AN INTRODUCTION TO RISK AND UNCERTAINTY IN THE EVALUATION OF ENVIRONMENTAL INVESTMENTS

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Evaluation of Environmental Investments Research Program

IWR Report 96-R-8
March 1996

PREFACE

This report was conducted as part of the Evaluation of Environmental Investments Research Program (EEIRP). The EEIRP is sponsored by Headquarters, U.S. Army Corps of Engineers (HQUSACE). It is jointly assigned to the U.S. Army Engineer Water Resources Support Center (WRSC), Institute for Water Resources (IWR), and the U.S. Army Engineer Waterways Experiment Station (WES), Environmental lab (EL). Mr. William J. Hansen of IWR is the Program Manager, and Mr. H. Roger Hamilton is the WES Manager. Program Monitors during this study were Mr. John W. Bellinger and Mr. K. Brad Fowler, HQUSACE. The field review group members that provide complete program direction and their District or Division affiliations are Mr. David Carney, New Orleans District; Mr. Larry Kilgo, Lower Mississippi Valley Division; Mr. Richard Gorton, Omaha District; Mr. Bruce D. Carlson, St. Paul District; Mr. Glendon L. Coffee, Mobile District; Ms. Susan E. Durden, Savannah District; Mr. Scott Miner, San Francisco District; Mr. Robert F. Scott, Fort Worth District; Mr. Clifford J. Kidd, Baltimore District; Mr. Edwin J. Woodruff, North Pacific Division; and Dr. Michael Passmore, Walla Walla District. The work was conducted under the Incorporating Risk and Uncertainty Into Environmental Evaluation Work Unit of the EEIRP. Mr. L. Leigh Skaggs of the Technical Analysis and Research Division (TARD), IWR and Mr. Richard Kasul of the Natural Resources Division (NRD), WES are the Principal Investigators.

The work was performed by The Greeley-Polhemus Group, Inc. (GPG) under Task Order No. 1, Contract No. DACW-72-95-D-0002, managed by Mr. Leigh Skaggs. Dr. Charles Yoe, a principal of GPG, was the principal author.

Valuable review comments and suggestions were received from Mr. Bob Bass, Galveston District; Mr. Bob Blama, Baltimore District; Mr. Bruce Carlson, St. Paul District; Ms. Pat Cory, Baltimore District; and Mr. Steve Garbarino, Baltimore District.

The report was prepared under the general supervision at IWR of Mr. Michael Krouse, Chief, TARD; and Mr. Kyle E. Schilling, Director, IWR; and at EL of Dr. Robert M. Engler, Chief, NRD and Dr. John W. Keeley, Director, EL.

EXECUTIVE SUMMARY

Incorporating risk and uncertainty analysis into environmental restoration planning studies is seen as a means of improving the quality of the decision-making process. This report introduces Corps personnel involved in the planning of environmental restoration projects to the basics of risk and uncertainty analysis. In addition, it presents a sample incorporation of risk analysis in the application of a habitat evaluation procedure, habitat suitability index model.

Environmental planning has been done by the Corps for a long time. The growing national interest in environmental issues has created a new emphasis on environmental values within the Corps' program. This new emphasis brings with it new initiatives. Environmental planning, at one level, is nothing more than the application of good planning techniques to environmental problems and opportunities. Although this report tends to focus on environmental restoration projects, the principles, tools and methods discussed throughout are equally applicable to any environmental planning activity.

Environmental planning is future-oriented problem solving and decision-making intended to restore, preserve, protect and enhance environmental resources or to mitigate unavoidable damages to them. As such, it is fundamentally decision-making under uncertainty. Incorporating risk and uncertainty analysis into environmental planning, wherever it is done in the organization, can improve both the planning process and the quality of decisions made to manage the nation's environmental resources.

Risk analysis is practiced by analysts from many disciplines. As a result, there is not a single broadly accepted taxonomy of terms. The terminology used by Corps analysts in environmental restoration is introduced in a simple manner. For example, risk is defined intuitively as the chance that something bad happens.

Risk and uncertainty analysis is easier to introduce to new applications when there is a structured and logical approach to the process. There are three broad types of uncertainty: knowledge uncertainty, model uncertainty and quantity uncertainty. Quantity uncertainty is the most commonly encountered. Understanding the nature of the uncertain quantity can go a long way toward prescribing a treatment for the uncertainty. Of all quantities, empirical quantity uncertainty can be the most complex to address, because there are at least seven different causes for these types of uncertainty. The taxonomy offered in this report provides the new risk analyst with a way to think about the uncertainty that is present in environmental planning work.

The time may come when risk and uncertainty protocols for environmental restoration studies are described in detail in Corps' guidance and the models and tools needed to conduct these analyses are well known to all. That day has not yet arrived and so the report presents a list of selected tools and broad concepts used by many risk analysts in Chapter Four. Described in the report are the basic concepts of which environmental planning risk analysts should be aware, including: acknowledging uncertainty, education and training, EPA's ecological risk assessment paradigm, full documentation, jargon and literature, peer review, post facto evaluation, publicity, risk communication, and software. These tend to address information/communication issues. The more specific tools described include: analytical solutions, decision criteria, decision trees and influence diagrams, expert opinion, probability, probability distributions, random sampling, sensitivity analysis, simulations, specialty models, and statistics.

Just as there are broad concepts that can be used in risk and uncertainty analysis there are "big picture" issues of uncertainty encountered in environmental planning studies. These issues are not unique to environmental planning. In fact, they are more indigenous to the planning process than they are to the environment. Uncertainties are encountered in each step of the planning process and they can become cumulative if not addressed, virtually assuring that decision-makers labor in ignorance of potentially important issues. Nonetheless, the uniqueness and complexity of environmental plans suggests that the uncertainties inherent in the planning process may become particularly acute in environmental planning. These generic sources of uncertainty are discussed on a planning step-by-planning-step basis in Chapter Five, where knowledge and use of the Principles and Guidelines six-step planning process is suggested as a means of reducing uncertainty.

In addition to the big picture uncertainties, there are many uncertainties specific to environmental planning. Four major sources of uncertainty include: project performance, extrapolation, models and the habitat evaluation procedures. Common potential sources of uncertainty include: delineation of the study area; identification of target species; the construction of habitat suitability index models; habitat variable measurements; calculation of existing and future habitat units; and modeling project performance in the habitat evaluation procedure.

An example introducing risk-based analysis to the estimation of habitat unit changes is offered to demonstrate the feasibility of some of the methods presented in the report. A simple example is presented in Chapter Six illustrating how risk-based analysis can be used to address some of the uncertainty inherent in the habitat evaluation procedures analysis that is so common to environmental restoration projects. Selected results from this analysis are presented to demonstrate the types of outputs that can be obtained from a risk-based analysis.

The example shows it is easy to use spreadsheet-based Monte Carlo/Latin Hypercube simulation to introduce risk analysis into the estimation of habitat suitability indices and habitat units by simply varying key data inputs. The results of some habitat suitability index computations are found to be extremely sensitive to the habitat suitability index model's structure. In addition, the example suggests that risk-based analysis could be come a valuable formulation tool insofar as it helps analysts understand the relative importance of the uncertain variables. The simple example establishes the feasibility of using a risk-based approach to habitat unit estimation with no significant increase in study costs or schedule and confirms its potential as a tool that can help improve the quality of environmental restoration planning decisions.

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CHAPTER ONE: INTRODUCTION

INTRODUCTION

The U.S. Army Corps of Engineers' Civil Works program has historically evolved and changed to meet the changing needs and priorities of the Nation. Two relatively recent changes in the Corps' program are of particular interest in this report. They are the increased emphasis on environmental outputs of existing and new projects and the increasing use of risk and uncertainty analysis in the Corps' decision-making processes.

The trends toward greater emphasis on environmental outputs and more use of risk and uncertainty analysis began at different times and for different reasons. Now, as environmental activities are routinely undertaken by planning, operations, engineering and construction divisions throughout all Corps districts and risk and uncertainty analyses have reached a level of maturity and acceptance, there is a confluence of these two trends.

The national interest in risk and uncertainty analysis had its genesis in the analysis of environmental risk analysis in the late 1960s. The National Environmental Policy Act of 1969 (NEPA) is generally credited with beginning the interest in risk and uncertainty analysis. It stands to reason therefore, that now that the Corps' involvement in environmental activities is reaching a critical mass, the Corps should begin to introduce techniques of risk and uncertainty analysis into its decision process in order to improve the quality of decisions.

Introducing risk and uncertainty analysis to the Corps' environmental activities is a new initiative. It will require personnel to learn a few new tricks. But the introduction of risk and uncertainty analysis to this area of endeavor will not impose new significant burdens on analysts or managers. It may be as simple a matter as using all the information you have, rather than some of it. It may involve playing a few "what if" games during the decision process. Over time, as the value of risk and uncertainty analysis is proven in the decision process, it may prove helpful to develop specific tools or adopt more sophisticated analytical techniques.

This report explores the potential for introducing risk and uncertainty analysis into environmental planning activities in much the same way the *Guidelines for Risk and Uncertainty Analysis in Water Resources Planning*, IWR Report 92-R-1 (Principles) and 92-R-2 (Example) did for water resources planning generally. It begins with the simplest, least effort and most effective ways to improve the quality of decision-making in the Corps' growing environmental planning activities. Those who learn to use risk and uncertainty analysis well, and early, will reap the benefits of improved decision-making through the better informed development of more robust plans.

THE PURPOSE OF THIS REPORT

The purpose of this report is to introduce Corps planners and other interested parties to the concepts of risk and uncertainty that already are or may soon become useful in improving the quality of decisions made in the formulation and evaluation of environmental investments. The reasons for doing this now are straightforward: I) risk and uncertainty analysis contributes to better decision- making; ii) the Corps is already making extensive and effective use of these techniques in other programs; iii) there is growing public demand for environmental risk analysis; and, iv) there is a reasonable likelihood that risk analysis will become a legislative requirement in the not-too-distant future. The objectives of this report are simple. First, it explains what is meant by environmental planning. Second, it provides a brief introduction to the "concept" of risk and uncertainty analysis. Third, it provides an introduction to some of the basic tools and methods of risk and uncertainty analysis. Fourth, it integrates the concepts of environmental planning and risk and uncertainty analysis through a generic identification of potential sources of risk and uncertainty in the Water Resources Council's six-step planning process used by the Corps. Finally, it introduces some potential tools and methods that can be used specifically to do risk and uncertainty analysis in environmental planning, with particular emphasis on the habitat evaluation procedure (HEP). It is not a procedures manual nor does it prescribe a specific approach for any situation. It is hoped that the introduction to the concepts, tools, and methods of risk and uncertainty analysis will stimulate creativity in their application that will ultimately lead to formal analytical approaches and tools.

INTENDED AUDIENCE

The basic audience for this report is "Corps planners." This includes personnel assigned to planning divisions and others as well. Environmental activities are being conducted in various locations throughout the Corps' organization. Planning divisions conduct Section 1135 and other planning studies. Operations personnel are looking for beneficial uses for dredged material and conducting their regulatory work. Environmentalists can be found throughout the organization doing analyses for various elements of the Corps' program. All of these people are making decisions that affect the environment and the future. As such, they are doing planning, though they may not recognize or consider what they do as "planning". It is to the people who do this kind of work, regardless of the division, section or branch to which they are assigned, that this report is targeted.

ORGANIZATION OF THE REPORT

The report is organized to achieve the above objectives. In the next two chapters, the basic concepts of environmental planning and risk and uncertainty analysis are presented. This is done to develop the scope of this report and to introduce some of the basic terminology it uses. The chapter on environmental planning indicates that this is not really so new, although the increasing emphasis on environmental restoration may be. The risk and uncertainty chapter defines basic terminology, discusses the reasons for doing risk and uncertainty analysis in more detail, and offers a taxonomy of uncertainty that may help the reader, new to this area, to think about uncertainty in their domain of expertise.

The fourth chapter presents an introductory overview to a number of broad concepts and specific tools that can be used to address the sources of risk and uncertainty identified in subsequent chapters. The next two chapters integrate environmental planning and risk and uncertainty analysis. Chapter 5 presents higher order sources of uncertainty in environmental planning. They are called "higher order" because they are, to a great extent, generic sources of uncertainty that might be found in any planning activities. They are illustrated and presented with an environmental flavor in the context of the Corps' six-step planning process. Chapter 6 presents some sources of risk and uncertainty that are specific to environmental planning activities and a sample application to the use of a habitat suitability index (HSI) model in a HEP analysis. The report concludes with a summary and some recommendations about which sources of risk and uncertainty can be addressed first in order to begin to incorporate risk and uncertainty analysis into environmental planning activities.

CHAPTER TWO: ENVIRONMENTAL PLANNING

OVERVIEW

This Chapter defines environmental planning, focussing on restoration as the environmental investment of primary interest in this report. Despite its focus, all the principles, tools and methods discussed in this report apply to virtually all types of environmental planning.

PLANNING

Planning is defined in different ways by different people. It was defined recently in the Corps' *Draft Planning Manual*[1] as "the deliberate social or organizational activity of developing an optimal strategy for solving problems and achieving a desired set of goals." Thus, planning is goal-oriented problem solving. Defined in this way, planning is an activity that is not confined to the Corps' planning offices. Personnel in operations, engineering and construction are doing planning. These may be different kinds of planning activities, granted, but they are planning activities nonetheless.

The general approach to planning will vary with the people doing it and the purposes for which it is done. In some cases, there will be a structured, formal approach to planning as there is in traditional planning studies. In other cases, the problem solving is more gut-level intuition or ad hoc in nature. In order to be able to discuss planning we need a common understanding of what we mean. Though there are many models, the one used here is the six-step planning process defined by the U.S. Water Resource Council's *Economic and Environmental Principles and Guidelines for Water and Related Land Resources Implementation Studies*, commonly called the "P&G".

The six planning steps are summarized in Figure 1. Though such a formal framework may not be used in all the environmental planning activities that are undertaken by the Corps, they easily could be. It is safe to assume that all the activities should at least have the fundamental elements of identifying problems, formulating alternative solutions and identifying the best solution from among the possibilities. Thus, planning as used in this report implies a more or less formal process comprising the six steps.

Figure 1: Corps Six-Step Planning Process

1. Identify problems & opportunities
2. Inventory & forecast resources
3. Formulate alternative plans
4. Evaluate plan effects
5. Compare effects of alternative plans
6. Select plan

ENVIRONMENTAL PLANNING

Environmental planning is differentiated from the more traditional types of planning the Corps has done, e.g., flood damage reduction and navigation, only by the specific goals to be achieved and the problems to be

[1] The report is circulating in draft form as IWR Report 95-R-15, December 1995.

solved. Though some consider environmental planning new, it is not. In fact, it is decades old. What is new is the emphasis it is receiving and the ways in which it is evolving. It might be more accurate to say that increasing national interest in and importance of environmental values is receiving new emphasis in the water resources planning process, rather than to suggest that "environmental planning" is something new.

New Emphasis on an Old Objective

The roots of the Corps' tradition of environmental planning can be found in a long list of authorization acts, environmental laws and executive orders. Examples of the Corps' new emphasis on environmental planning are evident in a number of places. These include the Chief of Engineers' February 1990 memorandum on "Strategic Direction for Environmental Engineering" and the Assistant Secretary of the Army's June 1990 "Statement on Environmental Approaches". Policy Guidance Letters 24 (March 1991) and 35 (March 1992) followed up on the earlier policy pronouncements.

New emphasis has come through legislation as well. The Water Resources Development Act (WRDA) of 1986 in Section 1135 instructed the Corps to consider how existing projects might be altered to achieve environmental objectives. Section 1103 of this act authorized the Upper Mississippi Environmental Management Plan. Section 306 of WRDA of 1990 authorizes "environmental protection" as a mission for the Corps. Section 307 calls for a wetlands action plan with a goal of "no net loss" of wetlands. The Coastal Wetlands Planning, Protection and Restoration Act of 1990 (Public Law (PL) 101-646) authorized the Corps to cooperate with other agencies and the State of Louisiana to identify and construct wetlands projects. Section 204 of WRDA of 1992 encourages the Corps to find beneficial uses of dredged material. Specific actions like the 1992 commitment of the Corps to the Kissimmee River, Florida restoration project have also served to enhance the new environmental emphasis.

In broad terms, environmental planning could be considered to be the development of optimal strategies that preserve, protect, restore or enhance environmental resources and systems or that mitigate adverse impacts upon environmental resources and systems. Although the Corps does not have the authority to pursue all of these strategies, environmental planning within the Corps has been going on for some time.

What does environmental planning mean in the context of the Corps' program? Is it the fish and wildlife work the Corps has been authorized to do since 1958? Does it mean enhancing hunting and fishing opportunities? Does environmental planning mean the evaluation of environmental quality (EQ) effects of projects? Environmental impact assessment is nothing new. To some, environmental planning involves the work of the Corps' regulatory program. Clearly, finding beneficial uses for dredged material is an example of environmental planning coincident with long-time disposal responsibilities. Some Corps personnel suggest hazardous, toxic and radioactive waste issues encountered by the Corps require environmental planning. Others think of ecosystem or environmental restoration when they think of environmental planning.

In this report, environmental planning means all these things and more. Any Corps' activities that involve environmental resources and systems directly or indirectly can be considered part of environmental planning. Whether this work is conducted by Planning, Operations, or other offices, the work is essentially planning so long as it is involves developing optimal strategies for goal-oriented problem solving.

THE EEIRP

This report is being developed as part of the Evaluation of Environmental Investments Research Program (EEIRP). As such, it has a narrower focus than what we have described as environmental planning. The focus of the EEIRP, hence this report, is on the evaluation of environmental investments. In practical terms this has come to mean the evaluation of environmental restoration projects. This would include projects authorized by Section 1135 of the Water Resources Development Act (WRDA) of 1986 and Section 313 of WRDA'92 as well as those listed in the sidebar on the preceding page.

Although this report tends to focus more narrowly on environmental restoration projects, its contents are equally applicable to any area of environmental planning. For example, to the extent that the uncertainty associated with habitat evaluation analyses are of interest to the restoration of degraded ecosystem structure function and dynamic processes (the focus of this report) it will also be of interest for mitigation studies, environmental impact assessments, and any other endeavors that require habitat evaluations.

Environmental restoration projects are new and they are different. "Traditional" Corps planning is national economic development (NED) oriented, insofar as the primary objective is to maximize net NED benefits. Environmental restoration is a prime example of "non-traditional" planning, i.e., planning that is not driven by the NED objective.[2] Absent the traditional metric of NED benefits and costs, it is necessary to develop new ways to evaluate the impacts of certain kinds of projects. One of the purposes of the EEIRP is to develop some of these evaluation methods. The purpose of this report is to begin to consider the need for and ways in which risk and uncertainty analysis may be introduced to the evaluation of environmental infrastructure aimed primarily at restoring degraded ecosystems. The reason for taking this step is to improve the quality of decisions made in these planning efforts.

SUMMARY AND LOOK FORWARD

Environmental planning has been done by the Corps for a long time. The growing national interest in environmental issues has created a new emphasis on environmental values within the Corps' program. This new emphasis brings with it new initiatives. Environmental planning, at one level, is nothing more than the application of good planning techniques to environmental problems and opportunities. Although this report tends to focus on environmental restoration projects, the principles, tools and methods discussed throughout are equally applicable to any environmental planning activities.

As this chapter has provided an overview to the notion of environmental planning, so the next chapter does for risk and uncertainty analysis. It provides the reader with an introduction to the principle language and concepts of risk and uncertainty analysis that will be used in subsequent chapters when environmental planning and risk analysis are brought together.

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[2] These non-traditional planning efforts involve environmental infrastructure, the Corps' regulatory program, support for the military and others, master planning, regional analysis, drought preparation studies, planning assistance to the States, and other special studies and projects.

CHAPTER THREE: RISK AND UNCERTAINTY ANALYSIS

INTRODUCTION

This chapter provides the reader with an introduction to the language and concepts of risk and uncertainty analysis that are needed in order to introduce risk and uncertainty analysis in the evaluation of environmental investments. There are six main sections including this one. The section that follows is about words. It defines the most basic terms, considers some of the confusing terminology that has evolved around the concepts of risk analysis and the environment, and concludes with a return to the distinction between what is risky and what is uncertain.

The third section of this chapter presents a rationale for environmental planners' being concerned with risk and uncertainty analysis. The bulk of the remainder of the chapter comprises two sections that provide the reader with a taxonomy of uncertainty. One discusses the kinds of things that can be uncertain. The other discusses the sources of this uncertainty. Although this taxonomy is not unique to environmental planning, it is very valuable because it gives an expert, untrained in uncertainty analysis, a structured way in which to begin to think about uncertainty in his or her domain of expertise. The chapter concludes with a summary and a look forward to the next chapter.

TERMINOLOGY

BASIC TERMS

Uncertainty describes any situation in which we are not absolutely sure. Risk describes a situation in which there is a chance of something bad happening. Risk analysis is the analysis of risky situations. Risk analysis is broken into two parts: risk evaluation and risk management. Risk evaluation is the objective analysis of the situation that answers the question, "How risky is this situation?" Risk management then answers the question, "What shall we do about it?"

Risk and uncertainty analysis is not a section of a report that is added after the study is complete. It is not playing "what if" games with a critical variable or two in order to satisfy a requirement. Introducing risk and uncertainty analysis to environmental restoration planning means changing the way analysts approach the planning process. At its most basic level, it requires planners to recognize and admit there is really very little of which they are absolutely sure. This humbling admission can then lead planners to approach their goal-oriented problem solving tasks in a more informed fashion, because recognizing the limits of our expertise and knowledge is always one of wisdom's more difficult tasks. Never is this more the case than in addressing complex environmental systems.

THE SPECIALIZED TERMINOLOGY OF RISK AND UNCERTAINTY

The previous section offers some simple definitions of basic terms used in risk and uncertainty analysis. Despite that apparent simplicity, the language of risk and uncertainty analysis can be very confusing because there are many disciplines that make use of its tools and methods. Unfortunately, each specialty application has developed its own language. For example, what one group calls risk analysis another calls risk assessment. These discrepancies can't be cleared up here but the meaning of terms as used in this report can be clarified. If you read the risk and uncertainty literature, expect to encounter a rather confusing terminology that will not always match the simple definitions offered here. Following are overviews of the more common specialized terminology of risk and uncertainty analysis.

The insurance industry first coined the term risk management to describe the tools and methods employed by businesses to limit and control the economic risks they faced. Loss through accident, fire, disaster, and so on were among the first hazards businesses faced. In recent decades, the hazards to a firm's financial health have mutated to the legal, political, and financial realms as well. Risk management, in this context, is the identification, measurement, and treatment of exposures to potential accidental losses. Risk management is essential to the survival and profitability of a business. Risk management is generally not what we mean when we speak about risk and uncertainty analysis for the Corps of Engineers.

Environmental risk analysis (a.k.a., environmental risk assessment or environmental health risk) sounds exactly like what this report is talking about. It is not. The term "environmental risk analysis" has most commonly come to mean the assessment of toxic risk to a species. Most often, the toxic risk is exposure to some chemical, radioactive or other hazardous material and the species of most interest is, of course, humans. The U.S. Environmental Protection Agency (EPA) has developed principles of environmental risk analysis that include the following four steps.

First, hazard identification is the identification of the adverse effects a substance/agent can cause. Second, the dose-response assessment is the process of establishing or characterizing the relationship between the dose of an agent and the incidence of adverse health effects. The Corps uses this concept explicitly in the bioassays it conducts when identifying contaminants in dredged material. LD50, or lethal dose 50, is that level of contaminant (i.e., the dose) that kills 50% of the population (i.e., the response). It uses the concept implicitly in its expected annual damage computations for flood damage reduction studies. The dose is flood stage, the response is damage. Third, exposure assessment is the process of estimating the intensity, frequency, and duration of human or animal exposure to an agent in the environment. Fourth, risk characterization is the final step. It is the synthesis of the dose-response and exposure assessments, often presented in the form of a toxicity/exposure or T/E ratio. The purpose of this step is to estimate the incidence of health effects under various conditions of human or animal exposure described in the exposure assessment. Although the Corps makes both explicit and implicit use of these concepts, environmental risk analysis is, generally, not what we meant by risk and uncertainty analysis in this report.

Human health risk assessment is split into cancer risks and non-cancer risks. As environmental risk analysis has more and more come to be identified with risks to human health through exposure to chemicals and other agents in the environment, it has been necessary to develop new terminology. Ecological risk assessment is one of these terms. Rather than concentrating on the effects of a toxic substance on a single species, ecological risk assessments are concerned with the effect of stressors found in the environment that can affect single species, communities of species, and entire ecosystems.

The risk assessment paradigm under development for ecological risk assessment is essentially an adaptation of the four-step environmental risk analysis paradigm summarized above. Instead of a dose-response relationship, a stress-response assessment has been proposed. Ecosystems are subject to a much wider range of stresses including man-made and natural, chemical and non-chemical. Generally, ecosystem risk assessment is not what is meant by risk and uncertainty in the Corps' context. However, the paradigm under development holds considerable promise for use in analyses related to habitat loss, global climate change and other non-chemical ecological stresses. Once basic acceptance of risk and uncertainty concepts has been established, adaptation, if not adoption, of some or all of the ecological risk assessment paradigm under development may warrant serious consideration.

An early effort[3] at assessing the extent to which risk and uncertainty analysis is currently used by environmental planners indicated that Corps personnel have a rather limited view of what risk and uncertainty means. The predominant notion of risk analysis is that it applies when there is some danger of loss of human life or failure of a project. There is no apparent awareness of uncertainty analysis. Though loss of life and project failure are part of risk and uncertainty analysis, they are only a small part.

To distinguish the Corps' applications of risk and uncertainty analysis from those addressed above, the types of analyses of interest to the Corps will be called risk and uncertainty in water resources. Thus, we're speaking about risk and uncertainty analysis in a generic sense with specific applications of the general theory and tools to situations that involve water resources.

