Watershed Analysis of Pulsing Freshwater Events Using Landscape Modeling in Coastal Louisiana

Enrique Reyes, Robert Lane, John W. Day

Abstract

Holistic performance measures for coastal restoration are needed as management alternatives are implemented in the Gulf of Mexico. Regional questions can be addressed with watershed models using large-scale spatial dynamics to examine environmental impacts. A watershed simulation model investigated habitat shifts as consequence of different event-pulsing scenarios, and evaluated watershed health in the Mississippi delta, an area with restricted freshwater inputs. Wetland conversion to open water and yearly shifts of marsh habitats were assessed. The watershed model forecasted effects of river diversion management plans for 50 years. Results indicated that healthy functioning of this delta area depended largely on river-borne contributions. Watershed models could provide natural resource managers and decision makers with a scientific instrument for environmental policy.

Keywords: river diversions, Gulf of Mexico, wetlands, habitat restoration

Introduction

Management of diminishing natural resources and economically important ones requires a combination of insight and scientific understanding (Boesch et al. 1994). Holistic perspectives on coastal restoration efforts are needed to provide accurate assessments of different management alternatives as they are developed and implemented along the Gulf of Mexico (Templet and Meyer-Ardent 1988). To date, restoration projects have developed extensive data sets under strict scientific protocols that allow managers to rate the likelihood of success at local scales. Ecological footprints of projects can be determined and local beneficiaries identified. However, watershed level evaluations are sorely lacking (Clark et al. 2001). Compound consequences of several local projects and their future development are largely unknown.

The Caernarvon marshes in coastal Louisiana, (Figure 1), were selected to evaluate restoration efforts at the watershed level. The Caernarvon marshes lie along the eastern side of the Mississippi River, an area with tidal influences and periodic flooding due to river water. It is in this watershed that river contributions are highly regulated by a man-made diversion structure (Villarrubia 1998). Regional management questions can be addressed using watershed models that couple large-scale hydrodynamics and ecological processes (Costanza et al. 1989, Costanza et al. 1990). As river diversions become a favored tool for restoration, it is important to evaluate this approach by using a watershed model capable of forecasting such management approach to long-term regional ecosystem planning.

This paper presents the results of an environmental assessment of river diversions and anthropogenic impacts on a large watershed. The goal was to utilize a spatially-articulated watershed model to forecast planned management alternatives. Several steps were taken to achieve this goal: (1) a watershed process model was developed for the Caernarvon marshes, capable of predicting regional habitat change; (2) this model included the effects of fresh water and sediment additions from river inputs on habitat preservation, changes in forest and marsh vegetation succession, primary production rates and, soil aggradation; (3) overall, the model analyzed hydrological and ecological dynamics at the watershed level. The model tested ideas about system functioning to form the basis for sustainable

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Figure 1. Location of the Caernarvon Marshes ecosystem simulation.

management of these coastal ecosystems (Day et al. 1997).

The Caernarvon freshwater diversion outlet is among seven diversions currently in operation on the lower Mississippi River. The diversion structure dominates the freshwater inputs into the watershed. The structure was completed in 1991 and freshwater discharge began in August of that year averaging 21 $m^3 s^{-1}$.

The Caernarvon Marshes and Breton Sound Estuary are located between the Mississippi River and the Mississippi River-Gulf Outlet (MRGO), with wetlands encompassing about 63 % of this watershed (Figure 1).

Methods

The watershed model used the previously described approach for spatially-articulated watersheds (Costanza et al. 1990, Reyes et al. 2000, Sklar et al. 2001, Martin et al. 2002). This approach required the development of three simulation modules: hydrodynamic, soil dynamics and ecological productivity. These modules were combined according to a geographical grid and calibration was done using previously collected environmental data. (Table 1).

The hydrodynamic module computed the water movement and material transport with a two-dimensional, vertically averaged, finite difference solution (Singh and Aravamuthan 1995). Water inputs into the system were only the freshwater discharge and tidal exchanges. Seasonal changes in tidal height were included as boundary conditions in the Gulf of Mexico boundary.

Table 1. Environmental and model characteristics for the Caernarvon watershed.

Environmental Characteristics	**Caernarvon Marshes**
Area *	1748 km^2
Discharge volume	0 - 266 $m^3 s^{-1}$
Model Specifications	
Hydrological resolution	0.25 km^2
Length of simulation	50 years
Num. of cells	14806
Num. of modeled habitats	6

* Total area includes only natural habitats.

