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Application of Risk Management and Uncertainty Concepts and Methods for Ecosystem Restoration: Principles and Best Practice

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OVERVIEW: Ecosystem restoration projects are often characterized by uncertainties that should be assessed according to current guidance (ER 1105-2-100) (USACE 2000), but in many projects, these issues are not always explicitly addressed. Inability to quantify risk and uncertainty often results in overly-conservative restoration management alternatives, resulting in inefficient allocations of capital and potentially significant, consequential damages and losses. The purpose of this technical note is to present one approach to risk management. Other approaches focus on more qualitative techniques. As part of this discussion, several case studies are used to illustrate aspects of current practice within the USACE.

BACKGROUND:

Risk and uncertainty are inherent aspects of USACE restoration projects. Current USACE policy requires an accounting for uncertainty in water resource planning. The Planning Guidance Notebook (PGN: ER 1105-2-100 (USACE 2000)) stipulates "Planners shall identify areas of risk and uncertainty in their analysis and describe them clearly, so that decisions can be made with knowledge of the degree of reliability of the estimated benefits and costs and of the effectiveness of alternative plans." The PGN also states that "planners shall characterize, to the extent possible, the different degrees of risk and uncertainty inherent in water resources planning and to [*sic*] describe them clearly so decisions can be based on the best available information."

For ecosystem restoration projects, the PGN also states that "For complex, specifically authorized projects that have high levels of risk and uncertainty of obtaining the proposed outputs, adaptive management may be recommended." In addition, August 2009 guidance from USACE headquarters, implementing Section 2039 of WRDA 2007, required that ecosystem restoration projects include plans for monitoring success and adaptively managing ecosystem restoration

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projects.[1] For these reasons, identifying, quantifying, evaluating and otherwise considering uncertainties as part of the planning process are strongly encouraged.

The Comprehensive Everglades Restoration Program (CERP) is an example of an ecosystem restoration project that required a robust approach to addressing risk and uncertainty, given the enormously complex nature of the Everglades ecosystem. USACE personnel responsible for implementing CERP were required to make decisions in the face of limited or incomplete and ever-changing information, and addressing risk and uncertainty would allow them to implement the CERP with more information. Because there was a pressing need to address such topics in restoration projects, USACE planners involved with the CERP held a "Model Uncertainty Workshop" in 2002 in South Florida (Lall et al. 2002). The workshop identified several inputs that were associated with uncertainty and that could impact models being developed for the CERP. In particular, the inputs from the spatial and temporal interpolation of point data, initial and boundary conditions, and for the calibration and verification procedures all could impact CERP models significantly. Workshop participants recommended that estimates of the probability distributions of uncertain output variables be obtained. They recommended 1) selecting independent input variables that contribute most significantly to final model predictions; 2) constructing probability density functions for each parameter to reflect the likelihood that the selected variable will take on various values within its possible range; 3) propagating uncertainties through the models to generate a probability density distribution of predicted output values; 4) deriving associated confidence limits; 5) using these confidence intervals as well as the probability density distributions to make quantitative statements about the probabilities of meeting selected suitability levels; and 6) that input variables should be linked to indexes being considered for monitoring as successful criteria (Lall et al. 2002). These recommendations from workshop participants highlighted the need to quantitatively address risk and uncertainty in USACE ecosystem restoration projects. Another important finding of the workshop was the need to identify key areas in which risk and uncertainty should be considered, providing a starting point for USACE practitioners.

The CERP experience is not new to the Corps. Risk analysis concepts have been included in the Principles and Guidelines for Water and Related Land Resources (P&G: Water Resources Council 1983; see specifically Section 1.4.13 on Risk and Uncertainty Analysis); thus, ample precedent has existed for more specific policies to evolve that would better represent uncertainties with regard to project performance during the planning process. The evaluation of flood risk reduction projects has always been an exercise in risk analysis, and a policy advisory in the form of an Engineer Circular (draft Engineer Regulation) was sent to the USACE field offices in 1992 outlining the primary components of an evolving risk analysis policy. The formal documentation of the policy was a joint Engineer Regulation (ER 1105-2-101; see especially Chapter 2, Section 2-4 on Principles and Analysis, Page 2-11) issued by USACE Planning and Engineering directorates (originally published in 1996 – updated and revised in January 2006; USACE 2006a), followed shortly thereafter by publication of an Engineer Manual (EM 1110-2-1619; USACE 1996). Technical and policy refinements were issued over the following ten years. ER 1105-2-101 stated that: "The ultimate goal is a comprehensive approach in which the values of all key variables,

[1] See Memorandum from CECW-PB, "Implementation Guidance for Section 2039, Monitoring Ecosystem Restoration" for flood damage reduction projects and more broadly P&G Section 1.4.13(b) on Risk and Uncertainty Analysis.

parameters, and components of flood damage reduction studies are subject to probabilistic analysis."

Similarly, Section 2033 of WRDA 2007 calls for application of risk analysis approaches for cost estimates for all civil works projects and more broadly, per the P&G (Section 1.4.13(b)). The wide-spread adoption of risk analysis policy and its application by USACE field offices for flood risk management continues to be a work in progress, in large measure because understanding of risk analysis and uncertainty principles and techniques is not widespread (Davis et al. 2008). The purpose of this technical note is to frame and document the application of risk management and uncertainty concepts and methods for ecosystem restoration, as a first step in fostering the learning necessary to expand these concepts beyond flood management to ecosystem management. The use of such risk assessment methods should be motivated by the importance of the actual decisions that environmental planners are seeking to inform, and should be scaled to the complexity and requirements of the problem(s) in question. Another purpose is to provide clear examples of best risk management practices and case studies that have been recently performed by district personnel. This technical note is divided into three main sections. The first section is a distillation of current best practice within the federal government as to how risk management challenges should be approached. This is followed by several examples and case studies illustrating how USACE is currently addressing risk and uncertainty in ecosystem restoration projects. The report concludes with a brief summary of the key recommendations, together with an outline of future research needs.

