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*Environmental Benefits Analysis Program*

# Science-based Framework for Environmental Benefits Assessment

J. Craig Fischenich, S. Kyle McKay, Sarah J. Miller, David Price, Bruce Pruitt, Leigh Skaggs, Burton Suedel, and Dave Tazik

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# Abstract

This report outlines a framework for evaluating ecosystem restoration benefits within the context of USACE Civil Works planning process. An emphasis is placed on knowledge gained from research conducted under the Environmental Benefits Analysis (EBA) Program to address needs for a science-based assessment strategy that moves the standard of practice closer to the state-of-science for EBA. Current practice can be improved with the explicit use of conceptual models, establishment of clear objectives and associated metrics, better predictive tools, quantification of uncertainty, more structured decision methods, and adaptive management. The report is intended to assist Corps water resources planners and Project Delivery Teams (PDTs) in evaluating ecosystem restoration projects, programmatic considerations and general advancements in restoration science. It should also assist ERDC researchers and program managers as well as USACE water resources planners in aligning EBA products to meet planning needs.

# Contents

# Figures and Tables

## Figures



## Tables

# Preface

The research documented in this report was conducted for and funded by the Environmental Benefits Analysis (EBA) Program. The EBA Program is sponsored by Headquarters, U.S. Army Corps of Engineers and is assigned to the U.S. Army Engineer Research and Development Center (ERDC) under the purview of the Environmental Laboratory (EL), Vicksburg, Mississippi. The USACE Proponent for the EBA Program was Rennie Sherman. The EBA Program Manager was Glenn Rhett, and Dr. Alfred Cofrancesco was the Technical Director.

This report was prepared by Dr. J. Craig Fischenich, Kyle McKay, Sarah Miller, Dr. David Price, and Dr. Bruce Pruitt, all of the Ecological Resources Branch (EE-E); Ecosystem Evaluation and Engineering Division (EE); Dr. Burton Suedel of the Environmental Risk Assessment Branch (EP-R), Environmental Processes and Engineering Division (EP); and Dr. David J. Tazik, ERDC-EL. At the time of publication, Antisa Webb was Chief of CEERD-EE-E; Dr. Edmond Russo was Chief, CEERD-EE; Buddy Goatcher was Chief of EP-R; and Warren Lorentz was Chief CEERD-EP. The Director of ERDC-EL was Dr. Beth Fleming.

COL Kevin J. Wilson was the Commander of ERDC, and Dr. Jeffery P. Holland was the Director.

# 1 Introduction

## Purpose

The capability to identify, quantify, and articulate environmental benefits is central to the formulation of sound ecosystem restoration projects and is necessary for making good restoration decisions. This technical report presents a framework for assessing benefits expected from aquatic ecosystem restoration actions. It outlines several key principles necessary for scientifically sound formulation and evaluation of restoration alternatives and is intended to promote good practice. The framework is applicable within the Corps' current six-step planning process and is deliberately flexible so it can be adapted to differing viewpoints regarding the ways in which "benefits" might be portrayed.

## Points of emphasis

The quality of an environmental benefits assessment (EBA) is contingent upon a number of factors. This report presents an overarching framework for recognizing, characterizing, assessing, and evaluating benefits potentially resulting from aquatic ecosystem restoration actions, and focuses upon the following factors offering opportunities to improve practice:

1. **Ecological understanding**. The relationships among the hydrologic, geomorphic, and biologic characteristics of ecosystems are the foundation of effective ecosystem restoration and benefits assessment. The manipulation of these relationships through engineering practices forms the basis for the Corps of Engineer's ecosystem restoration mission.
2. **Objectives and metric selection**. The quality of assessments and evaluations rests on the choice of metrics used to compare alternatives and evaluate the results of investments. Objectives and benefits generally extend beyond habitat improvements, and a more comprehensive accounting of restoration benefits is desirable.
3. **Forecasting**. Practitioners should embrace modeling and related techniques associated with forecasting of ecosystem condition(s). Quantifying expected benefits from ecosystem state changes requires the development, use, and interpretation of models.

4. **Uncertainty**. Good EBA practice requires the recognition, identification, characterization, and explicit consideration of uncertainty and associated risks.
5. **Reference concepts**. Reference concepts are important to understanding ecosystems and can be used to establish a "target" for restoration. Reference conditions can also be used to index ecosystem quality, which provides a means for quantifying benefits.
6. **Adaptive management**. Adaptive management practices, if embraced and exercised during a project's planning and lifecycle activities, can significantly improve the potential for realizing restoration benefits and decrease potential for making regretted decisions.
7. **Documentation**. An accurate and thorough, but concise, accounting of the EBA is necessary to effectively convey information to decision makers.

## Scope and limitations

This report addresses the technical aspects of an environmental benefits assessment (EBA), and provides a framework for scientifically sound practice. This framework is one of a series of documents, tools, and other resources prepared under the EBA Research Program. The reader should use this document as an entrée to the detailed technical information and guidelines incorporated within several related technical notes. The latter are referenced throughout this report and will be available online at the Ecosystem Restoration Gateway.[1] This document describes and/or otherwise characterizes the state of science or field and practice of ecosystem restoration and should in no way be perceived as an expression of Civil Works policy. It is expected that readers will consult formal Civil Works policy, regulations, and guidance for details regarding Civil Works policy and required/acceptable practices (U.S. Army Corps of Engineers (USACE) 1999a, 1999b, 1999c, 2000).

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[1] http://cw-environment.usace.army.mil/eba/index.cfm

# 2 Key Strategies and Concepts

## Ecosystem organization

Assessing the environmental benefits that arise from an ecosystem restoration project requires, among other things, a keen understanding of the linkages among the physical, chemical, and biological characteristics of the system. The effects of proposed management measures on the ecosystem condition over time and the value society places upon the resultant changes in ecological state form the basis for benefits quantification.

### Ecosystem restoration goals

The goal of the Corps' Civil Works ecosystem restoration activities is to “restore significant ecosystem function, structure, and dynamic processes that have been lost or degraded” with the intent of partially or fully reestablishing the attributes of a naturalistic, functioning, and self-sustaining system (USACE 1999a). This stated purpose provides context for the establishment of more specific planning objectives underpinning any aquatic restoration effort undertaken by the Corps. In many instances, a full return to pre-disturbance conditions may not be feasible, but partial restoration that yields significant improvements to degraded ecological resources may be possible. Actions that prevent continued degradation may also yield significant benefit, even if no “restoration” occurs. Thus, the ability to assess the restoration (in part or whole) of the structural and functional characteristics of ecosystems, and quantify the benefits resulting from those improvements, is fundamental to the EBA process.

### Structure and function

Ecosystem restoration is accomplished through improvements to some, and potentially all, of the structural or functional conditions or characteristics of the system. Ecosystem form, or ***structure***, refers to both the composition of the ecosystem and to its physical and biological organization (National Research Council (NRC) 2005). Structural characteristics vary in time and space, are unique to each system, and include, for example, system morphology, size and distribution of bed sediments, composition of the biotic community, and the system’s hydrodynamic regime.

Ecosystem ***functions*** are the physical, chemical, and biological processes[1] that create and sustain an ecosystem (Fischenich 2006). Examples of processes that sustain biological communities include primary productivity, nutrient cycling, hydrological processes, erosion and sedimentation, species interactions, and natural disturbance regimes. Functions are largely responsible for the "self-organizing" and dynamic characteristics of ecosystems. Structure and function are closely linked in aquatic ecosystems, such that change to one likely affects the other. Reducing sediment yield to a stream, for example, leads to channel incision and widening. Those functions associated with hydrology and geomorphology are particularly relevant to Corps' ecosystem restoration projects, as discussed below.

### Hydrogeomorphic process focus

Aquatic ecosystem restoration has historically focused on biotic habitat and water quality, but an emergent trend has emphasized the geomorphic structure, function, and evolutionary trajectory of systems (Bennett et al. 2009), coupled with an understanding of the landscape context within which ecohydrologic processes interact. A broad "eco-hydrogeomorphic" understanding is necessary to frame spatially and temporally rigorous approaches to assessing the diversity, variability, and complexity of aquatic ecosystems. It also serves as a foundation for identifying and characterizing benefits in a fashion consistent with the Corps' approach to ecosystem restoration. Hydrologic and geomorphic manipulations are the primary management measures employed by the Corps for aquatic restoration, and the Corps has a long history of dealing with these parameters. ***Environmental benefits assessment involves translating those hydrogeomorphic manipulations into ecological effects, then assessing those effects in terms of objectives that reflect relevant social values.***

## Restoration Benefits

Four elements are required to effectively quantify aquatic ecosystem restoration benefits:

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[1] The terms function and process are used interchangeably in the literature. Herein, the term function refers to a broader organization of interacting processes. For example, the function of nutrient cycling is a consequence of fixation, mineralization, nitrification, denitrification, and other chemical and biological *processes*.

1. A baseline against which ecological changes can be compared (this includes ecological changes in the absence of any project and is the "future without-project" condition).
2. An understanding of ecological changes likely to result from the restoration action (e.g., the "future with" project condition).
3. A timeline (the period of analysis).
4. A mechanism for recognizing and attributing value to changes in ecological conditions (i.e. Is the condition improved or made worse? By how much?).

Standards of practice have emerged for the first three elements, and some have been reasonably standardized for application within the Corps. However, opportunities for improvement, especially where criticisms from the science community have been leveled, are addressed in this report. Several mechanisms for associating values with changes in ecosystem condition exist, but no single approach has achieved consensus among scientists or the community of practice.

### Values and the origin of benefits

Alterations to the structure and function of an ecosystem, while benefiting some organisms or interests, typically come at the expense of others. For example, the removal of fine silts from the bed of a stream may provide clean gravel substrate benefitting some macroinvertebrate species, but other members of the invertebrate community may be adversely impacted by this action. Clearly, the benefits of any ecosystem restoration action depend upon perspective, and the perceived benefits of restoration reflect ecological, socioeconomic, cultural, and even personal values (Clewell and Aronson 2007). Because values change over time and vary among stakeholders, the value ascribed to restoration activities can be quite subjective. Likewise, the proposal of restoration actions can reveal conflicts and necessitate consideration of trade-offs.

### Classes of benefits

Fischenich and Payne (in preparation) describe three classes of benefits that utilize different metrics and reflect alternative viewpoints of the implicit and explicit values that arise from healthy ecosystems (Figure 1). These concepts of benefit are not mutually exclusive; they can arise from the same restoration action but reveal different views of the technical, cultural, and personal significance of ecosystems. Any or all viewpoints can be employed for benefits assessment; Table 1 provides an example of how the potential benefits arising from a stream restoration project depend upon the selected class of benefit.

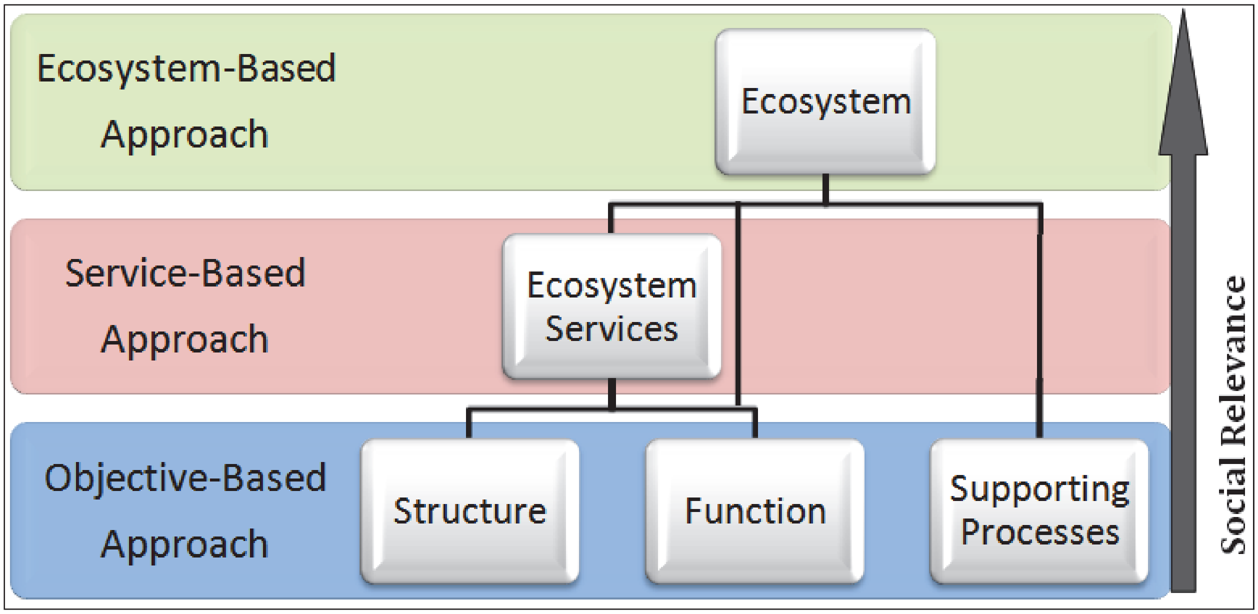


Figure 1. Classes of benefits associated with ecosystem restoration.

