Nueces Delta Ecological Modeling for Nueces River and Tributaries Texas

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Introduction

Coastal marshes are important ecosystems that provide many benefits to human health and well-being including: protecting the inland areas from storm surge, storing water, removing nutrients that flow in from watersheds, and providing nursery habitat for key commercial and recreational fisheries. Yet, marshes are under extreme pressure from development and 50% of the marshes nationwide have disappeared since the founding of the United States.

The Texas coast is flat, hot, and windy; which makes coastal marshes very susceptible to effects of climate change and water resource development. Climate change can have three effects: sea-level rise, water cycle alterations, and temperature alterations. The main effects will be to drown marshes during rising water levels or dry them out as evapotranspiration rates increase during droughts. Water resource development has decreased water delivery to marshes in the Nueces Delta by 45% over the last 40 years, which has led to marsh degradation (Ward et al. 2002).

There is a need to understand the dynamics and the interactive roles of climate and water cycle changes in order to predict changes in salt marshes in the future. This information is critical for resource management (Montagna et al. 2002a). However, few tools exist to forecast effects of human activities on marsh function. Results and models of the ongoing research could be extended to coastal estuaries in other regions of the world.

Marshlands

The main goal of this project is to develop a forecasting system to allow us to determine effects of human activities on marsh structure and function, in particular vegetation. One of the problems facing us in the Nueces Delta is to determine how much water to divert back into the marsh to increase water levels in order to restore the vegetated wetlands. To solve this problem, the goal of this project is to create good and workable mathematical models for marsh ecosystems for the wetlands at the Nueces River mouth (Figure 1). Then such mathematical models could be modified as needed and applied to marshes in other regions of the country that are susceptible to the negative ecological and environmental impact from construction and water resource development.

Figure 1. Nueces Marsh surrounding the Nueces River entering Nueces Bay. Photo by Paul Montagna July 1997 during high flow conditions.

Connectivity in the Nueces Estuary

Rincon Bayou is located at the junction between Nueces Bay and the Nueces River. This junction is integral in making the connection of nutrient-laden freshwater in the Nueces River with the salt water of Nueces Bay. Under current conditions, where inflow is approximately 1% of historic levels, freshwater inflow from the Nueces River does not reach Nueces Bay often (Irlbeck and Ward 2000). Tidal flooding of saltwater from Nueces Bay enters Rincon Bayou, which is concentrated by evaporation and a reverse estuary forms. A reverse estuary is where salinity increases as you move upstream rather than decreasing, as would occur in a normal estuary. The salinity gradient between the Nueces River and Nueces Bay reverts to a normal pattern (i.e. salinity increases downstream) periodically after large natural inflow events from the Nueces River (Irlbeck and Ward 2000) or when pumping of freshwater into Rincon Bayou occurs (Barajas 2011; Tunnell and Lloyd 2011; Hill *et al.* 2012). A return to a normal pattern of salinity in Rincon Bayou is evidence of lateral mixing within the Nueces Estuary, which has positive effects on the connectivity of aquatic fauna.

Connectivity, with respect to fishes and invertebrates, implies 'the enhanced storage of genetic and energetic pools due to variable migration and dispersal patterns across habitats and ecosystems' (Secor and Rooker 2005). Connectivity within estuaries and between estuaries and marine areas is especially important for mobile marine fauna that utilize different habitats along a salinity gradient in different parts of their life cycles, or utilize tides or other flow as mechanisms for larval dispersal (Riera *et al.* 2000; Gillanders *et al.* 2003; Vasconcelos *et al.* 2010). Techniques such as comparing carbon and nitrogen isotopes of tissues with those of potential food sources (Riera *et al.* 1996; Herzka 2005) and comparing elemental signatures in otoliths of fish found in similar and different habitats (Gillanders 2005) confirm that connectivity within estuaries, and between estuaries and marine waters is important in the life cycles of some mobile aquatic species.

Several aquatic invertebrate and fish species gain connectivity with Rincon Bayou, especially when freshwater inflows are favorable enough to create a positive salinity gradient (Barajas 2011; Kalke 2012). Juvenile brown shrimp (*Farfantepenaeus aztecus*) enter Rincon Bayou in late winter (February March) and usually peak in abundance in April, before migrating back downstream in May and June as sub-adults (Hill and Nicolau 2007; Kalke 2012). The main sources of food for brown shrimp are *Spartina alternaflora* and *S. spartinae* detritus and benthic diatoms and organic matter inputs carried by river flow contribute greatly to the brown shrimp diet while in Rincon Bayou (Riera *et al.* 2000).

White shrimp (*Litopenaeus setiferus*) also utilize Rincon Bayou in juvenile stages of their lives. White shrimp enter Rincon Bayou in late spring and leave at the start of winter. Both brown and white shrimp forage in the top 2 cm of the sediment, and are known to prey on infauna, such as polychaete worms, in addition to having other food sources (Hunter and Feller 1987; Beseres and Feller 2007). Infauna biomass and diversity are strongly correlated with

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temporal changes in salinity in Rincon Bayou (Montagna *et al.* 2002b), which in turn are directly related to freshwater inflows and tidal flushing.

Various other invertebrate and fish species (red drum [*Sciaenops ocellatus*], black drum [*Pogonias cromis*] menhaden [*Brevoortia patronus*] and croaker [*Micropogonias undulatus*], blue crab [*Callinectes sapidis*]) are ecologically connected to Rincon Bayou, however the link to freshwater inflow is less direct. Red and black drum feed on shrimp and other invertebrates, and can get temporarily isolated in shallow pools in Rincon Bayou if the flow into Rincon Bayou decreases to the extent that the water is not deep enough to easily swim. High blue crab abundances often coincide with low salinities in Rincon Bayou, however this is not always consistent (Hill and Nicolau 2007).

The flow required for ecological connectivity in Rincon Bayou does not occur often enough from existing freshwater flooding events because of the high extraction of water for municipal and agricultural uses. The artificial pumping of water from the Nueces River into Rincon Bayou at more frequent intervals (nine times from May 2009 to August 2012) has decreased salinities in mid-Rincon Bayou (station NUDE02) and therefore shows the potential to increase ecological connectivity in the area. However, the effects of the inflows on salinity are much shorter than natural flooding events and the flows are largely restricted to existing channels. Overbanking of the existing channels both dilutes salts in the surface sediments of surrounding areas, making it more suitable for marsh plants to grow, and washes detritus into the channels, which provides food for brown shrimp. It is inconclusive that there is enough flow from these pumping events to increase the amount of connectivity for species that inhabit Rincon Bayou for part of their life cycles. However, it is assumed that an increase in pumped and 'natural' freshwater inflows would increase the amount of food available and accessibility into and out of Rincon Bayou, thereby increasing the habitat available and connectivity in the system for mobile aquatic species.

