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Designing Wetland Conservation Strategies under Climate Change

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Wetlands are important elements of the ecosystem, performing essential functions such as water quality improvement, habitat and recreation sites provision, flood protection, bank stabilization, and sediment control. Natural forces play a major role in changing the function and distribution of wetlands. However, many activities that people engage in contribute significantly to the physically and functionally destruction of wetlands. The substantial wetland losses have profound impacts on the environment and the ecosystem. In recent years, increased attention to wetlands conservation has caused the public to become more appreciative of the functions that wetlands provide.

Tidal and estuarine wetlands are mostly located within a few feet of water level, so when facing climate change, they are particularly vulnerable to the intensified sea level rise. The Intergovernmental Panel on Climate Change (IPCC) concluded in 1996 that anthropocentric climate change is indeed occurring (IPCC, 1996). However, there exists substantial uncertainty about the magnitude of the change. Effective wetland conservation strategies must consider both climate change and its uncertainty. Of particular importance, land use controls are essential to effective wetlands conservation. Because land use change can be irreversible, it is crucial to anticipate where future wetlands will be viable, and establishing land controls in those areas to prevent irreversible development. Unfortunately, most of the current conservation efforts fail to account for these issues, which will quite possibly lead to failures.

Different wetland conservation policies have been implemented at national, state and local levels. There are three major kinds of conservation strategies, migration, creation, and restoration. Direct losses of coastal wetland due to sea-level rise can be offset by inland wetland migration. However, protection structures of developed areas, such as bulkheads and dikes, will keep wetland from migrating inland. So the migration strategy is basically to preserve the undeveloped land within a few feet above wetlands so that to keep the opportunity for wetland migration anywhere that is not already developed by constructing buffers and maintaining surrounding natural processes. As indicated by Environmental Protection Agency (EPA), the amount of available dryland is much less than the amount of wetlands that would be lost. Therefore, creation and restoration strategies need to be carried out in order to meet the national goal of "no net loss" of wetlands. Creation is the "construction of a wetland in an area that was not a wetland in the recent past (within the last 100-200 years) and that is isolated from existing wetlands (i.e., not directly adjacent)" (Gwin, et al., 1999). Ecological restoration is defined as the "return of an ecosystem to a alose approximation of its condition prior to disturbance" (NRC, 1992). Identifying potential sites with appropriate physical conditions and historical land use is essential to the success of wetland restoration. Considering only the cost factor, migration is the best choice because it only incurs the cost of buying land. Comparing creation and restoration, creation is a more difficult undertaking because it essentially tries to produce a new ecosystem. In addition, the outcome of a creation project is often difficult to predict. Therefore, the wetland conservation strategies we consider in this study will focus on migration and restoration.

This study develops a methodology for evaluating public wetlands conservation investments that takes climate change and the associated uncertainty into account, and demonstrates the methodology in a case study under plausible sea-level rise and land use scenarios. In the second section, we present the formal model of wetland conservation decision-making, using an optimization framework known as discrete stochastic sequential programming (DSSP). In the third section, we briefly introduce the research area, Elizabeth River watershed, Virginia, and discuss the land use scenarios, sea level rise scenarios and other inputs of the model. In the final section, we summarize our analysis and discuss future research.

Case Study

Wetlands serve as the link between land and water resources and they are important elements of a watershed. Therefore, we study wetland conservation strategies within the context of watersheds. Our research area is the Elizabeth River watershed in Virginia, which is located primarily within the cities of Norfolk, Portsmouth, Chesapeake and Virginia Beach. The Elizabeth River is one the rivers that contribute to the Chesapeake Bay, which in recent decades has been experiencing a general decline in the water quality. Since the days of the early 17th century, Elizabeth River has undergone dramatic changes. Particularly during the past century, because of its geographic position, the Elizabeth River has attracted various commercial and military facilities, including shipping, military bases, ship repair yards and other industrial plants, all dependent on the river for transportation (Alliance for the Chesapeake Bay, 2003).

Many areas of wetlands and shallow water have disappeared under the pressure of rapid population growth and facility construction. These losses of habitat and resultant degradation of water quality from pollution have led to significant impacts to the biota of the Elizabeth River that have compromised its function as an estuarine system (Priest, 1999). In recent years, the continued loss of coastal wetlands has become an increasingly important issue. Legislation aiming at improving water quality at the Chesapeake Bay also requires the conservation of wetlands. State and local government has been initiating efforts to preserve the wetlands in the watershed. In Virginia, a formal wetlands management policy began 20 years ago with passage of the Virginia Wetlands Act of 1972. The goal of the Act was to preserve tidal wetlands to “prevent their despoliation and destruction and to accommodate necessary economic development in a manner consistent with wetlands preservation” (Broomhall and Kerns, 1997). Enforcement of the provisions of the Act is a joint responsibility of the State and local governments. Local governments are given the authority to create and administer their own programs if they are in agreement with state legislation. Since approximately 1980, local governments have required most major construction projects in the Elizabeth River watershed that incur wetland loss to provide compensatory mitigation. Research projects have been carried out focusing on quantifying historic wetland losses, establishing management goals, and identifying potential wetland restoration sites. However, few of them consider the impact of climate change.

