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Estimating the Impacts of Sea Level Rise using Geoprocessing and Simulation Modeling

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Simulaion modeling was applied to predict the response of northeast Florida coastal wetlands to futrue sea levl rise due to global warming. Remote sensing and geographic information systems (GLS) were used to develop, manipulate, and synthesize input data, including land cover, digital elevation data, and site characteristics data. The SLAMM3 model evaluated this input data to predict responses of coastal wetlands and lowlands to inundation and erosion by sea level rise, and determined transfers from one habitat to another on a cell-by-cell basis. Significant changes were predicted from different scenarios of sea level rise: 0.5m, 1.0m, and 1.25m. The simulations indicated that 31.9 percent and 40.0 percent of wetlands within the study area would be lost with 1.0m and 1.25m sea level rise respectively, and a 6.5 percent loss with o.5m rise.

Key Words: sea level rise, coastal ecosystem, GIS, remote sensing.

1. Introduction

Recent scientific evidence strongly supports the contention that global warming due to human-induced greenhouse effects exists. When global temperatures reach levels currently predicted by climate models, acceleration of eustatic sea level rise will be one of the major environmental consequences. Although estimates vary (Figure 1), many investigators believe that sea level may rise by 1 m by the year 2100 (Revelle, 1983; Thomas, 1986; Robinson, 1986). Warming due to greenhouse gases currently in the atmosphere could result in a 33-cm sea level rise(IPCC, 1990).

Sea level rise could result in serious impacts on coastal wetlands and associated wildlife and fisheries. For much of the contiguous United States, inundation and erosion will probably destroy at least half of existing coastal marshes and swamps (Park, *et al.*, 1989; Park, *et al.*, 1991). Such large-scale impacts on coastal wetlands by sea level rise will result in significant environmental and economic damages, including saltwater intrusion into freshwater, reduced fishery products, and increased intensity and frequency of storm surges along shorelines. For a 1m rise in sea level, damage from shoreline retreat has been estimated to cost the U.S. $270 to $475 billion (Titus, *et al.*, 1991). For these reasons, a pre-

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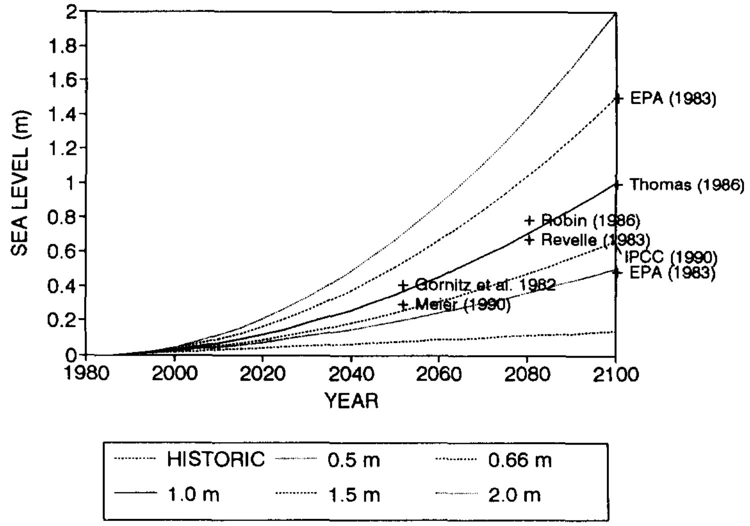

Figure 1. Previous estimates of sea level rise for 2100. EPA(1983) was from Hoffman *et al.* (1983).

cise estimate of the impacts of sea level rise on coastal wetlands is essential for making policy decisions associated with coastal resource management.

Estimating dynamic landscape changes over time in coastal ecosystems involves consideration of complete (and sometimes poorly defined) physical, spatial, and biological processes, and thus requires a great deal of information. Modeling is one approach for dealing with such complex processes (Dangermond, 1987) SLAMM (Sea Level Affecting Marshes Model) was developed to model landscape changes resulting from wetland responses to sea level changes. The model was first introduced in the late 1980's to support the U.S. EPA estimates of impacts of future sea level rise on U.S. coastal areas (Park, *et al.*, 1986; Armentano, *et al.*, 1988). Since that time, the model has been continuously refined to improve its performance and details. The model was also subjected to extensive peer review at a workshop held at the University of Maryland and sponsored by the U.S. EPA in 1990 ; the panel found the model acceptable. The current version of SLAMM3, introduced in 1991, employs satellite remote sensing and geographic information system (GIS) technologies in its modeling procedures.

Remote sensing and GIS technologies have become prominent tools in many ecological landscape studies (Iverson, 1988; Burke, *et al.*, 1990; Simmons, *et al.*, 1990). The objective of this paper is to show how geoprocessing techniques (i, e., remote sensing and GIS) are used in simulation modeling of the responses of coastal areas due to changing sea levels. The use of such analytical thchniques was essential for creating the SLAMM3 model.