Table 1. Examples of benefits[1] derived from a stream restoration project demonstrating the dependency upon objectives and viewpoint.

| Objective-Based Benefits | Social Benefits (goods and services) | | | | |
|---|---|---|---|---|---|
| | EPA/State DEQ | USFWS/NMFS/ State DFW | Local Government | Local Landowner | Trout Unlimited |
| Water Temperatures<br><br>Substrate<br><br>Refugia<br><br>Hydrologic Connectivity<br><br>Sediment Processes | Water Quality Standards Met | Fish Habitat Improvements<br><br>Improved Fish Community Composition | Reduced Erosion<br><br>Improved Water Quality<br><br>Recreation Enhancements<br><br>Increased Property Taxes | Increased Property Values<br><br>Aesthetic Enhancement | Increased Native Trout Numbers<br><br>Improved Recreational Opportunities |

[1] Note that the *ecosystem* benefits approach implicitly encompasses all the items in the table as well as others not specifically identified both in the present and future.

The *objective-based* approach to benefit characterization focuses upon improvements to specific ecological attributes of an ecosystem, and is presently the most common approach among the three classes. Restoration consequences can also be expressed in terms of the change in those *goods and services* produced by ecosystems that are valued by humans (Mooney and Ehrlich 1997). The provision of habitat is generally regarded as an ecosystem service and has long been used for assessing restoration within the Corps, but conventional application extends the concept to a much broader suite of services. The third viewpoint, referred to as *ecosystem* benefits, avoids the need to segregate or aggregate specific benefits and aims to implicitly capture the full suite of benefits associated with a healthy system. This approach uses a suite of metrics for one or more reference conditions to serve as a benchmark for comparison, assessment, and evaluation. Consensus regarding which of these three approaches is best has not been achieved. Rather, selection of the benefit accounting method depends upon how that information is going to be utilized, among other factors.

### Need for benefits quantification

Results that emerge from a benefits assessment are fundamentally influenced by the way in which the benefits question is framed, which in turn is a function of the purpose of the analysis. Motivation for quantifying the benefits is generally one or more of the following:

1. To distinguish between different actions, projects, or programs.
2. To characterize return on investment expected from a restoration initiative.
3. To prioritize restoration projects given finite financial resources.
4. To maximize desired ecological outcomes resulting from every dollar spent.
5. To ensure that mitigation requirements are met or to calculate banking credits.

Evaluations supporting the above differ in that alternative comparison and prioritization may only require that the relative benefits and costs be determined;[1] detailed or comprehensive quantification may be unnecessary so long as the analyses are sufficient to allow reasonable comparisons. The other questions demand more accurate accounting of benefits and consideration of other factors including the technical and institutional significance of the targeted ecosystem(s), the effectiveness of the actions at eliciting the desired results, the resiliency of the restored system, and the fund investment efficiency.

[1]Assuming each alternative being compared satisfies any ecological thresholds critical to formulation.

## Generic framework for EBA

As is the case with most planning efforts, the activities associated with EBA tend to be iterative in nature, and vary in degree and scope depending upon specific project characteristics. At the broadest level, EBA consists of four general phases listed below. The decision phase largely involves activities outside benefits "quantification," but is relevant to benefits "assessment."

1. A qualitative phase involving the development of a good understanding of the ecosystem, the underlying problems, and the objectives and constraints.
2. A quantitative phase that includes forecasting future ecological states, assigning values to the changes in ecological condition (through metrics reflecting change in ecological function or structure), and assessing associated costs and uncertainties.
3. The decision phase, which involves an assessment of the outputs relative to planning objectives, constraints, costs, and other factors.
4. A measurement phase, wherein the actual benefits are determined as part of a monitoring and adaptive management program.

### Steps in the EBA process

Benefits analysis involves multiple steps, many of which are common to all assessments and some that depend upon the specific project characteristics as well as types of metric and valuation techniques that are applied. Though the process is presented as linear, iterations are often employed in practice. The EBA steps outlined below are not necessarily congruent with current practice, but can be implemented within the Corps' six-step planning process:[1]

Qualitative phase

1. Ensure a sound qualitative understanding of the ecosystem. This may require the development of a conceptual model[2] representing a clear

[1] The Corps' planning process may require steps not specifically listed here, or may express a different ordering.

[2] The word "model," as used throughout this report, refers to a simplified representation of a system that allows for investigation of the system properties or, in some cases, forecasting likely future system states. Many kinds of models are applicable to EBA (e.g., CEMs, index-based habitat models, hydrologic models, etc.). The Corps has a very broad definition of models, including "analytical tools," which might consist of just a few calculations.

understanding of the causal mechanisms contributing to degradation and possible means to achieve restoration objectives.

2. Characterize the restoration planning and design objectives, and specifically define the spatial and temporal scopes of the analysis and the metrics that will be used to assess the future ecological states and degree of success attained. This step may utilize information from a reference condition or ecosystem.
3. Identify the restoration measures and alternatives to be evaluated based upon the following factors (among others):
   a) How the various actions influence the ecosystem processes or condition to yield desired improvements.
   b) Which adaptive management opportunities might be pursued and how they may affect costs and outcomes.

Quantitative Phase

4. Compute costs (including adverse impacts) for each alternative for the planning period.
5. Forecast the parameters of interest[1] for the future without-project (FWOP) condition[2] and each alternative. This can be a complex step, potentially involving different models and analytical tools as well as the application of professional judgment.
6. Conduct any needed sensitivity and uncertainty analyses,[3] and consider the value of adaptive management by assessing the costs of learning relative to the benefits.
7. Apply any additional valuation approaches, if necessary (e.g. ecological production functions, monetization of outputs, application of significance modifiers, etc.) to assess the outputs (i.e. benefits) for each alternative. This process may require combining several metrics and involve additional modeling. Outputs are typically based upon the annualized differences in benefit between each alternative and the FWOP condition.

[1] Examples of ecological forecast parameters include temperature, velocity, depth, population size, etc. These often differ from the output (benefit) metrics, which are addressed in step 7.

[2] Within the Corps planning process, forecasting the FWOP condition typically precedes the development of alternative plans and their evaluation. In this generic representation of the process, the semi-quantitative forecasting of FWOP is assumed as part of step 1, whereas the quantification of the FWOP and the with-project alternatives is shown concurrently because the tools, metrics, and approach are the same for all conditions and scenarios that are evaluated.

[3] Note that uncertainty analysis occurs at several steps in the process and tends also to be iterative.

Decision phase[1]

8. Conduct cost-effectiveness (CE) evaluation and incremental cost analyses (ICA) for the remaining alternatives using the outputs from Step 7, including the analyses believed necessary to adequately understand sensitivities to uncertainty in forecasted ecological conditions.
9. Make needed comparisons among the alternatives, applying appropriate decision criteria/factors (key thresholds, project constraints, etc.).
10. Select the alternative that reasonably and most cost-effectively satisfies planning objectives and prepare the documentation[2] needed to effectively communicate the process and results.

Confirmation phase

11. Monitor and adaptively manage the project as required to assess success, maximize achievement of project objectives, and improve EBA for future projects through knowledge gained from monitoring and assessment.

### Change as a basis for benefit quantification

To provide meaningful input to decision-makers, it is important that computed benefits and costs reasonably reflect important ***changes*** that occur to the ecosystem as a consequence of the restoration actions. Ecosystems are not static; their condition changes over time in response to both natural and anthropocentric influences and change can be expected even absent any intervention. Consequently, the basis for evaluating project benefits is the change over time in the “state” of the ecosystem, as evidenced by key metrics reflecting the quantity and/or quality of ecosystem resources or services. Figure 2 illustrates the impact of change when analyzing the benefits of restoration alternatives.

The baseline is referred to as the future without-project (FWOP) condition, and is represented by the projected system condition[3] over the planning

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[1] Actions in the decision phase are outside benefits “quantification,” but are presented here for context in benefits “assessment.” See the Institute of Water Resources (IWR) Planning Suite http://www.pmcl.com/iwrplan/ for decision support.

[2] Documentation should be continuous throughout the process; this step is aimed at compiling that documentation and adding necessary tables, figures, etc. for effective communication.

[3] Metrics used to describe the condition depend upon the benefit characterization strategy, and might include ecological state variables, an expression of the service production, or an index relative to a reference condition.

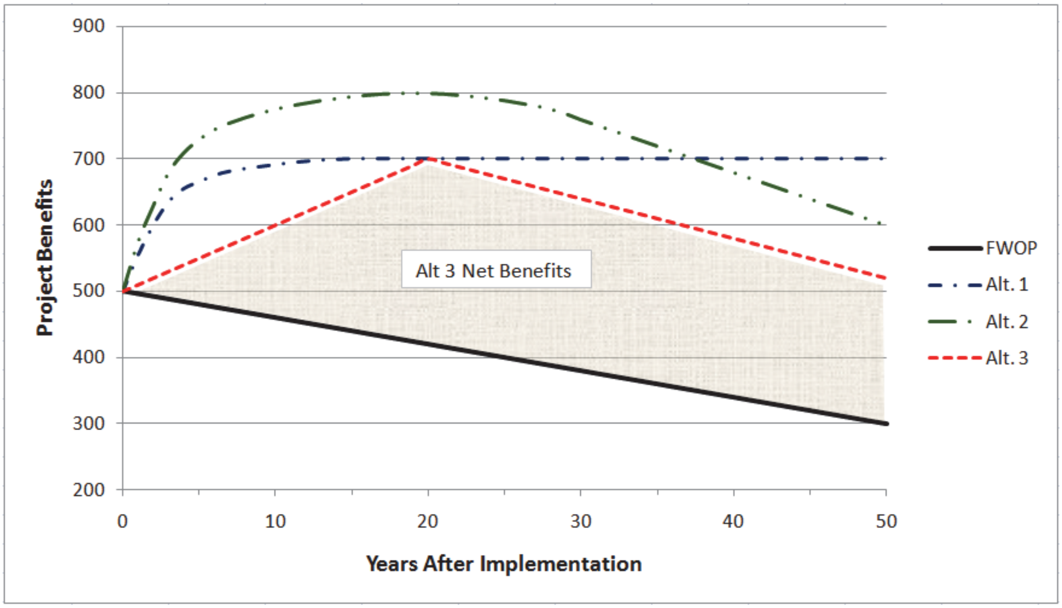



Figure 2. Schematic representation of benefit curves for restoration alternatives. The shaded area represents the net benefits (i.e. "output") for Alternative 3. Note that the y-axis units could be habitat units, population size, a reference-based index, or some other ecological benefit metric, depending on the study design.

timeframe (typically 50 years[1]) without the proposed restoration project.[2] The incremental benefit afforded by any alternative is the area between the benefit curve for that alternative and the curve for the FWOP condition, and is referred to as the "output" in Corps planning. The net benefit is typically annualized by dividing the area between the curves by the number of years. In Figure 2, Alternative 3 has a net benefit of 10,400 units (the area between Alternative 3 and FWOP curves) and an average annual benefit of 208 units (10,400 ÷ 50 years).

### Dealing with non-monetary benefits

Traditional water resources development employs cost-benefit analysis for project evaluation (i.e. the benefits on the y-axis of the above figure would be expressed in dollars). There are many challenges to the assignment of monetary values to ecosystems or ecosystem outputs (NRC 2005, Hussen 2004, Randall 1991, Freeman 1993). In any case, current policy mandates the use of non-monetary metrics for ecosystem restoration projects. Thus, a central need for ecosystem restoration planning involves the development

[1] Longer periods may be employed depending upon ecological response. Depending on the variation in the ecological outputs, it may be necessary to assess conditions at weekly, monthly, annual, or decadal time-steps to assure an accurate reflection of the overall benefits.

[2] Other actions likely to occur during the timeframe are included in the FWOP, but the action being considered is excluded from the analysis.

and use of non-monetary metrics that represent the predicted change in outputs of interest to decision-makers.

