A Framework for Risk Analysis in Ecological Restoration Projects

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Executive Summary

This report provides a framework for incorporating risk analysis into the U.S. Army Corps of Engineers (USACE) six-step planning process for ecosystem restoration projects. This report is part of a larger research and development effort to develop procedures and guidelines for risk analysis in USACE ecosystem restoration planning. The focus is on risk analysis: identifying the range of possible outcomes from alternative ecosystem restoration actions, assessing the potential for achieving the desired outcome, characterizing the likelihood of adverse consequences, and communicating these findings to stakeholders and decision makers. This framework document makes simplifying assumptions to allow a focus on incorporating risk information in the planning and decision-making process. A conceptual model of the site and landscape is advocated as a central organizing structure within the six-step process for ecosystem restoration project planning. This is responsive to USACE directives that restoration projects be conceived in a systems context using an ecosystem and/or watershed approach. The conceptual model delineates the empirical quantities to be addressed in risk analysis and modeling. Although the planning process is described in six distinct steps, in practice these steps are iterative and often carried out simultaneously. Risk analysis within this context has the same character. The approach for incorporating risk analysis into the planning process provides direction intended to help the planner:

- Identify the levels of uncertainty that are acceptable, at the start of the planning process.
- Use conceptual and numerical models to communicate the planning team's understanding of the ecosystem to others, and reduce the risk of mis-specifying the system.
- Consider the uncertainty associated with the variables chosen to measure project effects.
- Use alternative designs to manage identified uncertainty.
- Use risk information to eliminate alternatives with unacceptable risk from consideration.
- Incorporate risk analysis into the USACE four criteria of effectiveness, efficiency, completeness, and acceptability.
- Use an alternative's irreducible uncertainty as an attribute to be considered along with other attributes in the comparison of alternative plans.
- Use risk information in the final plan selection process.

There are three other efforts associated with this framework document, which offer information and guidance for incorporating risk analysis into cost-estimation, and biological and hydrologic modeling.

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1.0 Introduction

This report is a framework document that provides the general planner with a basic understanding of risk analysis in the USACE six-step ecosystem restoration planning process. The USACE objective in ecosystem restoration, one of the primary missions of the USACE Civil Works program, is to contribute to national ecosystem restoration by measurably increasing the net quantity and/or quality of desired ecosystem resources [1]. The focus of this report is on risk analysis: identifying the range of possible outcomes from alternative ecosystem restoration actions, assessing the potential for achieving the desired outcome, characterizing the likelihood of adverse consequences, and communicating these findings to stakeholders and decision makers.

Specifically, the USACE ecosystem restoration objective is "to restore degraded ecosystem structure, function, and dynamic processes to a less degraded, more natural condition [1]." This is further defined in USACE guidance, which states that "restored ecosystems should mimic, as closely as possible, conditions which would occur in the area in the absence of human changes to the landscape and hydrology. Indicators of success would include the presence of a large variety of native plants and animals, the ability of the area to sustain larger numbers of certain indicator species or more biologically desirable species, and the ability of the restored area to continue to function and produce the desired outputs with a minimum of continuing human intervention [1]."

In this report, a conceptual model of the site and landscape is advocated as a central organizing structure within the six-step process to achieve these objectives [2]. This is responsive to USACE directives that restoration projects be conceived in a systems context [1] using an ecosystem and/or watershed approach [3]. The incorporation of ecological tools and concepts into the USACE planning process for ecosystem restoration is evolving. The conceptual model delineates the empirical quantities to be addressed in risk analysis and modeling. Thus, this report describes an integration of concepts and tools from the science of ecological restoration with proven federal project planning processes. This integration, incorporating risk analysis into restoration planning, was called for by the USACE Evaluation of Environmental Investments Research Program (EEIRP) [7].

The risk analysis process requires planners to recognize and communicate the degree of uncertainty in each planning variable. The sharing of uncertainty information across a multidisciplinary planning team facilitates the identification of key variables affecting achievement of the planning objectives. The identification and inclusion of stakeholders further strengthens the knowledge base [7]. This process elevates risk management decisions from the sole province of the technical expert to the planning team and decision-makers.

Although the planning process is described in six distinct steps, in practice, these steps are iterative and often carried out simultaneously; the planning process is not linear. Planners and analysts work back and forth through the six steps until a comprehensive picture develops, which is communicated using the six steps as the reporting outline.

Risk analysis within this context has the same character. The approach for incorporating risk analysis into the project planning process provides direction intended to help the planner:

- Identify the levels of uncertainty that are acceptable, at the start of the planning process.
- Use conceptual and numerical models to communicate the planning team's understanding of the ecosystem to others, and reduce the risk of mis-specifying the system.
- Consider the uncertainty associated with the variables chosen to measure project effects.
- Use alternative designs to manage identified uncertainty.
- Use risk information to eliminate alternatives with unacceptable risk from consideration.
- Incorporate risk analysis into the USACE four criteria of effectiveness, efficiency, completeness, and acceptability.
- Use an alternative's irreducible uncertainty as an attribute to be considered along with other attributes in the comparison of alternative plans.
- Use risk information in the final plan selection process.

The proposed approach is applicable to ecosystem restoration planning. The framework is sufficiently flexible to be scaled to projects of any size or budget; the degree of specification and data-gathering can be tailored to the effort. The framework can be applied to studies of restoration, creation, reclamation, or protection alternatives.

This report makes simplifying assumptions to allow a focus on incorporating risk information in the planning and decision-making process. There are three other efforts associated with this framework document, which provide the technical detail needed to develop the necessary statistics. They offer information and guidance for incorporating risk assessment into cost-estimation, and biological and hydrologic modeling. The latter two have not yet been published. Three publications are available regarding cost-estimation: Noble et al. [8] is a post-construction analysis comparing project expectations to outcomes, and Yoe's reports [9,10] provide guidance and demonstrate cost-estimation when there is uncertainty.

This report is divided into four parts, including this introduction. The second section provides definitions and a brief background of risk analysis in USACE planning. The third develops the role of risk assessment in each of the six planning steps: 1) identifying problems and opportunities, 2) inventory and forecast, 3) plan formulation, 4) evaluation of plans, 5) comparison of alternatives, and 6) plan selection. The conceptual model is introduced in Planning Step 2, inventory and forecast. In Planning Step 3, plan formulation, habitat modeling methods are detailed. The fourth section is a brief conclusion, followed by Appendix A, which provides a fully developed example of a tidal wetland restoration planning process, demonstrating the application of the approach.

2.0 Background and Definitions

2.1 Risk and Uncertainty

The term *risk* incorporates the notion of a negative or undesirable outcome [11]. This may take the form of actual harm to the environment, failure to achieve the planning objectives, or not using the most cost-effective measure to achieve a planning objective. The term *uncertainty* is used to describe "a lack of sureness about something or someone."[1] Uncertainty exists whenever there is doubt about an event, a piece of information, or the outcome of a process. Uncertainty can be attributed to two sources: (1) the variability of processes (inherent variability), and (2) incomplete knowledge (knowledge uncertainty). *Probability* is a way of quantifying uncertainty [13].

Inherent variability is the ordinary variability in a system. In nature, it refers to the irreducible randomness of natural processes. In man-made systems it refers to the vagaries of the system; this randomness is irreducible from the perspective of the risk analyst. In the ecosystem restoration context, uncertainties related to inherent variability include things such as stream flow, assumed to be a random process in time; soil properties, assumed to be random in space; or the success rate of propagules deployed to revegetate a project area. Inherent variability is sometimes called aleatory uncertainty.

Knowledge uncertainty deals with a lack of understanding of events and processes, or with a lack of data from which to draw inferences; by assumption, such lack of knowledge is reducible with further information. Knowledge uncertainty is sometimes called epistemic uncertainty.

Many of the terms used to describe sources of error, uncertainty, and risk in the literature of risk analysis can be collapsed into the two above-named sources. There is considerable debate in the literature regarding the appropriate definitions of these terms, and it is acknowledged that the above definitions are more complex than the distinction made in the USACE planning guidance notebook [1]. The USACE guidance simply states that in situations of risk, "potential outcomes can be described in reasonably well known probability distributions," whereas in situations of uncertainty, they cannot. For the purpose of risk analysis in USACE ecosystem restoration, the taxonomy used to describe the uncertainty is not as important as determining the source of the uncertainty.

2.2 Risk in USACE Ecosystem Restoration Projects

"First, do no harm," the principle of the medical doctor, is as applicable to the management of an ecological system as it is to the health of a human being. Identifying and documenting the structure and function of ecosystem components, by creating a conceptual model, elevates the understanding of causal relationships and thus reduces the risk of unintended consequences from management actions. The examination of restoration project scale, the size and pattern of a project relative to the landscape and active stressors, also helps to manage risk. By reducing the risk of unintended

[1] The definitions of uncertainty in this section are modified from the report of the National Research Council Commission on Geosciences, Environment and Resources [12].

consequences, including ecological and economic consequences, risk analysis contributes to maximizing the cost-effectiveness of a restoration alternative.

The approach described in this report is not typical of health or ecological risk assessments, which typically focus on identifying the risks associated with sources of environmental stressors. Rather, the focus of risk analysis in the USACE planning context is to identify the range of possible and desirable outcomes of alternative environmental restoration actions, as well as the potential for any unwanted or adverse consequences of those actions.

2.3 Timing of Risk Analysis

Risk analysis is not something that is appended to the planning process or undertaken after a management measure has been selected. Effective risk analysis is woven into the iterative planning process, strengthening resulting decisions.

Iterative refinement of the problem statement and analysis [13] is key to restoration planning, from defining the objectives through the completion of post-construction monitoring. Morgan and Henrion [13] state, "We cannot overemphasize the importance of the difference between this iterative conceptualization of the process of policy analysis and the simple linear approach." New information informs redesign of the project or reconceptualization of the problem, and contributes to the body of knowledge that planners apply to other projects.

2.4 Risk Analysis

Risk analysis includes three components: risk assessment, risk management, and risk communication [14]. Risk assessment is the process of identifying the variety of potential outcomes from a decision and the nature, likelihood and uncertainty of adverse (undesirable) outcomes. Risk management describes the actions of decision-makers in response to the identified risk. Responses may range from doing nothing and accepting the chance of a negative outcome, to buying insurance to transfer the risk to others, to implementing a management measure to reduce or eliminate the risk. Risk communication is the vital step of informing the stakeholders and decision-makers of the risk assessment findings and risk management options.

It is important to understand that risk analysis – assessment, management and communication – occurs throughout the planning process. For example, conducting a reconnaissance analysis is a risk management technique with the goal of eliminating from further consideration studies with a high probability of not being in the federal interest. This reduces the chance of using resources unproductively. Properly understood, risk analysis is an analytical approach to every decision.

3.0 Procedures: The Planning Process

The risk analyses discussed below correspond to the key variables involved in each of the six steps of the USACE planning process for ecosystem restoration: identifying problems

and opportunities, inventory and forecast, plan formulation, evaluation of plans, comparison of alternatives, and plan selection.

3.1 Planning Step 1: Identifying Problems and Opportunities

The problem, or perceived degradation of ecosystem properties and reduction in related resources, must first be clearly stated. The first place to consider risk and uncertainty is in the selection of planning objectives. Planning objectives give a rational focus to the planning process. Optimal objectives for restoration projects will reflect a watershed, or other ecosystem perspective.

3.1.1 Federal Objective

In ecosystem restoration, the federal objective is to "restore degraded significant ecosystem structure, function, and dynamic processes to a less degraded, more natural condition" [1]. The federal objective becomes a goal for USACE planners in each ecosystem restoration planning study [15]. USACE planners then work with the stakeholders to develop planning objectives to meet this goal.

3.1.2 Planning Objectives (Outcomes) vs. Design Objectives (Outputs)

USACE planners and stakeholders identify project goals and objectives as follows:

> **Goal** – A clear statement of the project targets, which are not necessarily measurable.
>
> **Planning Objective** – A project objective, or beneficial outcome, is the outcome the project is designed to achieve, or an index of accomplishment that may be nonmonetary or monetary. An example is increasing the population of an endangered species through a salt marsh habitat restoration. Planning objectives often are not measurable, and a lesser index of goal accomplishment is used at the risk of misrepresentation of goal accomplishment; the lesser index used generally is the design objective (below).
>
> **Design Objective** – The material output, the result of changes to physical, chemical, or biological components of the ecosystem caused by the project. An example is the set of more natural habitat features and processes required by an endangered species, including habitat connections to recolonization sources or migratory pathways.

Planning objectives for ecosystem restoration are analogous to the objectives defined in the planning phase of ecological risk assessment. These objectives can take many forms, but regardless of the primary objective, an ecosystem or watershed perspective is needed to achieve them. Objectives may include, for instance, the restoration of populations of a single threatened or endangered species; a group of species, such as fish; or a community or ecosystem. One of the hallmarks of a good design objective is measurability. Setting the criteria to be measured will help to determine the requirements for risk analysis. If

the measurement is the culmination of disparate estimates, it is best analyzed and characterized with risk analysis. Habitat units are often the measure used in USACE environmental studies. Estimates of habitat units are especially prone to variability and are well suited to risk analysis.

The objectives of a project will shape the conceptual models to be developed in Planning Step 2. The planning ***goal*** of the project, after the federal objective above, might be to restore degraded significant salt marsh ecosystem structure, function, and dynamic processes to a less degraded, more natural condition. ***Planning objectives*** might include reestablishing historical salt marsh areas, and achieving sustainable populations of particular bird and fish species using the habitat. Measurable ***design objectives*** might be the increased area of salt marsh; increased resting, feeding and nesting areas for waterfowl; and increased feeding habitat and low tide refuge for fish. During Planning Step 1, when it is necessary to consider the criteria that will be established to assess the success or failure of the project, an ecosystem performance model can be developed to characterize potential progress toward the project goal.

3.1.3 Criteria and General Model for Ecosystem Performance

The general model for ecosystem performance (Figure 1) provides the general direction with respect to structure and function that the ecosystem is expected to take on its trajectory toward meeting the project goal. Under a restoration scenario, the goal is to move the system from a degraded condition to one that is less degraded and more desirable. For management purposes, it is assumed that there is a positive relationship between the structure and function of an ecosystem. The natural structure of an ecosystem, habitat, or community has a corresponding functional condition, and to the extent that this is predictable, this information may be used to construct the ecosystem performance model.

