Coastal Environment

Environmental Problems in Coastal Regions IV

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The restoration of tidal marsh hydrology

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Abstract

There has been extensive wetland destruction throughout the world. Efforts at restoration have met with mixed results. To improve success rates, an analytical tidal marsh hydrology model was developed to investigate the causal relationship between a limited set of edaphic, tidal, topographic and climatological factors in determining the spatial and temporal subsurface hydrology characteristics of wetlands. While the model can be used to simulate the hydrology of many different types of wetlands, here it is used to demonstrate how various physical parameters affect the hydrology of tidal marshes. The results of a sensitivity analysis on the model demonstrate the importance of site morphology, substrate transmissivity, and porosity as the primary determinants of tidal marsh hydrology patterns. Because restoration practitioners have an opportunity to specify these characteristics when they develop restoration designs for a given site, specific management and restoration ideas are also presented.

1 Introduction

In both developed and developing countries around the world wetland losses have been great, an alarming trend considering the historical role that wetlands have played in the development and sustenance of human civilization [1]. In North America, it has been estimated that during the last three centuries alone economic development is responsible for the destruction or impairment of approximately 53% of the estimated pre-colonial continental wetland coverage [2]. In densely populated coastal regions, losses have been even greater. For example, in New York City, the US Fish and Wildlife Service estimated in 1997 that approximately 300,000 acres of tidal wetlands and underwater lands have been filled [3], and that 75% of historical wetlands in NY/NJ Harbor Estuary have disappeared in the last century alone [4].

Because of the intimate relationship between hydrology and wetland function, a sound understanding of site hydrology is critical in the planning and design wetland restoration projects ([5], [6], [7], & [8]). In this paper, our interest is the restoration of tidal marshes. This paper is one part of a larger investigation into various aspects of the hydrology of tidal marshes in the New York Estuary. Comparison of previous attempts to model tidal wetland hydrology is complicated by intermarsh variability, the application of different modeling methodologies, and inconsistency in the focus of the modeling efforts. Moreover, few investigators have attempted to make recommendations about how best to restore the hydrology of tidal marshes.

The objective is to illustrate the effect that several potential restoration scenarios would have on hydrology patterns in a tidal marsh. This goal will be accomplished using an analytical wetland hydrology model and observations made at Piermont Marsh, a tidal wetland in the New York Estuary. Given a series of physical and time-dependent inputs, the model predicts the water surface elevation at points along a transect perpendicular to a tidal creek.

We conduct here an analysis on the model to determine the relative importance of several parameters in marsh hydrology restoration. First, a model run that predicts the transect hydrology to within a reasonable degree of accuracy is presented. Then, varying four critical input parameters, (the substrate transmissivity, the substrate porosity, the average marsh surface elevation, and the marsh width) one at a time, the deviation of the model in reproducing the original prediction is reported. When proposing creek networks, selecting island and oxbow diameters, specifying substrate type and handling instructions, and determining marsh plane elevations, restoration practitioners routinely specify each of these parameters in restoration design documents. This analysis reveals which parameters are the most important to consider in the restoration of a tidal marsh and which should be controlled most closely in design.

2 Model

The hydrologic model developed predicts the time and space dependent position of the water surface at various locations along a transect perpendicular to a tidal creek. The complete derivation is given elsewhere [9]. A brief synopsis of the derivation follows: surface drainage occurs instantaneously, while evapotranspiration and precipitation are uniform across the marsh surface during each time step of the simulation. Further, the substrate is assumed homogeneous with a uniform effective porosity and a horizontal and impermeable lower boundary. The fluid is assumed incompressible and flow is considered in the x-direction only. Groundwater upwelling, preferential flow through creekbank macropores and unsaturated flow are not considered.

The governing equation was Boussinesq's equation for unsteady flow in a phreatic aquifer with accretion, derived by considering the conservation of mass in a control volume. The original problem was decomposed into a series of simpler problems, the solutions of which were superimposed. The time and space dependent solution for the marsh water table, d(x,t), was calculated by summing

