

## **DYNAMIC SPATIAL SIMULATION MODELING OF COASTAL WETLAND HABITAT SUCCESSION**

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### **ABSTRACT**

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To adequately model many ecological systems and management problems, spatial dynamics need to be treated explicitly. A dynamic spatial simulation model composed of interacting cells was designed to project habitat changes as a function of marsh type, hydrology, subsidence, and sediment transport for a generalized coastal wetland area. The model with nine interacting cells was developed to test mathematical formulations and computer algorithms, and to help explain model structure and behavior. Each cell in the model is classified and assigned a habitat parameter 'signature' corresponding to a multidimensional niche space. Large-scale habitat changes ('succession') occur in the model when water and material fluxes between cells produce storages corresponding to the signature of a new habitat. After some time lag to reflect successional changes, the cell parameters are changed to reflect the new habitat signature. In this manner the model can be used to project the impact of natural and man-made changes (i.e., levees, canals) to the system on the spatial distribution and productivity of the various habitats.

### **INTRODUCTION**

The patterns of ecosystem development in time and space are the result of complex interactions of physical and biological forces. Much ecological modeling work has, however, focused on temporal changes with little or no spatial articulation. It is becoming clear that spatial dynamics need to be more explicitly included if ecological models are to be truly useful tools for understanding and managing real ecosystems (Risser et al., 1984).

Many of the decisions made by agencies charged with the management of ecological systems require information on both the spatial and temporal responses of the systems to various management scenarios. In this paper we develop a generalized model to project long-term, spatially articulated habitat changes ('succession'). Our model is designed with reference to particular



TABLE 1

Change in the number of 50-m<sup>2</sup> pixels (picture elements <sup>a</sup>) from 1956 to 1978 for each of the major habitat types in the Terrebonne marsh complex of the Atchafalaya Delta, LA

Habitat type	1956	1978
Uplands	4 736	5 594
Spoil banks and levees	7 009	23 053
Waterways	22 200	43 298
Swamp	65 103	68 625
Fresh marsh	366 087	289 196
Salt marsh	319 309	291 558
Total	1 162 641	1 162 089

<sup>a</sup> Resolution of digitized high-altitude photographs was 50 m × 50 m.

coastal ecosystems, but the problem is general and our approach represents a potentially general solution. Model development was stimulated by studies and management needs in the Louisiana coastal zone where a major new Mississippi River delta lobe (the Atchafalaya delta) is being formed. Vast introductions of water and sediments are leading to major successional shifts in habitats. In such systems we believe that spatial modeling can be a valuable theoretical and management tool. Thus, our objective is to develop a general approach (conceptual and mathematical) to modeling of spatial successional change and to apply this to a generalized coastal and wetland system.

In the Atchafalaya delta/Terrebonne marsh area of Louisiana (Fig. 1), incorporating spatial information is particularly relevant because the region is changing rapidly due to the introduction of large quantities of sediment and water from the Atchafalaya River (Table 1) (Roberts et al., 1980; Baumann and Adams, 1982). One management scenario currently under consideration by the U.S. Corps of Engineers is the extension of a levee along the east bank of the Atchafalaya River to improve navigation and control backwater flooding. This project would, however, shunt most of the sediment-laden river water into the Gulf of Mexico and alter the spatial pattern of water and sediment inputs to the Terrebonne marshes to the east. In order to assess the impact of projects like this, an understanding is needed not only of the total sediment and water input to the marshes, but also of the spatial distribution of these inputs and the projected changes in marsh habitat type and health that result. There is also the need to know how alternatives to the proposed levee extension would affect water, sediment, and habitat distribution. The following model is a new approach that can address these and similar problems.

## THE MODEL

The overall objective of the study is to develop the ability to predict spatial as well as temporal changes in habitat areas (along with information on the relative health of the habitats) as a result of natural processes and various management strategies. To do this we employ a general modeling approach that combines dynamic simulation with spatial articulation. The model is essentially an array of interacting 'cells' that represent fixed areas in a study region. Each cell contains a dynamic, nonlinear simulation model for a specific habitat that incorporates important forcing functions and processes. In our model these are water levels and flow, subsidence, river and tidal inputs, salinity, and sedimentation. Each cell is potentially connected to its neighbors, in this case primarily by exchanges of water. The water carries suspended sediments and dissolved salts, but also has the potential to carry nutrients and biomass between cells in larger, more complex spatial simulations.

To help in developing the model, and to make understanding its structure and behavior easier, we first developed a version consisting of nine interacting cells under hypothetical conditions that could be considered to represent typical cells in a larger model. The remainder of this paper elaborates the design and performance of this model.

## MODEL STRUCTURE

In constructing a model like this, one has to make several important decisions concerning the method used to depict space in the model: the method of numerical integration, which variables to include, and the size of the integration time step. Our decisions in these matters were not the only ones possible but we will try to justify them in light of the purposes of the model.

We chose a square, fixed grid of equally sized cells to represent space, because this arrangement is simple and does not impose any a priori structure on the system. An alternative approach is the finite element method used in hydrodynamic modeling (e.g., Wang et al., 1983) which uses a variably sized mesh connecting nodes. The finite element method is appropriate for systems with fixed hydrologic structure or for time intervals over which the structure is not expected to change. Our concern, however, is with long-term simulations during which the hydrologic structure is expected to change, and thus we felt a square grid that is flexible enough to allow for changing hydrologic structure would be more appropriate. The grid approach is used in modern general global atmospheric circulation models with some success (Kasahara and Washington, 1967; Williams et al., 1974), and

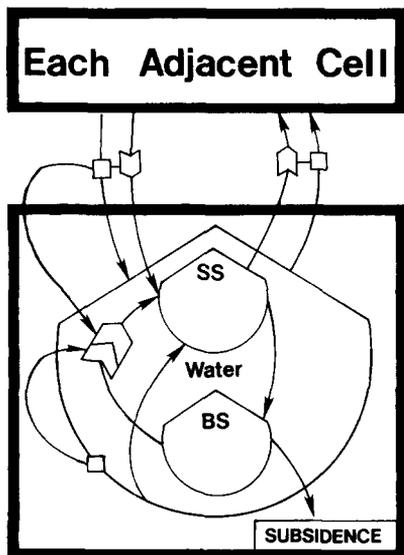


Fig. 2. Storages and flows of water, suspended sediments (SS), and bottom sediments (BS) for a typical cell in the nine-cell preliminary model.

we felt atmosphere circulation modeling was akin to the fluid nature of coastal wetlands, especially when viewed in the long term.