Processes that determined the movement of sediments in deltaic and estuarine environments occurred across a range of temporal and spatial scales. The watershed model simulated long-term geologic processes like subsidence and river shifts were included as boundary conditions. Changes in river regime were accounted for by manipulating the daily sediment concentrations and river flow.

At smaller scales, the sediment module computed the processes related to wetland formation, including resuspension, deposition, and transport of sediments, while ecological processes of soil formation and habitat change were derived from averaged results of the mechanistic processes simulated in the hydrodynamic and sediment modules.

Marsh and swamp productivity were calculated as net primary productivity for each plant community in the model. The ecological module computed above and below-ground biomass as a function of biomass, maximum growth rate and a limiting function. The limiting function accounted for daily temperature, water level, salinity, and their synergy (Hopkinson et al. 1988, Mitsch 1988, Nyman et al. 1990).

Results

The Caernarvon Watershed Model was calibrated and validated using a multiple resolution fit analysis (Costanza 1989) that compared actual habitat maps to simulated maps (Costanza et al. 1990, Reyes et al. 2000, Martin et al. 2002). A 1988 simulated map, resulting from a 10-year simulation, was compared to the 1988 USFWS habitat map (Figure 2) for calibration purposes. These 10-year calibration runs were repeated, varying the initial spatial parameters (elevation) and forcing functions (boundary salinity and tidal elevations), until a fit of 90 or greater (maximum 100) was reached. The model was accepted as calibrated after reaching a fit of 94.10. This value was well above acceptable validation standards for this type of model (Reyes et al. 2000, Martin et al. 2002).

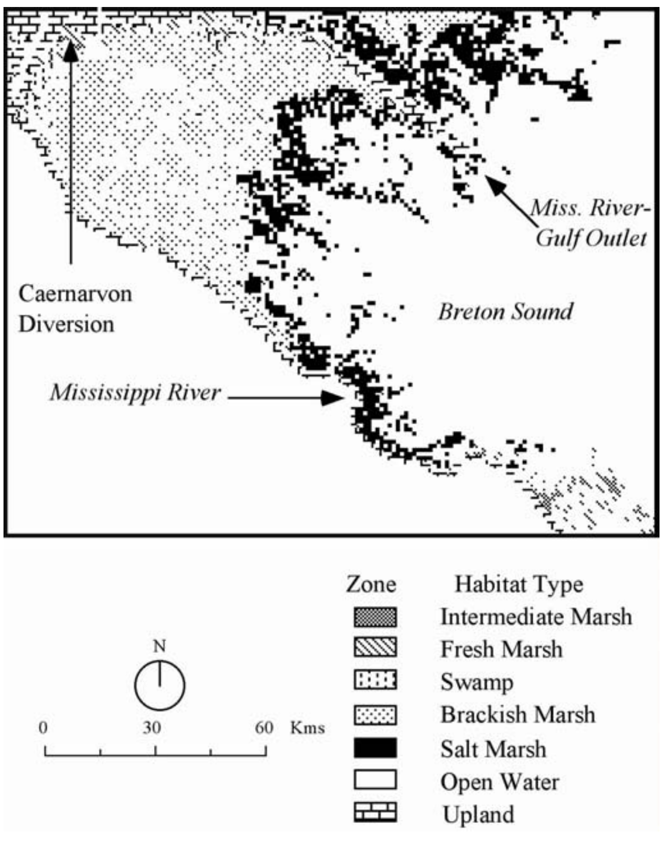

Figure 2. The 1988 U.S. Fish & Wildlife Service habitat map for the Caernarvon watershed.

The Caernarvon diversion controls the largest freshwater input to the watershed. In the past, the diversion discharge regime was established mainly to control salinity in the middle part of the basin (Villarrubia 1998). Starting in the year 2001, an experimental discharge was implemented as part of a research project (Day et al. 2000). This discharge regime involved a high flow discharge followed by a no discharge period, and thus creating a pulse in the freshwater input signal that serve to isolate response of the ecosystem. The scenarios implemented using the watershed model tested the long-term consequences of varying the discharge regime. We considered that river diversions could result in large modifications of the existing habitats. Specific scenarios tested included:

(1) No freshwater discharge (pre-1991 conditions),
(2) 1991-2000 freshwater discharge (scheduled discharge),
(3) Freshwater discharge as proposed for the Caernarvon Diversion experimental pulses regime (2001-2002 actual discharge).