Uncertainties and Decision-Making Process

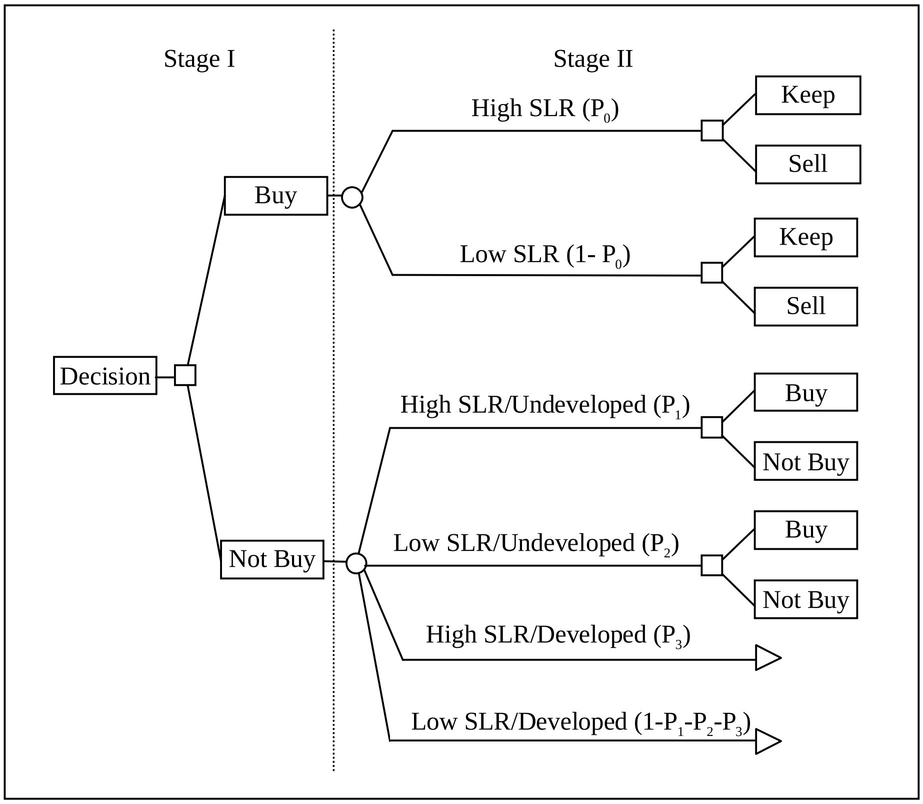
We realize that when consider future situations, various kinds of uncertainties exist and will affect people’s decisions and their outcomes. In the DSSP framework we develop above, we consider two major types of uncertain events that will affect the design and implementation of wetland conservation strategy. One is the acquisition of new information about sea-level rise. Although changes in other climate variables are also likely to affect wetlands, for the purposes of this study, we assume that climate change affects wetlands only through its effect on sea-level rise, i.e., the inundation of wetlands resulting form sea-level rise. We assume that new climate information will become available over time. We simplify the information as indicating low or high sea-level rise. The other type of uncertainty arises from the development probability of candidate undeveloped land parcel that decision-makers consider to buy for wetland migration and restoration. It is necessary to consider this uncertainty, because when decision-makers consider whether to buy an undeveloped land parcel during any future time spot, they need information about the likelihood of the availability of the parcel.

The time period we consider in the study is from 2005 to 2030. We model it as a two-stage decision process. After identifying the candidate undeveloped land parcels for wetland migration and restoration, at 2005 (stage I), we decide how many and which parcels to purchase and preserve. We assume that immediately restoration action will not be taken because decision-makers can wait for new information to avoid unnecessary irreversible investment. At 2030 (stage II), new information of sea-level rise will arrive and decision-makers can adjust their decisions in stage I. The decision process for one parcel is illustrated in figure 1.

Wetlands Conservation Strategies Model

The implementation of wetland conservation requires undeveloped land, which serves as either the buffers for wetland migration or the potential sties for wetland restoration and creation. A major task of conservation strategy is to acquire and preserve undeveloped land for current and/or future use. Because it is essentially impossible to confidently predict the future, an inevitable question we face is how to deal with the uncertainties.

