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Principles of Risk Analysis for Water Resources

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Principles of Risk Analysis for Water Resources

U.S. Army Corps of Engineers
Institute for Water Resources

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FOREWORD

This report represents an effort to document the state of the practice in risk analysis for use by US Army Corps of Engineers (USACE). It started as an update of the original "Guidelines for Risk and Uncertainty Analysis in Water Resources Planning" published by the USACE Institute for Water Resources in 1992. Since that time there has been a tremendous advance in standardization of risk language, the tools of risk assessment, and the practice of risk analysis notably with USACE. In 1992 there was no requirement to explicitly consider, assess, evaluate and display uncertainty for flood risk management studies. Even the term "flood risk management" was invented to replace the familiar but inaccurate terms "flood control" and "flood damage reduction."

Nontheless, this does not mean standardization of the risk language and terminology is complete. USACE has adopted the term "risk framework" in other contexts to refer to the three tasks of risk assessment, risk management, and risk communication activities which others refer to as the components of "risk analysis." For the purposes of this manual, the term "risk analysis" will be used to refer to the integrated activity conducted within the "risk framework."

Transparent and defensible analysis provides a critical piece of information for decision making. It is incumbent on the analysist to inform others about sources and validity of all the data, models, and assumptions that are part of the analysis. The analyst must also acknowledge and highlight the key uncertainties by reporting a range of values with their likelihoods when possible. Addtionally, the impacts of uncertainty on the results, and the overall confidence in the values of decision variables presented to decision makers must be part of any decision document.

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ACKNOWLEDGEMENTS

This report is a product of Theme 2, Risk Informed Decions Making, of the Actions for Change program initiated by USACE in 2006 as part of the agency response to the Hurricane Katrina disaster. The report by the Interagency Perfomance Evaluation Taskforce (IPET) and the Hurricane Protection Decision Chronology (HPDC) report both indicated the need for USACE to be more explicit in its treatment of uncertainty and the conderation of risk in its recommendations.

The principal author of this report is Dr. Charles Yoe of Notre Dame of Maryland University working under contract with CDMSmith. Mr. Brian Harper, formerly of IWR and now Chief, Civil Planning Branch, Regional Planning & Environmental Center, SWD, provided significant guidance and input to this report. Dr. David Moser, IWR, USACE Chief Economist and leader of AFC Theme 2, also helped shape the report and provided final editing.

Chapter 1: Introduction to the Risk Manual

1.1 Introduction

The U.S. Army Corps of Engineers (USACE) is a risk management organization. USACE has been engaged in risk analysis since its beginnings. Only in the last half of the 20th century has risk science evolved to the point where the discipline of risk analysis has become formally recognized. Risks of loss and risks of potential gain exist for many reasons but the pervasive presence of uncertainty in decision-making situations may well be the most constant reason for the existence of risk.

> **Civil Works Mission and Vision**
>
> Dedicated to providing quality, responsive service to the nation in peace and war, the Directorate of Civil Works is a major component of the U.S. Army Corps of Engineers. The Civil Works programs include water resource development activities including flood risk management, navigation, recreation, and infrastructure and environmental stewardship. The Civil Works mission also includes emergency response.
>
> Source: http://www.usace.army.mil/Missions/CivilWorks.aspx accessed November 7, 2012.

In its Civil Works program, USACE must manage risk over the entire life cycle of a project, from its conception during planning, through preconstruction engineering and design (PED), construction, operation and maintenance, and the final disposition and decommissioning of the project. Managing risks means recognizing and addressing uncertainty to make better decisions under uncertain conditions.

The Flood Control Act of 1936 created a national program to manage flood risks, which is now reflected in the name of the program: Flood Risk Management. The rise of a major rehabilitation program beginning in the 1990s marked a significant turning point for formal risk analysis by USACE. The USACE Dam Safety Program uses a risk-informed approach to manage its portfolio of over 600 dams, with public safety its number one priority. This robust risk-informed approach is a best practice adopted to develop balanced and informed assessments of the safety of the Nation's dams and to evaluate, prioritize and justify dam safety decisions.[1] In 2006 USACE created its Levee Safety Program with the mission to assess the integrity and viability of levees and recommend courses of action to ensure that levee systems do not present unacceptable risks to the public, property and environment.[2] Cost risk management was mandated by Section 2033 of the Water Resources Development Act (WRDA) of 2007. The Risk Management Center (RMC) was established in 2008 as a center of expertise under the U.S. Army Engineer Institute for Water Resources (IWR). Its purpose is to improve management controls over infrastructure decisions, serve as an independent advisor to senior leadership, maintain and develop risk competencies, and ensure consistency in