For the most part, Corps projects are concerned with a wide variety of nontoxic risks that are site-specific and are caused by such processes as dredging a navigation channel, construction of a dam, creation of wetlands, or natural disaster recovery efforts. The impacts tend to be systematic rather than incremental. That is, a single event - like the construction of a project, a flood, a volcanic eruption, an earthquake - produces widespread repercussions. These could include modification of the hydrologic cycle, alteration of natural hydraulics, or changes in fish and wildlife habitat; i.e., temporary or permanent changes in natural and human systems. The damages that result from these changes may be economic, environmental or safety related. Incremental effects are in some sense additive, like the build-up of toxins in the food chain or erosion of a streambank or island.

A paradigm is an example intended to demonstrate how something is to be done. It provides a pattern that can be followed by others. The EPA has devoted considerable effort to developing risk analysis paradigms. The four-step process described above is an example of a paradigm. The Corps does not rely on a single paradigm.

EC 1105-2-205, *Risk Analysis Framework for Evaluation of Hydrology/Hydraulics and Economics in Flood Damage Reduction Studies*, presents a paradigm for calculating expected annual damages. Risk-based models have been developed for use in major rehabilitation projects and dredging. Underlying all these risk-based models is a basic theoretical framework comprising the three steps shown in Figure 2. In each, the hazard (flooding, component failure, uncertain quantities) are identified. The probability of the hazard causing a problem is quantified and the consequence of the problem caused by the hazard is quantified and modeled.

[3] "Compilation and Review of Completed Restoration and Mitigation Studies in Developing an Evaluation Framework for Environmental Resources, Volumes I and II", IWR Reports 95-R-4 and 95-R-5, April 1995.

Figure 2: Elements of Risk Analysis

- Hazard identification
- Probability estimation
- Consequence modeling

The EPA health risk paradigm can be adapted for use by the Corps. Flooding is a hazard that is readily amenable to the hazard, dose-response, exposure, and risk characterization model. Contaminant analysis of dredged material requires no adaptation. There are easily imagined potential uses for an ecological risk assessment paradigm. But the Corps' work will never be reduced to a single or even a few risk and uncertainty analysis paradigms. The work is too diverse and too unique in its hazards and their consequences to ever reduce to one or two established ways of approaching risk and uncertainty. Nonetheless, there are recurring and important situations that do lend themselves to the development of paradigms and models that could be used over and over throughout the organization. In time, some may be developed for the Corps' environmental investment work. This report is content to speculate about where these paradigms might arise and where they are never likely to occur.

RISK OR UNCERTAINTY

The simple definitions offered above may not be enough to help the new reader to distinguish between risk and uncertainty. It is less important that a situation is properly classified as risk or uncertainty then that uncertain situations that are important to the decision process are recognized and dealt with forthrightly and as effectively as possible throughout the planning process. Any situation in which the outcome or final result is not known with complete certainty is an uncertain one. This covers a lot of ground. We are certain c-a-t spells cat. We are certain of our names. We are certain the sun will rise again tomorrow, aren't we? We are sure we set our keys here a minute ago. We know it's going to rain tomorrow. When you get right down to it, there is relatively little in our lives that we can be certain about.

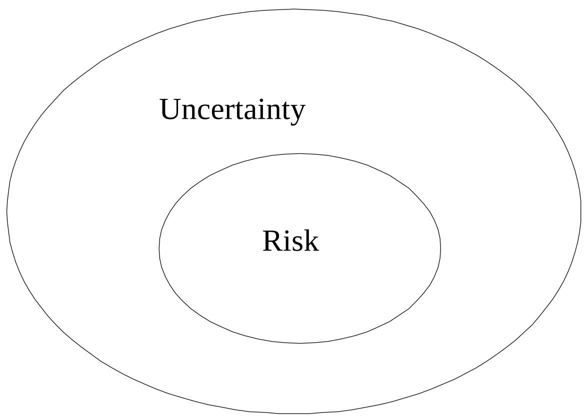
Not all the uncertainty we face is equally important. For all intents and purposes, we can ignore uncertainty about the sun's rising and setting. Though not absolutely certain, many things are effectively certain. Much of our scientific theory falls in this category of knowledge. Other things, like where our keys, glasses, umbrellas, and the like currently reside are rather trivial in the scheme of things and can be ignored.

Some uncertain things fall in between these extremes and they need to be addressed. You find yourself in a strange town at night, is it safe to walk in this neighborhood? You don't understand the question on a final exam. Do you drink the water in a foreign country? You have no idea where Faraway Street is.

It's the same in water resources planning generally and environmental restoration planning specifically. There are many things that are uncertain and many sources of uncertainty (topics covered later in this chapter). Not all are created equal. The first step in dealing with this uncertainty in a rational way is going to be to figure out what uncertainty is most important and what uncertainty can be ignored. The basic criteria for establishing that importance is to consider whether the uncertain variable could have a significant effect on the decision to be made. If it could, it's important. If it's important, you need to consider the uncertainty. Some tools and methods that can be used to address various uncertain situations are presented in the next chapter.

There is a class of uncertain situations that arise frequently enough to earn them the special designation of risky situations, as shown in Figure 3. Risk was defined above as the chance of something bad happening. The chance is often unknown as are the nature and extent of the "bad" thing that might happen. Risky situations are, then, characterized by uncertain likelihood of occurrence and uncertain consequences; clearly, a case of uncertainty.

Figure 3: Risk & Uncertainty Relationship



A few examples help illustrate these concepts. We may be uncertain about how an ecosystem functions; we may be uncertain about a habitat suitability index; we may not be comfortable extrapolating from the LD50 to the No Observed Adverse Effect Level (NOAEL) of a contaminant; and, we may be uncertain about the true output of a mitigation or restoration project. On the other hand, there is a risk of drought or flood and there is a risk that our project will not perform as expected. The differences can be subtle at times. How we label a decision problem is less important than that we entertain it. The terms, risk analysis, risk and uncertainty analysis, and uncertainty analysis are used as virtual synonyms in this report, less because there is no difference than because the difference is relatively unimportant.

One final note on jargon is necessary. Risk-based analysis is a term invented by the Corps that is essentially a synonym for risk and uncertainty analysis. Risk-based analysis is defined in EC 1105-2-205 as: "...an approach to evaluation and decision-making that explicitly, and to the extent practical, analytically incorporates considerations of risk and uncertainty."

WHY BOTHER WITH RISK AND UNCERTAINTY?

Each time risk and uncertainty analysis has been introduced to a new area of the Corps' program the reaction has always been the same. What is it? Is it just one more thing we have to do? Is it another way for people to keep us from doing what needs to be done. How do you do this? Who's going to do this? What's the point?

Four reasons are offered for Corps personnel, involved in environmental activities, to be concerned with risk and uncertainty analysis. First, planning requires decision-making under uncertainty, so it's just good planning. Second, risk and uncertainty analyses are already being used to improve decision- making in other parts of the Corps' program without difficulty. Third, there is a growing demand for it. Fourth, there is growing political interest in providing regulatory reform that focuses national resources on the greatest risks to human health, safety, and the environment. Any one of these reasons should be sufficient to encourage environmental resources planners and managers to use risk and uncertainty analysis. Taken together they form a rationale for beginning to incorporate risk and uncertainty analyses into the Corps environmental planning.

The first reason, that using risk and uncertainty analysis is just good planning, may be the most compelling. If planning is an attempt to control future consequences through present actions, an appropriate view of ecosystem restoration planning, it is obvious we are confronted with considerable uncertainty. We don't fully understand how complex ecosystems function. We have to work without all the data we'd like to have. We're not sure how our alternatives will perform and often don't know exactly what they will cost to build. There is also considerable uncertainty over how alternatives can best be evaluated.

Faced with these and other sources of uncertainty it would be unprofessional and irresponsible not to admit and face the uncertainty with which we are confronted. Given the reality of uncertainty, it only makes sense to deal with it in a rational and systematic way. This requires the application of the tools and methods of risk and uncertainty analysis. When a problem exists, it makes sense to recognize it and deal with it. That is simply good planning. Good planning leads to good plans and good decisions.

The second reason for using risk and uncertainty analysis is that it is already being successfully used by the Corps. Risk and uncertainty are nothing new. Applying these concepts to environmental planning may be new, but it's nothing more than the logical extension of good analysis to a new subject area. Risk analysis began with the dam safety program more than a decade ago. Flood damage reduction studies are required to use a risk-based analysis to evaluate hydrology/hydraulics and economics (see EC 1105-2-205). Major rehabilitation of locks and dams has been relying on risk-based analysis for years and the tools and methods in use have grown increasingly sophisticated. Dredging decisions are now assisted by risk-based analytical tools. Dredged material disposal programs that use the *Evaluation of Dredged Material Proposed for Ocean Disposal - Testing Manual*, 1991, also known as the "Green Book", have been applying risk-based analytical techniques for years. Risk and uncertainty analyses have been used for channel width determinations for navigation projects. Pilot studies have been conducted to explore the use of risk and uncertainty tools and methods in determining budgeting priorities of operation and maintenance budgets. These techniques are examples of some of the applications that have been used to improve the quality of decision-making within the Corps of Engineers.

Since the inception of the Corps' Risk Analysis Research Program at the Institute for Water Resources (IWR), there has been a snowball effect on the application of risk and uncertainty analysis methods to water resources planning. Now that the feasibility and value of these methods have been proven, efforts to spread them to new applications within the Corps program continue. Incorporating risk and uncertainty analysis into environmental investment programs is just part of the natural evolution of improving decision-making processes. It just makes sense.

The third reason is that there is a growing demand for risk-based analysis. Growing public awareness of environmental issues and of risks in general has raised public expectations of the quality of environmental risk analysis. Informed public debate has resulted in an unwillingness of public officials and the public to leave the discussion of environmental risks to the so-called experts. "Suppose," the non-Federal partner to a marsh creation project asks, "we put up our money and the project doesn't work, will it be redone? Who pays for that?"

This growing demand for risk analysis leads directly to a fourth argument for incorporating risk and uncertainty into environmental project planning; the current Administration and Congress have begun to move in the direction of requiring it. Any teenager recognizes the compelling nature of the "because I said so" rationale for doing something. There is a good chance that that may soon become a compelling reason for Corps personnel to conduct risk and uncertainty analysis.

On August 2, 1994 the Clinton Administration published its "Draft Administration Risk Assessment Principles". A review of these principles for the Chief of Engineers by IWR said in part:

> "Without any reservations, the principles are sound and are virtually the same as those that the Corps has been promoting in its various planning functions..."[4]

In addition to these principles, numerous bills were recently introduced in Congress to further the cause of risk and uncertainty analysis. Two examples were House Resolution (H.R.) 1022 the "Risk Assessment and Cost-Benefit Act of 1995" and HR 690 the "Risk Assessment and Cost-Benefit Analysis Act of 1995."[5] Either would have mandated the conduct of risk analyses that would have affected the Corps of Engineers. By beginning to incorporate risk and uncertainty analysis into environmental planning now, planning and decision-making can be improved and Corps personnel will be that much further along the learning curve if and when risk analysis becomes a Federal requirement.

If your goal as a reader is to understand the basic notions of risk and uncertainty, stop here. The remainder of this chapter goes beyond that modest goal to offer a few ideas that might help the new reader to think about uncertainty in a systematic manner. It begins with a classification system or taxonomy of the types of things that can be uncertain. From there it proceeds to a taxonomy of the sources of uncertainty. Much of the material in the remainder of this chapter is taken from *Uncertainty, a Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis* by M. Granger Morgan and Max Henrion.

[4] Memorandum for Chief, CECW-AO/EINARSEN from CEWRC-IWR-P dated 16 Nov 94, Subject: Draft Administration "Principles for Risk Assessment, Management and Communication."

[5] Senate Bills 229 and 333 and House Resolution 96 are additional risk analysis items before the 104th Congress.

TYPES OF UNCERTAINTY

How can we break the "uncertain" world down into just a few components so we can think rationally about them? What kinds of things are uncertain? Planners can think of uncertainty[6] as coming in three classes: uncertainty in knowledge; uncertainty about quantities; and uncertainty about models. Quarrel with this if you will, it's a purely arbitrary way to break things down. It does, however, provide a way to think about uncertainty encountered in environmental restoration planning. By thinking about the knowledge required to approach a problem, the data needed to analyze it and the models used in the analysis, one has a structured way to begin to think about the uncertainty inherent in any situation.

In the sub-sections that follow each of these three classifications are addressed. The discussion turns to the sources of uncertainty in the next section.

KNOWLEDGE UNCERTAINTY

Some things are uncertain for the most basic of reasons - we just don't know. That lack of knowledge can arise from two different sources. You may not know the capital of Belgium. That is an uncertainty that arises from ignorance. The information is known (Brussels), but not by you. The cure is relatively obvious, obtain the knowledge. This can be done through education, training, talking to experts, or acquiring experts through hiring, contract or coordination.

In other cases, some things are unknown at this point in time but they may become known in the future. The problem may be incomplete theory; we might simply lack a framework for thinking about or understanding a situation. Even when the theory is complete a lack of data may limit our understanding of a situation. Examples of this kind of uncertainty include cures for various diseases; knowledge of ungaged stream flow regimes; and the performance of environmental projects. In time, cures may be discovered, flow data collected and many projects monitored. As this happens uncertainty is reduced. The solutions here are more research, more time, more inspiration and more perspiration.

There are other things that are fundamentally unknowable. These include the questions of the great philosophers like, "Can God make a rock so heavy He can't lift it?" and "What makes you so sure God is a He?" It includes many more serious value-based questions about what "should" be done and the "right" thing to do in various situations. It also includes things that are random and unpredictable, like the year in which the standard project flood will occur. Many of the risk situations fall into this category. There is no cure for this kind of uncertainty. Situations like these must often be represented with probabilities.

One of the most common sources of uncertainty is our limited knowledge. Sometimes it is caused by a lack of expertise, data, or understanding. Other times it's caused by the fundamental randomness of the universe. Whatever it's cause, it's a problem that may need to be addressed.

[6] Here and in the remainder of this chapter we use uncertainty in the inclusive sense that includes risky situations as well.

QUANTITY UNCERTAINTY

Planning requires information, lots of it. That information is frequently gathered, organized, summarized, analyzed and expressed in a quantitative fashion. There are 167 acres of emerging wetlands. There are six eagle nests. The herbaceous cover suitability index is 0.6. The cost of a duck box is $320. The quantities used in the planning process are frequently a major source of uncertainty.

Table 1 presents a classification of empirical quantities encountered in planning as well as some methods for dealing with the uncertainty that may be found in them. Empirical quantities are measurable properties of the real world systems being analyzed and modeled. Each type of quantity is discussed briefly below.

Table 1: Types of Empirical Quantities Encountered in the Planning Framework

Type of Quantity	Example	Treatment of Uncertainty
Empirical quantities	Mortality rate, stream discharge	Probabilistic, parametric
Defined constant	Gallons per acre-foot	Certain by definition
Decision variable	Level of protection, mitigation goal	Parametric
Value parameter	Discount rate, value of life	Parametric
Index variable	Acreage, longitude & latitude	Certain by definition
Model domain parameter	Study area, planning horizon, base year	Parametric
Outcome criterion	BCR, incremental costs, habitat units	Depends on treatment of inputs

Empirical Quantities

Empirical quantities are the most common quantities encountered in a study. To be empirical, variables must be measurable in principle. Empirical quantities are the measurable properties of the resources and factors that need to be measured in the planning process. They include quantities such as population counts for significant species, water temperatures, stream flows, quantity estimates, the percent of unsubmerged substrate, the probability that a species will become locally extinct in the next ten years, average erosion or shoaling rates, roughness coefficients, contaminant loads, and so on. Empirical quantities need not be numerical. They can be nominal as well, like the lists of species present in a study area.

To illustrate the basic idea, suppose we're trying to estimate the resident population of white tail deer. There is a single true value for the white tail deer population at a given place and point in time. Whether we can actually determine that true value is another matter; we may have census data or only sample information. In either case there is a strong likelihood we do not know the true population with certainty.

Defined Constant

One type of quantity is always certain. These are defined constants. There will always be 43,560 square feet to an acre and there are 326,000 gallons of water in an acre-foot. These values are certain by definition and we never have to worry about their uncertainty.

Decision Variables

Decision variables are quantities the planning team exerts direct control over. They are sometimes called control variables or policy variables. There may be uncertainty about how densely to plant marsh grasses when trying to establish tidal wetlands or the best level of environmental mitigation. It makes no sense, however, to be uncertain about the "true" value of grass density or environmental mitigation because unlike empirical quantities, decision variables have no true values. Their values are selected by the planning team. Representing them as probabilistic variables detaches them from the decision process. It is better to vary decision variables systematically using sensitivity analysis, also known as parametric variation.

Value Parameters

Value parameters represent the preferences of the planning team or the people they represent - the general public, resource agencies, higher authority. The federal discount rate is an example of a value parameter. The choice of this uncertain variable has been decided for the Corps by Congress. At times, decision-makers assign weights to various project results to facilitate trade-off analysis. These weights may be explicit or implicit but they reflect the values of the decision-maker and should not be varied randomly.

It is not unusual for a value parameter to be treated as an empirical quantity and represented by a probability distribution. This, however, is usually a mistake, sometimes a serious one. Value parameters are value judgments. If the decision-maker is not sure what she prefers it is not helpful to leave the value judgment to chance. It is better to vary the values parametrically, i.e, first try one, then another. This allows the team to learn how changes in the parameter's value affect the outcomes in which they are interested.

People are often least sure about value parameters and they may contribute significantly to the uncertainty about the best alternative plan. If these quantities are treated as probabilistic it may mask the effect of the different value choices on the planning objectives. A systematic sensitivity analysis can be far more illuminating and can help decision-makers better understand and refine their preferences.

Index Variables

Index variables are used to identify and locate information in a model. For example, the base year, project year 10, grid cell 230, 90°50' longitude and 30°42' latitude, are all index variables. There is no reason to be uncertain about the value of an index variable. However, as long as humans are doing the work, human errors in measurement are always possible.

Model Domain Parameters

Model domain parameters specify the scope of the study. We identify the Potomac watershed as the study area and a 50-year planning horizon. Values like these define the extent of the study. The planning horizon delimits the temporal domain of the study, the study area delimits the spatial domain. Considering levee heights in two-foot increments and defined project increments in the incremental cost analysis are additional examples of model domain parameters.

There are no true model domain parameter values and it would be inappropriate to represent these model domain parameters with probability distributions. The choice of the domain values is up to the planning team.

Outcome Criteria

The outcome criteria are the variables we use to rank or measure the desirability of possible outcomes. The Corps has traditionally used net National Economic Development (NED) benefits in its planning studies. Habitat suitability indices, habitat units and incremental costs are other outcome criteria in common usage for mitigation and restoration planning.

New decision criteria will evolve as this branch of planning develops. These outcome criteria will be deterministic if there is no uncertainty in the inputs used to develop them and there is an unambiguous analytical method to develop the criteria. However, if the inputs are uncertain or there are no analytical methods for estimating the criteria, the outcome criteria will be uncertain. For example, if the habitat suitability index is uncertain and the acreage is certain, habitat units will be an uncertain outcome criteria because it is the product of an uncertain variable times a certain constant.

MODEL UNCERTAINTY

Models are simplifications of reality used in order to understand or represent complex situations and systems. Models can be physical or mathematical, the latter being far more common. The ideal model is a simple one that closely replicates the functioning of a system. Model uncertainty is a type of uncertainty that can be more important than knowledge or quantity uncertainty in some cases.

The issue with model uncertainty is closely related to knowledge uncertainty in that it poses the question, "are we thinking about this system correctly?" In other words, do the models used truly represent what is going on with the phenomena of interest? Model uncertainty includes the limits of our knowledge and theory as well as the specific forms of the models we use to represent complex relationships.

Many kinds of model uncertainty can be envisioned in a HEP analysis. There will be considerable uncertainty about the choice of target species. There is some question about whether the life requisites are truly understood. The methods by which suitability indices are combined to form a habitat suitability index are open to vigorous debate. The major appeal of the process may be more its acceptance than its accuracy.

It is not difficult to envision uncertainty about the values of the quantities that have to be entered into the HEP model. It is much more difficult to try to think about the uncertainty in the model itself. How much uncertainty is there in the form of the model? How well developed is the theory behind the HEP model? Are the assumptions underlying the model reasonable? Unassailable? How much uncertainty is there in the validity of identifying an indicator species to represent the functioning of an ecosystem? How much uncertainty is there in tying the future viability of a species to a habitat suitability index? Are these even proper ways to think about the problems?

These kinds of uncertainties are far more difficult to think about and confront and they are often overlooked as matter of convenience if not fear of what a critical analysis would reveal about our favorite models. Uncertainty about model form frequently reflects a lack of theory or data, or perhaps a disagreement among experts about the underlying scientific or technical mechanisms at work in the system we are trying to model. Given the complexity and fledgling state of ecosystem restoration planning there would appear to be potential model uncertainty present in many environmental investment planning activities.

The biological and habitat models currently in use are major sources of uncertainty in the evaluation of environmental resources investment plans. Lack of theory and knowledge about how even simple ecosystems function is another common source of model uncertainty. The danger of model uncertainty often lies in the fact that it is not recognized. Once the model has been used and accepted there is little incentive for its users to ask critical questions about its fundamental "appropriateness".

Model Uncertainty In An HSI Model

It may be easier to understand the nature of model uncertainty with a brief example. Consider the U.S. Department of the Interior Fish and Wildlife Service's HSI model for the mottled duck. The preface describes the model as ". . . a hypothesis of species-habitat relationships, not a statement of proven cause and effect relationships." This is a clear admission of model uncertainty.

The model uses a variety of literature to identify eight specific habitat variables. Might there be nine or more? Are these the eight most important variables? These are all legitimate questions that point up the nature of model uncertainty. The suitability graphs linking the percentage of a habitat variable present and the suitability of such a percentage expressed as a zero (low) to one (high) index are linear or piecewise linear relationships. Many scientists would agree that few biological relationships can be accurately described by linear relationships. This is another potential source of model uncertainty.

Equations used to combine suitability indices for groupings of habitat variables into cover values involve forms like cube roots of three factor products and other presumably arguable weights of the relative importance of the various habitat variables. Likewise, the calculations of life requisite values and ultimately the HSI are all contestable formulations. These questions raised about the manner in which we think about the mottled duck are examples of potential sources of model uncertainty.

SOURCES OF UNCERTAINTY IN EMPIRICAL QUANTITIES

Empirical quantities are the most common source of quantity uncertainty in planning studies. What causes the uncertainty? It's not enough to identify the type of uncertainty; we need to know something about its cause so that the uncertainty can be addressed in an appropriate manner. Some common sources of uncertainty[7] in empirical quantities are shown in Table 2. Each is discussed in turn below.

Table 2: Sources of Uncertainty in Empirical Quantities
Random error and statistical variation
Systematic error and subjective judgment
Linguistic imprecision
Variability
Randomness and unpredictability
Disagreement
Approximation

Random Error and Statistical Variation

One of the best understood sources of uncertainty is the random error or statistical variation that arises from errors in the direct measurement of a quantity. Few measurements are exactly right. Our instruments are not properly calibrated, our powers of observation are imperfect, we are flawed human beings. Our tools and ourselves make mistakes. These are random errors. Examples of this type of uncertainty in environmental investment will include estimates of the extent of different ground covers, infiltration of water through soil types, or fish and wildlife counts.

In addition, there is statistical variation that results from random processes like sampling error. Suppose the average depth of water is estimated by measuring depths at randomly selected locations in a study area. Imagine the locations were selected by laying a grid over a map of the water body and each grid cell was uniquely numbered from 1 to 500. If 40 cells are randomly selected and the average depth is computed we would not expect the same average depth to be obtained if a different sample was taken. In fact, if we could take every conceivable combination of 40 cells from the population of 500 we would have a distribution of sample means. The mean of this distribution of sample means would be the true average water depth.

[7] Most of the discussion of quantity and model uncertainty as well as the discussion that follows are adapted from *Uncertainty A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis* by M. Granger Morgan and Max Henrion.

The problem is that when we take one sample and calculate one sample mean we do not know where in that theoretical distribution of sample means our estimate comes from. The "laws" of chance suggest our estimate will be reasonably close to the true mean when our sample is large, but there is always a "dumb luck" chance we'll have a sample mean quite different from the true mean. Knowing this potential for sample error exists, it must be dealt with. Inferential statistics provides well known methods for doing just that.

Subjective Judgments and Systematic Errors

Subjective judgments are common sources of systematic errors. So-called experts are frequently ignorant of their own biases in estimating or assessing quantitative measures. Experts are sometimes the last to recognize the limits of their experience and knowledge. Even when experts know their limitations, their opinions are often little more than educated guesses. Guesses are uncertain by their very nature.

Systematic errors arise due to biases in the measurement instrument or the individual taking the measurement. Attempts to estimate populations from animal excrement counts can lead to errors if the ratio of excrement to organisms is incorrect. Estimating values with inappropriate or poorly calibrated tools yields systematic errors. Systematic error is defined as the difference between the true value of the quantity being measured (the actual number of animals) and the value to which the mean of the measurements converge as more observations are collected (the estimated population based on our counting method).

Systematic errors can occur in any values that have to be physically measured with equipment that needs periodic calibration (e.g., hand-levels, the length of a person's pace, flow meters) or that are estimated by people unaware of their imprecision (e.g., habitat suitability indices). The solutions to these types of uncertainty are well-calibrated equipment in sufficient quantity for all analysts and rigorous training in data collection techniques. New analysts, contractors with minimally trained field personnel, and inflexible experts are common sources of such errors.

Linguistic Imprecision

Language is frequently an imprecise vehicle for communication. Filling a lake shoreline to "minus one foot" with dredge material sounds very precise until we consider that one agency uses mean low water, another mean sea level, and a third national geodetic vertical datum. Though everyone is hearing the same words, they are all thinking something quite different. Worse, they may be unaware of the uncertainty because they understand exactly what the words mean to them.

In many cases, a bit of clear thinking and precise language can clear up most uncertainty stemming from imprecise communication. Unfortunately, when a new jargon is developing, as it is with environmental investments, ecosystem restoration programs, and risk analysis, there is going to be considerable imprecision in the language and considerable uncertainty about its meaning. There is a great deal of variation in the way different people interpret words and phrases and their interpretation is very context-dependent.