2. Model Description

SLAMM is primarily a cell-based simulation model. Initial conditions of coastal areas, characterized by land cover, elevation, and additional site characteristic data, are provided, and the response to changing sea level is simulated on a cell-by-cell basis.

The objective of SLAMM modeling is regional-scale simulation of the dominant processes involved in wetland conversions and related shoreline reconfigurations during long-term sea level rise. SLAMM3 differs from other wetland models (Day, *et al.*, 1973; Wiegert, *et al.*, 1975; Hopkinson, *et al.*, 1977; Costanza, *et al.*, 1987; Kana, *et al.*, 1988; Browder, *et al.*, 1989; Sklar, *et al.*, 1990) by its ability to predict map distributions of wetlands cover under conditions of accelerated sea level rise, and by its applicability to the diverse wetlands of the contiguous coastal United States. The earlier SLAMM2 model was applied to approximately 20 percent of the coast of the contiguous United States (Park, *et al.*, 1989; Park, *et al.*, 1991).

The model simulates the dominant processes involved in wetland conversions and shoreline reconfigurations during long-term sea level rise. A complex decision tree incorporating geometric and qualitative relationships is used to represent transfers among coastal classes(Figure 2). Each site is divided into cells of equal area, and each class existing within a cell is simulated separately. Map distributions of wetlands are predicted under conditions of accelerated sea level rise, and results are summarized in tabular and graphical form.

Relative sea level change is computed for each site for each time step; the change is the sum of the historic trend of 1.2 mm/yr (Gornitz, *et al.*, 1982; NRC, 1985; 1987), the site-specific rate of change of elevation due to subsidence and isostatic adjustment, and the accelerated rise depending on the scenario chosen. Eustatic sea level rise may be offset by sedimentation and accretion. In the absence of site-specific data, average

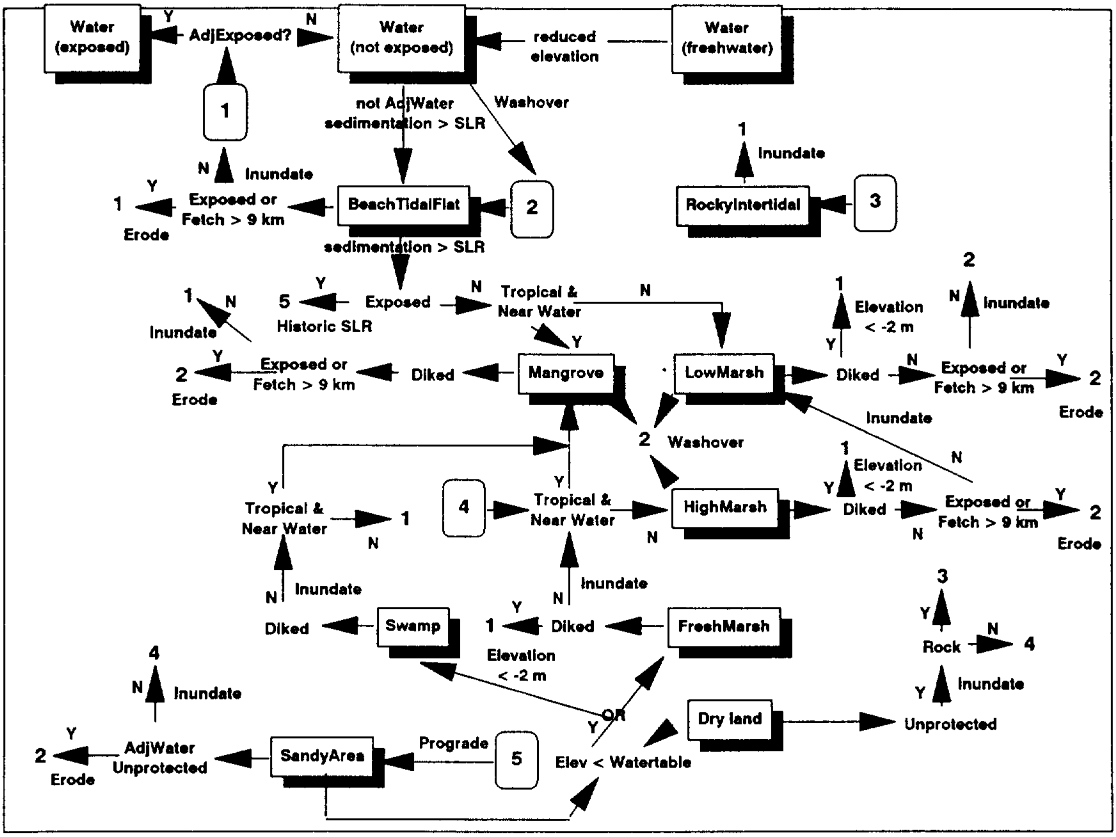

Figure 2. The logic embodied in SLAMM.