The definition and measurement of restoration outputs should follow logically from planning objectives. Based on Figure 1, three broad types of planning objectives that may be relevant include the promotion of 1) natural processes and dynamic properties that drive ecosystem self-design (e.g., hydrology and geomorphology), 2) desired ecological resources (e.g., wildlife habitat), and 3) restoration of the ecosystem to a desired reference condition (e.g. minimally disturbed condition). Each of the objective categories can have a set of associated metrics, and these typically vary among projects. Table 2 provides an example of different metrics that might apply to the restoration of a stream degraded by urbanization.

Table 2. Examples of metrics potentially applicable to an urban stream restoration project.

| Ecological Objective-Based | | | Service-Based | | Reference-Based |
|---|---|---|---|---|---|
| Structural | Functional | Other Process | Resources | Services | |
| Channel Cross Section Area | Bed Level Change | Streambank Erosion Rates | Habitat Quantity | Downstream Pollutant Concentration Gradient | RCI (i.e. Ratio of Project to Reference for Attribute Set) |
| Baseflow Pool Depth | Floodplain Inundation Frequency | Reproductive Success | Groundwater Recharge Rate | Flood Wave Attenuation | |
| Water Temperature | Biological Oxygen Demand[1] | Riparian Species Regeneration* | | Property Values WRT Distance From Stream | |
| Number of Fish per Mile | Macroinvertebrate Diversity[1] | | | | |
| Index of Biotic Integrity[1] | | | | | |

[1] Indicates an indirect measure.

Regardless of the management objective strategy, projecting future ecological states using relevant metrics is necessary. This is usually accomplished through the application of ecological production functions. Ecological production functions are mathematical expressions that estimate the effects of changes in the structure, function, and dynamics of an ecosystem on outputs that are directly relevant and useful to decision makers. In the context of Corps' ecosystem restoration, several functions may be necessary (see Figure 3). Each "function" can be regarded as a model, and different functions are generally required for each project, or perhaps more generally, for each type of project.

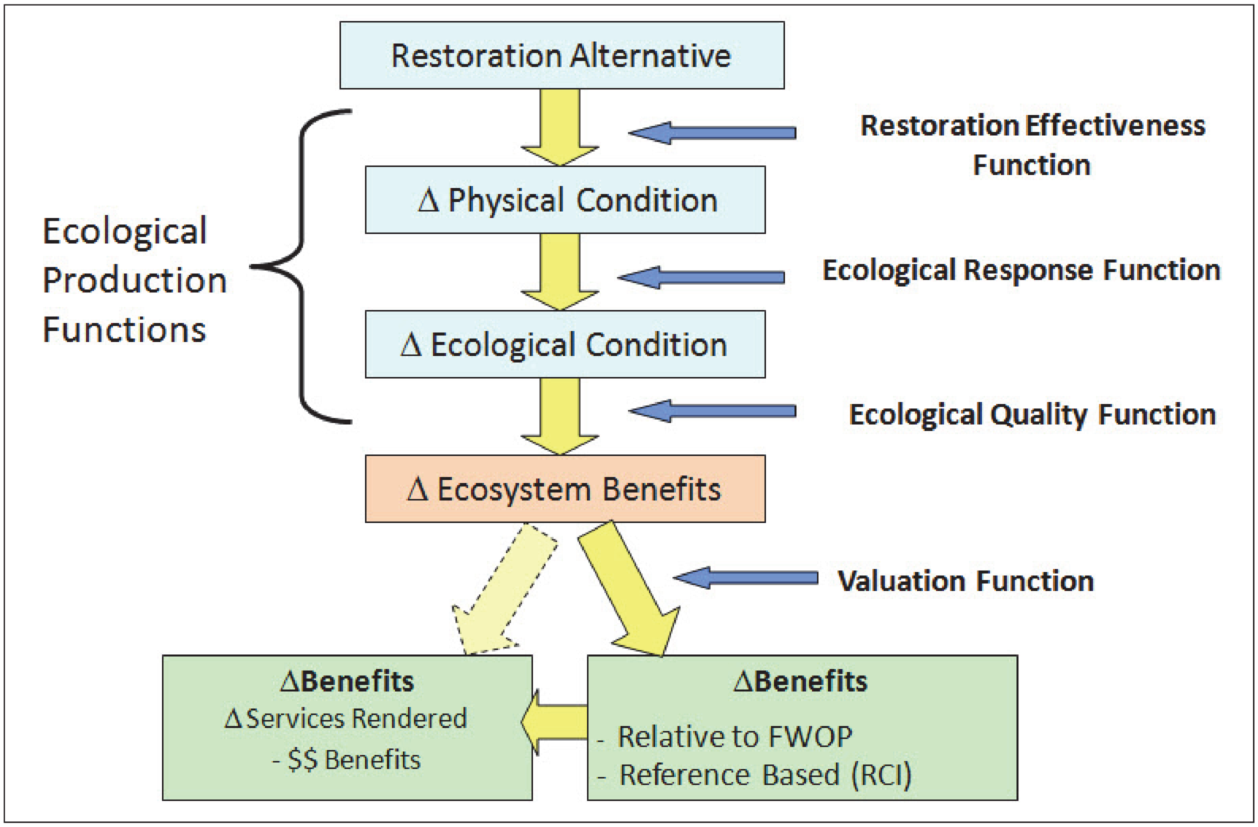



Figure 3. Ecological production functions are used to assess system response over time in terms of metrics that relate to the project objectives (adapted from U.S. Environmental Protection Agency (USEPA) (2009)).

The selection of appropriate metrics for non-monetary benefits is difficult and contentious, and there are no generally accepted standards, although criteria for assessing metric quality have been proposed (McKay et. al. 2012). When the units for metrics are not dollars, other decision support methods may be needed to evaluate alternatives. Techniques such as cost-effectiveness (CE) evaluations and incremental cost assessments (ICA) provide a way of comparing alternatives when using nonmonetary metrics. Other decision analysis methods (e.g. Multi-Criteria Decision Analysis (MCDA)) can be helpful when multiple metrics are required as well (Suedel et. al. 2012). These tools are introduced in the following sections.

### Economic assessment (CE/ICA)

CE/ICA is a form of efficiency analysis that serves to refine and illustrate tradeoffs among a set of alternatives for which the benefits are expressed in a non-monetary metric. Cost effectiveness (CE) analysis compares the costs of each project plan against its non-monetary measure of output and screens out plans that are not cost-effective from further consideration. The incremental cost (IC) analysis identifies incremental costs per unit output gained by moving from one cost-effective plan to the next higher-output cost-effective plan. The combined use of CE/ICA may not identify a single “best” plan, but it does eliminate those plans that are demonstrably inferior to others. The approach is widely used on federal water resource development projects, and tools exist to help in its implementation (Institute for Water Resources (IWR)2010).

### Addressing multiple benefits

The "benefits" shown on the Y-Axis of Figure 2 can be based on a single metric or several different metrics that can be individually referred to as benefits. For example, a proposed restoration alternative might improve stream, riparian, and wetland habitats. These benefits can be combined into a single proxy metric for CE/ICA evaluation, or may be treated separately in the evaluation process. The former approach has the benefit of simplifying comparisons (although the supporting analyses may be complex and problems can arise when combining dissimilar metrics), whereas the latter approach provides flexibility in dealing with trade-offs. A separate accounting of benefits is generally necessary in cases where a project contributes to multiple benefit categories (national economic development (NED), environmental quality (EQ), regional economic development (RED), and other social effects (OSE)).[1]

While it is desirable to "fully" account for project benefits, comprehensive valuation of aquatic ecosystems by summing specific benefits is typically impractical and potentially misleading. This is different from composite valuation of whole ecosystems because it involves quantifying and valuing specific processes, services, and characteristics with interdependent yet uncertain behaviors, then combining these through mathematical manipulation. This does not mean that ecosystem valuation cannot be accomplished, simply that summation of specific benefits to arrive at a total value should be approached with caution. Important concepts to keep in mind when addressing multiple benefits include the following:

- Account only for those benefits that can be reasonably identified and substantiated.
- Focus on benefits that clearly affect decision-making and are relevant to the project objectives; a core group of critical benefits is preferable to an exhaustive list.

[1] Consult current policies regarding the handling of multiple accounts.

- Establish interdependencies between benefits.
- Avoid double-counting of benefits.
- Identify trade-offs among conflicting benefits.

#### Addressing trade-offs

At several points in the EBA process, decisions are needed regarding alternative approaches that present various trade-offs. Table 3 summarizes methods that can help ensure structure, order, transparency, and repeatability in the decision-making process (Guinto 2008). These and other techniques (see Belton and Stewart 2002) can be useful for identifying relevant criteria, determining objectives, selecting metrics, formulating alternatives, illustrating and evaluating trade-offs, resolving conflicts and consensus-building, recommending a plan, and developing adaptive management strategies.

Table 3. Common decision analytic (DA) approaches (after Guinto 2008).

| Method | Description | Considerations |
|---|---|---|
| Ordinal ranking | Criteria and/or alternatives are simply ranked in order of preference | Decision makers know preference only; they do not know 'by how much' one alternative is preferred over another. A concern is that cardinal weights for aggregation may still be needed. |
| Rating | Users rate criteria and/or alternatives on a scale of 0-100. Likert scales can also be used. | This method is simple and transparent and does not constrain the decision makers' responses. |
| Point allocation/ Fixed Point Scoring | Decision makers allocate a fixed number of points such as 100, 10, etc. | The point allocation method is simple and transparent and requires users to make trade-offs by budgeting 100 points among attributes. |
| Paired comparison (e.g., analytic hierarchy process) | Requires the decision maker to consider each criterion against every other criterion in pairs. | If the number of decision criteria is not limited, the task of making comparisons becomes overwhelming and can lead to inconsistent and/or useless results. |

### EBA and the Corps' planning process

This report provides a technical framework for incorporating the tasks necessary to evaluate environmental benefits. Table 4 diagrams the relationship between the phases of EBA and the Corps' iterative six-step planning process. The EBA framework presented in this report consists of four discrete, and also iterative, phases that emphasize the more unique or critical aspects of the planning process as related to environmental

Table 4. Six-step planning process and EBA phases.

| Planning Process | EBA Activities | |
|---|---|---|
| 1--Specify Problems and Opportunities | Develop an understanding of the ecosystem to be restored including the history, landscape setting, source of problem, etc. | Qualitative Phase |
| | Prepare a conceptual ecological model including the drivers, stressors, ecological responses, and indicators (or equivalent factors if using a different type of CEM). The CEM may include other factors if needed. | |
| | Identify the spatial and temporal scales for evaluation and key uncertainties. Determine the potential for adaptive management. | |
| | Identify key uncertainties and preliminary reference conditions. | |
| | State the project objectives. Choose among objective-, service- or whole ecosystem-based approaches for characterizing benefits. | |
| 2--Inventory and Forecast Conditions | Establish metrics and performance measures for the project objectives and/or targeted ecological parameters. | Quantitative Phase |
| | Evaluate existing forecasting models and select the preferred model or modify or develop the model needed to forecast conditions. | |
| | Forecast the FWOP and alternative scenarios (if required), including appropriate sensitivity and uncertainty analyses. | |
| 3--Formulate Alternative Plans | Assess potential for adaptive management and include appropriate considerations in alternative formulation. | |
| | Revisit and adjust the CEM, objectives, and constraints as needed. | |
| 4--Evaluate Effects of Alternative Plans | Forecast the ecological conditions for each alternative plan. | |
| | Assess forecasting data to compute net changes to ecosystem quantity and/or quality, annualize outputs; make any necessary changes to metrics to capture values in terms of output metrics. | |
| | Quantify and assess uncertainties for each plan. | |
| 5--Compare Alternative Plans | Conduct cost-effectiveness and incremental cost analyses. | Decision Phase |
| | Apply other decision criteria based on thresholds, constraints, reference conditions, stakeholder criteria, etc., and identify the recommended plan. | |
| | Document the process and information helpful to decision makers. | |
| 6--Select Recommended Plan | Monitoring and adaptive management implementation phase is required to substantiate and optimize benefits. | AM Phase |

restoration and, in particular, EBA. Table 5 identifies key products developed under the EBA Research Program and references them to the appropriate phase/step. The referenced products are available on the Ecosystem Restoration Gateway at: http://cw-environment.usace.army.mil/cwenv.cfm.