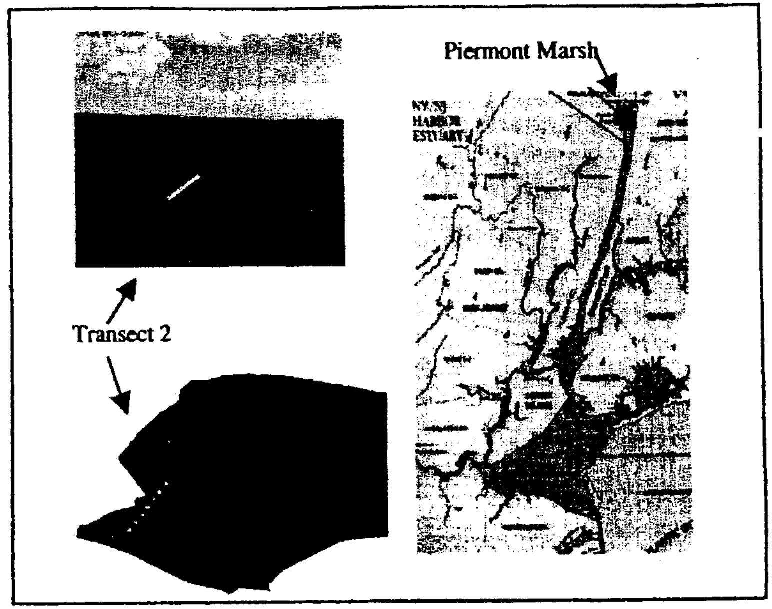

Figure 1: Transect 2 at Piermont Marsh; right: location of Piermont Marsh in NY Estuary; upper left: photo of study area from the uplands with Hudson River in the background; lower left: well locations shown on digital terrain model of study area

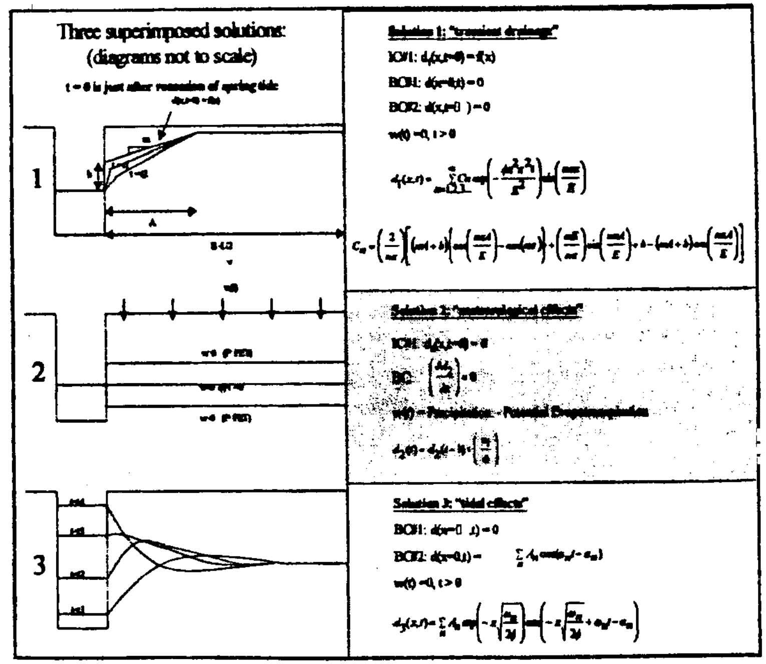

Figure 2: Superimposed solutions, initial and boundary conditions

three solutions (See Figure 2): $d1(x,t)$ depicts drainage from the soil substrate towards the creek, $d2(t)$ takes into account the uniform effects of precipitation and evapotranspiration across the marsh surface, and $d3(x,t)$ accounts for tidally induced fluctuations in the marsh water table. Table 1 summarizes the model's required input parameters.

3 Methods

To validate the model, hydrologic data was collected along four different transects in two different tidal marshes in the NY Estuary [9]. In this paper we will be considering observations made along what is known as Transect 2 at Piermont Marsh (See Figure 1). Piermont Marsh is an irregularly flooded tidal marsh, (i.e. inundated by spring high tides brought on by the new moon and full moon only,) and is located in the mesohaline span of the Hudson River. Along Transect 2, wells were installed at each of seven distances from the creekbank: 0.3 m (i.e. the creekbank levee), 6 m, 12 m, 18 m, 24 m, 36 m, and 48 m. Pressure transducers and data loggers were used to record the water surface in each well continuously at ten-minute intervals for approximately one full month (5/26/99 through 6/21/99). Pressure transducer calibration revealed errors of less than 1 cm in water surface observations made at the levee through 36-m wells. Errors of up to 4 cm were observed in the 48-m observations due to instrument noise at that location. Tide and precipitation gages were also set up on site. Topographic surveying was accomplished using real-time kinematic (RTK) GPS surveying and a laser plane unit. Hydraulic conductivity was measured in several locations using the augur hole method. Daily potential evapotranspiration (PET) rates were obtained from data measured at White Planes, NY, approximately 10 km due east of Piermont.