RISK MANAGEMENT IN PRACTICE

Decision makers charged with implementing risk management strategies as part of large-scale ecosystem restoration programs often face challenges in identifying and evaluating those restoration alternatives that are most likely to deliver the greatest programmatic- and/or system-level benefits per unit of expenditure. Characterizing and evaluating key uncertainties is, of course, an important element of any reasoned risk-informed approach to evaluating key facets or components of ecosystem restoration programs. How such efforts – directed as they are towards the *technical* appraisal of relevant risks, costs, and benefits – can best be oriented towards enhancing the decision quality underlying such programs requires an awareness and understanding of the broader risk management context in which these technical evaluations lie. In this section, this broader context is provided through a description of the rudiments of a risk management framework for environmental planning and ecosystem restoration. The conceptual foundations of the presented framework have their origins in several disciplines, including financial economics, decision science, organizational theory, and strategic management. Moreover, the framework builds on a number of National Academy of Science studies — together with several Presidential Commissions — that focused on risk assessment and risk management in Federal regulatory programs.[1]

There is, of course, a vast body of academic and professional literature that addresses many aspects of these risk management challenges. During the course of the past several decades, for example, the field of *decision analysis* has emerged as a useful paradigm for structuring and evaluating

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[1] See, for example, Proposed Risk Assessment Bulletin, Office of Management and Budget, 2006, downloadable at *http://www.whitehouse.gov/sites/default/files/omb/assets/omb/inforeg/proposed_risk_assessment_bulletin_010906.pdf*.

complex decision problems under uncertainty.[1] Similarly, the field of *risk analysis* has a long history, with much attention focused on the analysis of complex systems (e.g., energy, space systems, etc.) and the evaluation of environmental problems.[2] In the realm of ecosystem restoration, it is often the case that the tools and techniques of decision analysis and risk analysis are used in conjunction, especially in contexts where uncertainty is a pervasive element. The use of comparative risk assessment, for example, is common in public sector settings where efforts are directed at identifying broad risk categories and risks of high priority. Similarly, various risk analysis techniques can also be used in the evaluation of risk mitigation strategies.[3] At a higher level of abstraction, the tools of risk analysis can be seen to provide environmental planners with the analytic wherewithal for producing models of inferred causation (either *causal* or *diagnostic* in nature), whereas decision analysis helps decision makers structure and evaluate this information in a rational and transparent manner.

Drawing, first, from the management literature, the risk management framework presented here takes as its point of departure the view that *strategic intent* is ultimately what drives any sustained effort to manage risk in complex domains. Any attempt to characterize and evaluate risk leads quite naturally to a consideration of possible *risk mitigation strategies*; understanding the risks inherent to these alternatives becomes an important factor in programmatic efforts directed at achieving key strategic objectives within large-scale ecosystem restoration programs. The concept also applies at the project level, where risk mitigation largely focuses on avoiding undesirable outcomes.

Risk mitigation strategies can be differentiated along several dimensions, including cost, degree of risk mitigation, and ease of implementation. In evaluating these strategic alternatives, decision makers must integrate and weigh knowledge and information on a host of issues, including the risks, costs, and benefits associated with the strategic alternatives under consideration. In evaluating potential courses of action, decision makers must also look to explore fundamental trade-offs between risk and return, short-term vs. long-term gain, etc. As discussed below, the management selection process will inevitably require that other issues be considered as well, including relevant organizational constraints and risk tolerances.

Finally, any selection of risk mitigation strategy entails a process of implementation and monitoring, where strategic intent is executed, evaluated and monitored as to its aptness or efficacy, and — if possible and when necessary — adjusted in response to this new information through the application of adaptive management (see, e.g., Fischenich et al. (in preparation) for more details on adaptive management).

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[1] See, e.g., Keeney, and Raiffa, 1976 and Clemen, R., *Making Hard Decisions*, Duxbury Press, 2002.

[2] See, e.g., Morgan, G. and Henrion, M., *Uncertainty*, Cambridge, 1990.

[3] Various risk analysis techniques can be used in evaluating risk mitigation strategies. Fault trees, for example, can be used to focus attention and logical analysis on undesirable events. Failure Modes and Effects Analysis is often used to analyze the effects of external stressors (or other "disturbance" or initiating event of interest) on system performance. These and other techniques are often used in probabilistic risk analyses, which seek to measure the risks inherent to a particular systems design and/or operation. For an overview of relevant methods and techniques, see, for example, M. G. Morgan and M. Henrion, *Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis* (New York: Cambridge University Press, 1990); H. Raiffa, *Decision Analysis* (Reading: Addison-Wesley, 1968), W. Kip Viscusi, *Rational Risk Policy* (Oxford: Oxford University Press, 1998), and D. vonWinterfeldt and W. Edwards, *Decision Analysis and Behavioral Research* (Cambridge: Cambridge University Press, 1986).

As discussed below, the tools and techniques of risk management find application in a range of settings — from that of the individual decision maker to enterprise-wide settings and contexts.

Approaches to Risk Management

The five-step risk management (RM) framework that we present here is based on a synthesis of published literature. The framework is designed so that the individual components of the approach do not become ends in themselves; rather, the framework entails a full cycle of activities, ranging from strategic planning all the way through implementation, monitoring, and adaptive management. The five elements of the framework are as follows:

- *Strategic Goals, Objectives, and Constraints*
- *Risk Assessment*
- *Alternatives Evaluation*
- *Management Selection*
- *Implementation and Monitoring of Risk Mitigation Measures*

The RM Framework outlined below does not supplant the overall planning process; the framework is intended to enhance it, and to improve the *quality* of the decisions emerging from that process.