Figure 1. Two-Stage Decision Process



In this study, we adapt a technique called discrete stochastic sequential programming (DSSP). DSSP is a mathematical programming structure that is capable of modeling decision-making under uncertainty with a sequential structure. It was first introduced by Cocks (1968) as a method for “solving linear programming problems where the functional, restraint, and input-output coefficients are subject to discrete probability distributions”. In the presence of risk related factors, employing this method may be more accurately to reflect the true decision-making process, because it allows for explicit consideration of the priori known probabilities of uncertain events. The method involves the simultaneous generation of all (mutually exclusive) possible outcomes and the transference of all variability into the objective function. Rae (1971) enhanced the method and applied it in farm management. DSSP models are typically specified as linear programming structures. In this case, we construct an integer programming structure.

Definition of the probability model is the first step in the construction of a stochastic programming problem. It involves isolation of decision dates and division of the planning period into a number of stages; definition of possible random events (states of nature) within each stage; specification of the probabilities that each state will occur; and a statement of the appropriate information structure (Rae, 1971). The probability distribution of the states of nature determines the relative influence of the different states of nature. Next the activities and constraints of the decision model need to be defined; unlike deterministic programming models, sets of activities and constraints must be specified for each state of nature, i.e. they have to be "state-contingent". The final step is the specification of the decision-maker's goal as a suitable objective function.

The expected cost minimizing two-stage DSSP model that we use appears below.

$$(1)\quad \textit{Minimize} \quad \sum_i X_{1i}C_{1i} + \sum_i P_k X_{2ki}C_{2i} - \sum_i P_k Y_{2ki}S_{2i}$$

subject to:

$$(2)\quad \sum_i X_{1i} + \sum_i X_{2ki} \geq L_h \qquad \text{for } k \in K_h$$

$$(3)\quad \sum_i X_{1i} + \sum_i X_{2ki} \geq L_l \qquad \text{for } k \in K_l$$

$$(4)\quad \sum_i X_{1i}C_{1i} \leq B$$

$$(5)\quad X_{1i} + X_{2ki} \leq 1 \qquad \text{for all i}$$

(6) $Y_{2ki} - X_{1i} \leq 0$ for all i

Equation (1) is the expected cost minimizing objective function. k denotes occurrence of state of nature k in stage II, $k \in (K_h \cup K_l)$. K_h and K_l are two mutually exclusive main groups of states of nature in stage II. X_{1i} denotes the vector of decision variables associated with stage I. We define them as binary variables, which can only take values of "0" or "1" representing "not buy" and "buy" an undeveloped land parcel, respectively. X_{2ki} and Y_{2ki} denote the vectors of decision variables associated with stage II given state of nature k occurs, which are also defined as binary variables. X_{2ki} is similar to X_{1i}, which represents the "not buy" or "buy" decision. Y_{2ki} represents "not sell" or "sell" decision of an undeveloped land parcel[1]. C_{1i} is the costs of buying parcel i in stage I; C_{2ki} and S_{2ki} are the costs of buying parcel i and the revenue of selling parcel i in stage II given state of nature k occurs, respectively. P_k is the probability of state of nature k occurring in stage II.

Equation (2) and (3) are constraints that assure the satisfaction of the conservation goal of "no net loss" of wetlands under the occurrence of groups of state of nature K_h and K_l. Equation (4) is the budget constraint in stage I[2]. Equation (5) and (6) are logical constraints which assure that parcels can not be bought twice and un-bought parcels can not be sold, respectively.

Model Specifications

Sea-level Rise Scenarios

Scenarios are coherent, internally consistent and plausible descriptions of possible future states of the world. We construct climate change and land use scenarios to reflect future situations in our analysis. In this study, we use the sea-level rise projection of Warrick et al (1996) for the Mid-Atlantic region, which uses IS92a scenario, plus a local component of 0.008 inches per year. The projected sea-level rise for Year 2030 is 4 – 12 inches. We use 4 inches as low sea-level rise and 12 inches as high sea-level rise and arbitrarily assign probabilities to them.

Land Use Scenarios

The future land use scenarios developed in this study are originated from the development concepts used in the 2026 Comprehensive Plan of City of Chesapeake, Virginia. Based on current and historic land use growth patterns, we define three development patterns: compact, dispersed and nodal development.