[1] (http://www.usace.army.mil/Missions/CivilWorks/DamSafetyProgram.aspx accessed November 8, 2012).
[2] (http://www.usace.army.mil/Missions/CivilWorks/LeveeSafetyProgram.aspx accessed November 8, 2012).

processes, application of criteria and decision making. Over the last few decades there has been a proliferation in growth of risk-based analytical tools and techniques employed by USACE. So-called risk-based and risk-informed processes support decision making in allocating budget resources and in other decision-making contexts both horizontally and vertically throughout the organization. This manual presents the efforts USACE has taken to formalize its risk analysis approach at the time of this writing.

1.2 Purpose of this Manual

The purpose of this manual is to articulate for USACE and all of its stakeholders the risk analysis process used by USACE in its Civil Works program. The primary audience for this manual is the workforce of the U.S. Army Corps of Engineers. Its secondary audiences include those affected by the Civil Works program as well as those who work closely with USACE in support of their mission.

This manual is intended to help its audiences to:

- Describe the need to manage project risks throughout the entire project life cycle.
- Distinguish between risks of loss and risks of potential gain.
- Differentiate knowledge uncertainty from natural variability.
- Identify the major components of the USACE risk management framework.
- Discuss some of the specific challenges associated with risk communication.
- Discuss the four steps that comprise a risk assessment.
- List several examples of qualitative and quantitative risk assessment tools.
- Identify the key components of a risk-informed planning process.
- Use risk information to better inform the USACE decision-making processes.

The contents of this manual represent the latest evolution of thought on the USACE approach to risk analysis. That thinking can be expected to change in the future as the discipline of risk analysis continues to evolve.

1.3 Organization of this Manual

This manual consists of 9 Chapters and 3 Appendices. Following this brief introductory chapter is a chapter that presents the language and models of risk analysis as currently defined by “the Corps for the Corps”. The chapter defines two kinds of risk that are important to USACE; these are risks of loss and risks of potential gains that may or may not be realized by the actions USACE takes. The basic terminologies of risk, including the three tasks of risk analysis--risk management, risk assessment and risk communication--are also defined.

Chapter Three is devoted to the subject of uncertainty. Risk analysis is essentially decision making under uncertainty. Uncertainty, more than any other single word, explains the reason for the growing interest in risk analysis. It is examined in two dichotomous ways in this chapter. First, it is considered as an element of the USACE decision-making environment at the macro- and micro-levels of analysis. Second, it is decomposed into knowledge uncertainty and natural variability, from which perspectives it is examined in detail.

The USACE life cycle focus on risk management is the first topic developed in Chapter Four. From planning through final disposition, USACE is responsible for managing the risks associated with its projects. In order to manage these risks a framework is required. The current USACE risk management framework is presented in the second part of this chapter.

Risk analysis depends critically on the USACE ability to communicate effectively about the risks that it identifies and assesses as well as the rationale for the decision it makes to manage risks. Risk communication is defined in Chapter Five. The importance of the different ways that people perceive risk is also explained. USACE experts, for example, may focus on the science and facts of a risk while many stakeholders will be more interested in their beliefs, the values they have at risk, and the social and emotional context of the risks. The chapter also considers the 3 M's (message, messenger and media) of risk communication as well as some of the challenges of explaining technical information to the public.

Chapters Six, Seven, and Eight all focus on risk assessment. Chapter Six introduces the four steps of the USACE generic risk assessment model and the legitimacy of both qualitative and quantitative assessments. Several recurring risk assessment steps are described before the chapter turns to a discussion of the qualities of a good risk assessment. Chapter Seven provides summary descriptions of over a dozen qualitative risk assessment techniques. Chapter Eight summarizes thirty quantitative risk assessment tools and techniques. These three chapters together provide a thorough introduction to the concepts, tools and techniques of risk assessment.

The final chapter addresses the need to make decisions with risk information. The chapter begins by defining and differentiating risk-informed decisions and then presents a detailed discussion about how decision makers should understand risk-informed outputs before making decisions. The chapter ends by considering the necessity for risk assessment information in order to answer the risk manager's questions.