These scenarios examined the main forcing function by which the marshes and open water communities experienced in these hypothetical futures. Modifying the present conditions in a step-wise manner, the model results can be used as an indication of potential cumulative impacts on these environments.

No diversion discharge scenario

This scenario was considered to be representative of the pre-Caernarvon discharge (before 1991) or when the diversion closes for management reasons. The consequences of introducing freshwater into the ecosystems were assessed by comparison with the "Scheduled Discharge" scenario.

The habitat distribution under No Discharge showed extensive salt marsh growth in the southeastern part of the watershed. It was noticeable that the establishment of salt marsh on the northeastern part of the basin continued due to the enhanced saltwater intrusion through the Mississippi River Gulf Outlet. The total extension of salt marsh under this scenario surpassed the "Scheduled Discharge" scenario by 39 km^2 (Table 2), however total land loss was only 10 km^2.

We used the resulting map from the No Discharge scenario as base for comparison with the other two scenarios. Difference maps were prepared to spatially analyze where habitat changes occurred. A difference map was computed as the result of overlaying two scenarios on each other.

Scheduled discharge scenario

This scenario tested the overall effect of using the scheduled discharge for the 1991-2000 period for 50 years. The scheduled discharge for this period included several extreme events at the beginning of the discharge schedule. These included a long period of high discharge (Oct. 1993 to Apr. 1994) and another with no discharge (Jul. to Dec. 1997). The present discharge schedule was established in 1997 (Villarrubia 1998). For simulation purposes, the period of record was repeated as necessary to cover 50 years, instead of using an annual average of the actual discharge.

Table 2. Comparison of habitat extension for future conditions (2037) under three different discharge regimes.

	Habitat Extension (km^2)		
Habitat Type	No Discharge	Scheduled Discharge	PULSES Discharge
Intermediate Marsh	2	2	2
Fresh Marsh	34	34	34
Swamp	32	32	32
Brackish Marsh	562	601	562
Salt Marsh	362	333	361
Open water	2413	2403	2413

The distribution of habitats and salinity across the watershed with the Scheduled Discharge scenario *versus* the No Discharge was substantially different (Figure 3). Freshwater inputs to the basin resulted in a reduction of salt marsh of 29 km^2. When compared to the other two alternatives (Table 2), this scenario resulted in the most favorable conditions to preserve the spatial distribution of habitats and prevent further land loss.

PULSES discharge scenario

This scenario increased the frequency of discharge without modifying the total volume delivered through the diversion. This simulated discharge regime was applied in reality to the Caernarvon watershed under the PULSES project during January 2001 and January 2002 (Day et al. 2000).

The most interesting results from the PULSES scenario were the similar values for habitat distributions when compared to the 2037 No Discharge scenario (Figure 4). There were small wetland gains in using a pulsed regime, if the total amount of water delivered to the basin is less than the total from the Scheduled Discharge scenario (Table 2).

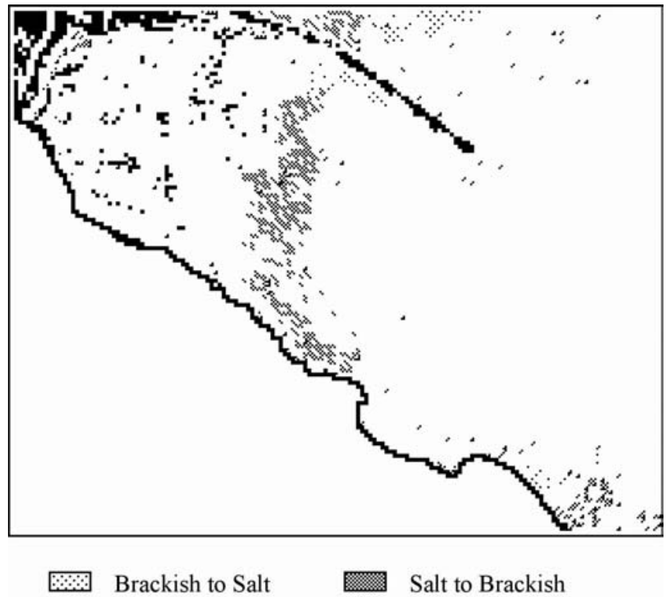

Figure 3. Habitat distribution difference for the Caernarvon watershed in 2037 under No discharge and Scheduled Regime scenarios.