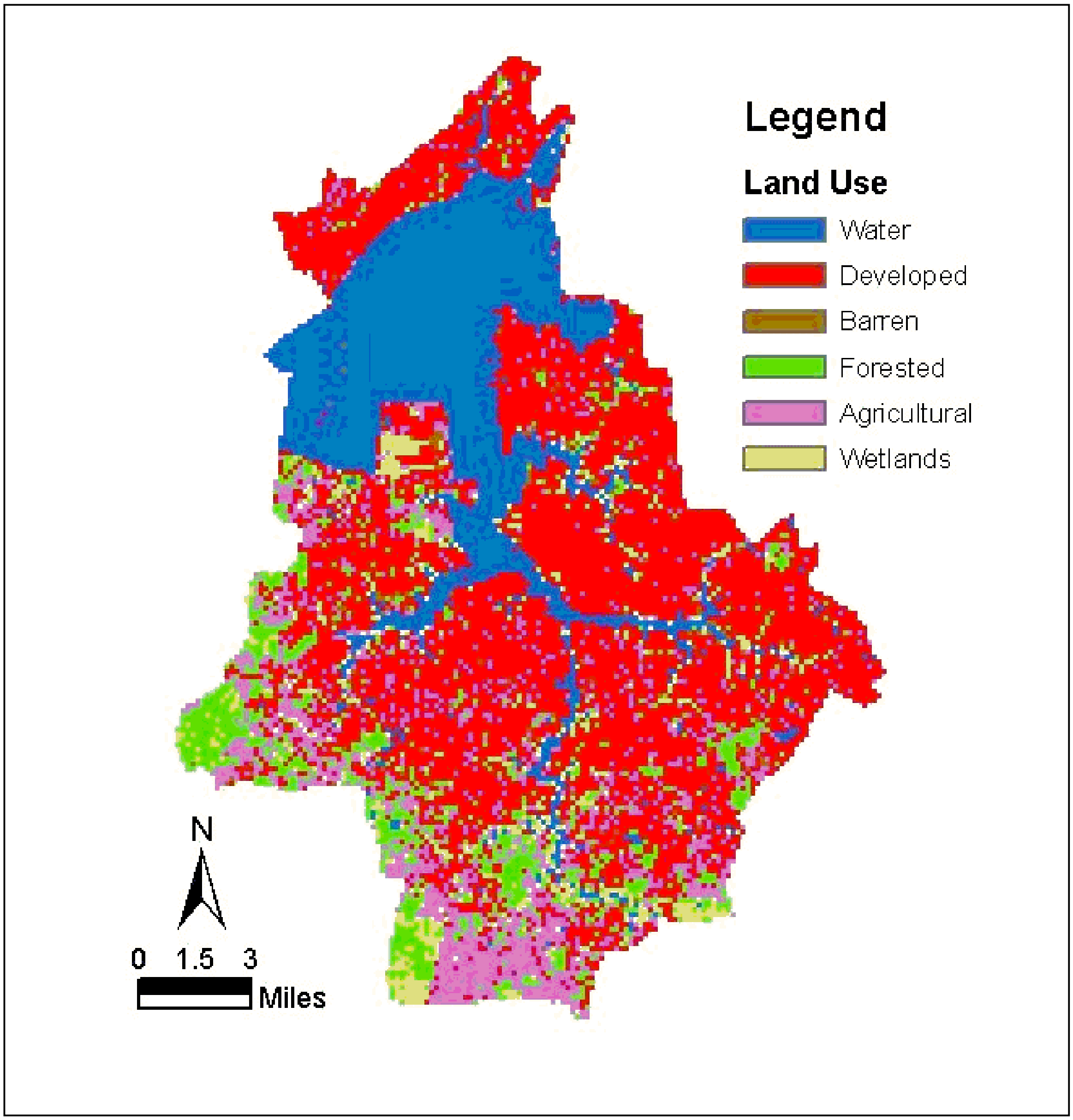
Compact development seeks a denser growth pattern inside a well-defined boundary and rural areas are preserved with low density development. Dispersed development extends the current growth pattern, low density housing, throughout the area. In nodal development, new growth occurs in “nodes” along transportation routes. Rural areas are preserved with well-defined growth areas.

Development Vulnerability Index

To be consistent with the sea-level rise projections, we develop future land use scenarios for Year 2030 using cellular automata (CA) model. CA models are developed to truly represent the dynamics of urban growth. Although early application of CA stresses their pedagogic use, later development extend far beyond the basic element. They are flexible in that they provide a framework which is not overburdened with theoretical assumptions, and which is applicable to space represented as a raster or grid (Almeida et al. 2002). These models can thus be directly connected to raster data surfaces used in geographic information system (GIS). Strict CA model land use change process as a function of what happens in the immediate vicinity of any particular cell. Action-at-distance is forbidden for it is argued that the intrinsic dynamics which generates emergent phenomena at the global level, is entirely a project of local decision which have no regard to what is happening outside their immediate neighborhood (Batty, 2000). The immediate vicinity requirement of strict CA later has been relaxed and the models that have emerged are best called cell-space – CS models rather than CA.