Even words in common usage like ecosystems, resources, and functioning, have clouded meanings in new contexts. What is a functioning ecosystem? Would lumbermen give the same answers an Audubon Society spokesperson would when describing the functions of the forests of the Pacific Northwest? The linguistic imprecision that permits two people to give widely varying and honest definitions to the same terminology is a significant source of uncertainty. Fortunately, linguistic imprecision can be relatively easily avoided once its potential existence is recognized.

Variability

Many quantities vary from time-to-time or from place-to-place. The flow or a stream through a project area during one year is expected to be different from the flow in another year. The birth weight of deer in one area may differ from the birth weight in another area. Conceptually we might have a high degree of certainty about a frequency or probability distribution. However, if a single organism is randomly selected from that population it may differ from the mean because of the variability inherent in the population.

Environmental variables of interest might include size of fish, weight of deer, flow in a stream, salinity, temperature, tidal fluctuations, or other such variables. An element from one of these populations might be a fish, a deer, a peak annual flow, an average annual flow, a salinity or temperature reading, and so on. Anyone of these can be expected to differ from another because of the variability that exists within the population. Uncertainty due to variability can best be reduced by disaggregation.

Randomness and Unpredictability

Inherent randomness is often defined as uncertainty that is impossible to reduce. The practical issue for the analyst is, is the uncertainty reducible in practice? A quantity that is random to one person who does not understand the systems at work may be deterministic for another person who knows the underlying process that generated the quantity. The planner should try to distinguish uncertainty that can be reduced by further study from that which is inherently random, for the latter cannot be reduced. This source is clearly related to the type of uncertainty due to lack of knowledge.

Taking full advantage of the expertise present in the interdisciplinary study team can help reduce this type of uncertainty to the maximum practical extent. Uncertainty about the cost of constructing structures can often be reduced by more detailed estimating techniques. Uncertainty about the years in which future floods will occur cannot be reduced by any practical means and it is not worth trying to do so.

Disagreement

Different people can view the same problem from very different perspectives. Two experts can look at the same evidence and draw different conclusions. The levees have prevented millions of dollars in damages. The levees have destroyed thousands of acres of wetlands. Which side is right? When experts disagree about a quantity, a project's effect, an ecosystem's function, or any other critical factor, the nature of the disagreement should be carefully explained and evaluated.

Approximation

Models are simplifications of complex real systems. Tradeoffs between model complexity and computation costs dictate that most model results yield mere approximations of the actual values. The only reliable way to estimate the uncertainty introduced by the approximation is to increase the resolution of the model and measure the difference between the two models. In other words, approximation uncertainty can be difficult to ascertain. It is most often addressed by sensitivity analysis.

Average erosion rates based on comparison of aerial photos taken 25 years apart are approximations. Depending on the methods used many quantities can be approximations. For example, analysts who base their estimate of the percent of unsubmerged substrate on visual inspection are using approximations. Calculations of habitat units are an approximation. Project cost estimates are approximated early in the study process. How good are the approximations? The only way to tell is to compute the habitat units or costs with a better model. This is rarely possible. If a better model were available it would have been used.

Occasionally, the best models are not used because they are too expensive. A reconnaissance report may quantify project outputs in acres of wetland or acres of a restored island. The feasibility report may use a HEP analysis to better quantify the project outputs. In a case like this, the uncertainty due to approximation can be estimated in subsequent studies by using the more sophisticated HEP evaluation. Likewise, the uncertainty in cost estimates is eliminated as projects move to implementation.

SUMMARY AND LOOK FORWARD

Environmental planning is future-oriented problem solving and decision-making intended to restore, preserve, protect and enhance environmental resources or to mitigate unavoidable damages to them. As such, it is fundamentally decision-making under uncertainty. Incorporating risk and uncertainty analysis into environmental planning, wherever it is done in the organization, will improve both the planning process and the quality of decisions made to manage the nation's environmental resources.

Risk and uncertainty analysis is easier to introduce to new applications when there is a structured and logical approach to the process. There are three broad types of uncertainty: knowledge, model and quantity uncertainty. Quantity uncertainty is the most commonly encountered. Understanding the nature of the uncertain quantity can go a long way toward prescribing a treatment for the uncertainty. Of all quantities, empirical quantity uncertainty can be the most complex to deal with, because there are at least seven different causes for these types of uncertainty. The taxonomy offered in this chapter provides the new risk analyst with a way to think about the uncertainty that is present in environmental planning work.

Although the taxonomy offers a way for analysts to think about the uncertainty encountered in environmental planning it does not suggest specific methods for dealing with that uncertainty. That is done generically in the next chapter which introduces some of the concepts and tools used by risk analysts. Subsequent chapters will suggest specific applications of some of these tools to environmental planning situations, both generally (Chapter Five) and specifically (Chapter Six).

CHAPTER FOUR: POTENTIAL RISK AND UNCERTAINTY TOOLS

INTRODUCTION

Once important sources of risk and uncertainty are identified in environmental restoration studies, what can be done about them? Fortunately, there are a wide variety of tools and methods available for addressing risk and uncertainty. This section introduces a number of them. The chapter is divided into two major sections, following this introduction. The first section presents some broad concepts that can be used to introduce risk and uncertainty to environmental planning. The second section concentrates on more specific tools.

The concepts and tools presented in this chapter are general methods that can be applied by anyone, such as hydrologists, economists, environmental scientists, engineers, and others, who are part of an interdisciplinary team. There is a great deal of range and diversity in the uncertainty analysts will encounter in their work. There are also a large number of tools available for considering much of this uncertainty. This chapter presents some of the concepts and tools in common usage in order to give the reader a feel for the nature of what is available without imparting any detailed knowledge about their usage. This means at times there will be too much detail for some readers and not enough for others. Additional details on these techniques are readily available in the literature or form standard college-level courses. It is, perhaps, most appropriate to think of this chapter as a partial catalogue of tools that are available for future use and adaptation by the Corps of Engineers as it integrates the use of risk and uncertainty analysis into the environmental planning decision process.

BROAD CONCEPTS

Some of the most obvious places to start with risk and uncertainty analysis are, in retrospect, rather broad and obvious. The first step might be to acknowledge that uncertainty exists and then to begin to educate people about the need to do something about it. This education process will require communication, but communication about risky situations has some unique elements to it. Acknowledgment, education and risk communication are examples of some of the broad concepts described in this section of the report. These broad concepts are, perhaps, the types of things common sense would lead us to, given the luxury of time to think about the application of risk and uncertainty analysis to environmental planning. A number of these broad concepts are presented here to give the reader the benefit of the common sense thinking others involved in risk analysis have already done. The concepts are presented in alphabetical order. The order of significance will depend on the circumstances of each planning activity.

ACKNOWLEDGING UNCERTAINTY

The simplest place to start in incorporating risk and uncertainty analysis into environmental planning is to explicitly acknowledge the existence of uncertainty in the analysis. Far too often, precision is substituted for accuracy. Analysts, failing to recognize the assumptions and limitations of their data and models, often present results as if they are far more certain that they in fact are.

It may be far more honest to say the percent of unsubmerged substrate is estimated, with 95% confidence, to be between 26% and 34% than to say it is 30%. The latter value, though precise, is likely to imply an accuracy/certainty, that does not likely exist in reality. It is not a weakness to be uncertain, it is essential honesty in many cases. Acknowledging our uncertainty is the cornerstone of any risk and uncertainty analysis.

EDUCATION AND TRAINING

The first and most important tool for the risk and uncertainty toolbox is knowledge. Risk and uncertainty-based analysis uses selected methods and tools that may or may not be known to Corps analysts. You can't do water resources planning without knowledge of the hydrologic cycle and you can't do risk-based analysis without some knowledge of probability, statistics, and the emerging literature on risk and uncertainty.

People are not born knowing these things and if Corps analysts are going to be expected to apply these techniques they must first be taught them. The necessary knowledge can be obtained in a variety of ways. There is a vast and growing literature treating probability, statistics and risk and uncertainty analysis. *Incorporating Risk and Uncertainty into Environmental Evaluation: An Annotated Bibliography* (IWR Report 96-R-9 March 1996) provides an excellent introduction to some of this literature. These are topics that many people find difficult to pick up on their own, however.

The standard college-level introduction to statistics courses will provide the rudimentary knowledge of probability and statistics that is required. These courses frequently emphasize descriptive statistics, interval estimation, and hypothesis testing while glossing over or ignoring distribution fitting and other topics more useful to Corps risk analysts. Application-specific training such as the Corps currently provides in a number of areas, including a risk analysis course, may be the most effective means of providing Corps personnel with the requisite skills for conducting risk-based analyses. Once trained, Corps field personnel will be perfectly capable of applying the tools and techniques, extending their usage and finding new and innovative applications in the field of environmental planning. It's not reasonable to expect that each Corps analyst will develop knowledge and expertise in every aspect of risk and uncertainty analysis. The necessary expertise can frequently be acquired through other people. This can mean consultation with other Corps experts, interpersonnel agreements with agencies/organizations outside the Corps, or contracting for the services of a consultant. Regardless of the preferred method for acquiring the necessary knowledge, acquiring it is an essential step in dealing with risk and uncertainty analysis.

EPA'S ECOLOGICAL RISK ANALYSIS PARADIGM

At this writing there is not yet a final ecological risk paradigm. It is under development. Nonetheless, the development of this paradigm bears watching. The existing environmental risk assessment paradigm is already finding useful applications where the concern is the effect of toxic substances on one or more species. As noted earlier, the Corps dredged material disposal agreements with EPA make some use of that paradigm.

The appeal of the ecological risk assessment paradigm is that it will employ a stress-response concept. That is, substances or events that introduce stress to an ecosystem will be identified and the ecosystem's response to those stressors will be quantified. The reliance on stressors will make this paradigm much more amenable to the evaluation of Corps projects because changes in stream flow velocity, disruption of sediment budgets, and the many perturbations of the natural hydrologic cycle that can result from Corps projects do stress ecosystems. The ecosystems orientation is also more appealing than a single species approach.

It is suggested that Corps analysts keep abreast of what EPA is doing in this area. Both the Corps and EPA are struggling with many of the same issues of target species selection, extrapolation of analytical results, habitat loss and higher level systems like ecosystems and the global environment.

FULL DOCUMENTATION

Full documentation of the risk and uncertainty analyses is very important, particularly during the early stages when these techniques are first being applied. Describing the initial uncertainty, the steps taken to reduce it, and the uncertainty that remained are essential steps in a full documentation. Describing the hazards, probabilities and consequences of risky situations are equally important.

A complete documentation is important to the related tasks of risk communication and peer review. There are other reasons for documenting the analysis. Positive examples of how to document analysis are always welcome. Although many analyses are case specific there may be components of the analysis or results that can be used elsewhere.

A well-documented analysis aids the decision process. The report should not banish documentation of the risk and uncertainty analysis to a brief section at the end of the report. If the problems are uncertain or risky, the analysis should be presented when the problems are described. Descriptions of sampling results, subjectively estimated data and model elements, rationales for assumptions and leaps of faith, justifications of decisions and the like should be documented throughout the study report. In some cases it may be appropriate to summarize the results of more formal risk and uncertainty analyses, for example, simulations or sensitivity analyses that could affect the decision, in a separate section of the report. Careful documentation can be an effective tool for the internal and external two-way flows of information and feedback that are so essential to a successful project.

JARGON AND LITERATURE

Risk has been described as a subset of uncertainty. Risk analysis, however, is a term in general usage that includes the analysis of uncertain situations. Hence, we find the cumbersome situation in which the jargon is quite confusing. Risk is a subset of uncertainty, but risk analysis includes uncertainty analysis? The way the language is used, that is correct! Be forewarned, the language of risk and uncertainty can be uncertain. When the distinctions are important it is best to take the time needed to clarify meanings precisely. Fortunately, there will not likely be many situations in which the distinctions are that important.

There is a dichotomous nature to risk analysis that is important and that bears repeating. There are the technical/scientific aspects of risk and uncertainty and there are the policy issues of risk and uncertainty. Often these two worlds are not well-suited to mutual communication. The rational world of science is ill-prepared to address the irrational fears and emotions of humans. Decision-makers are often unable to absorb the real meaning of a technical analysis. Risk analysis is a process that includes the assessment and management of risk information for an individual, group, society or environment. It is the combination and, hopefully, the synthesis of these two tasks.

One part of a risk analysis is the technical or scientific part. This is presumably an objective assessment of the hazards, their probabilities and consequences handled by qualified experts. This is a detailed investigation performed to understand the nature of unwanted, negative consequences. It's an analytical process that provides information regarding undesirable events by quantifying, to the extent possible, their probabilities and their consequences.

Once risks have been objectively assessed the limits of science have been reached and now social and political values are required to decide what to do about the assessed risks. Risk management is the decision-making or management process used to protect human life, health, property or the environment from unwanted adverse consequences. The management step of the risk analysis expressly weighs ethical, social and political values.

The risk assessment may identify a 10% to 30% chance that beaver will become locally extinct in the next 20 years. The risk management must determine whether or not that is an acceptable risk. If it is not, it must decide what, if anything, to do about it.

There is not a well-defined discipline called risk and uncertainty analysis. Risk analysis comprises a set of tools and methods developed in and borrowed from a variety of disciplines. Nonetheless, this collection of tools and methods have enough common elements that risk analysis has evolved into a specialty subfield of many disciplines. Risk analysis has its own language, its own theory, and its own paradigms.

Corps personnel doing risk analysis need to understand some of the basic language of this subfield, because it is not always precise. Different authors and agencies use the same terms to convey different meanings. Analysts need to be familiar with terms like expected utility, acceptable risk, risk assessment, environmental risk, ecological risk, the EPA paradigm, expected values, partitioned risk, comparative risk analysis, risk-cost and benefit-risk trade-offs, risk communication and the like.

There is a great deal of existing and emerging literature on risk analysis. This report refers the reader to the following books as a good place to start.

1) Managerial Decisions Under Uncertainty: An Introduction to the Analysis of Decision-Making. By Bruce F. Baird. New York: John Wiley & Sons, 1989.

2) Making Hard Decisions: An Introduction to Decision Analysis. By Robert T. Clemen. Boston, MA: PWS-Kent Publishing Company, 1990.

3) Readings in Risk. Edited by Theodore S. Glockman and Michael Gough. Washington, D.C.: Resources for the Future, 1993.

4) Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis. By M. Granger Morgan and Max Henrion with a chapter by Mitchell Small. New York and Cambridge: Cambridge University Press, 1992.

5) Simulation and Modeling and Analysis. By Averil M. Law and W. David Kelton. New York, NY: McGraw-Hill, Inc., 1991.

6) "Reducing Risk: Setting Priorities and Strategies for Environmental Protection." By Science Advisory Board (A-101), SAB-EC-90-021. The Report of the Science Advisory Board: Relative Risk Reduction Strategies Committee to the U.S. Environmental Protection Agency. Washington, D.C.: USEPA, September 25, 1990.

Basic awareness of the jargon and developments in the risk and uncertainty literature is essential.

PEER REVIEW

An independent review of any risk analysis can be an effective check on the integrity and credibility of a risk analysis. Peer review of risk analyses is a central part of many of the risk analysis legislation initiatives now before Congress. Legislative requirements aside, whenever risk analysis is an important part of a project with potential outrage factors (see section on Risk Communication that follows) that could affect the viability and/or performance of a plan, peer review can be an effective tool. This will be particularly so for studies with international or significant intercultural effects.

Consider a recent example. It had been proposed that the channel catfish be introduced to New Zealand via fish farming, not in the wild. An environmental impact assessment considered the consequences of these fish escaping to the wild and concluded the risks would be tolerable. Public concern resulted in a peer review that disclosed documented cases of catfish escapes from farms to the wild. Its rapid spread to various habitats and the resulting damage through predation and competition with indigenous species were enough to halt the introduction of the species.

More points of view and fuller information are obvious benefits of a peer review. The environmental impact statement (EIS) review by the public has been designed to assure these benefits. Corps studies have always been subjected to a peer review of sorts in recent decades. That review has, traditionally, been an in-house review by other agency personnel. As the Corps' review process continues to evolve, independent peer review as appropriate may prove a valuable feature of controversial risk and uncertainty analyses, especially in environmental restoration projects.

POST FACTO EVALUATION

Environmental restoration projects are relatively new in concept. There is much that is not known about the environments' we seek to restore and the methods by which this might be best accomplished. Monitoring would ideally be part of every project design. There is a tremendous need for information about the results of these projects. Were objectives achieved? Can errors in project design be corrected to avoid catastrophe?

One of the most effective ways to reduce uncertainty is through information. Monitoring and observing the performance of projects after they are built and disseminating that information broadly is one of the most efficient uses of project funds that could conceivably be made. Monitoring might include visual inspection, mapping, bathymetry, aerial photographs, water quality monitoring, fish and other species monitoring, field inspection, GIS mapping, and other methods.

Lessons learned with environmental restoration projects will be worth their weight in gold. Newsletters, conferences, seminars, training programs, world wide web site home pages, mailing lists, bulletin boards, news groups, Internet relay chat (IRC), teleconferences, video cassettes, multi-media presentations, photo libraries, and repository libraries for restoration projects are but some of the means by which valuable information can be disseminated and uncertainty reduced.

PUBLICITY

Publicity can be an important tool in risk and uncertainty analysis. Take something as basic as the recent conditions at a project site as an example. A typical analysis most often involves either a literature search or a comparison of old aerial photographs to the current condition to determine what changes have been taking place. Publicity can be very helpful in uncovering the maximum possible information. There may be obscure local journals or publications with valuable information of which Corps personnel are unaware. Personal histories from long-time residents may be important sources of information. The mere act of publicizing the need for information about a place where many interested people live can provide valuable information.

In the case of risky situations, publicity can provide an opportunity for all sides to come out and be heard. Publicity can be provided through formal means like meetings, newsletters and the like or through informal means like talk radio appearances, conversations with historical societies, community groups and the like. Personal communications can be a very effective part of a publicity campaign to reduce uncertainty and deal with risk.

RISK COMMUNICATION

Communication is always a critical element in any planning activity. In its absence, lack of information and uncertainty is the default condition. Risk communication, however, refers to something more specific. It is communication about situations in which risk is important. That communication may be among team members, between Federal and non-Federal partners, between risk assessors and risk evaluators, communication with the media, or communication with the public. The planner needs to consider the four elements of the risk communication process:

- Objective(s): Why is the communication being undertaken?

- Content of the message: What information is to be conveyed in order to accomplish the objectives?

- Form of communication: How should the message be transmitted from the source to the receiver?

- Feedback from the audience: What is being received?

There has been much debate about what defines an acceptable risk. In fact, it may be that risk is not accepted or acceptable in the sense that it's consciously balanced against a perceived good as much as it is tolerated where necessary. Generally, people are risk adverse. Risks are perceived as intolerable when specific "outrage factors" are present. Risks tend to be less tolerable if they include the characteristics shown in Figure 4.

Figure 4: Outrage Factors

- Inadequate or unclear benefits
- Imposed rather than voluntary risks
- Outside personal control
- Unethical or unfair distribution of risk burden
- Managed by untrustworthy information sources
- Artificial rather than natural risks
- Insidious damages
- Unknown duration
- Unfamiliar
- Associated with memorable events

Environmental projects can be controversial and subject to strong emotional reactions. Environmental risks are subject to outrage factors. This makes risk communication all the more important. The Corps of Engineers is confronted with past projects, now taken out of their historical context by some interest groups and stakeholders. Even when a restoration project succeeds there will be some who feel the Corps has failed by not doing more.

It is important that the perceptions of these and other groups, particularly as they concern the risks of a project, be considered part of the planning process and not a problem to be overcome. For example, if some people are concerned that a species may become locally extinct, or that a project will fail to result in the habitat quality expected, these are not things that people should be talked out of, i.e. problems to overcome. They are legitimate concerns of the public that need to be adequately addressed in the investigation. The results of the analysis must, likewise, be effectively communicated. As a general rule, when discussing uncertain situations it's wise not to use untested communications. Take care when discussing risk in the public sphere.

SOFTWARE

Risk analysis software comes from four different sources. First, there is the commercial software developed for sale in the retail market. These include such things as @RISK and Crystal Ball. Second, there are special application proprietary tools and models developed privately or commercially for very specific applications. These include efforts like HEC's new risk-based expected annual damage estimating software. Third, there is shareware that is available free on the Internet and through other on-line sources. Fourth, there is the do-it-yourself software that are individual models, developed for specific studies, by individuals, that are not intended for multiple uses.

The first class of software tools has become quite large. They include Monte Carlo and Latin Hypercube simulation modeling techniques (e.g., @RISK, Crystal Ball, FuzziCalc, Predict!), analytical hierarchy process multi-criteria decision models (e.g., Expert Choice), decision tree and influence diagram packages (e.g., DPL, DATA), visual spreadsheets (e.g., DS Lab), neural networks (Neuralyst, Braincel), systems dynamics (e.g., Powersim, ithink, Optima, Logical Decisions, Stella), distribution fitting (e.g., BestFit), linear and nonlinear programming (e.g., What's Best!, Evolver, Lindo) and traditional statistics packages (e.g., SPSS for Windows, Statgraphics, eHOP). Two sources of information are industry catalogues produced for and by the makers of this software: "Analytical PowerTools",[8] and "SciTech Software for Science".[9]

The second type of software has been developed for specific applications but has found a limited niche market. At times this software has been developed for a government agency and its availability is subject to agency regulation. In other cases the developer maintained control of the software and it is available for sale. This occasionally includes adaptation for the buyer. This type of software is sometimes substantially more expensive than software available on the retail market.

Examples of this software include Systems Analysis Programs for Hands-On Integrated Reliability Evaluations (SAPHIRE5.12), a fault tree package originally developed for the U.S. Nuclear Regulatory Commission. Much of this software has been developed for the health and safety aspects of risk analysis.

There is shareware and free software available from the Internet. These are of varying quality. One example is the risk/exposure assessment model developed for the EPA by the University of Nebraska available from the World Wide Web (at: http://eeyore.lv-hrc.nevada.edu/therdbase.html) at no cost. There are numerous mailing lists and home page web sites detailing these opportunities. A great number of these are software for processing graphical belief functions, e.g., BAYES, BELIEF 1.2, IDEAL, + MacEvidence, + Pulcinella, + SPI, + tresBel, and XBaies.

The final category of risk software includes models developed for specific project evaluations. These are normally developed by individuals working for the Corps in order to meet the specific needs of a project. Currently, there is no systematic cataloging of these models. Creating a Corps news group or mailing list where

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[8] Available from Palisade Corporation at 1-800-432-7475.

[9] Available from SciTech International, Inc. at 312-486-9191.

such information can be exchanged would be a valuable early step in facilitating the spread of risk analysis throughout the Corps' environmental planning program.

One particularly useful source of information about software and other risk-related topics is a risk analysis mailing list maintained on the Internet by Batelle Corporation. The e-mail address for this mailing list is riskanal@bbs.pnl.gov. This mailing list can put any risk analyst in instant contact with hundreds or thousands of other risk analysts around the world.

SPECIFIC TOOLS

In addition to the broad concepts of the preceding section there are a great variety of specific tools used by risk analysts. A basic familiarity with the existence of these methods and tools can be an invaluable aid to an analyst grappling with the introduction of risk and uncertainty analysis to a new domain area. It is not necessary to be an expert in all or even any of these techniques, as that expertise can be acquired by training or contract. It is, however, important to have some awareness of the range of tools used by risk analysts. What follows is another alphabetized list of selected tools in common usage among risk analysts. Several of them will be used in the example in Chapter Six.

ANALYTICAL SOLUTIONS

Linear programming, integer programming, nonlinear programming, dynamic programming, calculus, algebra, and game theory are some tools frequently used to solve problems. These tools yield analytical solutions to problems. Analytical solutions are solutions that meet all the criteria of a problem specification. The analytical solution to $2 + x = 4$ is $x = 2$. Some problems have more than one analytical solution, for example, $2x + y = 10$ has both (2,6) and (0,10) among its solution set. In more complex problems we are often interested in the solution that optimizes a value. We may be interested in the analytical solution that makes net benefits as large as possible or stream velocity as small as possible.

Some complex systems can be formulated as models that can be solved analytically. The goal of most of those models is to determine an optimal solution through the use of algorithms. For example, linear programming problems can be solved analytically. Not all problems can be represented adequately by such models. Some systems are too complex and they defy analytical solutions.

Where analytical models represent reality, simulation simply imitates it. Simulation, discussed below, imitates the operation of a real world system over time. It is a numerical technique that can be used to estimate the analytical solution to a problem. Simulation is not an optimization technique. The answers obtained from simulations are not analytical solutions. Solve the equation $2 + x = 4$ a thousand times and the answer will always be the same, $x = 2$. Simulations, on the other hand could yield many different answers to a question.

Analytical solutions are preferred whenever they can be obtained so long as the models from which they are derived adequately represent the real world system being analyzed. Risk analysis is a new concept to many Corps analysts. The first exposure for many people is a Monte Carlo process such as is used for the estimation of expected annual damages for flood damage reduction studies. A limited exposure to risk analysis tools and methods leads some to believe that risk analysis is synonymous with simulation. It is not.

Even when risk and uncertainty is involved, there is often an analytical solution to a problem. Suppose you are a gambler and you face a game based on the toss of a fair coin. If it comes up heads you lose $20 and if it comes up tails you win $10. Is this a game you want to play?

We don't need a simulation or any other fancy tools and methods to answer this question. The expected value of this game's result can be calculated. It is 0.5(-$20) + 0.5($10) = -$5. On average you expect to lose $5 per game if you play. Clearly it is not worth playing.

Many risky or uncertain situations are far more complex than this simple example. The important point, however, is that some problems have solutions that can be determined through analytical solutions. "Analytical Solutions" is included here to assure that Corps personnel do not make the mistake of thinking that simulation and Monte Carlo processes are always the best approach to a problem. An analytical solution is always to be preferred when one is available. Unfortunately, they are not often available or they are too complex to solve. Another limitation of analytical solutions is that they often require simplifying assumptions in order to make them solvable. These simplifying assumptions can often limit the usefulness of the resulting analytical solution.