Table 5. Key EBA documents cross referenced to relevant EBA phase / planning step.

| EBA Phase | Qualitative | Quantitative | | Decision | | | M&AM |
|---|---|---|---|---|---|---|---|
| Planning Step | 1–Specify Problems and Opportunities | 2–Inventory and Forecast Conditions | 3–Formulate Alternative Plans | 4–Evaluate Effects of Alternative Plans | 5–Compare Alternative Plans | 6–Select Recommended Plan | N/A |
| Reference Documents | | | | | | | |
| Fischenich - Science-Based Framework for Environmental Benefits Assessment (ie. this report) | X | X | X | X | X | X | X |
| Fischenich - The Application of Conceptual Models to Ecosystem Restoration Projects (Fischenich 2008) | X | | | X | | | X |
| McKay - Ecosystem Restoration Objectives and Metrics (McKay et al. 2012) | X | X | | X | | | |
| Linkov - Metric Selection for Ecosystem Restoration (Linkov, in preparation) | X | X | | X | | | |
| Swannack - Ecological Modeling Guide for Ecosystem Restoration and Management (Swannack et al. 2012) | | X | | X | | | |
| Suedel - Application of Risk Management and Uncertainty Concepts and Methods for Eco-system Restoration: Principles and Best Practice (Suedel et al. 2012) | | X | | X | X | | |
| Convertino - An Illustrative Case Study of the Application of Uncertainty Concepts and Methods for Ecosystem Restoration (Convertino et al. 2012) | | X | | X | X | | |
| Miller - Reference Concepts in Ecosystem Restoration and Environmental Benefits Analysis (EBA): Principles and Practices (Miller et al. 2012) | | X | X | | | | |
| Pruitt - The Use of Reference Ecosystems as a Basis for Assessing Restoration Benefits (Pruitt et al. 2012) | | X | | X | X | | |
| Fischenich - The Application of Adaptive Management to Ecosystem Restoration Projects (Fischenich et al. 2012) | | | X | X | X | | X |
| Conyngham - Guidance on Monitoring Requirements and Principles of Practice in USACE Ecosystem Restoration Efforts (In preparation) | | | | | | | X |

Phase 1 of the EBA, the qualitative phase, is consistent with step 1 of the planning process (*the specification of problems and opportunities*). This phase contains tasks predominantly related to understanding the ecosystem and the study objectives. Specific activities in this phase include developing a conceptual ecologic model (CEM), identifying the appropriate temporal and spatial scales for system evaluation, giving initial consideration to an adaptive management approach, and identifying key uncertainties. If a reference concept/ecosystem is to be employed, classification and preliminary identification of the reference is undertaken. The conclusion of this phase is the development of planning objectives for the restoration effort.

Phase 2 of the EBA, the quantitative phase, involves steps 2 through 4 of the planning process. This phase begins with establishing metrics and performance criteria that relate to the planning objectives. The initial quantitative activity is consistent with planning step 2 (*inventory and forecast conditions*), and involves an array of activities related to evaluating the ecological state of the system, including selecting or developing appropriate evaluation method(s) and forecasting techniques/models, forecasting the future without-project condition, and preparing scenarios (if required). Ecological attributes used for reference systems are identified and quantified if a reference approach is employed.

Planning step 3 (*formulate alternative plans*) includes the development of management measures for alternative plans/projects. This activity falls within the quantitative phase of EBA, but is not strictly a part of the EBA process. However, alternative formulation includes a deliberate revisit of the study's objectives and constraints, a refreshing of the CEM to accommodate responses to potential alternatives, and consideration of the potential for and implications of adaptive management.

Planning step 4 (*evaluate effects of alternative plans*) is the focus of the second half of the quantitative phase of EBA. This includes evaluating the effects associated with specific alternatives, refining or combining metrics to most effectively capture the estimated benefits, quantifying uncertainties, and computing the outputs from alternatives over the study period. For a whole-ecosystem approach, the selected system attributes for the with-project conditions are compared and indexed to the reference condition.

Phase 3 of the EBA framework, the decision phase, corresponds to steps 5 and 6 of the planning process (*compare alternative plans and recommend* *an alternative plan*). Phase 3 includes the cost-effectiveness and incremental cost analyses, subjecting the plans to the various decision criteria, and selecting the recommended plan. Documentation developed during the process is refined and additional information is presented that is needed to effectively communicate the benefits and decision processes used to arrive at the selected alternative.

The fourth EBA phase includes monitoring and implementing adaptive management to help secure the projected benefits and confirm the actual benefits realized by the project. This phase marks the final set of activities needed to complete an EBA. Monitoring and adaptive management do not have a correlate in the Corps' planning process, as they are typically regarded as operations activities. However, knowledge gained from monitoring and adaptive management does influence future planning, the implementation of adaptive actions influence benefits realized, and the ability to adaptively manage affects planning decisions.

# 3 Overarching Technical Issues

While many factors are associated with successfully conducting an environmental benefits assessment, opportunities for improvements in practice are especially obtainable for six topics discussed in this chapter: understanding the ecosystem, metric selection and combination, modeling and forecasting, addressing uncertainty, adaptive management, and documenting and communicating decisions.

## Understanding the ecosystem

An EBA cannot advance in the absence of a clear understanding of the problems leading to ecological degradation, the relationship between proposed remediation measures and ecological response, and the relationships among ecological conditions and those factors that are valued by society. This section addresses the role of reference concepts, conceptual ecological models, and thresholds and response trajectories in developing the above understanding.

### Reference systems

The use of reference approaches in environmental assessments is becoming more prevalent (Bowman and Somers 2005). Reference approaches generally involve comparing characteristics of a 'project' site to those found in a minimally impacted 'reference' site or to a suite of reference sites representing some range of conditions. Restoration success hinges upon a sound understanding of the ecosystem being restored and a guiding vision for the restoration project. A reference ecosystem provides a clear model of the intended outcome as well as a means for benchmarking success. Thus, reference systems can be used to help develop a conceptual model, identify restoration objectives, establish success metrics, and serve as a baseline for monitoring efforts, among other things.

Reference models have traditionally been based upon conditions prior to human disturbances. Such a historical reference is often unavailable, unachievable, or even undesirable and alternative formulations of reference condition have evolved (Stoddard et al. 2006). A reference might be an actual site or sites; for example, a nearby ecosystem in a similar setting. Alternatively, the reference might reflect a statistical model based upon several sites or even a "conceptual ecosystem" if actual sites are not available. Miller et al. (2012) describe approaches for developing and classifying reference systems, and Table 8 presented later in this document summarizes the considerations regarding use of references in EBA.

### Role of conceptual models

Conceptual ecosystem models (CEMs) are descriptions of the general functional relationships among essential components of a system. They tell the story of “how the system works” with respect to key processes and attributes and, in the case of ecosystem restoration, how the proposed alternatives aim to alter the processes or attributes of the restoration site to benefit the system (Fischenich 2008). The development of a CEM is recommended as a first step in the planning process, as it provides a key link between early planning (e.g., an effective statement of problem, need, opportunity, and constraint) and later evaluation and implementation. Fischenich and Barnes (in preparation) present a case study detailing the CEM development process, and other case study examples are available at the Ecosystem Restoration Gateway.

Conceptual models can be invaluable in supporting EBA because they promote understanding of ecosystem processes, help formulate goals and objectives, metrics, and alternatives, and play an important role in selecting evaluation methods and associated performance metrics for monitoring adaptive management. Detailed guidance on the development of CEMs can be found in Fischenich (2008), and a tool to assist the preparation of conceptual models is publicly available (Dalyander and Fischenich 2010). CEMs provide many benefits, but the following four are of special significance to EBA.

1. A CEM documents, in brief, the scientific rationale for engineered modifications and the externalities (such as climate change and sea-level rise) that might affect the degree to which modifications are likely to elicit desired ecosystem responses.
2. A CEM includes the essential ecosystem structure, functions, and processes to be measured, as well as those that may be unquantifiable but need to be considered in the overall evaluation. Thus, the CEM summarizes the rationale for metrics used in EBA.
3. During CEM development, uncertainties affecting the project's success are identified, discussed, and vetted. This initial assessment of key

assumptions (hypotheses) sets the stage for subsequent evaluation and documentation of uncertainty in the EBA.

4. When constructed collaboratively, CEMs facilitate communication, foster consensus, and capture the collective expertise of participating scientists, agencies, and the public, thus making the overall assessment of benefits and final plan selection more likely to gain support from decision makers and the public.

### Trajectories and thresholds

An understanding of potential ecological trajectories is necessary for developing effective alternatives, evaluating benefits, and implementing adaptive management measures. The concept of ecological trajectory with respect to both the impairment and recovery of a restored ecosystem is represented in Figure 4. In the figure, degradation has moved an ecosystem site from its "original condition" to a degraded state that is the present focus of restoration. A wide range of potential alternative states are shown along the right margin of the figure. The least complex (most degraded) of these indicates the forecasted state of the site with no restoration (i.e. the FWOP). The somewhat better future states of the site indicate a range that might be derived from two alternative plans that consist of either removing the stressor leading to degradation or undertaking other restorative measures (or both). The ecological trajectory initially pushed upward by restoration measures might not be linear, and the outcome can be uncertain, requiring scenario analyses.

Ecosystem ecology has moved in recent decades away from linear, single equilibrium state models of ecosystem behavior to an increased recognition of the importance of dynamism and the investigation of thresholds and multiple meta-stable states (Hobbs and Suding 2010). This recognition both complicates forecasting of restoration outcomes and potentially improves decision-making, given that assessments of restoration benefits are likely to be more realistic. Probability-based assessments that explicitly account for key ecological thresholds and alternative end states provide a sound basis for alternative comparisons and the application of adaptive management. Additional guidance on the identification and application of threshold and trajectory concepts can be found in Conyngham and Fischenich (in preparation).

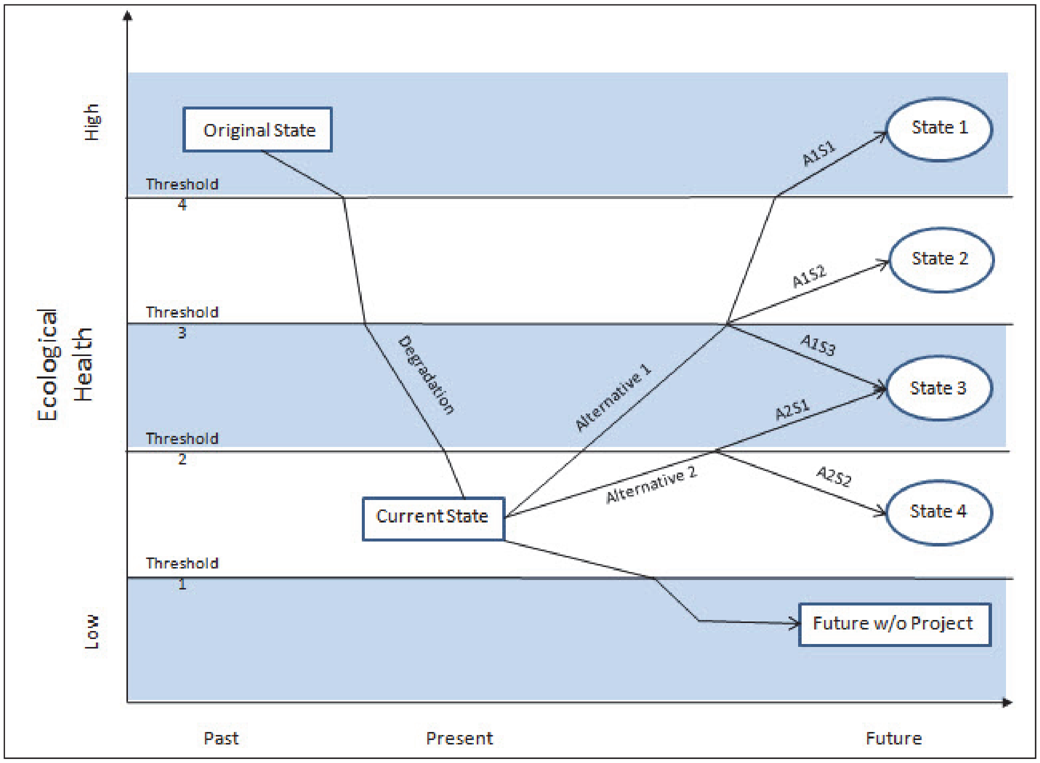



Figure 4. Various ecological trajectories and alternative future states of an impaired site.