However, in this study, we still adopt the idea of strict CA model to generate development vulnerability index for the undeveloped land within the Elizabeth River watershed. From the numerous studies that examine the drivers of land development, we identify four major drivers: percentage of undeveloped land in immediate vicinity, distance to shoreline, distance to primary roads, and distance to population centers. Theoretical and empirical studies suggest that closer to developed land, shoreline, roads or population centers results a higher probability to be developed.

Figure 2. Land Use of Elizabeth River Watershed, 2001



We use 2001 National Land Cover Dataset (NLCD) as the basis for calculating development vulnerability index (figure 2). NLCD is complied using Landsat 7 ETM+ data. It is in 30 meter pixels, which is too fine for our study, so we aggregate the 30*30 meter cells into 300*300 cells. Coastal NLCD includes 9 classes of land use: water, developed, barren, forested, shrub, non-natural woody, grass, agricultural, and wetlands. We also collected GIS data of shoreline, roads and population centers for the watershed. Then we calculate the four drives for each undeveloped land cell. In order to combine them into meaningful development vulnerability index, we standardize the distance measures. We assign different weights to drives to reflect the three different land use scenarios. For compact scenario, we weight percentage of undeveloped land immediate vicinity by 0.7 and the other three by 0.1 each. For dispersed scenario, we weight the four drives equally. For nodal scenario, we weight distance to primary roads by 0.7 and the other three by 0.1 each. We add a random term for each undeveloped cell to account for the factors that we do not include and the inherent randomness of the land development process. The weighted average of the four drives and the random term consist the development vulnerability index, in which a lower value means a higher probability to be developed. Then for each scenario, we rank the undeveloped cells from low to high based on the index and convert top certain percentage of the cells into developed land by 2030.

In order to make our projections more realistic, we exclude areas that are not likely to be developed in the foreseeable future from the conversion. We use three GIS layers, municipal parks, state property and federal property, as masks to prohibit conversion because development is very unlikely to take place in these areas. The municipal park layer includes public parks and golf courses within the watershed. The state property layer includes land help by state government and agencies, such as the Virginia Department of Transportation (VDOT), Virginia Port Authority and Department of

Military Affairs. The federal property layer includes federal facilities and military land, such as the National Cemetery, U.S. Navy Air Station and U.S. Navy shipyard.

Wetlands Restoration Sites Selection Protocol

In order to identify the potential sites for wetlands restoration, we use a GIS-based sites selection protocol developed by the Center for Coastal Resources Management of Virginia Institute of Marine Science of College of William and Mary in 2002. The protocol is developed based on the basic criteria of restoration sites and has been applied to a selected pilot region of southeastern Virginia.

The protocol is a hierarchical approach for evaluating a suite of conditions within the landscape. The foundation of the hierarchy is land use. The source of land use data is the 1992 National Land Cover Dataset (NLCD), from which they identify that forested and agriculture are the targeting land use type. Then they follow a four-level hierarchical approach.