values are used, depending on the extent of existing marshes (the assumption is that extensive marshes indicate higher accretion rates). The values used range from 2 to 10 mm/yr. The accretion rates for marshes which are not adjacent to water is assumed to have half the accretion rate of those adjacent to water (Gosselink, 1984). Sedimentation rates for tidal flats and open water areas are taken to be half of the accretion rates. Although the model is not sensitive to these assumptions for higher sea level rise scenarios, the predicted changes in wetlands for a 50 cm rise in a low-subsidence area can vary by as much as 50 percent if the accretion rates are twice as great (the maximum deviation expected). The time step of 5 to 25 years depends on the sea level rise scenario chosen; a shorter step is used for higher sea rise scenarios. For each time step, the fractional conversion from one class to another is computed on the basis of the relative change in elevation divided by the elevation range of the class in that cell. For this reason, marshes that extend across wide tidal ranges are only slowly converted to unvegetated tidal flats.

If a cell is protected by a dike or levee, it is not permitted to change. For a standard simulation, cells that are largely developed are assumed to be protected by dikes and dredge fill as necessary to prevent inundation. Dikes can severely affect the ability of wetlands to migrate to migrate onto adjacent shoreline.

In addition to the effects of inundation represented by the simple geometric model described above, second-order effects occur due to changes in the spatial relationships among the coastal elements. In particular, the model computes exposure to wave action; if the fetch (the distance across which wind-driven waves can be formed) is greater than 9 km, the model assumes moderate erosion. If a cell is exposed to open ocean, severe erosion of wetlands is assumed. Beach erosion is modeled using a relationship reported by Bruun (Bruun, 1962; 1986), and recession is modeled as 100 times the change of sea level because wetlands on the lee side of coastal barriers are subject to conversion due to overwash erosion of backshore and dune areas occurs and other lowlands are drowned. Although erosion of sandy areas to maintain equilibrium with adjacent beaches in modeled, erosion of other dry lands is ignored. This may seriously underestimate the availablility of sediment to replenish wetlands where accelerated bluff erosion may be expected to occur. Because coastal swamps and fresh marshes reflect the importance of high water tables in coastal areas, the model simulates the response of the water table due to rising sea level close to the coast.

SLAMM3 supports 125 m, 250 m, 500 m, and 1km grid cells. The initial version of the model, SLAMM1, supported only 1km grid cell. This grid size was selected to represent relevant scientific details, and reflected the computational requirements of the desktop computing environment for regional scale modeling. As desktop computing speed increased, the grid sizes were upgraded to 500 m and 250 m in SLAMM2, and 125 m in SLAMM3. The model-grid size was upgraded by dividing the grid size in half for relatively easy handling of file size and model modification. The uniform cell sizes were used because they are relatively easy to handle in evaluating major processes over the uniform spatial scale.

A validation study was performed for SLAMM2 to evaluate the realism of the model, which was applied to Pelican Pass, Louisiana, using 1973 Landsat Multispectral Scanner (MSS) data to simulate conditions for 1986, and comparing the results with 1986 observed Landsat MSS data. The site was chosen because subsidernce has been creating rates of relative sea level rise compartable to eustatic rates expected elsewhere in the next century. The model forecast results were within 1 percent of those observed (Park, *et al.*, 1991).

3. Methods

1) Study Area

The study area extends coastal lowlands in parts of Nassau and Duval Counties in northeastern Florida. This region typically consists of marshes and level plains resulting from the most recent advances and retreats of the sea during the late Pleistocene(Krause and Randolph, 1989). A variety of wetland and dyr land vegetation characterizes this low, gentle-to-flat topographic area, where most elevations are under 15 m.

Marshes are well developed in this region due to a combination of high tidal ranges (approximately 1.2 to 1.7 m) and high sedimentation rates. Swamps are also extensively developed in many areas of low elevation, while evergreen trees are dominant on better-drained and higher land. An area of approximately 900 km^2 was mapped and analyzed for the study.