Although the optimal condition is shown in the upper right corner of Figure 1, optimal functionality can occur in other system states. For example, the greatest net primary productivity of a marsh habitat may occur where only a subset of the species normally found in a climax community is present. Research has shown that a few species may account for the majority of productivity, and other species are redundant [e.g., 16]. Hence, choosing the species to focus restoration on in order to restore optimal productivity is critical [e.g., 17]. In addition, partial restorations, if done with the correct species, may produce optimal results. However, there is uncertainty as to which species have a significant impact on processes in which ecosystems [18].

Moderate disturbances of a climax community may result in the greatest numbers of species as well as productivity [e.g., 19,20]. This is because disturbance opens space for invasion of smaller, less competitive, but highly invasive species. Where sites may be subjected to relatively regular and moderate disturbances, optimal conditions may be at a moderate level of structure but have high functionality. The difficulty and risk is that disturbances may not be predictable in time and intensity, and therefore the long-term fate of the restoration project may be more uncertain.

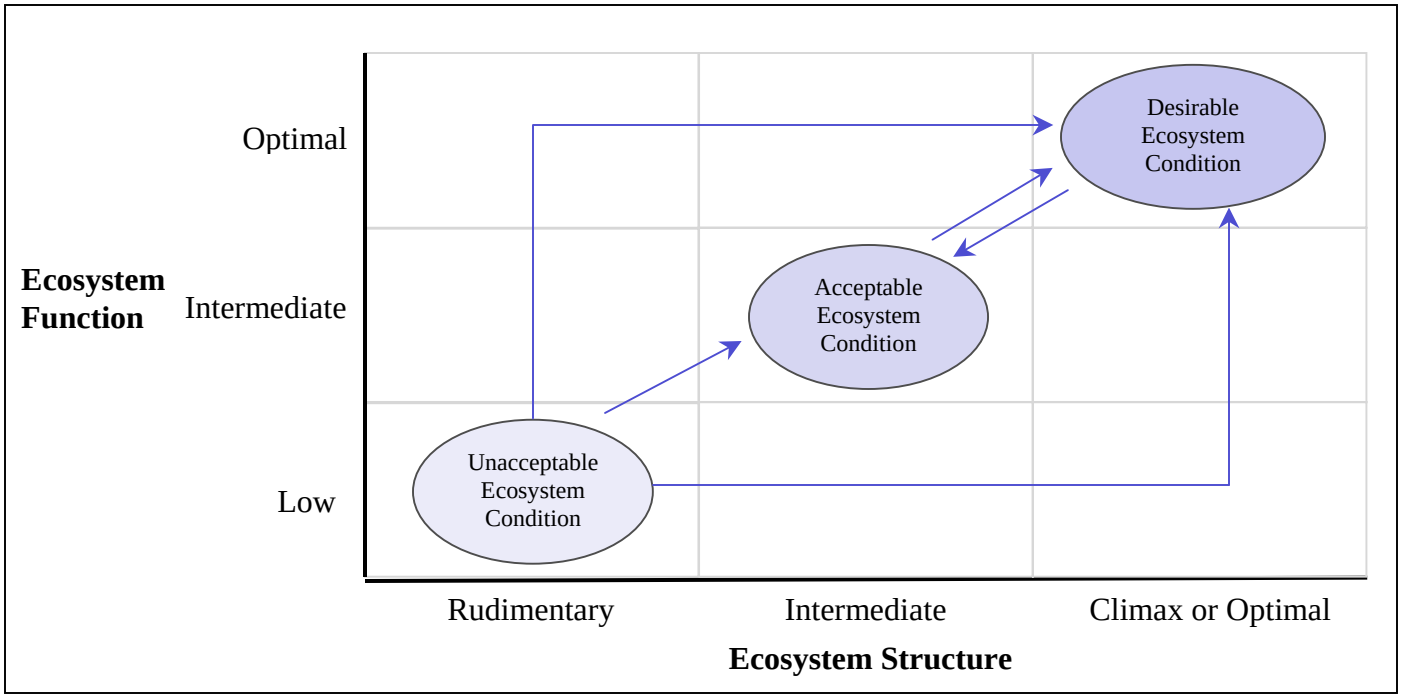


Figure 1: General model of ecosystem performance. An ecosystem or habitat that is in rudimentary condition with low functioning develops into a system with optimal structure and functioning. Development can take several pathways, and can oscillate between system states. (Modified from Thom, R., System-development matrix for adaptive management of coastal ecosystem restoration projects, *Ecological Engineering,* 8, 219, 1997. With permission.)

Figure 1 also indicates that a system may oscillate between states. This can be caused by stochastic processes such as human or natural disturbances, as well as stochastic climate-related forcing. This dynamic may be more pronounced in some system types than in others. It is important to recognize that the system can move between different structural and functional states and still maintain its long-term integrity.

Finally, and not explicit in Figure 1, is the fact that stability regimes are rarely ecosystem-wide, but are limited to some fraction of the ecosystem [e.g., 21]. This implies that if enough of an ecosystem is restored, sites within that system should support desirable resources.

If stressors are removed, the natural recovery *(passive restoration)* of ecosystems will tend to take place regardless of human intervention, but this may take a very long time—decades or centuries. *Active restoration* essentially means that humans act beyond stress removal to reduce the period of time required to improve ecosystem conditions, through a combination of physical intervention and natural recovery. At the desirable ecosystem condition, the system is fully functional, has an optimal structure, is resilient to disturbances, and is self-maintaining. However, the definition of "optimal" must be made with care and with relevance to the system under investigation. In the case presented here, it is assumed that optimal conditions are met with a natural climax community that, because of its persistence, is resistant and maintains itself through the ability to buffer changes. The term "optimal" implies a human value, and the optimal state represents what humans (i.e., restoration planners) view as the "best" condition for the system.

The levels of performance are divided into low, intermediate, and optimal in Figure 1. This essentially indicates that values (e.g., acreage) related to the structural conditions (e.g., the size of the pond-wetland interface) and the functional conditions (e.g., the annual duckling production/acre) can target a *range* (e.g., a ratio of wetland edge area to pond area of 1.0 to 2.0), rather than a single number. The ranges of values for structure and function are based on data from similar systems. An acceptable condition to project planners and stakeholders may be less than optimal. Hence, the goal for the project would be met if the system fell within a range of values for structure and function. Using a range of values acknowledges the following two sources of uncertainty:

- Uncertain understanding of relationships between ecosystem structure and function (knowledge uncertainty)

- Natural variability associated with the relationships between structural conditions and functional conditions (inherent variability).

Criteria for project success may also include constraints, or "zero impact thresholds." For instance, the criteria for success in the Sagamore Marsh restoration study included no negative effect on the local water supply, well and area septic systems; no increase of residential flooding; and no negative impact on navigation in the Cape Cod Canal [22]. Another criterion of success was that the project would not harm existing eelgrass.

3.2 Planning Step 2: Inventory and Forecast

3.2.1 Introduction

To effectively assess the existing conditions of an ecosystem and define the problem in detail, planners must understand the physical, biological, and chemical conditions and processes at work. This can be facilitated by developing a conceptual model. The ***conceptual model*** is developed to ensure a shared vision of the planning context and the relationship among ecosystem components. The conceptual model is used as a formulation tool, a communications tool, and an assessment tool. Properly constructed, the conceptual model facilitates stakeholder participation, clarifies what ecological factors affect the achievement of project objectives, and minimizes the chance of mis-specifying the system. Further, coupling the conceptual model with a decision process allows the planning team to deal with risk and uncertainty in a systematic way. The conceptual model identifies on paper the connections between the goal of the project and the physical and biological actions that need to be in place to achieve the project objectives.

3.2.2 Development of the Conceptual Model

What the Conceptual Model Provides

A conceptual model is a representation in words and illustrations of the major components and processes in a system, and the linkages between them. Although the conceptual model does not contain any quantitative information, it is frequently the first step in developing a quantitative model, such as a numerical simulation model that mathematically links the components of a system. It illustrates how stressors affect or inhibit ecosystem functions and services, and helps identify sources of uncertainty and potential threats to reaching the goal.

The conceptual model is a rendering of the state of knowledge about the system under assessment. It is developed as a tool to describe the *existing condition* at a project site and to forecast the *without-project condition.* Under a no-action alternative, the ecosystem might remain the same, degrade further, or improve, depending on the degree of alteration and continued disturbance of the ecosystem. It is critical that the conceptual model be as complete and accurate as is feasible to reduce uncertainty about the ultimate ecological performance of the system. In later steps of the planning process, the conceptual model will be used to help predict the effects of various project alternatives. If a conceptual model cannot be developed for the habitat or species at a site, the project should not be attempted, because the model provides a basis for management measures.

Conceptual Model Types

Several basic types of conceptual models are useful in ecosystem restoration planning. The first is the general model of *ecosystem performance* (see Figure 1). This model provides the general characterization of ecosystem output that is expected to take place on a trajectory toward meeting the project goal. The second model applies the principles

of *landscape ecology* that define the required context for project success. The third model, the *ecosystem model*, provides a map of all of the important community and habitat components and processes of the ecosystem and the ways in which they interact. The fourth model is the *subsystem model*, which often takes the form of a species-habitat model in ecosystem restoration planning. Finally, a model coupling the biological outputs of the project with social and economic outcomes from the project is termed the *ecosystem services* model. All of these models can be developed at various scales.

Understanding the relationships of these types of conceptual models is useful when selecting and applying them for planning. For example, the ecosystem model for the project area is nested within the landscape model, geographically. Likewise, the species-habitat model is nested geographically within the ecosystem model. A temporal dimension is added to the ecosystem model to create the ecosystem performance model. The ecosystem performance model also incorporates species-habitat interactions and landscape dynamics. The economic outcomes represented in the ecosystem services model are affected by the outcomes of all other conceptual models described here, as well as by interactions such as those between the ecosystem and the landscape. For example, the restoration of one site may change the levels and impacts of recreation, hunting or fishing in other areas, affecting the beneficial outcomes of the project.

General Form and Simple Example of a Conceptual Model

The general form of a conceptual model is shown in Figure 2a.

The design objectives of a project may be structural (e.g., restore a marsh of a certain size and stem density) or functional (e.g., restore marsh primary production). The planning objectives, however, may include beneficial services (e.g., bird watching, flood control, recreation, aesthetics, fishing, or endangered species support). Of these services, only endangered species support is a National Ecosystem Restoration benefit; the others are National Economic Development benefits. To achieve any of these types of objectives, the factors that control the structure and function must be established, restored, or otherwise created at the site. If a certain objective is a priority for a particular site, the factors that need to be established to achieve this objective may be defined through the conceptual model.

Examples of controlling factors for a coastal marsh system are shown in a simplified conceptual model in Figure 2b, which for the purposes of this example does not attempt to completely list the controlling factors, structural features, functions or ecosystem services of this system. Before the existing and future conditions of the ecosystem can be assessed, the ideal or preferred values of elevation, site morphology, substrata composition, and hydrology for this ecosystem type must be known. This information can be gathered through literature, discussions with experts, and new data collection. Current models using a hydrogeomorphic approach provide a good indication of some of the physical conditions and controlling factors for wetlands [23].

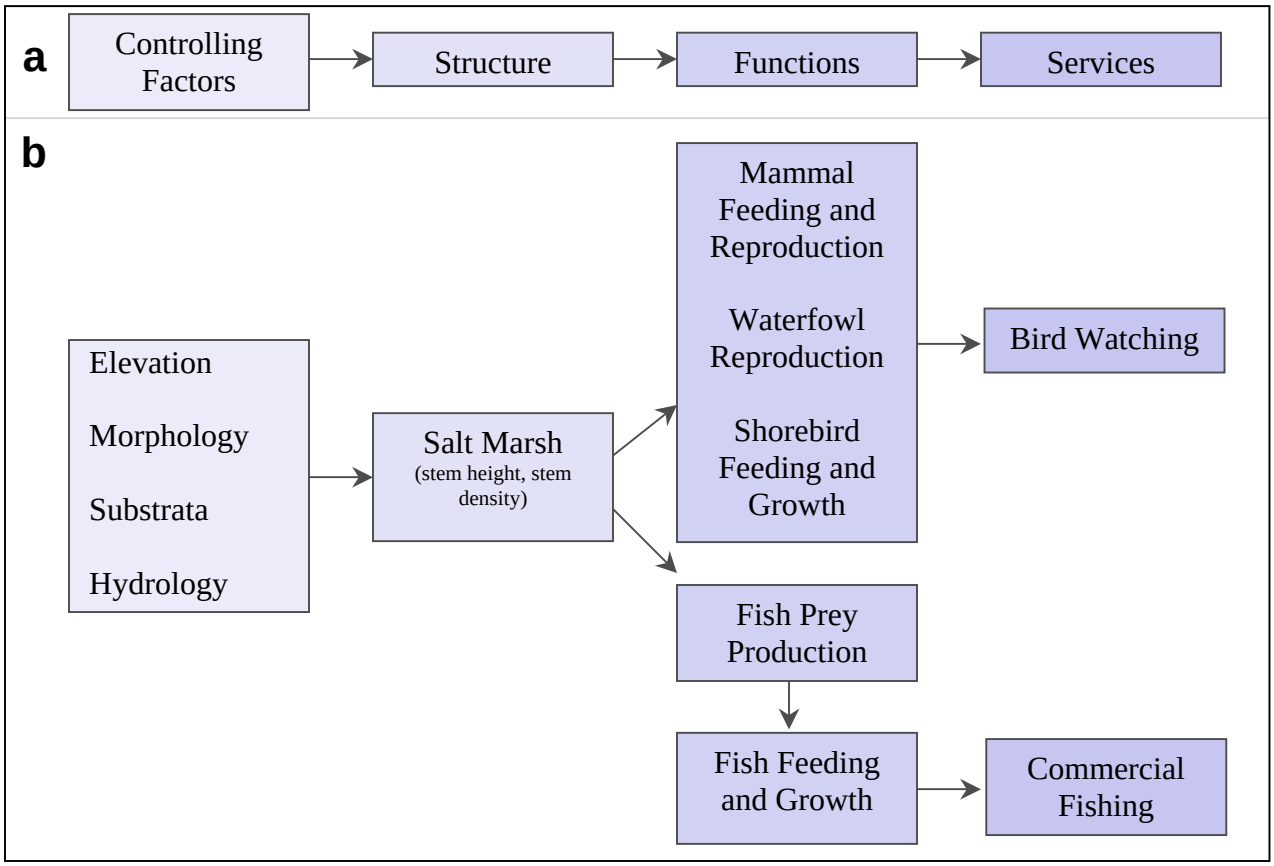


Figure 2: Generic structure of a conceptual model for ecosystem restoration (a) and simple conceptual model of a salt marsh system (b). General examples of, 1) controlling factors, are solar radiation, water depth, temperature and nutrients; of 2) ecosystem structure, are plant and animal biomass and diversity; of 3) functions are plant and animal production and diversification; and of 4) services are recreation, waste treatment, storm surge protection, and support for globally rare species.