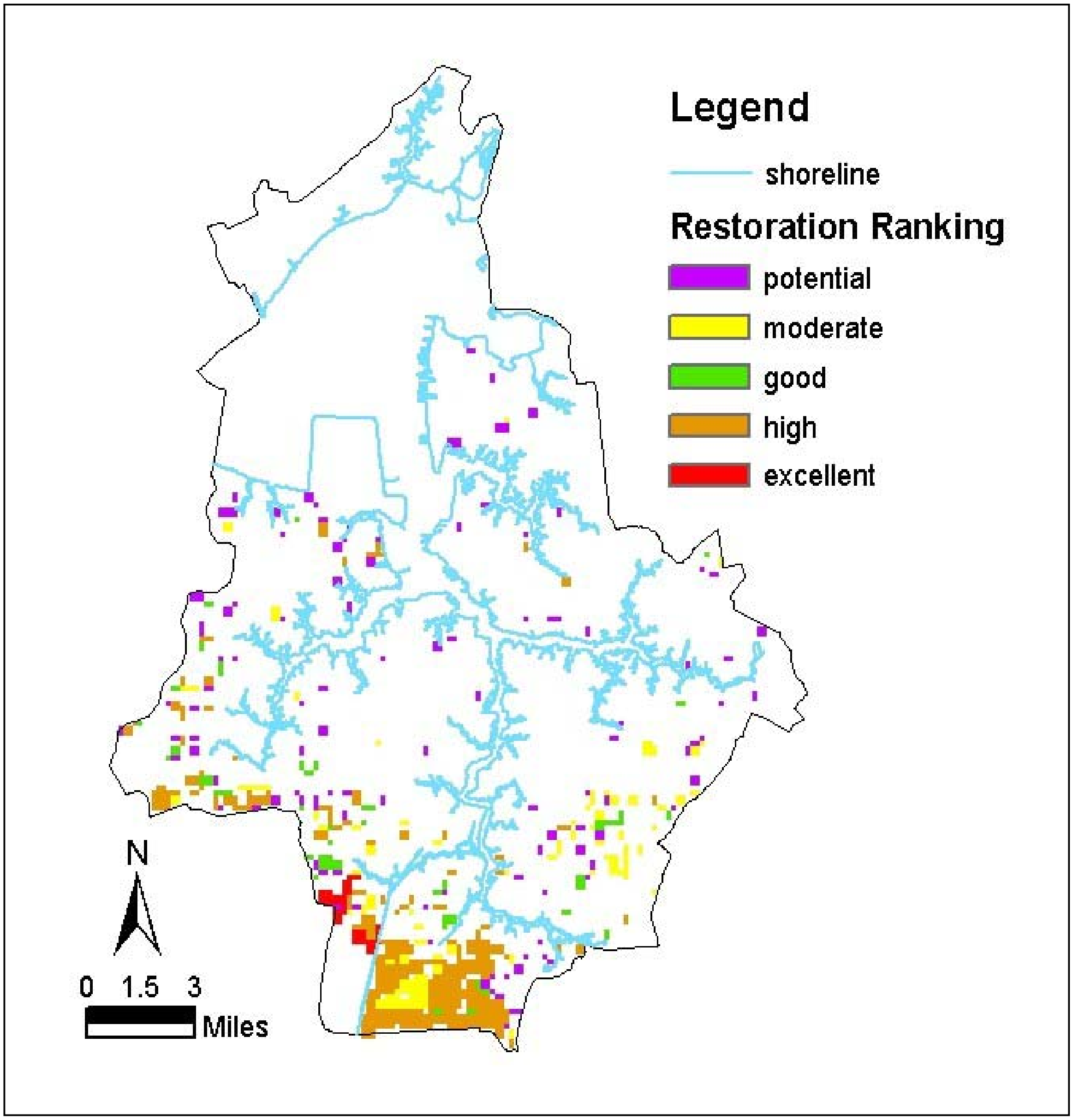
Level 1: Requires that hydric soils be present. All hydric soils greater than 0.25 acres within forested or agricultural land uses are considered plausible sites regardless of hydric soil type.

Level 2: Assumes that in addition to hydric soils, hydrologic connectivity to the hydric soil polygon is present.

Level 3: Integrates existing wetlands into the model. The premise behind this level is an assumption that success of a restored wetland should be enhanced if placed in a wetland landscape.

Level 4: Integrates existing conservation areas into the model. Adjacency to existing conservation areas is considered as a positive factor.

