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Addressing Risk and Uncertainty in Planning Ecological Restoration Projects

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INTRODUCTION: Corps of Engineers planners have been required to consider risk and uncertainty since the Principles and Standards Act of 1972. The Actions for Change are increasing the Corps of Engineers' reliance on risk-informed analysis and decision making. An informal review of the Corps' experience with ecosystem restoration plans has shown few, if any, systematic efforts to address the often significant uncertainties encountered in estimating and quantifying environmental benefits. Better evaluation of these uncertainties and consequent project risks will improve the quality of ecosystem restoration planning efforts.

The purpose of this technical note is to encourage the systematic and routine consideration of uncertainty when estimating environmental benefits of ecosystem restoration projects. To that end, this note will address:

- Reasons for addressing uncertainty.
- The language and meaning of uncertainty.
- Appropriate conditions for uncertainty analysis.
- Methodologies and tools appropriate for uncertainty analysis.

WHY CONDUCT UNCERTAINTY ANALYSIS? Uncertainty analysis is done to improve the quality of decisions that must be made when it is not possible to have all the desired information. Uncertainty analysis adds value to the decision-making process for the Corps, its stakeholders, and the public. It enables the Corps to better manage ecosystem restoration projects to achieve desired outcomes for national ecosystem restoration, national and regional economic development, and other social effects.

Burkes-Copes et al. (in review) explored the state of the science for incorporating uncertainty in ecosystem restoration projects. One of their main findings was the lack of uncertainty analysis being practiced in part due to the resistance to change in the ways "things are done." Pappenberger and Beven (2006) found that a significant part of the hydrological and hydraulic (H&H) modeling community is reluctant to embrace the estimation of uncertainty in their work. They explore seven common arguments for resisting uncertainty estimation and find each untenable. The rejected reasons for opposing uncertainty analysis in H&H work, which can also be applied to ecosystem restoration projects, are:

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- Uncertainty analysis is not necessary given physically realistic models.
- Uncertainty analysis cannot be used in hydrological and hydraulic hypothesis testing.
- Uncertainty (probability) distributions cannot be understood by policy makers and the public.
- Uncertainty analysis cannot be incorporated into the decision-making process.
- Uncertainty analysis is too subjective.
- Uncertainty analysis is too difficult to perform.
- Uncertainty does not really matter in making the final decision.

Risk analysis is an essential element of the U.S. Army Corps of Engineers Actions for Change, which consists of the following four themes:

- Comprehensive systems approach.
- Risk-informed decision making.
- Communication of risk to the public.
- Professional and technical expertise.

Besides addressing the actions for change, there are a number of additional reasons for addressing uncertainty in estimating environmental benefits for ecosystem restoration projects, including the following:

- To better estimate and manage risks. Uncertainty can contribute to the occurrence of adverse consequences and it can interfere with the realization of potential gains. Addressing attendant uncertainties in the assessment, implementation, and management of project alternatives is an essential part of good risk analysis.
- To improve the quality of information upon which decisions are based. In the past, project outcome forecasts have proven to be wrong. Assessing uncertainty in the candidate plans enables a more honest and realistic comparison of plan effects and their likelihoods. Decision makers should be able to make better decisions when informed of the nature and extent of uncertainty in analyses supporting that decision.
- To manage stakeholder expectations of project outcomes. Ecological responses to a restoration project are often difficult to predict. By assessing the uncertainty in project outcomes, planners can guard against unrealistic expectations of environmental benefits.
- To anticipate the possibility of undesirable outcomes and avoid surprise. Ecological restoration projects can sometimes yield undesirable outcomes. An uncertainty analysis can help planners anticipate the possibility that these outcomes may be realized and formulate plans to manage the likelihood that undesirable outcomes are realized.
- To evaluate the sensitivity of project outcomes. Exploration of uncertainty in a planning study can reveal useful insights about interdependencies in a project.
- To steer projects toward desirable outcomes. The Corps and its partners want to design “successful projects” that will achieve targeted outcomes. Identifying data gaps and uncertain relationships and evaluating management alternatives and the range of possible outcomes is part of implementing an adaptive management process.
- To reduce the potential propagation of random error or bias through the analysis. A careful, systematic, and transparent handling of the relevant uncertainties can reduce the

likelihood of the presence of undetected cumulative errors in model results and metrics upon which decisions are based.

- To ensure safe infrastructure. Examining uncertainty in the performance of project measures can identify and help mitigate any risks associated with infrastructure failure or malfunction.
- To help control costs. There are often uncertainties in estimating the cost of a proposed ecological restoration project alternative as well as estimating its ecological benefits. An understanding of these uncertainties can help improve the quality of net benefit estimates.
- To comply with current and emerging policy. Corps policy (for example, EC 1105-2-214 (U.S. Army Corps of Engineers (USACE) 1997) and ER 1105-2-100 (USACE 1990)) already includes requirements to account for uncertainty in water resources planning. The Actions for Change and OMB's growing reliance on risk analysis methodologies and concepts ensure that this reliance on uncertainty analysis will only increase in the future.
- To direct/target research efforts (uncertainty analyses reveal gaps in knowledge, allowing researchers to focus on those areas).