DECISION CRITERIA

Under uncertainty there might be several different estimates of a value of interest. For example, a sensitivity analysis could lead to three or more estimates of the number of habitat units (HU's) that would result from a project. If we elicit subjective probability estimates (see section on Expert Opinion) from three experts we can expect three different answers. What do you do when you have multiple estimates of an important value? How do you make a decision?

There are a number of well known decision criteria that can be used in decision-making under uncertainty. At this point the Corps has not taken a position on any of these criteria, so presumably the criterion that best suits the needs of the planning partners can be used. To facilitate the discussion assume three experts have identified the most likely, the minimum, and maximum number of white tail deer that would remain in the study area 50 years from now if no action is taken. These hypothetical estimates are presented in Table 3 and are used to illustrate the use of the selected criteria that follow.[10]

[10] For more information about these criteria see "Guidelines for Risk and Uncertainty Analysis in Water Resources Planning Volume I Principles with Technical Appendices, Appendix I", March 1992, IWR Report 92-R-1.

Table 3: Hypothetical Estimates of White Tail Deer Population			
	Expert 1	**Expert 2**	**Expert 3**
Minimum	0	50	30
Most Likely	21	75	300
Maximum	45	100	350

Laplace Criterion

The probability of Expert 1's outcome being realized is unknown, as is the probability of any other expert's outcome being realized. When the probabilities of the possible outcomes (i.e., the "partial probabilities") are not known, equal probabilities can be assigned to all the outcomes. The Laplace criterion assigns each of the outcomes an equal probability. With three estimates of the most likely population each outcome receives a weight of ⅓. The result of the Laplace criterion is an estimated population of ⅓(21) + ⅓(75) + ⅓(300) or 132 deer. This is a generally accepted default criterion.

Maximin Criterion

The maximin criterion yields the "best" of the worst potential outcomes. The worst outcomes are the minimum population estimates. The best of the worst outcomes is the one that has the largest minimum population estimate, in this case it is Expert 2's estimate of 50 deer. This emphasizes the worst case set of outcomes but takes an optimistic view of these outcomes.

Minimin Criterion

Under this criterion we choose the smallest of the minimum values. It is the most pessimistic estimate of all the population estimates offered here. The so-called "minimin" criterion is zero deer. This is the most severe criterion and may be favored when the worst case outcome is unacceptable.

Maximax Criterion

This is the opposite of the minimin criterion. It considers only the maximum population estimates and it uses the highest of these estimates. The maximax criteria yields a population estimate of 350 deer. This criterion is often preferred by those who want to stress the most optimistic outcome.

Minimax Criterion

The minimax criterion selects the estimate that is the lowest of all the maximum estimates. In this case, Expert 1's maximum estimate of 45 deer is the most pessimistic of all maximum population estimates.

Hurwicz Criterion

The maximin and maximax criteria are frequently used when alternative actions are compared. The maximin (best of the worst) and maximax (best of the best) criteria represent pessimistic and optimistic outcomes. The Hurwicz criterion represents a compromise between these two criteria. If we define a coefficient of optimism as α that ranges from 0 to 1, then $1-\alpha$ is a coefficient of pessimism. By weighting the maximum and minimum outcomes by the coefficients of optimism and pessimism, respectively, we can obtain results such as the following: Let $\alpha=0.7$ reflect a view that is more optimistic than pessimistic. The Hurwicz Criterion yields 0.3(50) + 0.7(350) = 260 deer.

Other Criteria

There are other criteria. The minimum, most likely, and maximum values can be combined with any weights that reflect the decision-makers belief in the likelihood of the respective outcomes. The dominance and regret criteria are two other common criteria found in the literature. There are additional criteria that are more complex.

The example presented here has been kept simple to make it easy to follow. The true appeal of these criteria gets lost in the simplicity of the example however. These criteria are most useful when we have multiple estimates of values for numerous alternatives. Imagine, if you will, a set of estimates of deer population for say eight alternative plans. In cases like this, these criteria become more useful decision criteria.

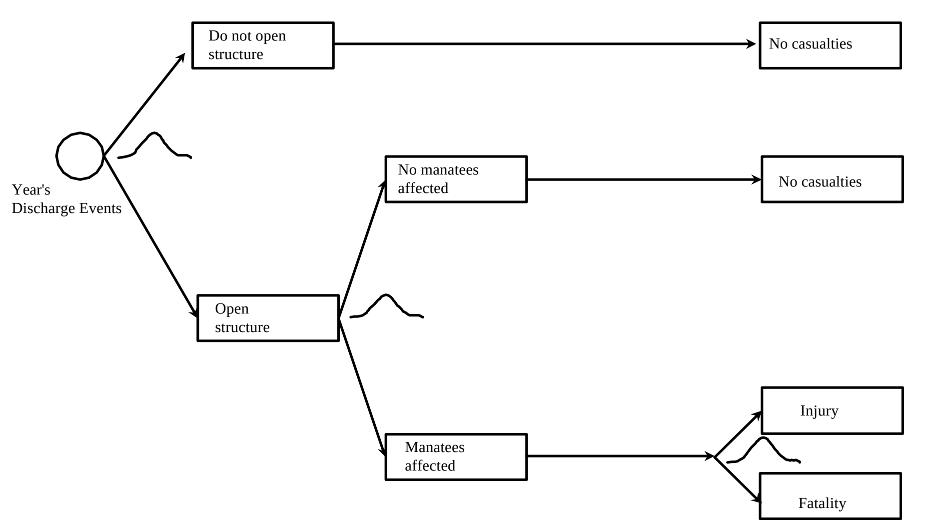
DECISION TREES AND INFLUENCE DIAGRAMS

There are many ways to represent a decision problem. Two of them are decision trees, sometimes called event trees, and influence diagrams. An event tree or decision tree is a modeling approach used to structure a decision problem. Construction of the tree helps to focus the analysts' attention on those elements of the decision problem that are most important. The completed event tree provides a blueprint for construction of the computer model needed to analyze the problem.

The event tree is not intended to capture every element of the decision problem. Its purpose is to capture the most important elements of the problem so they can be addressed in the analysis. Thus, the goal in developing a model is to make the analysis as simple as possible, but no simpler. Let's illustrate this with a simple example of an event tree for a gated spillway that when opened can cause manatees to be sucked through the gates under certain conditions. Suppose changes in the maximum allowable gate opening (MAGO) rules are being investigated.

Figure 5 shows the basic structure of the event tree used to model the situation. The analysis begins with a random discharge event that produces a head differential in excess of that which can be handled by the normal spillway opening. The "bell curves" indicate a chance event. If the gate is not opened there will be no manatee casualties. There may be flood damages but that is not the concern of this particular analysis. If the gate is opened there is some chance that manatees will be affected. If they are not there will be no

Figure 5: Sample Event Tree

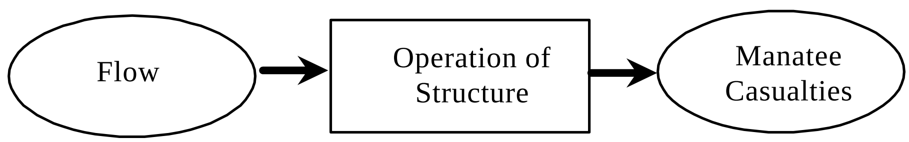


casualties. If they are affected there could be injuries or death to one or more animals. There is uncertainty associated with each branching in the event tree.

By assigning probability distributions to the uncertain values and constants to the known values a simulation model can be built to estimate the expected casualties or the probability of a casualty given the size of a discharge event. A similar model could be built for conditions with the new MAGO rules and if reductions in manatee casualties result these project outputs can be taken into account in the decision process. Decision/event trees can be a valuable tool for helping the analyst think through the major elements of a problem, even if a model is not subsequently built and run.

An influence diagram is used to represent the decisions, uncertainties, values and relationships among these elements in a decision problem. It is usually less detailed than a decision tree. Figure 6 shows an influence diagram for the above problem. The decision process begins with an uncertain flow (ovals represent chance values) that effects the structure's operation. Structure operation influences manatee casualties. The basic elements of the problem are here and the influences are clear. There are no feedback loops or other values in this simple model.

Figure 6: Influence Diagram



EXPERT OPINION

When uncertainty results because things are unknowable there are few options. You either ignore the uncertainty or you make some best guesses about its nature. When analysis comes down to guessing, we at least want the best guessers available. These are usually experts in the domain of that which we are guessing. Expert opinion is often the best option for estimating that which is unknown or unknowable.

Professional Judgment

There are a lot of variables, relationships, and situations encountered in environmental infrastructure planning that are not only uncertain but that are either unknown or unknowable. How does an ecosystem function? Will a species become locally extinct? When will the next 100-year flow occur? Where do you get information about those things that are unknown or unknowable? From experts. It is the professional judgment of the best informed people on these subjects that we generally must rely on.

Professional judgment has always been an important part of the Corps' decision process. Often professional judgment has been a mask for that blind leap of faith that must be made in many investigations. When data, information, theory and analysis have taken you as far as they can, it's time to drag out the hunches and gut feelings, dressing them up as professional judgment. To dispense with professional judgment in such a flippant way would be both extremely unfair and wrong. The knowledge gained from years of experience and observation have imbued people with an inherent understanding of systems and situations that is not easily reduced to a checklist, theory, or standard operating procedures. Professional judgment is one of the most important tools available in a risk-based analysis.

The essential difficulty with professional judgment often lies in the identification of the experts whose judgments will be sought. There is considerable professional literature that suggests that so-called experts often do not know the limits of their own knowledge and expertise. It is common procedure for experts to overstate their confidence. In other words, the experts aren't right as often as they think they are.

It is important to systematically search for the expertise that is required. The most knowledgeable person in the office may not be sufficiently expert on a subject to provide a full range of values or impacts that could result from an uncertain situation. The consultants with whom you have a contract may be willing to do the work, but they may lack true expertise in an area. It's a good general rule to search for and verify the expertise of your experts. Using multiple experts can help assure a more complete picture of the uncertainty involved in a situation.

Elicitation/Opinion Analysis

Experts have considerable knowledge. Obtaining it from them in a useful and reliable manner is not always as easy as it might seem. Suppose for example there is concern that some species of interest will become locally extinct. Take something as simple as the beaver. How would you go about getting an expert to estimate this event? How do we define local? Extinct? Over what time frame?

The process of discovering and quantifying the knowledge and opinions of experts so they can be communicated to others is called elicitation or opinion analysis. In risk-based analysis both the likelihood and the consequences of uncertain events can be unknown or unknowable. Environmental planning, because of its complexity and its relative newness, is full of unknown and unknowable events and situations. Eliciting information from experts will likely be an extremely important analytical method for risk analysts involved in this area.

Subjective Probability Assessment

Estimating the likelihood of events is a special subfield of elicitation that has received considerable attention in the human behavior and decision-making literature. Subjective probability assessments are techniques used to elicit from experts the probabilities of various events. Subjective probabilities (see section on Probability) are not based on analytical or frequency-based probability estimates. They are opinions based on the expert's strength of belief.

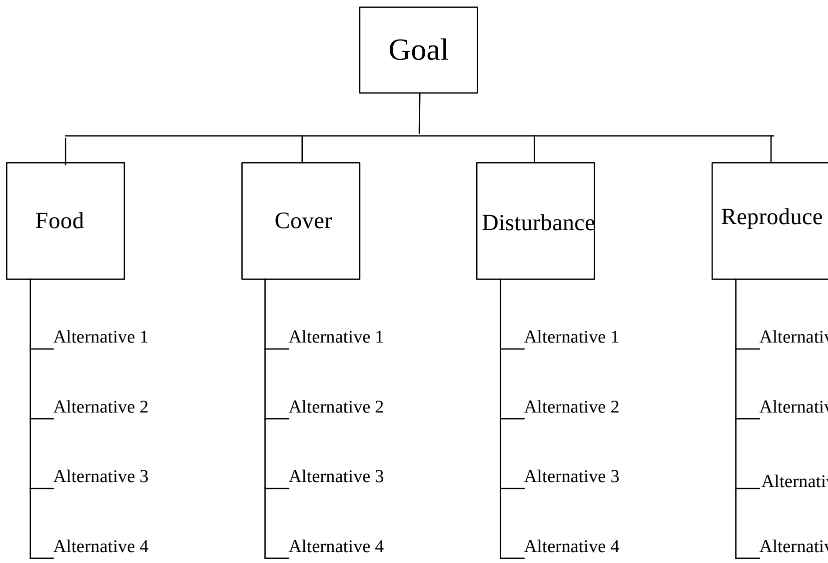
Experts assess and evaluate the available evidence and then use their professional judgment to estimate the likelihood of various events. These likelihoods can be point estimates (e.g., there is a 0.2 chance beaver will be extinct within 30 years) or estimates of entire distributions (there is a 0.9 chance that there will be 100 or less beavers per acre, a 0.6 chance there will be 45 or fewer beavers, a 0.2 chance of 15 or fewer beavers and 0.01 chance of 3 or fewer beavers). There is no right or wrong answer, only opinions that are more or less accurate.

Analytic Hierarchy Process

The analytic hierarchy process (AHP) was initially developed as a multi-criteria decision tool. Alternatives are chosen on the basis of their contributions to various objectives. AHP is a tool that can be used to make decisions in situations involving multiple objectives. Consider a decision problem like that shown in Figure 7 where we have a goal (the top square), criteria for reaching that goal (the second row of squares), and alternatives for meeting each criterion (the tic marks beneath the criteria). The number of levels is purely arbitrary with this technique; there can be as many levels of sub-criteria as desired.

Using pairwise comparisons, first of the criteria (and sub-criteria), then of the alternatives for reaching each criterion, this technique produces index numbers for each alternative plan that reflect the

Figure 7: Sample AHP Decision Problem



collective judgments of the decision-maker/expert. These index numbers identify the best alternative consistent with the experts judgment.

The pairwise comparisons proceed at each level of the hierarchical structure. For example, food source is compared first to cover, then food source is compared to the disturbance factor, and finally it is compared to reproduction potential. At each comparison the expert may assign a numerical or qualitative rating of the two factors, e.g., food = 1, cover = 3 or cover is moderately more important than food. Each criterion is eventually compared to every other criterion. Then each alternative is compared to every other alternative for each criterion. For example, with regard to food sources alternative 1 is strongly more important than alternative 2. With each such judgment the index number is constructed reflecting the expert's relative weighting of each criteria and alternative.

This technique can be readily adapted to situations involving uncertainty. In this case, the weights of sub-criteria and criteria are not the relative importance of these items but their relative likelihoods. AHP has proven to be a useful tool in quantifying the subjective judgments of experts in a variety of decisions under uncertainty. One of the more recent applications of this technique was the development of structure condition indices for the 80 largest locks and dams in the Corps' inland waterway system.

PROBABILITY

Many situations of uncertainty are represented by probabilities. An event such as a drought or extreme flow, for example, may or may not happen. What is the probability it will occur this year? A sample survey may indicate an indigenous population of white tail deer of 850, with 95% certainty the true population is between 700 and 1,000 deer. We might be interested in the likelihood that beavers will become locally extinct in the absence of a project. Experts would be relied upon to estimate this probability subjectively. There are endless possible uses for probabilities in environmental planning.

Three Approaches to Determining A Probability

The three approaches to determining a probability are classical probability, empirical probability, and subjective probability. In classical probabilities all outcomes are equally likely. Examples include the probability of rolling a six with a die, or drawing a king from a deck of cards. Empirical probabilities are based on past experience. Most hydrology is based on empirical probabilities, i.e., the observed frequencies of events. Probabilities based on available evidence and an individual's own judgment are called subjective probabilities.

Corps personnel doing risk analysis have to be extremely comfortable with the basic notions of probability and probability distributions. They need to understand the differences among analytical, empirical/frequentist, and subjective notions of probabilities. The laws and language of probability are minimum requirements for risk analysts.

A basic knowledge of the most common discrete and continuous distributions and when to use each is essential. This knowledge should include a knowledge of the distribution parameters, their shapes and locations, as well as distribution-fitting methods. Analysts should be able to move back and forth between probability density functions and the cumulative distribution functions.

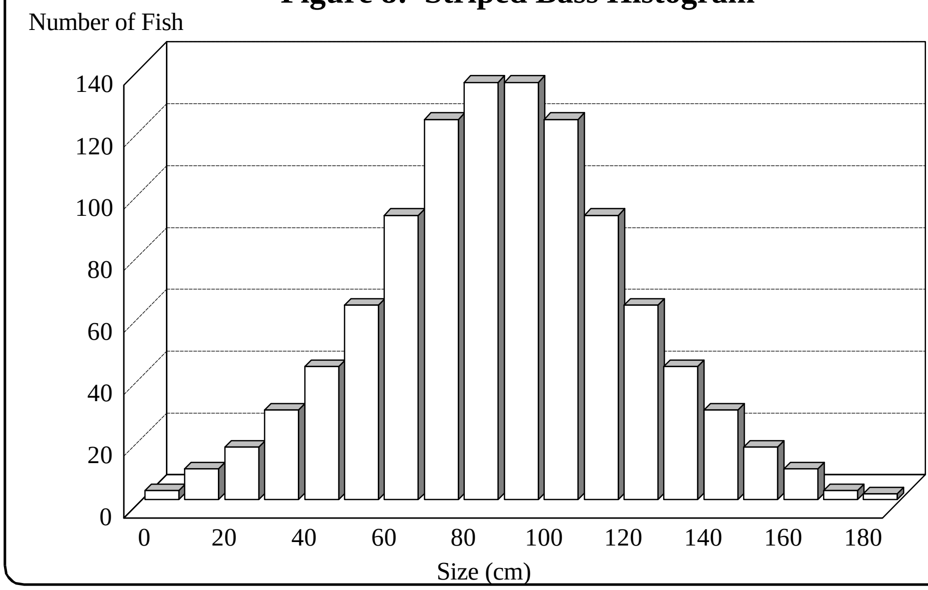
Armed with these skills, Corps personnel will have the probability background necessary for understanding the chance dimension of uncertain situations. Furthermore, this knowledge is a necessary precursor to the use of more sophisticated models, methods, and techniques.

PROBABILITY DISTRIBUTIONS

When the Corps first began to incorporate risk analysis into its planning studies a fundamental goal was to get analysts to represent the value of critical variables as distributions rather than as determinant single values. Issues of which distribution to use were clearly secondary to taking the first step and using a distribution. Now that risk analysis is gaining more widespread acceptance analysts readily embrace the use of probability distributions. The question has now become, which distribution should I use? For example, what distribution should we use to represent the uncertainty attending the HSI index?

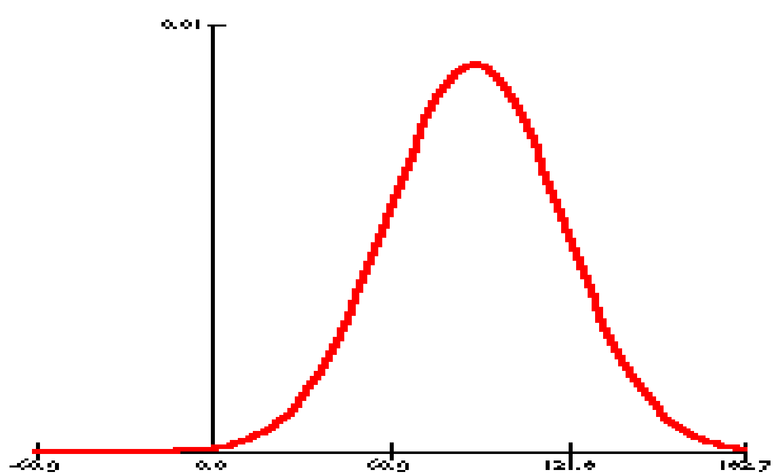
Suppose we could measure every striped bass in the bay. What would a graph of these data look like? A histogram is a bar graph that depicts the frequency with which values occur in a data set. Figure 8 presents a histogram of fish sizes that range from about 2 cm to over 180 cm. Most of the fish fall in the range of 90 cm. Each bar is 10 cm wide. If each bar were only 1 cm wide the graph would take on the smooth look of a normal distribution like the one shown in Figure 9. Histograms are pictures of frequency distributions. They show how values in a data set are distributed.

Figure 8: Striped Bass Histogram



Histograms need not have the neat symmetry of Figure 9. They can assume any shape at all. A histogram is a picture of how the elements of a data set are distributed. A probability distribution is a picture of how all the elements of a population is distributed. The distinction between the two is that a histogram is usually a picture of some of the data and a probability distribution is a picture of all the data. Because having "all the data" is often a practical impossibility, probability distributions are often theoretical rather than empirically observed the

Figure 9: Probability Distribution of Fish Lengths



way a histogram is.

For example, the histogram above was presented as a picture of the length of all the fish in the bay. Analysts never have that kind of information. The histogram above would more likely be a picture of the distribution of lengths for 1,000 fish sampled from the bay. Nonetheless there is a theoretical distribution of the length of all striped bass living, dead or yet to be born and it's called the probability distribution. That distribution yields information like the probability that a fish will be 76.4 cm or more in length and that probability can be estimated from the theoretical probability distribution of fish lengths.

The histogram yields information about the frequency with which fish 76.4 cm or longer are observed in the sample of 1,000 fish. As the sample gets bigger and bigger the frequency with which fish 76.4 cm or more are observed gets closer and closer to the true probability with which that occurs. Frequency distributions or histograms, then, are approximations of probability distributions.

Analysts are interested in more than fish lengths. They may be interested in the distribution of stream discharges, tidal fluctuations, salinities, weights of animals, heights of plants, depths of water, speed of winds, and so on. Each of these characteristics has a parent population that has some probability distribution. Experience and theory have revealed that these distributions tend to assume certain basic shapes; or, at least, they have certain basic characteristics.

The shapes of many of these distributions can be described by a mathematical formula. The normal distribution, for example, is described by the following formula:

$$f(x) = \frac{1}{(2\pi)^{.5}\sigma} e^{\frac{(x-\mu)^2}{2\sigma^2}}$$

where f(x) is the probability density function, what we have been calling the probability distribution. The values of π and e are known. Unknown are the values of μ and σ. These are the parameters or constants which, once known, give the distribution its location along a real number line and its shape above that line. The population mean is μ, the Greek mu, and σ, sigma, is the standard deviation of the population. Hence, given the population mean and standard deviation any normal distribution can be described. The normal distribution in Figure 9 is centered about a mean of 90 and its spread is dictated by its standard deviation of 30.

Other distribution shapes are described by other formulas. Frequently, the formulas describe families of distributions. That is, when the parameters of the distribution change the shape and location of the distribution can change as well. For example, there is not one normal distribution[11] but an entire family of distributions. Even though each has that distinctive single-peaked symmetrical bell shape each distribution can vary in its location

[11] Although the normal distribution is unique in that any normal distribution can be converted to the standard normal distribution, also known as the Z distribution.

on the normal line and the extent to which it is tall and thin or short and fat. Other families of distributions can vary in far more dramatic ways.

What are we to assume about the nature of the probability distributions that are used to describe the uncertainty in, for example, environmental restoration studies? If empirical data are available, visual assessments of the frequency distribution may be used to approximate the underlying probability distribution. Statistical distribution fitting tests using goodness-of-fit measures can be used to more effectively test how well the data conform to any given distribution. The chi-square and Kolmogorov-Smirnov statistics are goodness-of-fit measures most often used to determine if one's data are consistent with a normal distribution or any other distribution. These tests are available from a number of commercially available statistics packages. BestFit from Palisades Corporation is especially designed for distribution fitting tests.

When there are no empirical data to examine, theory or understanding the process that determines the data of interest may suggest the distribution to use. Prior studies and the literature may offer insights into the nature of the distributions that are appropriate to use. The books *A Guide to Probability Theory and Application* by C. Derman, L. Glaser and I. Olkin (1973) and *Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis* by M. Granger Morgan and Max Henrion (1990) are two sources of such insight. The users' manuals for @RISK and Crystal Ball are two examples of commercial software products that provide some useful information about probability distributions.

In the absence of better information, a systematic process of selecting a distribution may be the best approach in many circumstances. Following these few simple steps may help the analyst make a reasonable choice of a distribution for representing the uncertainty when there is no better guidance on distribution choice. First, clearly identify the variable of interest. Second, list everything you know about the variable being sure to include quantitative and qualitative aspects of the variable. Third, identify the type(s) of uncertainty with which you are dealing. Fourth, review the approaches to the different types of uncertainty. Fifth, list the description and characteristics of the candidate probability distributions. Sixth, identify the distribution(s) that best characterizes the variable in question. If none of these methods identify a single best distribution use sensitivity analysis to determine the significance of choosing one distribution over another.

The remainder of this section attempts to acquaint the reader with some of the most commonly encountered families of distributions used by risk analysts. It is impossible to do justice to this subject matter in a few sentences. Undoubtedly, it would be interesting to see the formulas, discuss the parameters, and look at sample distributions. The subject matter is too complex to do that here. Instead the briefest of introductions to the distributions is offered. Reasonably accessible additional detail can be obtained from the books cited above. A more concise and mathematical description can be found in *Statistical Distributions* by Merran Evans, Nicholas Hastings, and Brian Peacock or in many advanced statistics texts. In addition, there are several software packages that can be used to explore these distributions. RISKview and eHOP[12] are two packages that allow the user to explore the characteristics of a variety of distributions.

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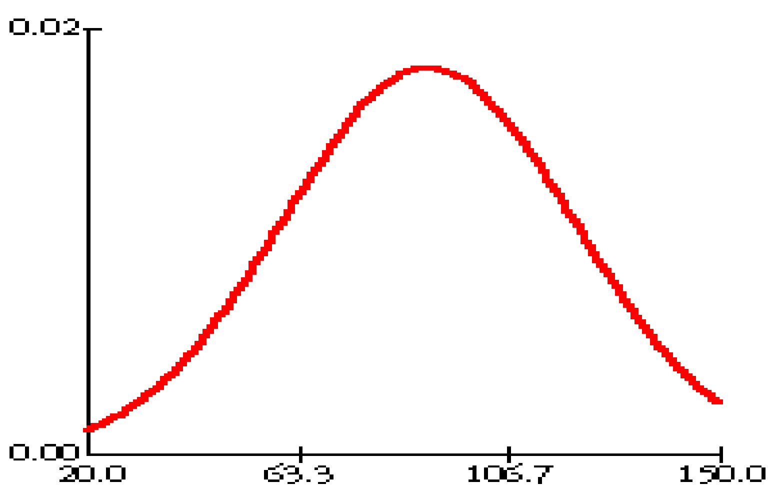
[12] RISKview is available from Palisades Corporation and eHOP, The Electronic Handbook of Probability, is available from the Crunch Software Corporation at 415-584-0122.