The square grids have exchanges across the four sides. We did not use a hexagonal or triangular grid, or a square one that allowed exchanges across the diagonals, mainly because we wanted the simplest arrangement that would work reasonably well for our purposes and was easy to program.

We used a simple Euler integration technique for the differential equations initially, with the option to apply more elaborate schemes (i.e., Runge–Kutta) should the model prove unstable. For the conditions used, the Euler method proved adequate with a reasonable time step but this may not be true in general.

Each cell in the model is potentially connected to each adjacent cell by the exchange of water and materials. Figure 2 shows diagrammatically the water, suspended sediment (SS), and bottom sediment (BS) components of the model for a typical cell. The volume of water crossing from one cell to another is a function of water storage ( $W$ ) and connectivity ( $K$ ) such that unidirectional water flow across a single boundary is  $KW$ . Water head differential is due mainly to differences in water volumes in equally sized cells rather than elevation gradients because of the flatness of coastal marsh habitats. For this study, the model assumed constant connectivity between all cells (the  $K$  parameter was equal for all boundaries) and there were no

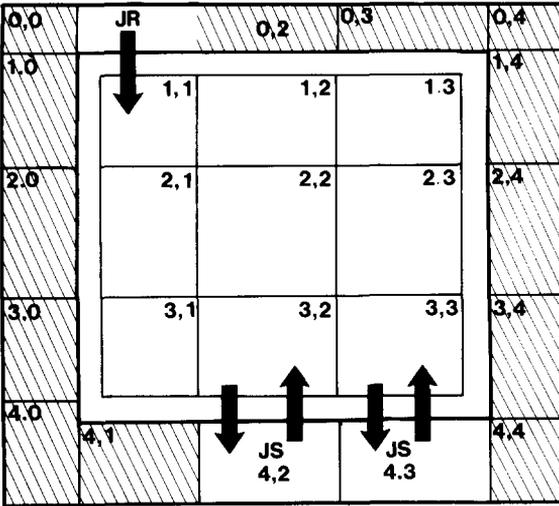


Fig. 3. Initial spatial structure of the nine-cell model. Hatched areas denote levees and areas of reduced exchange. JR, river flow; JS, tidal exchange.

waterways or barriers except at the system boundaries (Fig. 3). This simple arrangement was adequate for the purposes of preliminary investigation of the model’s structure and behavior without significant loss of generality. However, for a more realistic model, we recommend that connectivity be a function of: (a) habitat type, (b) drainage density, (c) waterway orientation, and (d) levee height, and that system boundary conditions be more flexible.

Water exchanges in both directions across all four boundaries are given by:

$$\begin{aligned}
 \frac{dW_{i,j}}{dt} = & (K_{i,j+1,i,j})(W_{i,j+1}) - (K_{i,j,i,j+1})(W_{i,j}) \\
 & + (K_{i,j-1,i,j})(W_{i,j-1}) - (K_{i,j,i,j-1})(W_{i,j}) \\
 & + (K_{i+1,j,i,j})(W_{i+1,j}) - (K_{i,j,i+1,j})(W_{i,j}) \\
 & + (K_{i-1,j,i,j})(W_{i-1,j}) - (K_{i,j,i-1,j})(W_{i,j})
 \end{aligned}
 \tag{1}$$

where  $K_{i,j+1,i,j}$  is the water flow parameter from cell  $i,j+1$  to cell  $i,j$  and  $W_{i,j}$  the volume of water in cell  $i,j$ .

The relationship between the volume of water crossing cell boundaries and the quantity of suspended sediments is illustrated in Fig. 2. Suspended sediments (SS), like water flow, are a function of the water storage differences between cells according to equation (2):

$$\begin{aligned}
\frac{dSS_{i,j}}{dt} = & (J_{i,j+1,i,j})(SS_{i,j+1}) - (J_{i,j,i,j+1})(SS_{i,j}) \\
& + (J_{i,j-1,i,j})(SS_{i,j-1}) - (J_{i,j,i,j-1})(SS_{i,j}) \\
& + (J_{i+1,j,i,j})(SS_{i+1,j}) - (J_{i,j,i+1,j})(SS_{i,j}) \\
& + (J_{i-1,j,i,j})(SS_{i-1,j}) - (J_{i,j,i-1,j})(SS_{i,j}) \\
& - (KSED)(SS_{i,j}) + (TV)(JIN_{ij})(BS_{i,j})
\end{aligned} \tag{2}$$

where TV is the turbulence vector parameter, KSED the sedimentation parameter,  $JIN_{ij}$  the total water flux into cell  $i,j$ ,  $SS_{i,j}$  the concentration of SS in cell  $i,j$ ,  $BS_{i,j}$  the bottom sediments (relative elevation) for cell  $i,j$ , and  $J_{i,j,i,j-1}$  the water flux from cell  $i,j$  to cell  $i,j-1$ .

Suspended sediment flux is a more complex equation than water flow because sediments settle out as a function of water velocity and marsh vegetation (KSED can vary with habitat type), but are also released by strong turbulent mixing of bottom sediments. The increase in suspended sediments due to turbulent mixing was modeled as a proportion of the total volume of water entering the cell. Later modeling efforts should also incorporate wind stress as a dominant force controlling resuspension in open water habitats, but we have not included this factor in the current model.

In the model, the removal of suspended sediments from the water column to bottom sediment storage (BS) is a function of its concentration (SS) and the sedimentation rate (KSED \* SS). The sedimentation parameter (KSED) is dependent upon water depth, habitat type, and vegetation density. However, the nature of this dependency needs further investigation. For this reason, KSED in the nine-cell model was set constant for each marsh type. Bottom sediment level was modeled as:

$$\frac{dBS_{i,j}}{dt} = (KSED)(SS_{i,j}) - (KSUB)(BS_{i,j}) - (TV)(JIN_{ij})(BS_{i,j}) \tag{3}$$

where KSED is the sedimentation coefficient, KSUB the subsidence coefficient, TV the turbulent mixing parameter,  $JIN_{ij}$  the total water flux into cell  $i,j$ ,  $SS_{i,j}$  the suspended sediments in cell  $i,j$ , and  $BS_{i,j}$  the bottom sediments in cell  $i,j$ .