Table 1: Preferred and existing conditions in a hypothetical salt marsh system.

Controlling Factor	Preferred Range of More Natural Condition	Existing Site Conditions	Other Factors
Elevation	+10 to +13 feet relative to Mean Lower Low Water (MLLW)	+10 to +15 feet MLLW	
Site morphology	•Low gradient slope (<2%) from backshore to mouth •Semi-protected from waves •Free opening to larger estuarine system	•Eroded steep slope •Little protection from waves	Site open to large ship wakes
Substrata composition	Silt to medium sand	Medium sand and clay	Heavy floatable debris and trash
Hydrology	•Tidal inundation •Salinity 10-35 ppt	•Tidal inundation •Salinity 10-35 ppt	

Table 1 provides examples of the existing and preferred conditions in a hypothetical salt marsh. The information about present conditions at the salt marsh points to two major issues limiting functional performance: frequent disturbance by boat wakes, and smothering and fouling of habitat by trash. In addition, the site elevations are too great for full development of the salt marsh. One would predict that wakes and trash would continue to degrade the site and prevent recovery.

The level of certainty about the quantitative relationship between the controlling factors and the structure of the system enters into the assessment of the uncertainty of the project. If there is a high degree of uncertainty about the relationship between a controlling factor and the structure of the system, and this factor is believed to be highly important, there is good justification for directed research into the relationship to reduce the uncertainty. This principle applies to identifying potential causes for the degraded condition of the site. Site investigation might be needed to evaluate causes and to determine whether they are still contributing to the degraded condition. If they have been corrected, then there would be less uncertainty associated with restoration.

Landscape Model

The basic premise of a landscape model is that the flow of energy, animals, and materials within an ecosystem can be affected by the landscape [24]. A landscape's features include the types, shapes, sizes, and distribution of habitat patches in the project-influential area. Landscape ecology provides an integrated approach to understanding how large systems function to influence smaller subsystems. For project planning, the ecosystem targeted by the project area, such as a discrete wetland or river segment, is influenced by the functions of other ecosystems embedded in the landscape. For instance, the controlling factors in Table 1 can be controlled by site-specific management actions, but factors such as weather and disturbances upstream cannot be controlled and their influence should be considered in project planning. For many Corps projects,

watershed boundaries define the landscape boundaries of interest. However, the influential landscapes of some projects may extend well beyond the influential watershed, such as the flyway landscapes of migratory birds. The principles of landscape ecology have direct applicability to the understanding, forecasting, planning, and design of ecosystem restoration projects.

Assessment on a *landscape scale* provides a wealth of data for understanding the relationship between changes such as landscape fragmentation and alterations in the populations of biological resources [25]. Removal or alteration of one or more elements may lead to the altered function of the remaining elements and ultimately result in degradation of significant resources in the project area. The U.S. Environmental Protection Agency specifically encourages resource managers responsible for wetlands cumulative impact assessment and protection to view wetlands in a landscape perspective [26]. In its review of aquatic ecosystem restoration, the National Research Council (NRC) made the following recommendations [27]:

> Wherever possible...restoration of aquatic resources...should not be made on a small-scale, short-term, site-by-site basis, but should instead be made to promote the long-term sustainability of all aquatic resources in the landscape. Whereas restoration on the large landscape scale is therefore definitely preferable to piecemeal restoration, small restoration efforts are not necessarily worthless or ineffective. Success in recreating a self-sustaining ecosystem is more likely, however, when the restoration is planned within the context of the target ecosystem's larger landscape.

Regardless of the magnitude of an ecosystem assessment, the understanding of landscape ecology is essential to the evaluation of the system's existing performance and future condition. The measurement of improved resource quality at a restoration site is qualified by landscape processes, which may reduce or negate site-specific effects. In addition to *scale*, considerations include landscape *structure*, *shape*, *linkages*, *configuration*, *number of patches*, and *disturbance*. For the salt marsh conceptual model example, the following questions at the landscape scale must be considered:

1) What is the quality of the landscape? If the salt marsh site is within a landscape that is highly degraded, the likelihood of the marsh's successful restoration diminishes. The landscape processes critical to the formation of habitats, such as sediment supply for marsh accretion, must be active at a level adequate to support development of the salt marsh without burying it during floods.

2) Are the target species present in sufficient numbers in the landscape? For example, if the goal of the project is to restore juvenile salmon habitat, but spawning habitat in the watershed has been eliminated and no salmon exist within the landscape, the probability of the site meeting its goal is zero.

3) Is the site large enough to be used by the species? As the size of the site increases, the probability that a species can find the site typically increases. Very small and isolated sites have a lower probability of use, and the residence time for

migratory species is predictably greater in larger sites that provide a broad array of habitat types. For example, larger marshes contain a greater number of channel orders that vary in length, width, and depth, with deeper channels at the outer edges. At low tide, when much of the marsh is drained, fish use the deeper channels as a low-tide refuge, and when the tide floods the marsh, the fish occupy the smaller channels.

4) Are there adequate routes of access to the site? Linkages to other habitats must be large and arranged such that there is a reasonable likelihood that the species will be able to reach the site.

5) How much disturbance will the salt marsh receive that might alter the controlling factor ranges? For example, will storms occur annually that flood the system and deposit large volumes of sediment or erode the marsh? Frequent disturbances, especially during early establishment, can hamper system development.

Ecosystem Model

Ecosystem models come in a wide variety of forms, ranging from highly conceptual to fully integrated numerical simulation models. They generally include the atmospheric, geological, hydrological, and biological components of the ecosystem, and attempt to provide all of the important connections among all of the major elements of each of these components. Compared with the relatively simple model shown in Figure 2b, ecosystem models are far more complex. Few, if any, fully integrated numerical ecosystem models have been developed for the purpose of restoration; however, models that simulate selected components (subsystems) of ecosystem models have been developed. For example, a simulation model of the hydrology of the Florida Everglades ecosystem was developed to provide specific information on the ways in which restoration of hydrology could improve ecological conditions in the ecosystem [28]. This large project required a level of modeling complexity greater than that needed for most projects.

Habitat or Subsystem Model

A habitat or subsystem model focuses on a particular component of the ecosystem. Figure 2b is an example of a conceptual model for one habitat type, but there are many useful methods that generally can be called habitat models, some of which are semiquantitative. Well-known examples include the HydroGeoMorphic Approach (HGM) and the Habitat Evaluation Procedure (HEP) [23,29].

HEP assigns relative weights to the habitat quality and quantity provided to one or more selected species. For example, the salt marsh in Figure 2b may be marginally useful to shorebirds. Using HEP, the habitat quality would be given a score of 0.2 on a scale of 0 to 1, which is its habitat suitability index (HSI). This index value is then multiplied by the geographical area of the habitat *potentially* used by shorebirds to calculate a weighted score in “habitat units” for the species-habitat subsystem. By incorporating more appropriate *natural* habitat(s) into the restoration plan for the marsh, one can elevate the shorebird score. According to the conceptual model, however, the more natural condition

that maximizes certain resources of significance, say shorebird use, may reduce the existing use of other significant resources, say rare waterfowl or rare fish. Although not detailed in Figure 2b, the avifauna have different subhabitat requirements within the salt marsh so the distribution and quantity of habitat types will favor certain species or groups. These uses can be balanced through combining HEP analysis for selected species and good information on the controlling factors needed to result in the desired system state. According to the matrix in Figure 1, the desired system state must fit within the natural range of succession in the landscape to maximize the probability that it will develop to a system status that is resilient to disturbances and self-sustaining.

Integrated Ecosystem Services Model

Integrated ecosystem services models link the ecosystem with related social and economic components. A simple integrated conceptual model for an aquatic ecosystem developed by Thom and Wellman [30] is shown in Figure 3. The primary assumptions in the model are that ecosystem processes provide resources that have economic and ultimately social benefits, and that human actions involved in using these resources have an impact on ecosystem processes. The model indicates that humans can make decisions that affect the ecosystem, which in turn affect the economic and social benefits accrued from the ecosystem. A more complex series of models, some of which attempt to integrate ecosystems with economic and social systems, were developed in an international effort to assess the effects of large-scale changes, such as climate, on the

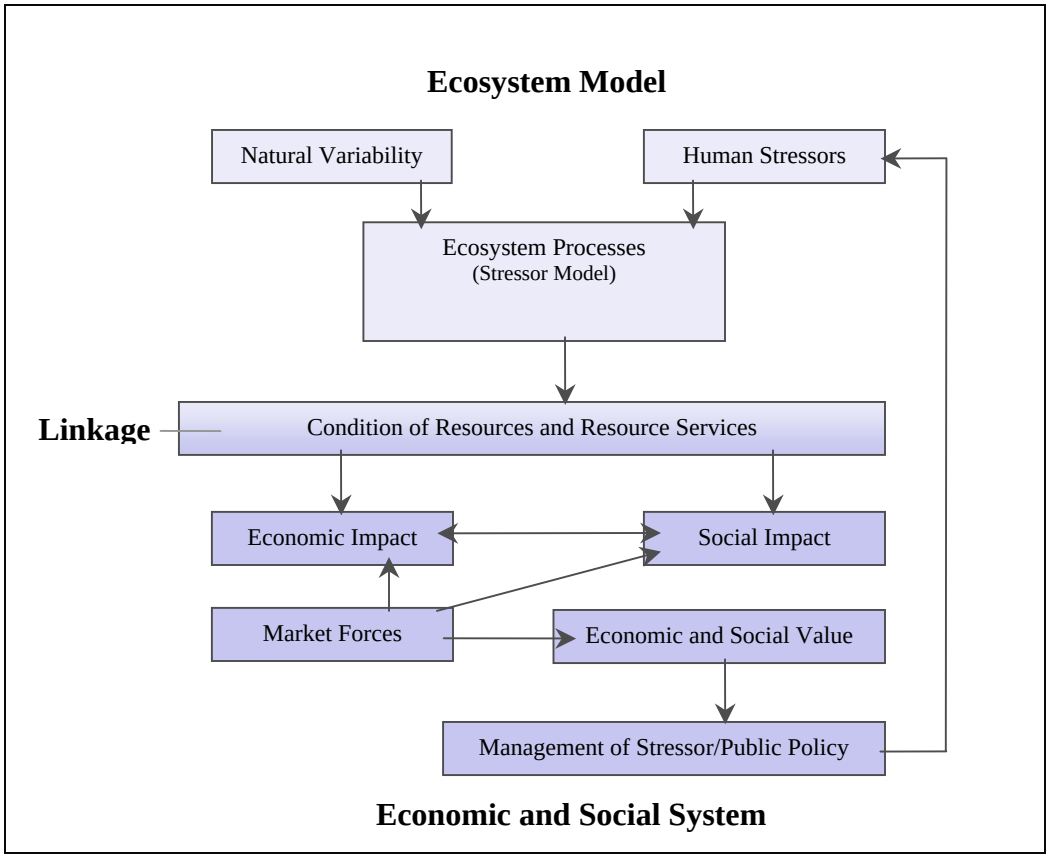


Figure 3: Conceptual model linking ecosystem model with social and economic model (From Thom, R.M. and K.F. Wellman, Integrated ecosystem services model, unpublished data, 1993.)

functions of coastal ecosystems: the Land-Ocean Interactions in the Coastal Zone program [31].

The conceptual model from Figure 2b is linked to the economic and social system model by the functions and values produced by the salt marsh. To the extent that use values associated with these functions and values can be monetized, they are considered National Economic Development benefits and are not the focus of the ecosystem restoration authority. Non-use values can be monetized as well, such as by using the contingent valuation method (see Appendix 5-A), but USACE considers these values speculative and subject to biases and does not consider their use in project selection [1]. Estimating values for the many services that people benefit from more indirectly, such as water purification or preservation of genetic diversity, is also problematic; for example, see Costanza et al. [32] and critique by Bockstael et al. [33]. Therefore, the emphasis in Corps restoration projects is on establishing these social and economic linkages in qualitative terms; for example, more waterfowl production leads to more dollars spent on commerce and recreation.

3.2.3 Steps to develop conceptual models

Models are often built "from the ground up." For example, simple relationships are identified for a selected process, such as emergent marsh primary productivity. The model is then expanded to include system-scale effects such as hydrodynamics, and the factors controlling these effects. As the model grows, it incorporates large-scale components including land-use and climate. Economic and social aspects may be included at the appropriate scale. It is advantageous to start simply at the smallest scale required to make decisions on the project. If the project is designed to provide nesting habitat for a selected bird species, for example, then the components of the habitat that meet nesting requirements, such as vegetation type and coverage, are the first elements specified in the model.

The steps to developing a conceptual model are described here for a model that focuses on restoration of a salt marsh habitat structure to support some of the marsh's native functions (Figure 2b).

1) Define the planning objectives of the restoration project. This is critical to developing the model. In our example, the planning objective is to restore the waterfowl and fish in association with supporting salt marsh.

2) Determine the aspects of the salt marsh that best meet the needs of the target species. For example, waterfowl may need ponds within the salt marsh for resting and feeding, and they may use vegetated islands in these ponds for nesting. Fish may need edges of the marsh within which to feed, and refuge areas where water remains during low tide. Verification or evaluation of these relationships can be carried out through directed field efforts or further literature reviews and discussions with experts in Planning Step 3. The initial model developed should identify critical data gaps and needs.

3) Determine the factors that control the development and maintenance of a salt marsh habitat necessary to meet the needs of the fish and birds, such as elevation, morphology, substrata, hydrology, and water quality.

4) Develop a diagram in the level of detail that accurately illustrates the connections among controlling factors, salt marsh structure, and the planning objectives of the project.

In practice, conceptual models are continuously updated throughout the planning process as information accumulates. In addition, post-construction monitoring of restored sites often provides new insights into linkages and pathways that help refine the completeness and accuracy of the model.

3.3 Planning Step 3: Plan Formulation

3.3.1 Introduction

Conceptual and empirical models can be employed together to formulate management measures.