RISK ANALYSIS: Risk can be defined as the probability of undesirable consequences. Risk analysis is an analytical process that includes the processes of risk assessment, risk management, and risk communication (Figure 1). Risk assessment is analytically based, whereas risk management is policy and preference based. Risk communication involves the interactive exchange of information about and preferences concerning risk. Risk analysis offers a systematic approach to decision making that can improve the quality of Corps decisions. Risk is often assessed in terms of potential loss of life, property damage, or undesirable ecological outcomes resulting from natural hazards or human actions. In the context of ecosystem restoration, project risks exist when there is uncertainty about realizing positive net benefits from an investment.

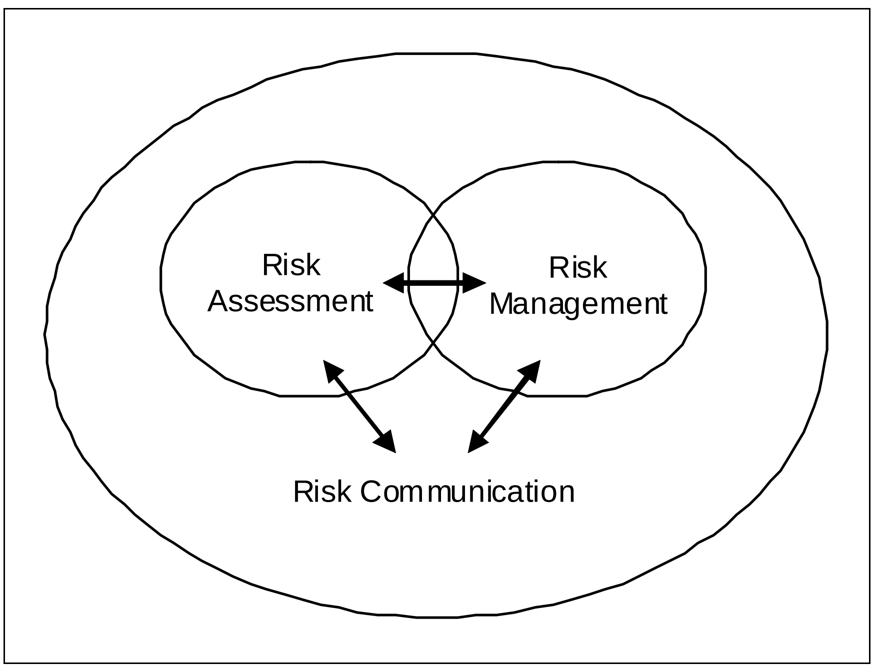

Figure 1. Risk analysis involves risk assessment, risk management, and risk communication.

Both the probability (likelihood) and consequences (outcome) of a decision may be uncertain; to distinguish these two types of risks, two terms are adopted. The first is *pure risk.* This is the risk of loss where there is no possibility for gain and it is consistent with the traditional definition of risk above. It most often involves a hazard that can produce adverse effects. In water resources these include natural phenomena (hazards) that cause accidents and structural failures. Examples include floods, storms, erosion, droughts, pollution, water quality degradation, infrastructure failure, and so on. Losses occur when ecosystems, resources, people, property, or other assets are exposed to the hazard.

Speculative risk or project management risk stems from the chance that an action will not achieve the predicted or desired outcomes. In some of these cases, there is also the possibility that an action will achieve outcomes more desired than those predicted as well as less preferred. Speculative risk refers to the uncertain outcome of actions taken to alter current states of the world. Failure to realize desired gains is one form of loss. Ecosystem restoration benefits are primary examples of desired gains.

For risk analysis to be successful, it requires analysts, managers, and stakeholders alike to give appropriate attention to the uncertainties that attend the decision problem.

WHAT IS UNCERTAINTY? At the most basic level, when we are not sure, we are uncertain. The literature has spawned a rich language to express this simple idea in more elegant, eloquent, and sometimes confusing terms. It is essential to understand the language of uncertainty in its current usage in order to implement best practice uncertainty analysis. Recognizing that other definitions and taxonomies of uncertainty are available (e.g., Yoe 1996; Regan et al. 2002), several terms are defined for the purposes of this technical note. Two basic kinds of uncertainty are defined as a starting point.

Epistemic uncertainty. This uncertainty is attributed to a lack of knowledge on the part of the observer and is reducible in principle, although it may be difficult or expensive to do so. It arises from incomplete theory and lack of knowledge about the behavior of the system under study. (Epistemic uncertainty is sometimes called subjective uncertainty, reducible uncertainty, and model form uncertainty.)

Examples:

- Lack of experimental data to characterize new materials and processes (e.g., nanomaterials).
- Poor understanding of the linkages between water quantity and habitat desirability.
- Assuming one species is more numerous than another in an area but being unable to confirm or refute this assumption.