Marsh Plant Zonation

Salt marshes are characterized by physical gradients including pore water salinity, frequency of inundation, both from freshwater pulses and tidal variation, and nutrient availability. Zonation of plants in the marsh is defined by these gradients (Chapman 1974; Adam 1990; Raffaelli and Hawkins 1996). The high and low areas of the marsh are the extreme points in the physical gradients and are characterized by distinct plant assemblages. The low marsh is characterized by higher tidal energy and is more frequently inundated by tidal flow. Salinities in the low marsh are usually dominated by bay salinities. The high marsh is rarely inundated by bay water and prolonged exposure to dry conditions leads to higher salinities. The mid-marsh, in semi-arid climates, contains plants from both the high and low marsh assemblages (Zedler *et al.* 1999).

The general patterns of zonation have a strong influence on how plants in the Nueces Marsh respond to elevation (Rasser 2009). The cover of plants and physical characteristics of

the Nueces Marsh was identified in a geographic information system and elevation was taken from a lidar digital elevation model (Figure 2). The plants *Borrichia frutescens* and *Salicornia virginica* dominate cover at the lowest elevations around 50 cm above mean sea level. *Spartina alterniflora* dominates cover at higher elevations between 120 -200 cm (Figure 3).
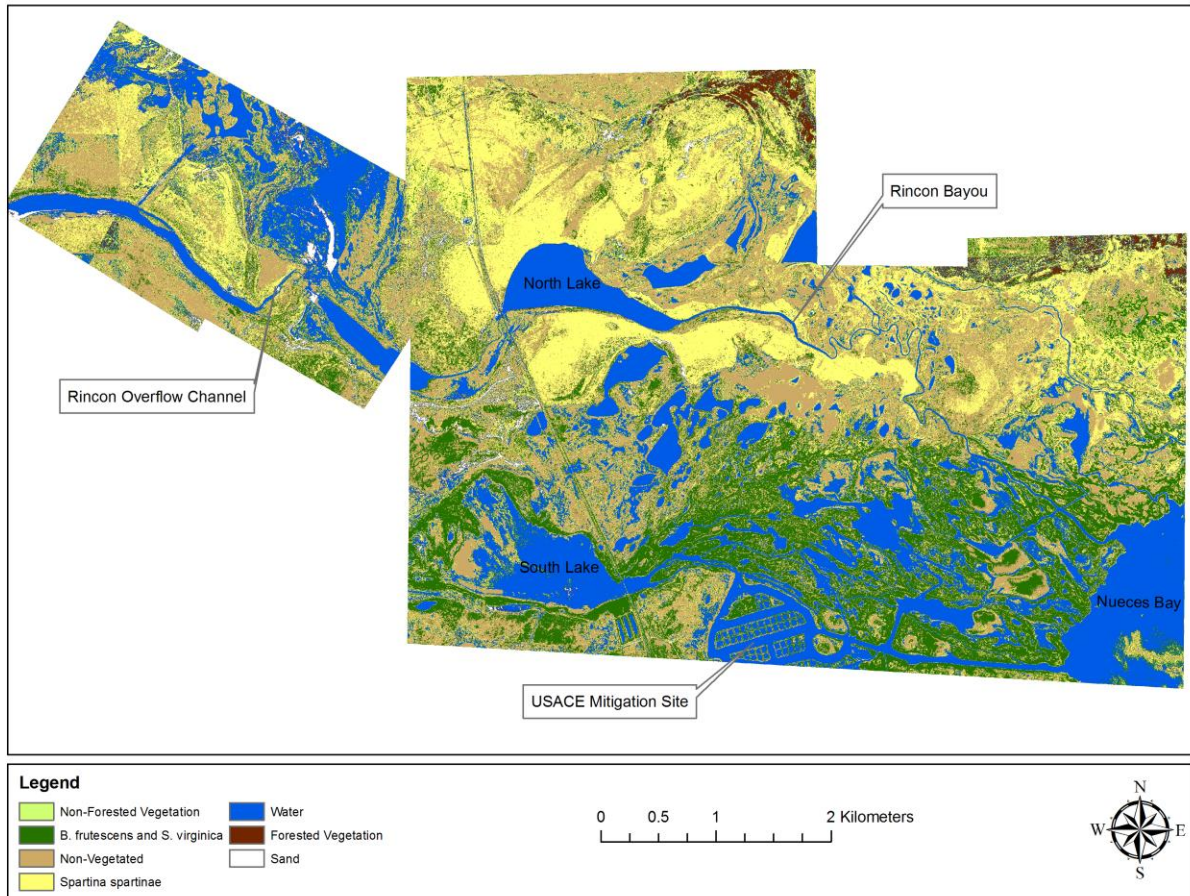
Figure 2. Classified image of the Nueces Marsh based on classification of digital aerial imagery acquired 1 November 2005 (Rasser 2009).
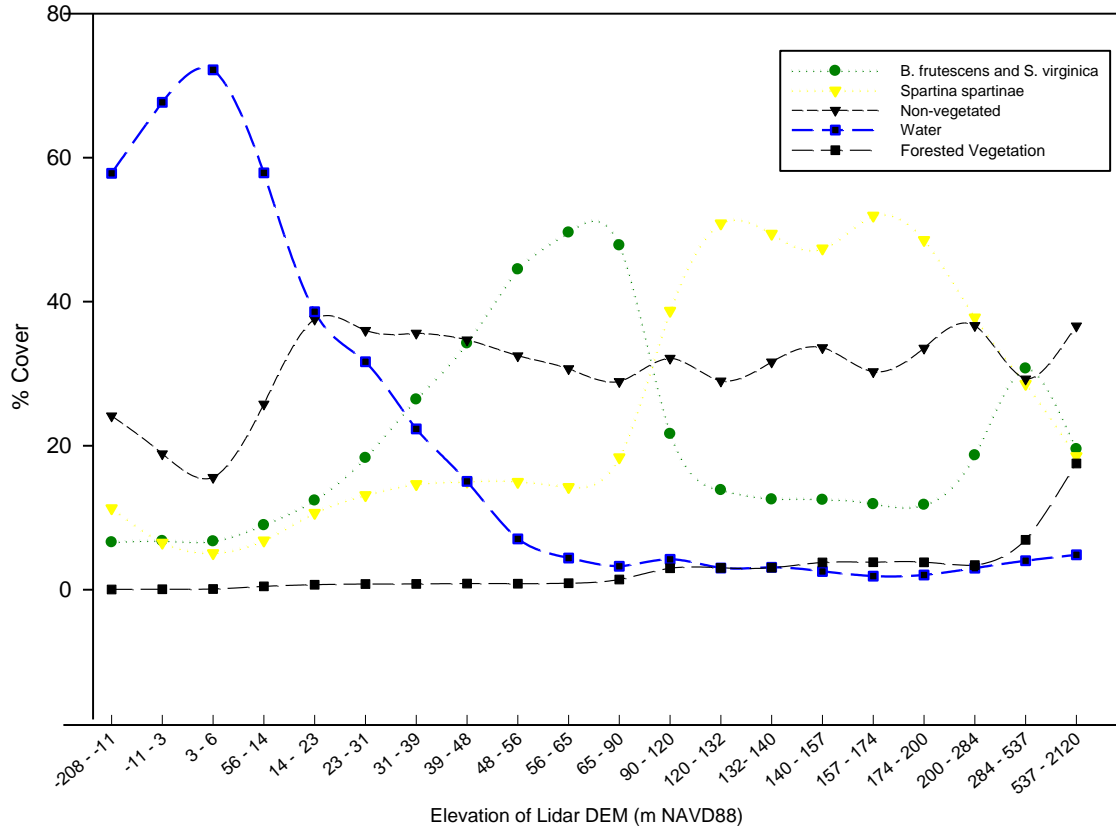
Figure 3. Percent cover of classes from Figure 2 within the Nueces Marsh as a function elevation (Rasser 2009).