Strategic Goals, Objectives, and Constraints

A central tenant of sound environmental decision making holds that agencies should make management decisions in the context of a strategic plan, with clearly articulated goals and objectives that identify resource issues and external threats and/or hazards to the agency. An organization's or program's strategic plan, or its separate risk-planning documents, should address risk-related issues that are central to the overall mission of the organization or program.

Different scales of planning may involve different constraints. Constraints posed by statute, department policy, budget, or other factors vary with the scale of application. Applying risk management within the limited confines of an ecosystem restoration program (as opposed to, say, large-scale environmental restoration programs) may involve fewer constraints, but clearly that will depend on context as well as political interests and values. More generally, constraints shape the perception of risks, as well as the range of options deemed possible by decision makers to address those risks.

In the context of ecosystem restoration, the consideration of risk in the larger strategic planning context may be incorporated in broad planning documents, or in specific risk management strategies or plans. For an agency, for example, the Government Performance and Results Act of 1993 (GPRA) requires that a strategic plan have six components:

- A comprehensive agency mission statement
- A statement of the agency's long-term goals and objectives for all major functions and operations

- Approaches or strategies to achieve the goals and objectives and the various resources needed
- A description of the relationship between long-term goals and objectives and annual performance goals
- The identification of key factors, external to the agency and beyond its control that could significantly affect the achievement of the strategic goals
- A description of how program evaluations were used to establish or revise strategic goals and a schedule for future program evaluations

Risk Assessment

Risk is typically defined by two characteristics or dimensions — the *likelihood* and the *consequence* of adverse effects — that may be approached in a variety of ways. Likelihood refers to the probability (numerically or qualitatively determined) that an adverse event will occur; consequence refers to the outcomes associated with the uncertain event. In a typical risk assessment, the following questions are addressed as part of the overall risk management process:

- What can go wrong?
- What is the likelihood that it will go wrong?
- What are the consequences?

As a field of professional practice, risk assessment provides an array of analytical tools for assessing qualitative and quantitative estimates of the probability of, and the possible consequences associated with, adverse (or even positive) events and organizing them for decision makers. Risks can be evaluated by various methods, depending on the specific application, the detail of knowledge/information available, and the decision makers' preferences. Whatever tools are used, the end result is the same: a quantitative or qualitative characterization of the probability of an outcome that has a consequence related to the decision maker's key strategic objectives for environmental management, ecosystem restoration, and the like. Illustrative sketches of commonly used tools include the following:

- *Risk-Ranking Methods.* Although potentially informed by quantitative measures, much current risk assessment practice depends on the qualitative, relative ranking of current risks. Such rankings may be purely qualitative, using informative but ad-hoc judgments, while others may have a more formal process such as a multi-attribute or multi-objective approach. Guidance for good practice is found primarily in the risk literature, although OMB has some guidance for project-level risk management as part of its capital investment process.[1]

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[1]T. Bedford and R. Cooke, *Probabilistic Risk Analysis: Foundations and Methods* (New York: Cambridge University Press, 2001); Y. Haimes, *Risk Modeling, Assessment, and Management,* 2nd ed. (New York: John Wiley & Sons, 2004); R. Cooke, *Experts in Uncertainty: Opinion and Subjective Probability in Science* (New York: Oxford University Press, 1991); R. L. Keeney, *Value-Focused Thinking* (Cambridge, Mass.: Harvard University Press, 1992); ODPM, *Multi-Criteria Analysis Manual, and* Morgan and Henrion, *Uncertainty.* See also OMB circular A-11, part 7, Supplement, "Capital Programming Guide."

In some simple cases, direct risk ranking is possible where the outcomes are of the same type. In most settings, different types or levels of outcomes occur and more complex analyses involving weights or trade-offs are typically used. In these latter cases, ranking risks typically follows a sequence of steps that include identifying the attributes of possible events (such as exposure or consequence), defining weights and scales for the attributes, scoring possible events on the attributes, and aggregating the weighted scores. These steps may be represented in a visual "heat diagram," where reds, yellows, and greens, for instance, identify outcomes along two dimensions. Or results may be represented numerically with multi-objective scales.

- *Quantitative Risk Assessment*. Quantitative risk assessments, by substituting different measures, can use much of the same criteria as qualitative risk assessments. Quantitative risk assessments may take the form of point estimates, sensitivity analysis, or stress testing, or they may use statistical distributions for uncertain variables. The latter often use Monte Carlo simulation tools.[1] The use of quantitative risk assessment methods should be motivated by the importance of the actual decisions that the environmental planners are looking to inform. In this regard, there are no hard and fast rules; the overarching goal is to use risk assessment methods that are consistent with the complexity and/or requirements of the problem(s) in question.

Alternatives Evaluation

A risk assessment is likely to identify alternative ways in which environmental planners or managers can act to alter either the likelihood or the outcome/consequence. Such suggestions may also be generated internally or externally through a publicly informed process at various stages of the process including the strategic planning stage and later stages. The alternatives may include the full range of tools of governance, such as direct government investment, regulations, procedural changes, and other actions.[2] This step, as well as the following step of management selection or choice, comprises what is sometimes called the "resource allocation decision."

Risks can be minimized by reducing either their likelihood or their impact (i.e., consequence). In this regard, two concepts are key. The first is that action alternatives should be fed back through the risk assessment process to determine the extent to which risks can be reduced by the alternatives being considered. The initial risk assessment establishes at least part of the structure for evaluating the benefits of alternatives. Consideration should also be given to the chance that the action may simply deflect risk elsewhere; for example, to other parts of the ecosystem in question, or even other parts of the government (or the private sector), which, in turn, reduces the overall benefit of the action. Understanding the potential downstream implications of short-term actions is an important element of any risk management effort.