Figure 3. Selected Wetlands Restoration Sites

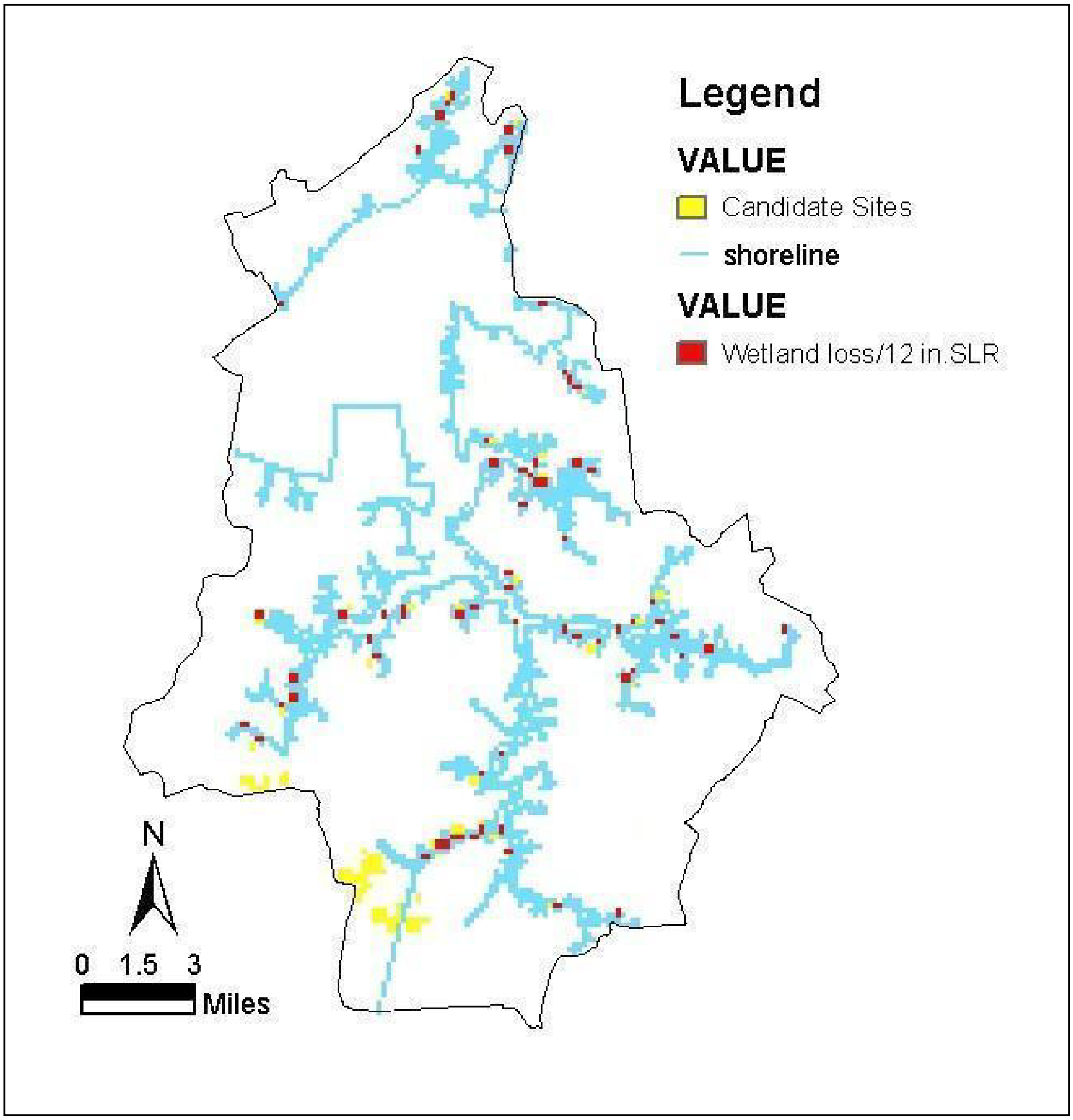


The protocol ranks potential sites based on this hierarchical approach and uses a simple appraisal system that classifies an area as potential, moderate, good, high and excellent. The protocol result for Elizabeth River watershed is shown is figure 3.

Candidate Undeveloped Parcel Selection

Identifying potential sites for wetland migration and restoration is the fundamental part of designing wetland conservation strategies. We first select the migration sites based on two criteria. One is that the undeveloped land cell has to be adjacent the wetland cells that will be inundated by 12 inches sea-level rise. The other one is that this cell has to have an elevation higher than 12 inches, so that in case of sea-level rise, this cell will not be inundated and can have wetland migrated on it. Under 4 inches sea-level rise, 1045.27 acres (47 cells) of wetlands will be lost. Under 12 inches sea-level rise, 1445.59 acres (65 cells) will be lost. However, the total area of available migration sites is 667.18 acres (30 cells), which is a situation that is consistent with the national situation. Therefore, in order to achieve the goal of “no net loss” of wetlands, we have to select restoration sites and restore wetlands. Based on the results of the wetlands restoration sites selection protocol, we select all the “excellent” sites, 533.76 acres (24 cells) and some of the “high” sites, 400.32 acres (18 cells). The candidate conservation sites and the wetlands that will be inundated under 12 inches sea-level rise is shown in figure 4.

Figure 4. Candidate Conservation Sites



The candidate conservation sites we consider are totally 72 cells. Ideally, we should use each of them as a decision unit. But as we mentioned above, the size of DSSP model increases rapidly as the number of state of nature increases. After testing the computation capacity, we decide to group every 6 cells into a parcel and end up with using 12 parcels as our decision units. When grouping the cells, we first distinguish migration sites from restoration sites. Within each functional set, we group the cells in We change the random term of the development vulnerability index 50 times for each cell in each scenario and calculate the probability of each undeveloped cell being developed. We make a conservative assumption that if one cell within a parcel is developed, we consider the whole parcel as developed. The development probability of each parcel under different land use scenarios and different conversion percentage is given in table 1. When considering 12 parcels, there are 2^12 = 4096 combinations. Given the development probability of each parcel, we can calculate the probability of each combination. States of nature in stage II are defined by sea-level rise and land development scenarios, so there are totally 8190 states of nature[3].