## Metric selection and combination

As applied in this report, the term metric refers generically to a quantifiable system property used to measure something, typically progress toward a goal or objective (McKay et al. 2010, 2012). Metrics are used in the EBA process for forecasting ecosystem response to proposed restoration alternatives, to inform decision making, and to report outcomes of restoration. The fundamental requirements for establishing technically sound metrics can apply to any of four uses in ecosystem restoration:

1. *Ecosystem state variables* refer to the measurable physical, chemical, and biological properties of the system that serve as targets for the restoration action; they generally should be the parameters being manipulated by the engineering action and forecasted over the future with- and without-project (for example, peak summer temperature, mean substrate size, frequency of floodplain inundation, population size, etc.) condition.
2. *Output metrics* are the primary basis for assessing benefits; they are used for cost-effectiveness and incremental cost analyses in Corps ecosystem restoration planning (for example, average annual habitat units based on a combination of the above factors). Output metrics can be the same as ecosystem state variables.

3. *Decision factors* refer to thresholds in output value, acceptable uncertainty or risk, stakeholder preferences, and other criteria used in conjunction with CE/ICA for decision making. These are not strictly necessary for EBA.
4. *Performance measures* are the monitoring parameters used to assess project success or for triggering adaptive management actions (Fischenich et al. 2012), and either directly (preferably) or indirectly reflect the above metrics.

### Universal metric sets

Given the diversity of aquatic ecosystem types, widely varying geographic factors, and an incredible range of possible ecosystem functions, goods, and services, it is no surprise that a single metric set applicable to all aquatic ecosystem restoration projects has failed to emerge. Good metrics must evolve from project objectives and most projects have multiple objectives that vary widely. Therefore, no single objective set applicable to all restoration projects can be specific enough for decision-making purposes.

### Metric development and evaluation

Good metrics evolve from and can be directly mapped to specific project objectives. Metrics that directly measure an objective, and that are recognized, documented, and widely used, are generally preferred. However, it is sometimes necessary to use indirect metrics or to develop metrics that might not have been previously applied and documented. Candidate metrics and metric sets can be evaluated based on whether they adequately address project objectives and the extent to which they possess the following qualities of good metrics (McKay et al. 2010):

- **Relevance.** The metrics address project objectives and priorities, are scientifically valid at appropriate temporal and spatial scales, and are appropriate to project decisions.
- **Ambiguity.** The metrics clearly measure the consequences of different alternatives, reveal direction of response, and have minimal natural and computational uncertainty.
- **Comprehensiveness**. Taken together, the metric set addresses the full suite of project objectives and project consequences.
- **Directness.** The metrics directly quantify project outcomes. If aggregate scores or indices are used, these are constructed and documented in a way that supports direct and clear interpretation in terms of project effects.

- **Operability.** The metrics can be developed, forecast, and potentially monitored within the time, labor, and budget limits for the project.
- **Understandability.** The metrics can be communicated in plain language to decision-makers and the public.

| Example: Developing useful objectives and metrics.<br>The following example objectives and metrics are presented for a hypothetical stream restoration project, and are characterized as poor, fair, or good. An explanation of the characterization and needed improvement is provided. | |
|---|---|
| Objective / Metric | Discussion |
| Restore degraded sections of River "X" by converting class D stream reaches to class C.<br>Metric: Linear feet of class C stream in study area. | Poor. Objective should not specify an alternative; there may be other ways of achieving restoration. Metric only addresses habitat quantity; should also account for quality (unless class is quality based). |
| Improve habitat diversity to support native aquatic species in the lower 10 miles of River "X."<br>Metric: Population size for species "Y." | Poor. Objective is vague and could be improved. Metric not sufficiently comprehensive, may be difficult to quantify and may be a poor indicator. |
| Improve fish passage for native species at river mile (RM) 3.4 and RM 5.2 of River "X."<br>Metric: Benthic Macroinvertebrate Index (BMI). | Poor. Objective is OK. Metric is not clearly relevant and at best would be a weak indicator. Use a metric that quantifies connectivity or is a reasonable measure of fish passage. |
| Restore habitat in lower 10 miles of River "X" to more closely match Minimally Disturbed Condition (MDC) based on reference systems.<br>Metric: Average Annual Habitat Units (AAHUs) based on depth, velocity and substrate. | Fair. Objective OK; could be improved with more specificity. Metric not well understood, especially by public, and is not easily scalable outside the immediate project. |
| Restore connectivity from mile 0 to 10 for native aquatic organisms as evidenced by successful cutthroat trout reproduction above RM 3.4.<br>Metrics: Passage efficiency (% passing) and habitat quality (AAHUs based on spawning needs). | Fair. Objective could be improved by adding a timeframe (eg. "…trout reproduction by year 5 above…"). Metrics may be difficult to combine, but otherwise OK. Reproductive success (if predictable) would be a more direct metric. |
| Restore habitat in lower 10 miles of River "X" to more closely match conditions for Minimally Disturbed reference systems.<br>Metric: Reference Condition Index (RCI) based on a suite of characteristics and processes. | Fair. Objective could be improved with more specificity. Metric may not be well understood, especially by public, but is scalable outside the project and potentially across ecosystem types. |
| Lower temperatures in side channel habitats to provide summer refugia for the endangered "Z."<br>Metric: 3-day maximum summer temperature in side channels. | Good. Objective is clear. Metric is relevant, direct, operable, understandable, and predictable. |
| Restore floodplain connectivity in the study reach to permit annual inundation of at least 3 days between March 15 and April 30.<br>Metric: Acres of floodplain meeting inundation criteria. | Good. Objective and metric meet all criteria. Additional objectives and metrics may apply unless floodplain connectivity is the only degraded process. |

### Metric combinations and comparisons

Although multiple metrics may be used during planning, the EBA itself should use only a subset of metrics, ideally few in number, that have clear relevance to decisions about plan selection and project justification. However, because the performance of a metric across the range of alternatives cannot be wholly anticipated at the outset, there is a danger in reducing the number of metrics for the EBA prematurely. One option is to develop a variety of metrics with different scales and expected response thresholds and then filter and refine these after initial forecasting has been conducted in order to reduce the number of metrics, improve their resolution, and ensure that benefits and impacts of alternatives are not overlooked.

The ability to compare metrics that measure diverse objectives is important to ecosystem restoration decision making, particularly for more complex projects involving multiple objectives. Techniques facilitating metric comparison and combination have been well-studied and may be coarsely divided into four major categories: 1) narrative description, 2) arithmetic combination, 3) multicriteria decision analysis (MCDA), and 4) interdependent combination. Each of these techniques has associated advantages and disadvantages that are discussed in more detail by McKay et al. (2012) and Convertino et al. (in preparation).

## Modeling and forecasting

Modeling is a necessary and central activity of an EBA. Modeling is essential for analyzing environmental systems; it provides the means to forecast ecosystem response to restoration and convert those forecasted conditions into quantified benefit estimates. The modeling process helps organize thoughts and contributes to an improved understanding of ecosystems. However, models do have limitations. Because environmental models are simplified representations of complex systems, they are often built using assumptions regarding the unknown components in the model. They don't yield "the answer;" rather, they provide information to support decision-making. The usefulness of a model hinges on understanding whether the data and assumptions used by the model are sufficient to inform decisions. Model utility sometimes can be judged (and improved) by post-project monitoring that reveals the accuracy of the model predictions.

### Types of models

Several different types of models can be used to determine environmental benefits. These range from simple empirical relations describing the expected habitat preferences of species to complex, multi-dimensional, dynamic models of material flow (water, sediment, etc.), to agent-based or spatially-explicit models that address large-scale dynamics (e.g., Foran et al. 2012, Guisan and Zimmermann 2000). In general, the models used for environmental benefits fall into six basic classes (conceptual, analytical, index-based, processed-based/simulation, statistical, and spatial), each with their strengths and weaknesses as well as potential applicability within the EBA process (see Table 6).

Table 6. Description of model types used for EBA (from Swannack et. al. 2012).

| Model Type | General Use | Example |
|---|---|---|
| Analytical | Systems where solution to closed form equations represent benefits | Population growth, Lotka-Volterra models |
| Conceptual | Diagramming relationships among components, organizing information, determining data needs | CEMCAT, see Fischenich (2008) for more examples |
| Index | Determining habitat quality across a landscape, relates species presence to environmental variables | Habitat Suitability Index models, Hydro-Geomorphic Method |
| Simulation | Modeling dynamics of complex systems that have multiple factors interacting across scales, often have spatial components | Agent-based models, ADH-CASM, ELAM, system dynamic models |
| Statistical | Analysis of datasets to determine distributional properties of the data. | ANOVA, goodness-of-fit, regression, t-test, other empirical models |
| Spatial | Projects where particular spatial attributes are important can be incorporated into simulation models | GIS-based models, Ecological Dynamics Simulation Model |

### Forecasting ecological conditions

A wide variety of ecological forecasting tools are available to support the project planning process. These range from relatively simple empirical relations describing the expected habitat preferences of species (or guilds of species) to complex, dynamic models of water movement, sediment, and other material fluxes, to behavior-based models of individual organisms (agent-based models) and spatially-explicit tool(s) that address habitat and landscape mosaics (Foran et al. 2012). The choice of a tool or set of tools should be based on the specific ecological objectives for the project, although several other factors not directly related to a formal, technical evaluation of tool capability or suitability invariably come into play (e.g. project size, data availability, funding, duration, etc.).

Regardless of the particular tool set, forecasting ecological conditions involves quantifying the future states of key variables describing an ecosystem's structure, processes, dynamics, or some other relevant characteristic. The forecast is made for both the future without-project (baseline) condition as well as for each alternative being evaluated. Given the inherent uncertainty in such forecasts, it is beneficial if the tools being applied can be used to help quantify this uncertainty either directly in the form of probability distributions, or indirectly through sensitivity analyses, scenario analyses, or other appropriate means. The results of these analyses may serve directly as the basis for evaluating benefits in the case of ecologically focused objectives, or may require further analysis (often involving additional tools) to convert the results into meaningful outputs that capture the appropriate values (see Section titled “Metric combination”).

### Computing outputs

Index models have been commonly used as the basis for computing outputs for Corps restoration projects. These models typically use species-habitat, community habitat, biotic integrity, and functional capacity indexes to reflect relative quality of a system anchored in some optimal condition of maximum quality and varying downward toward zero as conditions change from optimum. Quality indices and geographical area are typically “integrated” by multiplying unit area (e.g., 1 acre) by the unit quality index and summing the multiples. One example of the product of this multiplication is the habitat unit of Habitat Evaluation Procedure (HEP) (U.S. Fish and Wildlife Service (USFWS) 1981), which can be compared directly to other habitat units of different spatial quantities and quality index values only in ideal circumstances. Alternatively, Index of Biological Integrity (IBI) (Karr 1981) and some other multi-metric index models scale over a broader range and are intended to reflect biological condition relative to desired reference conditions independent of stream length or wetland area.

Including benefits that extend beyond the traditional habitat perspective implies that other model types will likely be required. Depending upon the objectives, certain forms of statistical models, population models, or other model types can be useful for quantifying outputs. In some circumstances, existing models will be available to quantify the parameters of interest;

often, the model will need to be developed or adapted from an existing tool. Various analytical models might also be constructed to integrate benefits arising from different sources of ecological change. Additional guidance is provided in Swannack et al. (2012).

**Example: Model Outputs**

The eastern oyster, *Crassostrea virginica*, also known as the American oyster, Atlantic oyster, or the Virginia oyster, is a species of oyster that is native to the eastern seaboard of North America.
*Crassostrea virginica* may be the target of restoration efforts because of a direct interest in the species, because they are an indicator of estuarine health, or because they are an important component of the coastal ecosystem and affect other species. Modeling for oyster restoration efforts can take many forms depending on the goals and objectives, availability of data and other resources, and other study needs. Although the ecological requirements for oysters are the same, the outputs differ depending on the modeling approach, as shown in the following examples.

Habitat Suitability Modeling.

One approach to evaluating restoration alternatives is through the use of a Habitat Suitability Index (HSI) model. Oysters have preferences for specific environmental factors such as salinity, temperature, depth, and substrate. Professional judgment or statistical analyses can be used to identify ranges of values for these variables that can be expressed in the form of an index, ranging from 0 (extremely poor) to 1 (excellent). For example, salinities lower than 5 ppt or higher than 40 ppt may be lethal to oysters, and would be given an index value of 0. Salinities from 10 to 30 ppt may be ideal, and are scored 1.0, with the ranges from 5–10 and 30–40 ppt expressed as a linear function between 0 and 1. The resultant "suitability curve" is used to assign index scores based on any predicted or measured value of the variable. Suitability curves for the other model variables are likewise developed, and scores for each variable are assigned and input into an equation that combines the variables to yield a single Suitability Index (SI) value (eg. $SI = (V_1 * V_2 * V_3 * V_4)^{1/4}$, where the subscripts refer to each variable. The SI value is multiplied by the available habitat (usually in acres) to yield a Habitat Unit (HU). Values for HU are forecasted for several points in future time, and the sum of the HU values is divided by the total time to yield an Average Annual Habitat Unit (AAHU), which is the model output. Values for AAHU can be compared among alternatives and against a future condition without any restoration.