Objectives

The motivation of the current study is to determine how changes in freshwater inflow patterns might be used to restore the Nueces Marsh. The marsh has been degraded because of reductions of freshwater inflow following construction of the Choke Canyon Reservoir in 1983 (Ward et al. 2002, Montagna et al. 2009a, Montagna et al. 2009b). So, it is important to determine what effect an increase or decrease of freshwater inflow would have on salt marsh plant growth and development. Growth and development here is defined in units of percent cover of salt marsh surface. The approach is to develop a model for growth of plant cover.

In the model developed for this project, the definition of marsh regions is based on elevation. For this report, water areas are designated by areas of elevation less than 0.0 m. The low marsh is all points between 0.0 m to 1.0 m, the mid marsh from 1.0 m to 2.0 m and the high marsh anything above 2.0 m. While three elevation ranges were used in this study, the number of ranges and the size of the elevation bins can be varied in the model. Elevation was used for grouping plant species in this study. Other grouping schemes could have been used, such as distance from water edge, or salinity tolerance.

Methods

Field studies have been ongoing in the Nueces Marsh since 1994 (Ward et al. 2002, Montagna et al. 2002b, Alexander and Dunton 2002), so there is a large amount of spatial and temporal data. The original purpose of the data collection was to determine the freshwater inflow needs of the marsh in the context of marsh restoration. Recent projects have focused on synthesizing the data (Montagna et al. 2009b).

The vegetation data set includes plant species, elevation distributions, percent cover, growth rates, and biomass (Rasser 2009, Alexander and Dunton 2002). This data set is available at www.ccbay.tamucc.edu (Montagna et al. 2012). The physical data set includes water flows and levels obtained from flow USGS flow gauges and a digital elevation model (DEM) obtained from James Gibeaut of the Harte Research Institute. Largely this data is acquired from cells, that is, specific locations on the surface (space) at specific moments in time.

The data set is ideal for creating a forecast system on how the marsh might change with changes in climate or water resource development. This forecast system is the new research direction that this project will enable.

Functional Groupings, Growth Rates, and Climate

The model developed for this project can be tailored to represent individual species or groups of species based on any group definition. Following a previous study in the Nueces Delta, plants were divided functionally into two groupings: 1) clonal stress tolerant (CST) plants, and 2) clonal dominants (CD) (Forbes and Dunton 2006). Clonal stress tolerant plants are small, slow-growing plants including *Batis maritima, Distichlis spicata, Monanthcloe littoralis,* and *Salicornia virginica.* The clonal dominant plants are taller, faster-growing species, which include *Borrichia frutescens* and *Spartina alterniflora* (Grime 1979; Boutin and Keddy 1993). Facultative annuals, which do not spread clonally, were not included in this study, but with suitable growth rate estimates, could be easily included.

Growth rates for the two functional groupings for use in the model were determined from long-term observations of the marsh plant cover over three distinct climatological periods characterized by the average number of freshwater flooding events in a year during the period from 1996 to 2006 (Figure 4) (Forbes and Dunton 2006). Growth rates were estimated from linear trends (Forbes and Dunton 2006) in each of the three marsh zones (

Table 1).

The graph denoting the number of events passing the flooding threshold shows events where the Nueces River discharge was >= 14.2 cubic meters per second for two or more days (Figure 4). This rate was determined to be the rate that will cause flow into the delta. (Bureau of Reclamation (BOR) 2000). This rate was revised down from 59.5 cm when the Nueces Overflow Channel was built.
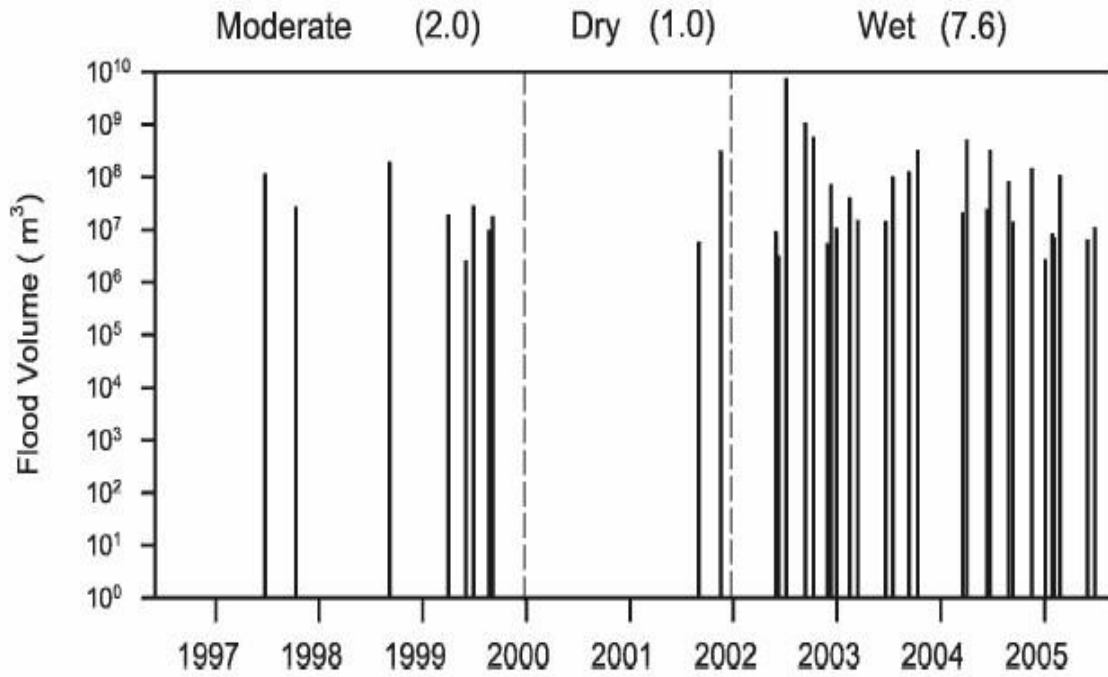
Figure 4. Nueces River flood volumes where mean daily discharge exceeded flood threshold for two or more days. Annual flood frequencies within each climate period are shown in parentheses. From (Forbes and Dunton 2006).