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1 T. Bedford and R. Cooke, *Probabilistic Risk Analysis: Foundations and Methods* (New York: Cambridge University Press, 2001); Y. Haimes, *Risk Modeling, Assessment, and Management,* 2nd ed. (New York: John Wiley & Sons, 2004); and Morgan and Henrion, *Uncertainty.* See also OMB circular A-11, part 7, Supplement, "Capital Programming Guide ", R. T. Clemen with T. Reilly, *Making Hard Decisions with Decision Tools*, (Pacific Grove, Calif.: Duxbury, 2001).
2 Haimes, *Risk Modeling, Assessment, and Management.*

The second concept is the role of costs to both government and the public (as it is assumed that risks are considered for both government and the public); costs are a critical element of alternatives evaluation. Major regulatory actions or capital investments generally require a benefit-cost or cost-effectiveness approach.[1] This approach can be useful in assessing alternatives, because it links the benefits derived from risk-reducing alternatives to the costs associated with them. In the development of such analysis, quantitative impacts affecting both costs and benefits are, to the extent possible, identified and valued in monetary terms except in the case of ecosystem restoration, where nonmonetary benefits are required by policy.[2] Ideally, the quantification of costs and benefits should focus on both the tangible and intangible elements of value. For intangible costs and benefits, tools such as multi-attribute value theory can aid efforts to quantify those factors that are not easily monetizable.[3]

Management Selection

The distinction between analysis and management is so important in some contexts, as in environmental applications, that the discussion of risk management as encompassing risk assessment is instead typically broken into two steps: *risk assessment* and *risk management*. In the five-step framework presented here, management is clearly involved with Step 1: strategic planning. Steps 2 and 3 are primarily, but not exclusively, analytical. Step 4: management selection (sometimes called management choice or alternative selection), is for choosing between alternative actions. The decision maker's active participation is important at this stage, for a number of reasons. First, it is the decision maker's responsibility to ensure that the risk management process has sought to properly frame the decision(s) in question, making Step 1 as explicit and transparent as possible. For their part, planners should aid management's efforts to this end, making clear the various assumptions (especially about key uncertainties and risk preferences) that underlie their analysis and that may require review at the management level. Management may, of course, also have values or information that the analysts have not fully assessed. There is, of course, value in managing the risk management process in ways that facilitate the interface that exists between programmatic and project-level execution of ecosystem restoration initiatives. Finally, once decisions have been reached, evidence that they were informed by risk-based information should be documented in a manner that lends the overall management selection process as much transparency as possible.

Implementation, Monitoring and Adaptive Management (AM)

Preventing and mitigating risk require the successful transition from planning to the field. A sound risk management approach should document a reasoned approach to implementation and monitoring. A wealth of empirical studies has shown that agencies are often challenged to implement complex, expensive activities in a timely and cost-effective way. Risk issues related to cost, performance, and scheduling are typical. Among other tools important to program success are internal controls, performance measurement, and adaptive management measures.

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1 Executive Order 12866 and circulars A-4 and A-94 apply to regulation, and circulars A-11 (sect. 7), A-94, and A-130 apply to capital investment.

2 ER 1105-2-100.

3 See, e.g., McDaniels, T. L., and Roessler, C., "Multiattribute elicitation of wilderness preservation benefits: A constructive approach," *Ecological Economics* 27, 1998, pp. 299-312.

Finally, risk communication is another critical component in risk management strategies that involve stakeholders. Monitoring may take place in several time periods that involve frequent operational information for management and broader, periodic evaluations that may be followed by management actions aimed at avoiding or minimizing risk.

Emerging best practice with regard to ecosystem planning and restoration focuses on implementation and monitoring coupled with AM. Environmental planners must consistently seek to evaluate the management, effectiveness, timeliness, and cost of implementing planned actions, and take steps to support the regular evaluation of project or program performance. These are the motivating cornerstones of adopting AM-based approaches to ecosystem planning and restoration. Criteria for evaluating implementation are often contained in an agency's plans and in federal guidance, such as internal controls and performance measurement; for an ecosystem restoration project, such criteria will typically be stipulated in the monitoring and AM plan.

Monitoring includes both ongoing internal controls and periodic performance evaluation. Monitoring activities can focus on outcomes and/or procedural aspects of performance. In this way, effectiveness and/or efficiency are the ultimate goals of well-motivated AM-based approaches to ecosystem planning and restoration. Internal controls should generally be designed to ensure ongoing monitoring in the course of normal operations. Monitoring should be performed continually and should be interwoven with ongoing operations. It involves regular management and supervisory activities, comparisons, reconciliations, and other actions of individuals as they perform their duties.

Program evaluation is another important tool for assessing effectiveness. Specification of quality assurance metrics (in program and/or project plans) is a common approach to measuring the degree to which program effectiveness and program efficiency goals are achieved. As part of this process, data quality is an issue that often requires explicit consideration, with careful thought and attention paid to meeting the requisite level of data quality for the decisions at hand, as well as testing the sensitivity of policy recommendations to data utilized to inform the decision-making process. The scope and frequency of evaluations of the entire risk management system depend on current assessment of risks and the effectiveness of ongoing monitoring and AM procedures. Consultation with external experts can help provide an unbiased review.