The model-input parameters were derived using a variety of methods. Fourier analysis was used to convert the levee well data into a sine series to be used as the creekbank boundary condition in Solution 3. The standard error incurred by this approximation was 0.4 cm. In Solution 1, the initial condition, $f(x)$, was determined based on well observations. Two sets of initial conditions were developed. Initial condition 1 describes the water surface profile at the first time step of the simulation. Initial condition 2 describes the water surface profile just after the ebbing of an inundating high tide. A typical model run starts at time, $t=0$, with initial condition 1. The model run then proceeds by making new predictions at ten minute intervals until just after a spring tide inundation of the marsh surface, at which point initial condition 2 is triggered and time is reset to zero. The physical parameters used to describe the initial condition profiles (b, m and A) were gleaned from the well observations. Standard errors of fewer than 1.4 cm were calculated on both initial conditions. The average marsh surface elevation in the vicinity of Transect 2 was obtained from the topographic survey data collected using GPS, as was the marsh width. Errors associated with RTK GPS surveyed elevations are 0.5 – 1.0 cm horizontally, and 0.5- 2.0 cm vertically. To calculate the transmissivity, the hydraulic conductivity measured

in the creekbank peat was multiplied by the depth to an organic clay layer as observed in a soil core extracted on site [10].

Table 1. Input parameters, best-fit values, and range modeled.

Input Parameter Description	Symbol	Units	Best Fit	Range Modeled
Marsh Linear Width	L	M	250	18m – 475m
Average Marsh Surface Elevation	S	M	1.03	0.5 m – 1.4 m
Transmissivity (product of hydraulic conductivity times the effective depth)	T=kD	m2/d	0.3575	+/- 10% on log scale (0.03575 to 3.575)
Substrate Porosity	Θ	-	0.50	+/- 30% (0.35 to 0.65)
Elevation of Bottom of High Permeability Root Zone (Initial Condition 2)	B	M	0.869	N.A.
Slope of Initial Water Table in Creekbank (Initial Condition 2)	M	-	0.0072	N.A.
Width of Creekbank Zone (Initial Conditions 1-2)	A	M		N.A.

4 Results

The model was run several hundred times using different sets of input parameters. Good agreement has been found between predictions and well observations made at this and other sites in the New York Estuary [9]. Error calculations were made for each run at each of the seven distances from the creekbank where well measurements had been made. Several trials yielded low overall errors. However, the best fit obtained using the parameters shown in Table 1 was retained due to the closeness of these parameters to measured and expected values. The predictions and the standard error calculated at each well distance are shown along with the well observations in Figure 3. In most cases the standard error of the prediction was under 3 cm- reasonable considering the precision with which the model-input parameters were derived. Standard errors of 4.6 and 4.2 cm were incurred at the 6 and 12 meter wells, respectively. These higher errors are due to the inability of the model to take account of preferential flow occurring in the creekbank region, the subject of another paper [11].

In order to measure the control that each of the input parameters exerted on the marsh hydrology, a sensitivity analysis was conducted. The transmissivity, porosity, marsh width, and average marsh surface elevation were each varied individually within realistic ranges while all other parameters were held constant and the model was rerun. The range of values considered for each of the parameters is shown in Table 1 above. The marsh surface elevation was varied from 0.5 m, just below the lowest levee boundary condition elevation, to 1.4 m, 25 cm above the highest observed tide. The marsh width was varied between 18 and 475 m. The porosity was varied between 6 30% of the best-fit value of 0.5. Because of the difficulty in accurately measuring or estimating the hydraulic conductivity and effective depth of a soil substrate, the transmissivity was varied over a wider range, from 10% to 10 times its best-fit value of 0.3575 m2/d.