Normal Distribution

The normal distribution is probably the most common distribution encountered. Variables formed by the addition of other uncertain quantities are, generally, normally distributed. A total cost that is the sum of several uncertain line item costs will tend to be normally distributed. Uncertainty that results from unbiased measurement errors can be represented by a normal distribution. Thus, if the chief concern about the size of a local population of a species is the potential measurement error, the uncertainty may be represented by a normal distribution. Many other distributions approach or reduce to a normal distribution under circumstances (i.e., for certain parameter distributions) that vary from distribution-to-distribution. The Central Limit Theorem contributes to the utility of the normal distribution in assuring that the distribution of some sample statistics is always normal, regardless of the parent distribution from which the sample was drawn, as long as the sample size is large enough.

The normal distribution can be described by two parameters, the mean and standard deviation. For quantities where negative values are not meaningful (populations, costs, flows) it may be inappropriate to use the normal distribution unless it is truncated to eliminate the illogical values. Distributions can be truncated at any values required by the analysis. Figure 10 shows Figure 9 truncated at values of 20 and 150.

Figure 10: Truncated Normal Distribution



Lognormal Distribution

If the logarithm of the random variable of interest is normally distributed the random variable has a lognormal distribution. Variables formed by the multiplication of other uncertain quantities tend to have a lognormal distribution because the sum of the logs approaches the normal distribution. For example, an uncertain area estimate times an uncertain habitat suitability index will yield a lognormal distributed estimate of the number of habitat units.

If we know a value within an order-of-magnitude, say a factor of two or ten and when uncertainties are large, the lognormal is appropriate to use. The lognormal distribution cannot be used with non-positive values so it's useful when negative values of the variable of interest are not permitted. It is a useful distribution to use when values are positively skewed, i.e., most values occur near the minimum value. The distribution is described by the mean of the logs of the random variable and the standard deviation of the log of the variable.

Exponential Distribution

The time between events that are purely random[13] often has an exponential distribution as does the size of random events. The exponential distribution can be used to describe the duration and size of events, like storms and oil spills. It is commonly used in reliability theory, waiting times and queuing theory. It is described by a single parameter, λ, that is equal to one divided by the average time between events. Thus, the single parameter is the rate at which the events occur[14].

The exponential distribution has a mode of zero and is constrained to non-negative numbers. Because the distribution has a fixed shape the single parameter determines only the scale of the distribution. It is not a very flexible distribution and is useful for a very limited type of phenomena.

Poisson Distribution

Unlike the continuous distributions above, the Poisson distribution is a discrete probability distribution that is constrained to non-negative numbers. The Poisson is useful when we're dealing with the number of occurrences of an event over a specific interval of time or space. For example, the number of plants per acre or the number of floods per 100 years may have Poisson distributions. If a single trial can be defined as some fixed area of opportunity, like a fixed length of time (minute, day, year, planning period) or space (per foot, acre, cubic meter) the Poisson may be useful. The number of events that occur in the fixed time period or space may have a Poisson distribution.

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[13] A purely random process of events is called a Poisson process. The exponential, Poisson, and gamma distributions deal with Poisson processes.

[14] Suppose the average time between customers is ten minutes. The parameter is 0.1, and 0.1 is the number of customers per minute.

The single parameter of the distribution, α, is the average number of events per area of opportunity, e.g., the average number of floods per 100 years or the average number of plants per acre.[15] Like other single parameter distributions, the Poisson lacks flexibility. When the parameter is large the discrete Poisson distribution may be approximated by a continuous normal distribution.

Gamma Distribution

Poisson processes confined to non-negative values that, for various reasons, yield distributions skewed to the right can be described by a gamma distribution. The bulk of the area under a gamma density function is located near the origin and the density function area drops gradually as the random variable increases in value. The gamma distribution describes the time required for k events to occur.

The gamma distribution is a two parameter distribution that describes a Poisson process. The shape of the distribution is determined by k, while λ is the scale parameter. This distribution is similar to the lognormal but it is less positively skewed and less tail-heavy. Thus, it may be used in situations similar to those appropriate to the lognormal. The gamma is useful for describing times (or spaces) between events (items) that are not pure random processes. Some quantities frequently exhibiting skewed distributions like the gamma include physical quantities such as precipitation quantities and pollutant concentrations as well as the time between malfunctions of aircraft engines, time between customers at a checkout counter, and the time required to complete maintenance on an engine.

Weibull Distribution

The Weibull distribution is actually a family of distributions that can assume the properties of several other distributions. With location, scale, and shape parameters the Weibull can resemble the exponential and normal distributions as well as assume a number of other shapes.

The performance of many complex systems depends upon the reliability of the components making up the system, perhaps an ecosystem. The time to failure or length of life of a component from a specified time to its failure can often be described by a Weibull distribution. It has also been used to describe some physical quantities like wind speeds. In its more common form it is similar in shape to the gamma distribution though it is less skewed and tail heavy. Use it only with non-negative values.

Beta Distribution

The beta distribution yields a two parameter distribution that is defined over the interval from zero to one. There is a four-parameter form of the beta distribution where the additional parameters define the range endpoints.[16] It is a very flexible distribution for representing variability over a fixed range. Defining the way a

[15] Alpha, α, is defined as the average number of events per time (or space) interval, λ, times the length (size) of the time (space) interval, T. Thus we define, $\alpha = \lambda T$.

[16] The additional parameters translate the distribution and change its scale, so it is possible to model variation over any scale.

variable varies over a range makes the beta a valuable distribution for modeling proportions, fractions and percentages. It can be used to represent the probability of occurrence of an event or the proportion of time that a structure or system functions as designed.

Uniform Distribution

The simplest of all probability distributions is the uniform distribution, where the random variable assumes all its values with equal probability. The probability that a value from a given sub-interval will be realized only depends on the size of the sub-interval relative to the overall interval.[17]

Use the uniform distribution when you can identify a range of possible values but are unable to say which values in that range are more likely to occur. In other words, the uniform can be used when any one value is as likely as any other. It is a two-parameter distribution where the parameters are the minimum and maximum values that can occur. Subjective reasoning can often be used to estimate the parameters. When the uncertainties are large and somewhat asymmetric you may use a loguniform distribution to make them more orderly.[18]

Triangular Distribution

Most likely values are frequently identified in the planning process. If it is believed that values close to the most likely value will occur more often than values near the extreme ends of the range of possible values a triangular distribution may be used. The arbitrary shape of the triangular distribution and its sharp corners telegraph the fact that the precise nature of the distribution are unknown. A default distribution of sorts, the triangular should not be used too quickly or too frequently. Its three parameters are the most likely, minimum and maximum values the variable can assume. If the uncertainties are large, a logtriangular distribution can be used.

Binomial Distribution

The binomial distribution gives the probability of obtaining x events, each with probability p of occurring, from n independent trials where each trial has only two outcomes, frequently called success and failure. We might want to know the probability of observing two or more terns with toxic levels of cadmium from a group of 100 terns when the probability that a tern has a toxic level is 0.005. Its parameters are the number of events, x, and the probability of the event occurring on a given trial, p. Use the binomial distribution when the probability of success, p, or failure, 1 - p, are known. Do not use the binomial distribution when the event probability is unknown.

[17] If the bus always comes between 7:00 and 7:10, the probability that it will come between 7:05 and 7:07 is exactly the same as the probability that it will come between 7:02 and 7:04.

[18] For a random variable X create Y = lnX. The loguniform is a uniform distribution of Y.

Discrete Distribution

A discrete distribution allows for a finite number of discrete outcomes. Each possible outcome is assigned a probability. The probabilities must be mutually exclusive and sum to one. For example, when describing the performance of a tidal wetland restoration project we would identify three discrete outcomes: 1) tidal wetlands, 2) mudflats, and 3) daisies. We might estimate the probabilities of these events as 0.6, 0.2, and 0.2, respectively.

Summary of Distribution Usage

The proper distribution to use is an empirical issue. Ideally, we'd like to fit a distribution to some existing data to determine the distribution to use. Lacking data, theory and similar studies can be used for suggestions. Undoubtedly, this will frustrate many people because it doesn't provide specific guidance on which distributions to use and when to use them. The truth of the matter is there is much yet to be learned about the uncertainty confronted in environmental infrastructure studies. Table 4 summarizes the distributions described above.

RANDOM SAMPLING

Information from a sample used to make generalizations about the population from which it came must be representative of that population. In order for a sample to be representative of the population, the elements of the sample should be randomly selected from the population. The basic idea here is that if every member of the population has the same possibility of being selected as part of the sample and if the sample size is large enough, pure chance will generally assure a representative sample.

Simple random sampling is the most common method for obtaining such a sample. Stratified random sampling, cluster sampling, two-stage cluster sampling, sequential sampling, and systematic sampling are sampling techniques with which those in environmental planning should be familiar. Quadrat sampling involves estimating the number or percentage of elements (deer, fish, trees, submerged substrate, people, etc.) in a defined area or quadrat (per acre, per hectare). Quadrat sampling is useful in estimating population densities and size.

It's not practical to expect all Corps analysts to be expert in sampling techniques. The techniques are quite straightforward and not at all difficult to implement. Many analysts will be able to master them with modest training and support. Inevitably, complex sampling situations will arise in which it will be sufficient for Corps analysts to be familiar with the existence of other tools and methods so they can supervise and review the work of others.

SENSITIVITY ANALYSIS

This is one of the more practical methods for introducing risk and uncertainty analysis to environmental restoration projects. Completing an analysis of an uncertain situation requires numerous assumptions. It might be important to know if the results of the analysis are sensitive to the assumptions that have been made. An investigation that is intended to determine the sensitivity of the analysis' results to different assumptions is called a sensitivity analysis. It is also called parametric variation. A number or parameter that is treated like a constant in the analysis is varied systematically over a range of values to examine its impact on the decision.

Table 4: Distribution Summary

Normal distribution	• Variable has a most likely value (mean) • Uncertain value as likely above as below mean • Uncertain value near mean more likely than far away
Lognormal distribution	• Variable is non-negative • Uncertain value more likely near lower limit • Natural log of variable yields normal distribution
Exponential distribution	• Describes duration and size of events • Variable is non-negative
Poisson distribution	• Single parameter discrete distribution confined to non-negative values • Number of events over interval of time or space
Gamma distribution	•Time/space between events/items • Two parameter distribution of non-negative variable
Weibull distribution	• Three parameter distribution of non-negative variable • Can resemble many other distributions • Time-to-failure, life of component
Beta distribution	• Two or four parameter distribution • Defines variation over a range •Proportions, fractions, and percentages
Uniform distribution	• Minimum value is fixed • Maximum value is fixed • All values between min and max are equally likely
Triangular distribution	• Minimum value is fixed • Maximum value is fixed • Most likely value falls between min and max, with values near min and max less likely than values near most likely
Binomial distribution	• Only two outcomes possible • Trials are independent • Probability of "x" events in "n" tries given probability on any trial is "p"
Discrete distribution	• Finite integer number of outcomes possible • Each outcome has independent probability of occurrence

Consider a very simple sensitivity analysis/parametric variation. Suppose you have 100 acres of land and you estimate the HSI to be 0.5. There are 50 HU's in this example. But, suppose the HSI, normally treated like a constant, was a matter of professional judgment that was uncertain. Suppose the HSI could be 0.75. Then we have 75 HU's. The number of HU's is very sensitive to the HSI estimate. The HSI was the parameter in this example that was allowed to vary.

The purpose of a sensitivity analysis is at least two-fold. Sensitivity analyses conducted early in the investigation can help you identify the key parameters/variables/factors. If you vary one of these values and the result changes significantly, you know you have identified an important source of uncertainty or a key parameter. In this case you do one of two things. First, you should try to reduce the uncertainty if at all possible. Second, if the uncertainty cannot be reduced it must be addressed[19] and its potential importance in the decision-making process to the decision-makers needs to be explained.

A second purpose of sensitivity analysis may be to examine the cumulative effects of various uncertain factors. For example, suppose the area estimate and the HSI are both uncertain. Though neither alone may have a significant impact on the HU's, the two together might.

Sensitivity analysis is a controlled and deliberate process. Allowing things to vary randomly over a range of values, as one does in a Monte Carlo process, is not sensitivity analysis. It would not be proper, for example, to do a simulation in which the period of analysis is allowed to vary according to some probability distribution. We may be unsure how long a project will last but that is not a value one allows to vary randomly. The proper approach is to vary that parameter systematically. Consider the plan impacts at 25, 30, 50 or whatever number of years is reasonable and see if the decision would vary with the period of analysis.

Sensitivity analysis is a valuable tool. It can be a reasonable compromise between a detailed and sophisticated risk-based analysis and completely ignoring the uncertainty that exists in your investigations. Identifying the important variables in an investigation and varying the key parameters and noting the effect on the best decision can be an effective way to begin to address risk and uncertainty in environmental projects.

SIMULATIONS

Simulation is a technique used to answer what-if types of questions. It is used most appropriately when a decision problem under analysis is too complex to be solved by analytical models. Simulation is a quantitative procedure that describes a process by constructing a model of the process and then observing how the model behaves over a series of iterations in order to learn how the process itself might behave.

The simulations that Corps personnel use are most often mathematical models that cannot be solved analytically so they are run on trial data to simulate the behavior of a system. As a general rule, simulation should be used only as a last resort and never as the first option. There may be theory or analytical techniques available to solve a problem. When there are they should be used.

[19] In some instances it may be appropriate to treat these critical variables in a probabilistic fashion. In others, they will be varied in a systematic fashion. The determining factors are the types of quantities that are uncertain and the nature of the uncertainty. See Chapter Four for additional discussion of this point.

Simulation can be useful in situations that are commonly encountered in environmental planning studies, however. Some of the reasons for using simulation include the following:

1) Simulation is the only method available because the actual environment is too difficult to observe. (The fate of a contaminant introduced to a new environment may be impossible to track.)

2) It is not possible to develop an analytical solution.

3) Actual observation of a system is too expensive. (Planting tidal wetlands with different numbers and densities of plants to determine the optimal scheme may be too expensive to be feasible.)

4) There is insufficient time to allow the system to operate extensively. (We cannot wait to see the results of a study of long-term trends in the population of a certain species.)

5) Actual operation and observation of a system is too disruptive. (If we would like to know the impacts of a hiatus from maintenance dredging on submerged aquatic vegetation (SAV) it is not feasible to actually cease dredging.)

6) Simulation reveals new facts about the problem. (Building a model requires careful and logical thought about the process under investigation.)

7) Simulation can be an effective training tool. (It allows controlled experimentation with a process.)

8) Simulation allows testing of a greater range of situations than have been observed.

If you use simulation in place of another technique there are trade-offs. Analysts should bear in mind some of the disadvantages of simulations. A simulation is not an optimization process. It is not precise because you do not get an "answer". What you get from a simulation is a set (or distribution) of a system's responses to different operating conditions.

Suppose, for example, we have a simulation model that estimates project benefits and project costs in order to estimate the project's net benefits. Though we might examine 10,000 different sets of operating conditions and estimate the resulting costs 10,000 times, the resulting benefits 10,000 times, and the estimated net benefits 10,000 times we will not know what the actual net benefits are. We might know the average net benefits for the 10,000 iterations and we might know the minimum and maximum observed values, but we will not have a precise and accurate answer.

Simulation models can take a long time to build and they can be very expensive. Not all situations can be evaluated using simulation. There must be uncertainty and the uncertainty must be the kind that is amenable to probabilistic modeling. The method for treating the uncertainty depends in part on the type of quantity that is uncertain and the source of the uncertainty as indicated in Chapter Three. For example, uncertainty that results from management's inability to resolve questions is not a proper subject for simulation in many cases. Such instances are more properly handled with sensitivity analysis.

Simulations vary greatly in complexity but all generally consist of the following steps:

1) Define the problem or system to be simulated.

2) Formulate the model to be used.

3) Identify and collect the data needed to test the model.

4) Test the model and compare its behavior with the behavior of the actual problem environment.

5) Run the simulation.

6) Analyze the simulation results and make changes to the situation/scenario under investigation.

Flowcharts are commonly used in simulations. They are graphic aids (like decision trees discussed above) that help one think logically about a process and to keep track of it. Process generators are usually needed to generate the data needed for the simulation. The Monte Carlo process is one of the most commonly used process generators.

The Monte Carlo process is a procedure that generates values of a random variable based on one or more specific probability distributions, such as those described above. The Monte Carlo process is not a simulation method or model per se, although it has become almost synonymous with stochastic simulation. The Monte Carlo process begins with the generation of a random (or pseudo-random) number from a uniform distribution. This number is then transformed into a value from the specific probability distribution used by the model builder.

In essence, the process works as if you specify a type of probability distribution and its parameters and a number is randomly selected from that distribution. Numbers that are common in the specified distribution are selected more often than the numbers that are less common in the parent distribution. If you select enough numbers from the parent distribution, you would recreate the original distribution with your sampled values. The random numbers generated by a Monte Carlo process can represent a sample of potential results in the process under consideration. By contrast, Latin Hypercube[20] is an alternative process for generating random numbers.

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[20] In a Latin Hypercube process the cumulative probability distribution of an input variable is stratified into n equal intervals, where n is the number of iterations in the simulation, along its probability axis. A sample is drawn from each interval. Sampling is "forced" to represent values in each interval, thus recreating the input's probability distribution. Latin Hypercube is generally regarded as a more efficient sampling technique.

SPECIALTY MODELS

Risk-based models have been developed for a wide variety of applications. The insurance industry has its own set of models, the chemical industry has developed numerous models, as has the EPA. The Corps of Engineers is not without its own specialty models for expected annual damage estimation and major rehabilitation of locks and dams.

Special models have been developed for use by the Corps in many of their areas of endeavor. The Hydrologic Engineering Center has developed numerous hydrologic and hydraulic models for use by Corps personnel. HEP, developed by the U.S. Fish and Wildlife Service, is but one of many special models developed for use in the evaluation of habitat. It may well prove useful to explore ways in which risk and uncertainty tools and methods can be incorporated into a redesign of existing tools that are serving their users well. This could include HSI models as the example in Chapter Six illustrates.

STATISTICS

Statistics are used to make sense of data. Specifically, they are used to obtain information from data. There are two main bodies of statistics that Corps risk analysts need to master: descriptive and inferential statistics. Descriptive statistics are used to organize, describe, summarize, present and understand data. This includes measures of central tendency (means, medians, modes), measures of dispersion (range, percentiles, variation, skewness, etc.), and tabular and graphical techniques (contingency tables/ cross tabulations, stem-and-leaf displays, frequency distributions, histograms, pie and bar charts, line graphs, and so on) used to present the information embodied in the data.

Frequently, we do not have or cannot get information about the entire population in which we are interested. For example, we will never know the true flow regime. At best we will have a sample of several years of data. It may be impractical to measure the true percentage of each type of ground cover found in the study area for an HSI model. Instead, we may inventory a few sample sites and use that information to make generalizations about the entire study area. Inferential statistics use information from a sample to generalize to the population from which it was drawn.

Anytime a sample is used to make some generalizations about the population there is risk involved. We are using available and incomplete information to make judgments about the population. There is always a chance the sample is unrepresentative of the population from which it came. An important part of any risk analysis is properly quantifying the risks associated with sampling. This is, in part, the purpose of inferential statistics.

Inferential statistics involves the use of sample statistic distributions and the calculation of interval estimates that can be used in sensitivity analyses or Monte Carlo simulations. Interval estimates can be calculated for various confidence levels. These same interval estimates can be used in hypothesis testing. Hypothesis testing has many applications, one of which is testing the goodness-of-fit of a data set to a probability distribution.

It will often be useful for analysts to understand and be able to estimate correlations between and among variables that may interrelate in models or calculations used in the planning process. The need for nonparametric statistical techniques would be more likely to arise in environmental planning than in many other professional settings. Although these techniques may not be the analyst's highest priority, neither should they be considered exotic techniques.

Many of us sat in our statistics classes and wondered, "When am I ever going to need this again?" One answer is, "When you begin to incorporate risk analysis into your planning in order to improve the decision-making process." A good command of the basics of inferential statistics is essential for every risk analyst.

SUMMARY AND LOOK FORWARD

The time may come when risk and uncertainty protocols for environmental restoration studies are described in detail in Corps' guidance and the models and tools needed to conduct these analyses are well known to all. That day has not yet arrived and so this chapter has presented a list of selected tools and concepts used by many risk analysts. The chapter began with some basic concepts of which environmental planning risk analysts will need to be aware. These tend to deal with information/communication issues. The latter half of the chapter addressed more specific types of knowledge or tools that are generally encountered by risk analysts.

The purpose of this chapter is not to say these are the techniques and here's how you use them. Rather, its intent is to say here are some techniques you might want to learn more about. The reasons for learning more about them begin to become apparent in the next two chapters. Chapter Five presents some general sources of risk and uncertainty in environmental planning. This discussion tends to use the broad concepts found in this chapter. Chapter Six, by contrast, discusses more specific examples of risk and uncertainty encountered in environmental planning. These examples make more use of the specific tools presented here.

CHAPTER FIVE: GENERAL SOURCES OF RISK AND UNCERTAINTY IN ENVIRONMENTAL RESTORATION PLANNING

INTRODUCTION

> ". . . it is impossible to predict with certainty how animal populations will respond to restored or improved hydrological conditions." Central and South Florida Project Reconnaissance Report Comprehensive Review Study, November 1994, p. 108, U.S. Army Corps of Engineers, Jacksonville District.

The above quotation sums up the frustration of the environmental planner's job quite well. Their task is a difficult one. Many things are uncertain in their studies. The best way to proceed is to acknowledge those uncertainties, identify the most important among them, and address them in a rational fashion, subject to study constraints. This chapter identifies sources of risk and uncertainty that could be generic to virtually any water resources planning project. They are also the broad concepts of risk and uncertainty encountered in environmental planning.

An earlier research report[21] reviewed a number of Corps environmental project reports. Very little evidence of risk and uncertainty analysis was found in them. A number of environmental project reports were reviewed for this effort with a similar result. There is considerable evidence of uncertainty in the project reports. Frequently, the limits of the analysts' knowledge are straightforwardly acknowledged. For example, comments like ". . . insufficient information is available to make definitive statements about the habitat requirements of hickory shad. . ." are not uncommon. This acknowledgment of the existence of uncertainty is an important first step in doing something about it.

Despite some acknowledgment of uncertainty it is still more common to see very precise values presented as if they are absolute certainties. For example, in one study 17,281 habitat units were reportedly affected in the past. Though an incredibly precise number, it is pure folly to believe that number is anything more than an approximation of conditions that used to exist. There is still a great deal to be done in acknowledging the limits of our knowledge.

This report's review of project documents made it clear that there were different categories of sources of uncertainty and different places where risk and uncertainty analyses could be introduced. Ignorance of the planning process is one of the greatest sources of uncertainty evident in many reports. Many reports did not have clearly identified problems and relatively few had any planning objectives. Absent these fundamentals, it was often difficult to know what objectives the plans were formulated to meet and what problems they might solve. These shortcomings are not in any way unique to environmental planning.

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[21] *Compilation and Review of Completed Restoration and Mitigation Studies in Developing an Evaluation Framework for Environmental Resources, Volumes I and II*, IWR Reports #95-R-4 and 5.

There are, however, uncertainties that are unique to the environmental restoration process. One of these is the entire habitat evaluation process. Another is the, "If we build it, will they come?" question, i.e., will projects actually result in environmental improvements? With issues running from the general to the very specific it is necessary to provide some order to the manner in which these issues are to be discussed. Some general sources of risk and uncertainty are presented in this chapter. They are presented here because they may be expected to occur with greater regularity, and perhaps with more impact, in environmental restoration studies.

To organize the presentation, the P&G-mandated six-step planning process used by the Corps in its traditional planning work provides the organizational structure for the chapter. Those steps are presented in Figure 1. The chapter is divided into ten sections: this introduction, some general observations, one section for each planning step, and two summary sections. Discussion related to specific environmental restoration issues are covered in Chapter Six.

FOUR GENERAL OBSERVATIONS

Before some broad concepts of risk and uncertainty are discussed, a few observations, too general to fit elsewhere, are introduced here. First, risk analysis is not intended to increase the work requirements for anyone. Any risk analysis must be purposeful, i.e., it must contribute to improved decision-making. In order to be purposeful, we need to examine and understand what is already being done by environmental planners. That process only begins with this report.

The second observation follows from the first. There is a need to identify critical variables and key relationships in what planners are already doing in environmental restoration studies. This will take more time and focussed effort than were possible in this initial step in the process of introducing risk and uncertainty analysis to environmental planning.

A third observation is not specifically related to risk and uncertainty. Many planners do not know about or understand the P&G planning process. When planners don't know how to go about planning there is a good chance there will be considerable uncertainty about what they have done.

The last general observation is a simple one. Assumptions must constantly be made by planners in order for work to proceed. Professional judgment, intuition and gut feelings are important tools. Assumptions should be avoided where answers exist. The need for and rationale of assumptions that are made should always be clear, as the assumptions themselves need to be clear.

These are "big picture" uncertainties as is most of what follows in this chapter. Much of what follows considers uncertainty about the decision-making process itself. If the process by which decisions are made is uncertain or poorly understood, the decisions that stem from it are questionable. Fundamental uncertainties such as, "Are we addressing the right problems?" or "Do we have the best solution?" are indeed broad in concept. But they are far from trivial.