Aleatory uncertainty. This is uncertainty due to a random process. It is attributed to the natural variability of a quantity over time and/or space or among members of a population. It can arise because of natural, unpredictable variation in the performance of the system under study. It is, in principle, irreducible. In other words, the variability cannot be altered by obtaining more information, although one's characterization of that variability might change given additional information. (Aleatory uncertainty is sometimes called variability, irreducible uncertainty, stochastic uncertainty, or random uncertainty.)

Examples:

- Variation in daily rainfall and runoff over the next 30 years.
- Variation in fish population recruitment due to seasonal flooding.
- Variation in daily mean high water temperatures.

Uncertainty is not an easy concept to grasp and it is sometimes useful to consider the difference between closed and open systems when characterizing the effects of uncertainty. Both kinds of systems occur frequently in ecosystem restoration planning. Consider the inherent randomness of the natural and social systems with which planners deal. In a closed system it is possible for analysis to bound the range of outcomes (e.g., ecosystem restoration benefits) and offer some estimate of the likelihood of their occurrence. In an open system, planners must recognize that water bodies, watersheds, ecosystems, and human decisions are not only characterized by randomness, but also difficult to predict with any degree of confidence.

Different kinds and sources of uncertainty will most likely require different tools, techniques, and methodologies to best address them in the planning process. In addition to the epistemic and aleatory distinctions above it is also common to see uncertainty distinguished by its source. Three possible sources of uncertainty in estimating ecological restoration benefits are described here.

Model uncertainty. This is uncertainty about the models used to estimate the benefits of ecological restoration projects. Model uncertainty can arise from bias or imprecision associated with compromises made or lack of adequate knowledge in specifying the structure and calibration (parameter estimation) of a model.

Examples:

- Index model formulas and the relationships amongst variables therein.
- Assumed correlations between ecosystem function and vegetation composition and structure.
- Cumulative effects (dependencies) between abiotic and biotic model components.

Quantity uncertainty. This is uncertainty about which value to use for an input variable in a model to estimate ecological restoration outcomes. This category also includes uncertainty in measurements from a population of interest. This source is the practical manifestation of aleatory uncertainty.

Examples:

- The number of bears living in a park.
- Mean phosphorous load in a stream.
- Distance between water control structures.

Scenario uncertainty. This uncertainty results when the elements of a scenario or their relationships are unknown or incomplete. Scenarios can be thought of as the stories told to explain how ecosystem restoration benefits are realized.

Examples:

- Misunderstanding pathways by which water affects a habitat.
- The effects of disturbance on an ecosystem subjected to urban growth.
- The response of the ecosystem to climate change.

Figure 2 illustrates the types of uncertainty and includes example elements such as stressors and sources. Scenario, model, and quantity (inputs) uncertainty are likely to be common in estimating ecosystem restoration benefits.