Table 1 - Growth rates for drought, moderate and wet periods for clonal dominants (CD) and clonal stress tolerant plants (CST) for the low, mid, and high marsh zones. Rates are percent change in coverage per year.

Climate Period	Plant Group	Growth Rate (%/y)		
		Marsh Zone		
		High	Mid	Low
Drought	CD	-0.24	-0.18	-0.36
	CST	-0.83	0.01	-0.25
Moderate	CD	0.01	0.01	-0.10
	CST	0.01	-0.07	0.08
Wet	CD	1.75	-0.50	1.40
	CST	-0.20	1.86	1.29

Modeling Changes in Marsh Plant Coverage

The change over time in the population **X** for species **s** (X_S), for a particular area that has a carrying capacity of **C** is modeled with:

$$\frac{\partial X_s}{\partial t} = r_s X_s * \left(1 - \sum_s^N \frac{X_s}{C_s}\right) + \varepsilon_s \nabla^2 \left(\frac{X_s}{C_s}\right)$$

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Where **N** is the number of species, **r** is the growth rate, and **ε** is the diffusion rate. In our system, we model the Marsh as a regular grid of areas, with the highest resolution being 1 square meter areas, since that is the resolution of our elevation map and the plant coverage observations. In theory, ∂t should be very small, but we use 1 day as noticeable changes in plant coverage take many days, and the observations are 90 days apart. The above equation models individuals, but here we use it to model clonal expansion, so we consider instead percent of area covered by a species. We therefore set C_s to 100, which allows X_s to represent the percentage of area covered. The diffusion rate, ε_s, controls the rate of expansion between grid cells and diffusion happens when there are differences (pressure) in populations between neighboring cells. If the percent coverage gets above 100, then the model forces the change to go negative. This is why ∂t, needs to be small, so that you don't get the populations to go above 100 by very much.

In reality, the growth rate of a species, r_s, changes over time and is affected by many factors. Our implementation allows r_s to be a function that can vary over whatever we want: t, grid location, species, salinity, weather, precipitation, water flow, etc. For the results presented here, masks are used to specify which group a grid belongs to: high marsh, mid marsh, or low marsh. Instead of using just elevation, the masks can also be created interactively and any number of groups can be used. To determine the second derivative, $\nabla^2 \left(\frac{X_s}{C_s} \right)$, we use 2nd order central difference in each grid direction (i and j).

The Nueces Marsh covers an area roughly 14 km × 10 km (Figure 5). At 1 meter resolution, which creates a map that has 10,018 rows and 14,451 columns yielding a total of 144,770,118 cells. Elevation data is used to determine the land-water-marsh group, where water is 0 m and below, low marsh is 0 - 1 m, mid marsh is 1 - 2 m, and high marsh is 2 m and above. Using this scheme, 7,093,931 of the cells are labeled as water and 99,676,278 cells are labeled as marsh land (30,849,641 cells as low marsh, 22,160,762 cells as mid marsh, and 46,665,875 cells as high marsh). The remaining 37,999,909 cells are outside the marsh area. The grid is aligned with longitude and latitude lines, but the Nueces Marsh is not, giving rise to the extra cells.
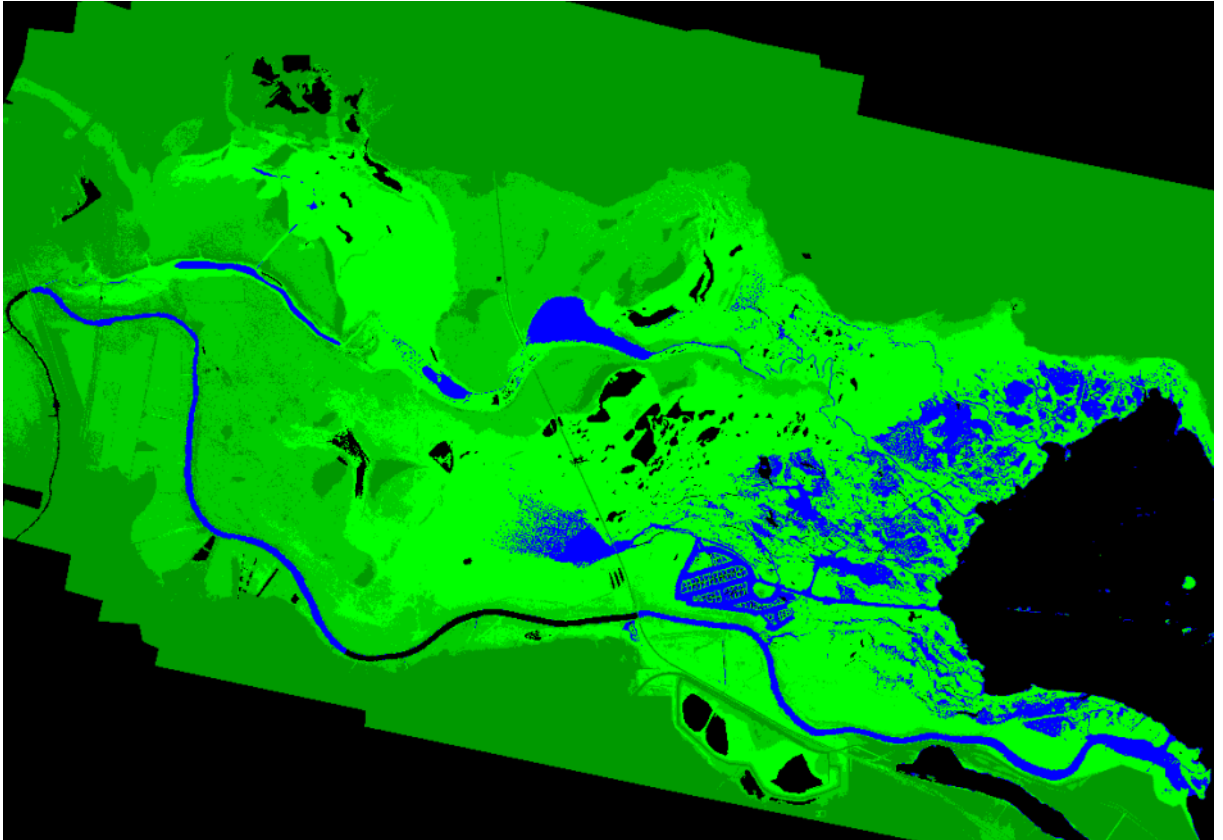
Figure 5. Nueces Marsh areas: blue = water, light green = lower marsh, medium green = middle marsh, dark green = high marsh, black – non marsh areas, mainly open water (such as ponds and Nueces Bay).

