USGS

WATER RESOURCES RESEARCH GRANT PROPOSAL

Title: An Integrated Modeling Framework for Analyzing Wetlands Policies: Balancing Ecosystem Services and Economic Factors

Research Category: Category V: Water Law, Institutions, and Policy

[Also addresses objectives for Categories II, III and IV]

Keywords: wetland management, policy analysis, GIS, optimization, spatial statistics, water quality, habitat, flood management.

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Problem Statement

In the last two centuries nearly half of all wetland acres in the conterminous United States have been drained and/or filled in efforts to "reclaim" these lands for agriculture and other "more productive" uses. Wetland conversions have been even more extensive in California, which has lost approximately ninety percent of its historic wetlands. Many of the benefits of un-impacted wetland systems were lost in the process. Wetlands can contribute to water quality enhancement, flood control, recreation opportunities, provision of habitat for valued species, contribution to the stability of global elemental cycles, and more. These benefits, or "ecosystem services," from wetlands are increasingly being recognized and are motivating wetlands preservation and conservation efforts. For example, CALFED, a collaborative planning effort between federal and state agencies in California, is charged with restoring the natural functions of the San Francisco Bay-Delta ecosystem, and wetland restoration is a central component of this high-profile activity. However, development pressure on wetlands remains high in California and throughout the U.S. Many recent economic analyses of trends in wetlands conversion indicate that the costs to society from further wetlands conversions exceed the benefits, so wetland conservation and restoration efforts will often be justified from an economic as well as an ecological point of view. Unfortunately, policy makers currently do not have the tools to effectively incorporate these ecosystem services into on-the-ground wetlands management decisions. Insofar as these considerations do find their way into wetlands policies, it is usually in an uncoordinated fashion, with different agencies focusing on different wetland characteristics or ecosystem services. For large scale planning and restoration efforts, such as the one headed by CALFED, explicitly incorporating wetland ecosystem services into the planning process can provide a rational basis for prioritizing conservation and restoration efforts.

On a regional scale, wetlands managers must decide how many acres of wetlands should be preserved, conserved, and/or restored in a given area, and they must make these decisions in the face of budget and other resource constraints. These decisions are complicated by the interdependent nature of the landscape-level processes that determine the level of these valued ecosystem services. One wetland's contribution to water quality enhancement, for example, will be affected by the type of land-use upstream. A wetland downstream of an agricultural area will be more valuable, from a water quality perspective, than a wetland downstream of an un-impacted natural upland. Management decisions are also complicated by multiple planning objectives. For example, making wetland management decisions to maximize the availability of high quality habitat for migrating bird species may conflict with a strategy to maximize the water quality benefits of wetlands. The aforementioned wetland situated immediately downstream of an agricultural area would be less valuable to a wetland bird species that required large buffer areas of forested uplands around its preferred wetland feeding habitat. The placement of wetlands in the landscape, or their configuration, may be critical in determining the overall level of services that these systems will provide. In addition to the problems associated with balancing competing land uses, managers must balance their desires to make fully-informed decisions with the realities of the current policy-making environment, characterized by imperfect information, legislative and bureaucratic constraints, both budgetary and jurisdictional, and time limitations.

The overarching goal of this research is to create and operationalize a holistic framework for analyzing various ecosystem services provided by wetlands and incorporating this information into wetland policy and management decisions. This framework will aid wetlands managers in making these difficult decisions by giving them the means for empirically investigating the many region-wide trade-offs involved in wetlands policy decisions.

Procedures and anticipated results

To accomplish these goals, this project will integrate various methodologies for analyzing ecosystem services provided by wetlands into a spatially explicit decision-making framework. The project will proceed in two phases. First, we will employ statistical methods to quantify wetland functions and processes as they relate to services that are valued by humans. Biologists and wetland scientists do not generally tailor their research efforts towards providing purely policy-relevant information. Wetland managers need to know how their various environmental objectives will be affected by conditions that they can control. Wetland managers have the potential to affect the number of acres and the placement of wetlands in a region through wetlands restoration and conservation efforts or the granting or denial of conversion permits. Understanding how these land-use changes will affect their overall environmental goals is, thus, of critical import for efficient and effective decision making. In spite of continuing advances in our level of understanding of wetland processes, we still cannot predict how a marginal change in the overall amount of edge that riparian wetlands share with agriculture, for example, will affect the water quality of the adjacent stream, the population numbers of wetland dependant birds, and the expected annual flood damages to neighboring developed land. Expectations can be pieced together, based on a wide array of past ecological and hydrological studies, but since most were not designed with these specific questions in mind, confidence in these predictions is low. Thus, in the first phase of this research project we will conduct empirical ecological investigations with policy questions in mind, thus bridging the gap between what ecologists know about wetland systems and the ecological sophistication, or lack thereof, of our wetland policies. Specifically, we will use spatial econometric and modeling techniques to relate observed levels of indicators of three classes of ecosystem services provided by wetlands – surface water quality enhancement, provision of habitat for important species, and flood control benefits – to landscape wetland other land-use characteristics. Understanding these relationships will allow us to predict the likely impacts of changing these land-use characteristics – i.e. conserving or restoring wetlands in the region.

Many environmental writers refer to these wetland ecosystem services as “free” services. This is true only in the sense that humans do not directly provide inputs into the processes that provide these benefits. However, there are often real opportunity costs associated with these services. If we choose to preserve a riparian wetland adjacent to a stream to reap the water quality benefits from this natural system, we cannot farm that land or otherwise develop it. Not only will economic and environmental objectives conflict, but different environmental goals may conflict with each other as well. This project will determine the degree to which wetland management objectives related to water quality, flood control, and habitat quality may conflict, or complement, each other in the San Francisco Bay-Delta and Central Valley regions of California.