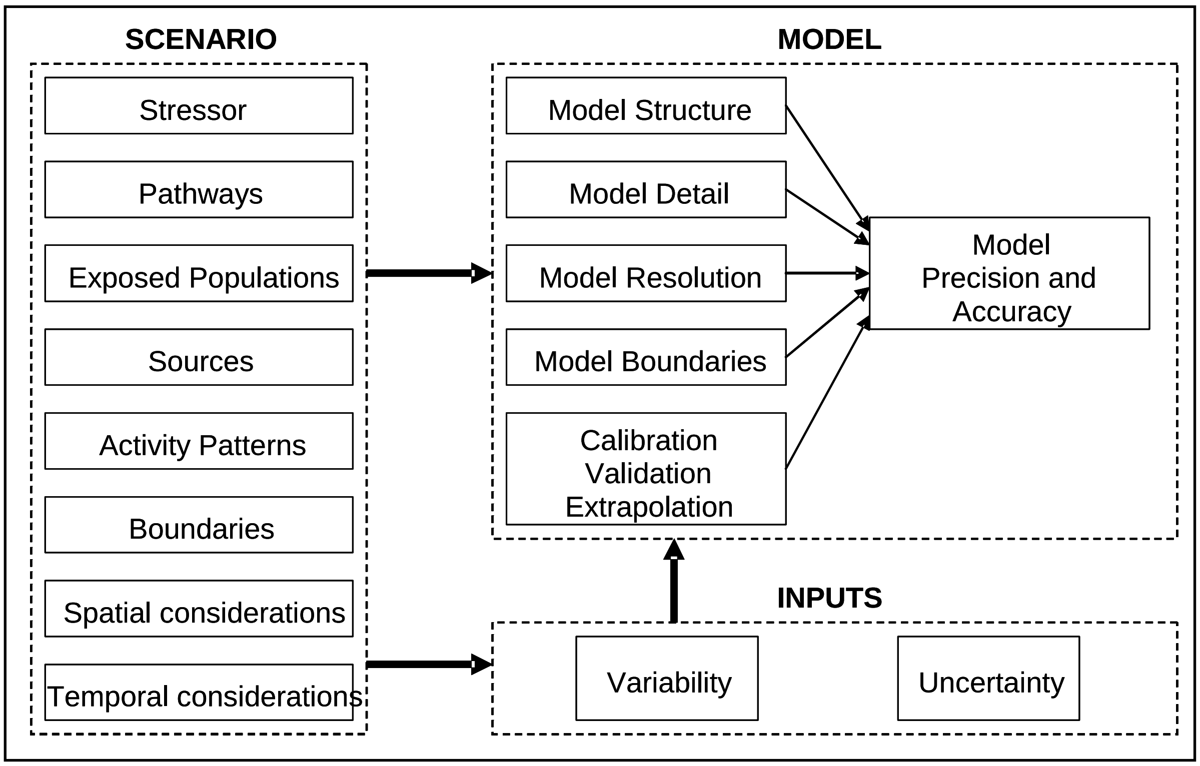

Figure 2. Sources of variability and uncertainty in ecosystem restoration.

Scenarios are the stories told to explain ecosystem restoration benefits. In planning they include without- and with-project conditions, historic conditions, and perhaps preferred or ideal conditions. Think of the element boxes in Figure 2 as identifying plot lines and main characters in these stories. They give structure to the nature of the problems, the plan effects and the resulting benefits. These scenarios in turn define the kinds of models needed to estimate ecosystem restoration benefits. They also identify the data inputs needed to run those models. This quantity uncertainty is discussed in some detail below.

The structure of the model includes things like the type of model and its functional form. Models can contain varying levels of detail; more realism in a model may or may not improve the model's ability to support good decision making. Temporal, spatial, and other resolution issues can often affect model outputs significantly. The model's boundaries will assure the extent to which the model depicts the desired scenarios. Calibrating and validating models can often be a challenge when data are inadequate for traditional means of doing so. The potential cumulative effects of these sources of model uncertainty in the model's outputs are easy to envision from this figure. As a matter of practice model uncertainty has not received the attention it deserves. Models are rarely considered explicitly as a potential type of uncertainty in ecosystem restoration benefit estimation.

QUANTITY UNCERTAINTY: Quantity uncertainty is frequently encountered in models used to estimate the benefits of ecological restoration projects. Morgan and Henrion (1990) offer a very useful taxonomy for those seeking to understand the basic types of uncertainty in models. Yoe (1996) describes knowledge, quantity, and model uncertainty for environmental investments. This section follows Morgan and Henrion's work.

Planning requires a lot of information that is frequently gathered, organized, summarized, analyzed, and expressed in a quantitative manner. If there are 167 acres of emerging wetlands and there are six eagle nests, then the wood duck's habitat suitability index is 0.6. The cost of a duck box is $320. The discount rate is 6.25%. The study area is Cyber's Ranch. The quantities used in the planning process are frequently a major source of uncertainty. Having a way to think and talk about uncertainty is critical to the success of any uncertainty analysis.

Table 1 presents Morgan and Henrion's (1990) classification of quantity uncertainty sources along with some examples and methods for dealing with the specific type of quantity uncertainty. An important distinction should be made about the nature of these quantities. Only the empirical quantities have an objectively "true" or exact value. The other quantities have subjective values. Hence, it is most appropriate to say that the only uncertain quantities are the empirical quantities. For all other quantities, it is the analyst that is uncertain, not the quantity itself. This technical note assumes there can be significant uncertainty about the best or preferred value for these other quantities. The significance of this distinction becomes germane when one chooses a tool, technique, or methodology to treat the uncertainty appropriately.

Table 1
Types of Quantities Encountered in the Planning Framework

Quantity	Example	Treatment
Empirical quantities	Birth rate, mortality rate, basal area of hardwoods, Manning's n	Probabilistic, parametric variation
Defined constant	Speed of light, gallons per acre-foot, number of square feet in an acre	Look it up
Decision variable	Design characteristics of decision alternatives such as planting densities or beach replenishment rates	Parametric variation
Value parameter	Discount rate, value of life, weights in a multi-attribute value function	Parametric variation
Index variable	References to locations or time steps in a model	Certain by definition
Model domain parameter	Study area boundaries, planning horizon, base year	Parametric variation
Outcome criterion	National economic development benefits, benefit cost ratio, habitat units	Depends on treatment of inputs

Empirical quantities. Empirical quantities may be the most common quantities encountered in a planning study. These are exact values that are unknown to the analyst. Where these quantities are measurable in principle, measurement may be difficult in practice. Examples of empirical quantities at a restoration site might include the basal area of hardwoods, the density of nesting birds, the birth rate of alligators, or the number of seeds produced by a flower. Although there may be many uncertain empirical quantities in a planning study, it is often sufficient to consider only those quantities with the greatest uncertainty importance (discussed below).

Defined constants. Defined constants are fixed, nevertheless they may not be known to the analyst. For example, there are 43,560 ft^2 in 1 acre and 325,851 gal of water in 1 acre-foot. These constants have well known values that can be found by consulting references.