At the end of the manual is a series of appendices that illustrate a few chosen techniques in greater detail. Appendix A examines the enhanced criteria ranking technique introduced in Chapter Seven. Appendix B takes a careful look at risk matrices. Appendix C presents an example of a generic approach to qualitative risk assessment using the experiences of the Great Lakes and Mississippi River Interbasin Study as a takeoff point.

1.4 References

U.S. Army Corps of Engineers. 2012. "Civil Works." Accessed November 7, 2012. http://www.usace.army.mil/Missions/CivilWorks.aspx.

Chapter 2: The Language and Models of Risk

2.1 Introduction

Despite all of our years on this planet, communication remains one of our species' most difficult tasks. I know what the words mean to me when I say them and you know what the words mean when you hear them. Too often we do not understand one another because I mean something that you are not hearing. It makes sense, therefore, to begin with some simple definitions of terms and some conceptual models used in risk analysis.

Risk analysis did not evolve from a single source. It evolved independently and simultaneously in many different disciplines. Each discipline and community of practice has developed its own terminology to describe the nature of risk analysis. Consequently, there are many dialects of risk spoken. For instance, the term "risk analysis" has no universally accepted definition and usage. Even within USACE one will find multiple meanings for specific terms and multiple terms for specific meanings.

2.2 Risk

Risk is a measure of the probability and consequence of uncertain future events. It is the chance of an undesirable outcome. USACE faces two broad categories of risk--risks of loss and risks of unrealized gains. A risk of loss is called a pure risk and it could be a loss due to flood, storm damage, infrastructure failure, disruption of project services, bad weather, economic setbacks, or any sort of hazard. The losses include loss of life, health and safety, property damage, environmental degradation and loss, loss of ecosystem services, loss of transportation services, etc. The risk of an unrealized gain is called a speculative risk. Examples of unrealized gains, or potential gains that are not realized, include reductions in transportation cost savings that do not occur, ecosystem restoration benefits that do not materialize, operation and maintenance efficiencies that are not realized, an investment that does not produce the expected benefits, and the like.

It is a lack of information about events that have not yet occurred that gives rise to risks. This lack of information stems from two sources: there are facts we do not know and the universe is inherently variable. Let's call these two sources uncertainty. Uncertainty is defined more completely in the next chapter.

It is sometimes convenient to differentiate the nature or status of a risk by considering the following kinds of risk:

- Existing risk
- Future risk
- Historical risk
- Risk reductions

- New risks
- Residual risk
- Transferred risk
- Transformed risk

An existing risk is the risk that exists now. A future risk is a forecast of a risk at some point in the future. A historical risk is a risk that was present at some point in the past. A risk reduction is the extent to which an existing, future or historical risk is or might be reduced by a risk management option. A new risk is a risk that did not heretofore exist. A residual risk is the amount of existing, future or historical risk that remains or might remain after a risk management option has been implemented. When a risk management option reduces risk at one point in time or space for one kind of event or activity while increasing risk at another time or space for the same event or activity, it is called a transferred risk. When a risk management option alters the nature of a hazard/opportunity or a population's exposure to that hazard/opportunity, it is called a transformed risk.

Risk is often described by the following simple equation:

(1.1) Risk = Probability x Consequence

This is not a literal formula for calculating risks. Most risk calculations are more complex. It is instead a conceptual model that helps us think about risk. What it tells us is that there are two essential elements to a risk. If a loss or opportunity of any consequence has no probability of occurring, there is no risk. Likewise, no matter how probable an event, if there is no consequence or undesirable outcome, there is no risk. Risks can be estimated and described qualitatively or quantitatively.

It's possible to gain another important insight from this simple conceptual model. Imagine a risk that can be calculated by multiplying two numbers as suggested by the equation. If the probability is low and the consequence is large, imagine a risk, R_1, that results.

Now imagine a situation where the probability is high and the consequence is low such that the two produce an identical risk estimate of R_1 when multiplied together. However, these seemingly identical numerical risks have very different characteristics and are frequently not viewed as equal.

The consequences of risks have a social context. That means people will respond differently to different risks and technical attributes. The public will not perceive $1 billion in flood damages due to levee failure in the same way that they will perceive $1 billion of flood damages to an unprotected community. Risk has a social context and it is multidimensional. It cannot be adequately described by a single number.