Results

Model Behavior

The model behavior for two different species groups X-species and Y-species was investigated in a rectangle area that is 3x4 unit squares of marshland with arbitrary initial conditions and arbitrary carrying capacity for each area and species. The dynamics of the populations of species X (Figure 6A) and species Y (Figure 6B) exhibit those of a so-called weakly coupled system of parabolic partial differential (difference) equations with Dirichlet boundary conditions (Bandle and Levine 1989).
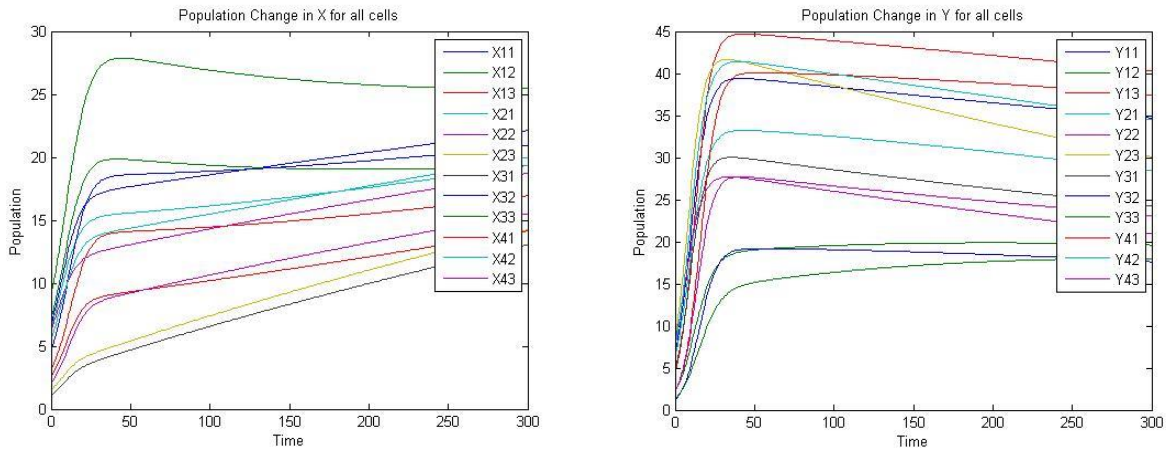
Figure 6. Population change in 12 cells from a 3 x 4 spatial matrix. A) Species X and B) Species Y.

It has been proven that such systems have a unique solution that is asymptotically stable if diffusion coefficients and other parameters of the system are satisfied with some conditions (Leiva and Sequera 2003, Ramsey and Schager 2002). The system can be extended to the 5 to 7 species of marshland vegetation that exist in the Nueces system by simply creating a system of 5 to 7 weakly connected differential equations with given boundary conditions. The simulations demonstrate that populations of two species have asymptotic stability and that diversity of species is preserved at all areas of marshlands under consideration in these models (Figure 6). Therefore, for two species: the system of partial differential equations with N=2, nonzero, and smooth carrying capacities functions $L_i(x,y)$, i=1,2 has unique asymptotically stable solution.

Model Results

The model predicts mostly reductions in plant cover for various initial plant coverage conditions (Figure 7). In both drought and moderate conditions (as defined in Table 1), the model as currently configured predicts a decline in plant coverage. Marsh plant coverage increase in area only during the wet conditions when there is space available (Figure 7). In this simulation, both groups of plants were given equal coverage in all areas as the initial starting

condition. Thus for areas where a group doesn't have an advantage we see a decline that is more rapid than the increase in a group that does have an advantage in an area. It takes longer than 3 months for the faster growing plants to dominate, thus we see overall declines if we start with a lot of coverage.   If the initial condition is 100% coverage for one plant group then there is no room for plants to grow and fill more space. It is not until there is at least about 20% space vacant that plants will grow and fill the remaining space.
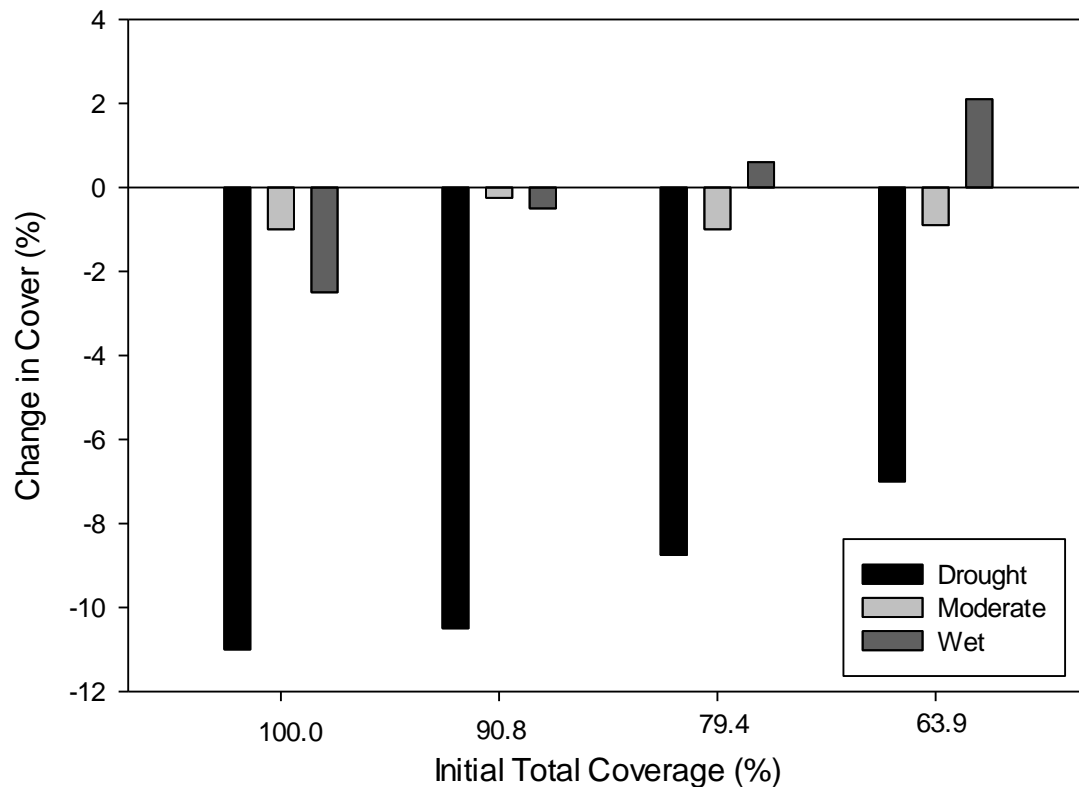
Figure 7. Change in percent coverage based on various initial coverage conditions. Run duration was 3-months, and climate is defined in Table 1.