In assessing the implementation of risk mitigation actions, it is useful to ask the following questions:

- Are objectives and time schedules specified for implementation actions?
- Were risk mitigation actions implemented as specified?
- Were risk mitigation actions implemented in a timely manner?
- Did risk mitigation actions meet cost objectives?
- Have risk communication issues been addressed, and if so, have they been addressed in a manner that is consistent with best practices?

In addressing monitoring and evaluation activities, some critical questions for environmental managers include:

- What types of ongoing monitoring occur?
- If performance measures exist, what is the outcome of performance measurement?
- Do AM measures exist, and have they been applied?
- Has the agency previously evaluated the program/project or does it have a detailed plan for evaluating the program?
- Does the evaluation conform to best practices?
- Are the recommended activities reviewed periodically?
- Are risk scenarios kept up to date and is the system tested periodically?
- How often does the agency review the entire risk management system?
- What mechanisms identify and deal with risks affected by changing circumstances or new information?

Of course, many of these questions will be part-and-parcel of the AM plan required for ecosystem restoration. Learning and observation are key elements of AM-based approaches to such efforts strategy, and the questions above can be seen to motivate efforts to enhance the adaptive capacity of ecosystem restoration programs.

In the following section, facets of the risk management framework presented above are explored as they related to a set of illustrative case studies. Each case study utilizes one or more of the RM facets described in this section.

DISTILLATION OF CURRENT USACE PRACTICE

This section provides a distillation of USACE current practice describing how risk and uncertainty were addressed in recent USACE ecosystem restoration projects. The degree to which USACE is currently addressing uncertainty is somewhat limited, but there are some key examples of good planning to illustrate how this has been done in recent large projects, and can serve as a basis for making recommendations that will advance the practice. Districts have approached uncertainty in various ways; for example, by performing scenario analyses and sensitivity analyses, but there are gaps and inconsistencies in current practice. While many districts acknowledge the uncertainty associated with their project, there are relatively few cases in which they have specifically quantified uncertainty. In the following examples, we explore the ways in which various approaches to risk and uncertainty have affected project outcomes.

Case Study #1: Environmental Benefits Analysis of Fish Passage on the Truckee River, Nevada: A Case Study of Multi-Action-Dependent Benefits Quantification

In 2010, the USACE published a report detailing the restoration by USACE of the upstream and downstream fish passage on the Truckee River between Pyramid Lake and Lake Tahoe (Conyngham et. al. 2011). To address uncertainty in estimates of non-monetary benefits of remediation, Sacramento District planners and ERDC identified three outcome scenarios in the cost effectiveness and incremental cost analyses: the expected, most pessimistic, and most optimistic outcomes. The scenarios were based on data elicited from subject matter experts

(SMEs) from different Federal agencies, including the USACE, the Fish and Wildlife Service, and the USGS, as well as representatives from local universities and stakeholders from local tribes. Optimal plans were selected from the given scenarios; however, only the *extent* of all possible outcomes from the given plans was noted. In what sort of distribution these outcomes fell in relation to one another was not examined in the course of this uncertainty analysis.

Quantitative uncertainty analyses were pursued for a sub-set of the plans given that the expected scenario was not likely to occur in every case and examining each case would have been an unneccesary burden. Given the large number of structures and combinations of upstream and downstream values, a high number of iterations would have been required to examine all possible outcomes. Therefore, the project development team examined uncertainty through a Monte Carlo analysis using a random set of minimum, expected, and maximum values. The outcomes were assumed to be normally distributed with the expected outcome set to the mean and minimum and maximum outcomes to the third standard deviation. Five thousand random sets were generated, and although this is less than the total possible number of potential outcomes, a characterization of the distribution of the potential benefits is provided in the report (Conyngham et. al. 2011). From these analyses, significant statistical properties (for example, confidence intervals and maximum and minimum values) were obtained to support decisions made by USACE restoration planners with respect to uncertainty in the alternatives decision-making process (Figure 1).

The study report acknowledged that there were additional sources of uncertainty related to the weighting of upstream passage benefits as compared to downstream passage benefits. Other sources of uncertainty were the importance of upstream, coldwater refugia and other habitats for specific species of trout. The report noted that these uncertainties — and the SMEs, who had past experience in such topic areas — were able to suggest means of amelioration rather than performing a quantitative uncertainty analysis. Thus, this report addressed uncertainty both quantitatively and qualitatively, acknowledging and addressing uncertainty in a thorough manner. The modeling effort helped planners narrow down a broad range of 54 possible alternatives to a smaller subset of six plans. Overall, the uncertainty analysis allowed the team to focus on a smaller number of alternative restoration plans to consider.

In general, then, we see how various aspects of the risk management framework presented earlier were utilized in this specific case study. Primarily, the tools of risk assessment were used to identify a plausible set of risk mitigation strategies. Uncertainty analysis was then used to narrow the range of options considered to one option that was deemed requisite to the specific situation being confronted.