Although AAHUs can be thought of in terms of a "quality-weighted" expression of available habitat, the units have little meaning to resource professionals and even less to the public. Comparing outputs for different projects is difficult at best and more typically meaningless because the construct of the model equations is open to interpretation and can be manipulated to yield either higher or lower values. The use of an average value for habitat units might disguise important trends, and assessing the relative contributions of quantity and quality can be difficult. Nevertheless, this is a common modeling approach and is usually within the means of a study team.

Population Modeling.

Another approach to evaluating oyster restoration alternatives is through the use of models to assess population features such as size and age structure. Population characteristics are a function of the same habitat conditions as described above, along with other processes such as spawning, recruitment, growth, and mortality. Population models can be statistical- or process-based, and often rely upon the use of other models. For example, a hydrodynamic model might be used to forecast salinity ranges within the study area for each of the proposed alternatives and for the FWOP, with output from the hydrodynamic model input to a statistical model for growth rate. Outputs from population models typically focus on relevant population parameters such as population size, age structure, biomass/unit area, etc., and these can be compared among alternatives.

The outputs from population models are usually more easily understood by and relevant to decision makers and the public than are outputs from habitat suitability models. Evaluating an investment that would result in a 20% increase in AAHUs is likely more difficult and abstract than an investment that would yield a 40% increase in sustainable harvest, for example. The added fidelity and acuity offered by population modeling comes at a price, however. The models can be much more complex, require more data, and have higher associated uncertainties, among other limitations.

<u>Other Ecosystem Models</u>.

Depending on the project objectives and associated metrics, other modeling approaches might be required. For example, if objectives either directly or indirectly relate to the effects of oysters in improving water quality, a model of seston uptake (or other similar factor) would be applied based upon assumed oyster densities, distribution, water column mixing, and seston uptake rates, among other factors. The outputs would ideally be related to water quality (eg. percent seston reduction, turbidity, etc.,) in these situations. If water quality is an intermediate concern, the model outputs might relate to the other objectives. For example, oyster uptake of nutrients and resulting reduction in turbidity might be shown to improve submerged aquatic vegetation (SAV) distribution or health. In that case, several models might be employed but the model outputs would relate to the SAV characteristics of interest. Similar concepts could apply when evaluating oysters as a food source for marine fisheries; the modeling may involve assessing oyster populations or habitat as an intermediate step, but the outputs should be related to the metrics for the overall project objectives.

### Model selection, adaptation, and development

Determining the "best" models to use for evaluating restoration of aquatic ecosystems is situational, depending on a number of factors including: the specific processes or conditions needing evaluation, required accuracy, available resources (expertise, time, funding), needed data, and institutional acceptability. Selecting from available models can be daunting because of the large number and variety of existing models. In many cases, the "correct" model does not exist, and a model must be developed or adapted to meet the needs of the specific project and circumstances.

Swannack et al. (2012) provide generalized guidance regarding the steps that constitute good practice for evaluating models for technical efficacy. Candidate models may be evaluated using the following five steps:

1. Evaluate correspondence between model results and expected patterns of model behavior.
2. Examine correspondence between model projections and data from real system (model validation).
3. Adjust empirical parameters or model coefficients to match a known behavior (model calibration).
4. Determine levels of uncertainty associated with model projections.
5. Identify data gaps and research needs that may not have been obvious during conceptual model development.

In the event that an existing model does not meet the needs of a given study, Swannack et al. (2012) also detail the process of model adaptation and development. The basic approach is to 1) develop a conceptual model of the specific cause-effect relationships among important components of the system, 2) quantify these relationships based on analysis of the best information possible, which can include scientific data or expert opinion, 3) evaluate the usefulness of the model in terms of its ability to simulate system behavior, and 4) apply the model to address needed questions. In practice, model development does not proceed linearly from the conceptual model to model application; rather it iterates through a series of intermediate models of increasing complexity.

## Addressing uncertainty

Corps policy requires that uncertainty in water resource planning be evaluated and communicated. Methods for assessing uncertainty in ecosystem restoration projects continue to evolve, but include sensitivity analyses, scenario planning, and parametric uncertainty analysis. These and other means of identifying, quantifying, evaluating, and otherwise considering uncertainties as part of the planning process provide important information that assists decision-making. Important considerations include the following:

- Uncertainty should be identified early in planning and efforts should be made to reduce the causes of analytical uncertainty as resources permit.
- Residual sources of uncertainty should be classified as to type, analyzed and documented, and then addressed iteratively throughout the planning process, from CEM development through benefits estimation, plan selection, and adaptive management plan development.
- Uncertainty should be quantified where possible, and confidence intervals or probability distributions used as opposed to point estimates when describing predicted outcomes with and without alternatives.
- The relative uncertainty of alternative plans should be presented, as uncertainty in outcomes may be considered during plan comparison, and is an important part of an overall risk management/communication strategy.
- If the recommended plan has uncertainty that can be practically reduced through post-construction monitoring, assessment and adjustment, an adaptive management plan should be developed to manage risks and maximize realized benefits.

### Identifying analytical uncertainty

All restoration projects face uncertainties, and identifying the likely sources is the first step in uncertainty management. Although uncertainties can arise at any point in a study, the identification, classification, and documenttation of uncertainties is critical during the development of a CEM, during modeling and forecasting, and during formulation of the monitoring and adaptive management plan. Sources of uncertainty can include the following:

- *Ecosystem uncertainty,* which is due to incomplete description and understanding of relevant ecosystem structure and function, or unpredictable and highly stochastic events and interactions affecting key processes (e.g. flooding, fire, drought, regional climate change, etc.).
- *Model uncertainty*, which arises from incomplete knowledge, bias, or error in the structure of a model, often as a result of a lack of knowledge or because of approximations used to simplify computation.
- *Quantity uncertainty,* which encompasses the uncertainty in specific parameters or input data used in a model.
- *Scenario uncertainty,* which arises from inaccurate specification of the cause-and-effect linkages between management measures and their predicted ecosystem effects.
- *Implementation uncertainty,* which is due to potential policy, funding, or other external factors that might influence the timing or degree of project implementation.

### Quantifying uncertainty

The ability to quantify uncertainties depends upon a number of factors including the source, available data and tools, and the extent to which the associated phenomena are understood. Some uncertainty is sufficiently tractable that it can be described in terms of statistical probabilities; this situation is ideal because it facilitates easier risk assessment and decision-making. Frequency distributions, statistical variances, coefficients of variation, confidence intervals, and probability distributions are commonly used to describe the uncertainty in quantities. Of these, probability distributions offer the most complete and compact form of representation. The emerging approach for these situations is essentially probabilistic rather than deterministic (Landres et al. 1999).

Some uncertainties, while identifiable and describable, are difficult to objectively quantify. A Likert Scale can be employed to allow subject matter experts to express their certainty and uncertainty in these situations. Table 7 reproduces a Likert Scale used by authors of the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report to represent their judgment in the validity of a conclusion in the report (IPCC 2001, p. 44). Another simple form of expressing uncertainty is accomplished by giving the mean plus or minus some limits (often a standard deviation or range). When assessing uncertainty in a more complete manner, the nature of the statistical distribution that is appropriate for a given situation needs to be defined.

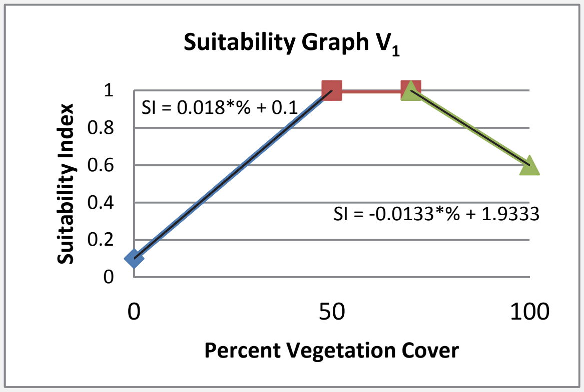
Table 7. Verbal and mathematical expression of certainties and probabilities (from IPCC 2001, p. 44).

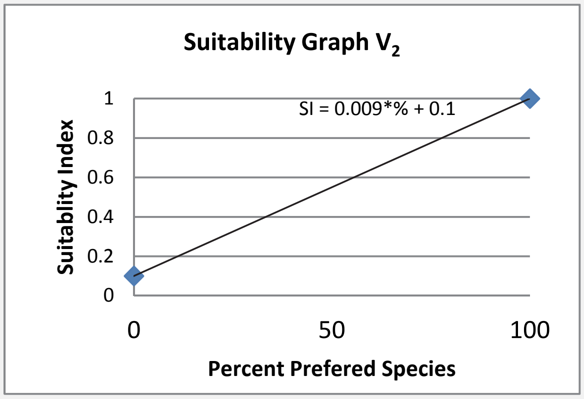
| Verbal Expression of Certainty (indicating likelihood) | Corresponding Mathematical Expression of Probability |
|---|---|
| Virtually certain | 0.99 to 1.00 |
| Very likely | 0.90 to 0.99 |
| Likely | 0.66 to 0.90 |
| Medium likelihood | 0.33 to 0.66 |
| Unlikely | 0.10 to 0.33 |
| Very unlikely | 0.01 to 0.10 |
| Exceptionally unlikely | 0.00 to 0.01 |

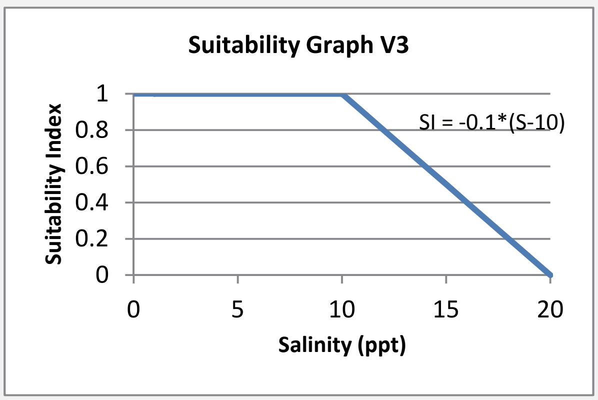
A variety of tools and techniques exist for assessing and quantifying uncertainty in estimating ecosystem benefits (see Convertino et al. (2012) for details). Casper et al. (2010) present an approach to documenting and rating uncertainties in the initial development of CEMs. Yoe et al. (2010) discuss a diverse array of approaches to evaluating uncertainty in benefits estimates, including qualitative narratives, model sensitivity analysis, use of scenarios, and probabilistic methods. Fischenich (2011) discusses uncertainty in stream restoration projects, while McKay and Fischenich (in preparation) describe the application of a Monte Carlo analysis to evaluating quantity and scenario uncertainty in estimated benefits for a coastal restoration project. It is possible to assign probabilities to scenarios as well. Although it can sometimes be difficult to create such estimates, techniques are available that can be used to overcome such difficulties (Vose 2000).