The modeling experiment was run for a 10-year period nine times: three climate periods times three initial coverage conditions (Figure 8). The three climate conditions were dry, moderate, and wet as defined in Table 1. The three initial starting plant coverage conditions were 2%, 50%, and 100% (Figure 8, solid lines, thick lines, and dotted lines respectively). It was assumed that the initial conditions contained equal amounts of each functional group, thus two species starting at 25% cover (the thick lines) have a total coverage of 50%. The marsh plants consistently approach a steady state of maximum coverage during wet periods for all starting

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conditions. Coverage decreases during moderate conditions and more dramatically during drought conditions.
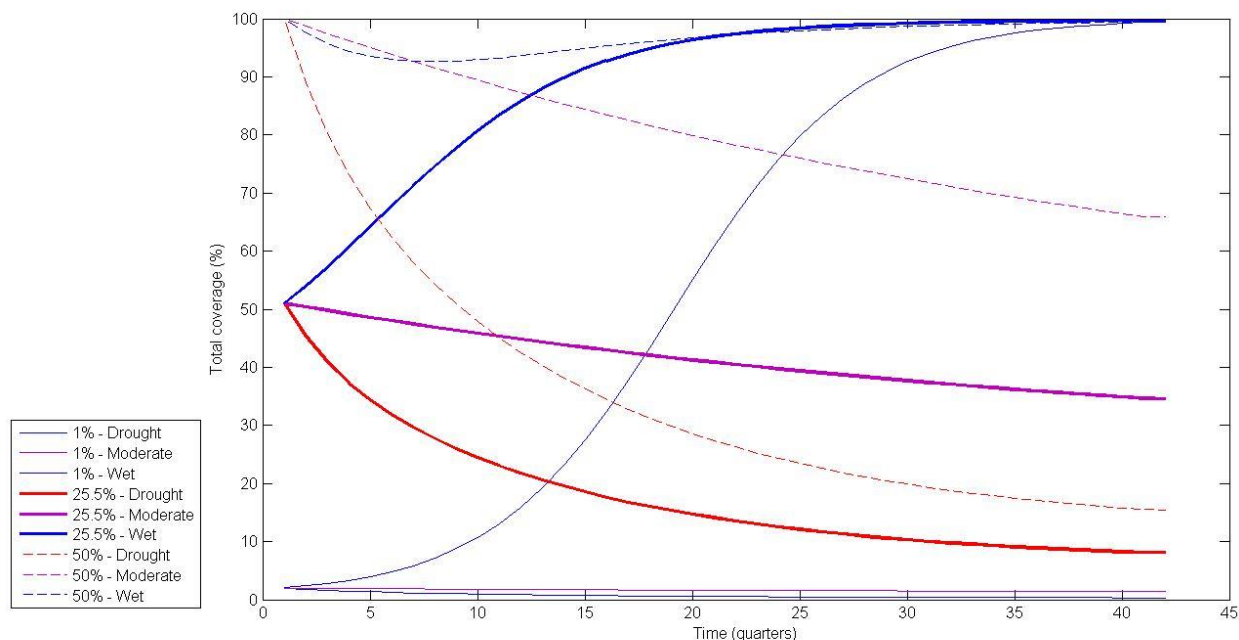
Figure 8. Modeled marsh coverage over 10-year run starting at 2%, 51%, and 100% initial coverage.

The simulation of plant cover change over the entire Nueces Marsh was run at 10 m resolution using the two functional groups: clonal stress tolerant (CST) plants and clonal dominant (CD) plants. There was about a 1% difference in outcome between the 10 m and the 100 m resolution, and between 0.1% and 1% difference when running the model at the highest resolution of 1 m. The simulation was run for a 10-year period with daily time steps and on a high-end laptop the simulations took about 5 seconds to run at 100 m resolution, 15 minutes at 10 m resolution, and about a full day at 1 m resolution. Because of the small differences in changes at the different resolutions, but significant time savings at 10 m, the simulations are run at 10 m resolution for reporting here. The simulations were run for three climate regimes: wet, moderate, and dry as defined in Figure 4 and Table 1.
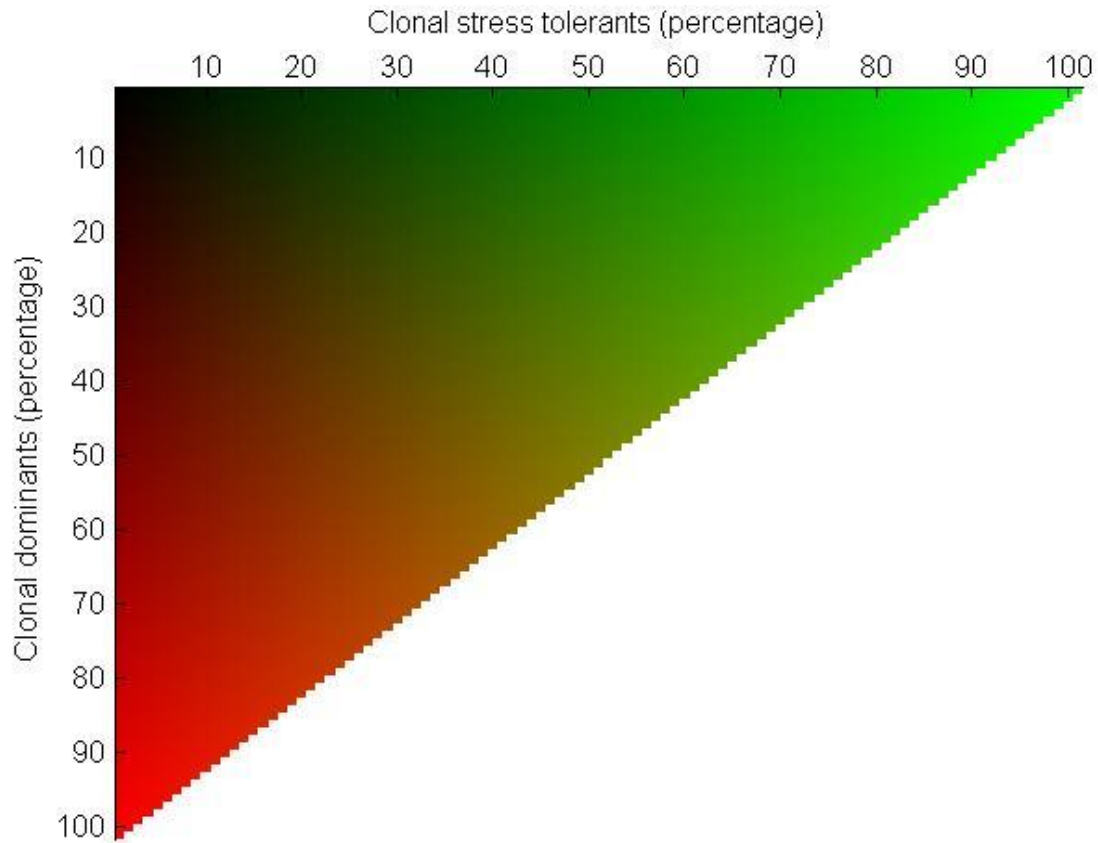
Figure 9. Color scale for for simulations in Figures 10-12 where 100% cover of clonal dominant species is red, and 100% of clonal stress tolerant species is green.