The first phase of the research project will consist of an integration of analyses using a GIS, statistics and econometrics methods, and modeling techniques. A GIS, or geographic information system, is an integrated set of geographically referenced data along with computer hardware and software systems capable of manipulating and analyzing the data. A GIS will be used to obtain measures of the landscape-level variables that are hypothesized to be driving the provision of these wetland ecosystem services in the study area. These variables include the extent and relative position of different land-use types, including different types of wetlands. Multiple regression techniques will then be used to estimate the relationships between these wetland characteristics and three classes of ecosystem services that wetlands can provide: water quality enhancement, flood control, and provision of habitat. The study area for this project will include the San Francisco Bay-Delta region and much of the Central Valley of California. This region of California is an ideal place to undertake this type of analysis. Heavy demands are placed on the remaining wetlands in the area, as scarce water resources must be distributed between urban, agriculture, and other environmental interests.

The second phase of the research project will incorporate the relationships between the extent and configuration of different land-use types and ecosystem services developed in the first phase into a decision-making framework relevant for wetlands policy analysis. Since we know that the provision of various wetland ecosystem services depends to a large degree on spatial considerations – where certain types of wetlands occur in the landscape relative to other natural systems and other types of land uses – explicitly incorporating these spatial considerations, as well as the important ecological characteristics of these systems, into a decision-making framework is essential to fully inform wetlands policy analysis. In this second phase of the project, mathematical programming and optimization techniques will be used to investigate various policy questions. The modeling framework is designed to determine the optimal level of wetlands management (preservation, conservation, and restoration) in the study area, subject to resource and other constraints. The policy analysis will be based on multiple model runs corresponding to different potential management strategies. This project will yield the following results: 1) estimates of the potential environmental benefits from "optimal" wetlands management, subject to agency budget constraints, 2) estimates of the minimum costs of meeting pre-specified environmental objectives through wetlands management, 3) estimates of the differences in environmental benefits between uncoordinated and coordinated wetlands policy-making, and 4) each of these models will result in a map of management actions, so the spatial configuration of the different scenarios can be compared. Finally, and more generally, the project will also yield improved techniques for designing policy-relevant spatially-explicit ecological research. Many classes of environmental issues, in addition to wetland management, have an important spatial dimension, so much of the theory and methods utilized and developed here will be broadly applicable.

In summary, environmental policy-making is often an exercise in balancing values that are not always consistent with each other in the face of budget and other resource constraints. The purpose of this research program is to provide decision-makers with the framework and the means of gathering the information that is necessary to make well-informed trade-offs between wetlands and other land uses, as well as to balance potentially competing environmental goals. From a theoretical standpoint this research will attempt to illuminate the difference between policies that incorporate information regarding ecosystem services and policies that do not. From a practical standpoint, this research will build a set of tools that can aid policy-makers in more efficiently managing our limited wetland resources. Therefore, this project will also be an exercise in balancing important theoretical considerations with practical, real-world applications. Finally, this project will represent a significant step forward in applying new GIS technologies to environmental policy problems. To date, most applications of geographic information systems to environmental policy questions have sorely underutilized the potential of this technology. By incorporating many of the landscape-level interdependencies that are important components of the relationships between wetlands and the provision of ecosystem services valued by society, this project will improve upon GIS studies that merely utilize the spatial data handling capabilities of these systems, and then stack these data layers vertically to display results. Many of these past efforts incorporate only the coincidence of the variables of interest. Though results are spatially explicit, they often ignore many of the important spatial relationships driving the phenomena under study – the adjacencies and overall patterns. By fully incorporating these spatial relationships – adjacencies and patterns as well as coincidences – into the models that will serve as the foundation of this project, we will be able to undertake a more complete analysis of California wetlands policy issues, as well as advance the current level of sophistication of regional environmental policy analysis in general.

Research Proposal

As wetland acres in the U.S. continue to decline, concerns increase over the potential losses of valuable environmental benefits from these natural systems. Wetland losses have been especially severe in California, which has seen a reduction of more than ninety percent from its historic wetlands base. Wetland losses have slowed in recent years, but pressures remain high for conversions to agricultural and urban land-uses. With increased focus on wetlands policy issues, and continuing advancements in the state of wetlands science, effectively incorporating our best understanding of these systems and the societal benefits that they can provide into wetlands management decisions presents a great and meaningful challenge. This project will utilize GIS and mathematical programming techniques to construct and operationalize a set of policy models that can incorporate the landscape-level interdependencies that drive the provision of wetland ecosystem services and address the multiple-objective nature of wetlands policy-making. With this framework we will estimate the environmental impacts and the economic costs of various wetlands management strategies for the San Francisco Bay-Delta and Central Valley regions of California.

The first section of this proposal describes the nature, scope, and objectives of the project. Here, the motivations for the research are discussed, and the expected results are placed in the context of today's wetlands and water policies in California. The next section describes the methods, the modeling framework, and the data and software requirements for the project. The final section presents a review of the literature on wetlands functions and valuation and policy analysis that provide the foundation for this research program.

Nature, Scope and Objectives of Proposed Research

This project will combine spatial econometric analyses of wetland ecosystem services with policy models designed to estimate the impacts of various wetland management strategies. The research described here will represent one of the most integrated and holistic frameworks for analyzing wetland policies to date. The study area includes the San Francisco Bay-Delta and Central Valley regions of California. The estimated models and the numeric results will be specific to the study area, but the techniques and modeling strategies can be readily transferred to other regions.