Opportunity and hazard all at once

Portworld on November 17, 2010 reported that USACE will assist the Georgia Ports Authority in dredging the Savannah River to expand container facilities in time for the opening of the enlarged Panama Canal. This risky investment opportunity could produce greater or lesser benefits than estimated in planning studies. There is also a risk of saltwater intrusion into the inland areas and resulting adverse effects on marine life. Thus, this opportunity risk also has the potential to create one or more pure risks. The two kinds of risk often coincide and a risk management decision can involve both taking and avoiding risks. Risk tradeoffs like this are not uncommon.

Source: Portworld http://www.portworld.com/news/i98070/US_Army_brought_in_to_evaluate_dredging_of_Savannah_River Accessed November 19, 2010.

2.2.1 Hazard

In a general sense, a "hazard" is anything that is a potential source of harm to a valued asset. It includes all natural and anthropogenic (i.e., relating to or resulting from the influence of humans) events capable of causing adverse effects on people, property, economy, culture, social structure, or environment and is readily expanded to include biological, chemical, physical and radiological agents. USACE is primarily engaged with natural, technological and anthropogenic hazards.

2.2.2 Opportunity

An opportunity is any situation that causes, creates or presents the potential for a positive consequence. It is any set of circumstances that presents a good chance for progress, advancement or other desirable gain to a valued asset. The gain may be personal, communal, societal, national or global. USACE is primarily engaged with opportunities for ecological, economic and financial gain.

2.2.3 Uncertainty

Uncertainty reflects a lack of awareness, knowledge, data or evidence about circumstances relevant to a decision problem. When you are unsure, you are uncertain. The International Organization for Standardization (IEC 31010 Ed. 1.0, 2009) describes uncertainty as a "state, even partial, of deficiency of information related to or understanding or knowledge of an event, its consequence, or likelihood." Uncertainty will be covered in depth in the next chapter.

2.3 Acceptable Risk

A risk is acceptable when its probability of occurrence is so small, its consequences are so slight or its benefits (perceived or real) are so great, that individuals or groups in society are willing to take or be subjected to the risk that the event might occur. Determining whether an assessed risk is acceptable or not is always the responsibility of the USACE risk manager. It is a matter of subjective judgment, not a scientific determination. A pure risk that is judged acceptable requires no risk management. A risk that is not acceptable is therefore by definition unacceptable and must be managed. It's conceptually possible to take steps to reduce an unacceptable level of risk to an acceptable level. More often than not however, unacceptable risks are managed to tolerable levels.

2.4 Tolerable Risk

A tolerable risk is not an acceptable risk. It is a non-negligible risk that has not yet been reduced to an acceptable level. Such a risk is tolerated for one of three general reasons: it may be impossible to reduce the risk further, the costs of further reduction are considered excessive, or the magnitude of the benefits associated with the risky activity are too great to reduce it further. A tolerable risk is an unacceptable risk whose severity has been reduced to a point where it is tolerated. If a risk is initially judged to be unacceptable, USACE risk managers should seek to reduce it to a level of risk that can be tolerated. This too is a subjective judgment.

> **Speculative Risks**
>
> When we consider the concepts of acceptable and tolerable risk from the perspective of a speculative or opportunity risk, they look a little different. An acceptable speculative risk is one with a negligible probability of a negative outcome or with positive consequences so large that it offsets the chance of a negative outcome. Alternatively, the negative consequences may be so slight that individuals or groups in society are willing to take the risk. Investing in a project that has zero chance of negative net environmental benefits might be an example of an acceptable risk.
>
> A tolerable opportunity risk is one that decision makers or society is willing to take. Risk taking is essentially different from risk avoidance. Risk-taking decisions are conscious decisions to expose oneself to a risk that could have otherwise been avoided. Consequently, managing uncertainty prior to decision making or during evolutionary decision making is a significant risk management strategy for opportunity risks.

Tolerable level of risk (TLR) is a phrase describing this level of risk that has been associated with a national, corporate, regulatory, or otherwise fixed level of risk. For example, Congress could, hypothetically, establish the 0.2 percent annual exceedance frequency as the tolerable level of risk for flood risk management (FRM) in urban areas. Then all urban FRM projects must protect against floods with a recurrence interval of 500-years or less as a matter of national policy.