For each cell in the model, it is the balance between net inputs of suspended sediments and outputs due to subsidence that is primarily responsible for the build-up of new land or the development of open water habitats. Subsidence is principally a regional process and was modeled as such. It is generally unaffected by local overburdening because coastal marshes have very small elevation gradients.

TABLE 2

Initial conditions and parameter values used in the nine-cell model of marsh habitat succession

Variable	Value	Description
Water	1000 m <sup>3</sup>	initial conditions for all cells
Salt	0.04–27‰	fresh = 0.04; brackish = 15; salt = 27
SS	2.0 g/m <sup>3</sup>	initial suspended sediments for all cells
BS	500 cm <sup>3</sup>	initial bottom sediments (relative elevation) for all cells
KWATER	0.26	water flow parameter (range: 0.22–0.30)
KMUD	7.28	river sediment input parameter (range: 5.84–8.73)
KSED	0.0225	sedimentation parameter (range: 0.0175–0.03)
KSUB	0.0001	basal subsidence parameter (range: 0.0001–0.0005)
TV	0.002	turbulent mixing parameter
HTYPE	'FRSH'	cells(1,1), (1,2), (1,3)
	'BRAC'	cells(2,1), (2,2), (2,3)
	'SALT'	cells(3,1), (3,2), (3,3)

Although not shown in Fig. 2 (so as not to overly complicate the diagram), the salt concentration in each cell was modeled in a manner analogous to suspended sediments:

$$\begin{aligned} \frac{dSALT_{i,j}}{dt} = & ((J_{i,j+1,i,j})(SALT_{i,j+1}) - (J_{i,j,i,j+1})(SALT_{i,j})) \\ & + (J_{i,j-1,i,j})(SALT_{i,j-1}) - (J_{i,j,i,j-1})(SALT_{i,j}) \\ & + (J_{i+1,j,i,j})(SALT_{i+1,j}) - (J_{i,j,i+1,j})(SALT_{i,j}) \\ & + (J_{i-1,j,i,j})(SALT_{i-1,j}) - (J_{i,j,i-1,j})(SALT_{i,j}) / W_{i,j} \end{aligned} \quad (4)$$

where  $J_{i,j,i,j-1}$  is the water flux from cell  $i,j$  to cell  $i,j-1$ ,  $SALT_{i,j}$  the concentration of salt in cell  $i,j$ , and  $W_{i,j}$  the volume of water in cell  $i,j$ .

Parameter values for the flows of water, salt, and sediments are listed in Table 2. Included are the range of parameter values used in the sensitivity analysis and the initial conditions for each of the nine cells. These are idealized values representing relative proportional differences between state variables found in the coastal marshes of south Louisiana. Real values for water volumes, river discharge, and tidal inputs would have to be incorporated in any specific application of the model. The results of this nine-cell model are used only to test for generality and realistic response rather than quantitative goodness-of-fit to a specific situation.

Temporal-spatial variations were driven by two forcing functions, river and tidal flows (Fig. 3). Iterations were weekly, rather than daily or hourly, to minimize computer costs. River inputs (JR), ranging from 250 to 2900

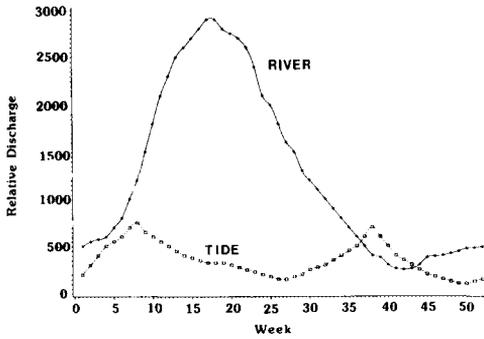


Fig. 4. Relative seasonality of the hydrologic forcing functions in  $\text{m}^3/\text{s}$  for the nine-cell model. River inputs are approximately 8 times tidal inputs.

$\text{m}^3/\text{h}$  with a salinity of zero, enter the simulated marsh at cell(1,1). Tidal influences (JS), ranging from 100 to 600  $\text{m}^3/\text{h}$  with a salinity of 32‰, enter the simulated marsh area at cells(3,2) and (3,3). The relative seasonalities of the two driving forces are illustrated in Fig. 4. River inputs reach a single maximum in the spring, while sea water inputs are bimodal because of the accentuation of spring tides (Denes, 1983).

The values for all the parameters represent relative differences and are not precise in terms of seasonal response. They are meant only to give a perspective of the range of likely parameter settings. Actual temporal-spatial input values of water, sediments, salt, and other variables should be used for site-specific large-scale models. In this model, all other outside connections to the nine-cell model were set to zero representing the impedance caused by high spoil banks and levees.

Habitat succession was modeled as a series of IF-THEN statements. A range of values for a group of variables was used to represent a particular habitat type (Table 3). A subroutine monitors the state variables in each cell, tags those cells with a high probability of being able to change to a new habitat, and checks to see if this 'transitional' state has occurred for a relatively long period of time. The time lag can be adjusted to represent the average transition period for any habitat. In this model, the time lag was set so as not to destabilize the model. That is, if the values for a cell's state variables corresponded with all the representative signature values for a time period greater than the time it took for the model to stabilize with constant inputs (6 months), then the cell switched to a new set of parameters that were more representative of the newly developed habitat type. For example, a brackish marsh can switch to a fresh marsh if river inputs increase or tidal inputs decrease enough to change salinity for more than 6 months. Each habitat has its own set of parameter values and as one cell switches to a new

TABLE 3

Range of values for the state variables that were used as habitat 'signature' values in the habitat switching, IF-THEN statements; cells switched to a new habitat when state variables exceeded the signature range for a 'sufficient' period of time (i.e. at least greater than the time required for the model to stabilize with constant inputs)