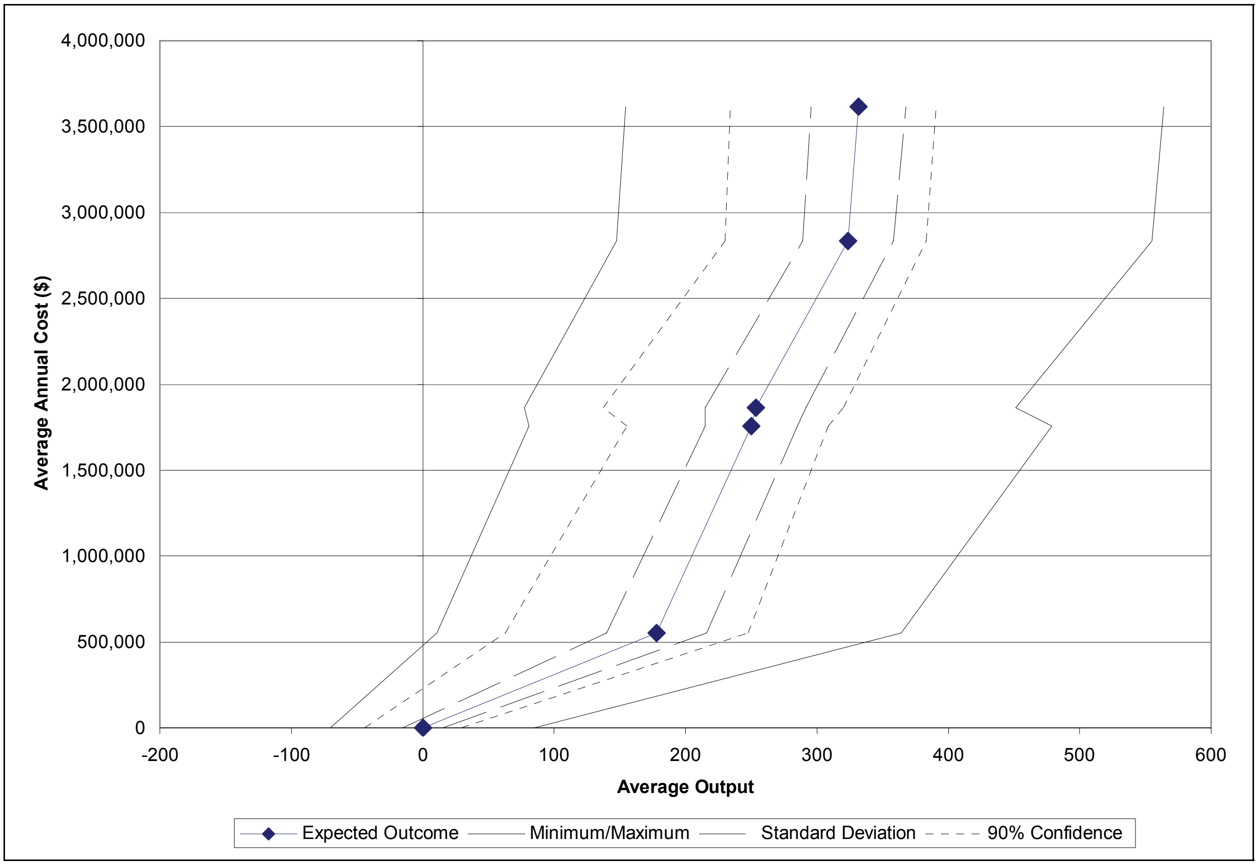

Figure 1. Confidence intervals for select plans, namely: the expected outcome, the most pessimistic and optimistic outcomes (minimum and maximum, respectively), the standard deviations of the 5,000 benefit values from the Monte Carlo analysis, and the 90% confidence interval resulting from the Monte Carlo analysis (from Conyngham et. al. 2011).

Case Study #2: Sensitivity of the Barataria Basin Barrier Shoreline Wetland Value Assessment Model

This case study focused on uncertainty analysis that evaluated the sensitivity of model output as a consequence of suggested changes in model parameters. The suggested changes in model parameters arose during the model certification review in the Barataria Basin Barrier Shoreline project (McKay and Fischenich in preparation). Noting that sensitivity analysis could be used as a viable means for addressing uncertainty, the case study provides details about how a sensitivity analysis was performed to test the robustness of the Wetlands Value Assessment (WVA) model used by the New Orleans District (MVN). USACE Planning Guidelines require that such models be evaluated for quality, and given that the model had been developed by other government agencies, especially the Fish and Wildlife Service and the Louisiana Department of Natural Resources, an internal review by the USACE was considered essential. The sensitivity analysis was performed as follows. Two components of the model structure were examined: 1) boundary conditions applied in suitability index curves and 2) methods by which suitability index curves were aggregated into a Habitat Suitability Index. All combinations of the two analyses were examined to test sensitivity to changes in boundary conditions and aggregation techniques. The results provided insight into the response of models relative to two parameters that were the focus of concerns raised during a certification review of the model. Thus, this report addressed the issue of uncertainty via sensitivity analysis which indicated how models might be affected by measurement uncertainty related to ecological parameters. The value that this sensitivity analysis added to the planning process was that it allowed planners to understand how and in what direction certain variables influenced the results of the wetland models. The assessment demonstrated that the model outputs were relatively insensitive to changes suggested by model reviewers, and that modification of the models would not have affected the final decisions regarding the preferred alternative. A better understanding of how the WVA model outputs responded to certain conditions was also achieved.

Case Study #3: Upper Mississippi River System Navigation and Ecosystem Sustainability Program

The Upper Mississippi River System Navigation and Ecosystem Sustainability Program (UMRS NESP) performed by the Mississippi Valley Division also addressed risk and uncertainty to various degrees in their report (Bartell 2003). The UMRS first notes that uncertainty can enter into risk assessments through the abundance and diversity of ecological factors that are a part of any restoration effort, such as the estimated effects of future barge traffic and estimated initial conditions and parameter values for ecological and physical force models. This study specifically addressed the issue that unacceptably high estimates of risk may result from the high degrees of uncertainty entering into initial data gathering analyses and that these may not represent the actual magnitude posed by the risks. The methods used by UMRS NESP dealt with uncertainty propagation and excluded single-point, extreme predictions that result when extreme values of the input parameters are used for model simulations. Rather than determining such worst-case estimates of ecological impact, analyses in this study were conducted to obtain conservative, non-conservative, and central estimates of the impacts. Simulations in the uncertainty analyses were subsequently conducted to compare single-point predictions with confidence intervals and central estimates developed from the uncertainty propagation methods. These exercises served to improve confidence in modeling done by the UMRS NESP for restoration projects.