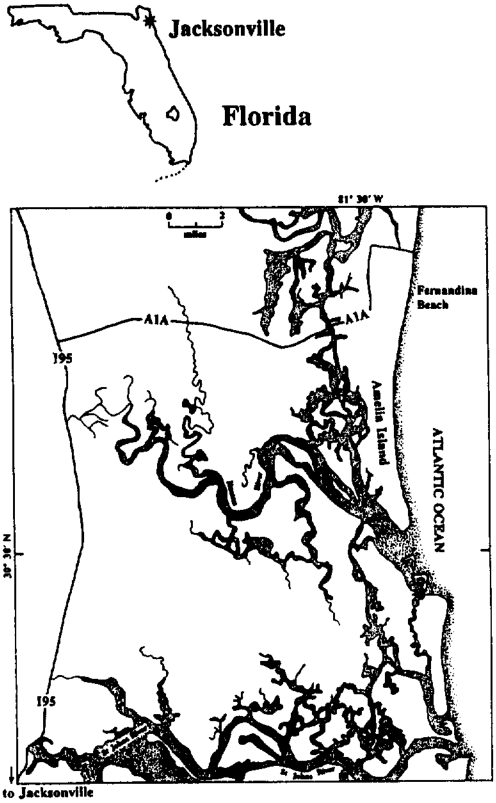

Figure 3. Map of the study site.

2) Data Materials

Three-band multispectral SPOT data were used to generate land cover information over the study area through computer classification. The data were acquired at 20 × 20 m ground resolution on September 28, 1986, under cloul-free conditions. A set of ancillary data was used to help develop training samples of spectral data, to interactively edit the initial classification results, and to generate digitized contour data. The ancillary dots consists of 7.5-minute topographic quadrangle maps (1:24, 000 scale, 1958-1981), a land use map (1: 250,000 scale, 1972-1973), a National High Altitude Photography (NHAP) color infrared photograph (1:58,000 scale, 1983) from U.S Geological Survey (USGS), and National Wetland Inventory Maps (1:24,000 Scale, undated) from U.S Fish & Wildlife Service (USFWS). These data were processed on an Earth Resource Data Analysis System (ERDAS) and a pcARC/INFO geographic information system. These GIS packages were linked to the SLAMM3 model via interface routines shown in Fig 4.

3) Land Cover Generation

A 1500-row by 1500-column subset of SPOT imagery developed from a full scene covered extensive wetlands and lowlands north of Jacksonville, Florida. The subset was geometrically rectified by applying a first-degree linear functionn at approximately 0.4 root-mean-square (RMS) value based on UTM coordinates. The linear function was developed from 28 ground control points (GCPs) generated from both imagery and ground-truth data. Bilinear interpolation was applied to resample gray values of spectral data. The bilinear interpolation is a reasonable compromise be-

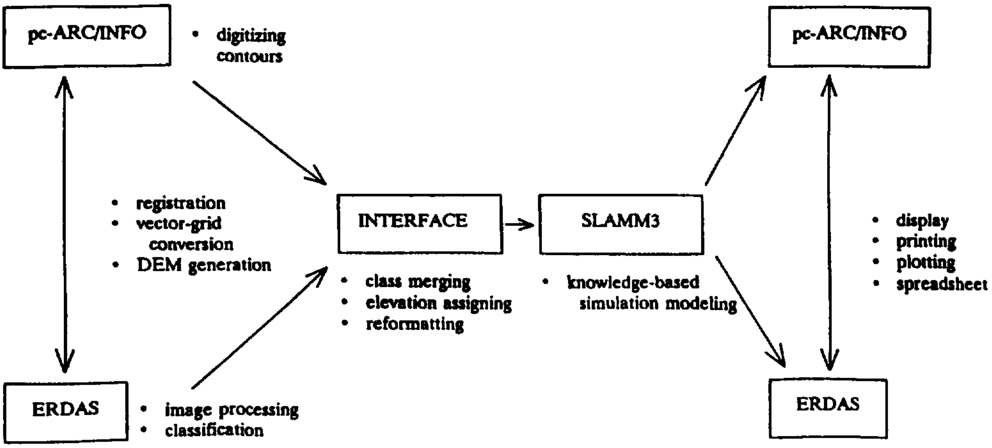

Figure 4. System ocnfiguration used in the study.

tween computational time and image distortion(Gonzalea and Wintz, 1987).

Classification of the study site was divided into two phases. The first phase was spectral classification of SPOT data using a supervised approach. A maximun-likelihood classifier was used to classify the spectral data based on statistics from the training samples. In the second phase, the data were merged and redefined into SLAMM3 classifications for modeling on the basis of ground truth and field-checking information. SLAMM3 considered 12 cover classes for simulation (Table 1). Since the primary modeling objective was to simulate wetland vegetation classes, the classification for dry land was very general: only developed areas, undeveloped areas, and sand areas. Beach and tidal mud flats were categorized in the same calss, but modeled separately, according to whether the cell was exposed or sheltered. In a recent modification of SLAMM3, the mixed swamp class was split into two differedt types, hardwod and cypress, because their responses to rising sea level are different. With sea level rise, hardwood swamp will be converted to marsh, while cypress swamp is likely to be converted directly to open water because of greater inundation. However, processing of data for this study was done before this modification, so all swamps were treated as mixed hardwood swamps. Accuracy assessments of classification results were done by developing a reference polygon map from a randomly selected NHAP photograph and field checking. A detailed reference polygon map was developed by drawing polygons onto a mylar sheet from visual interpretation of the selected photograph; the interpretation was intensively checked in the field. Accuracy was estimated for all cassified classes except for ocean water, because the selected photograph did not contain that class. Congalton (Congalton, 1988a, 1988b) provided useful guidelines for the accuracy assessmetn of classified remotely sensed data; he suggested a random samle of at least 1 percent of the total munber of pixels. The reference polygon map covered approximately 15 percent of the classified area. The selected method was a compromise between Congalton's guidelines and available time and funding.