3.3.2 Systems Context

USACE ecosystem restoration planning seeks to reestablish a "self-regulating, functioning system" [1]. A perspective focused on entire systems is an important means to this end. USACE planning guidance states:

> Restoration projects should be conceived in a systems context, considering aquatic (including marine, estuarine and riverine), wetland and terrestrial complexes, as appropriate, in order to improve the potential for long-term survival as self-regulating, functioning systems. This system view will be applied both in examination of the problems and the development of alternative means for their solution. Consideration should be given to the interconnectedness and dynamics of natural systems, along with human activities in the landscape, which may influence the results of restoration measures …
>
> The planning for ecosystem restoration objectives is essentially the same as for other water resources development purposes. However, there are some special considerations because of limitations in understanding the complex interrelationships of the components of ecological resources and services which are the focus of these studies, and because the environmental outputs considered in the evaluation process are typically not monetized. The consideration of significant resources and significant effects is integral to plan formulation and evaluation for any type of water resources development project. In ecosystem restoration planning, the concept of significance of outputs plays an especially important role because of the challenge of addressing non-monetized benefits [1].

A “system view,” as described above, means consideration of biological outputs of a restored system at a range of scales from the species to the community and from the patch to the landscape.

3.3.3 Conceptual and Empirical Models

Restoring an ecosystem is a complex undertaking. The better the understanding of the system components and controlling factors, the more likely project planning objectives will be achieved. Furthermore, having the best information from the start will result in better refinement of the physical actions that must take place, thus reducing costs associated with unnecessary activity. Ultimately, development of the conceptual model and its associated empirical models reduces the potential for specification error associated with the restoration actions and with the cost estimation for the project.

The conceptual model, with the identified pathways between chemical, physical, and biological components, can also provide insight into the changes that might be accomplished to restore the site. The general relationships represented by the conceptual model are used as a guide for the application or development of empirical models in an effort to quantify these relationships.

The conceptual model is used together with applicable empirical models, such as hydrological models and habitat suitability indices (HSIs), for example, to generate a series of measures that would alter the system according to different design objectives that meet project planning objectives. For example, factors such as inundation depth and duration, or components such as removal of an invasive species, could be considered for their effect on achievement of planning objectives.

In many cases, one or more species are emphasized. For example, if the project planning objectives included provision of habitat for the marsh wren (*Cistothorus palustris)*, the HSI marsh wren model would be consulted [34]. The HSI marsh wren model would rate the possible water-depth outcomes based on the empirical relationship between mean water depth and cover/reproduction suitability for the marsh wren. The conceptual model would provide information on variables influencing the mean water depth at the restoration site. Plans might then be formulated for different design objectives at the site, providing a range of suitability for the marsh wren based on mean water depth.

The conceptual model can also be used for planning at the community, ecosystem, and landscape levels. By delineating relationships among important components of the system, planners are able to envision the effects that changing variables have on groups of components, not only on single species. The conceptual model is a tool that helps planners apply the regulation cited in the previous section by bringing a system view to bear on understanding the problem and developing solutions.

The conceptual model provides an organization for the understanding of the habitat or subsystem upon which a quantitative model can be developed by adding mathematical links between subcomponents of the model. Although models such as the HSI are

subsystem models, they can be linked with processes in the landscape that affect the subsystem. The reliability of the linkage will affect the ability to predict how changes in the landscape will affect changes in the habitat or subsystem. For simple projects like the one described in the example (Appendix A), linkages between the subsystem and landscape processes can generally be articulated sufficiently for project planning using subsystem models. However, in very complex or large systems such as the Florida Everglades, where a large investment is made, subsystem models may not be adequate for evaluating sources of risk to the project. In such cases, spatially and temporally explicit process simulation models should be considered.

3.3.4 Landscape Variables

Several of the most important principles of landscape ecology relative to ecosystem restoration are considered in the plan formulation stage. Landscapes can be divided into matrices, patches and corridors. A matrix is the area within which patches and corridors occur and represents the most extensive and most connected landscape element. The matrix, therefore, plays a dominant role in the functioning of the landscape. The works of Gosselink and Lee [25], Forman and Godron [24] and Turner et al. [31], among others, contribute to our understanding of the landscape ecology of the wetland, river and coastal systems most associated with USACE restoration planning.

The scale at which humans perceive boundaries and patches in the landscape may have little relevance to the flows of energy and materials. Hence, investigations of the flows of energy and materials may be required to determine the appropriate scale at which to design restoration projects. In a practical sense, the scale of a restoration project is important for four reasons: 1) the project area needs to be large enough to limit deleterious effects that boundary conditions may impose on interior aquatic functions; 2) project managers must be able to exert influence over zones in which major causes of ecological disturbance to the project are occurring; 3) the area needs to be sufficiently large to allow the monitoring and assessment of important effects of the project; and 4) the project should be of an affordable magnitude [27].

The appropriate scale for restoration is likely to be defined by the requirements of target ecosystems and species groups. Allen and Hoekstra [35] suggested a hierarchical approach to restoration in which the prescribed size of the landscape to be restored determines which processes have sufficient space or time to be relevant in the restoration effort. Restoration, in this sense, is limited qualitatively, rather than quantitatively by area: that is, in consideration of the processes to be included or excluded, rather than by the acreage to be restored. Migratory waterfowl and shorebirds of Commencement Bay, for example, operate at the scale of the estuary and of the Pacific flyway. Thus, restoration projects for these birds must be sited within the flyway and designed to be of appropriate size and structure to both attract the birds and restore their numbers by providing available food, protection from predators, and resting areas in locations where those factors are limiting numbers. Attraction alone would simply move the birds from existing locations to new locations with no net gain in numbers or human benefit.

Management of natural wildlife reserves has supplied considerable information on scale issues affecting restoration. Based on island biogeography [36], a well established relationship between number of species and habitat area has been used to predict the effect of habitat fragmentation on species in reserves. Hence, as a general rule, larger reserves are better than smaller to maintain high numbers of species. In an example presented by Gosselink and Lee [25], one large reserve supported more native, interior species than two or more smaller reserves equal to the large reserve in total size. Although fragmentation and moderate levels of disturbance may increase the number of species in an area [37], such an increase would be largely due to opportunistic species that generally do not require reserves for survival. The goal of reserves is generally to preserve species that would otherwise decline.

It is well established that the number of species within a patch is a function of a number of factors in addition to patch area, including within-patch heterogeneity, disturbance patterns, degree of isolation from sources of species, patch age, and matrix heterogeneity. Flow of species population members among patches is dependent on patch density and arrangement in the matrix and other factors that pose impediments to movement.

The NRC [27] recommended that historical records, including maps of resources, hydrology, and geomorphology, be consulted to determine an appropriate structure for target species groups. The primary reason for this recommendation is that the natural forces that resulted in the structure of the landscape will still be active, or can be restored, and will tend to push the system toward predisturbance structure once impediments are removed or circumvented. A secondary reason is that plant and animal communities have become adapted for optimally using the system in its natural state. A third and more pragmatic reason is that one cannot possibly model all of the chemical, physical, and biological interactions that shape the system and control its stability and functional performance; therefore, historical information on the site's natural state, particularly geography, provides the best information for a model upon which to base a restoration design.

The shape of a patch, or contiguous habitat, affects the type and number of species in the patch. Species may show preferences for either the edges or the interiors of patches. A quantitative metric of shape is the interior-to-edge ratio. For example, round patches have a large interior-to-edge ratio compared with that of very narrow, linear patches. Small patches may act only as edges, depending upon the size of the animal that potentially occupies them. The number of edge-dwelling or interior-dwelling species in a patch will be dependent to a certain extent on this ratio. Processes such as benthic productivity and nutrient flux will also be dependent on shape.

Certain habitat patches can act as corridors of movement for animals, if they link two or more patches. For example, narrow strips of sedge marshes along river banks, ravines leading from uplands to intertidal areas, channels from deep areas to marsh flats, bands of eelgrass and kelp, and even drainage ditches represent landscape linkages for animals in estuarine environments in the Pacific Northwest. These linkages are generally rich in food resources or cover that increase the probability of an animal's successful use of two

or more habitats in an estuary. Restored habitats must incorporate avenues of ingress and egress to be fully functional within the estuarine landscape. However, such corridors may also allow access of non-native, invasive species [38]. If the restoration goal is to maintain native biodiversity and ecological integrity, optimum results are most likely when the natural connectivity among habitats in the landscape is restored and the connectivity of artificial habitats, such as clear cuts or agricultural fields, is minimized [38].

Landscapes change naturally with time. Restoration must therefore account for aspects of landscapes that can evolve and influence long-term functional performance of constructed systems. The long-term viability of a restored system is dependent upon the landscape dynamics: a variety of factors inherent to the system, including stability, persistence, resistance and resilience, creating a pattern of change over time. The stability of a system is the degree to which it displays long-term variability, or the tendency to convert from one to another type of system. Persistence refers to the period during which a certain characteristic of a landscape continues to be present. Resistance and resilience mean, respectively, the ability of a system to withstand and to recover from disturbances. In general, the goal of a restoration effort should be to create a system that is relatively stable, persistent, resistant and resilient. Size of the habitat or ecosystem relative to the effect of disturbance is a major concern. Protected ecosystem types must be sufficiently large to maintain viable populations of all native species [38].

3.3.5 Examples – Marsh Wren and Mississippi Delta Marsh HSI models

Examples of plan formulation for projects at regional and site-specific scales are the Mississippi River delta marshes restoration program, and the hypothetical restoration of marsh wren habitat, both of which incorporate an understanding of landscape-level processes.

Marsh Wren Example

This example demonstrates how a conceptual model and an empirical model can be employed to formulate management measures incorporating the landscape context. The approach employs information contained in the HSI marsh wren model [34], guidance from Orth [39] on how to employ the HSI in USACE water resource planning, and a landscape ecology conceptual model. While it is unlikely that the marsh wren HSI would be used in restoration planning, because this abundant bird is not considered an indicator of significance or of ecosystem condition, this relatively simple HSI is useful for demonstration.

The marsh wren breeds in freshwater and saltwater marshes. It feeds on a variety of insect species, and the food selected depends on the size and age of the bird. It is important that the bird winters in warmer areas, such as Mexico and Florida, and accordingly, depends not only on breeding habitat but also on the availability of productive and protective wintering habitat, often far from the breeding site. Nests are typically built in cattail (*Typha* spp.), emergent sedge (*Carex* spp.) or rush (*Scirpus* spp.)

marshes, although other marsh habitats are also used. The wren nests in areas with standing water ranging from approximately 3 cm to 91 cm deep. Permanent standing water is generally required throughout the breeding season to supply a dependable food source and refuge from predators. In intertidal habitats, however, the marsh wren can nest where water is present only during high tides. Also important is the total area: marshes under 0.40 ha in size usually are not used by breeding marsh wrens. The HSI model applies primarily to the northern half and coastal areas of the U.S., the marsh wren's breeding range. It provides an estimate of the suitability of a habitat for breeding based on the controlling factors and structure. The HSI marsh wren model is as follows:

$$HSI = (SIV1 \times SIV2 \times SIV3)^{1/3} \times SIV4 \qquad 1$$

where the suitability indices are assigned based on data on controlling factors and structure, as follows:

SIV1 = the suitability index for the vegetation growth form
SIV2 = the suitability index for canopy cover of emergent herbaceous vegetation
SIV3 = the suitability index for mean water depth
SIV4 = the suitability index for canopy cover of woody vegetation.

The value of an index ranges from 0.0 (completely unsuitable) to 1.0 (ideal condition). For example, the suitability index SIV1, based on data for the variable V1, the growth form of emergent hydrophytes, would be 1.0 if cattails, cordgrasses or bulrushes dominated the site. In contrast, the value for mangroves would be 0.1. The indices can also be continuous. For example, the suitability index for a site would be 0.3 if the average water depth (SIV3) were 5 cm, or 1.0 if the depth were 15 cm or greater.

A conceptual model for marsh wren breeding can be created from the HSI information. It is important to include broader landscape aspects, as represented in Figure 4, although they cannot be drawn from the HSI. The landscape aspects relevant to this example include, but are not limited to, the following:

- Presence and availability of adequate overwintering habitat
- Presence of suitable migratory corridors between wintering and breeding habitats, providing resting and feeding sites
- Adequate surrounding buffer habitats
- Metapopulation dynamics (features of a series of populations at a landscape level that change over time, such as extinction and recolonization)
- Absence of human threats to survival, such as hunting and contaminants in the food web, over entire winter and summer range
- Tolerable climate for marsh wren over the entire range.

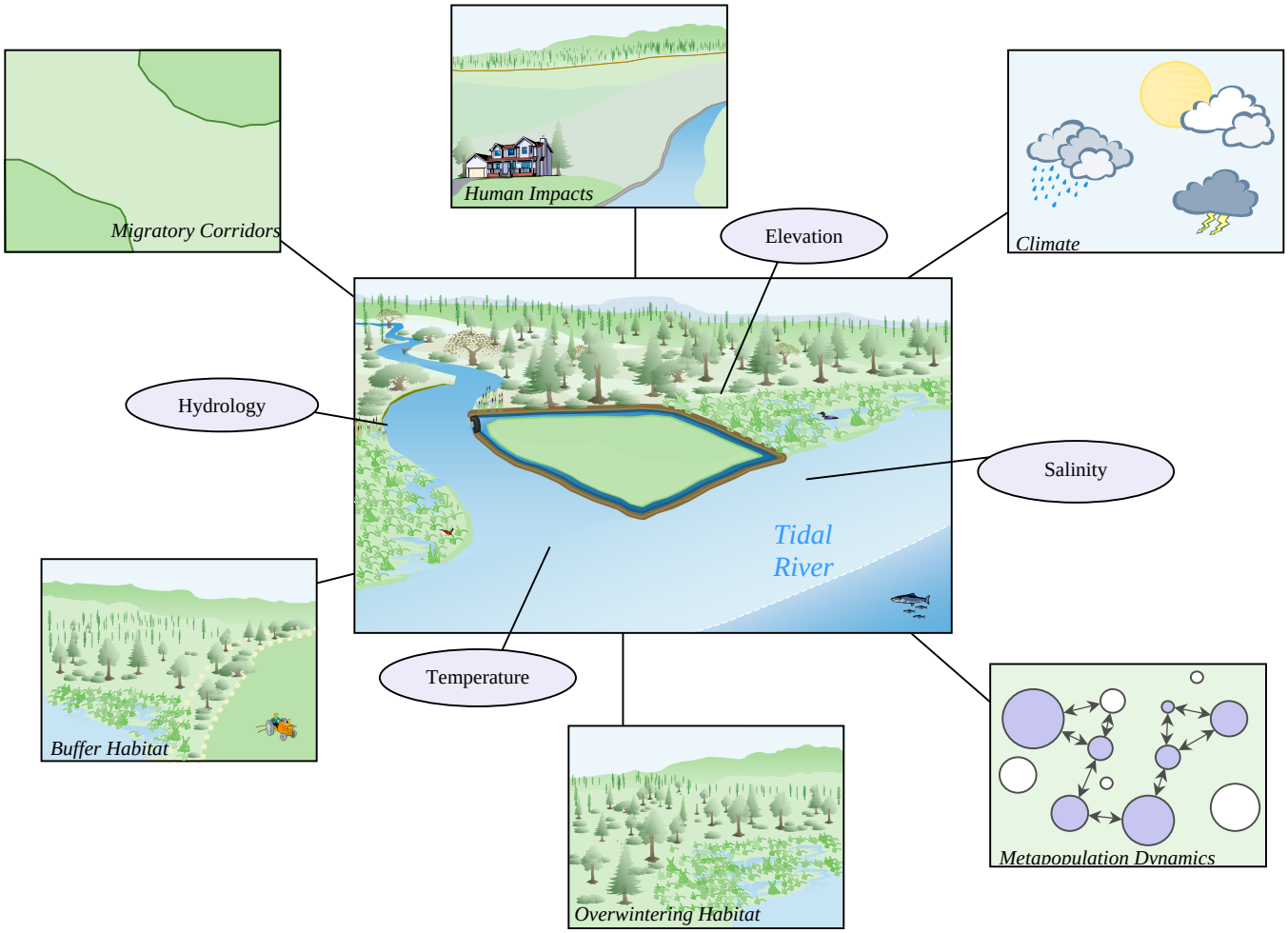


Figure 4: Site and landscape-scale conditions controlling habitat structure and function.