This line of research is motivated by a desire to explicitly incorporate considerations of wetland ecosystem services into wetlands policy decisions. Society is coming to recognize the value of these services as the ecological state of understanding of wetland systems continues to increase. However, these developments have only provided general incentives for wetland policies designed to stem the loss of total wetland acres. The "no net loss" policies of the last two presidential administrations represents the culmination of political and societal support for protecting this dwindling resource, and the best scientific understanding of the functions and values of these systems. However, it is not clear that simply ensuring that the total amount of wetland acres does not change over time is the most economically or environmentally efficient way to manage our remaining wetlands (USDA 1998). The "no net loss" policy seems to be based on an implicit assumption that functions and values of wetlands are homogeneous for all wetland types and locations. Advancements in wetlands science and landscape ecology tell us that this assumption is false (Murkin 1997, Roth 1996, Turner 1989, Whigham 1988). The impetus for this project comes from our belief that by incorporating our growing understanding of the differences between wetland types and the importance of spatial relationships for determining the "value" of wetland systems, wetlands policy making can be improved. We begin with two premises: 1) Wetland policy and management decisions that are better informed by considerations of the degree to which these systems contribute to the provision of "ecosystem services" valued by humans will be more efficient and effective, and 2) as mentioned above, we believe that differences in wetland type and position in the landscape will be important factors determining each wetland's contribution to these services.

The "ecosystem services" that wetlands can provide include water quality enhancement, flood control, recreation opportunities, provision of habitat for valued species, contribution to the stability of global elemental cycles, and more (Mitsch and Gosselink 1993). This project will focus on three of these: water quality, flood control, and provision of habitat. These three are the most frequently cited in the literature and are presumed to be the most important for policy purposes. All three are indisputably integral to California water policy. From a theoretical standpoint, analysis of these three classes of environmental benefits should provide sufficient insights into the potentially complementary or conflicting nature of the different types of environmental objectives that policy makers and managers must often incorporate into their decisions. Also, given the highly contentious nature of water policy in the San Francisco Bay-Delta and Central Valley regions of California, the choice of these three classes of environmental benefits should be especially appropriate for this research project. The relationships between wetlands and surface water quality and flood management will directly inform water policy issues in the region, and the inclusion of habitat values of wetlands will provide a potential counterpoint for these water-related objectives.

The ultimate objective of this project is to construct an integrated policy analytic model of the environmental impacts and economic costs of wetland management decisions in the study area. More specifically, the project will be driven by the following goals:

I. Estimate parameters for functions relating wetland characteristics and other land-use characteristics to the provision of the three classes of wetland ecosystem services mentioned above. For the water quality relationships, this will be done using spatial econometric techniques to relate wetlands and land-use data manipulated using a GIS to surface water quality data collected from surface waters in the study area. The habitat relationships will be analyzed using a similar strategy, by relating wetlands and land-use data to species occurrence and count data in the study area. The flood management functions of wetlands will be estimated using GIS-based hydrologic models to predict changes in expected flooding levels and duration resulting from changes in land-use patterns in the study area.

II. Construct a policy model to estimate the impacts of different wetlands management decisions, and determine the optimal configuration of wetlands management actions in the study area given specific environmental objectives and resource constraints. These objectives and estimated impacts will be in terms of the three classes of environmental benefits mentioned earlier. For example, the model will be able to estimate the expected changes in surface water quality throughout the study area resulting from a wetlands policy strategy intended to maximize the flood control benefits of wetlands, subject to a budget constraint. Also, the model will estimate the expected costs of each management strategy.

III. Finally, through various model runs we will produce a set of outputs that will represent: 1) estimates of the potential environmental benefits from "optimal" wetlands management, subject to agency budget constraints, 2) estimates of the minimum costs of meeting pre-specified environmental objectives through wetlands management, 3) estimates of the differences in environmental benefits between uncoordinated and coordinated wetlands policy-making, and finally, 4) each of these models will result in a map of management actions, so the spatial configuration of the different scenarios can be compared.

In summary, this project will operationalize a general method for regional wetlands policy analysis and produce estimates of the impacts of various wetlands management scenarios. It is motivated by a desire to address a particular set of environmental policy issues in the study area, but the techniques developed here will be applicable to other regions and other policy issues as well. Like the wetlands policy model in this project, many other environmental problems are driven by land-use patterns and multi-objective decision situations.

Methods, Procedures and Facilities

The first phase of the project requires estimation of functions describing the provision of the three classes of ecosystem services from wetlands in the study area: water quality, flood control, and habitat for other species. The independent variables of interest will depend on the class of ecosystem services being investigated. The following section describing the modeling approach gives a more explicit review of the approach and the variables to be included.

Phase I: Estimating relationships

The study area for this project includes the San Francisco Bay-Delta region and much of the Central Valley of California (Figure 1). This region is an ideal place to undertake this type of analysis since heavy demands are placed on the remaining wetlands in the area and scarce water resources must be distributed between urban, agriculture, and other environmental interests. The study area must be broken down into units of analysis, or "patches," to estimate the relationships between land-use and wetland characteristics and the provision of the three types of ecosystem services. The size and configuration of each patch will be delineated in the GIS and determined by the pattern of land-use types in the study area and the resolution of the analysis. The median sized patch might be a 160 acre agricultural field, with some patches with no potential for management (conversion to wetlands), such as core urban areas, being much larger. Each path will be characterized by one or more land-use types, including different wetland types hypothesized to affect the provision of each ecosystem service. Land-use types may include urban, agriculture, and wetlands. Agricultural land may be subdivided further into field-crop types, orchards, and pastures, and wetlands can be broken down into more specific types such as riverine, palustrine, and lacustrine.

This section proceeds by outlining the functional estimation approach for each ecosystem service in turn. The relationship between wetland variables and water quality and habitat indicators for the study area will be empirically estimated using statistical multiple regression techniques supported by a GIS. A GIS facilitates the integration of many disparate data sources as long as the data is geographically referenced. We then discuss the policy model and how we integrate these estimated relationships into the decision-making framework. This section concludes with a discussion of the data and software requirements.