Table 1. The Twelve Land Categories Considered by SLAMM3 Model

developed dry land
undeveloped dry land
dry sand
mixed swamp
fresh marsh
high salt marsh
low salt marsh
mangrove*
beach/tidal flat
rocky intertidal*
nonocean water
ocean water

• These classes do not exist in the study site.

4) Generation of Digital Elevation Data

Because USGS Digital Elevation Model (DEM) data (1:24,000 scale) were not available for the site, digital elevation data were generated by interpolation of manually digitized contour data. Contour lines and survey points for elevation on topographic quadrangle maps (1:24,000 scale) were digitized as line and point features on a pcARC /INFO system. Interpolation was applied to the digitized data to create continuous elevational surface data at a 10 m sampling interval. The 10 m sampling interval was a minimum tolerance required to avoid snapping of contour lines of the study area in the vector-to-grid conversion process. A linear interpolation algorithm was selected, based on the following considerations;

- The linear interpolation was a computationally simle algorithm suitable for the personal computer environment.
- The study area was coastal plain with flat topography; thus, changes in slope were not a major factor in the interpolation process.
- The linear interpolation algorithm provided fairly good and consistent results over different types of terrain in a previous comparative study (Lay, 1987).

Elevations for unknown points were interpolated from the known elevations in four directions; x, y. and two diagonals. A 3 ×3 average filtering was applied to reduce vertical discontinuity observed from the interpolated data. Finally, th elevation data were resampled onto a 20 m grin and registered to classification results from SPOT data on a pixel-by-pixel based on UTM wordinates.

5) Further Database Development

The land cover data were aggregated into a grid of 125 × 125 m and stored as percent cover within each grid cell. Elevation data were developed in two layers of minimum and maximum elevation for each class within each grid cell. These two types of elevation data were developed by registering digitl evevation data to class data and by developing elevation range (minimum and maximum elevations) for each class existing within a 125 m grid cell. VErtical oceanic and sheltered-water tidal ranges were obtained, and local average fetch was estimated from topographic maps. Also, dike locations were digitized from the maps. A local land subsidence rate of 0.7 mm/yr was developed from a long-term trend of relative sea level rise measured at the tidal gauge at Fernandina Beach, located in the center of the study area. Assuming that the current eustatic sea level would rises at the historic rate (1.2 mm/yr), this value was subtracted from the observed relative sea level rise value of 1.9mm/yr (Hicks, *et al.*, 1983) following the method of the National Research Council (NRC, 1987). The subsidence rate is in line with the regional subsidence trend reported by Holdahl and Morrison(Holdahl and Morrison, 1974).

6) Modeling

In this study, the 125 m grid size was used to provide the greatest spatial resolution of the mode. The 0.5, 1.0, and 1.25 m scenarios for sea level rise by 2100 were used for simulations based on previous estimates (Figure 1). The simulations were performed with the assumption that the significantly developed coastal areas would be protected against rising sea level by dikes or other engineering structures. To facilitate comparison with a previous study (Park, *et al.*, 1989), the simulations were run to the year 2100. The model is sensitive to the rates used for land subsidence, marsh accretion, and erosion.

4. Results and Discussion

From the initial supervised classification of SPOT data, 22 cover classes were developed, including seven different marsh types. Since the model simulates primarily wetland vegetaion classes, particular attention was given to classification of the wetland classes. The 22 classes were grouped into 10 categories considered by the SLAMM3 model. Classification accuracy estimated for the 10-class cover map was high because the categorical levels were general. An overall classification accuracy of 87.8 percent (except for the ocean water) was achieved from the classification of SPOT data.

1) Simulation Results

Plate 1 illustrates the initial conditions of the site with existing land cover in 1986 when SPOT data were acquired. All classes within the grid cell were stored as percent cover of the grid cell area. In this map, each cell is represented by the most dominant class within the grid cell of 125×125 m; however, every existing class was simulated within the grid cell.

With a 0.5 m rise in sea leve, the notable changes were a decrease in fresh marsh and low salt marsh, and an increase in high salt marsh and beach/tidal flat (Figure 5). With inundation, the low salt marshes near the tidal creeks was converted to tidal mud flats and the fresh marsh was converted to high salt marsh. The high salt marsh was defined as salt marsh at higher elevations.