These elements control the development of the structures essential for marsh wren habitat as detailed in the HSI model: for example, marshes greater than 0.4 ha in size, sufficiently tall and dense to support nests, and made up of plants such as cattails, sedges, and rushes. Functions of such habitat include feeding, refuge from predators, and nesting success.

The HSI model does not explicitly treat all controlling factors at the site and landscape levels. Its starting point is habitat structure, itself an endpoint of other processes. If the HSI approach supports the conclusion that habitat is marginal, the cause may lie with landscape-level variables. The conceptual model is used to represent community, ecosystem and landscape-level relationships and controlling factors. While the landscape-level assessment often is qualitative, empirical models of aspects such as metapopulation dynamics are sometimes developed as well. The landscape can be further examined by a newer approach, the HGM, which is described in the Mississippi Delta Marshes example in the following section.

Mississippi Delta Marshes Example

Restoration of the Mississippi River delta marshes of Louisiana provides an example of a large-scale, landscape-level restoration effort that is implemented under the Coastal Wetlands Planning, Protection and Restoration Act of 1990. At the heart of this program is a hydrologic basin-wide approach to restoring wetlands on the delta. Delta wetlands are being lost at a rate of about 65 km^2 (25 sq mi) annually. The loss not only threatens the wetlands and the fisheries resources it supports, but also the infrastructure of towns and industry on the delta. A piecemeal, small-scale approach to restoring this system would not provide the scale of change required to slow or reverse the trend [40].

The marshes are being lost through a combination of factors. A diagram of the major factors contributing to the loss is shown in Figure 5. Fundamentally, the marshes are eroding because they are not building elevation (accreting) to keep pace with relative sea-level rise. Subsidence, the combined effect of geological movement along faults and compaction of poorly consolidated sediments, is taking place on the delta [41]. Sediment input from the river to the marshes has largely been eliminated because of the levees. Although organic matter from marsh plants contributes to accretion, the buildup is not great enough to overcome the subsidence due to compaction of poorly consolidated clay and peat material. Salinity intrusion from the Gulf of Mexico affects the marsh vegetation and can contribute to changes in marsh production and organic matter deposition. Through channel dredging for oil and gas extraction, the hydrology of the delta has been drastically altered. The net result has been impedance of sheetflow across the marsh plain, accumulation of standing water and drowning of the marsh interior. Storms and waves have eroded the marsh edges. The introduction of the nutria, a voracious herbivore of marsh plants, has created additional stress. At an even larger scale, the sediment supply has probably been altered throughout the watershed. The role that this alteration plays in deltaic marsh loss is unknown.

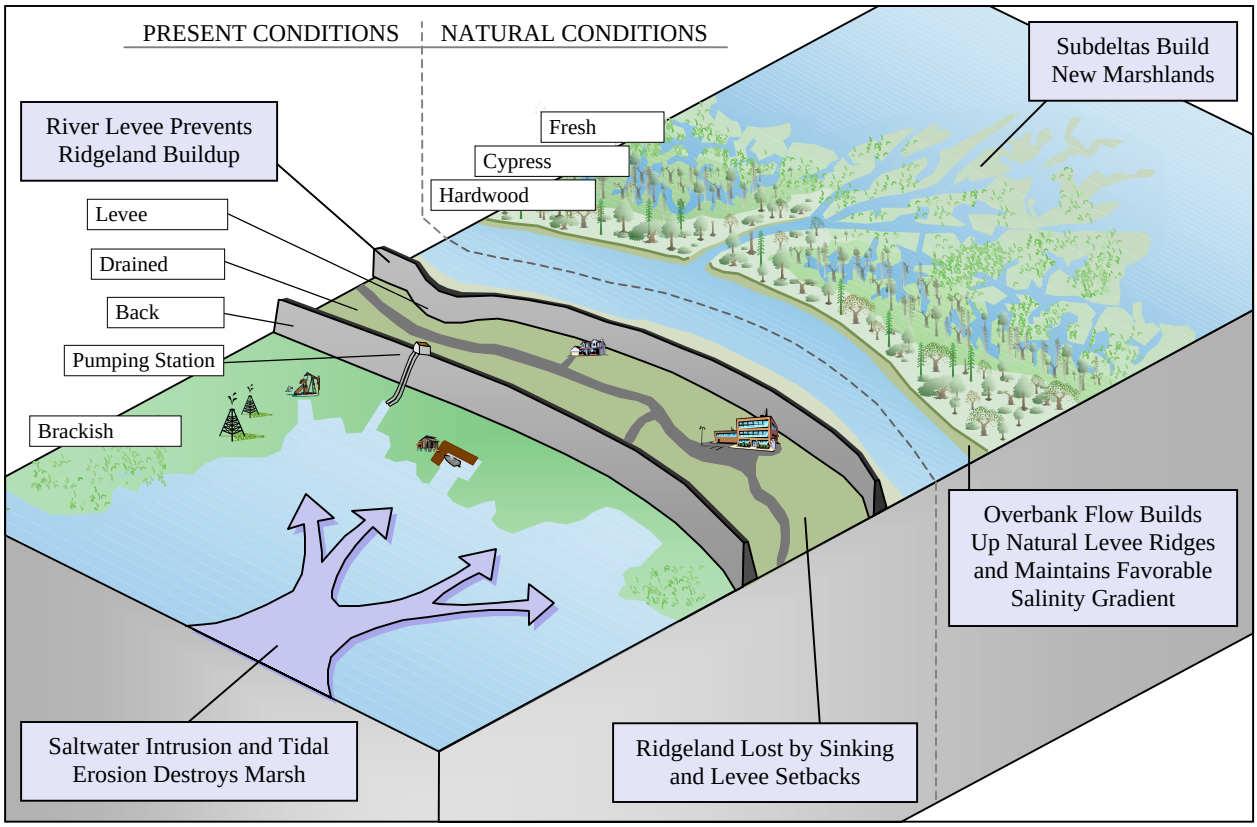


Figure 5: Natural and modified conditions along the Mississippi River corridor (Modified from Louisiana Coastal Wetlands Conservation and Restoration Task Force and Wetlands Conservation and Restoration Authority, Coast 2050: Toward a sustainable coastal Louisiana, Louisiana Department of Natural Resources, Baton Rouge, LA, 1998, and Gagliano, S.M., Controlled diversions in the Mississippi River deltaic plain, in Proceedings of International Symposium (Wetlands and River Corridor Management, July 5-9, Charleston, South Carolina), Association of Wetland Managers, Kusler, J.A. and Daly, S., (eds), 1989, 257.)

The understanding of each factor's role is key to designing the restoration plans. The primary strategy is to reintroduce sediment along with nutrients into the marshes to fuel marsh plant productivity and to build elevation. This strategy has led to the development of a project list that includes various methods to introduce sediment, stabilize and protect marsh edges, introduce nutrients, and recreate hydrology.

The delta marshes harbor an enormous abundance of bird species and a variety of economically and recreationally important aquatic animals. The production of the paneid brown shrimp (*Panaeus aztecus*) and to a lesser extent, the white shrimp (*Panaeus setiferus*) is dependent on a healthy marsh and adjacent submerged seagrass habitat. Therefore, shrimp habitat is a primary basis for delta marsh restoration. Increased shrimp production is believed to be linked to higher food resources and protection from predators afforded by marsh surfaces, channels, and rivulets, particularly the length of the land-water interface, or "edge" habitat [40].

An HSI model for brown shrimp has been developed [42]. The model, which was developed before the edge-research findings cited above, indicated that the suitability of the estuary increases with increasing coverage of the estuary by marsh, with a maximum suitability at 100%. The shrimp also prefer soft peaty silt bottoms, an intermediate salinity range (10 ppt-20 ppt) during spring, and moderately warm spring temperatures (20^oC -30^oC). One index in the model incorporates variables for food and cover (*fc*), and one incorporates water quality variables (*wq*) as follows:

$$HSI_{fc} = (SI_{V1}^2 \text{ x } SI_{V2})^{1/3} \qquad 2$$

$$HSI_{wq} = (SI_{V3} \text{ x } SI_{V4})^{1/2} \qquad 3$$

where the indices are

SI_{V1} = the suitability index for marsh and seagrass cover
SI_{V2} = the suitability index for substrate composition
SI_{V3} = the suitability index for mean spring salinity
SI_{V4} = the suitability index for mean spring water temperature.

SI_{V1}^2 is squared to weight it more heavily in the composite index value. The HSI for a site is either HSI_{fc} (food, cover) or HSI_{wq} (water quality), whichever is lower.

Broader landscape conditions can have a strong influence on estuarine shrimp populations. Although no minimum habitat size is included in the HSI for brown shrimp, it is clear that increasing the area of highly suitable habitat would generally result in increased support for shrimp. The population levels would theoretically increase in concordance with increasing habitat area to a point at which other factors would limit shrimp populations. Because brown shrimp spawn in deep offshore areas, poor offshore spawning conditions may limit larval recruitment into the estuary. Heavy predation on adult shrimp offshore or heavy fishing pressure may also limit shrimp recruiting to estuarine habitats. Conversely, favorable offshore spawning conditions, removal of

predators, and reduced fishing pressure may combine to produce massive recruitment to estuarine habitats.

The example of the Mississippi deltaic marsh restoration program illustrates the issues and uncertainties associated with restoration. First, the program rightly has determined that marsh restoration is dependent on major processes that are involved in delta formation (Figure 5). Restoration is focused on measures that can restore natural processes through interventions such as the introduction of sediment or the installation of wave protection. The program acknowledges that some processes, such as a weak zone in the Earth's crust, are not possible to address. Further, brown shrimp populations are dependent not only on habitat characteristics but on a variety of landscape-scale factors, such as spawning habitat conditions and fishing pressure. Hence, the success of the restoration in terms of brown shrimp is complex. Because of this complexity, and the limited understanding of their biology and natural variability, there is uncertainty regarding the response of shrimp to physical actions. Understanding the sources of these uncertainties represents a major step toward understanding potential outcomes from a restoration action.

3.3.6 Other Tools – HGM models

The HGM, which is currently under development by USACE, yields indices that can be used to evaluate wetland functions. It is not absolute but relative to regional reference sites and, like the HSI, is unitless. Guidebooks for its implementation in tidal fringe wetlands [43] and riverine wetlands [44] have been published. In comparison with the HSI models, which have a single-species focus, the HGM focuses on a suite of co-occurring species that inhabit a particular system. For example, among the functions that the HGM takes into account are not only those that are *hydrogeomorphic*, but also others that are *habitat-related.* Because the HGM relies heavily on data from regional reference sites to develop the rating for a restoration site, HGM guidebooks require extensive development and evaluation by region. There are presently only a few regions for which HGM models have been developed.

For the tidal fringe wetland HGM, four examples of functional capacity indices (FCI), are as follows [43]. These equations combine subindices assigned to each variable after the variable is measured in the field. A published "functional profile," to be developed from data from regional reference standard sites, is consulted to assign the subindex.

Hydrogeomorphic functions

(1) Tidal surge attenuation (TSA) = the capacity of a wetland to reduce the amplitude of tidal storm surges

$$\text{TSA} = (V_{DIST} + V_{ROUGH}) / 2 \qquad 4$$

where

V_{DIST} = a variable subindex based on the distance that water must travel across an intervening tidal fringe wetland

V_{ROUGH} = a variable subindex based on the potential effects of emergent vegetation, obstructions, and microtopographic features on hydrodynamics of tidal floodwaters.

(2) Sediment deposition (SD) = the deposition and retention of organic and inorganic particulates from the water column through physical processes

$$SD = (V_{PSC} + V_{FD} + V_{ROUGH}) / 3 \qquad 5$$

where
V_{PSC} = a variable subindex based on the proximity to the source channel
V_{FD} = a variable subindex based on flooding duration.

Habitat functions

(3) Plant community composition (PCC) = ability of the wetland to support a native plant community of characteristic species composition

$$PCC = (V_{COV} + V_{EXOTIC}) / 2 \qquad 6$$

where
V_{COV} = a variable subindex based on total percentage of vegetative cover
V_{EXOTIC} = a variable subindex based on percentage of vegetative cover by exotic or nuisance species.

(4) Wildlife habitat utilization (WHU) = the potential use of a marsh by resident and migratory avifauna, herpetofauna, and mammals

$$WHU = (V_{AE} + V_{UE} + V_{WHC}) / 3 \qquad 7$$

where
V_{AE} = a variable subindex based on the amount of edge between the intertidal vegetated, intertidal unvegetated, and subtidal areas
V_{UE} = a variable subindex based on amount and quality of upland edge
V_{WHC} = a variable subindex based on the wildlife habitat complexity.

Both the FCI and the HSI are indices associated with approaches, the HGM and HEP approaches, respectively. The latter FCI, "wildlife habitat utilization," is analogous to the HSI model presented above. However, the HGM addresses associations of species with common behaviors and habitat requirements. For a regional HGM, marsh wren, for example, may be a major component of the avifauna, and therefore may influence the reference sites that are selected. If the reference sites selected are best for the marsh wren and species with similar habitat requirements, then the HGM functional capacity index for WHU will be a strong indicator of habitat quality for the individual species, as is the HSI.