- *Water Quality*

For the purposes of estimating the water quality functions, the land-use patches must be grouped into a number of (relatively) independent hydrologic basins. These basins will be defined by the portion of the landscape that drains into each stream reach between water quality sampling stations from which data will be utilized. Standard GIS techniques will be used to delineate these basins based on water monitoring station locations and a digital elevation model (DEM) of the study area. Initial efforts will focus on the concentration of total Nitrogen as a general indicator of water quality. Other constituents may also be modeled as time and available data allows.

We model the concentration of total nitrogen at monitoring station *v*, N_v, as a function of the nitrogen concentration at the monitoring station immediately upstream and the distance weighted area of each land-use type adjacent to the stream reach. Interactive terms can also be included to account for some of the land-use-type specific edge effects that may be important In its most basic form, this model is operationalized as follows:

$$N_v = \alpha + \beta_0 N_{v-1} + \sum_{j=1}^{m} \beta_j \sum_{i=1}^{n} \frac{p_{ij}}{hd_{i,v}} \qquad (1)$$

where

N_v = the concentration of total-N at water quality monitoring station *v*,

N_{v-1} = the concentration of total-N at water quality monitoring station *v*-1, immediately upstream of station *v*

$p_{i,j}$ = the area of patch *i* in land-use *j*. There are a total of I patches in the study area (*i* = 1,…I),

and a total of J different land-use types (*j* = 1, … J).

$hd_{i,v}$ = hydrologic distance of patch *i* from stream reach *v*; $hd_{i,v}$ = an arbitrarily large number if

patch *i* is not hydrologically connected to stream reach *v*

α, β_0, β_1, … β_J are the parameters to be estimated. β_j is the marginal change in the concentration of total-Nitrogen at the downstream end of stream reach *v* resulting from a unit change in the distance weighted area of land-use type *j* that is hydrologically connected with the stream reach.

- *Habitat quality*

The estimation of the habitat values of wetlands will rely on a similar methodological approach. Occurrence or count data for bird species that rely on wetland habitats will be associated with the land-use patches described above. The following independent variables are assumed to be functionally related to the abundance of species *y* on a given patch *i*: the amount of area in each land-use type in the patch, the length of edge the patch shares with other land use types, the proportion of the surrounding landscape in each land use type, the diversity of land use surrounding the patch, and the general shape of the patch.

The habitat model is then operationalized as follows:

$$S_{yi} = \sum_{j=1}^{J} \delta_j p_{ij} + \sum_{j=1}^{J} \tau_{yjl} \sum_{l=1}^{J} \frac{EP_{ij} p_{il}}{a_i} + \sum_{j=1}^{J} \varphi_{yjg} PP_{ijg} + \gamma_{yg} DIVP_{ig} + \varphi_y \frac{PER_i}{a_i} \quad (2)$$

where

δ_j = the change in the number of individuals of species *y* observed on a patch with a unit change in the area of the patch in land-use type j,

$\tau_{y,j,l}$ = the change in the number of individuals of species *y* observed on a patch with a unit change in the length of edge shared with land use type *j*,

$\varphi_{y,j,g}$ = the change in the number of individuals of species *y* observed on a patch with a unit change in the proportion of land-use type *j* within a distance *g* of the patch,

$\gamma_{y,g}$ = the change in the number of individuals of species *y* observed on a patch with a unit change in the diversity of land-uses within a distance *g* of the patch,

ϕ_y = the change in the number of individuals of species *y* observed on a patch with a unit change in the perimeter to area ratio of the patch,

$EP_{i,j} = \sum_{k=1}^{I} \frac{el_{i,k} p_{k,j}}{a_k}$ = the amount of edge patch *i* shares with land-use type *j*,

where

$el_{i,k}$ = length of edge shared between patch *i* and patch *k*; *k* = 1, … I

$PP_{i,j,g} = \frac{\sum_{k=1}^{I} bd_{i,k} p_{q,j}}{\sum_{j=1}^{J} \sum_{k=1}^{I} bd_{i,k} p_{k,j}}$ = the percentage of the landscape in land-use type *j* within a distance *g* from the edge of patch *i*,

$bd_{i,k} = 1$ if $d_{i,k} \leq g$, 0 otherwise, where *g* is the radius of the buffer around patch *i*, and

$DIVP_{i,g} = \sum_{j=1}^{J} PP_{i,j,g} \ln(PP_{i,j,g})$ = the diversity of land-use within a radius *g* of patch *i*.

The first term in equation (2) represents the area of each land-use type that occurs on the patch in question. The second term accounts for the amount of edge that the patch shares with other land-use types. The third term represents the proportion of each land-use type within a buffer of width *g* (which approximates the average "roaming range" of the species) around the patch. The fourth term represents the diversity of land-use types surrounding the patch. This measure will increase with an increase in the number of land-use types in the range, and it will decrease with an increase in the relative areal dominance of one or a few of the land-use types in the range. The final term is the perimeter to area ratio of the patch, which accounts for the shape of the patch. Each of these variables are hypothesized to be potentially important factors affecting habitat quality for various species (Turner 1989, Forman 1997). This first phase of the project will estimate the relative importance of each factors for the species of interest by statistically relating these measures to occurrence and abundance data for that species.

- *Flood control*

The flood control functions will be modeled using a different strategy. A GIS will be used to model the extent of flooding expected to result from different sized storm events in the study area. For this analysis, the study area will be broken down into equal sized “cells,” to form a grid, to facilitate the hydrologic modeling functions of ARC/INFO’s GRID module. The model must include parameters for each land-use type that describe the behavior of water as it flows over each cell in the landscape. Then, the impacts of changing different sections of the landscape (corresponding to the land-use patches described earlier) can be analyzed by forcing a change in the model and comparing the results to the outputs of earlier model runs. These simulations will capture some of the uncertainly associated with the provision of wetland ecosystem services because estimated flood control benefits will depend upon the severity and frequency of precipitation events in the study area – a fundamentally stochastic phenomenon.