Thus, the high salt marsh was treated as a transtition-type marsh between fresh marsh and low salt marsh. At this rate of sea level rise, 1571 ha of wetlands (6.5 percent) and 1753 ha of dry lands (4.1 percent) were lost (Table 2). Plate 2 illustrates the predicted conditions of the site for the year 2100 with 0.5 m sea level rise.

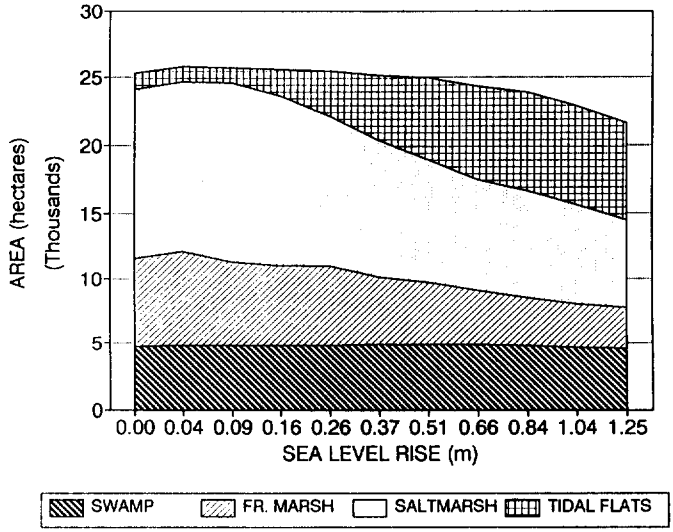

Figure 5. Changing areas of wetlands at the study site with incremental sea level rise.

Table 2. Estimated Percent Changes of Each Class by Sea Level Rise with Different Scenarios

	0.5m	1.0m	1.25m
developed dry land	− 0.43	− 1.39	− 1.74
undeveloped	− 4.79	− 11.25	− 13.23
dry sand	− 41.00	− 55.35	− 64.91
mixed swamp	+ 2.50	− 0.88	− 2.44
fresh marsh	− 30.22	− 50.77	− 54.16
high salt marsh	+ 55.87	+ 61.07	+ 38.46
low salt marsh	− 12.62	− 61.57	− 71.76
beach/tidal flat	+196.29	+514.64	+503.99
water*	+ 5.27	+ 29.00	+ 44.70

* both ocean and nonocean water classes.

With a 1 m sea level rise, an appreciable change was predicted. 4014 ha of wetlands (32.0 percent) and 7735 ha of dry lands (9.4 percent) were lost (Table 2 and Figure 5). The substantial loss of weltlands at this rate due to the low elevation of march classes relative to rising ses level. All wetlands and dry lands decreased in size except for the high salt marshes, which increased due to the conversion of fresh marsh. Water and tidal flats expanded due to inundation. The predicted conditions with 1.0 m rise are illustratd in Plate 3.

With a 1.25 m ses level rise, all classes except open waters decreased in size. At this rate, 4730 ha of wetlands (40.0 percent) and 9684 ha of dry lands (11.1 percent) were lost at this rate (Table 2 and Figure 5). Some marshes persisted at higher elevations. A conversion from undeveloped dry land (dry land vegetation) and swamps to marshes was also observed. The predicted conditions with the 1.25 m scenario are shown in Plate 4.

2) Implications

Under reasonable scenarios, the overall simulation predicted significant losses of coastal marshes due to sea level rise. Such a loss has significant economic and environmental implications. For example, disintegration of marsh-water interfaces (marsh coastlines) will result in habita framentation for nearshore fisheries. The length of wetand shoreline is known to be a good indicator for brown shrimp habitat (Browder, *et al.*, 1989) working in areas of high subsidence, investigators at the National Marine Fisheries Service Galveston Laboratory observed that shrimp production may increase temporarily with slightly accelerated level rise, but decline sharply with greater rates of rise (Zimmerman, *et al.*, 1992). In addition, wetalands act s a filter for reducing the intensity of stroms. The loss of wetlands would increase the frequency of storm surges along the shoreline (Titus, *et al.*, 199).

In the simulations in this study, the loss of dry lands was relatively low because it was assumed that the development areas would be produced by engineering structures. Coastal protection will have a significant role in loss of coastal marshes by sea level rise. When coastal lowlands are protected by engineering structures, marshes cannot migrate inland, resulting in a greater loss of marshes between dikes and the rising sea. One key policy decision associated with wetland associated with weltand protection is wheher coastal lowlands should be protected instead of wetlands; various options are discussed by Titus (1991).