Decision variables. Decision variables are quantities over which the planning team exerts direct control. Examples include the density at which marsh grass would be planted under a particular revegetation plan, the amount of sand that would be delivered annually under a beach replenishment plan, or the volume of water that would be diverted each month to nourish and maintain wetlands. In general, these are the characteristics that differentiate decision alternatives (plans) from one another. While a planner may be uncertain about what rate of beach replenishment would actually stabilize the beach, the replenishment rate is a chosen characteristic of the proposed alternative; thus, it is certain.

Value parameters. These parameters describe the values or preferences of stakeholders, the planning team, or decision makers. Examples include the rate of time preference for money (i.e., discount rate) or the weights used in a multicriteria decision analysis. Planners may be uncertain about decision makers' preferences and the value these parameters should take in a decision model, but these parameters have no true value in nature.

Index variables. Index variables identify elements within a model, such as a location within the model's spatial and temporal domain. For example, a point in time can be referenced as a time step and a grid cell can be referenced using spatial coordinates. Index variables are integral parts of a model and are not considered to be uncertain variables.

Model domain parameters. These parameters describe the geographic and temporal boundaries (domain) of a model and the resolution of its inputs and outputs. These scale characteristics are chosen by the modeler and have no true value in nature. They reflect judgment regarding the model domain and resolution needed to estimate ecological restoration benefits given the processes described in the model. Not all representations of physical or ecological processes can be easily ported across scales or resolution, and considerable effort may be required to alter model domain parameters. Uncertainty about domain parameters may also be considered a form of model uncertainty. The sensitivity of model output to the choice of model domain parameters can be evaluated by treating the models as alternative model forms.

Outcome criteria. Outcome criteria, also termed metrics, are variables used to rank or measure the desirability of possible outcomes. Examples include national economic development benefits and net present value. When evaluating the benefits of proposed ecological restoration projects, outcome criteria might be expressed in ecological, physical, chemical, or social terms. Examples include habitat suitability index scores, bank migration rates, nutrient concentrations, and stakeholder desirability. Uncertainty in the output of a model is evaluated by propagating uncertainty from the input variables to the output variables using one of several different methods. If model uncertainty is considered, characterizations of uncertainty in the outputs of different models can also be compared and evaluated.

An illustration. There are often large uncertainties in the outputs of ecological models such as the HSI models used in a Habitat Evaluation Procedure. These uncertainties can be large relative to the ecological effects of a proposed project. If so, outcome criteria under the “with-” and “without-” project conditions may not be statistically different from each other. Figure 3 illustrates such a hypothetical situation. Panel (a) illustrates uncertainty in modeled ecological outcomes (which might be measured in thousands of habitat units on the x-axis) under a “with-” and “without-” project condition. The restoration project shifts the uncertainty in the ecological outcome to the right, indicating an overall improvement in ecological condition. However, there is so much uncertainty in these ecological outcomes that they are not statistically different from one another. The difference in expected outcomes under the distribution Δ is small relative to the uncertainty in HUs. Panel (b) illustrates uncertainty in the ecological benefit of the proposed restoration project. The ecological benefit is the difference between outcomes under with- and without-project conditions. This example demonstrates that uncertainty analysis can yield a probability distribution on the benefit measure Δ. The benefits are uncertain, but results show non-negative benefits of the restoration effort and enable decision makers to evaluate the probability that ecological restoration benefits will exceed some amount.

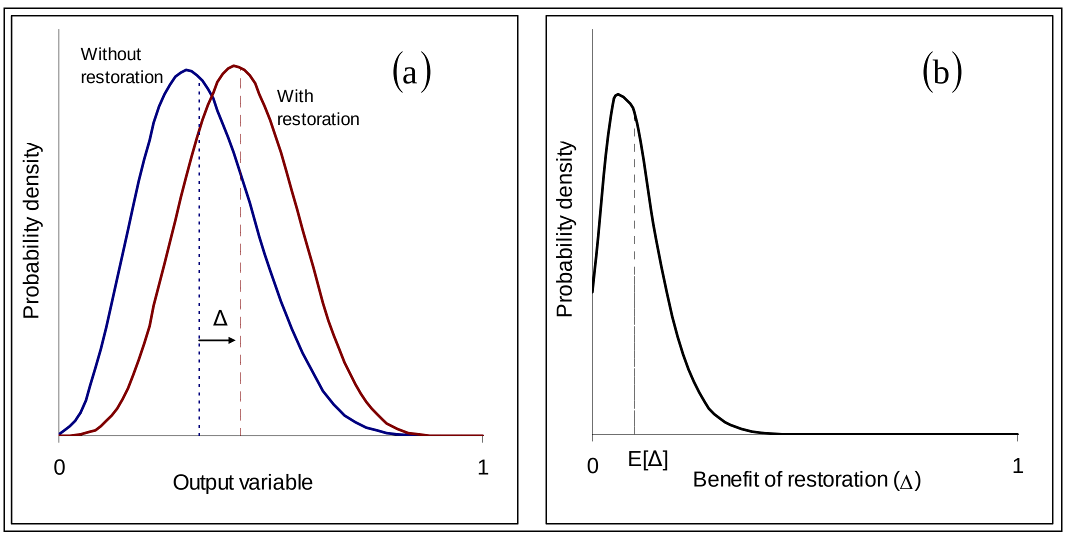

Figure 3. Uncertainty in the benefit measure can be derived from uncertainty in model inputs and outputs. Panel (a) illustrates uncertainty in modeled ecological outcomes under a “with-” and “without-” project condition. Panel (b) illustrates uncertainty in the ecological benefit of the proposed restoration project.