In contrast to HSI, the HGM is based on the recognition that wetland types are formed under hydrologic and geomorphic processes. For example, tidal fringe wetlands occur in a much different hydrological and geological regime than do organic soil flats. Therefore, maintenance of the larger regimes is important in assuring the continued development and functioning of the different wetlands that occur within them. This broader-scale setting requires that a restoration planner take a landscape or watershed view of the system within which he or she is working to reduce the uncertainty about the functional performance and long-term viability of a restored site.

3.3.7 Implications for Plan Formulation

Both HSI [39] and HGM models can be used with conceptual models for planning restoration projects. Because conceptual models illustrate scientific knowledge about the system or species, they provide both the basic understanding of the major aspects of the system and a pictorial description of how the system works. This is critical to any habitat-planning effort. Variables in the HGM models can be manipulated by several management measures to achieve an outcome; however, manipulations to improve conditions for one particular species would require special consideration. For example, habitat for the marsh wren could be enhanced through controlling water levels to improve intertidal and nontidal habitats, which would ultimately improve conditions for marsh wren nesting. The HSI models are conceptual, but they are partially parameterized by assignment of quantitative values to at least some of the variables. The HSI models were designed for rapid, semiquantitative, onsite assessments of habitat conditions relative to selected species. There are two important assumptions to the HSI models:

- If the ideal habitat conditions are established, optimal functions will be realized.
- Broader landscape conditions are ideal or at least adequate.

There are, of course, significant uncertainties associated with each of these assumptions. These will be discussed below. Nonetheless, management measures can be developed to arrive at site conditions that are at least conducive to a selected species' breeding.

Orth [39] provided a scenario for application of the HSI models in developing management measures. According to Orth, HEP and its HSI models were traditionally used to inventory resources (Planning Step 2) and to assess the effects of alternative planning formulations (Planning Step 4); the use of HSI models in Planning Step 3, plan formulation, has come into being only more recently in mitigation and restoration planning efforts. The goal for planning purposes is to achieve the highest total HSI value possible within physical and economic constraints. By adjusting the number, degree and kind of management measures at a site (e.g., percentage of cover type flooded, average height of herbaceous canopy), one can see in relative terms the ecological outcome as a change in the HSI. In the restoration planning context, HSI models are used to identify potentially useful management measures rather than to predict the effects of nonrestoration management measures.

The process described by Orth [39] involves examination of each of the habitat variables in relevant HSI models in light of four factors:

- proximity to optimum conditions
- responsiveness to manipulation
- relative effect in calculating an HSI
- manipulation costs.

This process provides information that is particularly relevant to the individual species identified in the HSI models, and is therefore most useful when the goals of a restoration project involve specific populations. Extrapolation from HSI results to restoration goals at the ecosystem level involves additional uncertainties. Orth cautioned that planning for target species may have undesirable effects on other species and suggested using community-based HSI models or performing the analysis on a suite of evaluation species to "balance their habitat needs" [39].

Because some of the HSI model variables can be manipulated in several ways to improve habitat quality, Orth noted that planners have several management options. For example, pipe irrigation systems, controlled flooding, and increased groundwater levels can manipulate the soil moisture regime. Each of these options has an associated cost and uncertainty, which can be evaluated as part of the planning process. However, not all variables are equally important in determining habitat quality, nor are they comparable at every unique site.

The conceptual understanding of the habitat from patch to landscape and from species to community can be used to conduct the risk assessment. The following are examples of questions that can be asked to link the project site to the landscape and to the conceptual model that represents it.

- Will there be adequate corridors?
- How will restoration for a species affect the community?
- Is the site large enough?
- How will the project's resistance and resilience change over time? Is this acceptable?
- What are the likely landscape changes over time? How will they affect the site?
- Does the design invite invasive species?
- How will the community affect the species of interest?
- What else could go wrong?

When risk is identified, the conceptual model can be used to develop risk management techniques, alternative plans, or construction methods. The project example at the end of this report illustrates these concepts.

3.3.8 Uncertainties Associated with the Models used for Management

Morgan and Henrion [13] pointed out that "Careful thought leads us to the following disturbing conclusion: *Every model is definitely false*." Given that no model perfectly represents the real world, in this section we discuss the more salient uncertainties associated with the use of conceptual models, HSI models and the HGM in restoration projects, and some considerations for reducing such uncertainties in practice.

Conceptual models are not quantitative; therefore the uncertainty directly associated with them derives from the possibility that relationships are depicted inaccurately. Relationships may be indicated where there are none, or cause-and-effect relationships may be implied inaccurately in the model. Conceptual models reflect the state of knowledge and the uncertainties of expert opinion. They are also based on quantitative data and are thus subject to the uncertainty associated with empirical measurements.

Both HSI and HGM models have built-in uncertainties, as well as uncertainties associated with their application to plan-formulation in ecosystem restoration projects. The built-in uncertainties of both models include those derived from their basis in expert opinion, which is to some degree subjective; incomplete data sources; and imperfect application of numerical equivalencies for habitat quality and functions. In the terminology of risk analysis, these are all forms of *knowledge uncertainty*. Sources of knowledge uncertainty in the HSI and HGM models include the standard sources of uncertainty associated with empirical quantities, since the models are based on such data. These sources of uncertainty, some of which also derive from inherent variability, are further described in Morgan and Henrion [13]: statistical variation, systematic error, subjective judgment, linguistic imprecision, variability over time or space, inherent randomness, disagreement, and approximation by the model. These uncertainties can be reduced to some degree by studies directed at data gaps.

Another source of uncertainty associated with empirical quantities is called randomness and unpredictability by Morgan and Henrion [13], and is synonymous with the inherent variability of natural systems under study, defined previously. When the HSI or HGM models are applied in plan-formulation for specific natural or man-made systems, inherent variability may affect the outcome of the project in unpredictable ways. An example would be a major storm event occurring within months of a restoration planting effort, when plants are particularly susceptible to damage. As a general rule, it is possible to reduce knowledge uncertainty, but impossible to reduce such inherent variability.

A simple analysis of the HSI and HGM models shows that in restoration project planning applications, they are best applied at different scales. Because HSI is focused on the individual species, whereas HGM integrates landscape- and community-scale information and general habitat use, there are risks associated with the selection of one or the other of these model types to formulate alternative restoration plans. When HSI

models are applied to plan-formulation in ecosystem restoration projects, there is a risk that results will be extrapolated from the habitat of one species to another or from a species to objectives at a larger scale, such as the ecosystem. When HGM models are used in plan-formulation, there is a risk that the unique requirements of certain species will not be adequately accommodated.

3.3.9 Design Risk

In the plan formulation step, design is used to reduce the risks associated with both knowledge uncertainty and inherent variability. Such approaches, however, can lead to over-design. The costs of reducing knowledge uncertainty using studies to fill data gaps can be directly compared with the costs of proposed design modifications suggested to manage the uncertainty. Designs proposed to manage engineering uncertainties, such as the level of tidal flooding that will result from opening a dike, need to be carefully weighed against their cost. Also, residual risk due to engineering limitations or engineering uncertainties should be documented for consideration when the alternative plans are evaluated in Planning Step 4 of the planning process.

3.4 Planning Step 4: Evaluation of Plans

It is important to identify all potential significant effects of each plan. Effects are usually measured relative to the planning objectives established in Planning Step 1. However, it is important to broaden the focus to the watershed or landscape level, using both the conceptual and empirical models to evaluate the system and examine the possibility of unintended or incidental consequences. When the variables being used to measure the effects on the planning objectives are determined to encompass all significant effects, the evaluation process may proceed.

Five primary tasks are required to evaluate an alternative:

- Forecast the with- and without-project conditions.
- Compare the with- and without-project conditions.
- Assess the differences.
- Appraise plan effects.
- Qualify plans for further consideration.

In practice, forecasting the with-project conditions simply means projecting the state of the planning objectives into the future. The state or condition variables established in Planning Step 1 to measure the design objectives are forecast for each project alternative. The forecasts are made for each year of the period of analysis and averaged to yield an average annual equivalent value. Comparisons and descriptions of with- and without-project conditions identify the net difference in the average annual equivalent values of the variables assessed relative to the planning objectives. Appraisal of a plan entails a subjective judgment of its effects: positive, negative or neutral; important or not.

Qualifying plans is the first screening of the alternatives; each alternative is assessed to determine its suitability for further consideration.

Alternative plans are qualified for further consideration using four criteria: c*ompleteness, effectiveness, efficiency* and *acceptability* [1]. One goal of this report is to explain how risk analysis relates to each of these criteria. Completeness is the measure "to which a given alternative plan provides and accounts for all necessary investments or other actions to ensure the realization of the planned effects" [1]. Investments or other actions can include design features and construction methods used to ensure the realization of the planned effects. Completeness is clearly a statement of risk assessment (i.e., probability of project success). Effectiveness is "the extent to which an alternative plan alleviates the specified problems and achieves the specified opportunities" [1]. Incorporating uncertainty into the analysis allows the analyst to measure and communicate the effectiveness of an alternative plan as a range of possible outcomes, along with their probability of occurrence. Efficiency is "the extent to which an alternative plan is the most cost-effective means of alleviating the specified problems…" [1]. When uncertainty is incorporated into the cost estimate, cost-effectiveness is not only measured at the expected value, but at the range of identified outcomes. Acceptability is "the workability and viability of the alternative plan with respect to acceptance by State [*sic*] and local entities…" [1]. Explicitly incorporating risk analysis into the decision-making process allows stakeholders to consider their risk preferences when determining acceptability. These concepts are illustrated in Step 4 of the project example in Appendix A of this report.

3.5 Planning Step 5: Comparison of Alternatives

The surviving alternatives, which have been judged complete, effective, efficient, and acceptable, are compared to evaluate their relative contribution to the planning objectives, their cost, and other objectives that are important to the stakeholders. When metrics used to measure the effects of each alternative are incommensurate,[b] such as PCC habitat units and WHU habitat units, there is no *objective* way to choose between the alternatives. Value judgments must be used to make trade-offs between project cost and project outputs [9].

Subjective values are often expressed as weights for each output measure. Many methods have been developed to elicit and quantify the relative weights of alternative outputs. They range from the simple assignation of weights to the complex pairwise comparison method used in the analytical hierarchy process (AHP) [45].

Once weights have been established, the alternatives can be ranked, the least-cost route to an outcome (the efficient frontier) identified, and incremental cost analysis conducted. However, decisions are often taken by imputing the relative value of each output without explicitly establishing weights. The sophistication of the methods for assigning weights to outcomes often outruns the subjective nature of the process.

[b] As explained in Section 4.3.2.2, ecosystem restoration measures are formulated only for environmental benefits, and any National Economic Development benefits are incidental to the restoration plan.

The inclusion of uncertainty in the analysis calls for a comparison of the overlapping ranges of potential outcomes for each alternative, rather than a simple examination of the alternatives at their mean values. This allows alternatives that may be dominated by other alternatives at the mean to be included in the final set of choices.

3.6 Planning Step 6: Plan Selection

Selection criteria should consider all important outputs and effects of the projects. This includes not only the design objective metrics assessed relative to the planning objectives, but any other factors important to the stakeholders. At this point in a restoration study, all remaining plans, including the no-action plan, are equally rational choices given the metrics of the design objectives. In theory, the "best" choice is the one that maximizes general welfare. However, without commensurate outputs or market prices for such outputs, there is no objective way to identify this alternative. Therefore, one of the most important parts of plan-selection is a convincing rationale.

4.0 Conclusion

The absence of complete information about ecosystems makes risk analysis an important part of any ecosystem restoration evaluation. The USACE 6-step project planning process, augmented with concepts and tools from the science of ecological restoration, provides a framework for risk analysis in ecosystem restoration project planning. Conceptual models used in project planning include models of the ecosystem and ecosystem services, the landscape, and the habitat or subsystem. These models communicate to stakeholders our understanding of the system and reduce the chance of specification error. Empirical models, such as HGM and HSI, are known to have estimate error. The process presented here allows the analyst to explicate risk information to the stakeholders for the purposes of decision making. This procedure is illustrated in detail in Appendix A, Example Application of Risk Analysis to a USACE Ecological Restoration Project.

Appendix A - Example Application of Risk Analysis to a USACE Ecological Restoration Project

The following example employs the six planning steps described in this report to create and select an approach for restoring the functions of a degraded tidal wetland. The planning ***goal*** of the project is to restore degraded significant salt marsh ecosystem structure, function, and dynamic processes to a less degraded, more natural condition.

Project Example Step 1 - Problems and Opportunities: Setting Planning Objectives
The tidal wetland is located adjacent to a river with a navigation channel (Figure A-1), which requires periodic dredging to maintain authorized depths. Until the late 1970s, clean dredged material was discharged into a portion of the tidal wetland that was contained within a dike. A small tide gate allows water to drain from the filled area back into the river. The diked area of approximately 25 acres is bordered on the downstream side by a relatively undisturbed wetland, on the upland side by naturally vegetated upland habitat, and on the upstream side by a small stream with an adjacent tidal wetland.

Diking and filling have cut off hydrodynamic processes critical to maintenance of a viable wetland habitat. Prior to diking, water flushed over the site at a minimum of 12 times per month. Since tidal flushing was stopped, precipitation is the only source of water to the site. Hence, in addition to the physical loss of wetland habitat by fill, any remaining habitat is now freshwater/terrestrial, and completely different from the natural conditions. The changes have resulted in wetland habitat losses, which have had an effect on wildlife and habitat quality and functions. Removal of fill and breaching of the dike to restore natural tidal processes are the key actions required to restore the system.

The following ***planning objectives*** were established by USACE planners and stakeholders in response to the need to restore the site:

- Restore tidal marsh wildlife habitat.
- Restore natural tidal marsh wetland vegetation communities.

The planning objectives will be measured by proxy through design objectives. Tidal wildlife habitat and tidal wetland vegetation communities will be quantified using the HSI model for marsh wren along with the wildlife utilization and plant community composition components of the HGM model. Together, these models account for species as well as for the general conditions for wildlife at the site. While it is unlikely that the abundant marsh wren would ever be the target of restoration planning, this relatively simple model is useful for the purpose of example. The HGM model provides a simple and direct measure of the amount of native vegetation cover relative to non-native vegetation cover.

Given the inherent variability of natural systems, the planning team established the ***design objective*** that a viable alternative would be required to have at least a 50% chance of achieving a marsh wren habitat unit score of 9 or above.