Although it might be convenient to maintain a distinction between tolerable risk and tolerable level of risk, that is not likely to be practical in practice. Unless and until USACE chooses to create policy regarding TLRs, it may make more sense to treat the two terms as synonyms.

2.5 Risk Analysis[3]

Risk analysis is a systematic way of identifying decision problems, then gathering and evaluating evidence that can lead to recommendations for a decision or action in response to an identified hazard or opportunity for gain. It is a process that has evolved specifically for decision making under uncertainty. It is a risk framework with three tasks: risk management, risk assessment and risk communication seen in Figure 2.1. It examines the whole of a risk by assessing the risk

[3] As noted in the forward, USACE has adopted the term "risk framework" in other contexts to refer to the three tasks of risk assessment, risk management, and risk communication activities which others refer to as the components of "risk analysis." For the purposes of this manual, the term "risk analysis" will be used to refer to the integrated activity conducted within the "risk framework."

and its related relevant uncertainties for the purpose of efficacious management of the risk, facilitated by effective communication about the risk.

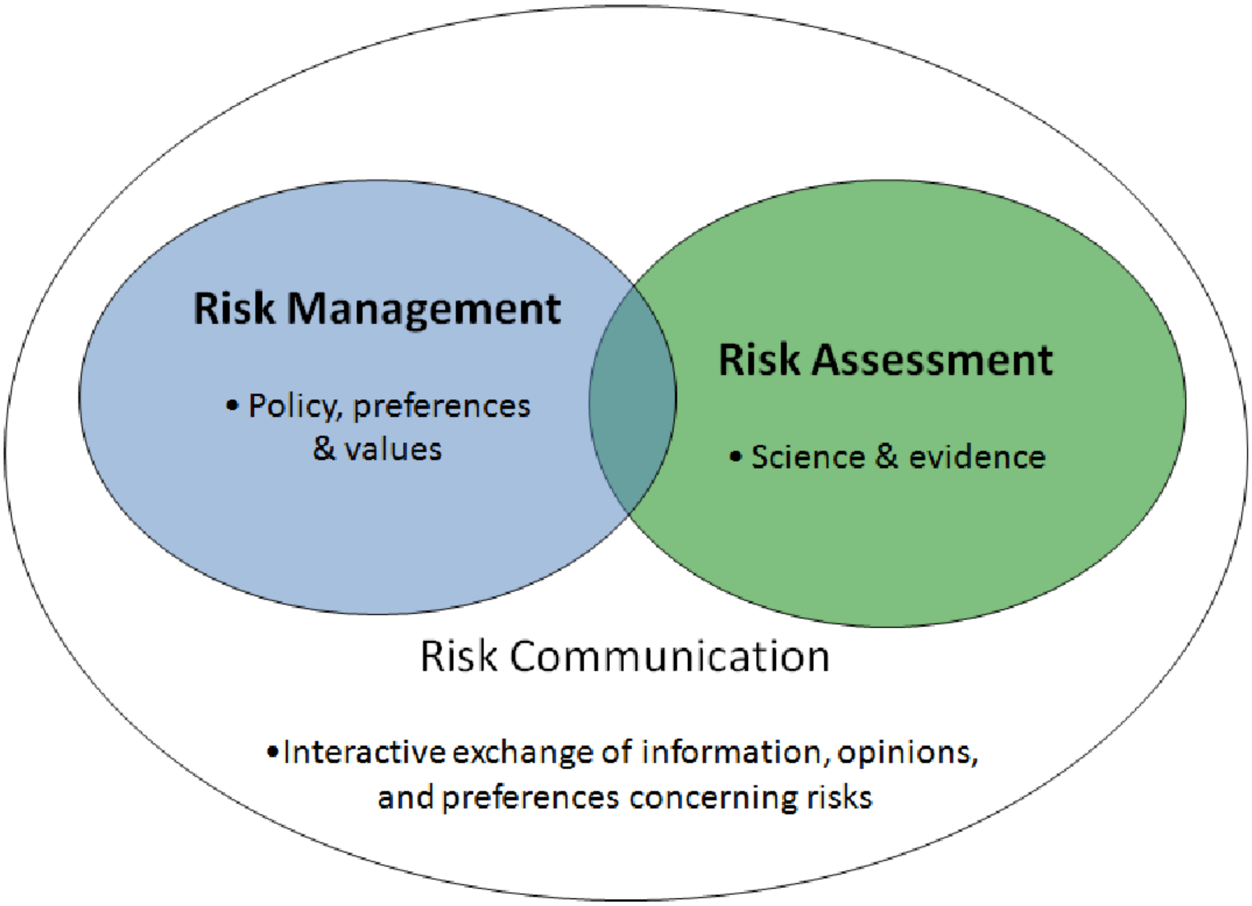

Figure 2.1: Risk analysis comprises three tasks

Risk analysis has evolved into a paradigm for decision making under uncertainty. It recognizes that we may be uncertain about one or more aspects of the likelihood or the consequence of a risk of concern. Consequently, risk analysis is intentional in the way it directs analysts and decision makers alike to base their decisions on the available science while paying appropriate attention to the remaining uncertainty.

2.5.1 When Is Risk Analysis Needed?

Risk analysis is for decision making under uncertainty. When there is little to no uncertainty in decision making, risk analysis is not needed. Most administrative tasks (e.g., assigning personnel, buying supplies, changing reporting formats, making travel arrangements) involve little uncertainty. Furthermore, the consequences of a wrong decision are usually minor and reversible. On the other hand, many management and mission critical decisions do involve significant uncertainty and the consequences of a wrong decision are usually more serious.

When uncertainty is great and the consequences of a wrong decision are serious, risk analysis is needed. When there is little uncertainty and the consequences of a mistake are minor, other decision paradigms will work just as well. Figure 2.2 summarizes this idea.