In the simulation, the clonal dominant (CD) plant group is denoted in red and the clonal stress tolerant (CST) plant group is denoted in green. Pure red or green denotes 100% coverage of that functional grouping while shades of yellow/orange/brown denote a mix of members from each functions grouping (Figure 9).
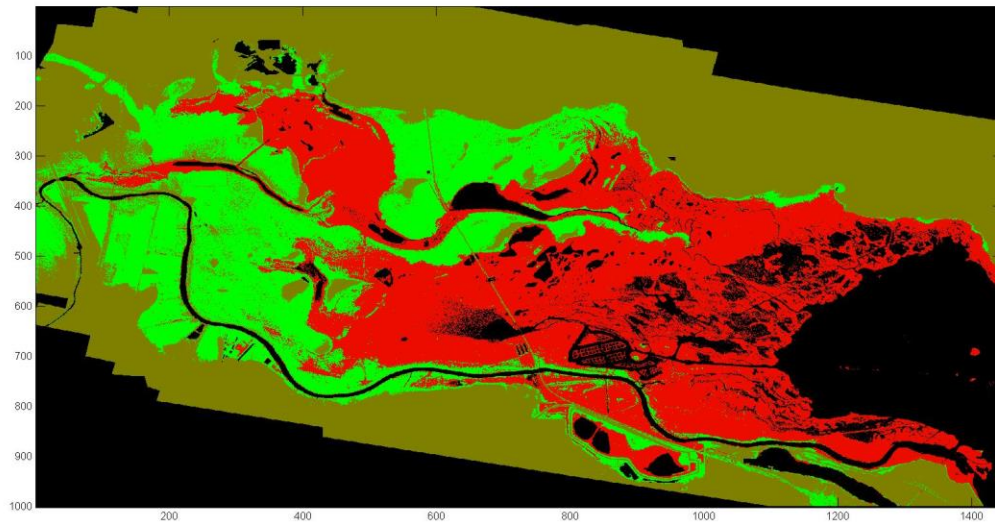
Figure 10. Modeled marsh coverage over 10-year run during wet conditions for two species. Clonal dominant (CD) species is red, and clonal stress tolerant (CST) species is green. At full red, that species is at 100% coverage, cells with both species will be combinations of red and green colors (yellow when equal). See Figure 9 for color scale.

The relative spatial coverage of the two functional groups was different under different climate regimes (Figures 10 – 12 and Table 2). There is more coverage of clonal dominant (CD) species after 10 years of wet conditions (Figure 10) than moderate climate conditions (Figure 11), but virtually no CD during dry conditions (Figure 12). While there is little diversity during dry conditions, moderate climate conditions yield mixtures of the two plant community groups, thus higher plant diversity.

Under dry conditions the area of bare marsh without vegetation is quite large because marsh vegetation coverage decreases by 84.1% (Table 2). Conversely, under wet conditions, nearly all of the marsh grouping categories (i.e., > 98%) is covered with vegetation. The largest losses of marsh cover are for the low and high marsh during dry conditions where vegetation cover loss is 97%.

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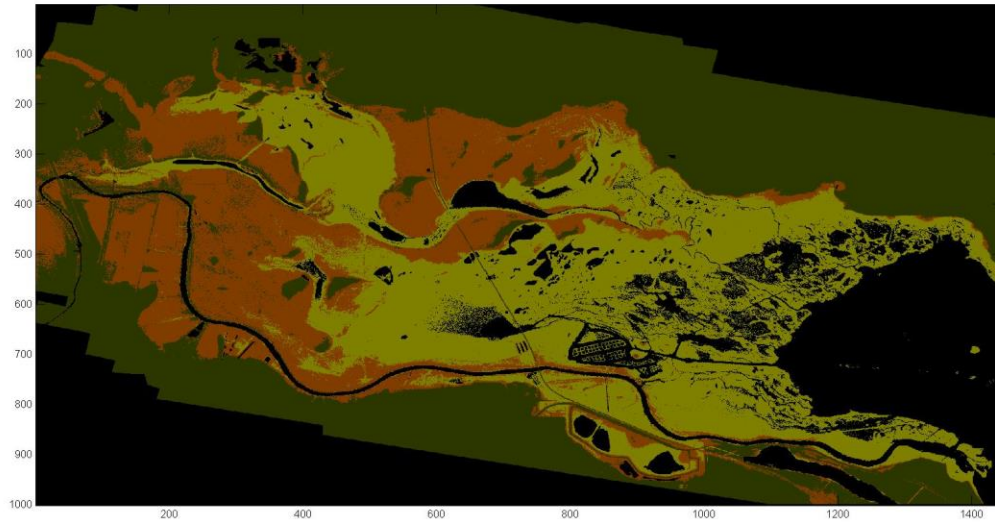
Figure 11. Modeled marsh coverage over 10-year run during moderate conditions for two species. CD species is red, and CST species is green. At full red, that species is at 100% coverage. Yellow is thus a mix of the two species. See Figure 9 for color scale.

Figure 12. Modeled marsh coverage over 10-year run during dry conditions for two species. CD species is red, and CST species is green. At full green, CST species is at 100% coverage. See Figure 9 for color scale.

Table 2. Cover and change in marsh areal extent for three climate regime simulations. Marsh groupings are defined in Figure 5.