WHEN IS UNCERTAINTY ANALYSIS REQUIRED? In best practice planning for ecosystem restoration, it is always appropriate to examine the effects of uncertainty on decisions. The extent of the uncertainty analysis will depend on the amount of uncertainty encountered as well as the consequences of a wrong decision. Figure 4 illustrates considerations in determining the need for uncertainty analysis.

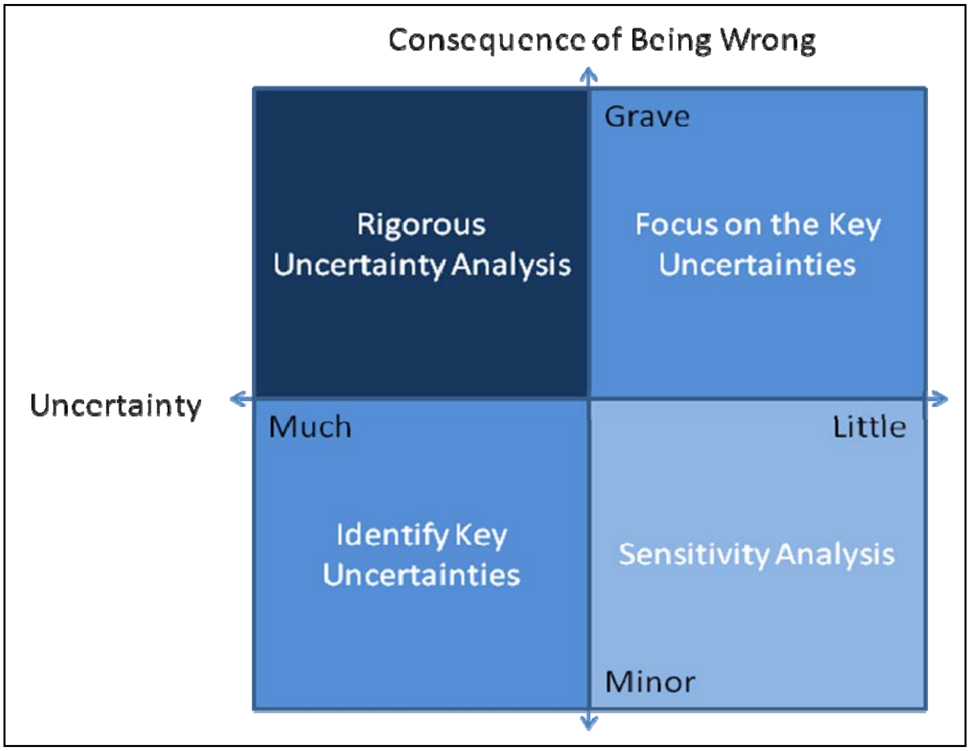

Figure 4. When to perform uncertainty analysis.

The most rigorous uncertainty analysis is required when the uncertainty is extensive and the consequences of making a wrong decision are serious. When there is little uncertainty and the consequences of a wrong decision are minor, it is still desirable to conduct a sensitivity analysis that describes the range of consequences, if only to verify the minor consequences.

In the intermediate instances when there is much uncertainty in an analysis but the consequences of being wrong are not as serious, it is advisable to identify the key uncertainties and address them. When the uncertainties are fewer in number but have more serious consequences, it is important to focus on them to examine their consequences for decision making.

It is always appropriate to perform uncertainty analysis for ecosystem restoration projects. The relevant questions are how extensive or rigorous does the analysis have to be and what techniques and methodologies are available for each situation. The next section identifies some conceptual approaches to uncertainty analysis as well as some of the techniques and methodologies available to the analyst that are suitable for uncertainty analysis.

UNCERTAINTY ANALYSIS TOOLBOX: The appropriate techniques for uncertainty analysis in a planning investigation depend on both the type of uncertainty (epistemic, aleatory, scenario, model, quantity) and the cause of the uncertainty. It may be convenient to think of aleatory uncertainty as out there in the world, these are the true values, the exact values we seek. This is contrasted by epistemic uncertainty, which can be thought of as inherent in the analyst; it is the analyst's uncertain knowledge. Different tools are appropriate for the various kinds of uncertainty.