STEP ONE: PROBLEM IDENTIFICATION

There should be no uncertainty about the purpose and objectives of an environmental restoration study. The first step in the planing process is the most critical one. In this step, planners identify the problems that have motivated the study. Problems may be identified by the public or by technical experts. In addition to problems, planners should identify opportunities for improving conditions now and into the future. Building on the identification of problems and opportunities, the planning team develops specific objectives they want to achieve in the planning process. At the same time, they identify constraints, i.e., those things they want their plans to avoid doing.

The planning objectives and constraints effectively become the mission statement for the Federal/non-Federal planning partnership. They are a concise and unique statement of the reasons these two parties have come together in this study effort. Plans are formulated, evaluated, compared and selected based on their contributions to the planning objectives.

A review of 15 environmental restoration project studies in preparation of this report revealed an uneven record in terms of their faithfulness to this planning process. Some studies used a study team. Other studies were done almost entirely by an individual. Problem identification was the part of this first planning step that was generally handled best. Although there was rarely a clear and concise statement of the problems with the kind of directness found in statements like, "The problem is. . ."; one usually understood the problem after reading the report.

Cause and effect linkages were frequently missing from problem discussions. A somewhat typical problem identification follows:

> "There is a deficiency of at least 15 acres of barrier island habitat at or above the 10-year flood elevation, with stabilizing vegetation."

Statements like these do a good job of specifically identifying problems - lack of a specific habitat type. They are less effective in explaining why 15 acres is singled out and they do not clearly establish the cause of the problem. Frequently, these additional details can be ferreted out from the surrounding text. That is not always the case. When it's not, problems remain uncertain. When problems are uncertain so are the solutions.

The manner in which problems are discussed and described, largely absent clear and concise descriptive problem statements, can contribute to uncertainty over what the problems are perceived to be. We might all agree there is a lack of a certain habitat type, but we might each have a different idea about why that is so. This potential uncertainty can be limited by a careful problem statement that includes a cause and effect linkage.

This is not a trivial matter. It may be easy to note a decrease in duck habitat that accompanies a decline in migratory duck populations. The temptation to link the two is strong. However, understanding the problem is essential. If the decline in ducks is due to overhunting over a multi-state region, then no amount of habitat restoration will solve the problem. In order for plans to be effective, studies must begin with clear and definitive problem statements, devoid of ambiguity or other uncertainty.

The reports reviewed tended to do less well with other important aspects of this first planning step. Solving problems is clearly one way to make things better. Seizing opportunities is another. Opportunities are rarely addressed. And yet, altering projects to seize opportunities seems very much in concert with the spirit of environmental restoration. As a result, there can be uncertainty about the planners' responsiveness to potential opportunities.

Another common shortcoming is the manner in which planning objectives and constraints are handled. Too often, there are no clearly stated planning objectives. Too many reports lean on discussions of the NED objective which, though a Federal objective, is not a planning objective. In other cases the objectives remain vague, for example, ". . . to preserve and enhance the existing aquatic plant beds for fish and wildlife habitat," to be truly useful in plan formulation. When this happens there is substantial uncertainty about the objectives of the entire planning process.

At the other extreme, objectives sometimes include plan formulation and selection. For example, an objective that said, "Re-establish 15 acres of stabilized islands from river miles 300 to 300.8", is too specific. Objectives should never include solutions.

One of the most glaring offenses of the planning reports is that once planning objectives are identified there is no apparent further use of them in the planning process in the majority of the reports reviewed. This is one of the more troubling indications of a potential general ignorance of the Corps' planning process. The work done in this first step is essential to the success of the planning process. Identifying problems and opportunities and specifying objectives and constraints are essential steps in limiting the uncertainty of purpose that can be encountered in a planning study.

There are, on occasions, studies in which it's never really clear what is being accomplished, despite the copious details on project design and increased habitat units. This may be due to ignorance of the planning process. Some planning steps may not have been taken or were taken incorrectly. In other cases, the report writers have simply failed to tell their story effectively. In either case, it is in everyone's interests that planners eliminate all uncertainty about the fundamental purposes of the study effort. Knowledge of the planning process and a clear "story telling" style of documentation are the best ways to eliminate or reduce this potential uncertainty of purpose.

STEP TWO: INVENTORY AND FORECAST

In the second step of the planning process, planners identify the data they'll need to solve problems, seize opportunities and formulate plans to meet their planning objectives. At this step, information is gathered in sufficient detail to adequately define the existing conditions and to define a most likely future condition without a project.

Uncertainty is removed by information. So, it should be evident that this information gathering step is an essential one in any attempt to limit uncertainty. It should be equally evident that any attempt to describe a future condition is fundamentally an exercise in uncertainty.

At times, environmental restoration studies may rely too much on "cut and paste" data. This may seem a contradiction when Section 1135 studies are expected to make use of existing data sources. The problem is not so much using existing data as much as it is using data because it exists. In some cases, the recitation of existing condition data have no material bearing on the problems, opportunities, objectives, plans or their effects. When that's the case, the data are extraneous and should not be used.

If these data are used in lieu of the data required to enlighten the decision process, uncertainty will persist. There are countless potential sources of uncertainty. They include professional judgments, professional disagreements, lack of information, inaccessibility of private property, interpolations and extrapolations of existing information, failure to recognize limiting factors, and on and on. For example, measurements of habitat variables critical to the estimation of habitat unit changes attributable to a plan frequently appear in precise point estimates that cover the data in a mantle of false precision and certainty. This issue is taken up in Chapter Six.

To a very great extent, efforts to quantify past conditions are, at best, guesswork. Rarely will planners have sufficient information to describe past environmental conditions with certainty. What would the current state of the environment have been in the absence of the Corps project? Is that what is motivating the restoration study? Would it have been different without the project? If so, would it have been better or worse? When we consider the cumulative impact of all the stresses on an ecosystem, it is not always evident that such a discussion has any real meaning for a complex, dynamic ecosystem. Thus, it may be better to acknowledge the uncertainty inherent in this backward looking analysis and to concentrate resources more on solving problems and seizing opportunities.

One of the more common situations in which uncertain values are left to stand unchallenged is when planners must rely on the judgments of professionals to describe past, present, and future conditions. These judgments are used in the absence of better information but they are rarely varied or tested. Planners infrequently say why this judgment is best and they never say why it is the only possibility. The accuracy of subjective data and judgments is always improved by providing an interval estimate. We're always more likely to be right when we can say an uncertain thing is between "this and that" rather than by stating precisely what it will be.

A complicating factor in identifying existing and future conditions for environmental restoration studies is that a static condition is inadequate for describing a dynamic system. What does it mean to describe the natural conditions of a dynamic ecosystem when conditions are constantly changing in nature? The point of these and other such questions is not to bog analysis down in esoteric questions as much as it is to get planners who work in the field of environmental restoration to begin to develop some introspection and insight into what is uncertain in the work they do so that they can identify those uncertainties that are most important; then find ways to address them.

STEP THREE: FORMULATE ALTERNATIVE PLANS

How can we have the best plan unless it's chosen from the set of best alternatives? If there is not a clear set of planning objectives, what guides the plan formulation process? How can there be a certain link between problems and solutions if we do not have, or have but don't use, planning objectives? From where do plans come? How do you know you have a good set of alternatives? Having the best plan is a "big picture" uncertainty, but it is most certainly not a trivial issue.

The greatest source of uncertainty in this step is, once again, ignorance of the planning process. If there is not a principled and structured approach to solving problems and seizing opportunities there is no way to know if an implementable project is really the best one or even a good one. Most project reports offered little evidence of a thorough formulation process. The choice of a plan is the most important decision made in the planning process. If risk and uncertainty analysis is intended to improve the quality of the decisions as well as the decision process, it is a tautological fact that the best choice can only come from the best set of alternatives. Planners can reduce the uncertainty about whether they have identified the best plan by eliminating the uncertainty attending their planning objectives and by providing as broad a range of alternatives as possible.

STEP FOUR: EVALUATE PLANS

The evaluation of plans requires well defined planning objectives and well formulated plans. This step is subject to many of the generic uncertainties already mentioned. A with project future condition must be identified for each alternative plan. This will require data, judgment and guesswork because it, like identification of the without project future condition, is a fundamentally uncertain exercise.

The decision process becomes even more uncertain in this step, however, because it requires assumptions about project performance. The performance of environmental restoration projects may be subject to more uncertainty than most projects, a topic taken up again in Chapter Six.

Any project is subject to uncertainties about costs and design. A common problem encountered in measuring plan effects is the tendency to substitute precision for accuracy. It may be comforting to see the cost of earth moving precisely estimated to be $2.45 per cubic yard (CY). The accuracy of this cost is another question. Do we really expect the cost per CY to be $2.45? How often are costs as accurate as they are precise?

Generally, estimators work with costs from a number of similar jobs. These costs tend to cover a range of values. The estimator's expertise comes into play in how he develops a point estimate from all the information gathered. The quality of the decision might actually be improved, however, if costs were estimated as a range. Then, decision-makers could see the range that costs could eventually span. Such information could also be used by analysts in combination with other information to provide a better estimate of the possible true range in costs per habitat unit produced by the project.

Environmental restoration projects may be more uncertain than other studies because there has been relatively less experience in building and maintaining them. Many things being done may be done for the first time. Even when planners are experienced it is not uncommon to run into substantial design and cost uncertainties because of a lack of foundation or hydrologic and hydraulic data, and so on. Planners might be wise to expect these common sources of uncertainty to be exacerbated in unique environmental restoration studies.

STEP FIVE: COMPARE PLANS

Once plan effects have been evaluated it is necessary to compare the effects of one plan to the effects of another plan as well as to the option of taking no action. A comparison of plan effects requires some criteria upon which the comparison will be based. Once again, those who are ignorant of the planning process may be laboring in the shadows of uncertainty. If the criteria upon which the comparison is based are not known to decision-makers there is the potential for considerable misunderstanding and error in the decision process.

The plans' relative contributions to the planning objectives provide the basis for the most objective comparison of plans. What is not known are the weights that stakeholders will place on the different plans' effects and their contributions to the various planning objectives. It may be easy to say that more of one thing beats less of that thing but it becomes very difficult to trade-off differences in the mix of contributions plans make to planning objectives. Thus, clarity and certainty of purpose in the study as well as in the explanation and display of results are essential to the reduction of common sources of uncertainty in many planning studies.

There is an additional source of uncertainty in environmental restoration planning. Not all of the benefits of these projects can be measured in dollar terms. This lack of a common metric means there is less reliance on the national economic development criterion of net benefits and more reliance on other criteria that may be less familiar to planners and stakeholders.

STEP SIX: SELECT A PLAN

In the final step of the planning process a course of action is chosen. This usually means the selection of a plan, although no action is always an option. At this step in the planning process, all the uncertainties encountered in the study become cumulatively and hopelessly hidden from the view of unsuspecting decision-makers unless there has been a systematic attempt to deal with risk and uncertainty throughout the process.

If significant issues have been obscured from the view of decision-makers there is a real possibility that an error will be made in plan selection. Bad investments may be made. Good investments may be overlooked. The sole purpose of introducing risk and uncertainty analysis to environmental restoration planning is to improve decisions. That happens in this step, but only if it has taken place throughout the planning process.

None of the sources of risk and uncertainty discussed in this section are unique to environmental restoration projects. Inasmuch as the newness of environmental restoration challenges planners at many levels, it would seem all the more important to engage in a structured, rational planning process as devoid of uncertainty as possible.

WHAT IS TO BE DONE ABOUT GENERAL SOURCES OF RISK AND UNCERTAINTY?

This chapter is not an indictment of the state of planning. It is instead an endorsement of the Corps' planning process. Virtually all of the sources of uncertainty identified in the preceding sections can be eliminated through the knowledge and use of the six-step planning process promulgated by the Principles and Guidelines.

A structured, rational framework for approaching environmental restoration problems can eliminate confusion about the purpose and the process of planning for planners and stakeholders alike. This would free planners to concentrate on those specific elements of a study in which risk and uncertainty analysis can be systematically applied in order to improve the quality of decision-making.

SUMMARY AND LOOK FORWARD

Just as there are broad concepts that can be used in risk and uncertainty analysis there are "big picture" issues of uncertainty encountered in environmental planning studies. These issues are not unique to environmental planning. In fact, they are more indigenous to the planning process than they are to the environment. Uncertainties are encountered in each step of the planning process and they can become cumulative if not addressed, virtually assuring that decision-makers labor in ignorance of potentially important issues. Nonetheless, the uniqueness and complexity of environmental plans suggests that the uncertainties inherent in the planning process may become particularly acute in environmental planning.

In addition to the big picture uncertainties, there are many uncertainties specific to environmental planning. Some of these are discussed in the chapter that follows. An example introducing risk-based analysis to the estimation of habitat unit changes is also offered to demonstrate the feasibility of some of the methods presented in the last chapter to addressing some of the problems of the next.

CHAPTER SIX: SELECTED SPECIFIC SOURCES OF RISK AND UNCERTAINTY IN ENVIRONMENTAL RESTORATION PLANNING

INTRODUCTION

This chapter considers potential sources of risk and uncertainty that are specific, if not necessarily unique, to environmental restoration projects. These sources of risk and uncertainty have been grouped for convenience into four topics for discussion. These are project performance, models, extrapolation, and, the habitat evaluation procedures (HEP) process. The HEP process is the primary focus of this chapter because it is one of the primary tools of environmental restoration analyses and, as such, is a logical point at which to begin looking for ways to introduce risk and uncertainty analysis.

PROJECT PERFORMANCE

Project performance involves some fundamentally uncertain issues. They range from questions about what environmental restoration projects produce to whether the management measures will result in what is wanted. This is the most basic environmental restoration uncertainty. What are environmental projects supposed to do and do they work? There was a surprising candor about the relevance of these questions encountered among Corps personnel interviewed during the preparation of this report.

PROJECT OUTPUTS

Many environmental restoration projects increase habitat units. But, what does that mean? The actual outputs of environmental projects were not often identified in the reports reviewed for this document despite the fact that EC 1105-2-206 *Project Modifications for Improvement of the Environment* requires them to be. When they are identified, they are frequently poorly specified. For example, one Section 1135 report's sole description of project outputs was "... aquatic insects would benefit...". Without judging the worthiness of such an output, most would agree that it may have been useful to identify the types of insects that would benefit, the extent of their benefit and the significance of that benefit.

There is no reason for project outputs to remain uncertain to either planners, decision-makers, or the readers of project reports. Although the outputs of flood damage reduction or navigation projects may be more or less taken for granted, outputs of environmental restoration projects need to be specified especially because they are new. Although habitat units may be one measure of project outputs, it should be clear that what a project produces is far more specific than simple HU's. They should be identified as completely as possible.

To do this well requires good planning. If problems and opportunities are carefully identified in the planning process, planning objectives can be specified. Achieving the planning objectives is the purpose of any plan. Hence, careful identification of planning objectives is an essential step in the specification of project outputs. Estimating habitat units is simply one means of evaluating and comparing the effects of plans developed during the planning process. Outputs can be measured in any number of ways, including habitat units, population counts, biological integrity, environmental values, energy flow, physical and chemical characteristics of water, and other ecosystem components. The Corps' Evaluation of Environmental Investments Research Program has an ongoing work unit, "Determining Objectives and Measuring Outputs", that addresses some of these concerns.

Too often, the vagueness or uncertainty surrounding project outputs is due to incomplete planning. It is impossible to develop good plans unless the objectives of those plans are clearly identified. Project outputs are contributions to the planning objectives. These should never be uncertain and they should always be clearly identified in the study documentation.

EFFECTIVENESS OF PLANS

A number of environmentalists and planners interviewed during the preparation of this report identified project performance as a fundamental source of uncertainty. One planner, paraphrased below, described the uncertainty rather succinctly. "We're fiddling with landscape - the spacing of plants, height of fill, number of duck boxes - and we're using our hydraulics and hydrology and water quality data to manipulate water. Will this result in what we want? If we build it, will they come?"

Can we manage salinity and water levels to increase diversity in the aquatic plant community for wildlife? Dozens of such questions can be posed. In some cases we can pinpoint projects that are remarkable successes. In other instances there have been abject failures. In all honesty, planners may not always know how well, if at all, their projects will succeed in achieving the planning objectives and producing the desired project outputs.

The uncertainty of project performance can be addressed in a number of ways. In some cases, planners have adjacent areas or similar projects they can use to gage project performance and place more reasonable bounds on the uncertainty accompanying project performance. When such projects are not available, sensitivity analysis can be used to test project performance.

For example, once the most likely future scenario has been used to evaluate plan effects, reductions in critical outputs can be considered. One might ask, if water quality improvements are only 90 percent of what we expect them to be, would we continue with the project? How about if they are 80, 70 or 60 percent of what we expect? Simple consideration of alternative outputs like this can help identify thresholds for the plan's success or for project support. Then the likelihood of those thresholds can be subjectively estimated to determine if this presents a significant possibility. See the sidebar on the next page for an example.

Sensitivity analysis can be more sophisticated. Critical variables in the evaluation and comparison of plan effects can be systematically varied or simulations can be used to model potential outcomes. An example illustrating how estimates of habitat units can vary is provided later in this chapter.

In some instances, the ecosystems are so complex and the solutions so experimental that monitoring of project performance after the fact is the only way to reasonably gage project performance. In these instances, the uncertainty of project performance would best be acknowledged during the study and used to design a satisfactory monitoring program. As more projects are constructed and monitored the bounds of uncertainty about project performance will be narrowed.

Some uncertainty over project performance can be addressed through simple sensitivity analysis. In other cases more sophisticated and systematic analyses may be helpful. In still other cases, monitoring of experimental projects may be the most appropriate way to handle uncertain project performance. In any event, one or more of these techniques are within easy grasp of Corps planners.

Simple Sensitivity

Suppose a project to produce a freshwater marsh has a salinity goal of 0-0.5 parts per thousand (ppt). If the project results in 1 ppt would it still be constructed? How about 1.5 ppt? Let's further suppose that such a thought process leads the study team to conclude that salinities could reach as high as 4 ppt before the project would be considered undesirable, based on the plan's contributions to the full set of planning objectives.

The next step in the sensitivity analysis would be to try and gage the likelihood of the events that would have to transpire to result in a 4 ppt salinity level. If these are judged to be unlikely, the plan can proceed with relative confidence that the project will at least achieve acceptable salinity levels. If the likelihood is greater than decision- makers would like then perhaps the plan requires some fine tuning or a more detailed risk analysis.

EXTRAPOLATION

Extrapolation is extending judgments or conclusions into an area that is not known or experienced. It is conjectural knowledge and it's everywhere in environmental restoration projects. Under the best circumstances, extrapolation is scientific guesswork. It is often the best we can do given the present limits to our knowledge. Planners are forced to extrapolate because the systems they work with are so complex and our knowledge of them is so incomplete. Under the worst circumstances, extrapolation can result from lack of knowledge or a lack of resources required to complete a study.

The very notion of identifying a target species and then using the condition of the habitat for this species as an indicator of the ecosystem's condition involves considerable conjecture. The assumed linear relationship between an HSI and carrying capacity, that is built into this approach, is also conjecture. Extrapolating the results of a project at one location to expected results of a project at another location is redolent with uncertainty, especially when there are significant differences between the locations.

Even fundamental cause and effect relationships are frequently extrapolated. For example, a decrease in habitat accompanied by a decrease in migratory ducks would often be considered prima facie evidence that habitat loss is causing duck losses. More careful study might indicate duck losses are due to overhunting and duck habitat is being lost because, as the ducks in this part of the country have disappeared over time, the opportunities (and hence the demand) for hunting, have fallen off. As a result, land that was once preserved for hunting the ducks that populated it may now be put to alternative uses. To some, these alternative uses could appear to be the cause of the decline in ducks when they are in fact the effect.

In more traditional environmental risk analysis, i.e., the analysis of human health risks, extrapolation is a major problem. Analysts must extrapolate the effects of low dosage exposure to a contaminant from data on high dose exposures. To complicate matters, the extrapolations must be made from laboratory animals to humans. Dredging studies consider similar issues when estimating the lethal doses that will kill 50% (LD50) of the fish exposed to a contaminant. To the extent that the EPA risk analysis paradigm may be adapted for Corps studies, for either environmental or ecological risk analyses, extrapolation may become an even greater problem.

Identifying extrapolation from the known to the unknown as a source of uncertainty is, in some respects, a cheap shot. When planners are forced to confront and deal with the unknown what else can they do but extrapolate? Given they have no choices, is it fair to criticize this method? Certainly not, if the sole intent is criticism.

Extrapolation, under the best circumstances, is stepping tentatively from the known to the unknown. Recognition of the uses of extrapolation is the most important first step in addressing the uncertainty that accompanies extrapolation. Frequently, planners extrapolate without recognizing they have passed from the known to the unknown. Little if any distinction is made between scientifically based facts and conjecture or speculation. Planners should recognize when they are extrapolating and say that is how they got from point A to point B.

Sensitivity analysis is, again, one of the most useful ways of resolving this problem. If we are forced to speculate and conjecture as we step from the known to the unknown, surely we can speculate on alternative outcomes of this step. When extrapolation is critical to study results it is advisable to first extend the limits of what is known. If additional data or analysis can reduce the realm of the unknown and, consequently, the uncertainty attending our extrapolation, getting the data and doing the analysis should always be the first step. When extrapolation is the best approach to a problem, it should be done openly and accompanied by sensitivity analysis when the results of the extrapolation could affect project performance or plan selection.

MODELS

Reality is complicated. Ecosystems are too complex to consider comprehensively in an effective manner. Models are used to get around these problems. Models are simplified representations of real systems that capture the most important elements of the system we want to understand.

Consider a map. If you want to tell someone how to get from one place to another you do not need a life size map that details every landmark and street encountered along the way. State maps show interstate highways and major roads only. If you draw a map for a friend it generally shows only the route you want her to follow, with occasional cross streets for reference. When giving directions you want people to have only the information they'll need to arrive at their destination. All else is extraneous detail. A map is a model of a much more complex and detailed real world.

Just as maps leave out most of the details and ignore a great deal of information, so do the models used by planners. Model uncertainty has been discussed previously and will be discussed in the next section as well. Nonetheless, model uncertainty presents a potentially significant source of uncertainty.

Models come in many forms. The Hydrologic Engineering Center's (HEC) models are well known by the Corps and around the world. The habitat evaluation process has spawned hundreds of HSI models. The Corps has developed a cost effectiveness and incremental cost analysis model for use in evaluating environmental projects. Dozens of spreadsheet models may be developed to perform specific calculations during any one study.

Expert opinions may comprise models. The six-step planning process used by the Corps is itself a model. Models abound in the environmental restoration planning process.

The responsibility of the planner who wants to deal effectively with uncertainty is to be aware of the assumptions underlying the models he uses and their limits. If important details are omitted from the model you use you're not likely to arrive at the proper destination. It makes no difference whether the model is an HSI model, HEC-2, or a simple spreadsheet computation you developed; if it lacks important details it could lead you to the wrong conclusion.

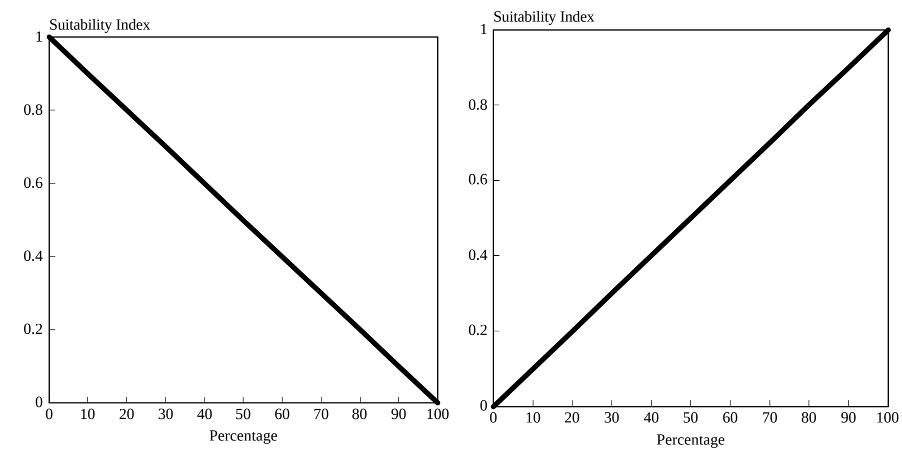
Many environmental restoration projects are conducted with existing data on limited budgets using available tools. These are circumstances that can lead to the use of models that are not ideally suited for the analysis. When this is the case, and it may often have to be, risk analysis may help compensate for the lack of detailed information.

Most HSI models are predicated upon an extensive review of the relevant literature. Conflicting views are sometimes averaged, other times ignored. Some suitability graphs are based on scientific evidence, many others are straight lines running from an SI of 0 and percentage of the habitat variable of 100 through an SI of 1 and a percentage of the variable of 0, or vice versa, as shown in Figure 11. The quality of the input data is usually an important constraint in any habitat evaluation. The following section takes a closer look at the potential uncertainty in the HEP analysis.

HABITAT EVALUATION PROCEDURE

Planners are interested in the restoration and protection of ecological resources. The viability of plant and animal populations is, however, difficult to quantify. Populations are generally assumed to be a function of the site's carrying capacity. Carrying capacity, in turn, is generally assumed to be a function of the quantity and quality of available habitat. Biological models linking levels of habitat quality and observable characteristics of the ecosystem of interest are a popular tool for estimating the effectiveness of a variety of management measures.

Figure 11: Sample SI Functions



At least 14 different techniques and models[22] have been developed to assist planners in the task of measuring plan effects on ecological resources. In general, these models rely on quantitative relationships among habitat variables such as depth of water, height of vegetation, percentage of submerged substrate and the like. Environmental restoration plans consist of management measures, either features or activities, that are expected to produce changes in the habitat variables. These changes in variables, in turn, translate into changes in habitat quality.

This section uses the U.S. Fish and Wildlife Service's (USFWS) habitat evaluation procedures, known as HEP, as the basis for its discussion. The HEP is one of the more widespread modeling procedures. The USFWS has developed a series of Ecological Services Manuals (ESM's) that provide considerable detail in the background and development of the habitat evaluation procedures. 101 ESM *Habitat as a Basis for Environmental Assessment*, 102 ESM *Habitat Evaluation Procedures (HEP)*, 103 ESM *Standards for the Development of Habitat Suitability Index Models*, and 104 ESM *Human Use and Economic Evaluation (HUEE)* provide the best available discussion of the HEP process. This discussion approaches the HEP process from the user's perspective rather than from the perspective of an analyst developing a new HSI model.

