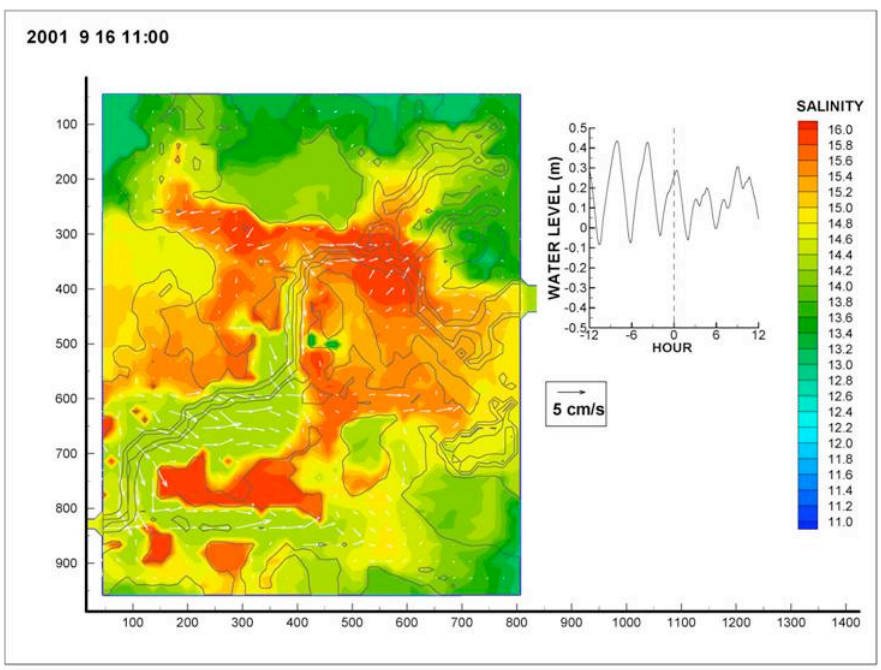


Figure 12. Images (upper and lower) for an inundation event by high–salinity water, and its retention on the lower elevation parts of the marsh