5. Conclusion

Numerous advantages were observed from the system linkage used in this study. Remote sensing was an invaluable source of data for seting the initial conditions of modeling by providing a synoptic view of the modeling site. Furthermore, by its multitemporal capablility, remotely sensed data can be used as an independent data source for model validation. Currently, a validation study for the SLAMM3 model is in progress using 1973 Landsat Multispectral Scanner (MSS) data to simulate sea level rise impacts for the late 1980's and to compare the results with late 1980's Landsat observation for selected sites along the

Gulf Coast. Geographic information systems provided an efficient means of model proparation through sophisticated data handling, and high quality graphic and cartographic presentations. In addition, GIS allowed a flexibility in modeling through simple verification and calibration of the model. The model performed complex rule-based simulations of inundation and erosion. Integration of these components provides an efficient tool for future coastal resource managemetn.

The integrated system can be enhanced by adding a statistical analysis component. Statistical analysis can be a useful addition to the integrated modeling system for sensitivity analysis, surface structural modeling, model valudation and calibration, and quality control assurance. Currently, the shifting of the modeling system from a personal computer to UNIX-based workstation environment is planned. The new modeling environment for SLAMM3 on the UNIX-based workstation will include a relational database management system (RDBMS), vector and raster GIS, and a statistical analysis package, along with the simulation model.

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지리정보시스템과 시뮬레이션 모델을 이용한 해면상승의 예측과 해안지형에 미치는 영향

이재극* · 권순식**

지구 온난화 현상에 의한 해안지역에서의 가능한 미래의 해수면 상승의 영향을 예측하기 위한 연구가 미국 Florida주 북동 해안지역을 대상으로 행해졌다. 시뮬레이션 모델링을 위한 토지이용도, 지표고도, 그리고 그외 지역의 자연적 특성에 관한 자료가 원격 탐사와 지리정보시스템을 이용해서 준비, 분석, 합성이 되었다. 준비된 모든 자료는 개발된 모델 (SLAMM 3)에 의해 분석되어 침수와 침식에 대한 결과로서 발생될 수 있는 해안지역에서의 현상이 예측되었다. 해수면 상승에 관해 0.5m, 1m, 1.25m의 세 가지 시나리오로서 진행된 연구결과, 유용한 환경자원인 해안 저습지의 손실이 최고 40%까지 예측되었다.

主要語 : 해면상승, 해안생태계, GIS, 원격탐사

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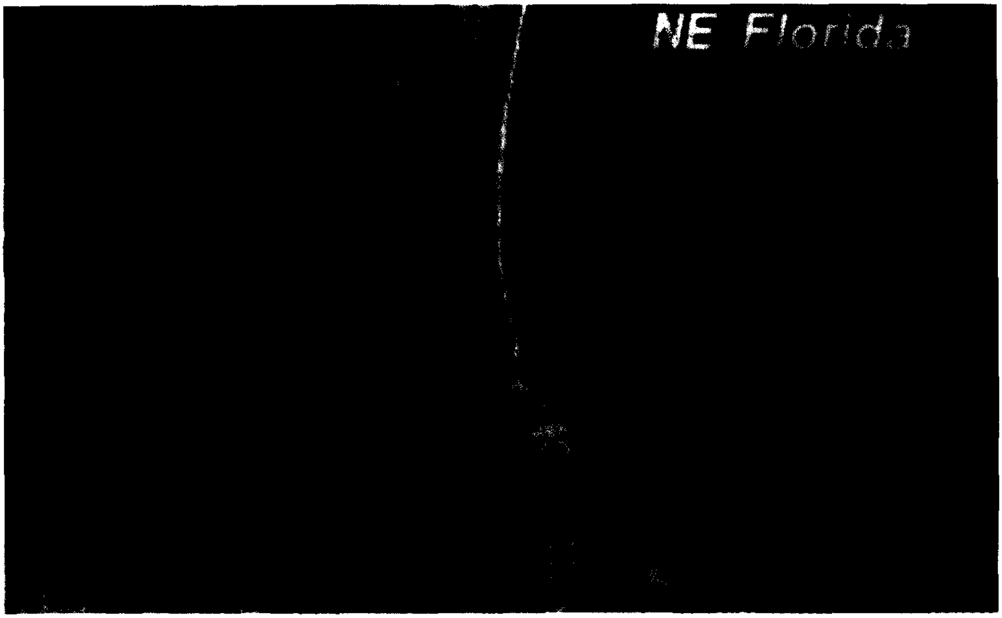

Plate 1. Initial conditions of the site based on classified 1986 multispectral SPOT data aggregated in 125 × 125 m grid.