Aleatory uncertainty of empirical quantities is perhaps the most common uncertainty addressed in estimating ecosystem restoration benefits. To consider this uncertainty, it is convenient to follow the work of Morgan and Henrion on the basic causes of uncertainty in empirical quantities (Morgan and Henrion 1990; Yoe 1996). Probabilistic methods are used for the first three causes but other tools like parametric variation (intentionally choosing different specific values for an uncertain value) are more appropriate for other causes. These causes are:

- Random error and statistical variation.
- Randomness and unpredictability.
- Variability.
- Systematic error and subjective judgment.
- Linguistic imprecision.
- Disagreement.
- Approximation.

Framework. An anecdotal review of selected Corps reports indicates that "uncertainty analysis" rarely consists of more than a brief paragraph or two discussing the topic in general and nonspecific ways rather than the actual uncertainty present in the analysis. The best way to begin to address uncertainty in a systematic and transparent manner is to begin simply. The simple steps below provide a skeletal framework for any uncertainty analysis. Analysts should:

- Acknowledge the existence of uncertainty.
- Recognize the things that are uncertain (e.g., inputs, assumptions).
- Identify the specific uncertainties of concern or significance.
- Describe the nature and extent of the uncertainty.
- Qualify or quantify the importance of uncertainty for decision making.
- Communicate the extent and significance of uncertainty to decision makers.
- Document the uncertainty analysis.

Toolbox.

Narratives. Approaches to uncertainty analysis can be divided broadly into qualitative and quantitative techniques. The most basic way to address uncertainty is via a narrative. This qualitative technique is simply telling the story of the key uncertainties and their significance to the decision outcomes. This is the absolute bare minimum effort to address uncertainty.

Although very simple and qualitative, the importance of this technique should not be overlooked as an important starting point for uncertainty analysis. In fact, an effective narrative needs to accompany every uncertainty analysis. Not everyone will need to understand the details of the uncertainty analysis, but all stakeholders and decision makers need to know the significance of uncertainty to the estimation of ecosystem restoration benefits and decision making.

Sensitivity analysis. The most common analytical technique used to explore the significance of uncertainty is sensitivity analysis. It can be either qualitative or quantitative. Some project outcomes and decisions are sensitive to minor changes in assumptions and input values. Thorough, rational decision making requires an explicit examination of such sensitivities. It is not always immediately obvious which assumptions and uncertainties may affect outputs, conclusions, and decisions most. The purpose of sensitivity analysis is to systematically make this determination.

Sensitivity analysis is a systematic investigation of model parameters, model inputs, assumptions, and model functional forms. The cornerstones of sensitivity analysis include challenging (and changing) assumptions, along with parametric variation of input variable/parameter values to examine these effects on project outputs.

Sensitivity analysis is used to increase confidence in the models and their predictions. It provides understanding of how model outputs respond to changes in inputs (i.e., the data used), model structures, and other factors.

Some sensitivity analysis tools include:

- Assumption variation.
- Deterministic one-at-a-time analysis of each factor.
- Deterministic joint analysis.
- Subjective estimates of significant threshold values.
- Parametric analysis (using a range of values).
- Probabilistic analysis to support importance analysis.

Scenario planning. Scenario planning (Ralston and Wilson 2006) is an appropriate response when there are relatively few but relatively important epistemic uncertainties and the consequences of being wrong are great. Scenarios are narrative descriptions of markedly different plausible alternative futures. Scenario planning allows planners to consider a range of without- or with-project conditions, each of which is dramatically different from the other and from the current operating environment. Rather than rely on a single “most likely” forecast, planners can compare and contrast alternative opinions on how the future may evolve (e.g., IPCC climate change scenarios).

Scenario analysis. Scenario analysis is a term often used to describe a varied bundle of tools used in risk and uncertainty analyses. Scenarios are the stories we tell about problems, plans, and their effects. The Corps relies on without- and with-condition scenario analysis in its planning work and other scenarios are often considered. Deterministic scenario analysis examines specific scenarios used to explore the range of effects uncertainty can have on decision criteria. Some common deterministic scenarios include a worst case, best case, most likely, locally preferred, nonstructural, and no action scenarios.

Probabilistic scenario analysis is one of the most common and powerful quantitative responses to empirical quantity uncertainty. Because of the presence of variability and uncertainty in so many ecosystem restoration studies there are often an infinite number of possible future scenarios. It is not possible to describe them all, but some of them may be important to the decision process.

Probability is the language of variability and uncertainty and it can be incorporated into scenario analysis using such techniques as the Monte Carlo process, interval analysis, fuzzy set theory, possibility theory, evidence theory (Dempster-Shafer), and imprecise probability theory. Most of these theories are in an early stage of development relative to classical probability theory (i.e., Monte Carlo processes and Bayesian estimation).

Uncertain quantities can be represented as random variables. Random variables can be described using frequency distributions, statistical variances, confidence intervals, and probability distributions. Point estimates of values in a model may be replaced with one of these representations of uncertainty and then a technique such as Monte Carlo simulation is used to propagate the uncertainty of the outcomes of interest through multiple calculations of the model. Figure 5 illustrates three ways of describing uncertainty in a random variable.