Phase II: The policy model

Next, we construct an optimization model that incorporates the functions described above. We consider a hypothetical manager who must decide how to manage all of the wetland patches (or potential wetlands) in the region. Potential management actions will include:

> 1. Preservation – this could involve purchasing a wetland patch outright, purchasing a conservation easement, or refusing to grant a conversion permit to ensure that the wetland is not converted to another land-use type in the future;
>
> 2. Conservation – actively managing an existing wetland patch to enhance its ability to provide some valued service; for example, managing a marsh to provide high quality waterfowl habitat;
>
> 3. Restoration – purchasing a non-wetland patch and converting it to a wetland.

Patches with the potential for management will be defined by the extent of current wetlands, as well as the extent of hydric soils, historic wetlands, and areas with topographic characteristics appropriate for wetlands construction. The policy models will also incorporate conversion expectations for each land-use patch in the study area independent of management actions. Historic conversion rates in the study area, modified by information on the relative value of each land-use patch in different uses, will be used to estimate the probability that each patch will be converted to another land-use type. These probabilities will form the basis of our expectations of the future configuration of the landscape if no management actions are taken.

The wetland management strategies will be modeled as different optimization problems. For example, a decision-maker most interested managing wetlands for the surface water quality enhancement benefits they can provide will be modeled as choosing patches for management to minimize the expected volume-weighted concentration of a key water quality parameter (here total-Nitrogen) in the study area, subject to a budget constraint:

$$\text{Min} \sum_{v=1}^{V} \text{Vol}_v \times E[N_v] \qquad (3)$$

$$\sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{l=1}^{J} \sum_{q=1}^{Q} (c_{i,q} p_{i,j} r_{i,l,q} mc_{j,l}) \leq \text{BUDGET}$$

where

$$E[N_v] = \alpha + \beta_0 E[N_{v-1}] + \sum_{j=1}^{J} \beta_j \sum_{i=1}^{I} \frac{p_{i,j} + \sum_{q=1}^{Q} c_{i,q}(r_{i,j,q} - p_{i,j})}{hd_{i,v}}$$

Vol_v = the volume of water in stream reach *v*,

$c_{i,q}$ = 1 if patch *i* is managed at level *q*, 0 otherwise

$p_{i,j}$ = the expected area of patch *i* in land-use *j* if the patch is not managed

$r_{i,j,k}$ = the expected area of patch *i* in land-use *j* if the patch is managed at level *q*

$mc_{j,q}$ = per area cost of converting land-use type *j* to land-use type *l*

The manager's problem is to choose $c_{i,q}$ – a {0,1} variable indicating management – for all potential management patches in the region to optimize the objective function (Equation 3). This model has a similar form as the model used to estimate the relationship between land-use patterns in the study area and water quality described earlier (Equation 1), and we use the parameters estimated from that model here. But the policy model includes the management decision ($c_{i,q}$) and takes on a different interpretation. The expected concentration of total-Nitrogen at the downstream end of stream reach *v* is a function of management decisions *and* expectations regarding the configuration of the landscape after all changes have been made. These expectations are represented in by $p_{i,j}$ and $r_{i,j,q}$, which are defined above. By modifying the numerator of the third term in the equation above, we introduce the management decision into the policy model while retaining the functional form of the models used to estimate these relationships previously. We assume that the parameters α, β_0, β_1, … β_J will remain constant through the course of the land-use changes.

The management decision can be similarly incorporated into the habitat models. For example, the strategy of a decision-maker who is most interested in managing wetlands in the study area for their habitat benefits will be modeled by choosing $c_{i,q}$ for all *i* to maximize the expected total population(s) of one or more important species subject to a budget constraint:

$$\text{Max} \sum_{y=1}^{Y} W_y E[S_y] \tag{4}$$

$$\sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{l=1}^{J} \sum_{q=1}^{Q} (c_{i,q} p_{i,j} r_{i,l,q} mc_{j,l}) \leq \text{BUDGET}$$

where

W_y = the relative management importance, or weight, assigned to species *y* by the manager,

$$E[S_y] = \sum_{i=1}^{I} \left[E[A] + E[B] + E[C] + \gamma_{y,g} E[DIVP_{i,g}] + \varphi_y \frac{P_i}{a_i} \right]$$

$$E[A] = \sum_{j=1}^{J} \delta_j \left[p_{i,j} + \sum_{q=1}^{Q} c_{i,q} (r_{i,j,q} - p_{i,j}) \right],$$

$$E[B] = \sum_{j=1}^{J} \tau_{y,j,l} \sum_{i=1}^{I} \left[E[EP_{i,j}] p_{i,l} + \sum_{q=1}^{Q} c_{i,q} (E[EP_{i,j}] r_{i,j,q} - E[EP_{i,j}] p_{i,l}) \right], \text{ and}$$

$$E[C] = \sum_{j=1}^{J} \varphi_{y,j,g} E[PP_{i,j,g}]$$

Again, this model has the same functional form as the habitat model described in the previous section, but includes the management decision in an optimization framework. The policy analysis will be based on multiple model runs corresponding to different management strategies. First, patches will be chosen to maximize gains in each environmental objective (ecosystem service) in turn, subject only to an agency budget constraint. A fourth objective that will be included in the policy framework will be to preserve a “representative set” of wetland types. Managers may be interested in ensuring that, at a minimum, a certain number of acres of tidal salt marsh, vernal pools, riparian wetlands, and other, even more specific types of wetlands remain protected regardless of their contribution to any other environmental objectives. This wetlands policy objective is analogous to the problem of selecting reserve sites for efficient species conservation (Camm et al 1996). Specifically, these management strategies are as follows:

- Choose patches for wetlands management to maximize the expected volume-weighted total-Nitrogen concentration reduction in surface waters in the study area, subject to a budget constraint.