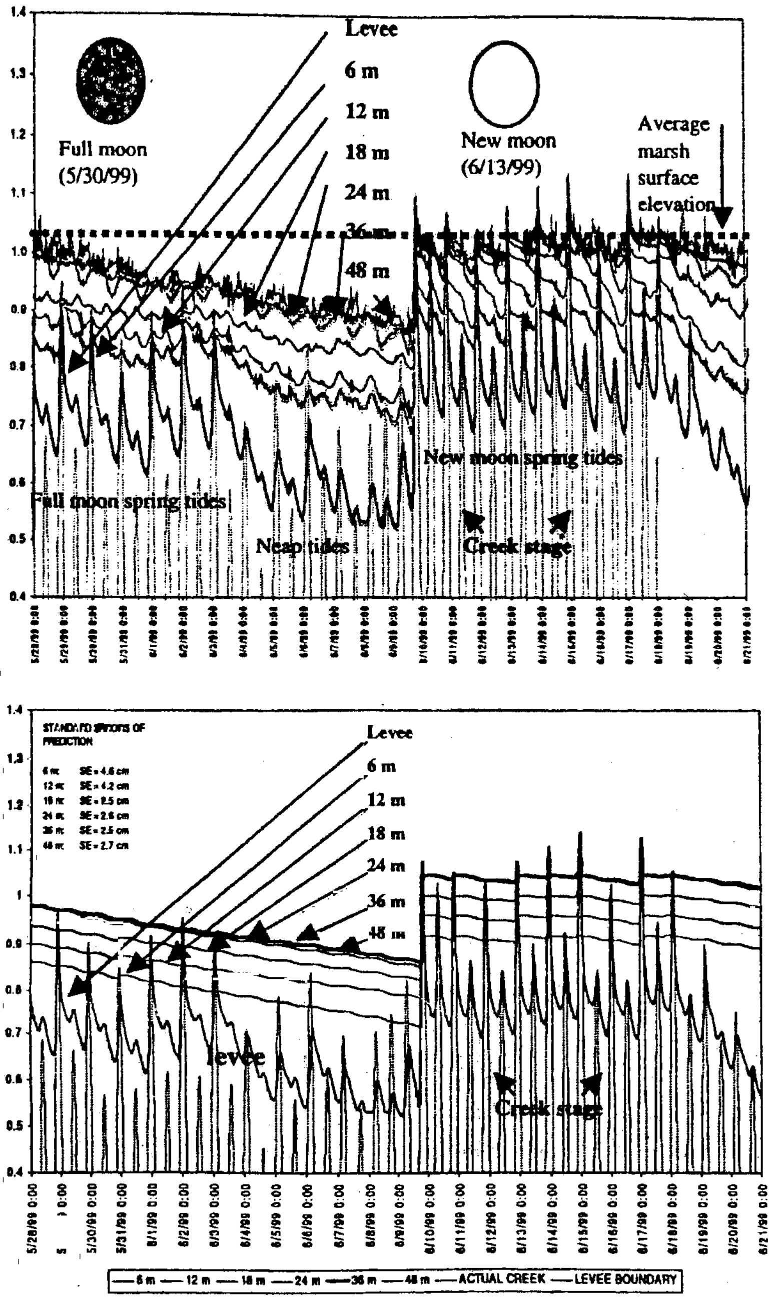

Figure 3: Top: Observations of water surface elevation versus time made along Transect 2 at Piermont Marsh; Bottom: "best fit" predictions

To measure the deviation of each new run, the standard error was calculated between the predictions made with the new input parameters set and the predictions made with the best-fit values. These deviations are shown in Figures 4 through 7. Note that the x-axis of all Figures involving the transmissivity is on a log scale.

5 Discussion

At Piermont Marsh, the tides only exceed the average marsh surface elevation during the new moon and full moon spring tides. During the first and third quarters of the lunar month, the amplitude of the tidal fluctuations in the estuary is smaller and the tides during this period are known as neap tides.

The elevation of the marsh surface, therefore, determines the frequency of tidal inundation. The higher the marsh surface, the less frequently the marsh is inundated by high tides, and vice versa. During periods of marsh surface exposure, such as occur during neap tides or in between inundating spring high tides, the water table drops slowly as a result of evapotranspiration and creekward drainage. During each tidal inundation event, lost pore water is replenished and the water table is raised across the marsh. The more frequently the marsh is inundated, the longer the period of time that the water table is close to the marsh surface.

The rate at which water is lost from the marsh during periods of marsh exposure is related to the transmissivity of the substrate. The transmissivity is a property that describes the rate at which water is transmitted through a unit width of aquifer under a unit hydraulic gradient. The higher the transmissivity, the higher the flow rate possible under a given head. Because the transmissivity is the product of the effective depth and the hydraulic conductivity, both a deep soil profile, and a highly conductive one, can increase the rate of flow through the soil, leading to greater drawdown of the water table during periods of marsh exposure.