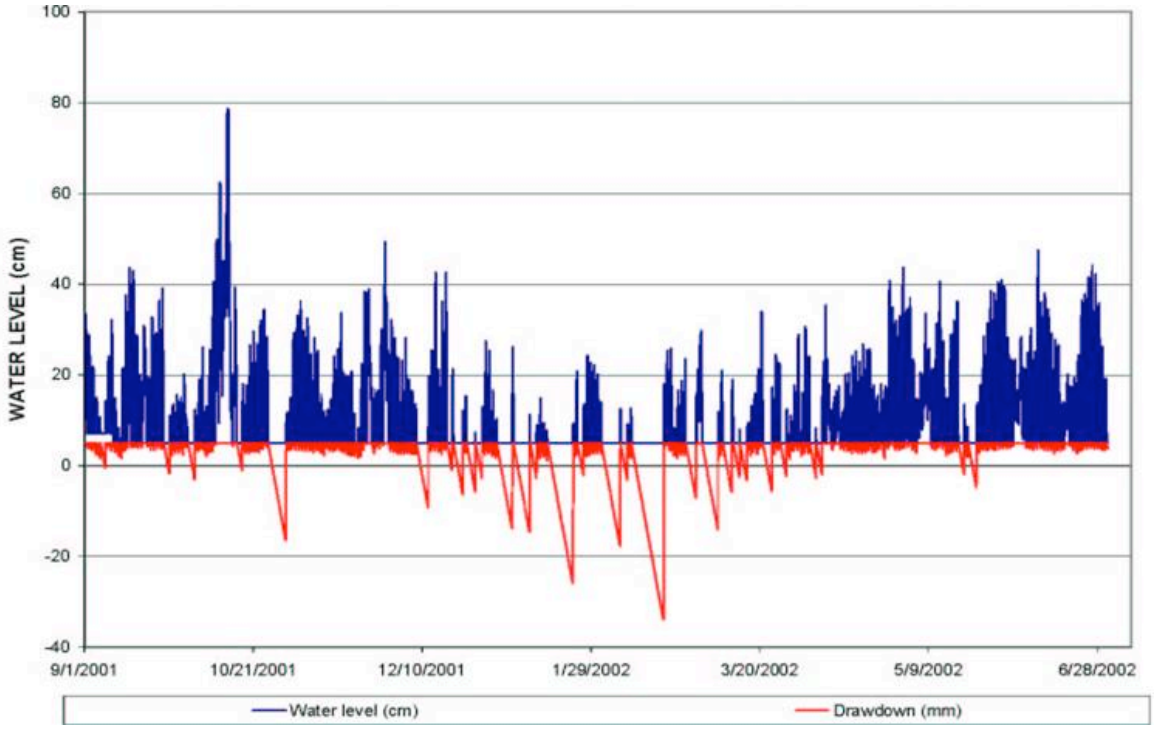


Figure 13. Integration of surface and groundwater components: Drawdown from HYMAR model

REFERENCES

Bradley, P.M. and Morris, J.T. 1991. The influence of salinity on the kinetics of NH_4^+ uptake in *Spartina alterniflora*. Oecologia 85:375-380.

Hwang, Y.H. and Morris, J.T. 1994. Whole plant gas exchange responses of *Spartina alterniflora* (Poaceae) to a range of constant and transient salinities. Amer.J.Bot. 81:659-665.

Meselhe, E.A, and Noshi, H. (2001) "Hydrodynamic and salinity modeling of the Calcasieu-Sabine basin." Final report submitted to Louisiana Department of Natural Resources, Coastal Restoration Division, Baton Rouge, Louisiana.

Morris, J.T. 1995. The mass balance of salt and water in intertidal sediments: results from North Inlet, South Carolina. Estuaries 18:556-567.

Morris, J.T., Sundareshwar, P.V., Nietch, C.T., Kjerfve, B. and Cahoon, D.R. 2001. Responses of coastal wetlands to rising sea level. submitted

Nestler, J. 1977. Interstitial salinity as a cause of ecophenic variation in *Spartina alterniflora*. Estuarine Coastal Mar.Sci. 5:707-714.

Parrondo, R.T., Gosselink, J.G. and Hopkinson, C.S. 1978. Effects of salinity and drainage on the growth of three salt marsh grasses. Bot.Gaz. 139:102-107.

Perez, B. C., D. R. Cahoon, J. C. Lynch, B. Segura and R. Holland. Use of the Surface-Elevation Table in measuring elevation change in wetlands. SWS/INTECOL Millenium Wetland Event, August 6-12, Quebec City, p. 458.

Pezeshki, S.R. and DeLaune, R.D. 1995. Variations in response of two U.S. Gulf Coast populations of *Spartina alterniflora* to hypersalinity. J.Coast.Res. 11:89-95.

Sellers, W.D.1965. Physcial Climatology. University of Chicago Press.

Stronach, J.A., Backhaus, J.O., & Murty, T.S. (1993). An update on the numerical simulation of the waters between Vancouver Island and the mainland: the GF8 model. *Oceanography and Marine Biology Annual Review.* **31,** 1-86.

Twilley, R.R. and R. Chen. 1998. A water budget and hydrology model of a basin mangrove forest in Rookery Bay, Florida. Australian Journal of Freshwater and Marine Research. 49:309-323.

Twilley, R.R, Rivera-Monroy, V.H., Chen, R., Botero, L. 1999. Adapting an ecological mangrove model to simulate trajectories in restoration ecology. Marine Pollution Bulletin 37:404-419.

Webb, J.W. 1983. Soil water salinity variations and their effects on *Spartina alterniflora*. Contrib.Mar.Sci. 26:1-13.