**Example: Characterizing and Quantifying Uncertainty**

A habitat-suitable model for a wetlands restoration utilizes three variables: $V_1$ - Percent of area covered by emergent vegetation, $V_2$ - Percent of vegetation on preferred species list, and $V_3$ - Average annual salinity. Suitability curves are as shown below, and the composite suitability index is determined by: $SI = (V_1 + V_2 + V_3)^{\frac{1}{3}}$. The table below shows a typical assessment of a 50-acre wetland construction in an estuary with 200 acres of existing marsh. For this simple deterministic analysis, the resulting net gain in AAHUs is 51, based upon the best projections of future condition and assumptions regarding the effects of the restoration and outside stressors.



| FWOP | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | TY | 0 | TY | 1 | TY | 10 | TY | 50 |
| Variable | Value | SI | Value | SI | Value | SI | Value | SI |
| V1 | 60 | 1.00 | 60 | 1.00 | 55 | 1.00 | 40 | 0.82 |
| V2 | 50 | 0.55 | 50 | 0.55 | 50 | 0.55 | 40 | 0.46 |
| V3 | 10 | 1.00 | 10 | 1.00 | 10 | 1.00 | 15 | 0.50 |
| Acreage | 200 | | 199 | | 190 | | 156 | |
| | HSI = | 0.82 | | 0.82 | | 0.82 | | 0.57 |
| | HU = | 163.9 | | 163.1 | | 155.7 | | 89.5 |
| | CUM = | | | 163.5 | | 1434.5 | | 4848.6 |
| | | | | | | AAHUs | | 128.9 |

| Future With Project | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | TY | 0 | TY | 1 | TY | 10 | TY | 50 |
| Variable | Value | SI | Value | SI | Value | SI | Value | SI |
| V1 | 60 | 1.00 | 70 | 1.00 | 65 | 1.00 | 50 | 1.00 |
| V2 | 50 | 0.55 | 65 | 0.69 | 65 | 0.69 | 65 | 0.69 |
| V3 | 10 | 1.00 | 10 | 1.00 | 10 | 1.00 | 15 | 0.50 |
| Acreage | 200 | | 249 | | 238 | | 195 | |
| | HSI = | 0.82 | | 0.88 | | 0.88 | | 0.70 |
| | HU = | 163.9 | | 219.5 | | 209.8 | | 136.5 |
| | CUM = | | | 191.2 | | 1932.1 | | 6874.1 |
| | | | | | | AAHUs | | 179.9 |
| NET CHANGE IN AAHUs DUE TO PROJECT | | | | | | | | 51.0 |

<u>Sources of Uncertainty</u>

Each of the sources of uncertainty described above exists for the example project, and could be addressed in the model. For this example, the following two sources are incorporated:

*Ecosystem uncertainty,* due to unpredictable and highly stochastic effects of hurricanes and global and regional climate change, could affect the predicted values for wetland area. This could be addressed using scenario analyses, employing higher and lower estimates of marsh area to effectively bracket the range of likely area. For the assessment, loss rates were set at 0.25, 0.5, and 1.0% for the low, medium, and high loss rates. The resulting net AAHUs are 54.2 for the low loss rate and 41.5 for the high loss rate, which can be presented as bracketing the best estimate of 51.0 AAHUs (see tables below).

| FWOP - Low SLR | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | TY | 0 | TY | 1 | TY | 10 | TY | 50 |
| Variable | Value | SI | Value | SI | Value | SI | Value | SI |
| V1 | 60 | 1.00 | 60 | 1.00 | 55 | 1.00 | 40 | 0.82 |
| V2 | 50 | 0.55 | 50 | 0.55 | 50 | 0.55 | 40 | 0.46 |
| V3 | 10 | 1.00 | 10 | 1.00 | 10 | 1.00 | 15 | 0.50 |
| Acreage | 200 | | 200 | | 195 | | 176 | |
| | HSI = | 0.82 | | 0.82 | | 0.82 | | 0.57 |
| | HU = | 163.9 | | 163.9 | | 159.8 | | 101.0 |
| | CUM = | | | 163.9 | | 1456.6 | | 5184.6 |
| | | | | | | AAHUs | | 136.1 |

| FWOP - High SLR | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | TY | 0 | TY | 1 | TY | 10 | TY | 50 |
| Variable | Value | SI | Value | SI | Value | SI | Value | SI |
| V1 | 60 | 1.00 | 60 | 1.00 | 55 | 1.00 | 40 | 0.82 |
| V2 | 50 | 0.55 | 50 | 0.55 | 50 | 0.55 | 40 | 0.46 |
| V3 | 10 | 1.00 | 10 | 1.00 | 10 | 1.00 | 15 | 0.50 |
| Acreage | 200 | | 198 | | 191 | | 121 | |
| | HSI = | 0.82 | | 0.82 | | 0.82 | | 0.57 |
| | HU = | 163.9 | | 162.3 | | 156.5 | | 69.4 |
| | CUM = | | | 163.1 | | 1434.5 | | 4404.4 |
| | | | | | | AAHUs | | 120.0 |

| Future With Project - Low SLR | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | TY | 0 | TY | 1 | TY | 10 | TY | 50 |
| Variable | Value | SI | Value | SI | Value | SI | Value | SI |
| V1 | 60 | 1.00 | 70 | 1.00 | 65 | 1.00 | 50 | 1.00 |
| V2 | 50 | 0.55 | 65 | 0.69 | 65 | 0.69 | 65 | 0.69 |
| V3 | 10 | 1.00 | 10 | 1.00 | 10 | 1.00 | 15 | 0.50 |
| Acreage | 200 | | 249 | | 244 | | 221 | |
| | HSI = | 0.82 | | 0.88 | | 0.88 | | 0.70 |
| | HU = | 163.9 | | 219.5 | | 215.1 | | 154.7 |
| | CUM = | | | 191.2 | | 1955.9 | | 7368.1 |
| | | | | | | AAHUs | | 190.3 |
| NET CHANGE IN AAHUs DUE TO PROJECT | | | | | | | | 54.2 |

| Future With Project - High SLR | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | TY | 0 | TY | 1 | TY | 10 | TY | 50 |
| Variable | Value | SI | Value | SI | Value | SI | Value | SI |
| V1 | 60 | 1.00 | 70 | 1.00 | 65 | 1.00 | 50 | 1.00 |
| V2 | 50 | 0.55 | 65 | 0.69 | 65 | 0.69 | 65 | 0.69 |
| V3 | 10 | 1.00 | 10 | 1.00 | 10 | 1.00 | 15 | 0.50 |
| Acreage | 200 | | 248 | | 226 | | 151 | |
| | HSI = | 0.82 | | 0.88 | | 0.88 | | 0.70 |
| | HU = | 163.9 | | 218.6 | | 199.2 | | 105.7 |
| | CUM = | | | 190.8 | | 1880.5 | | 6007.8 |
| | | | | | | AAHUs | | 161.6 |
| NET CHANGE IN AAHUs DUE TO PROJECT | | | | | | | | 41.5 |

*Quantity uncertainty,* which encompasses the uncertainty in estimates of future conditions for the variables used in a model. For example, confidence may be low that the percent vegetation cover in year 50 for the FWOP will be exactly 40, and it is likely the value would be somewhat higher or lower than this estimate. Depending upon the sensitivity of the model to this variable and the modeler's confidence in alternative values, the models can be run with a range of values of equal probability (eg. 30 to 50 percent), or as some probability distribution (eg. 40 +/–14.5% ). If several model variables have ranges of values, a *Monte Carlo* analysis might be needed to assess a set of possible combinations of values. A Monte Carlo analysis employing ranges of values for all three variables as well as uncertain sea level rise effects with 1000 iterations yielded a mean net AAHU of 50.8, with 95% confidence limits of 40.3 and 55.1 (calculations not shown).

### Uncertainty and risk management

Despite a vast academic and professional literature addressing many aspects of risk management, implementing these concepts for ecosystem restoration planning is a far from mainstream effort. Risk, over a given time, is a product of likelihoods and consequences of adverse outcomes. This definition implies that four aspects are involved in considering risk—a time scale, scenarios, relevant consequences, and corresponding likelihoods or probabilities (Beer 2006). In a typical risk assessment, the following questions are addressed as part of the overall risk management process (after Suedel et al. (2012)):

1. What can go wrong?
2. What is the likelihood that it will go wrong?
3. What are the consequences?
4. What can be done to mitigate the risks?

A corresponding risk management framework for ecosystem restoration projects would involve subjecting each alternative and the FWOP to the above considerations. In cases where the potential regret from a "risky" alternative is high, other alternatives may be favored or the risks can be reduced to acceptable levels. Risk reduction strategies for ecosystem restoration projects usually involve adaptive management, but might also include more detailed analyses that reduce uncertainties or reformulation/redesign of management measures to make them more resilient or adaptive under scenarios likely to affect performance.

## Reference concepts

Reference concepts have long been used to support ecosystem restoration. The notion of a reference system that serves both as a "guiding image" for what restoration should look like and a benchmark for assessing specific details of the restoration is appealing. Consequently, ecosystem references have been used to set restoration or mitigation priorities, develop ecosystem restoration designs, support ecological monitoring programs, evaluate sustainability, and set and assess restoration success criteria, among other uses. Miller et al. (2012) provide an overview of the different ways in which reference concepts have been used and discuss the strengths and limitations of alternative reference formulations (see Table 8).

Table 8. Approaches to characterizing reference condition for use in ecosystem restoration project planning (adapted from Miller et al. 2012).

| Reference Approach | Description | Applicable Reference Condition[1] | Requirements / Assumptions | Benefits | Limitations |
|---|---|---|---|---|---|
| On-site analogous | A present, on-site condition (within project footprint) | LDC most likely | Requires enough on-site information to determine degree of function and degradation and to set targets; may require consideration of broader watershed conditions | Low mobilization costs, parallel stressors, many parameters equal (e.g., hydrology) | May not represent target reference condition, may not represent range of condition, may not represent ecological trajectory |
| Off-site analogous | A present, ecologically representative condition outside project footprint | LDC most likely, MDC possible | Requires enough information at a suitable off-site location to determine degradation and set target, comparable class of system with parallel stressors, measurable P/C/B parameters | More likely to find reference that can help define target reference condition with parallel stressors, parameters | May not represent range of condition, may not represent target reference condition, more cost to locate and characterize another site, may not represent ecological trajectory |
| Historical reference | A selected historical condition within project area (can be applied as off-site analogous approach if conditions are met) | HCPI or HCPA<br>HCPD if a specific isolated event caused disturbance | Requires the right data type / resolution to set targets matched to objectives; if on-site, may not require classification | Opportunity to characterize adjustment of processes to known stressors, if stressors not in flux or pre-disturbance data are proximal, can represent target reference condition or MDC | Stressors may have changed, other parameters may be changing, constraints may eliminate historical reference from consideration as target reference condition |
| Virtual (also called *constructed*) | Developed from a combination of sources to represent target reference condition for given physical setting, other constraints | Any of HCPI, HCPA, HCPD, MDC or LDC in combination with site or other data | Typically requires data from multiple sources, Best Professional Judgement (BPJ), and models | Highly flexible if good information is available, high resolution in defining target condition, best for use in settings with many constraints, costs can be low if existing models, BPJ, and collaborative processes are used | Highly dependent on good information, good interpretation/ analysis of available information, can be quite reliant on models, and subject to notable debate, costs can be high if requiring new or extensive modeling, |
| Regional Index | A range of existing reference sites reflecting a continuum of conditions | MDC | Requires classification and considerable data to characterize the range of conditions to evaluate degradation and set targets | Highly robust representative of full range of conditions, puts projects into context, best characterization of target reference condition | Highly data dependent, can take years to develop, and can be costly |

[1] BAC – Best Attainable Condition; LDC – Least Disturbed Condition; MDC – Minimally Disturbed Condition; HC – Historic Condition (PD- Pre-Disturbed; PI- Pre-Industrial; PD- Pre-Disturbance)

A key application of reference concepts for EBA is the use of a reference as a means of scaling ecological benefits; indexing the degree to which a project ecosystem achieves the structure and function of a reference is a way of ascribing "value" to an ecologically-motivated project. In a simple sense, a Reference Condition Index (RCI) can be established using any number of ecosystem attributes and would replace the “habitat quality index” commonly used as part of a HEP analysis. Pruitt et al. (2012) provide an overview of the ways in which reference concepts can be applied to an EBA and more detail on the application of an RCI. Figure 6 below is a schematic representation of an application adapted from Pruitt et al. (2012), and can be loosely interpreted as showing an ecosystem in a current state at 60% of full function, with alternative future states of 30% (FWOP) and 75% (with-project). The index values for the various states can be multiplied by the number of acres to obtain an output analogous to habitat units.