Habitat type	State variables	Range
Upland	Water	0–8000 m <sup>3</sup>
	Salt	0–30‰
	Bottom sediments	< 510 cm <sup>3</sup>
Fresh marsh	Water	20–10000 m <sup>3</sup>
	Salt	0–5‰
	Bottom sediments	480–510 cm <sup>3</sup>
Brackish marsh	Water	20–10000 m <sup>3</sup>
	Salt	5–15‰
	Bottom sediments	480–510 cm <sup>3</sup>
Salt marsh	Water	20–10000 m <sup>3</sup>
	Salt	10–30‰
	Bottom sediments	480–510 cm <sup>3</sup>
Open water	Water	< 1000 m <sup>3</sup>
	Salt	0–30‰
	Bottom sediments	< 480 cm <sup>3</sup>

habitat type, it affects all the surrounding cells. The entire area 'evolves' in response to system changes. For this version of the model, salinity was stable for each marsh type. Thus, habitat switching was based on only two variables: water per cell and bottom sediment (relative elevation) for simplification. For larger, more complex, spatial models each habitat should have a large array of signature values capable of affecting habitat switching.

## SIMULATION RESULTS

### *State variables*

The seasonality of relative water volume, salinity, suspended sediments, and elevation (Figs. 5a, 5b, 5c, and 5d, respectively) represent the weekly average of a 10-year simulation using the initial conditions and parameter settings given in Table 1. The seasonality of river and tidal inputs was repeated annually. An average of all ten years of output was used since it well illustrated the long-term mean differences between state variables for each of the three habitats in the nine-cell model. If only the final output had been used, these differences would have been obscured by cells in transition between marsh and open water or marsh and upland (i.e., short-term habitat switching).

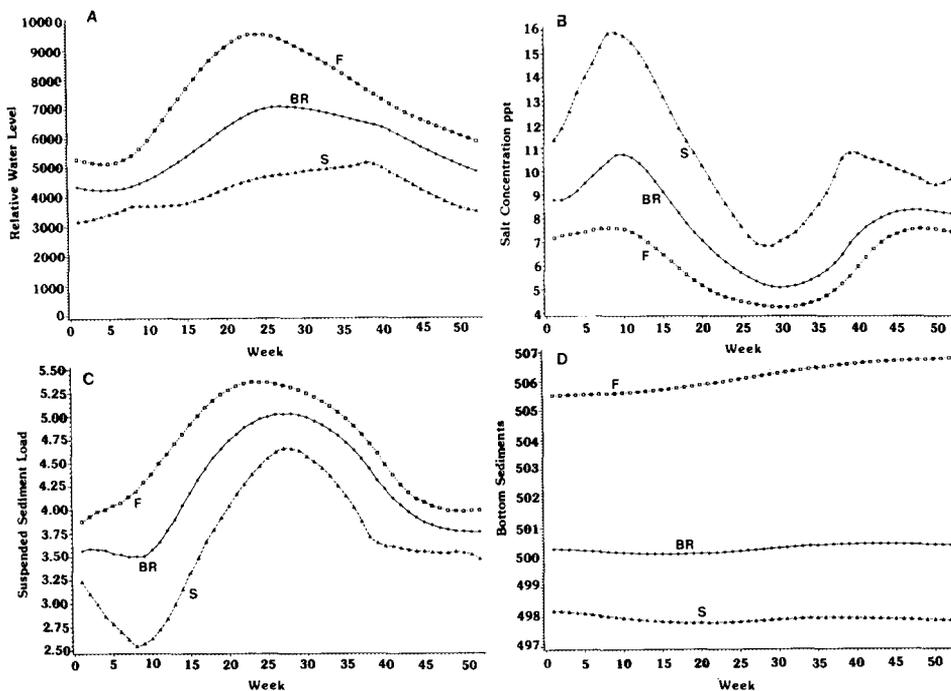


Fig. 5. Simulation results for 1 year starting 1 January, averaged for a 10-year run and partitioned into fresh (F), brackish (BR), and salt (S) marsh habitats: (A) average water volume per cell; (B) average salinity per cell; (C) average suspended sediments per cell; and (D) average bottom sediments per cell.

Relative water volumes (Fig. 5a) for the fresh marsh habitats followed the seasonality of riverine inputs very closely. Salt marsh habitats maintained lower water levels than fresh or brackish marshes and although influenced by riverine inputs, tended to follow the seasonality of tidal inputs. There was approximately a 20% difference in the mean water volume between each of the three marsh types ('FRSH' = 6000, 'BRAC' = 5000, and 'SALT' = 4000). These water volume differences (based upon a hypothetical cell size of 1 km<sup>2</sup>) represent a net water flow from fresh to salt marsh habitats that are driven by head differences of 0.1–0.2 m.

Annual salinity fluctuations for each marsh type varied with the seasonality of river inputs (Fig. 5b). Salinity dropped by approximately 50% in the salt marsh habitats as a result of freshwater inputs, while fresh marsh habitats reached salinities of as much as 7‰ as a result of tidal influences during low river discharge.

The seasonality of the suspended sediment load for each of the habitats was much the same and, as expected, varied in relation to river inputs (Fig. 5c). The amount of suspended sediment entering a habitat had an impact on