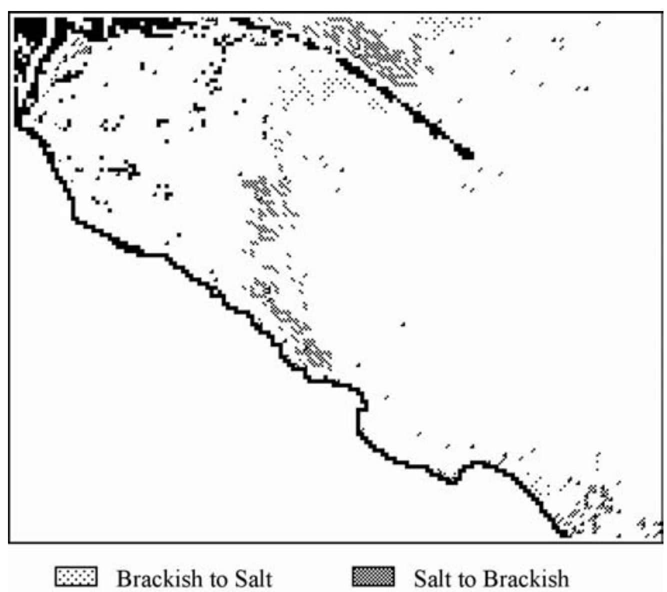

Figure 4. Habitat distribution difference for the Caernarvon watershed in 2037 under No Discharge and Pulses regime scenarios.

Discussion

Traditionally management and implementation of restoration alternatives have used a piece-meal approach, with permits and environmental impact assessments issued for small land parcels. The cumulative effects of these actions made difficult to evaluate their regional consequences without a holistic perspective and an ecosystem-level analysis (Boesch et al. 1994, Sklar et al. 2001). Watershed simulation models have been used to evaluate the potential for success of diverse management strategies and the response of wetland habitats to increased effects of global warming, cumulative impacts and future human development (Reyes et al. 1994, Rybczyk 1998, Reyes et al. 2000). The present watershed model considered large-scale effects of large and punctual impacts, providing a regional view and evaluation, and allowing the exploration of future trends of ecosystem response.

Faced with continued land loss, as result of increased sea-level rise and subsidence, the State of Louisiana response has been the implementation of freshwater diversions. The Caernarvon watershed model represented an area where massive restoration efforts are in place. The objective for freshwater diversions was to compensate land loss by restoring the sediment contribution to the watersheds. Generally, these diversion impacts were projected to be beneficial to wetland health and sustainability, but it remains to be determined if there are threshold increases in freshwater input due to anthropomorphic alterations (diversion management scenarios) that might impact the system negatively (Day et al. 1995). Possible negative impacts included flood stress to the wetlands and potential algal blooms in water bodies. River diversions represent a viable mechanism for decreasing the nutrient load of river water prior to its reaching offshore waters and salinity intrusions (Weisner et al. 1994, Adler et al. 1996).

As with any large-scale tool, data availability and long-term time series limit the precision of both the watershed models. This was particularly evident in the Caernarvon watershed model as it treated the degree of separation between brackish and intermediate marshes by a unit of salinity. This sharp delineation has to be explored experimentally to a greater depth. The hydrodynamic module used a two-dimensional model on a fixed grid, thus limited in the vertical dimension and averaging values through large areas (0.25 km^2). However, the model predictions (Table 2) demonstrated the unique competence of the Caernarvon hydrodynamic module to replicate observed conditions continuously for long periods, well beyond the practical run length for any other two-dimensional coastal model.

Conclusions

A fully spatially articulated ecological model was developed for the Caernarvon watershed. Historical environmental conditions were used for the calibration of the Caernarvon Watershed Model. A comparison of 1988 habitat spatial patterns with the results of the model showed a fit index of 94.1.

Three different future scenarios were evaluated. A No Discharge, Schedule Discharge and Pulses Discharge water regimes were used to forecast habitat conditions in 50 years. Resulting yearly average salinity maps indicated similar overall conditions for all three scenarios. However, habitat distribution patterns varied substantially. As the different scenarios were computed it became apparent that freshwater has a beneficial effect on the marsh communities. This increased freshwater discharge translated in less land loss and a preservation of the original 1988 habitat diversity.

The present study serves as an example of the scientific tools available to resource managers for the evaluation of long-term cumulative impacts. As demonstrated in other areas of Louisiana, the use of spatially articulated models allows to identify gaps and problematic areas for the decision maker (Smith-Korfmacher 2001).

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