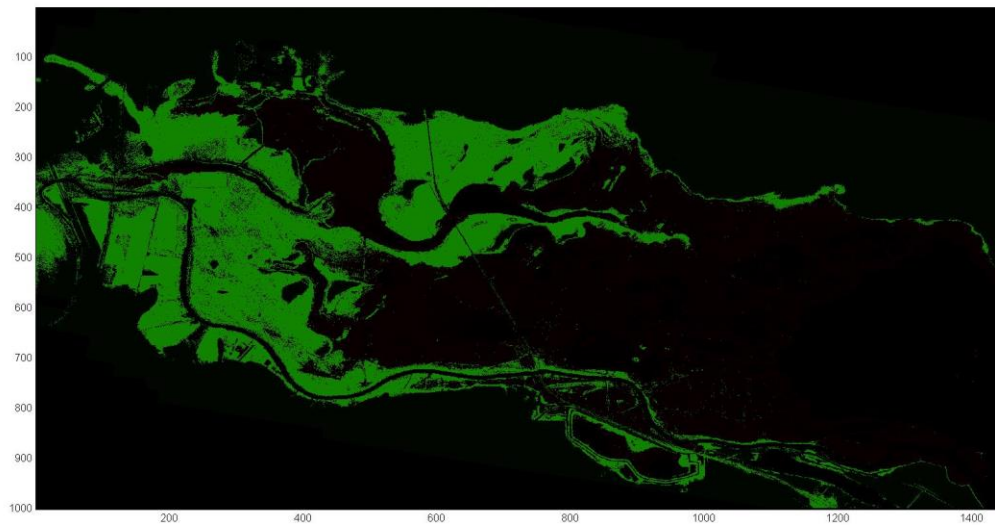| Climate Period	Area (km²)		Cover		Change	
			km²	%	km²	%
Wet	Total Marsh	(99.7)	99.1	99%	-0.4	-0.4
	Low Marsh	(30.9)	30.3	98%	-0.4	-1.4
	Mid Marsh	(22.1)	22.1	100%	0	-0.1
	High Marsh	(46.7)	46.7	100%	0	0
Moderate	Total Marsh	(99.7)	65.7	66%	-33.8	-33.9
	Low Marsh	(30.9)	30.9	100%	0.1	0.4
	Mid Marsh	(22.1)	16.6	75%	-5.5	-25
	High Marsh	(46.7)	18.3	39%	-28.4	-60.9
Dry	Total Marsh	(99.7)	15.5	16%	-84.1	-84.4
	Low Marsh	(30.9)	1	3%	-29.9	-96.8
	Mid Marsh	(22.1)	12.9	58%	-9.1	-41.3
	High Marsh	(46.7)	1.6	3%	-45.1	-96.7

Discussion

Fresh water flow from the Nueces River through Rincon Bayou into the Nueces Marsh is important for two reasons: 1) it creates connectivity between the marsh and Nueces Bay that is critical for growth and development of estuarine dependent animal species, and 2) it promotes growth of marsh plants that require fresh water for growth. These two functions (connectivity and marsh growth) are also synergistic because marshes provide the critical habitat that the estuarine dependent species require. For example, detrital remnants of clonal dominant species *Spartina alternaflora* and *S. spartinae* are an important part of the diet of brown shrimp (*Farfantepenaeus aztecus*), which migrate into and out of the marsh (Riera et al. 2000). Extended wet periods (ten years) allow a greater spatial coverage of clonal dominant species then during moderate or drought conditions (Figures 10 - 12), therefore increasing potential conductivity of brown shrimp. Thus every gallon of fresh water that enters the marsh provides multiple environmental benefits. However, there must be sufficient water flow to flush the marsh from the point where the Nueces River enters Rincon Bayou and Rincon Bayou exits to Nueces Bay (Palmer et al. 2002).

To provide for marsh growth and development, the flow must also be sufficient to overbank the berms along the marsh edge and fill the marsh with fresh water. The results from the current modeling study appear to indicate that there are rarely sufficient flows to promote full connectivity along the complete axis of Rincon Bayou, nor provide for overbanking. This is because only during the wettest periods do we see growth in marsh areal coverage (Figure 6).

One would expect the marsh coverage to expand when there is a transition from dry to wet conditions. But under the current definition of moderate climate (Figure 4, Table 1), there is still not enough water entering the marsh to increase plant coverage in the short term. This condition could become worse as climate change is likely to affect coastal south Texas with higher temperatures in the summer, less frequent rainfall, and longer periods of dry conditions between wetter periods (Twilley et al. 2001).

There model shows decreases in coverage during wet conditions under some initial starting conditions (Figure 7). This could be because some plants, particularly in the lower marsh decrease coverage during wet conditions when salinity declines. Additionally, since the growth rates used for this model are aggregate rates for functional groupings, different species can dominate the growth rate in a grouping depending differences in zonation and climate. These differences within a functional grouping are not reflected in the model. In essence, a decline in one species could be offset by an increase in another within a functional group leading the aggregate rate being near zero.

One would expect that during moderate or wet conditions, the marsh vegetation coverage would expand. However, cannot happen if the marsh is in healthy conditions such as near 100% cover (Figure 7). If the plants have already filled the area, then the growth rates are very small

because cover cannot exceed 100%. There are also decreases in coverage during wet conditions under some starting conditions. This is likely because some plants, particularly in the lower marsh decrease coverage during wet conditions when salinity declines. While the model allows for diffusion from one grid to another, this does not account for competition or the propensity for some plants such as pioneer species to move more aggressively into bare areas.

Further, marsh coverage approaches equilibrium in the long-term only during wet periods (Figure 8). The temporal simulation also shows that several years, depending upon the model's initial conditions, are required for the marsh to return to full coverage. This is seems to contradict shorter-duration empirical measurements (Forbes and Dunton 2006). The current modeled growth rates are based on long-term observations of plant cover. However, actual growth rates are influenced by shorter-term events like inundation and the following recovery. During these times, the growth rates could be different due to the lack of competition and other species-specific factors.

Improvements can be made to the existing marsh development model. The diffusion equations employed in the current study allows for dispersal of plants from one grid to another, however it does not account for competition between plants or the ability of some plants (such as pioneering species) to colonize bare areas rapidly. Adding competition and distinguishing between pioneer and climax species could improve model performance.

Improvements to the model performance may be possible by modeling individual species instead of functional groupings. This would make it possible to see species growth or decline irrespective of functional grouping. Another possible improvement could be to create growth rate functions based on other physical aspects such as finer resolution of elevation and distance from the tidal creek or bay.

Implications

Now that we have a spatial-temporal model that describes vegetation growth in Nueces Marsh, it is apparent that growth in areal extent of the marsh largely depends on water flow and elevation, which in turn depends on the quantity of fresh water in marshes and also drives salinity of marsh waters. This fresh water has two sources: flows down the Nueces River from precipitation in the watershed or pass-through releases from Lake Corpus Christi. The next logical step is to determine whether it is possible to control releases of fresh water in such a way that it produces the most desirable quantity and quality of restoration of marshes. Here we have to deal with the modeling system governed by the partial differential equations, and a stochastic factor, namely, precipitation and storm events. This is essentially a problem of optimal control where we have to define the objectives of the control problem. Here is a short but incomplete list of a few possible objective restoration goals:

- To minimize time of restoration of vegetation cover
- To maximize the area of vegetation cover or habitat

- To promote a species or functional group to enhance ecosystem services
- To conserve fresh water
- To minimize the cost of restoration
- Any combination of all of the above

If we are to deal with the cost problem and/or with multiple restoration goals then we would need to use experts to evaluate importance of goals and objectives, and compare the cost of water for human consumption and for environmental needs.

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