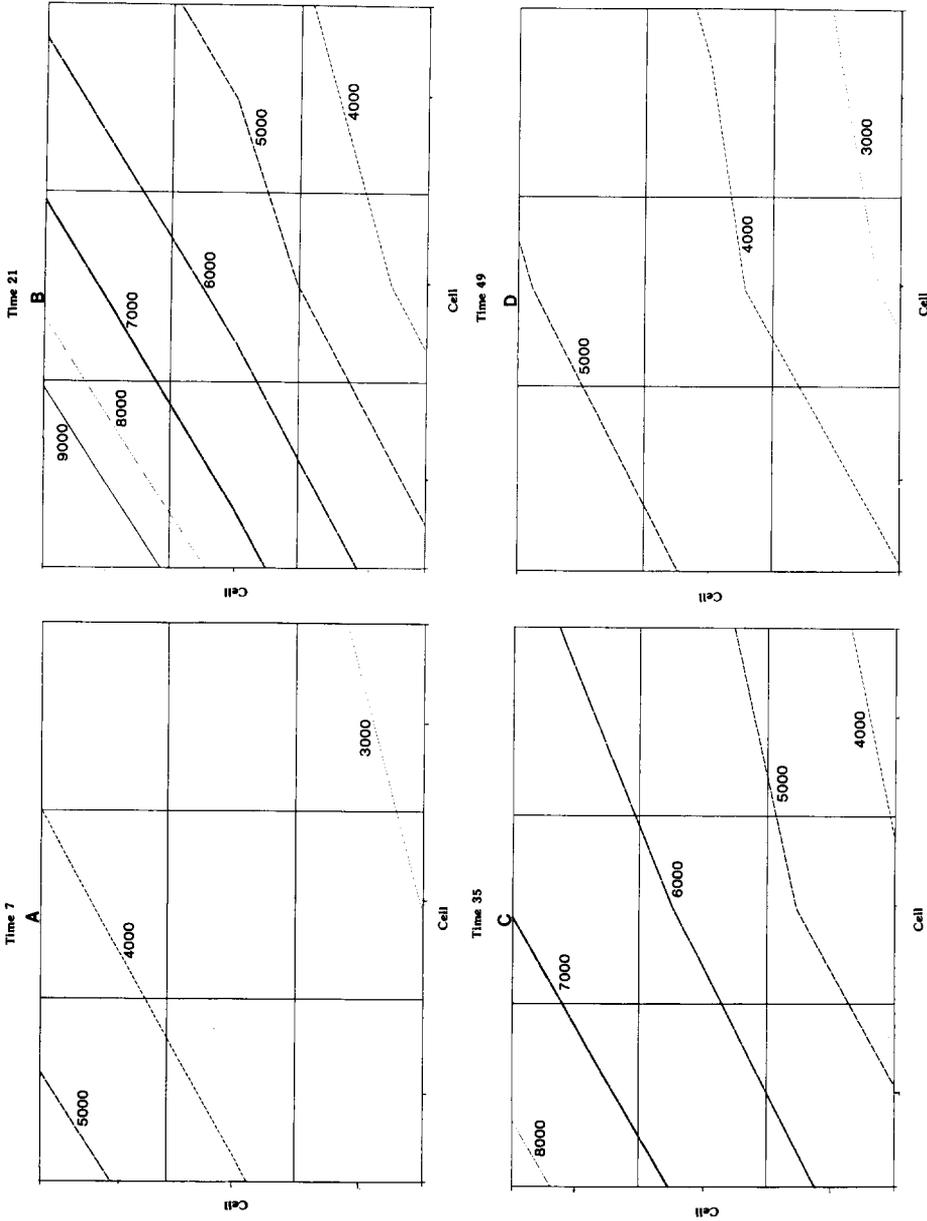


Fig. 6. Spatial distribution of water volumes across the nine-cell model (as illustrated in Fig. 3) are shown as contour lines: (A) 7 weeks (river discharge begins to increase, 700  $m^3/s$ ); (B) 21 weeks (maximum river discharge, 2800  $m^3/s$ ); (C) 35 weeks (decreasing river discharge, 800  $m^3/s$ ); (D) 49 weeks (winter discharge, 400  $m^3/s$ ).

habitat stability, deterioration, or accretion (Fig. 5d). High inputs of water into the fresh marsh cells of the model carried large quantities of sediments that more than compensated for subsidence. Meanwhile, riverine inputs were spread over space, downstream brackish and salt marsh habitats received fewer inputs of fresh water per cell, and less sedimentation occurred. The result was a stable brackish marsh and a deteriorating salt marsh.

The exact spatial response of the model is not shown in Fig. 5. In an attempt to illustrate temporal response, we aggregated cells by habitat type. Plotting isoclines across cell boundaries produces a more detailed spatial picture of model response (Fig. 6). The contour plots in Fig. 6 illustrate how water flows across space. At time = 7 (7 weeks), the difference in the volume of water between cells was small. At 21 weeks, river inputs are at a maximum and large quantities of water flow diagonally from cell(1,1) to cell(3,3). As river inputs abated, the differences between cells decreased and water levels were maintained by tidal inputs.

### *Sensitivity*

The suspended sediment equation (2) and the bottom sediment equation (3) are more sensitive to parameter adjustments than either the water or salt equations. They are affected by water flow variations as well as sedimentation and subsidence dynamics. For this reason, variability of suspended sediments and bottom sediment to plus or minus 10% variations in KWATER, KSED, and KMUD were used to produce a rather simplified sensitivity analysis (Fig. 7). These results indicated that changes in the water-flow parameter (KWATER) between cells had the least impact of the three parameters tested. The total range of variation about the mean KWATER (31%O resulted in only a 3.5% variation about the mean SS (Fig. 7A) and only a 0.4% variation about the mean BS (Fig. 7B).

Varying the sedimentation rate parameter (KSED) not only produced a larger percent of variation in output than KWATER (Fig. 7C), it also altered the general trend for the accumulation of bottom sediments (Fig. 7D). As sedimentation rates decreased with decreasing KSED values, the total storage of bottom sediments at the end of the year was less than at the beginning of the year. If this were to continue year after year, the storage of BS would eventually reach a level that was insufficient to maintain marsh elevation above mean sea level. In other words, low parameter values will result in marsh deterioration and high parameter values will result in marsh stability in the model. A 56% variation about the mean KSED resulted in a 17.8% variation about the mean SS and a 1.8% variation about the mean SED.