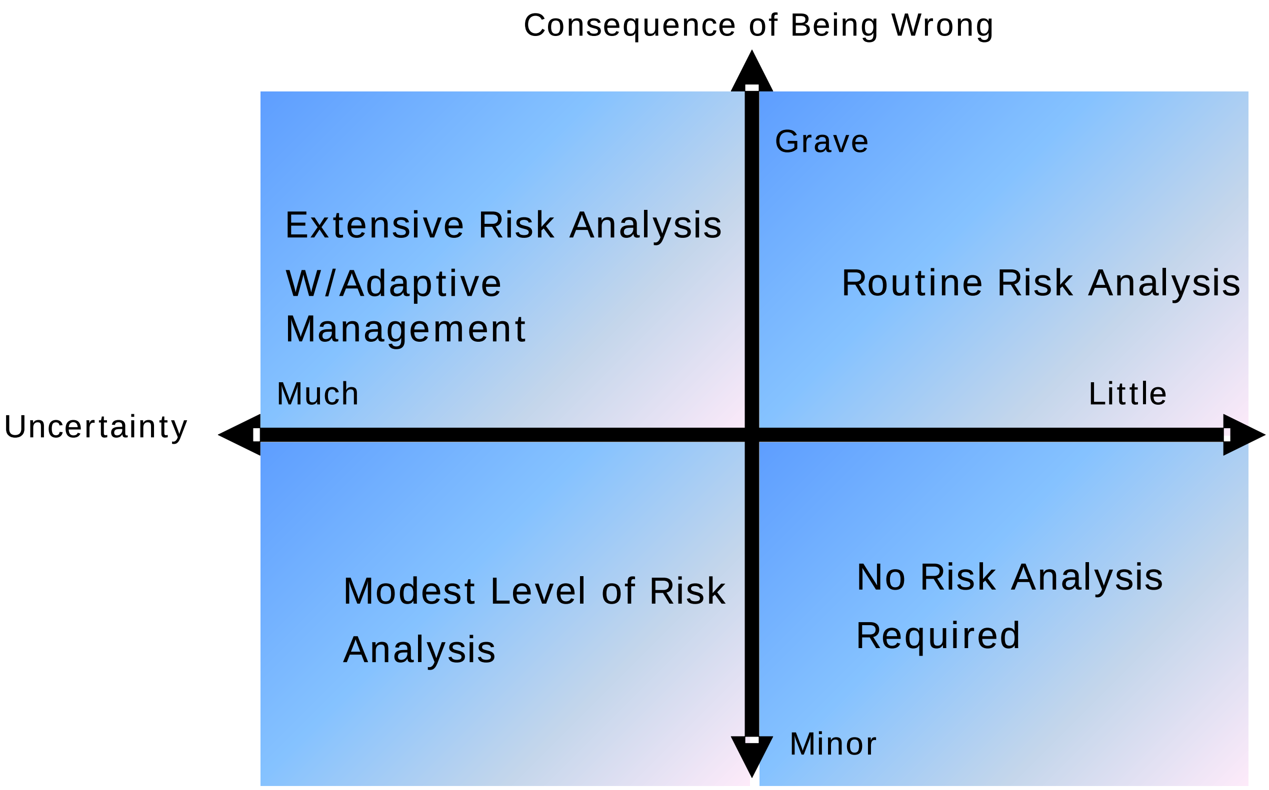

Figure 2.2: Suggestions for when to use risk analysis

The lower right quadrant describes activities like personnel assignments, routine purchases, data collection, routine permit applications, routine coordination activities, administrative activities, budget updates, responding to questions from Congress and the like. These are routine tasks with little uncertainty or situations where a wrong decision will have trivial or easily reversed consequences. Moving to the lower left we define a class of decision problems where there may well be significant amounts of uncertainty but the consequence of a decision mistake are relatively minor. These situations require a modest amount of risk analysis. That might mean at least enough analysis to reassure decision makers that the consequences of a mistake are indeed slight. Examples of such decisions could include some routine or recurring aspects of project design, routine emergency management activities, managing construction projects, allocating operation and maintenance resources within a District, and so on.

As the consequences of a mistake grow more serious, the need for more rigorous risk analysis grows as well. The presumed normal situation for USACE decision making is described as one with relatively less uncertainty but serious consequences for a decision error. Thus, risk analysis is presumed to be a routine part of such decision-making processes. Ideally it will be the dominant decision-making paradigm. Examples of such areas include recurring but always unique situations like lake siltation, reservoir reallocation, maintenance dredging, reconnaissance studies, feasibility studies, dam and levee safety programs, managing the annual USACE budget, program management, allocating inspection resources, and so on.

The need for the greatest amount of risk analysis occurs for those decisions with both a lot of uncertainty and potentially severe consequences for a decision error. This is where the most rigorous risk analysis is needed. When the uncertainty is great enough, adaptive management techniques may be needed to reduce the uncertainty to support decision making. Some examples for this quadrant might include such things as the Interagency Performance Evaluation Task Force (IPET) that followed hurricanes Katrina and Rita, post-disaster work in general, complex flood risk management or other investigations, landscape scale studies like the Comprehensive Everglades Restoration Plan (CERP), and consideration of the effects of climate change.