Table 1. Development Probability of Compact Development Scenario

Parcel	Conversion Percentage (Compact, Dispersed, Nodal)											
	30%			40%			50%			60%		
	C	D	N	C	D	N	C	D	N	C	D	N
1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	0.9	1	1	1	1	1	1	1	1	1
3	1	1	0.98	1	1	1	1	1	1	1	1	1
4	0.98	0.78	0.76	1	0.94	1	1	1	1	1	1	1
5	1	1	0.92	1	1	1	1	1	1	1	1	1

6	0	0	0.14	0	0	0.3	0	0.4	0.48	0.58	0.58	0.64
7	0	0	0.54	0	0.14	0.68	0	0.46	0.88	0.68	0.76	1
8	0.16	0	0	0.56	0.18	0.1	0.96	0.54	0.38	1	0.82	0.6
9	0	0	0	0	0	0	0	0	0.02	0	0.06	0.16
10	0.86	0.48	0.44	1	0.78	0.72	1	0.96	0.9	1	1	1
11	0.24	0.08	0.32	0.58	0.5	0.44	1	0.78	0.62	1	1	0.86
12	0	0	0.48	0.14	0.18	0.76	0.62	0.52	0.94	1	0.8	1

Other Inputs of the DSSP Model

We model land price based on the development vulnerability index and make the assumption that the higher the development probability, the higher the land price. The candidate conservation sites are either agricultural or forested land. The agricultural land price ranges from $4,500 / acre to $8,000 / acre; the forested land price ranges from $2,000 / acre to $ 6,000 / acre. We use the range of land price and the range of development vulnerability index to set up a linear relationship and use interpolation to get land price for each parcel. Real land price appreciation is also a factor that needs to be considered. We make the assumption that land with a higher current price will have a higher rate of real price appreciation. Again, we assume a linear relationship. Wetland restoration cost has a very wide range, from $10,000 to $80,000 per acre, with an average of $20,000 to $30,000 per acre.

Results and Future Research

We use the CPLEX module of GAMS to solve the DSSP problem. Although the optimal results include the value of decision variables in both stage I and stage II, we are more interested in the decision variables in stage I and the value of the objective function, because the stage II, nothing will be uncertain and it is just a realization of a random event. Sensitivity analysis is conducted in order to identify the effects of input parameters on the model outputs. Because this is an integer programming problem, CPLEX can not generate a sensitivity report. The sensitivity analysis scheme we use is presented in table 2. First we choose a baseline value for each parameter and change one parameter at a time while holding the others at their baseline values.

Table 2. Sensitivity Analysis Scheme

Factor	Values				
Conversion percentage	20%	30%	**40%***	50%	60%
High SLR probability	0.1	0.3	**0.5**	0.7	0.9
Land price adjustment (%)	-20%	-10%	**0**	10%	20%
Real land price appreciation (%)	0	1%	**2%**	3%	4%
Discount rate (%)	1%	2%	**3%**	4%	5%
Budget constraint of stage I (%)**	40%	55%	**70%**	85%	100%

Restoration costs ($1,000/acre)	10	20	**25**	30	80

* Bold font style denotes baseline values.

** Budget constraints are constructed as the percentage of the cost of purchasing all the twelve parcels in stage I.

For the compact development scenario, when all the input parameters take their baseline values, the expected cost is $13,446,000.The optimal decision is to buy Parcel 1, 2, 3, 4, 5, 8, 11, and 12 at stage I, which are the parcels with the highest development probabilities when reaching stage II. We also perform the sensitivity analysis on the compact development scenario. The expected cost changes as the values of input parameter change, the direction conforms to intuition. However, the optimal decision stays the same, which always suggests buying the parcels with the highest development probabilities. One interesting result comes from changing the budget constraint. If we assume that the rate of real land price appreciation is greater than the discount rate, when the budget increases, the expect cost decreases. The optimal decision is to buy as much land as budget permits in stage I and sell the unnecessary part in stage II. A wetland conservation program can actually make money by this buy-low-sell-high action.

For future research, we will run the same analysis for dispersed and nodal development scenarios and compare the results with the compact development scenario. We will also try to see if we add a little tolerance to the goal of "no net loss" of wetlands, how it will affect the expected cost. Restoration cost is the major part of the total expected cost. We can assume technology improvement and examine how it will affect the results. Uncertainty and irreversibility are two features of our framework so we can derive value of information (VOI) from it.

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[1] At stage II, as new information becomes available, we may find that in order to meet a certain wetland conservation goal, we don't need to preserve as much undeveloped land as we planned before. Therefore, we model the option that decision-makers sell a certain amount of undeveloped land.

[2] The budget constraint of stage I is our interest. Because the budget constraint of stage II only affect whether the wetland conservation goals can be reached or not, but will not affect the optimization process.

[3] We exclude the possibility that all the 12 parcels have been developed in stage II, because there is no decision variable associated with this state of nature.

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