In order to make the linkage between plan effects and changes in ecological resources, the typical HEP analysis identifies a single species to serve as the target species. The underlying presumption is that if this target species is doing well, most other species in that ecosystem will likewise do well. In order to quantify existing and future habitat quality for the target species, a habitat suitability index (HSI) model is frequently used. These models may be developed specifically for a study or they may be USFWS models developed for general use for specific target species.

[22] These models are identified in Appendix C of EC 1105-2-210 *Ecosystem Restoration in the Civil Works Program*, 1 June 1995.

The HSI models identify the habitat variables that are most critical to determining the quality of the target species' habitat. In addition, they describe the nature of the mathematical relationships among those variables based on informed professional judgments, a potentially significant source of model uncertainties. The models provide a framework for describing the overall habitat quality through the estimation and measurement of habitat variables and the calculation of a variety of model components.

There is considerable uncertainty inherent in this evaluation process. The section that follows identifies some of the potentially more significant sources of uncertainty. The subsequent section presents an example risk analysis of a hypothetical HEP analysis to demonstrate the feasibility of incorporating basic principles of risk and uncertainty analysis into the habitat evaluation procedures.

POTENTIAL SOURCES OF UNCERTAINTY IN HEP ANALYSIS

The HSI model is one of the principal determinants of the change in habitat units that results from an environmental restoration plan, the other being the area of habitat affected by the plan. The HSI model is the focus of the discussion that follows.

There are four categories of uncertainty encountered in a typical HSI model. First, there are theoretical uncertainties. These include the basic premise of the HEP procedure and the model uncertainties discussed in previous sections. The existence of such uncertainties are acknowledged but not further addressed in this report. Second, there is uncertainty inherent in the "hard wiring" of the model, i.e., the relationships field analysts use without question, based on the literature review and professional judgments of the model's creators. Third, there are uncertainties attending measurements of model inputs by field personnel. Finally, there are uncertainties about project performance and future variable values without and with a project.

This section concentrates primarily on the uncertainty accompanying habitat variables for existing conditions as well as future conditions without and with a project , the third and fourth categories of uncertainty. Using the Morgan and Henrion approach to uncertainty analysis, the following subsections identify the type of quantity that is uncertain as well as the source of uncertainty and potential methods for addressing this type of uncertainty. This information is summarized in a table at the end of the section.

DELINEATION OF THE STUDY AREA

The HEP analysis study area is defined by the USFWS as ". . . those areas where biological changes related to the land or water use proposal under study are expected to occur." This would include areas affected directly or indirectly. Uncertainties can arise because project effects can involve complex biological linkages. Alternatively, privately owned lands that may be affected by a project are sometimes inaccessible to planners and may be excluded from the project area simply because they cannot be adequately investigated.

Simply identifying the area affected by a project is often an exercise in uncertainty. The planning area is a domain variable. The source of the uncertainty is approximation. Because this is a model domain parameter to be determined by project analysts it would be most appropriate to address the uncertainty, if it is judged significant, through sensitivity analysis. That is, alternative definitions of the study area can be analyzed to determine whether or not the recommended plan or its impacts are significantly affected by the definition of the study area. A more comprehensive definition of the study area could result in larger project-related changes in HU's and, consequently, lower incremental costs per HU. This is not likely to be a serious source of uncertainty in most instances. The default strategy would be to select the more encompassing area as the study area.

TARGET SPECIES

Formulation of plans intended to benefit a single target species could result in unintended adverse effects on other species. An HEP assessment is directly applicable only to the evaluation species. The degree to which results of an HEP analysis can be extrapolated to the larger wildlife community depends on the care taken in selecting the evaluation species. No one target species can adequately represent the welfare of all ecological resources in any but the simplest of ecosystems. Even species in the same guild can have very different responses to certain changes in the habitat variables.

During the early years of habitat evaluation, identification of a single target species was considered a giant step forward. As experience in developing and applying models has been gained, there is a growing realization that what was learned about target species modeling can be applied to communities as well. Many biologists contend the best HSI models would be community-level habitat evaluation models.[23] If that is not feasible, using a suite of evaluation/target species may better balance the diverse habitat needs of a community.

In truth, evaluation species are often selected with far less analysis and for far more pragmatic reasons. For example, advisory groups may have identified key species for previous studies or other purposes. Adopting one of them gains instant credibility from these groups even if the selections were not optimal for the specific study area. In other cases, non-Federal partners or other powerful stakeholders may identify the evaluation species. The less scientific the selection process the more important it becomes to do a sensitivity analysis, using a species that more effectively indicates the ecosystem function.

The target species is a decision variable. The associated uncertainty arises primarily from subjective judgment but there is potential for professional disagreement. Given the complexity of ecosystems it may be impossible to identify a single target species that represents the full range of potential ecological effects. Yet, study budgets may make community-level models or suites of species impractical choices. In this case the analyst picks the model that is most practical after weighing the analytical requirements of the study, its budget and other constraints.

A common source of disagreement can arise from the fact that there are at least two approaches to selecting the evaluation species. One is to pick a species with high public interest. Another is to pick a species that provides a broad ecological perspective of the area. A species of interest to hunters or fishers may be a pragmatic choice but it may not be a good indicator of the ecosystem's well-being. Disagreement over the objectives of the study could lead to disagreement over the evaluation species as well.

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[23] See "Guidelines for the Development of Community-level Habitat Evaluation Models" by Richard L. Schroeder and Sandra L. Haire, Biological Report 8 dated February 1993 for the USFWS.

The most appropriate treatment of uncertain decision variables from either of these two causes is to use a sensitivity analysis. That is, try other species and see if the plans would change. Given the potential sensitivity of habitat quality to key habitat variables and the sensitivity of these variables to management measures it is not difficult to imagine that plans could change significantly in some cases if different target species are used.

This analysis of different species can be done as a pure sensitivity analysis or it could be more appropriately done in the evaluation of a suite of target species. It is not likely that such a step would be possible for most small budget studies. However, in larger studies suites and sensitivity analyses may be appropriate.

HSI MODELS

Model uncertainty is not the focus of this discussion, but it is important enough that to ignore it would be negligent. The HEP analysis and the HSI models that are used in the HEP are all the result of informed professional judgment. Nevertheless, they are subjective. They are scientific guesswork.

There are some who would challenge the assumption that habitat quality is a good indicator of the viability of ecological resources, opting instead for condition or diversity indices, studies of energy flow and so on. There may be a tenuous relationship between carrying capacity and habitat quality as measured by the variables. The problem of extrapolating assumed impacts on the habitat of a target species to the well being of an entire ecosystem has already been touched upon.

There are still more specific sources of uncertainty. Habitat models in the HEP analysis must be in index form. The index runs from 0 to 1.0 and is dimensionless. An index of 0 indicates a complete lack of suitability of any area as habitat for the indicator species. An HSI of 1 identifies the area as an ideal habitat, in a practical sense. The HSI is defined as:

$$\text{HSI} = \frac{\text{Study Area Habitat Conditions}}{\text{Optimum Habitat Conditions}}$$

Furthermore, the use of an HSI model in an HEP process requires the HSI to be a linear index. That is, an improvement from 0.1 to 0.2 is the same magnitude as an improvement from 0.8 to 0.9. It requires a heroically optimistic leap of faith to expect the relationship between HSI and carrying capacity to be linear. Linearity may not be a realistic assumption but it does allow us to proceed.

The HSI is an index variable that purports to relate habitat and carrying capacity. Many users of the HEP may not understand its assumptions and limitations. Uncertainty may arise from imprecise language that results in less than a clear understanding of what an HEP or an HSI is to do. The most effective treatments for this are education and training.

The structure of the models, i.e. the “hard wiring”, is another important source of potential model uncertainty. Not all habitat variables are of equal importance to the quality of the target species’ habitat. Assumptions about the relative importance, the additivity, and compensation among variables are built into the mathematical assumptions of the model. For example, the relationships among variables that determine a particular life requisite might be modeled as follows:

$$HSI = \text{lesser of } V_1 \text{ or } [(V_2\ V_3)^{.5} + .5(V_4\ V_5)^{.5}]$$

This formula yields an analytical result. It is nothing more than an attempt to reflect the relative importance of different variables in determining the quality of a habitat. It gives a predominate role to the limiting factor V_1. The weights assigned to the other four variables by the formula are very subjective. Suppose we used a cube root instead of a square root? Suppose the variables were additive rather than multiplicative? Should the weight for the $(V_4\ V_5)^{.5}$ factor be .25 or .75 instead of .5? Would these or any other changes have an effect, significant or otherwise, on the evaluated effects of the plan or on plan formulation?

In addition to concerns about the extent to which the models reflect the workings of ecosystems, we need to be concerned about how people learn the HSI procedures. Are they all trained and certified by USFWS or do they learn it by looking at previous reports, talking to people who have done them before, or winging it? Expert opinion, the development of special models, and peer review may be methods for improving the structure of HSI models.

As good as these new biological models are, they are still only models and are subject to potential model uncertainty. As noted earlier, model uncertainties may be the most significant and the most difficult to deal with. Model uncertainties, as important as they may be, are not the uncertainties that Corps planners should deal with first. They are mentioned here, however, because they may, in the long-run, prove to be among the more important sources of uncertainty and they should not be forgotten.

HABITAT VARIABLE MEASUREMENTS

Estimating the existing values of habitat variables is perhaps the most basic source of uncertainty in the HEP analysis. Many environmental restoration projects are small budget planning studies. Although the HSI models usually provide recommendations on the collection of data, Section 1135 studies, for example, are intended to be based as much as possible on existing data. The HEP analyses for these projects are often subjective.

Typically, data must be collected on variables that define the species' life requisites. These include cover type, food, and other factors. Baseline habitat data will generally be based on subjective estimates (opinion), primary data (field measurement) and secondary data (e.g., remote sensing). For example, estimates of the percentage of unsubmerged substrate, the percentage of land in the affected area, the height of vegetation or the depth of water may be based on conversations with professionals familiar with the study area or on very cursory eyeball estimates. These estimates carry the weight of informed professional opinion. It is a matter of convenience that we not challenge these numbers because to do so would increase study budgets and analytical requirements. Or would they?

As the example in the section that follows shows, it is a relatively easy matter to increase the accuracy of one's estimate of the value of habitat variables by using interval estimates rather than point estimates.

Although point estimates are more precise, they are never more accurate. If an analyst's job depended on being right, who would prefer to say the average depth of water is 30 cm to saying it is between 25 and 35 cm?

When an analyst is not sure of the exact value of a variable it is just as easy to have him estimate it as an interval as a point. That is no extra work. In fact, going from an uncertain interval over which he feels fairly comfortable in his accuracy to a seemingly certain single point, is often the more difficult task.

When study budgets are sufficient or when the problems are significant enough, planners may actually take measurements of variables. This will invariably be a sampling process. It may be done through remote sensing techniques, using geographic information system databases or it may be direct field measurements. When sampling is used, inferential statistical techniques can be used to estimate the parameters of the sampling distribution. The sample data are used to estimate a sample mean and a standard error. These values can then be used to define a normally distributed sampling distribution or confidence intervals. These results can be used for subsequent risk analyses.

The habitat variable quantities are empirical quantities. They are uncertain because of measurement error, statistical variation, subjective judgement, disagreement, variability, inherent randomness or approximation. The treatments of such uncertainties span the range of analytical techniques discussed earlier in the manual.

EXISTING HABITAT UNIT ESTIMATES

An HEP analysis is structured around the calculation of habitat units for each evaluation or target species in the study area. HU's are defined as the product of the Habitat Suitability Index (quality) and the total area of habitat (quantity).

The HSI for available habitat is a function of the suitability of all the evaluation species' life requisites in the study area. Every model has specific data requirements and a unique mathematical relationship for combining the habitat variables into an HSI. The HSI for available habitat can embody many different and cumulative sources of uncertainty. These include uncertainties about the representativeness of the target species selection, uncertainty about the habitat variables as well as model uncertainty about the manner in which an HSI is calculated.

Ideally, it may be desirable to develop different HSI's for sections of the study area over which the quality or quantity of the habitat variables vary significantly. It is common practice, however, to calculate a single HSI. Although such an HSI should represent average conditions over the study area, it is rarely clear from the study reports whether that is the case or not. Thus, there is a fundamental question about what the calculated HSI represents. Is it the average HSI? Is it representative of the entire study area or a small part of it?

In addition, there may be some uncertainty about the amount of land that will be affected by the proposed project. This uncertainty could arise from measurement errors (e.g., planimetering inexact areas on maps of questionable accuracy) or basic uncertainty about the spatial extent of project effects.

The estimate of existing HU's is an outcome variable and its uncertainty is derived from the various sources of uncertainty that affect the quantities that determine HU's. The treatments of these uncertainties span the gamut of known methods.

FUTURE HABITAT VARIABLE ESTIMATES

Measurements of existing habitat variables are theoretically determinate. Given enough time and money, analysts could go out into the field and take careful measurements that would enable them to quantify habitat variables with a high degree of certainty. Estimates of future habitat variable values are by their nature uncertain. There is no way these values can be certain no matter how much time or money the investigators have. Forecasting the future is fundamentally uncertain.

At least two estimates of future habitat variable values must be prepared. One describes what will most likely happen to the habitat variables if no project is implemented. The other describes what will most likely happen if a project is implemented. There must be a with project future forecast for every alternative plan evaluated. It seems a matter of basic honesty in the analysis to acknowledge the uncertainty inherent in this aspect of the HEP analysis.

These values are chance variable quantities (i.e., empirical quantities) and their sources of uncertainty include subjective judgment, professional disagreement, statistical variation, variability, and inherent randomness. Treatments of the uncertainty could include most known methods.

CHANGE IN HU'S

Ostensibly, the purpose of the HEP analysis is to calculate changes in habitat units that are attributable to project effects. An increase in HU's is one measure of the presumed outputs of the project. The change in HU's is, in Morgan and Henrion's language of uncertainty, an outcome variable. It is an uncertain value if any of the models or values required to estimate it are uncertain. If there is model uncertainty, uncertainty about the spatial extent of project effects, uncertainty about the choice of evaluation species, uncertainty in the measurement of variables, and so on, then there is also uncertainty in the measurement of project outputs as evidenced through the change in habitat units from the without project to the with project condition.

The timing of changes in habitat variables can ultimately have significant effects on the change in HU's for a study area. That is, do the forecast changes in habitat variables take place instantaneously or over many years? Devoting more attention and detail to estimating the temporal sequence of changes in habitat units can be another effective way of dealing with a potentially significant source of uncertainty.

PROJECT PERFORMANCE IN HEP ANALYSIS

A Corps biologist consulted during the preparation of this manual pointed out that the public often knows what it wants but translating that into terms an engineer can deal with is difficult. He aptly described the challenge when he said, "Land managers talk function and feathers while engineers talk feet and inches." Nonetheless, he pointed out that when a community has the resources and facilities of the Corps of Engineers to do good things for the environment, that is an advantage most environmentalists will never have.

Two uncertain issues arise regarding environmental projects. One is, do we have the right project? The other is, will it work? The first issue requires us to ask the question, can this project contribute to our planning objectives? The follow-up question is, will it? During the preparation of this manual a surprising degree of frankness was encountered among Corps personnel concerning the basic uncertainty about the performance of environmental projects.

The environmental restoration programs are new. The ecosystems are complex. And, although the science is often state-of-the-art, it can only take the analysts so far, then they must guess and hope. How long will the geotubes last in the water? Will the coconut fiber grass mats take root? Will the plants that grow in the restored wetlands provide a diversity of food and cover for species or will invasive plants with little or no food and cover values grow? Will the closure structure allow the marsh to drain in time to prevent disruption of salinities and nests in the normally unsubmerged substrate? The performance questions go on and on.

Even though virtually every analyst consulted could raise questions about the performance of their projects, none of the project reports reviewed reflected this uncertainty. That is not surprising. Admitting a project could have an outcome other than the one the partners hope for does nothing to build support for the project. Until data on project performance begin to become available through monitoring programs, there is no objective way to know how serious a problem this may be, if it is a problem at all.

At this point, we simply note that project performance is a potentially significant source of uncertainty. It is, in fact, an empirical quantity, a chance variable, but it is estimated as an outcome variable. Defining alternative with project conditions that reflect different outcomes and evaluating the changes in habitat units under each is one feasible way to address this problem.

Table 5 summarizes the uncertainties described in this section. They are precisely the kinds of uncertainty that would be addressed in the example that follows, although emphasis in the example is on the last two items in the table.

Table 5: HEP Uncertainties			
Item	**Type of Quantity**	**Source of Uncertainty**	**Treatment of Uncertainty**
Study area	Model domain	Approximation	Sensitivity analysis
Evaluation species	Decision	Disagreement, statistical variation, subjective judgment	Sensitivity analysis
Total area	Empirical	Approximation, statistical variation, subjective judgment, variability, disagreement	Sensitivity analysis, probability distribution, sampling distribution, uncertainty criteria, expert opinion
Habitat variable measurements	Empirical, decision, index	Approximation, statistical variation, subjective judgment, variability, linguistic imprecision, disagreement	Education & training, sensitivity analysis, probability distribution, sampling distribution, uncertainty criteria, expert opinion
HU's	Outcome	Approximation, statistical variation, subjective judgment, variability, linguistic imprecision, disagreement	Education & training, sensitivity analysis, probability distribution, sampling distribution, uncertainty criteria, expert opinion

RISK ANALYSIS EXAMPLE: MOTTLED DUCK HSI MODEL

Is risk-based analysis of environmental restoration projects feasible? What will it take to do such analyses? This section presents a simple example of how risk-based analysis can be used to estimate the expected change in HU's. The example uses the mottled duck HSI model to demonstrate the feasibility of risk analysis with commonly available basic information. Data from a 1992 Section 1135 study were modified and used for this analysis. The subsections that follows describe the analysis and its results.

The basic elements of the mottled duck model are described below. This example focuses on how the uncertainty in input data can be reflected. No attempt is made to address model uncertainty, though some opportunities for doing so are discussed. The modification of the data was arbitrary. The results of the example analysis have no significance beyond the demonstration. They have absolutely no bearing on the original study.

Mottled Duck HSI Model

The description that follows is taken from the September 1983 *Habitat Suitability Index Models: Mottled Duck*, FWS/OBS-82/10.52. The model was prepared by James C. Rorabaugh and Phillip J. Zwank of Louisiana State University for the Fish and Wildlife Service of the U.S. Department of the Interior. The relationship of the habitat variables and life requisites to the habitat suitability index are shown in Figure 12. The HSI is a function of three life requisites: cover, food and other (disturbance level). There are eight habitat variables defined as shown below. Suitability graphs transform habitat variable measurements into suitability indices on a 0 to 1 scale. The functional form of their suitability graph is given in parenthesis.

V_1 = Percentage of unsubmerged substrate covered by rushes, bullrushes, or cattails. (Linear suitability graph.)

V_2 = Percentage canopy cover of trees and shrubs on unsubmerged substrate. (Piecewise linear suitability graph.)

V_3 = Structure of herbaceous vegetation on unsubmerged substrate. (Step function suitability graph with four classes/steps.)

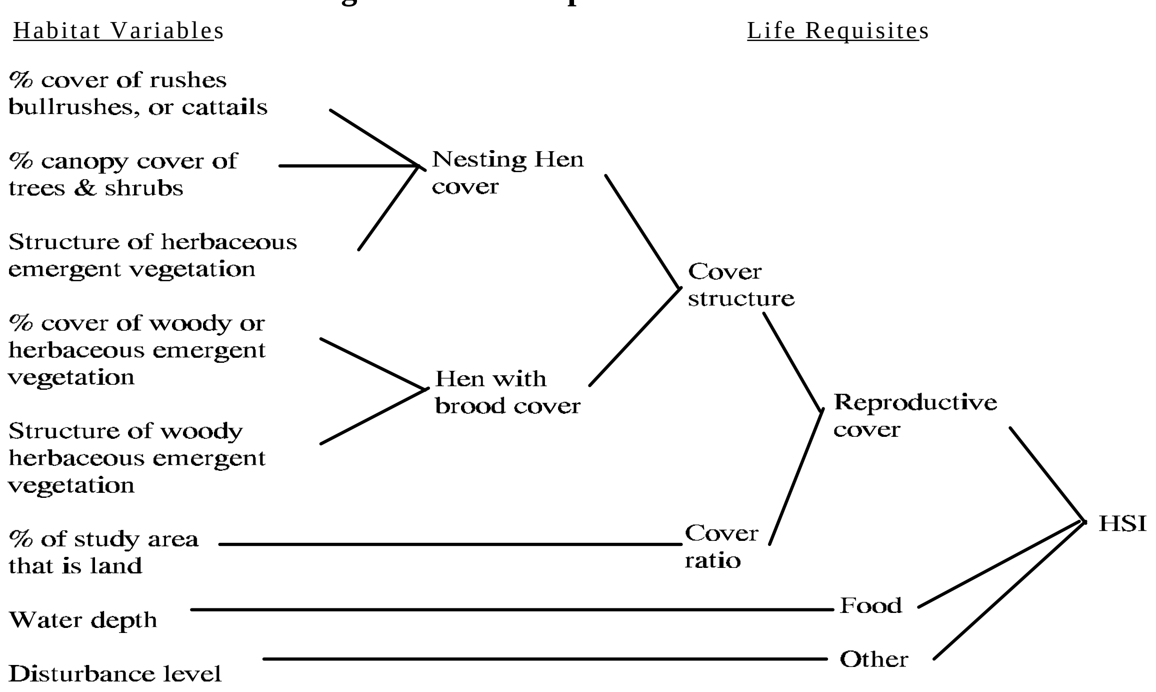
V_4 = Percentage of continually submerged substrate covered by woody or herbaceous emergent vegetation. (Piecewise linear suitability graph.)

V_5 = Structure of woody or herbaceous emergent vegetation growing in continually submerged substrate. (Step function suitability graph with four classes/steps.)

V_6 = Percentage of study area that is land. (Piecewise linear suitability graph.)

V_7 = Percentage of continually submerged substrates with water depth less than 30 cm at

Figure 12: Sample HSI Model



low mean tide. (Linear suitability graph.)

V_8 = Disturbance level: extreme; moderate; minimal; and, none. (Step function suitability graph.)

Four model components and three life requisites are calculated using these input variables. Nesting hen cover (NHC) is the cube root of the product of the SI's for V_1, V_2, and V_3. Hen with brood cover (HBC) is the square root of the product of the SI's for V_4 and V_5. Cover structure (CS) is defined as the minimum of NHC or HBC. The cover ratio (CR) is the SI for V_6. The reproductive cover life requisite (C) is the cube root of the product of CS squared and CR. The food life requisite (F) is the SI for V_7. The other life requisite (O) is the SI for V_8. The mottled duck HSI is the minimum of C, F or O.

To demonstrate the feasibility of introducing simple risk analysis to the estimation of an HSI the mottled duck model was built in a spreadsheet.[24] Appendix A explains the spreadsheet model in greater detail. The original Corps analysis estimated the existing condition HSI to be 0.31 and the improved condition HSI was 0.79. To simplify this demonstration a simple comparison of with and without condition HSI's is used. There is no discounting or multi-year analysis. In order to allow the investigation of the effect of a risk analysis on potential incremental costs, habitat units were computed using the same 1,000 acres of land used in the original Section 1135 report. Project costs of $1,824,000 were used. Because a single increment of 1,000 acres was used in this calculation for demonstration purposes, the example should not be considered a true incremental cost analysis. Although it does reflect the approach of the original report a true incremental cost analysis requires different increments of output.

Using the original without and with project condition input data from the 1992 report, habitat variable values were allowed to vary according to a simple probability distribution. A value for each variable was randomly sampled from this distribution using a Latin Hypercube process and these values were then used to generate other model components, the HSI's without and with the project, and the change in HU's and the incremental costs of those changes.

For example, V_1, the percentage of unsubmerged substrate, was estimated in the report to be 10 percent without or with the project. In the example, this value was arbitrarily allowed to vary from 0 to 20 percent[25]. A uniform distribution was used for simplicity.

It would not be uncommon for an analyst working under budget and time constraints to be uncertain of the actual percentages and classes of habitat variable values. Although it may be more precise for the analyst to say the percentage of unsubmerged vegetation is 10 percent that is not likely to be the actual value. It would most likely be far more accurate to estimate this variable with an interval, like 0 to 20 percent. Though far more

[24] Excel v. 5.0 with the @RISK add-in v. 3.1 was used to develop the model. A more detailed explanation of the model is presented at Appendix A.

[25] Uniform distributions were used. The minimum and maximum values were obtained by adding and subtracting 10 percent to/from the value used by the District, except where a logical constraint of 0 or 100 prevent this. These arbitrary changes were made for the sake of simplicity.

sophisticated analyses could be done, this simple change serves the purpose of demonstrating the ease with which interval input data can be obtained and used.

The actual range of values could be estimated from confidence intervals obtained from the sampling distribution of a proportion (or mean) if sampling from aerial photographs or field measurements are used. Or, it could be based upon the opinion of knowledgeable personnel of the resource management agency. Alternatively, it might be based on the "eyeball" estimate of the Corps biologist. In any case, it is a relatively simple matter to prepare interval estimates of input variable values.

Rather than enter V_1 as 10 percent, the unsubmerged substrate was estimated to range from 0 percent to 20 percent. A uniform distribution was assumed for all input variables in this example. Table 6 summarizes the without project condition distributions used for the input variables. With condition distributions were changed for the variables the project was expected to improve. The minimums and maximums of the uniform distributions are presented as percentages in the table. Percentages of each of the four classes for the step function habitat variables are provided. Classes that are not listed are not present in the study area and are assumed to equal zero percent. Thus, for V_3 there is 0 to 10 percent in Class 3 with the remainder (90 to 100 percent) in Class 4.