The response of SS and BS to variations in the amounts of sediments entering cell(1,1) as a proportion of water inputs (KMUD) was greater than

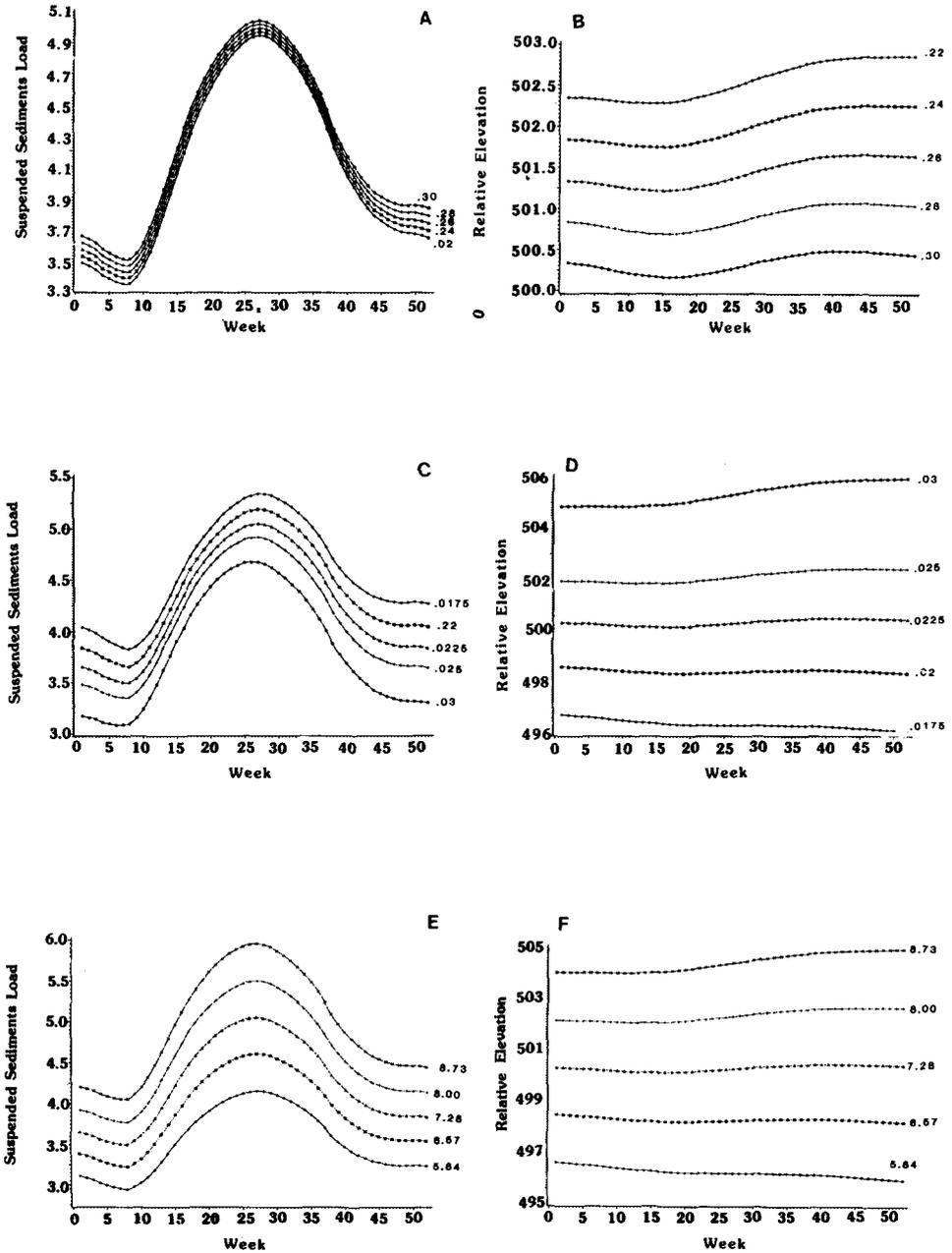


Fig. 7. Sensitivity of suspended sediments (A, C, E) and bottom sediments (B, D, F) in 10% variations in the water flow parameter (A, B), the sedimentation rate parameter (C, D), and the suspended sediment load of river inputs (E, F). Curves represent relative annual changes averaged for all nine cells for a 10-year simulation. Asterisk (\*) value was used to simulate marsh succession.