- Choose patches for wetlands management to maximize the expected increase in total population numbers of wetland-dependent birds in the study area, subject to a budget constraint.
- Choose patches for wetland restoration to maximize the expected reduction in annual flood damages, subject to a budget constraint.
- Choose patches for wetland restoration to maximize the expected diversity of wetland types in the study area, subject to a budget constraint.

Other model runs will consider various means for incorporating multiple criteria, either through modification of the constraint set or the objective function. For example, we can choose patches for wetlands restoration to maximize the expected volume-weighted total-Nitrogen concentration reduction in surface waters in the study area subject to a budget constraint, *and* subject to constraints that ensure there will be no reduction in expected total population numbers of wetland-dependent bird species, no increase in expected flood damages, and no reduction in the expected diversity of wetland types in the study area. This allows us to analyze the implicit trade-offs involved in wetlands management (i.e. How much less water quality enhancement can we attain if the manager is constrained to maintain the other ecosystem services?). Finally, we will use a multi-objective model with pre-specified weights indicating the relative importance of each of the three classes of environmental benefits to estimate the effects of shifting priorities (i.e. changing the weights). The full suite of results from all of the model runs will indicate the complimentary, or conflicting, nature of these different environmental objectives.

Data, software, and facilities

The data requirements for this type of analysis are formidable, and the success of this project will depend to a large degree on the depth and quality of the database constructed. However, a significant data collection effort is already under way and a majority of the data is in hand.

Several potential sources of data provide the foundation of the database. First, the National Wetlands Inventory database,[1] maintained by the U.S. Fish and Wildlife Service, contains geographically referenced data on wetland distributions by vegetation type, substrate type, water regime, water chemistry, and soil type. The water quality data will be based on EPA's STORET database.[2] Additional water quality data is drawn from the USGS water data storage and retrieval system (WATSTOR) which consists primarily of data from sampling points at the downstream end of hydrologic accounting units.[3] Bird abundance data will be based principally on the Christmas Bird Count

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1[1] http://www.nwi.fws.gov/Welcome.html

2[2] http://www.epa.gov/WOW/STORET/ sthp.html

3[3] http://www.fgdc.gov/FGDP/Water_Data.html database maintained by the Audubon society,[4] and the North American Breeding Bird Survey database maintained by the USGS.[5] Abundance or occurrence data for other species may be derived from the Natural Diversity Database maintained by the California Department of Fish and Game.[6] Further data will be collected from local, more detailed studies of wetlands in the study area, including breeding bird atlases for specific counties in the study area.

The methods required for the second phase of the project include spatial modeling using a GIS, numerical optimization techniques, and multi-objective decision-making techniques. The spatial analyses and modeling will be done with ESRI's ARC/INFO, GRID, and ArcView software. Most statistical analyses will be done in SAS, and the optimization models will be programmed in GAMS. UC Davis is the home of one of the state's premiere GIS laboratories, the Information Center for the Environment (ICE). As a Co-PI for ICE, we will be able to take advantage of much of the hardware, software, and expertise of the ICE lab, which has been utilizing GIS technologies to address some of California's most pressing environmental and natural resource issues virtually since the advent of the technology.

Related Research and Literature Review

Working under the assumption that wetlands were merely wastelands that stood in the way of more valuable land uses, private parties as well as government agencies directly and indirectly contributed to the destruction of millions of acres of wetlands. Of the 221 million acres of freshwater marshes, prairie potholes, bottomland hardwood swamps, and other types of systems that all fall under the title of "wetlands," only about 103 million acres remain (Dahl 1990, Hook 1993). Wetland losses have not been distributed evenly, by location or by type. Some states have lost nearly all of their wetlands, and some types of wetlands have been hit especially hard. Reasons for these losses are varied and complex. Purely private incentives were and are an important source of pressure on our wetland resources (Machacek et al 1994). Also, there is a long history in this country of government programs that provided extra incentives for converting wetlands to other uses (Roberts 1993, Robinson 1993, Turner 1991). But even today's relatively progressive attempts to restore a better balance between wetland conservation and conversion suffer from a lack of understanding of how these systems function ecologically, especially on a landscape scale, and how these functions contribute benefits to society.

The relationship between wetland processes and water quality has received significant attention in the literature. Many of these studies are input-output studies of individual wetlands or small watersheds that treat the wetland as a black box through which water flows and across which water quality changes. A mass balance approach is generally used to describe the fate of the constituents of concern entering the wetland, although very few

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4[4] http://www.nmt.edu/~shipman/z/cbc/db_spec.html#cen

5[5] http://www.mbr-pwrc.usgs.gov/bbs/bbs.html

6[6] http://www.dfg.ca.gov/Nddb/nddb.html of these studies actually account for all of the pathways known to be important for water quality functions (Nixon and Lee 1986). Considering the volume of published research of this type, surprisingly few concrete generalizations have emerged. Further research needs to be undertaken to investigate how the oft-studied small-scale ecosystem translate into larger-scale landscape level phenomena (Brinson 1993, Gosselink 1990, Mitsch 1992).