Soils are composed of a combination of solid particles and the empty pore spaces that exist between them. The porosity of a soil is the ratio of the volume of voids to the total volume. Soils that are less porous, therefore, will show a greater fluctuation in water table when a given amount of water is added or removed from them. This is because there is less storage capacity for water in a given volume of low porosity soil than there is in a higher porosity soil.

There is a gradient in the water table profile of edge portions of the marsh evident throughout the month (See both observed and predicted data in Figure). At distances greater than 24 meters from the creekbank, however, the water table flattens out. Across the vast plane that is the marsh interior, the water table is horizontal and parallel to the marsh surface.

5.1 The effect of individual input parameters on marsh hydrology

The maximum deviation possible of any simulation from the original predictions is the difference between the marsh surface elevation and the average levee

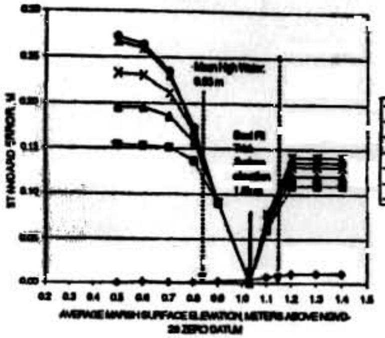

Figure 4

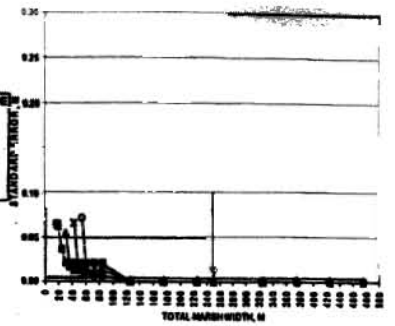

Figure 5

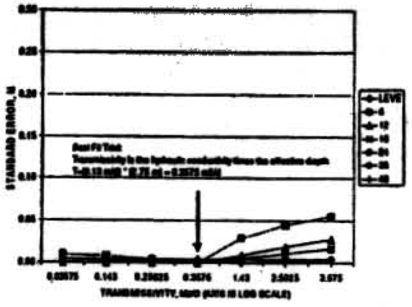

Figure 6

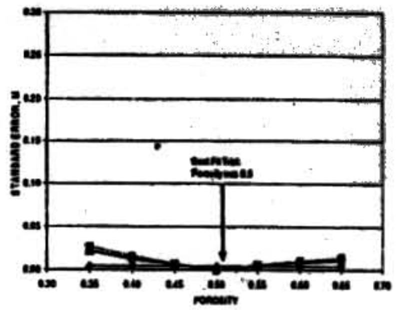

Figure 7

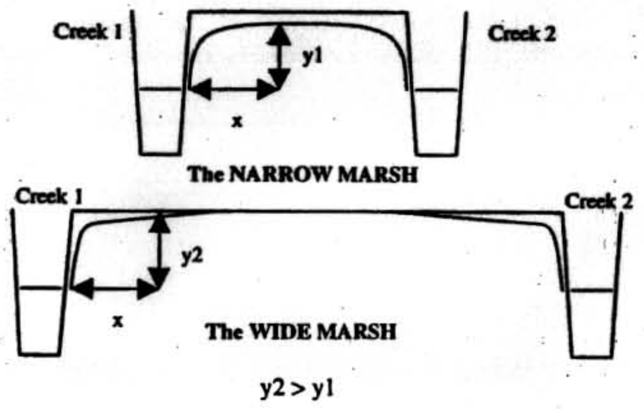

Figure 8: In a narrower marsh, the water table at a given distance from the creek is lower than the water table at the same distance from the creek in a wider marsh. This is because in the narrow marsh, the water table "feels" the effect of both Creek 1 and Creek 2, while in the wide marsh, Creek 2 is too far away to exert any effect

boundary condition. Within the range of values tested, the standard error at all distances from the creekbank and for all runs was always under 30 cm. The average value of the levee boundary condition was 0.72 m and the modeled marsh surface was 1.03 m, a difference of approximately 30-cm, explaining the maximum error threshold observed. (For simulations involving higher marsh surfaces, the elevation of the initial condition water table was unchanged. For lower simulated marsh surfaces, the initial conditions were lowered in proportion to the surface.) It should also be noted that the water table as predicted at 48 meters from the creekbank closely represents the elevation of the water surface over the majority of the interior marsh plane.