Risk Management for Opportunities

Risk management includes taking risks as well as controlling them. Some of the questions must be altered for speculative risks. They might be restated as follows:

•What's the opportunity?
•What information do we need to attain it, i.e., what questions do we want risk assessment to answer?
•What can be done to increase the positive impact of the opportunity risk described?
•What can be done to increase the likelihood of the desired outcomes?
•What is the best way to attain the desired result?
•Did it work?

2.6 Risk Management

Risk management consists of identifying a problem, defining the decision context, requesting the information needed to make that decision, evaluating assessed risks, and initiating action to identify, evaluate, select, implement, monitor and modify actions taken to alter levels of unacceptable risk to acceptable or tolerable levels as opposed to taking no action. More informally, risk management is the work one has to do to ask and then answer the following kinds of questions:

1. What's the problem?
2. What information do we need to solve the problem, i.e., what questions do we want risk assessment to answer?
3. What can be done to reduce the impact of the risk described?
4. What can be done to reduce the likelihood of the risk described?
5. What are the tradeoffs of the available options?
6. What is the best way to address the described risk?
7. (Once implemented) Is it working?

Risk management includes scientifically sound, cost-effective, integrated actions that reduce risks of loss or pursue opportunities for gain while taking into account economic, environmental, social, cultural, ethical, political and legal considerations. There are several distinct risk management strategies for both risk taking and risk reduction. The risk reduction strategies and their opportunity risk equivalents are shown in Table 2.1. These strategies are described in the sections below and risk management is taken up at length in Chapter Four.