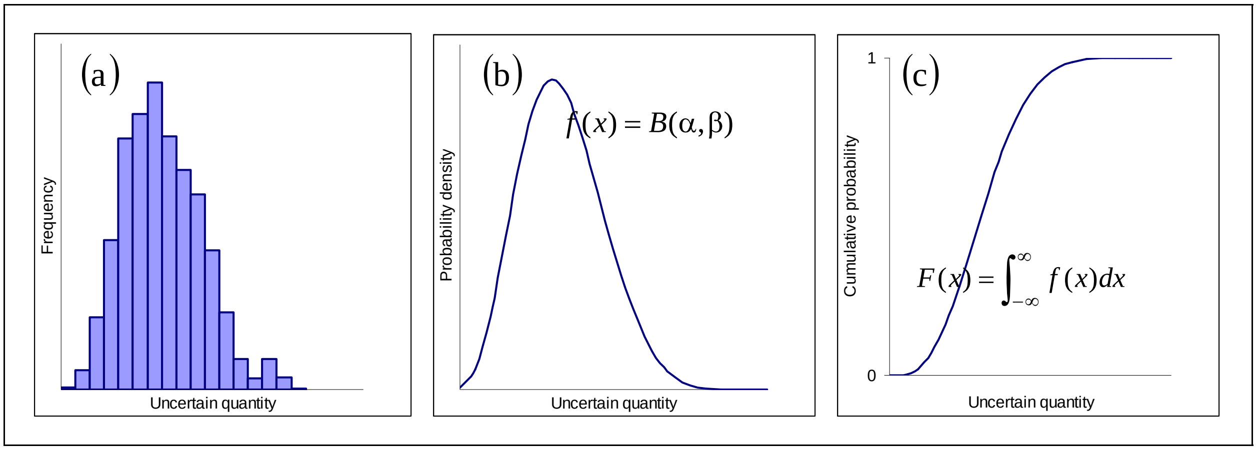

Figure 5. Three ways to describe uncertainty in a random variable. Panel (a) presents a histogram (often used to model empirical data), Panel (b) presents a probability density function (PDF), and Panel (c) presents a cumulative distribution function.

Adaptive management. Uncertainty analysis gives rise to the development of adaptive management strategies. Adaptive management recognizes at the beginning that uncertainty is inherent in any natural system and seeks to minimize this uncertainty by learning about the system being managed and reducing epistemic uncertainties that are recognized at the time the action is taken. In the adaptive management process, one chooses an action, monitors the effects of the action, and adjusts the action based on the monitoring results (Satterstrom et al. 2005).

Premise sets. Premise sets were used by the Corps to address significant uncertainties encountered in the aftermath of the Mount Saint Helens eruption. Analysts identify the range of possible outcomes as well the assumptions and other things one must believe for each outcome to be realized. Decision makers then identify their view of the uncertain future by choosing from these sets of premises and their consequences; analysts prepare the set decision-makers consider most likely.

IWR plan. The IWR Planning Suite is decision support software developed by and for the Corps' ecosystem restoration planning efforts (Robinson et al. 1995; Rogers et al. 2006). Although originally developed to assist plan formulation by combining user-defined solutions to planning problems and calculating the effects of each combination (or "plan"), it now includes enhancements for addressing uncertainty. These are most nearly described as probabilistic scenario analysis of the cost-effectiveness of the various plans and incremental cost analyses.

Other techniques. Several other techniques can be used to address uncertainty. Uncertainty rankings can be used to rank benefit estimates from the least to most uncertain. Confidence rankings enable analysts to express their degree of confidence about analyses. Qualitative scales, defined by the analyst, such as very certain, reasonably certain, moderately certain, moderately uncertain, and very uncertain can be used to place the analysis in a context for decision makers to consider.

The minimax regret criteria approach (Yoe 1992) is designed to aid decision making under uncertainty that estimates the opportunity cost (regret) associated with each possible course of action. The decision-maker selects the activity that minimizes the maximum regret, or loss. Regret is measured as the difference between the best and worst possible payoff for each option.

WHAT CAN BE DONE WITH RESULTS? The ultimate purpose of uncertainty analysis is to improve the quality of ecosystem restoration project decisions. This in essence means managing the risks associated with natural systems, natural hazards, and decision making under uncertain conditions. The goal of risk management is to improve the capacity for decision participants to understand and then make decisions in consideration of natural system variability and analytical uncertainty, so as to increase the likelihood that the intended gains will be realized. Risk management, then, can be thought of as planning, analyzing, organizing, implementing, and monitoring efforts to control the effects of risk, both pure and speculative, on the Corps' Civil Works Program. An effectively conducted and communicated uncertainty analysis is an essential component of good risk management.

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> Yoe, C. E., K. Burks-Copes, M. T. Schultz, and B. C. Suedel. 2009. *Addressing risk and uncertainty in ecological restoration projects*. EMRRP Technical Notes Collection. ERDC TN EMRRP-ER-13. Vicksburg, MS: U.S. Army Engineer Research and Development Center. *http://el.erdc.usace.army.mil/emrrp/emrrp.html*

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