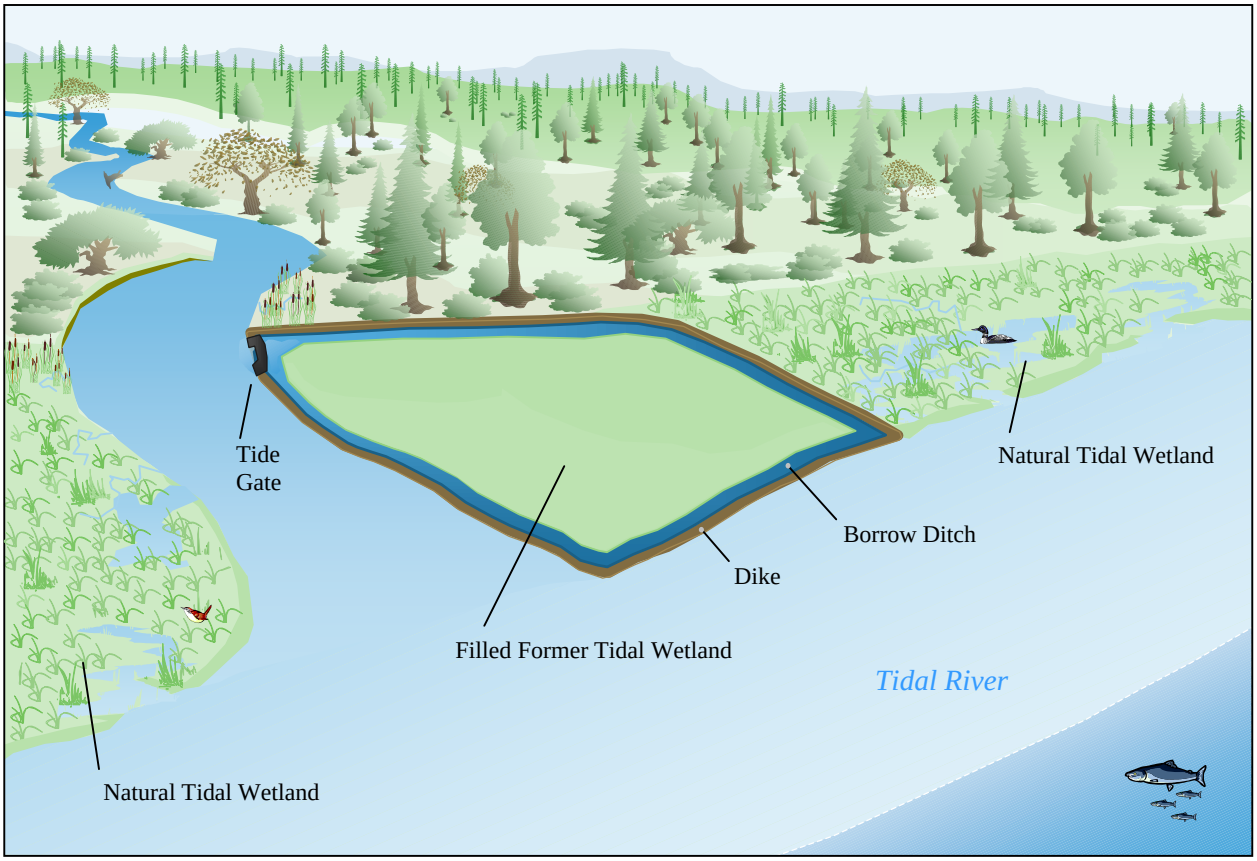


Figure A-1: Diked and filled former marsh and adjacent habitats.

There is uncertainty associated with the project. The risk of failure to meet the planning objectives is assessed through evaluation of the distribution of index values for the with- and without-project conditions. Yoe [14] presented a method to estimate the range of index values, which results in a minimum, median, and maximum value for an index. Yoe recommended that the values for variables be treated as ranges rather than point estimates. The purpose was to recognize and communicate to the extent possible the degree of uncertainty the study team associates with the values.

For example, the variable for cover of suitable vegetation type in the HSI model for marsh wren can have a point estimate of 50%. However, uncertainties associated with cover estimates result in a range of 30% to 70%. In such a case, Yoe [14] suggested that the range be used for the analysis; if the distribution of the values were known, then the range could be based on the 95% confidence limits. The HSI index would be calculated using a range of values for each variable. Minimum, maximum and mean HSI index values would result from the series of calculations using all combinations of values. In a similar fashion, the minimum, maximum, and mean index values can be determined for with-project conditions. By comparing the with- and without-project results, one can determine whether, at a minimum, maximum, and on average, the with-project conditions of the HSI index will be improved over the without-project conditions.

Project Example Step 2 - Inventory and Forecast

Conceptual Model

The conceptual model of landscape and controlling factors for marsh wren habitat (Figure 4), provides a basis for understanding the existing conditions and their relationship to the status of wildlife and wetland habitat functions. This model is based on information summarized from the HSI report for marsh wren and an understanding of landscape-level processes that can affect the formation and maintenance of marsh wren habitat [34]. Using the model as a guide, the relevant processes and structures that have been affected are tidal hydrology, standing water, and marsh cover featuring cattails, sedge, and rush. Some of the broader landscape-level features that have been changed are the presence of surrounding buffer habitats and potential human threats.

Existing Conditions Analysis

The HSI marsh wren model (Equation 1) indicates the quality of existing ecosystem conditions. Because the HSI model is not necessarily inclusive of tidal marsh wildlife, the HGM tidal marsh models provide additional guidance to the design [43,44]. For example, the HGM model for WHU (Equation 7) includes factors related to edge between intertidal vegetation and unvegetated edge, as well as upland edge, and habitat complexity. The HGM model for native vegetation (Equation 6) indicates only that highest scores are assigned to systems entirely containing native vegetation species. Hence, potential threats for invasion of the system by non-native vegetation must be considered in the assessment of alternatives.

Without modification of hydrology and removal of fill, the existing conditions will remain indefinitely. There is no expected improvement or reduction in overall habitat

quality or functioning. The existing conditions are poor for wildlife and vegetation, as indicated by the calculations of HSI and HGM indices (Table A-1).

Project Example Step 3 - Plan Formulation

The conceptual model and the HSI and HGM models reveal that restoration of hydrology and vegetation features is required to restore the desired functions expressed as planning objectives. Evaluation of the HSI model (Equation 1) indicates that the percentage of canopy cover of woody vegetation is the most responsive variable; this is also a variable in the HGM PCC model (Equation 6). Mean water depth is a limiting factor; there cannot be emergent herbaceous vegetation without standing water. An obvious measure would be to remove the entire facility (dike and fill) and allow the area to be flooded again. Plant recruitment is expected to occur naturally by airborne, waterborne, and bird dispersal mechanisms.

What could go wrong?

1) As plant recruitment mechanisms potentially limit both the number and rate of species recruitment to the site, invasive exotic species may become established and dominate the site. To reduce this risk, desirable species could be planted in the project area.

2) Storm waves could wipe out immature vegetative stands or prevent natural vegetation from becoming established. This suggests an alternative that leaves the dike in place until the vegetation is mature. The existing tide gate could be used to regulate the water depth behind the dike.

3) Grazing activity by species such as Canada goose may delay colonization of the site. Various techniques can be used to reduce this risk.

4) Protected vegetation may never develop the root system necessary to withstand storm waves, resulting in the loss of tidal vegetation when the dike is removed. Allowing limited exposure of the vegetative stand by partial removal of the dike may reduce this risk.

The following alternatives will be carried forward in this example.

1. Removal of dike and fill.
2. Removal of dike and fill with planting of desirable species and grazing prevention.
3. Removal of fill only with planting of desirable species and grazing prevention. The tide gate will be modified to regulate water depths.
4. Removal of fill, planting of desirable species, grazing prevention, and partial removal of the dike to allow a robust environment for vegetative stand to develop.
5. Removal of fill, planting of desirable species, prevention of grazing and removal of the dike in segments over time to allow a robust environment for vegetative stand to develop and achieve a completely natural tidal wetland environment.

Table A-1: HGM and HSI indices for existing conditions analysis

Index	Minimum	Median	Maximum
Marsh wren HSI	.00	.10	.20
WHU HGM	.00	.10	.20
PCC HGM	.00	.05	.10

Potential Sources of Errors in the Analysis

There are several sources of errors and uncertainties in the above example. For instance, it is assumed that if the habitat conditions were built, the marsh wren would occupy the site. However, the wren may not have sufficient numbers in the region to colonize the site, an uncertainty that can be investigated by consulting experts. Elevations of the site may be difficult to determine and to excavate precisely during construction, resulting in another source of uncertainty. In a microtidal marsh system, a few inches of change in elevation can significantly affect the type of plant community that develops. Further, the fill and dike material are assumed to be clean and disposable without hazardous material costs, an uncertainty that needs to be addressed through assessment of the materials and careful control during construction.

Project Example Step 4 - Evaluation of Alternative Plans

Initial Appraisal of the Alternatives

Five alternatives were identified during the plan-formulation phase. The first step in forecasting the with-project conditions is to consider these alternatives in the context of the landscape. Given the limited scale of the project, it is assumed that most effects of the alternatives would be limited to the project area, and that all significant effects would be adequately measured by the variables selected in Planning Step 1: the HSI for the marsh wren, and the HGM scores for tidal marsh. It is necessary to convert these values to habitat units for comparison, because not all alternatives have the same spatial footprint.

The habitat value scores for each alternative are estimated using the method described in Yoe [14]. Briefly, this method takes a distribution, rather than a point estimate, as the input for each variable in the model. A Monte Carlo process is used, in which the input distributions for each variable are convolved into the distribution of habitat units score. For this example, triangular distributions are used to describe each variable.

The cost estimates used in this evaluation also include uncertainty. Using the method outlined in Yoe [10] and Yoe [14], the cost estimates account for both unit cost and unit quantity uncertainty. This method also uses a Monte Carlo process, and it produces a distribution of total cost for each alternative.

Alternative 1: Removal of dike and fill.

With removal of the dike and fill, the system should tend toward development of marsh vegetation, and, ultimately, of ponding. However, without planting or grazing prevention and with uncertainty in the proximity of a seed source, the most likely values for HSI model vegetation variables SIV1, SIV2, and SIV4 are limited (Table A-2). The

Table A-2: HSI input variable scores (average annual values)

Variable[(a)]	Alternative 1 Index			Alternative 2 Index			Alternative 3 Index			Alternative 4 Index			Alternative 5 Index		
	most likely	min	max	most likely	min	max	most likely	min	max	most likely	min	max	most likely	min	max
SIV1	0.80	0.40	0.99	0.70	0.20	0.99	0.90	0.40	0.99	0.80	0.40	0.99	0.90	0.50	0.99
SIV2	0.80	0.40	0.99	0.70	0.20	0.99	0.90	0.40	0.99	0.80	0.40	0.99	0.90	0.40	0.99
SIV3	0.85	0.30	0.99	0.80	0.20	0.99	0.90	0.40	0.99	0.85	0.30	0.99	0.90	0.40	0.99
SIV4	0.80	0.40	0.99	0.70	0.20	0.99	0.90	0.40	0.99	0.80	0.40	0.99	0.90	0.40	0.99

[(a)] SIV1 = vegetation growth form
SIV2 = % canopy emergent herbaceous vegetation
SIV3 = mean water depth
SIV4 = % canopy woody vegetation

minimum values for these vegetation variables are very low, due to the possibility for system-wide sediment deposition and erosion with complete dike removal. This possibility for disturbance also tends to keep the most likely and minimum values for SIV3, mean water depth, relatively low. Uncertainty in construction techniques also affects this variable, specifically, bulldozing to an HSI target for the marsh wren that is measured in centimeters. Distributions such as these typically are developed by a panel of experts and are subject to error based on the experience and perspective of the participants [46].

The total percentage of vegetation cover, which is a variable in the PCC score in the HGM model, is affected by uncertainties in several factors: grazing, natural colonization, the proximity of seed sources, and disturbance, as discussed above (Table A-3). The other component in the PCC score, the percentage of cover of exotic or nuisance species, is affected by the proximity of seed sources and by grazer preferences.

The qualities of edge and habitat complexity that drive the WHU indices are positively affected by removal of the dike, which restores intertidal-subtidal and upland edges. Without planting and grazing prevention, however, the vegetation and ponding will develop slowly and limit the development of associated edge habitats. Uncertainties in the quality of post-construction edges will also exist without the use of planting as a restoration tool. Wildlife habitat complexity is positively affected by the presence of stream and subtidal habitats, but vegetation and ponds will develop relatively slowly under this alternative, keeping the most likely and maximum values low (Table A-4).

Using the process outlined by Yoe [10], the input distributions for Alternative 1 resulted in a distribution of habitat unit scores for each model, and a distribution of estimated costs (Figure A-2). Including uncertainty in the analysis allows the analyst to communicate to other decision-makers a degree of belief about the expected outcome of the plan.

Alternative 2: Removal of dike and fill with planting of desirable species and grazing prevention.
This alternative, like Alternative 1, produces a system that is exposed to sediment deposition and erosion because of dike removal, but in addition, desirable species are planted and stressors are removed by grazing prevention. This tends to increase the most likely and maximum values for the vegetation variables in both the HSI model (Table A-2) and the PCC score (Table A-3), while keeping the minimum values low, due to the possibility of disturbance. The quality of vegetative cover is likely to be improved by giving desirable species a head start over invasive exotics, and therefore the most likely percentage of cover by exotic and nuisance species is lowered. Maximum possible values for this variable remain high because an invasion is always possible, depending on the proximity of seed sources and dispersal vectors. Mean water depth, SIV3, is unchanged.

The accelerated succession of plant communities due to grazing prevention and planting tends to hasten the development of ponds and thus to increase the WHU scores for edge in the HGM model (Table A-4). As with Alternative 1, restoration of both intertidal-subtidal and upland edges is begun with complete dike removal. Uncertainties remain in the quality of post-construction edge, but these can be minimized by planting. Wildlife habitat complexity is increased by the presence of more developed plant communities and ponds, although the minimum possible value remains low due to the exposure to sedimentation and erosion in the early stages of marsh development.

Alternative 3: Removal of fill only with planting of desirable species, grazing prevention, and modification of the tide gate to regulate water depths.
Alternative 3 affords a very protected start for plants, and therefore increases the most likely and maximum values for the HSI and PCC vegetation variables, with the exception of exotic and nuisance species cover; the most likely and maximum values for this variable decrease, because desirable species are planted in relatively protected conditions (Tables A-2 and A-3). Reducing the exposure of the system to major sediment deposition or erosion also increases the most likely and maximum values for mean water depth. In general, minimum values increase under this alternative as well, due to the low likelihood of catastrophic disturbance.