In general, the model is most sensitive to changes to the average marsh surface elevation. Large deviation of the model from the original prediction was found when S was varied within just a 10-cm envelope around the best-fit value. The second most important input parameter is the marsh width, but only at the low end of the range tested. The model was least sensitive to changes to the substrate transmissivity and porosity, respectively.

The model was most sensitive to changes in the average marsh surface elevation of within +/- 20-cm of the best-fit value. When the average marsh surface elevation was increased by just 7 cm above the best-fit value (see Figure 9), the marsh was deprived of inundation during the 6/9 through 6/12 high tides. When the average marsh surface elevation was decreased by 13 cm, the marsh surface was inundated by the 5/28, 5/29, 6/1 and 6/3 high tides as well as the 6/9 through 6/18 spring tides. (See Figure 10).

Predictions of the marsh water table elevation were made for distances of up to 48 meters from the creekbank. Very little errors were calculated with marsh widths extending from 125 m to 475 m. However, as the marsh width was decreased to under 125 meters, deviations developed in the predictions. These deviations might be attributed to the fact that, in narrower marshes, the water table at a given distance from one creek "feels" the effect of the creek on the other side of the marsh plane. In a very wide marsh, defined in the case of Piermont as over 125 m in width, the opposite creek was too far away to influence the predictions at the distances studied. Figure 5, for example, shows that with L=42m, the prediction made at 18 meters carried an error of 6 cm. To explain this deviation, we need to consider that with L=42m, the 18 meter prediction is "feeling" the effect of also being 24 meter from the creek on the other side of the marsh. Figure 8 illustrates graphically this concept.

The model proved to be only moderately sensitive to changes in the transmissivity of the substrate, and more so in the creekbank than further in towards the marsh interior. This is because higher water table gradients in the creekbank cause there to be more horizontal flow towards the creek in this area. Further inland, where horizontal flow becomes negligible, the effect of the transmissivity on the predictions is only minor. It took a ten-fold increase in the transmissivity to generate a 5-centimeter error in the 6-meter prediction. Interestingly, no errors in excess of 1 cm were generated when the transmissivity was diminished by a factor of 10 from its best-fit value.

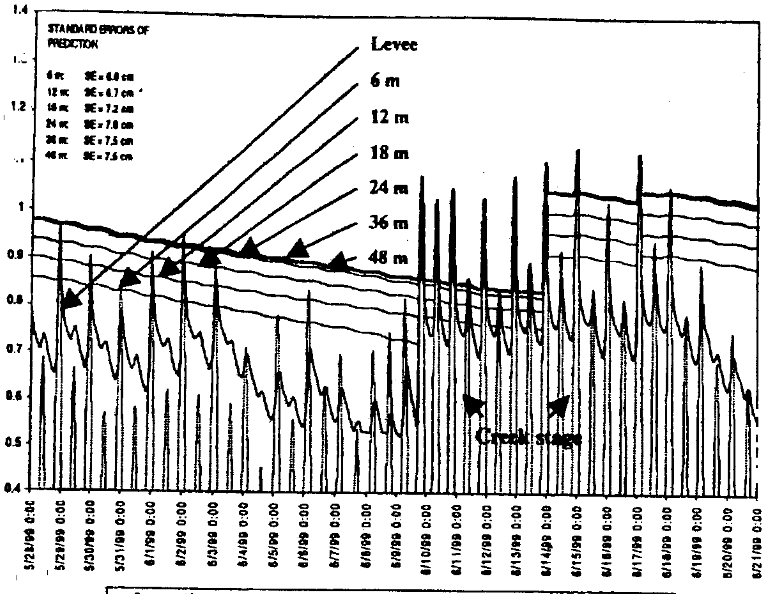

Figure 9: By increasing the marsh surface elevation only 7 cm, the marsh is not inundated by the 6/9 through 6/12 high tides