Table 6: Without Project Condition Distribution Parameters

Variable	Uniform Distribution Min and Max
Class 3% for V_3	0, 10
Class 4% for V_3	90, 100
Class 3% for V_5	0, 10
Class 4% for V_5	90, 100
Class 3% for V_8	0, 10
Class 4% for V_8	90, 100
V_1	0, 20
V_2	0, 10
V_4	0, 20
V_6	10, 30
V_7	70, 90

Using the Terminology

Early sections of this report developed a taxonomy of uncertainty that can be used to help an analyst to think about how to approach the analysis. Table 5 presented a somewhat generic example. Here you'll find a more specific application of the concepts to the mottled duck model. The example is a hypothetical one, loosely based on an actual study.

Item	Type of Quantity	Source of Uncertainty	Treatment of Uncertainty
Study Area	Model domain parameter	Approximation	Assumed certain
Mottled Duck	Decision variable	Subjective judgment	Assumed certain
1,000 Acres	Empirical parameter	Approximation	Assumed certain
V_1	Empirical parameter	Variability	Probability distribution
V_2	Empirical parameter	Variability	Probability distribution
V_3	Empirical parameter	Variability	Probability distribution
V_4	Empirical parameter	Variability	Probability distribution
V_5	Empirical parameter	Variability	Probability distribution
V_6	Empirical parameter	Approximation	Probability distribution
V_7	Empirical parameter	Approximation	Probability distribution
V_8	Empirical parameter	Subjective judgment	Probability distribution
HSI	Outcome criterion	All the above	Determined by inputs
HU's	Outcome criterion	All the above	Determined by inputs
$ per HU	Outcome criterion	All the above	Determined by inputs

The first three quantities have been assumed to be determinate values, i.e., the analyst considers them to be certain values. These items are not treated as uncertain in this analysis. This was done because of the "politics" of the study. The first five habitat variable values are based on the results of sample measurements. They are uncertain because of the variability in the sample results. The sixth and seventh habitat values were based on approximations made from aerial photographs. The eighth variable value is based on the subjective judgment of the park rangers who are most familiar with the project area.

The treatment for the habitat variable uncertainty is to represent the potential range of values as a probability distribution. The last three items are outputs of the model. The uncertainty in them is a result of the uncertainty in the variables from which they are calculated.

A Latin Hypercube procedure was used to transform the HSI model from a simple calculation to a simulation model. The model calculated a without project HSI, a with project HSI, HU's without and with the project, as well as the change in the number of HU's attributable to the project during each iteration of the model. The cost per each additional HU was also calculated. One thousand iterations of the model were run in which a value was randomly selected from each input distribution and "plugged" into the HSI computation. Thus, 1,000 pairs of HSI values, HU's and their costs were separately computed based on the varying inputs shown in Table 6.

The results of the simulation are summarized in Table 7. Minimum, maximum and mean values are presented for selected model outputs. For example, the minimum observed HSI without the project was 0 while the maximum observed value was 0.42. The average without project HSI for the 1,000 calculations was 0.23[26]A simple variation of the input variables results in a considerable range in potential project outputs. The project could produce as few as 282 HU's at an incremental cost of $6,479 each (costs are present values, not average annual equivalents) or as many as 750 HU's at $2,432 each. Figure 13 shows a cumulative distribution of costs per habitat unit. There is a 30% chance HU's will cost less than $4,000 each and nearly a 70% chance they'll cost less than $5,000 each. The mean number of HU's obtained in this 1,000 iteration simulation was 456 HU's at an incremental cost of $4,350 each.

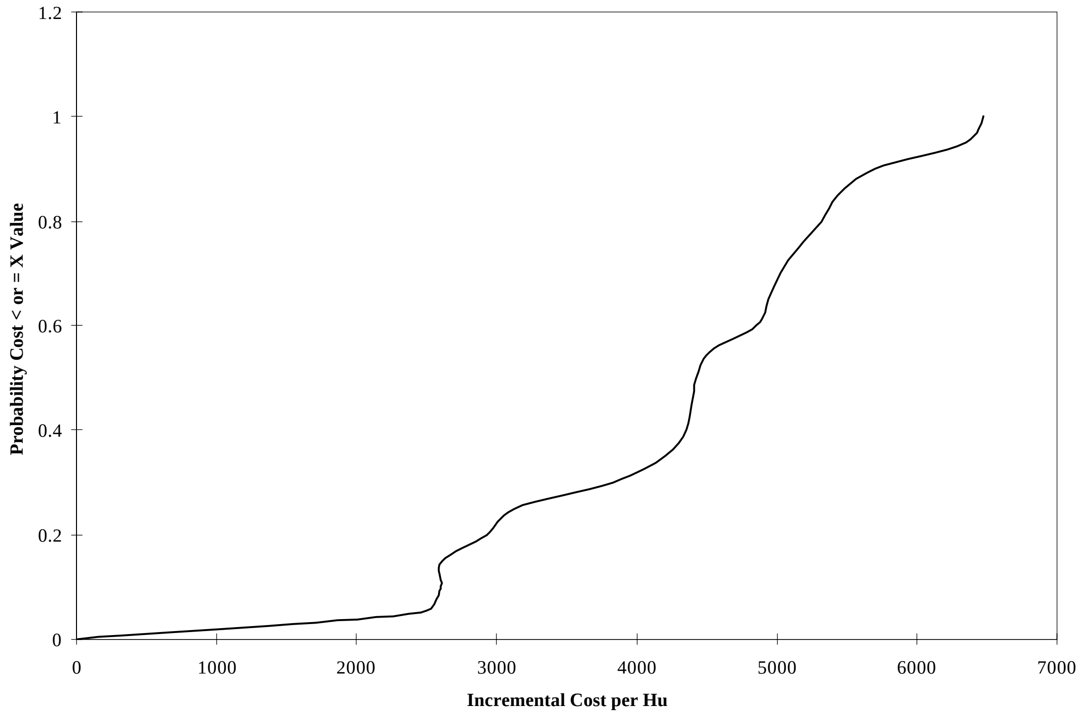
Table 7: Selected Simulation Results

Item	Minimum	Mean	Maximum
HSI Without	0	.23	.42
HSI With	.58	.69	.75
HU's Without	0	232	417
HU's With	580	688	750
Change in HU's	282	456	750
Cost per HU	$2,432	$4,350	$6,479

These results make the uncertainty in project performance very apparent. The number of HU's that result are estimated to be between 282 and 750 HU's. The incremental cost of these HU's is likewise uncertain. However, if the maximum cost of $6,479 per HU is reasonable there is little reason to question the wisdom of implementing the project. Now, suppose for the sake of this example that $6,000 per HU is considered the maximum feasible incremental cost for political, institutional, economic or other reasons.

[26] Despite the tendency to want to reproduce table results from table values, that generally cannot be done. For example, the minimum change in HU's is 282 but the minimum number of HU's with the project less the maximum number of HU's without the project do not yield this value. That is because these minimum and maximum values were not observed during the same iteration of the simulation.

Figure 13: Cumulative Distribution Function for HU Costs



The cumulative distribution function (CDF) indicates that taking all the considered uncertainty into account there is only a 10 percent chance costs will exceed this level. Thus, we're about 90 percent sure the project will result in acceptable costs per unit of output. These are a few examples of the results of a risk analysis that could lead to a better informed decision process.

The range in the HSI, HU and cost values is due largely to the structure of the HSI model[27]. In this case, once life requisite indices are calculated for cover, food, and other (i.e., disturbance), the minimum of the three becomes the HSI. Although model uncertainty is not the focus of this example, a simple sensitivity analysis of this HSI formula was conducted to demonstrate the feasibility of such analyses.

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27 A preliminary test of the risk-based HSI model used data provided in the USFWS description of the mottled duck model. Varying the input variable values in this document as described above led to quite a different result. Because the HSI in this model is simply the minimum of three life requisite SI's, a single SI always determined the HSI. In an extreme case like this an analyst need gather data only on a that single constraining input variable, the one that determined the controlling SI in this preliminary case. The point to be drawn from this is that there is a great deal that can be learned about HSI models from risk analysis. Some of this may be helpful in directing data collection and other strategies.

In addition to examining the decision rule of selecting the minimum life requisite SI as the HSI, two alternative decision formulas were investigated to determine the sensitivity of project outputs to the HSI formula. The first was a simple average of the three SI's. The second was the cube root of the product of the three SI's. There are substantial differences among the means, as well as the extreme values that result from such a sensitivity analysis as Table 8 shows. "Minimum" means the HSI is based on the minimum of the three life requisite SI's. "Average" means the HSI is the average of the three life requisite HSI's. "Cube Root" means the HSI is based on the cube root of the product of the three life requisite SI's. Using an average of the SI's leads to substantially higher HU costs. The cube root formula could lead to cheaper HU's but, on average, HU costs would be expected to increase.

This is a single example and generalizations cannot be made from it. It's a hypothetical example that offers only anecdotal evidence about the mottled duck HSI and no evidence about other HSI models. The example is sufficient, however, to make the point that model uncertainty can be a significant concern in the estimation of HSI's.

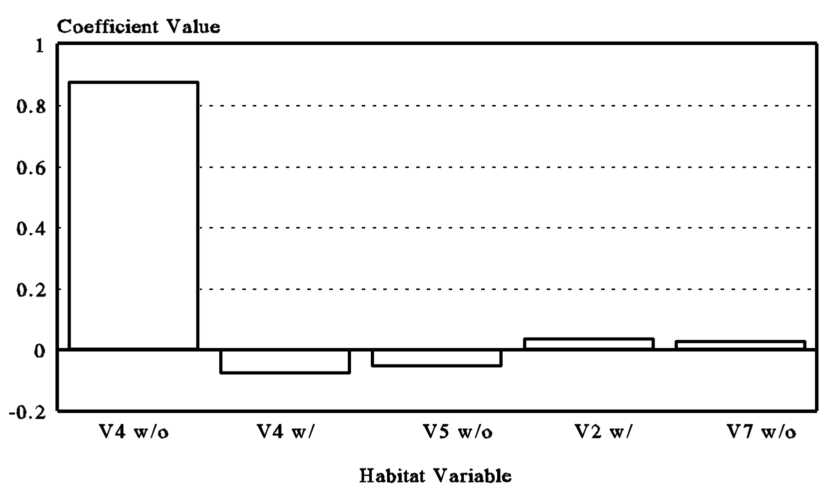
There are many points in an HSI model where somewhat arbitrary looking formulas are used to weight variable SI's or life requisites SI's. These formulas ultimately determine the HSI's and the change in HU's.

Table 8 indicates that estimates of project outputs are very sensitive to how life requisite SI's are combined into an HSI. These alternatives were used as an arbitrary test of the sensitivity of the HSI to the decision rule. They were not used to suggest the model is incorrect, only that the results are sensitive to the model's structure. Investigating the cumulative sensitivities of HSI's to these various formulas as well as to the suitability graphs and input data would seem to be a fruitful area of future risk analysis research.

Table 8: Model Sensitivity Based on Choice of HSI Formula			
Rule	**Minimum**	**Mean**	**Maximum**
HU's: Minimum	281	456	750
HU's: Average	95	168	291
HU's: Cube Root	156	360	842
$/HU: Minimum	$2,432	$4,350	$6,479
$/HU: Average	$6,278	$11,758	$19,257
$/HU: Cube Root	$2,168	$7,330	$11,711

Risk analysis has the ability to indicate which variables are most important in the determination of the HSI's, the HU's, or the incremental cost per HU. Figure 14 shows the relative importance of variables influencing the cost of HU's[28]. The most important variable was the percentage of submerged substrate under the without project condition, which has a strong positive influence on costs. The second most influential variable was the percentage of submerged substrate under with project conditions. Variable V_5 without the project, V_2 with the project, and V_7 without the project, are the other influential variables shown in the tornado graph.

Figure 14: Regression Sensitivity for $/HU



[28] Using cost per HU as the dependent variable, single variable linear regressions were run using each input variable as the independent variable. The graph reports those input variables with the largest significant coefficients.

Results like these may be helpful in providing insight into the workings of HSI models. It would surely be helpful to know which variables are most important before data are collected. Such information could be very useful in developing data collection strategies. Even after the fact this information is useful. It suggests that if we want to improve our estimates of HU costs it would be best to get careful estimates of the percentage of submerged substrate.

The example presented here establishes at least three facts. First, it is relatively easy to use spreadsheet-based Monte Carlo/Latin Hypercube simulation to introduce risk analysis into the estimation of HSI's and HU's based on varying data inputs. Second, the results of at least some HSI computations will be extremely sensitive to the HSI model's structure. This implies that HSI model uncertainty may be important enough to warrant future investigation. Third, the results of risk analysis can help analysts understand the relative importance of the various uncertain factors. This information may be helpful in data collection strategies, plan formulation, and incremental cost estimation.

The possibilities for introducing risk analysis to environmental restoration projects does not end with this brief discussion of HSI models. For example, at this writing a beta version (2.6) of *ECO-EASY: Cost Effectiveness and Incremental Cost Analysis* software is available to Corps personnel. It marks a significant contribution to the evaluation of environmental restoration projects. It is, however, a deterministic evaluation that could possibly be modified to incorporate variation in the expected number of habitat units produced by a project as well as to reflect uncertainty in project costs.

SUMMARY AND LOOK FORWARD

Four major sources of uncertainty in environmental restoration projects have been tentatively identified. They are project performance, extrapolation, models, and the habitat evaluation procedure. A simple example was presented illustrating how risk-based analysis could be used to address some of the uncertainty inherent in the HEP analysis that is so common to environmental restoration projects. Selected results from this analysis were presented to demonstrate the types of outputs that can result from a risk-based analysis. A few suggestions were offered to show how these outputs might enlighten and improve the decision process.

The report concludes with the summary found in the next chapter.

CHAPTER SEVEN: SUMMARY AND CONCLUSIONS

First steps are always frustrating. It takes so long to work up the courage to take one, then, once taken, there are so many places we'd like to go, and so quickly. Introducing risk and uncertainty analysis into the evaluation of environmental restoration projects now stands where introducing risk and uncertainty analysis in general stood with the Corps a decade ago. The concepts are vague. Illustrative examples using specific tools and methods field personnel can use are yet to be developed. The required expertise does not yet exist in many districts. The costs to the study are unknown. The impacts on plan formulation and project construction are speculative but largely feared. The motivation for the change is poorly understood and widely suspected. The people who will have to embrace the changes may be unconvinced of the need to do so and appear resistant. And few can imagine how any of this could possibly improve decisions and decision-making.

To combat these, and other attitudes, two things are absolutely clear. First, any risk and uncertainty analysis must be purposeful. Second, it must be scaled to the study.

A purposeful risk and uncertainty analysis will improve decision-making. This has always been the primary purpose of risk and uncertainty analysis. Risk analysis, once implemented, will help us to avoid errors. In a world of scarce program resources it is essential that bad investments be avoided. It is equally essential that good investments not be overlooked. Simple analyses, such as the example presented in the preceding chapter, present a full range of potential results that provide decision-makers with a much more complete picture of the range of potential project outcomes. The true value of such analysis will not be evident until the tools are used.

Risk and uncertainty analysis will subject studies to more scrutiny. They will require new analysis and possibly some more data, but these are reasonable costs to incur to improve decision-making if the analysis is scaled to the study. Environmental restoration analyses, like other Corps studies, vary in size, significance, priority and budget. It would be inappropriate, for example, to require analysts to address all the potential sources of uncertainty identified in this report for any environmental restoration study. For example, although model uncertainty may be a significant source of uncertainty in the HEP analysis, the Corps analyst does not always have influence over the development of these models. To address these concerns could require inter-agency cooperation that is well beyond the scope of agency needs at this point. When Corps analysts develop the HSI models it would be prudent to consider model uncertainty.

It is more important to look for things that can be done easily to improve decision-making. Section 1135 studies were to be done based largely on existing data. Habitat variable measurements in these studies may be along the lines of, "It looks like 40 percent to me, how about you?" In such cases, it would be inappropriate to require detailed field measurements to limit the uncertainty attending these "eyeball" estimates, but it would not be unreasonable to make that subjective estimate as an interval. "That's somewhere between 30 and 45 percent, don't you think?" As the study's scope, budget, and significance increase there may be compelling reasons to increase the sophistication of the analyses, but only if those changes can be demonstrated to improve the quality and timing of decision-making.

This report has attempted to advance the discussion of introducing risk and uncertainty analysis into the evaluation of environmental restoration projects. It has done that by providing some overview discussion of environmental planning and risk and uncertainty analysis. It has considered generic and specific potential sources of uncertainty likely to be encountered in the environmental planning process. A simple example has shown the feasibility of developing low cost methods for using some risk-based analysis.

At least two subsequent steps appear warranted. The first and most important is to expand the discussion of introducing risk and uncertainty into environmental restoration analysis. The attitudes mentioned at the opening of this section can only be addressed as the education and debate processes proceed. This report may find some role in furthering that education and debate.

The second step would appear to be to demonstrate the feasibility and purpose of risk and uncertainty analysis by applying it to an on-going study effort. Nothing succeeds like success, it has been said. And nothing will advance the cause of risk-based decision-making in environmental restoration projects as well as a successful demonstration of its ability to contribute positively to the decision-making process.

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APPENDIX A:

MOTTLED DUCK RISK MODEL

INTRODUCTION

The risk-based analysis presented in Chapter Six is based on the spreadsheet model described in this appendix and shown at Figure A-1. The model was built using Excel v. 5.0 and @RISK v. 3.1. It was built to demonstrate the feasibility of doing such an analysis. As such, there are redundancies and inefficiencies that could be eliminated in future versions. Or, the basic rationale could be adapted to existing HEP or ECO-EASY software. The explanations that follow assumes a basic familiarity with the structure of an HSI model.

The example discussed below is a single iteration of a simulation. The simulations used for this report consisted of 1,000 iterations. Each iteration begins with a new set of randomly generated values for the habitat variables. These, in turn, result in a different set of output values.

THE MODEL

Rows 3 through 24 reproduce the suitability graphs found in the U.S. Fish and Wildlife Service (FWS) HSI model for the mottled duck. Column A presents the percentage values that correspond to the SI's for each of the five habitat variables contained in columns B through H. A more efficient model would simply reproduce the function. For example, all of the simple linear functions could be replaced by a simple function of the form: $y = mx + b$. The table format is easier to follow, so it was used for demonstration purposes.

Rows 27 through 33 present values for classes that comprise habitat variables V_3, V_5, and V_8 under the without project condition. The SIs for these variables are weighted sums of the four classes of conditions. Definitions of the classes and details of the weighting function can be found in the mottled duck HSI model. The classes are defined as random variables. For example, cell B32, class 4 for V_3, is a uniform distribution ranging from 0.9 to 1. Class 3 for V_3 is 1 minus the class 4 variable. In this iteration there was 94 percent Class 4 and 6 percent Class 3 for the V_3. There were no observed class 1 or 2 conditions for V_3 in the Corps study upon which this analysis was built.

Rows 34 through 40 repeat the process for with project conditions. The difference this time is that the percent of each class observed in the project area will vary. For example, consider the column C values for V_5. Without the project this variable comprises classes 2 and 3 only. With the project it comprises classes 3 and 4 only. Changes like these reflect project impacts.

Rows 42 through 51 present measurements of the habitat variables displaying the without project condition values in column B and the with project values in column D. These values are all subject to uncertainty and are estimated using probability distributions that reflect this uncertainty. In this example uniform distributions were used for simplicity for all variables. Variables V_6 and V_7 must logically sum to one so once one variable is randomly determined the other is known.

	A	B	C	D	E	F	G	H
1	**Figure A-1: Mottled Duck HSI Model with Risk Analysis**							
2	**Rows 3 through 24 display linear suitability index graphs**							
3	**Percent**	**SI for V1**	**SI for V2**	**SI for V4**	**SI for V6**	**SI for V7**		
4	0	1	1	0	0	0		
5	5	0.95	0.8333	0.1176	0.125	0.05		
6	10	0.9	0.6666	0.2353	0.25	0.1		
7	15	0.85	0.5	0.3529	0.375	0.15		
8	20	0.8	0.3333	0.4706	0.5	0.2		
9	25	0.75	0.1667	0.5882	0.625	0.25		
10	30	0.7	0	0.7059	0.75	0.3		
11	35	0.65	0	0.8235	0.875	0.35		
12	40	0.6	0	0.9412	1	0.4		
13	45	0.55	0	1	1	0.45		
14	50	0.5	0	1	1	0.5		
15	55	0.45	0	1	1	0.55		
16	60	0.4	0	0.9412	1	0.6		
17	65	0.35	0	0.8235	0.875	0.65		
18	70	0.3	0	0.7059	0.75	0.7		
19	75	0.25	0	0.5882	0.625	0.75		
20	80	0.2	0	0.4706	0.5	0.8		
21	85	0.15	0	0.3529	0.375	0.85		
22	90	0.1	0	0.2353	0.25	0.9		
23	95	0.05	0	0.1176	0.125	0.95		
24	100	0	0	0	0	1		
25	**Rows 27 through 40 allow for input of without and with project condition values for habitat**							
26	**values based on class/step functions rather than linear suitability graphs.**							
27	**Without Project**	**Enter % of each class as decimal**						
28		**% for V3**	**% for V5**	**% for V8**				
29	class 1=	0	0	0				
30	class 2 =	0	0.92988066	0				
31	class 3 =	0.061555	0.07011934	0.040817				
32	class 4 =	0.938445	0	0.959183				
33	Sum	1	1	1				
34	**With Project**	**Enter % of each class as decimal**						
35		**% for V3**	**% for V5**	**% for V8**				
36	class 1=	0	0	0				
37	class 2 =	0	0	0				
38	class 3 =	0.0341965	0.08156815	0.0315256				
39	class 4 =	0.9658035	0.91843185	0.9684744				
40	Sum	1	1	1				
41	**Rows 42 through 51 present measurements of the habitat variables and their corresponding SI's.**							
42	**Model**	**Without Project**		**With Project**				
43	**Component**	**Data**	**SI**	**Data**	**SI**			
44	V1:% Unsubmerged substrate	4.8841023	1	1.5245874	1			
45	V2: % Canopy cover	8.4760538	0.8333	7.8370752	0.8333			
46	V3: Unsubmerged substrate vegetation		0.975378		0.98632142			
47	V4: % Submerged substrate	5.4579538	0.1176	41.333654	0.9412			
48	V5: Submerged substrate vegetation		0.3210358		0.96737274			
49	V6: % Land	25.410497	0.625	25.410497	0.625			
50	V7: % Water	74.589503	0.7	74.589503	0.7			
51	V8: Disturbance level		0.98367319		0.98738976			
52	**Rows 53 through 56 calculate model components, (W/ and W/O). Life requisites are calculated in rows 57 through 59.**							
53	Nesting Hen Cover ((NHC)	0.9332359		0.9367131				
54	Hen with Brood Cover (HBC)	0.1943034		0.9541966				
55	Cover Structure	0.1943034		0.9367131				
56	Cover Ratio	0.625		0.625				
57	Cover Life Requisite	0.2868228		0.8185234				
58	Food Life Requisite	0.7		0.7				
59	Other Life Requisite	0.9836732		0.9873898				
60	**Model outputs, including HSI values, HU's, costs, and sensitivity analysis results are presented below.**							
61	Habitat Suitability Index: Minimum	0.2868228	HSI W/Min	0.7	HSI Change	0.4131772	Incremental	
62	HSI: Average	0.656832	HSI W/Ave	0.8353044		0.1784724	Cost per	
63	HSI: Cube Root	0.5823546	HSI W/CR	0.8270642		0.2447097	HU	
64	Habitat Units W/O: Minimum	286.82275	HU W/Min	700	CH HU Min	413.17725	$/HU Min	4414.5703
65	HU's W/O: Average	656.83198	HU W/Ave	835.30437	Ch HU Ave	178.47239	$/HU Ave	10220.068
66	HU's W/O: Cube Root	582.35458	HU W/CR	827.06425	CH HU CR	244.70967	$/HU CR	7453.7308
67	Cost	1824000						

Columns C and E present the suitability indices for the habitat variable values presented. The SI values for variables V_3, V_5, and V_8 are based on the values presented in rows 29 through 40 above. Notice that most SI values differ between the without and with project conditions.

Model components and life requisites are calculated in rows 53 through 59. The components in rows 53 through 56 are functions of the habitat variables. The specific details of these functions can be found in the HSI model and are discussed briefly in Chapter Six. The life requisites are functions of the components and habitat variables. These are all straightforward calculations or equalities, e.g., the food life requisite is simply the SI of V_7. Life requisites are shown in rows 57 through 59.

The HSI is defined as the minimum of the three life requisite SIs. Under the without project condition in the example this would be the cover life requisite of 0.29 (cell B57). Under the with project condition it is the food life requisite of 0.70 (cell D58). Thus, in this example the HSI improves from 0.29 to 0.70 as a result of the project, a change of 0.41 as shown in cell F61.

Row 62 tests the sensitivity of the HSI to the decision rule, i.e., choosing the minimum life requisite, by taking the average of the three HSI's. The with project HSI improves from 0.66 to 0.84 a change of 0.18. A third decision rule, the cube root of the product of the three life requisites, yields values of 0.58 and 0.83 for a change of 0.24, as shown in row 63.

The habitat units corresponding to each of these three decision rules are presented in rows 64, 65 and 66. For simplicity it was assumed the mitigation area consisted of 1,000 acres. Thus, the HSI of cell B61 times 1,000 acres yields 287 HU's (cell B64) without the project and 700 HU's (cell D64) with the project for a change in HU's (cell F64) of 413 HU's. Row 64 presents results using the model decision rule while rows 65 and 66 present alternative results.

The Corps project used for this example did not use a true incremental cost analysis. It basically used a single increment of 1,000 acres. Costs were assumed to be determinate so this demonstration could focus on environmental input data. They could have easily been allowed to vary to reflect the uncertainty inherent in them. Incremental costs for this single increment are presented in cells H64 through H66. Using the model's decision rule of the minimum life requisite as the HSI, costs are $4,415 per HU. In this iteration the other rules yield incremental costs of $10,220 and $7,454.