The key processes which determine the effects of a wetland on the quality of waters flowing through it include: sediment deposition (mineral or organic), atmospheric deposition, nitrogen fixation, uptake by vegetation (Adamus et al 1991, Marble 1990), litter accumulation and decomposition, denitrification (wetlands (Chescheir et al 1991, Zak and Grigal 1991, Groffman and Hanson 1997, Gilliam 1994), and volatilization. Sediment deposition can improve water quality by reducing turbidity and removing phosphorus or heavy metals sorbed to particles. Sedimentation increases with a decrease in flow rate, and water velocity is generally slower in a wetland than in the incoming or outgoing streams. Therefore, wetlands can often serve as "retention basins" where long detention times allow for significant particulate settling. Denitrification is the most important mechanism for nitrate removal in wetlands (Chescheir et al 1991, Zak and Grigal 1991, Groffman and Hanson 1997, Gilliam 1994). Denitrification occurs mostly at the soil-water interface in flooded soils with low redox potential. This would imply that the most important factor for determining the rate of nitrate removal in wetlands is the frequency and duration of flooding, which controls the degree to which wetland soils are anoxic. Sorbtion of nutrients by wetland soils can also have a significant effect on water quality, especially in terms of phosphorus retention. Richardson (1989) found that the potential for wetland soils to sorb phosphorus is highly correlated with the extractable aluminum content in the soil (especially under anaerobic conditions), which means mineral soils will generally be better at retaining phosphorus than organic soils. Many of these physical and hydrologic characteristics of wetlands are captured by the classification system utilized by the National Wetlands inventory, which forms the foundation of the wetlands land-use data for this project. Thus, we will be able to incorporate many of these hypotheses regarding wetland processes into the ecosystem service model estimations in the first phase of the project.

In addition to the above studies, which focused on site-specific ecosystem processes, there is a growing body of literature that investigates some of these same relationships on a landscape scale. Childers and Gosselink (1990) found that the percentage of wetland forest cover cleared was significantly positively related to concentrations of these constituents in nearby streams. Whigham et al (1988) found that water quality functions of wetlands depended in part on their relative position in the landscape. They suggest that upstream riparian wetlands are most important for nitrogen assimilation and sedimentation of large particles, but downstream wetlands have a larger role in fine sediment and associated phosphorus retention. De Laney (1995) discussed some of the competing hypotheses regarding the optimal placement of wetlands in the landscape for flood control and water quality benefits. One school of thought maintains that multiple, smaller freshwater marshes in a watershed's upper reaches can prevent downstream wetlands from getting washed out during storm events since they can act as detention basins and prevent flood waters from becoming organized. A competing perspective maintains that a single, large downstream wetland would perform better at reducing floodwater velocity and volume. Our methods for estimating the water quality and flood control relationships in the first phase of the project will address these hypotheses as well. One of the more ambitious landscape studies of wetlands and water quality is presented by Johnston el al (1990). Johnston and her colleagues used regression analysis to relate a number of landscape wetland attributes to downstream yearly and seasonal water quality and flow averages for fifteen watersheds in the Minneapolis St. Paul region. A GIS was used to measure thirty-three watershed variables, and these were related to data on downstream water quality. Three of the eight significant principal components were associated with wetland variables: wetland extent, wetland proximity, and herbaceous marsh extent. These landscape wetland studies are at the appropriate scale to inform regional policy analysis, so we will adopt many of the approaches of these researchers. However, wetland landscape studies in California are conspicuously underrepresented, so we will be estimating many of these relationships in the study area for the first time.

The flood control benefits of wetlands have also received attention in the literature. Some of these studies are principally concerned with the hypothesized relationships between flood control benefits and wetland extent and location in the landscape (De Laney 1995, Hey 1995, Rothe 1995, Hillman 1998). Other researchers have undertaken modeling studies in attempts to predict the likely results of manipulating wetlands in the landscape (Roman et al 1995, Curmi et al 1998). This research project will follow the lead of these earlier studies and utilize the most appropriate spatial hydrology modeling techniques available in order to estimate the relationships between the probability of flooding and the extent and location of wetlands in the study area. But the thrust of our analysis is to model the hydrological relationships so that the results can serve as inputs into the policy models in phase two of the project.

Finally, a number of wetland scientists have studied the habitat values of wetlands for important species (e.g. Doust and Doust 1995, Faulk and Monahan 1996). Baker et al (1995) studied Sandhill Crane nesting habitat preferences using a GIS. They were able to differentiate between preferred habitat and avoided habitat within an area encompassed by a 200-m radius around nest sites. They could find no significant differences at coarser spatial scales. Their results illustrate the potential scale dependence of species-habitat preferences. Batzer and Resh (1992) studied wetland traits that can enhance waterfowl habitat. They were principally concerned with measures for controlling mosquitoes, but they also studied strategies for enhancing the populations of the macroinvertebrates that are important in waterfowl diets. Skagen and Knopf (1994) studied the responses of migrating shorebirds to wetland habitat dynamics within and between seasons. Studies such as this one illustrate the high within-year variability that can characterize the wetland processes that affect local species abundances. For regional policy analysis, what is needed most are estimates of how long-term average bird abundances will respond to changes in extent and/or location of certain wetland types. The species-habitat model estimations in the first phase of this project will be designed to provide just this type of information.

It is this growing body of literature reviewed above that will provide the foundation for our empirical investigations of these three classes of wetland ecosystem services. But we will also appeal to the wetlands valuation literature, which provides several good examples of attempts to rigorously specify the functional relationships between certain wetland characteristics and some output valued by society. This wetland valuation literature can be categorized into two general classes. The first type attempts to estimate the economic contribution of wetlands in a certain geographical area, usually based only on one class of the potential benefits mentioned above. These studies often employ relatively rigorous valuation functions and empirical estimation techniques, effectively sacrificing comprehensiveness for a precise estimate of one component of the total value (Farber 1987, Lynne et al 1981, Barbier 1994, Gren 1995, Swallow 1994). Studies in the second category sacrifice precision for comprehensiveness as they attempt to estimate a number closer to the total value of the wetlands in a certain area using gross economic measures based on the market value of goods and services supported by wetland functions (Farber and Costanza 1989, Thibodeau 1981, Gupta and Foster 1975). Unfortunately, none of these studies provide the holistic methodological framework necessary for making wetlands management decisions on a regional scale.