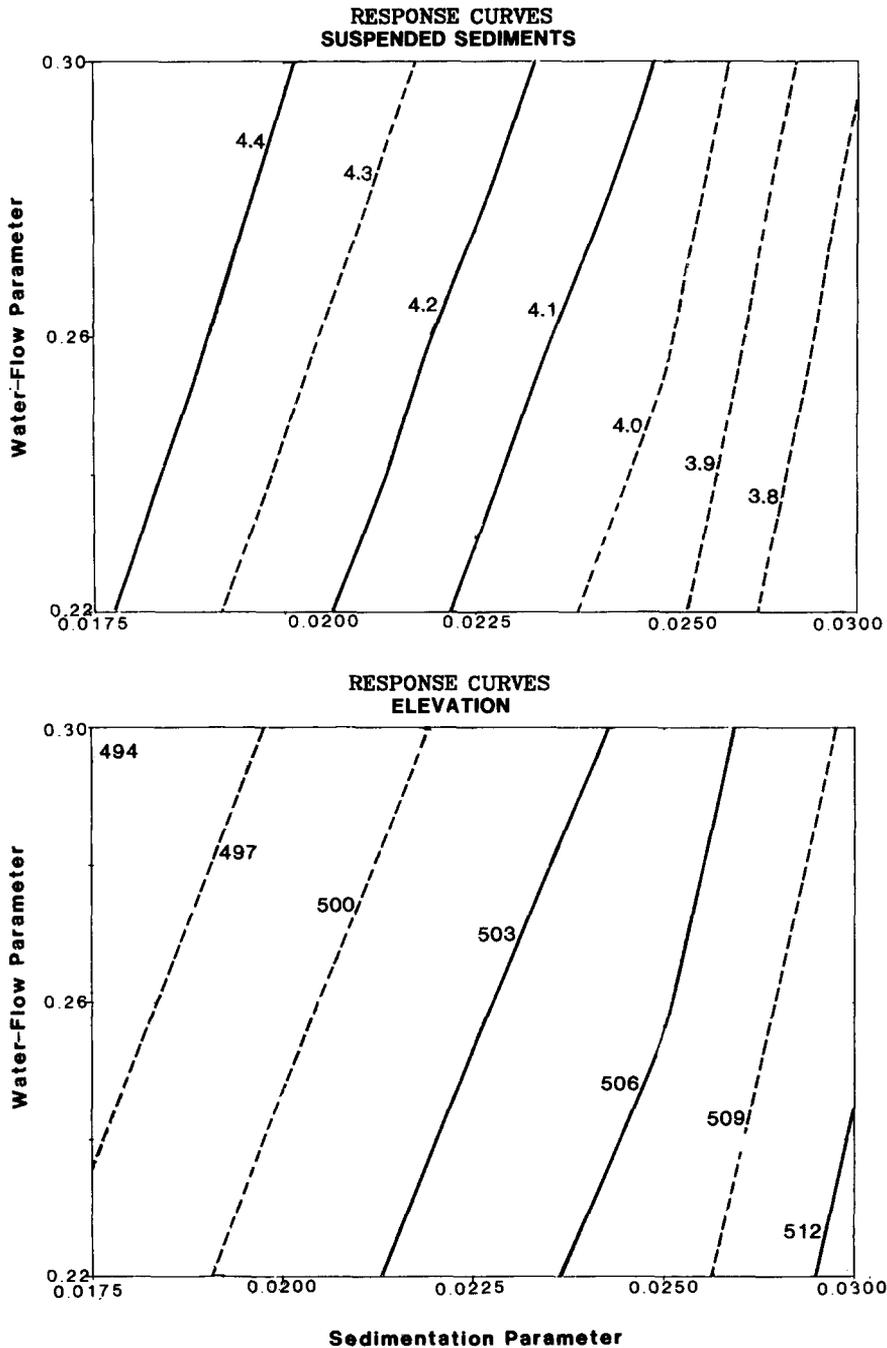


Fig. 8. Response curves for suspended sediments ( $\text{g}/\text{m}^3$ ) (top) and bottom sediment levels ( $\text{cm}^3$ ) (bottom) as a function of 10% variations in both the water flow parameter ( $y$ -axis) and the sedimentation rate parameter ( $x$ -axis).

their response to either KWATER or KSED. A 40% variation about the mean KMUD resulted in a 33.8% variation about the mean SS (Fig. 7E) and a 1.6% variation about the mean SED (Fig. 7F). In terms of marsh accretion or destruction, changes in KMUD and KSED produced very similar responses. The interaction of these two parameters seemed to mimic natural processes, especially the fact that relatively high sedimentation rates cannot compensate for subsidence if total sediment loads are low.

Varying two parameters simultaneously was used to produce a more complete analysis of sensitivity. The responses of bottom sediments and suspended sediments, averaged for all nine cells for years 9 and 10 combined, to 10% variations in the water-flow parameter (KWATER) and 10% variations in the sedimentation parameter (KSED) are shown as contour response curves (Fig. 8). A completely elastic response to these parameter variations would appear as diagonal contours. The slopes shown in Fig. 8 are much steeper than diagonal, however, and tend to increase with decreasing KWATER and increasing KSED.

The data in Fig. 8a also reveal that marsh elevation is: (a) a result of the interaction between water flow (and its suspended sediment load) and sedimentation rates (with a constant subsidence rate), and (b) more sensitive to changes in the sedimentation parameter (KSED) than to the water-flow parameter (KWATER). A KSED increase from 0.026 to 0.029 (a 10% change) when KWATER was equal to 0.22, increased bottom sediments from 509 to 512. A relatively larger percent of increase in KWATER was needed to produce the same degree of marsh elevation change. Bottom sediments increased from 509 to 512 (holding KSED constant at 0.029) when KWATER changed from 0.22 to 0.30 (a 27% change).

Similarly, suspended sediment changes were more sensitive to changes in the sedimentation parameter than to the water-flow parameter (Fig. 8b). An increase in the sedimentation parameter by 7% (0.026 to 0.028) decreased suspended sediments by 3% whereas, a decrease in the water-flow parameter of 27% (0.30 to 0.22) was necessary to produce the same 3% decrease in suspended sediments.

### *Habitat switching*

Using the initial conditions and parameter values in Table 1 and holding river and tidal inputs constant, it was possible to test the habitat switching algorithm and to plot each cell's change to either an upland habitat (with a large channel) or an open-water habitat (Fig. 9). The habitat switching shown in Fig. 9 was based primarily upon threshold values for bottom sediments (BS), water levels, and lag times. The objective of this preliminary model was to test the switching technique, not to test the validity of specific

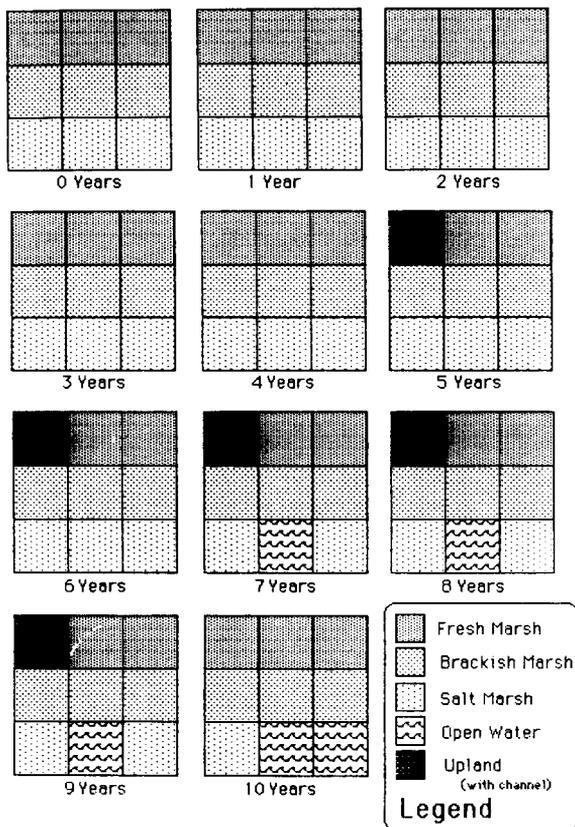


Fig. 9. Marsh habitat changes for each cell in the nine-cell model as a function of water volume and elevation, see text for details. 0 years, initial conditions.

ecological parameter values. Thus, when BS values exceeded 510 for more than 20 consecutive weeks, it was assumed that marsh elevation was high enough to constrain the water to a channel if water volumes did not exceed  $8000 \text{ m}^3$  per cell. Under these conditions the parameter values were changed to reflect lower marsh sedimentation and increased turbulent resuspension of bottom sediments. Habitat switching occurred in cell(1,1) after 4.8 years of high sediment inputs. Subsidence was responsible for lowering the upland elevation enough to once again make cell(1,1) a fresh marsh habitat after 4 years of no sediment inputs. Qualitatively, these successional changes reflect what happens under 'natural' conditions (Baumann et al., 1984).