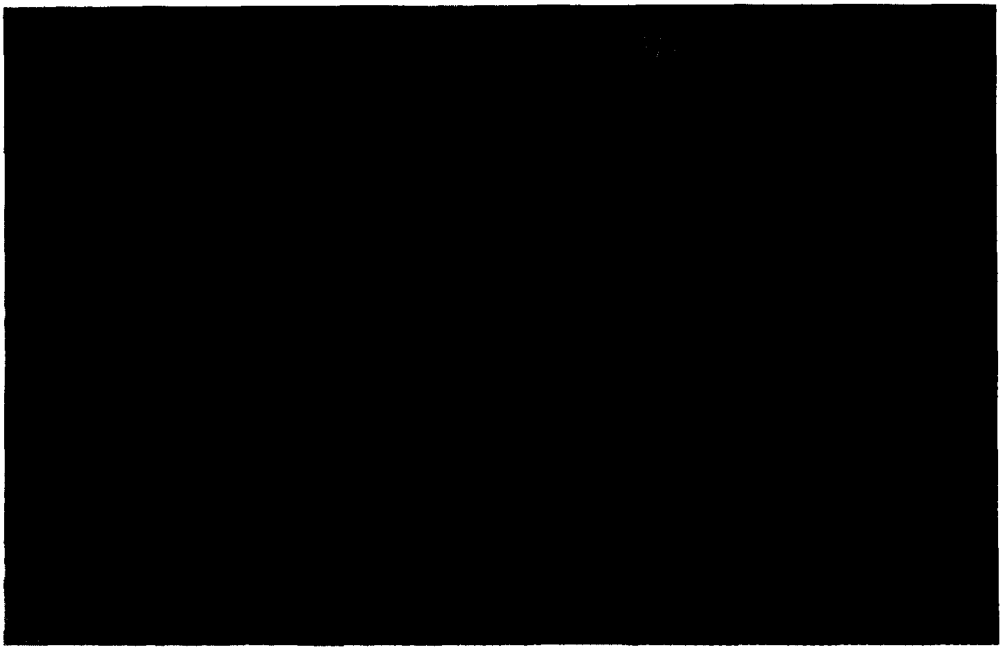

Plate 2. Predicted conditions for 2100 with 0.5 m sea level rise scenario. Each pixl (125 × 125 m) is represented only by the most dominant class, while the model simulates all classes within each cell. Note the conversion of fresh marsh to high salt marsh, of high salt marsh to low salt marsh, and of beach/tidal flat to open water.

Plate 3. Predicted conditions for 2100 with 1.0 m sea level rise scenario. Note the conversion of low salf marsh to tidal flats, of fresh marsh to high salt marsh, of swamp to high salt marsh, and of undeveloped dry land to marshes.

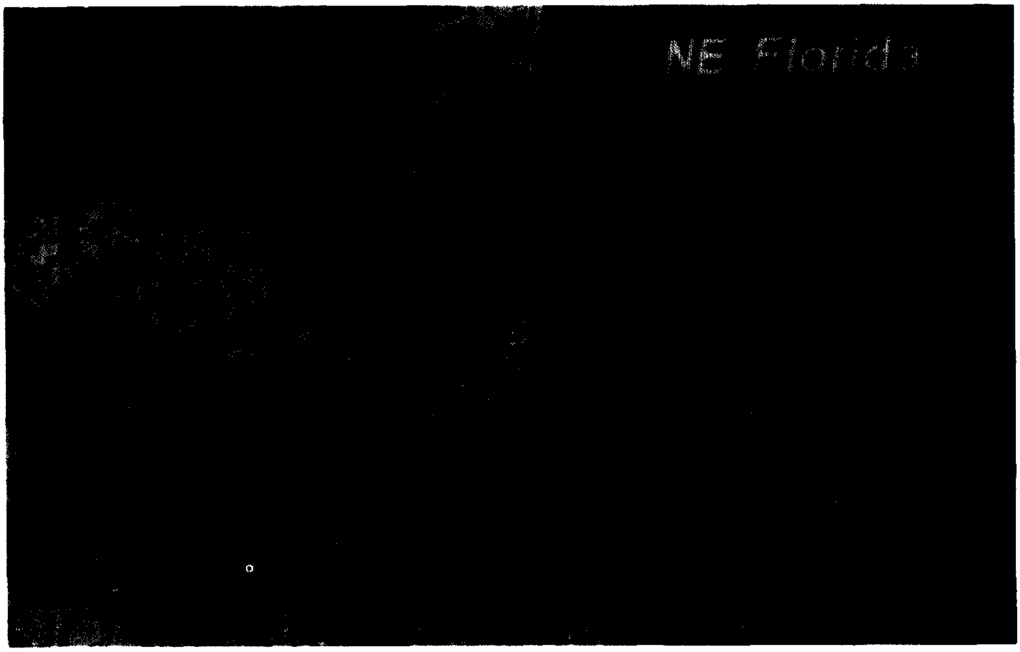

Plate 4. Predicted conditions for 2100 with 1.25 m sea level rise scenario. Note the expansion of open water and conversion of swamp to high salt marsh.