A specific example demonstrating an approach to addressing uncertainty in ecological modeling was presented in the report "Ecological Risk Assessment of the Effects of the Incremental Traffic (25, 50, 75, and 100 percent Increase of 1992 Baseline Traffic) on Fish" prepared for the Upper Mississippi River – Illinois Waterway System Navigation Study (Bartell and Campbell 2000). In the study, ecological stressors were identified as water quantities entrained through the propellers of commercial vessels navigating the system. To characterize commercial traffic intensity, a baseline number of vessels passing through each pool was developed using historical data from 1992. Future traffic scenarios were then developed assuming 25, 50, 75, and 100 percent increases over the 1992 data. Over 100 possible configurations for commercial vessel operations in the UMR-IWW System were developed applicable through the year 2050. The principal focus of the assessment was commercial traffic-induced increases in larval fish mortality. The Conditional Entrainment Mortality (CEM) model, a standard modeling approach for evaluating fish entrainment by power plant water intakes, was used to calculate the potential impacts on fish larvae. The results of the calculations were extrapolated through the use of other metric-specific models to create estimates of future lost adults (using the Equivalent Adults Lost model), recruitment forgone (RF model), and production forgone (PF model). Taken together, these models provided a more complete picture of the possible effects of increases in commercial traffic in the UMR-IWW system. The results provided a context for management decisions given uncertain future scenarios. The study explicitly identified and quantified the uncertainties that were considered in the analysis. These uncertainties were included in the assessment calculations to produce probabilistic estimates of ecological impacts on fish populations which presented a more comprehensive picture of the possible effects of increased vessel traffic. This study was used to inform future NESP studies, as well as management decisions made by the USACE in the region that was working to restore the UMRS. In this way, all of the steps in our risk management were utilized, with the possible exception of Implementation & Monitoring.

Case Study #4: Upper Mississippi River Restoration Environmental Management Program

A veritable inter-agency undertaking (partnerships between the USACE, USEPA, USFWS, USGS, and state governments), the Upper Mississippi River Restoration Environmental Management Program (EMP) was authorized in 1986 (http://www.mvr.usace.army.mil/EMP/). Since that time, it has planned, designed and restored or enhanced approximately 100,000 acres of habitat within the Upper Mississippi River System (UMRS) while conducting the dedicated Long Term Resource Monitoring Program to track the overall health of the system. In its 2010 report to Congress, the program sought to highlight what had been learned over the 25 years of funding for ecosystem rehabilitation and scientific monitoring and research efforts (USACE 2010a). While not directly addressing risk or uncertainty, the need to develop and apply adaptive management strategies in the context of ecosystem restoration projects was noted, and this is the most direct way that risk and uncertainty were addressed. Given that the document does address uncertainty in this oblique way, it can only be understood as an improvement over the general state of the practice when it comes to addressing these topics. Indeed, applying the adaptive management framework to EMP programming has been shown to aid decision making in situations with high levels of uncertainty.

Adaptive management strategies are said to be employed mostly in Habitat Rehabilitation and Enhancement Projects (HREPs) where significant uncertainties exist regarding outcomes and alternatives. For example, the Long Term Resource Monitoring Program, the USACE, Iowa and Wisconsin's Departments of Natural Resources, and USFWS conducted a multi-pool study of the ecological and biological features of several panfish species. By studying the habits of these fish species, project managers were able to scale back the water flow management scheme in the area to both save on cost and natural resources and create a more suitable habitat for fish species. This kind of monitoring can lead to adjusted management practices and is one means of dealing with situations with high uncertainty.

Further application of adaptive management principles to reduce uncertainty in HREP projects is reflected in the completion of the Pool 11 Islands (UMRS RM 583-593) HREP in 2003. In 1989 the Browns Lake (UMRS RM 545.8) HREP attempted to address low dissolved oxygen (DO) that was limiting overwintering fisheries by constructing a four bay 5-foot square stop log structure to introduce oxygenated water to the backwater during observed low DO conditions. Being one of the first ecosystem restoration projects undertaken within USACE, great uncertainty existed as to the quantity of water necessary to re-oxygenate the backwater fishery during overwintering periods. To compensate, a robust structure was constructed. Subsequent monitoring and operation indicated that flow through one bay at 5-by-2 foot was adequate to achieve project objectives. This reduction in uncertainty, related to water inflow requirements, was incorporated into two notched weir-type structures constructed at the Pool 11 Islands HREP resulting in significant construction cost and operation savings and more natural structures that provided habitat value as submerged aquatic structure during spring and fall high-water events.

Thus, this case study shows well-thought-out and practical usages of adaptive management strategies for dealing with situations in which the decision maker has limited knowledge. Therefore, the acknowledgement of the need for adaptive management strategies and their implementation, as exemplified in this case study, represent positive steps towards addressing uncertainty in large-scale ecosystem restoration projects. Clearly, subsequent steps would seek to implement other key phases of the risk management framework articulated here.

The Environmental Design Handbook (USACE 2006b) provided a compendium of "lessons learned" from ecosystem restoration and rehabilitation efforts in the Upper Mississippi River Environmental Management Program. Risk and uncertainty are explicitly acknowledged as playing major roles in restoration projects and ways of mitigating uncertainty are recommended. While the idea of risk as the possibility for a negative outcome is mentioned, ways in which to mitigate it are provided only insofar as they relate to the specific project being examined. For example, when discussing riprap construction, new engineering design standards are noted and suggested as means of preventing riprap failure in the future. New HREPs address risk in the plan formulation process such that restoration measures being considered incorporate risk mitigation as part of their design criteria. As far as uncertainty goes, complex goals and objectives are noted as well as the prevalence of uncertain metrics for determining the success in meeting these objectives as they pertain to habitat restoration. Remote sensing and an adaptive management framework were implied as possible solutions to this issue. A clear enunciation of objectives and parameters to be used in the design project are also stated as of utmost importance in rehabilitation efforts, and a group of parameters are suggested for river system restoration projects. In this way, uncertainty regarding the fluid nature of biological systems is addressed, though in a more qualitative manner. Acknowledging the ways in which risk and uncertainty can be addressed in restoration projects is a means of dealing with such topics and provides the added value for planners of knowing to be alert for such issues when they arise.