The habitat switching observed in cell(3,2) and cell(3,3) was caused by an insufficient supply of sediment-laden river water to an area where subsidence lowered the salt marsh elevation. Continued imbalance between subsidence and sediment inputs resulted in a habitat change to open water after 6 years in cells(3,2) and after 9 years in cell(3,3).

## DISCUSSION AND CONCLUSIONS

According to our own field experience and those reported by Boesch (1982), Baumann et al. (1984) and Deegan and Kennedy (1984), these simulation studies indicate that the hydrologic, sediment, salinity, and succession components of the model are behaving in a qualitatively acceptable manner. Spatial articulation of marsh variables by the nine-cell model was also realistic and relatively accurate across time. That is, like the Terrebonne complex, marshes tend to aggrade near sediment sources and degrade away from these sources (Baumann and Adams, 1982). Cells responded rapidly to seasonal variations in the forcing functions and the interconnectiveness of the system allowed succession to be modeled spatially as well as temporally. The results indicate that material fluxes across cell boundaries can be simulated by parameters that represent the average or aggregate of many simultaneous processes. For example, simulating both tidal and river inputs to a cell by a single parameter (one that is sensitive to average weekly storages of water regardless of its source) did not mask the seasonality of either forcing function. By using parameter values that are habitat specific rather than cell specific, we lower the number of parameters needed to simulate spatial changes. This reduces model complexity, which may potentially increase the model's explanatory power or 'effectiveness' as a simulation of reality (Costanza and Sklar, 1985).

The finding that model behavior was most sensitive to changes in the sedimentation and sediment loading parameters is consistent with results reported in the literature. The high rates of wetland loss in the Mississippi deltaic plain (Craig et al., 1979; Boesch, 1982; Scaife et al., 1983) have focused attention on the mechanisms that lead to wetland formation and deterioration. Wetlands exist in a fairly narrow elevational range relative to local water level changes. If the elevation of the land surface rises above this range there is succession to terrestrial vegetation. If the elevation drops below this range, wetlands change to open water.

In an area such as coastal Louisiana where regional subsidence is a dominant process, the land surface must continually be built up if wetlands are to maintain themselves. This maintenance is predominantly a function of new sediment input. Plant growth alone is apparently not sufficient to maintain the marsh surface elevation in the face of subsidence (DeLaune et al., 1978; Baumann et al., 1984). In light of this, and for simplicity, the production of organic sediments was not included in this model. This is not to say that organic sediment production should be ignored. We intend to incorporate a variety of marsh production parameters in the development of a larger, more realistic spatial model for the Atchafalaya/Terrebonne marsh complex in Louisiana.

The importance of sediment inputs has been demonstrated in a number of studies. Baumann and Adams (1982) found that marshes receiving sediments from the Atchafalaya delta were growing in contrast to deteriorating marshes farther to the east. Baumann et al. (1984) showed that the Atchafalaya marshes had sufficient sediment inputs from the river to maintain their elevation relative to local subsidence and thus were increasing in area. Marshes to the east, surrounding Barataria Bay, which no longer receive riverine sediments were not maintaining their elevation and were deteriorating. In addition, DeLaune and Patrick (1980) found that sediment input was the single most important source of new nutrients to Louisiana marshes. These nutrients increase marsh productivity and thus the production of organic sediments (factors to be included in models under development). These findings show the importance of sedimentation to marsh maintenance that is, in general, consistent with our model structure and results.

Since this model was highly aggregated and generalized, it was not possible to investigate its quantitative fit to the real system or to attempt optimization of its parameters. We see this as the next stage of development and discuss some attendant problems below.

In applying the model to real systems, it would first be necessary to increase the number of spatial cells significantly to allow reasonable spatial articulation. The degree of articulation (number of cells) would depend on the system, the problem, and the available resources. Since the primary goal of the model is predicting habitat succession and the majority of the available spatial data consists of time series maps of habitat distributions, it is appropriate to use an index of the goodness-of-fit between the model's predicted habitat map and the real habitat map as the criterion of the model's success. Constructing this index of goodness-of-fit presents some problems, however, since habitats are categorical and not ordinal or interval variables. The simplest index would be to give all cells in which the model habitat and the real habitat were the same a value of 1 and all other cells a 0, with the goodness-of-fit being the percentage of cells with 1's. This would measure the percentage of the categorical variation in the data explained by the model. This does not allow for near misses, however. Habitats are not purely categorical, and at least an interval scale can probably be constructed for them. For example, if the model predicted salt marsh in a cell where there was actually brackish marsh, the model would have done better than had it predicted uplands, since uplands are more different from brackish marsh than salt marsh is. To take this into account, one can use an interval scale for habitats and give partial credit for near misses. The salt marsh prediction above would get a score of, say, 0.5, while a brackish marsh prediction would get a 1, and an uplands prediction would get a 0. The goodness-of-fit index would then be the sum of the scores divided by the

number of cells and would still be interpreted as the percentage of the variation in the data explained by the model.

The process of optimizing the model's parameters is then one of iteratively adjusting the parameters within preset acceptable ranges until the model has achieved the maximum possible goodness-of-fit. This process not only indicates a particular model's best performance, but also allows tests of critical model assumptions. For example, whether or not the connectivity coefficient between cells should be a function of habitat type can be tested by looking at the relative performance of models that incorporate this function compared with ones that do not, all else being equal.

In conclusion, the construction of the nine-cell spatial model demonstrated that the flux of materials from one habitat to another in both space and time can be modeled using a matrix of fixed-size cells and simulated as described above. In the past, researchers have concentrated their modeling efforts on temporal response equations for single populations, communities, or ecosystems at one level of organization. Few have connected processes at one hierarchical level with those at another hierarchical level. The spatial modeling approach presented in this paper was built upon small cellular models at the community level, which can interact with neighboring communities to produce large blocks of habitat types at an ecosystem level which, in turn, can interact with neighboring ecosystems to produce a regional model of succession. It serves to demonstrate that larger, more complex spatial articulation in models of long-term wetland hydrology and succession is possible.

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