Without dike removal, however, the number of edge habitats in the system remains very low. No upland edge or intertidal-subtidal edge habitat is restored, and therefore the most likely and maximum values for these variables in the HGM model are low or zero (Table A-4). Some edge habitats are created by the accelerated development of plant communities in this protected environment, leading to the establishment of ponds. Although the protected development of vegetation in this system will create some wildlife habitat complexity, the most likely and maximum values for this variable are not high, because habitat connectivity is impeded by the dike; the protection from disturbance keeps the minimum value relatively high.

Table A-3: PCC input variable scores (average annual values)

Variable[a]	Alternative 1 Index			Alternative 2 Index			Alternative 3 Index			Alternative 4 Index			Alternative 5 Index		
	most likely	min	max	most likely	min	max	most likely	min	max	most likely	min	max	most likely	min	max
Vcov	0.90	0.20	0.99	0.85	0.10	0.99	0.95	0.40	0.99	0.90	0.20	0.99	0.95	0.40	0.99
Vexotic	0.20	0.01	0.99	0.20	0.01	0.99	0.20	0.01	0.99	0.20	0.01	0.99	0.20	0.01	0.99

[a] Vcov = total % vegetative cover
Vexotic = % vegetative cover by exotic/nuisance species

Table A-4: WHU input variable scores (average annual values)

Variable[a]	Alternative 1 Index			Alternative 2 Index			Alternative 3 Index			Alternative 4 Index			Alternative 5 Index		
	most likely	min	max	most likely	min	max	most likely	min	max	most likely	min	max	most likely	min	max
Vae	0.70	0.50	0.80	0.80	0.50	0.90	0.50	0.30	0.60	0.70	0.50	0.80	0.85	0.60	0.95
Vue	0.00	0.00	0.00	0.90	0.80	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.90	0.80	1.00
Vwhc	0.60	0.30	0.80	0.70	0.10	0.99	0.70	0.50	0.80	0.60	0.30	0.80	0.90	0.60	0.99

[a] Vae = amount edge between the intertidal vegetated, intertidal unvegetated, and subtidal areas
Vue = amount and quality of upland edge
Vwhc = wildlife habitat complexity

Alternative 4: Removal of fill, planting of desirable species, grazing prevention, and partial removal of the dike.

A portion of the dike on the stream side of the project site is removed in this alternative, increasing the possibility of local disturbance. This uncertainty reduces the most likely values of the vegetation variables in the HSI model and the PCC score to slightly below the levels for Alternative 3 (Tables A-2 and A-3). The most likely and minimum values for mean water depth are also reduced, due to the possibility of localized deposition or scour in the area of the dike breach. Overall, this alternative provides a relatively protected environment for the development of plant communities to target levels. The PCC values for exotic and nuisance vegetation are unchanged, with invasions relatively well controlled.

Alternative 4 is an improvement over Alternative 3 in providing some intertidal-subtidal edge habitat in the area of the dike breach, which increases the edge scores in the WHU module. However, because the purpose of the dike breach is to provide tidal inflow to the project site, there is no construction activity on the upland side, and no upland edge is restored; the score for the amount and quality of upland edge remains zero, as in Alternative 3 (Table A-4). Wildlife habitat may reach the level of complexity estimated for Alternative 3, but there is also the possibility of disturbance slowing community development or affecting the mean water level.

Alternative 5: Removal of fill, planting of desirable species, grazing prevention, and removal of the dike in segments over time.
Overall, this alternative provides a protected start for plants, and ultimately should achieve a restored ecosystem without remnants of the dike limiting habitat continuity. The possibility of disturbance during the most vulnerable post-planting period is kept low by removing the dike in segments, which increases the minimum values for the vegetation variables in the HSI model and for total percentage of cover in the PCC score (Tables A-2 and A-3). The most likely and maximum values for these variables are high, equal to those of Alternative 3. The PCC values for exotic and nuisance vegetation remain unchanged.

The design of the project phases is critical to the values assigned to the variables in the WHU model. The upland portion of the dike should be removed in the first phase of construction, when the dike is first breached to permit tidal inundation, in order to allow habitat connectivity to develop across the upland-marsh boundary. With this specification, the most likely and maximum values for the edge and complexity variables in the HGM model are the highest of any alternative (Table A-4). Intertidal-subtidal edge is also created as the dike is removed in segments, and ponding begins as the plant communities develop rapidly from the initial planting in a relatively protected environment. Minimum values for these variables are also the highest of any alternative, due to the low probability of disturbance.

Qualifying Plans for Further Consideration
Having appraised the effects of each plan, the analyst can now qualify each plan for further consideration based on the four criteria: completeness, effectiveness, efficiency and acceptability [1]. Completeness or actions to ensure the realization of the planned effects can now be judged by the uncertainty associated with each plan. Completeness was defined in Planning Step 1 in terms of uncertainty; to avoid unacceptable risk, viable alternatives were required to have at least a 50% chance of achieving a marsh wren habitat unit score of 9 or above.

The evaluation results for all alternatives are summarized in Figure A-2. Examining these graphs of habitat unit scores, the following observations can be made. The identified outcomes of Alternative 1 are clearly below the planning requirement of 50% over a marsh wren habitat score of 9 (Figure A-2a). Therefore, Alternative 1 fails the criterion of completeness. Regarding effectiveness, a perfect habitat would have a score of 25: the higher the habitat unit score, the more effective the measure. The inclusion of uncertainty in the analysis allows the analyst to determine whether an alternative is more effective over the entire range of outcomes or simply at the average value. In our example, Alternative 5 is the most effective plan by all three measures; however, there is considerable overlap between Alternative 5 and Alternative 2. Efficiency, or cost-effectiveness, is also revealed in the analysis. For example, the Alternative 3 score for marsh wren habitat units exceeds scores for Alternatives 1, 2 and 4, which cost more and yield less in terms of marsh wren habitat.[2] Alternatives 3 and 4 do share some solution

[2] Orders of stochastic dominance, correlation of outcomes and dependencies are ignored to simplify the example.

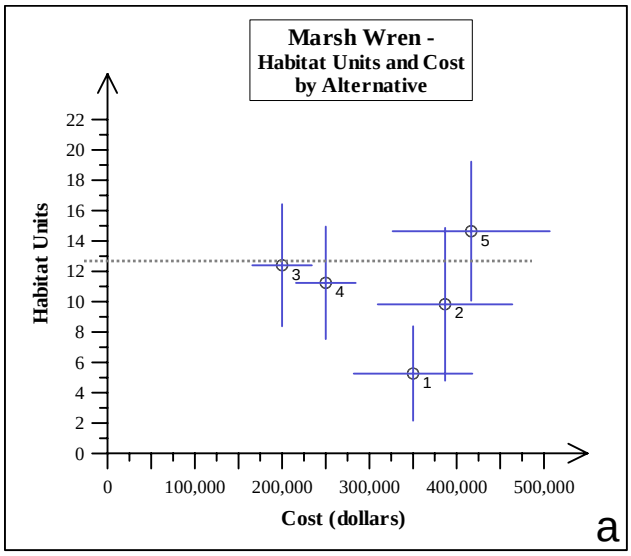
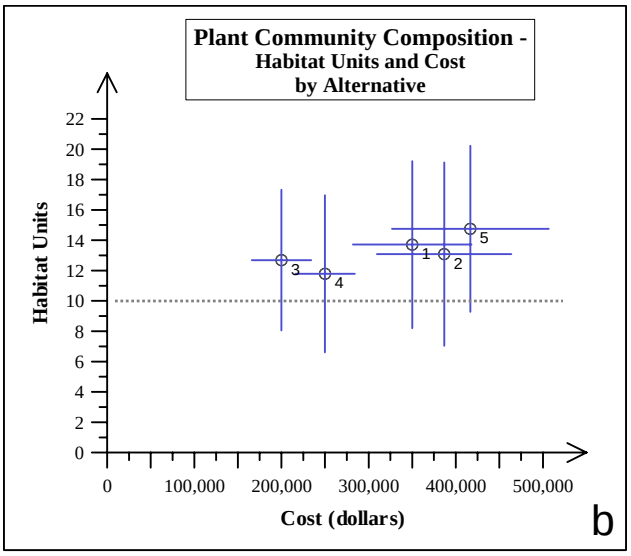
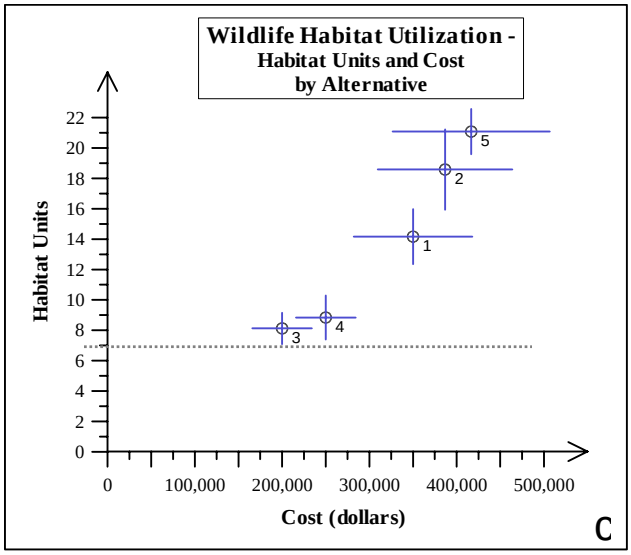


Figure A-2: Habitat units and cost by alternative for three models: marsh wren habitat suitability index

(a), plant community composition



(b) and wildlife habitat utilization index



(c). The mean score and the fifth and ninety-fifth percentiles are shown for habitat units and cost.

space, as do Alternatives 2 and 5. Using the PCC, Alternative 3 scores exceed those for Alternative 4, and Alternative 1 scores exceed those for Alternative 2 (Figure A-2b). With respect to the WHU, all of the plans are efficient (Figure A-2c), in that a more costly alternative is never less effective.

From an efficiency standpoint, the analyst could qualify the following for further consideration: all plans, based on the WHU scores; Alternatives 1, 3 and 5, based on the PCC scores; or only Alternatives 3 and 5, based on the Marsh Wren HSI scores. The final decision will depend on the relative weight assigned to each model score. Acceptability can also be assessed by the risk information revealed in the analysis. The local sponsor may be unwilling to participate in an alternative that costs too much. In this example, if the local sponsor were limited to $450,000, Alternative 5 could be unacceptable because it represents some risk of exceeding that cost.

The plans that qualify for further consideration in this example are Alternatives 2, 3 and 5. The marsh wren habitat score for Alternative 1 presents too great a risk of failure. This alternative is incomplete. Alternative 4 was judged inefficient in that Alternative 3 produces more for less cost in terms of both the PCC score and the marsh wren score. The final three alternatives will be compared in Step 5.

Project Example Step 5 - Plan Comparison

In this example, the measures used to evaluate the alternatives are incommensurate; i.e., marsh wren habitat units cannot be added to PCC habitat units or wildlife habitat units. Comparison must either proceed by examining each output separately or by establishing weights for each. If weights are established, the outputs can be summed and cost-effectiveness and incremental cost analysis used to compare plans. This example proceeds by examining each output separately.

The remaining alternatives in our example are the no-action plan and Alternatives 2, 3, and 5. Based on Figure A-2, the following observations can be made. The common metric to each output is cost. Comparing the cost of each alternative shows that Alternative 3 will always cost less than Alternatives 2 or 5. Alternative 5 costs more than Alternative 2 at the mean; however, the cost estimates have considerable overlap. This overlap indicates that Alternative 5 could end up costing less than Alternative 2.

Because Alternative 3 is the least-cost with-action alternative, it is considered the “first added” and the others are compared incrementally with it. Alternative 2 contributes a clear incremental increase of 10.5 WHU habitat units over Alternative 3. However, PCC units are only marginally improved at the mean, 0.4 habitat units, and have a greater degree of dispersion, with some potential outcomes lower in PCC by as much as 2 habitat units. The output of Marsh Wren habitat units for Alternative 2 is lower at the mean and the fifth and ninety-fifth percentiles than for Alternative 3. Given these outcomes, it is only Alternative 2’s contribution to WHU that gives it potential merit. It will be the subjective evaluation of WHU relative to marsh wren habitat and PCC that determines the strength of this advantage.

Alternative 5 makes incremental contributions to all three measures for its additional cost, whether it is considered added to Alternative 3 or to Alternative 2. For example, at the mean, Alternative 5 contributes an additional 2.2 marsh wren habitat units over Alternative 3. The incremental cost of Alternative 5 from Alternative 3 at the mean is $217,000. Subjective judgment will be needed to answer the incremental cost analysis question: "Is it worth it?"

Depending on the weights given to each output it is possible to construct a scenario in which all three alternatives remain on the efficient frontier. However, in this example, we assume the contribution of an additional 10.5 WHU habitat units by Alternative 2 is not sufficient to offset the mean loss of 2.6 marsh wren habitat units incurred by selecting Alternative 2 over 3. Therefore, Alternative 2 is removed from further consideration.

Project Example Step 6 - Plan Selection

The final choice set in our example consists of Alternatives 3, 5 and the no-action plan. All three options can be defended. The no-action plan has low habitat values, but the decision-makers may think the restoration project is too expensive for the outcomes achieved. Alternative 3 has similar accomplishments on the marsh wren and PCC metrics for less than half the cost of Alternative 5. Alternative 5 makes a significant contribution to the WHU index. The subjective values brought to the analysis by the decision-makers will determine the final selection.

What are the other criteria to consider in the final plan selection? One of the risks identified earlier in this report was the risk that the metrics used to measure the contribution of a plan to the planning objectives (the marsh wren, PCC and WHU habitat units in our example) do not fully reflect the stated goals of the planning effort. One goal of the USACE restoration program is to reestablish natural, self-regulating ecosystems. In contrast to Alternative 5, Alternative 3 leaves in place the man-made levees and tide gate. This is reflected in the indices, in that the number of acres restored is less, and thus the habitat unit scores will be less for an equal HSI score. However, this numerical difference may not adequately express the importance of this outcome to the stakeholders.

What is the convincing argument for selecting a single alternative from the three remaining? Planners soon learn that what convinces some does not convince others. One example assumes that Alternative 5 is selected because of the significant contribution it makes to the WHU index and because it completely restores the site to a more natural condition. The cost for this is more than double the cost of Alternative 3. However, some decision-makers may think this additional cost is not worth the incremental gain, and that the difference may be better spent restoring a different site. This is when the public debate begins in earnest. At this stage, after the planning team has made its recommendation, it should step back and let the decision-makers, such as USACE leadership, local sponsors and stakeholders, make the final judgment.

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