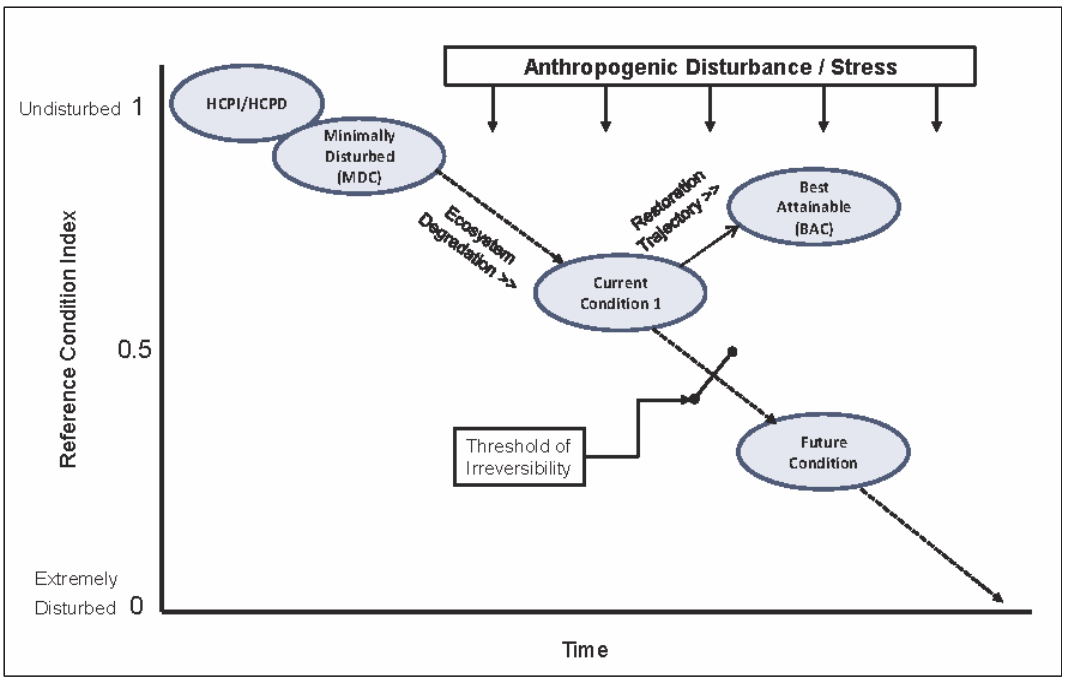



Figure 6. Schematic representation of a Reference Condition Index (RCI) for assessing alternative benefits. The RCI value for the historic condition is 1.0, for the current condition is 0.6, for the FWOP is 0.3, and for the alternative achieving the BAC is 0.75.

## Adaptive management (AM)

As implied by the term, “adaptive management” prescribes a process wherein management actions can be changed in relation to their efficacy in restoring and/or maintaining an ecological or engineered system in a specified desired state (Walters 1986). The desired state (e.g., goals and objectives) might be some precisely defined structural condition or, more realistically, a range of structural conditions, rates of ecological processes, or some description of biotic potential (e.g., productivity). Adaptive management helps to achieve desired goals by addressing uncertainty, incorporating flexibility and robustness into project design, and using new information to inform decision-making.

### Role of adaptive management in EBA

The development of an adaptive management plan is now required for all ecosystem restoration feasibility studies.[1] Adaptive management provides a decision-making framework that can adjust management actions based on newly acquired information and monitored outcomes of previous decisions. Importantly, this adaptive decision-making process can increase the chances that management goals and objectives (e.g., ecosystem restoration or sustainability) will be achieved despite uncertainties. While adaptive management has traditionally been viewed as a post-project implementation activity, the planning phase for adaptive management is critical to its successful implementation. The nature of AM planning is such that it allows for adjustments to plans that result in increased benefits. Implementation of AM measures improves the realization of benefits, and associated monitoring contributes to the accounting of project benefits.

### Adaptive management planning

"Adaptive management (AM) does not represent an end in itself, but rather a means to more effective decisions and enhanced benefits. Its true measure is in how well it helps meet environmental, social, and economic goals, increases scientific knowledge, and reduces tensions among stakeholders" (NRC 2004). AM can be regarded in terms of two principle phases; the planning phase wherein the proposed adaptive management strategy is developed, and an implementation phase during which it is executed. The planning phase is summarized below while the implementation phase is summarized in the section titled "Monitoring and adaptive management (implementation)." Fischenich et al. (2012) and Barr et. al. (in preparation) provide more details on the application of adaptive management.

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[1] On August 31, 2009, a memorandum from CECW-PB, was issued to Commanders and Major Subordinate Commands providing detailed requirements for implementation of Section 2039 of WRDA 2007. http://cw-environment.usace.army.mil/pdfs/09sep2-wrda-monitor.pdf

Adaptive management adds several considerations to the traditional planning process. The identification and assessment of performance measures and decision criteria, as well as required monitoring before, during, and following project construction are obvious needs. Adaptive management planning also requires consideration of the flexibility and reversibility of alternatives, and a determination of what adjustments to the project restoration actions may be needed. Plans must also be made for the acquisition and management of data, as well as the analysis and decision-making required to implement management decisions. These requirements force planning teams to contemplate objectives and project performance at a high level of detail, and the resulting plans inevitably benefit from this additional degree of thought.

The planning phase for AM is iterative in nature and comes to play in all six steps of the traditional planning process. Planning for AM means carefully assessing 1) critical uncertainties associated with project execution, 2) the potential to address those uncertainties through systematic monitoring and adjustment of project features, and 3) an assessment of the costs and potential benefits from implementation of an AM plan. This process requires planners to carefully consider potential outcomes for each alternative, including various outcomes associated with key uncertainties, and to contemplate what (if any) actions might be taken should the outcome differ from that which is desired. This can influence the formulation of alternatives as certain design strategies lend themselves more readily to AM. The explicit treatment of uncertainty as part of planning and the development of contingency plans to address undesirable or unexpected responses are at the core of AM.

## Documentation

### Need and approach

Documentation is critical for presenting a transparent and logical decision-making process and a defensible recommendation. The decision document must tie together the CEM and its linkage to the planning objectives, evaluation metrics, model selection, project benefits, plan selection, remaining uncertainties, and how uncertainties will be addressed through adaptive management. Credible documentation that demonstrates the rationale for plan selection is particularly important for ecosystem restoration projects, since plan selection is not strictly dictated by economic evaluation.

The process of conducting an EBA for an ecosystem restoration project can take months to years, involving hundreds of decisions by several individuals. Therefore, it is critical that the key decisions be documented *as they occur*; it is simply not possible to recall the details with sufficient accuracy to properly document decisions if documentation occurs only at periodic review stages.

### Scope and content

Requirements for documentation associated with the planning process for the USACE are spelled out in the Planning Guidance Notebook (PGN) and in several policy documents. With regards to the EBA specifically, it is important to tell the story of how the study evolved from an understanding of the problem and opportunities through the many analyses and decisions to the selection of the recommended plan. Particular attention should be paid to the following:

- Identification of the problem and presentation of the CEM.
- Complete and clear statement of objectives.
- Logic and rationale for selected metrics and which objectives they measure.
- Role of adaptive management in shaping alternatives, metrics, or outputs.
- Available and selected techniques for assessing and forecasting the metric (e.g., numerical models, expert judgment, monitoring plans, data collection protocols).
- Literature, expert, or past-project support for use of the metrics and models.
- Assumptions and limitations associated with metrics, models, and analysis.
- Application of professional judgment in metric or model development or assessment.
- Identification, classification, and quantification of critical uncertainties.
- Basis for any scenarios used in the analyses.
- Any review the metric set or models have undergone (e.g., interagency project team).
- Results of forecasting, including plots of outputs over time.
- Results of CE/ICA analyses including appropriate figures. Decision criteria applied to assessment results and corresponding preferred alternative.

### Units and significant digits

It is important that benefits be expressed in proper units and at an appropriate level of precision. Measurements always have a limited precision; and many estimates used in calculating benefits are more limited in precision than the actual measurements. Because these inputs have limited precision, the results of calculations based upon them likewise have limited precision. Significant figures track measurement precision. The rules for significant figures are straightforward, and can be found in many texts or in on-line resources.

# 4 Evaluating Project Success

## Performance measures and monitoring

Decision criteria[1] are used to determine project success and if and when adaptive management actions should be implemented. Decision criteria can be expressed in terms of performance measures or risk endpoints. *Performance measures* (*or targets*) are quantified expressions of project objectives at a particular point in time. Performance measures are derived from project objectives and should: 1) be measurable; 2) have a relatively strong degree of predictability (*i.e.*, targets specified by predictive models or by best professional judgment); 3) change in response to project implementation; and 4) verify progress and evaluate hypotheses through monitoring and assessment.

*Risk endpoints* refer to undesired effects of management actions; they are essentially measures of negative project performance (i.e. adverse impacts or constraint violations). The concept of risk includes 1) the possibility that the anticipated project outcomes will not be achieved, 2) the potential that some other unexpected, undesired (and perhaps irreversible) outcome will occur, or 3) the knowledge that certain adverse impacts are to be avoided, minimized, or mitigated during or following project implementation.

The decision criteria can be specified as single values or ranges of desirable outcomes. They can be qualitative or quantitative based on the nature of the performance measure and the level of information necessary to make a decision, but should be quantified when possible. Because of the long response time for many ecosystem restoration efforts, decision criteria are often based upon trajectories or rates of change for metrics that are indicative of ecological function. Success for ecosystem restoration projects occurs when decision criteria suggest that the objectives have been met, or that specific thresholds have been crossed and the ecosystem is on a recovery trajectory that will result in the achievement of the objectives.

[1] Sometimes referred to as adaptive management triggers.

## Monitoring and adaptive management (implementation)[1]

Implementation of the Adaptive Management Plan is fairly straightforward, but needs technical, management, and financial support as well as a functional governance structure with sufficient authority to make decisions. The implementation steps[2] are as follows:

1. Results of the ongoing monitoring programs are collated and analyzed by the Adaptive Management Team (AMT[3]) to assess whether any performance measures or risk endpoints are triggered.
2. If none of the decision criteria are triggered, the adaptive management process can simply continue with the current monitoring programs until the next evaluation is performed.
3. If decision criteria are triggered, the AMT evaluates the circumstances and decides to a) implement prescribed adjustments to the management actions, b) undertake additional monitoring or study, or c) redress the performance standards or risk endpoints that have not been met. This approach permits flexibility in interpreting monitoring results and allows for adjustments to the process and criteria as warranted.
4. Following resolution of the AMT recommendations for adjustments to the management actions, the adaptive management process continues by cycling back to step 1. This process continues until either a) criteria for project success have been met as determined by the Division Commander, or b) federal funding can no longer be used for monitoring or adaptive management (currently after 10 years).

One of the most important aspects of an adaptive management process is documentation. Implementation of adaptive management emphasizes an open and transparent management practice wherein the results of monitoring, assessment, and decision-making are routinely and consistently documented. The set-up phase and the resulting adaptive management plan should specify the provisions for regularly documenting adaptive management.

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[1] Implementation Guidance for Section 2039 of the Water Resources Development Act of 2007 (WRDA 2007)—Monitoring Ecosystem Restoration, Memorandum from the USACE Chief of Planning dated 31 August 2009. http://cw-environment.usace.army.mil/pdfs/09sep2-wrda-monitor.pdf

[2] Policies regarding monitoring and adaptive management are evolving. Planners are encouraged to familiarize themselves with current policy and note that the approach described herein must be adjusted as needed to conform to current policy requirements.

[3] The composition and role of the AMT is determined during the AM planning phase and can include representatives from the USACE, key resource agencies, and/or the stakeholders.

# 5 Supporting Information and Guidance

## EBA Program products

The work presented in this technical report was conducted by the U.S. Army Engineer Research and Development Center (ERDC) as part of the EBA Program. Numerous additional products have been prepared under the program, including technical notes and reports, journal papers, models, tools, fact sheets, and webinars. These products provide more detailed information on many of the topics presented in this report, and can be accessed through the Ecosystem Restoration Gateway (discussed below), or directly from the EBA Program website at:

http://el.erdc.usace.army.mil/programs.cfm?Topic=eba&Option=Program

## Ecosystem Restoration Gateway

The Civil Works Environment Gateway was established as the Corps' web portal to news, information, guidance, tools, data, and other resources supporting the community of practice within the environmental business line. Information about environmental benefits assessment within the Corps and the products of this research effort are accessible through the Gateway at:

http://cw-environment.usace.army.mil/cwenv.cfm

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**14. ABSTRACT**

This report outlines a framework for evaluating ecosystem restoration benefits within the context of USACE Civil Works planning process. An emphasis is placed on knowledge gained from research conducted under the Environmental Benefits Analysis (EBA) Program to address needs for a science-based assessment strategy that moves the standard of practice closer to the state-of-science for EBA. Current practice can be improved with the explicit use of conceptual models, establishment of clear objectives and associated metrics, better predictive tools, quantification of uncertainty, more structured decision methods, and adaptive management. The report is intended to assist Corps water resources planners and Project Delivery Teams (PDTs) in evaluating ecosystem restoration projects, programmatic considerations and general advancements in restoration science. It should also assist ERDC researchers and program managers as well as USACE water resources planners in aligning EBA products to meet planning needs.

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