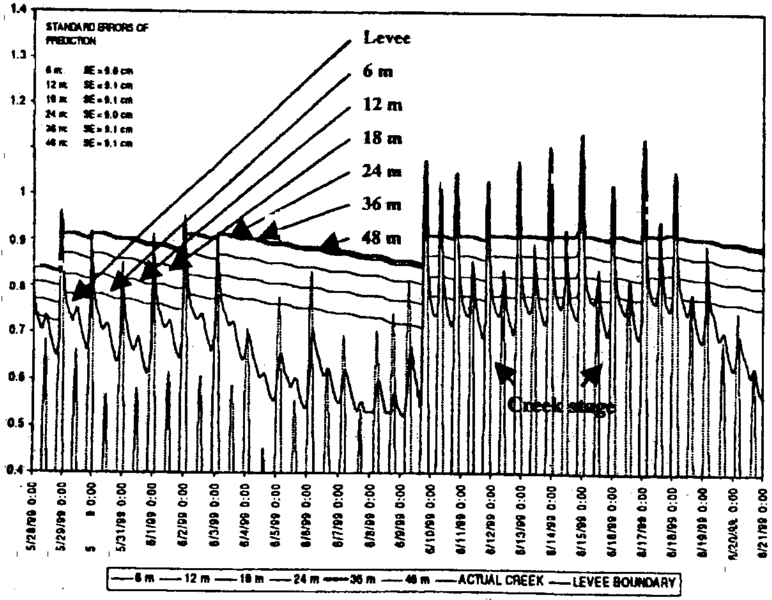

Figure 10: By decreasing the marsh surface by 13 cm, the marsh is inundated as early as 5/28

Of all the parameters modeled, the model was least sensitive to changes in the effective porosity of the soil. However, as might be expected, the deviations calculated were similar across the entire marsh due to the fact that evapotranspiration and precipitation occur uniformly across the surface. Slightly larger deviations were noted in the predictions made in the creekbank region due to the fact that, in addition to the meteorological advection across the surface, there is horizontal flow towards the creek also taking place in this area. No deviation, however, ever exceeded about 2.6 centimeters.

6 Conclusions

This investigation underlines first and foremost the importance of the relationship between the marsh surface elevation and local tidal data in the hydrology of the tidal marsh. Even small increases in the elevation of the tidal marsh with respect to local tidal data generate very different hydrologic patterns across the marsh, from creekbank to interior. Small differences in the depth and duration of flooding can have a significant effect on the rate of accumulation and allocation of nutrients and biomass in different wetland plants [12]. Periodic wetting and drying also modulates gas emissions and air entry ([13] &[14]) into tidal marsh sediments, and primary productivity *vis-à-vis* the control of substrate sulfide concentrations [15], redox potential [16] and creekbank porewater chemistry [17]. While tidal marsh vegetation zonation is determined by a combination of factors [18], a positive correlation between the local, mean tidal range (MTR) and the elevational growth range of *Spartina alterniflora* has been shown consistently in the literature [19]. A marsh's pulsing hydroperiod also determines its habitat value by controlling access to its surface by natant marine life (nekton) [20] and the higher trophic species that feed on them.
For restored marshes to function properly, an ecologically appropriate hydroperiod needs to be re-established. To do this, practitioners need to monitor the tide adequately on site. It is also important that the project have well defined objectives in terms of the final hydroperiod desired. Hydrologic monitoring in a nearby and ecologically functioning tidal marsh is the best way to accomplish this.

Secondly, the marsh width determines the proportion of the marsh that will "feel and act" like a creekbank. When a span of marsh is narrow enough, the sloping water tables under the creekbanks on either side will converge, resulting in a lower overall watertable across the span. The sensitivity analysis presented above suggests that small islands or oxbows, for example, are destined to have lower water tables with respect to the average marsh surface elevation than would be found over wider expanses of marsh. This conclusion is especially significant along the north eastern coast of the United States given evidence that *Phragmites australis* is most likely to colonize tidal marshes along well drained features like creekbanks ([21] & [22]). It is interesting to note that greenhouse studies have also found strong correlation between the success of *Phragmites* and the frequency and extent of flooding [23].

Finally, this analysis shows that the transmissivity and porosity exert the least control over the marsh hydrology of the parameters tested. Closer to the creekbank, the sensitivity to changes in the transmissivity was greatest. This is an indication of horizontal flow toward the creek in this region. Modeled changes to the substrate porosity caused similar deviations across the marsh surface due to uniform evapotranspiration and precipitation rates. Deviations are slightly higher in the creekbank due to the additional loss of water via horizontal creekward drainage there.

There is no recipe for restoration that will work at all sites. The success of tidal marsh restoration efforts depends heavily on the extent to which the designer understands the site and the materials being utilized during construction. Projects need well-defined objectives and attention paid to detail. Site morphology, substrate transmissivity, and porosity all have the potential to make or break a project, and should be therefore be considered carefully in design development.

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