A small body of literature relates to prioritizing wetland management goals (Hruby et al 1995, Coiacetto 1996, Llewellyn et al 1996). However, each of these studies is designed to provide "best guesses" based on expert opinion in the absence of hard evidence regarding the values of wetland services in a region. They are admittedly ad-hoc in that the final ranking of sites that deserve management attention is based on subjective weighting of the importance of different wetland characteristics. This research project incorporates empirically rigorous functions describing the relationship between wetland characteristics and their valued services into a formal decision making framework, and thus represents a significant advancement over these studies.

Finally, Underhill (1994), Camm et al (1996), and Ando et al (1998) investigate the problem of choosing reserve sites for efficient species conservation in the United States. Their objective is to choose counties within which to set up reserves to minimize the cost of including all species in the reserve network. Ando et al (1998) find that the solution to the reserve selection problem is significantly affected by the differences in the cost of land in each county. Our problem of choosing wetland patches to manage is a similar one. However, the previous studies are conducted at a county level of aggregation, which is not as useful for policy makers as a regional study with a much smaller unit of analysis. We will choose patches, on the order of 200 acres in size, and the level of management for each patch, to maximize the provision of environmental benefits from wetlands. As with the reserve site selection results, we expect differences in the cost of land throughout the study area to significantly affect the solutions.

The wetlands literature is still short on studies that investigate the large-scale spatial processes of these systems, and large-scale spatial policy and management studies are even more rare. There are certainly no studies that address the important spatial issues for wetlands and combine them with an integrated ecological and economic model that can address the trade-offs between several wetland services at the same time.

Lakshminarayan and others (1995) use a multi-objective decision-making framework to look at tradeoffs between water quality and soil conservation resulting from different farm management practices. This project will follow their lead, but will apply these techniques to wetlands policies as well as incorporate the important spatial aspects of the problem into the decision-making models. This research program will be unprecedented in its attempt to provide a truly integrated framework that will incorporate ecological models with economic and policy models while addressing the crucial spatial components of this important environmental issue.

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INVESTIGATOR'S OVERALL RESEARCH

Dr. Weinberg's research program focuses generally on economic analysis of policy options for addressing problems associated with water use in the West. This general research agenda incorporates projects that analyze water quantity/quality tradeoffs, federal water policy reform, economic implications of the Endangered Species Act as it is applied to species dependent on riverine ecosystems, and the implications of overlapping and uncoordinated environmental and resource policies. Applications for this research include problems associated with agricultural drainage discharges from the western San Joaquin Valley, management of the Bureau of Reclamation's Central Valley Project, and efforts to protect threatened and endangered fish species in the Sacramento and Columbia River basins.

Currently funded research of particular relevance is a project titled "An Integrated Approach to Assessing Water Management Options in a Major Watershed: Extending a Hydrodynamic-Water Quality Model to Include Biological and Politico-Economic Components," funded to October 1999 by a grant from the NSF/EPA Watersheds program (Weinberg is a co-PI). The principal objective of the economic portion of this project is to develop a model of agricultural and urban water demand and link it to water flow and fish population models being developed by co-PI's, so as to simultaneously assess the economic costs and the benefits to selected fish populations from alternative water management strategies for the Sacramento River watershed.

While research undertaken to date has not focused explicitly on wetland management, the proposed project represents a natural extension of this work. It compliments previous and current research efforts in several ways: it continues the tradition of application to agricultural-environmental water management conflicts in the San Francisco Bay-Delta region, by explicitly modeling alternative policy objectives, it extends that component of the research program that focuses on the implications of overlapping policy jurisdictions and policy conflicts, and it relies on a methodology common to all previous research efforts – empirically based simulation analysis.

This project is not being supported by any current or pending funding sources. However, the very topical policy question, and cutting-edge nature of the conceptual and empirical modeling effort, suggests that good options may exist from state or federal sources for supplemental funding. These may include the NSF's Decision, Risk, and Management Science program, its Social, Behavioral, and Economic Research division, or the NSF/EPA watersheds program. Ultimately, entities such as CALFED and the California Interagency Floodplain Management Coordination Group may also be interested in this research. More generally, policy makers and funding agencies increasingly are emphasizing interdisciplinary research on important environmental policy questions. Likewise, they are anxious to participate in projects incorporating spatial information into decision processes. The Davis campus generally, and the Department of Environmental Science and Policy in particular, is well positioned to fill that role. While much effort has been expended in providing the framework for such studies, very little comprehensive analysis has been completed to date. Support of this project could indeed provid the means to facilitate future links between UC faculty with interests in inter-disciplinary, spatially-explicit analysis of California's many water issues.

STUDENT TRAINING

Project funds will be used to support the dissertation research for Stephen C. Newbold, a 3rd-year Ph.D. student in the Environmental Policy Analysis area of emphasis of the Graduate Group in Ecology here at Davis. Steve is uniquely qualified and prepared to undertake this investigation. He entered our program as the top ranked applicant in the best class we have had in years, and he is well on his way to finishing as the top student in his cohort. He has maintained a near perfect grade point average – 3.97 on a 4.0 scale – while taking very competitive graduate-level courses in economics (micro-economic theory, econometrics, environmental and resource economics), policy process, policy analysis, research methods, engineering (energy systems and transit system analysis), and ecology, as well as several undergraduate GIS and wetlands courses. In the current academic year, he will further expand his expertise by taking advanced (Ph.D.-level) courses in optimization and econometric methods. He will also complete his qualifying exams this year and, thus, will be advanced to candidacy when the project commences. Moreover, Steve has been invaluable to me as a research assistant for the past two years. He worked on two projects involving development of economic optimization models to predict farmer response (and associated costs) to water or drainage management policies in the Sacramento and San Joaquin Valleys. The combination of his formal academic qualifications and research experience in both the methods and general problem area position him well to undertake, and complete, this complex and innovative inter-disciplinary project.