Case Study #5: Louisiana Coastal Area Ecosystem Restoration

The Louisiana Coastal Area (LCA) Conditionally Authorized Ecosystem Restoration projects are large-scale restoration projects seeking to restore historical hydrological and biological patterns along the Louisiana gulf coast. Each of the six projects addressed risk and uncertainty in a specific way (as it relates to a number of factors that affect restoration efforts). Risk and uncertainty were addressed in each project from the standpoint of a certain issue that can allow problems to develop in restoration efforts. For example, in the Medium Diversion at the White Ditch (White Ditch project), aspects of risk and uncertainty affecting the restoration efforts were 1) induced shoaling in the Mississippi River near the diversion; 2) sea-level rise impacts to potential habitat benefits and project viability beyond the period of analysis; 3) use of the ERDC-SAND2 model to predict future marsh creation; 4) real estate; 5) sediment availability at proposed diversion locations; 6) cumulative impacts of the proposed structure operating in combination with the existing

Caernarvon Diversion; 7) water quality (salinity) impacts; and 8) endangered fishery resources (pallid sturgeon). Essentially, each "uncertain" situation associated with risks that might prevent the successful completion of restoration was examined with qualitative rigor and then quantitative design standards were recommended to mitigate that risk. Looking specifically at how USACE planners addressed the risk of sea-level rise with respect to the White Ditch LCA restoration project, the ERDC-SAND2 model was used to predict to what extent climate change would affect the marsh habitat (USACE 2010b). Scenario analysis techniques were utilized by applying the model to three possible future states of sea-level rise (high, medium, low), to quantify the outcomes for each scenario and evaluate the robustness of the various alternatives to this source of uncertainty.

Risk and uncertainty were similarly evaluated for the other five LCA projects. In several of the other projects, there was much discussion regarding the effects of adding diversion structures on ecosystem health and historical water flows. In a type of adaptive management analysis of possible outcomes, the authors noted in each of the alternatives (which consisted of different levels of diversion discharges in cubic feet per second) what the effects would be on water flow and wildlife populations (USACE 2010b). The value added of such an analysis is clear – it is shown in an obvious way how each alternative would impact, more generally, restoration efforts. This is a very practical, quantitative and qualitative fusion approach to dealing with risk and uncertainty, and is quite useful in the context of a project where there is a great deal of monitoring data and a high level of understanding of how hydraulic engineering actions can affect the aquatic environment.

SUMMARY

The case studies presented above represent some innovative thinking in the USACE that addresses risk and uncertainty in ecosystem restoration projects. This is a limited distillation and is not intended to be representative of the spectrum of approaches to ecosystem restoration uncertainty available within the USACE. Indeed, it is recognized that most projects probably receive less attention to the issues of uncertainty and risk management. While the examples presented here are credible and helpful, they merely represent the early steps in what will, no doubt, be a long process in the advancement of USACE risk and uncertainty practice. Convertino et al. (2012) provide a hypothetical restoration example illustrating how risk and uncertainty tools and techniques could advance USACE practice. There is room to incorporate new methods of addressing uncertainty in such projects as discussed above.

In the near future, the Institute for Water Resources Planning Suite (IWRPS), a decision support software tool designed to assist users engaged in the formulation and evaluation of water resource projects, will include two new modules that address aspects of risk and uncertainty. A Multiple Criteria Decision Analysis (MCDA) module is being developed to provide users with a means of imparting greater transparency to studies requiring consideration of greater than one cost or benefit stream, and is being developed to help users understand and communicate the manner in which various integration and weighting methods are likely to influence decisions. In addition, a preliminary functional version of an Uncertainty and Risk module is being developed to provide users with the capacity to express costs and benefits, individually or as variables contributing to a computed/derived value, as probabilistic distributions in lieu of point values. The Uncertainty and

Risk module is being developed to deliver a platform within which uncertainty-informed cost effectiveness and incremental cost analyses can be performed and used to support risk-based investment decisions involving monetary and non-monetary costs and benefits.

Another means of advancing the practice of addressing risk and uncertainty in ecosystem restoration projects would be to combine different tools and techniques employed in the case studies described above. In the Truckee River example, the quantitative Monte Carlo analyses, and some of the qualitative techniques used to understand ecological processes, were useful for reducing the broad range of alternatives being considered. The sensitivity analysis for the WVA model performed in the Barataria case study was useful for vetting the quality of the models. The sensitivity analysis was also useful for gaining a clear understanding of the extent and directions of the bias that exists in models used by USACE planners. The AM techniques performed by the UMRS Environmental Management Program and the uncertainty propagation analyses done by the UMRS Navigation and Ecosystem Sustainability Program are other useful means of approaching risk and uncertainty. Integrating such techniques would lead to a more robust and complete modeling of risk and uncertainty in restoration projects. The purpose of using uncertainty analyses is to help USACE planners make decisions when faced with incomplete information. The risk management framework introduced herein can integrate different risk and uncertainty techniques into restoration projects as a way to advance the practice within the USACE. Potential next steps might include developing one or more case studies illustrating how such techniques can be integrated to further advance the practice.

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