Risk Management Strategies	
Risk Reduction	Risk Taking
Avoidance	Creation
Prevention	Enhancement
Mitigation	Exploitation
Transfer	Sharing
Retention	Ignoring

Table 2.1: Risk control strategies and their equivalent risk taking strategy

2.6.1 Risk Taking

When faced with an opportunity for an uncertain gain the USACE risk manager must decide whether or not to assume the risk of taking an action that could result in less than the expected, desired or even necessary outcome. This is the risk taking role of the risk manager. The kind of strategy the USACE risk manager employs in decision making can directly affect the likelihood and/or consequences of the opportunity's outcome. These strategies can be grouped according to their effect on the risk to be managed. Hilson (2001) identifies four risk taking strategies which are modified and supplemented in the discussion below:

- Create the opportunity risk
- Enhance the risk
- Exploit the risk
- Share the risk
- Ignore the risk

Creating an opportunity with an uncertain outcome is, in a sense, creating a risk, the opportunity equivalent of avoiding a pure risk. This means creating circumstances for a known desirable consequence to occur, i.e., increasing the likelihood from zero to a positive value; or creating circumstances for a positive impact to accompany events already occurring with some likelihood. In the extreme, risk creation causes both the likelihood and positive consequence to come into being.

Enhancing a risk is the opportunity equivalent of prevention strategies for a pure risk. It involves increasing the likelihood that an event or desired outcome will occur. Enhancement seeks to eliminate uncertainty in the likelihood and tries to make the desired event definitely happen. This is, effectively, seeking to increase the probability of the desired outcome to as close to 100 percent as possible. Under an enhancement strategy, aggressive measures are taken to assure the necessary conditions arise as a result of the USACE action taken.

Exploiting a risk is the opportunity equivalent of mitigating a risk. Exploiting a risk seeks to increase the impact of the opportunity in order to maximize the benefit to the project or activity undertaken. A risk exploitation strategy operates primarily on the consequence dimension of a risk to ensure that the benefits from the opportunity are as fully realized as possible.

Risk sharing is the opportunity equivalent of a pure risk transfer. Risk sharing seeks a partner able to manage the opportunity such that the likelihood of it happening or the potential benefits can be maximized. A successful risk sharing strategy results in mutual enjoyment of the project's or activity's benefits.

Ignoring a risk is choosing to take no action to realize an opportunity. It requires Corps risk managers to take a reactive approach to risk management.

2.6.2 Risk Reduction

Risk management strategies that address risks of loss are called risk reduction strategies. They have also been called risk mitigation, risk elimination, risk prevention, risk repression and risk correction strategies. Risks can be reduced by removing the source of the risk; changing the nature and magnitude of its likelihood; changing the nature, magnitude, duration or frequency of the consequences; transferring the risk to another party or parties; or retaining the risk by choice. Each of these strategies is described below.

Risk avoidance reduces or eliminates uncertainty by removing the source of the risk or executing the project or activity in a way that achieves the desired outcome while insulating valued assets from the effect of the risk. Risk avoidance either reduces the likelihood or the impact of the consequences to zero so that the risk no longer exists.

Risk prevention strategies reduce the likelihood of adverse consequences. Although the likelihood of the risk may not be reduced to zero, it may be reduced to a level considered acceptable or at least tolerable.

Risk mitigation strategies reduce the magnitude of a risk by reducing the impact of the consequences. This may be done by changing the nature, magnitude, duration or frequency of the negative consequences. When the consequences cannot be eliminated in their entirety it may be possible to reduce them to a level that is acceptable or at least tolerable.

Risk transfer is a strategy for identifying stakeholders better able to manage the risk or finding a way to share a risk among many stakeholders. In the extreme, this means passing the liability and responsibility for action to another stakeholder. This is sometimes done in lands, easements, rights-of-way and damages (LERRD) agreements on USACE projects. Flood insurance is an example of risk pooling, a popular form of risk control that shares and transfers the risk.

Risk retention is necessary when no means exist for reducing a risk or when the residual risks cannot be reduced to a tolerable level. Thus, risk retention generally refers to the situation where stakeholders are forced to live with an unacceptable and intolerable level of risk. In such cases, monitoring the status of the risk may be the only viable response to the risk.

2.7 Risk Assessment

Risk assessment is a systematic process for describing the nature, likelihood and magnitude of risk associated with some substance, situation, action or event that includes consideration of relevant uncertainties (Yoe, 2012). It provides an understanding of risks, their causes, consequences and likelihoods or probabilities. Risk assessment provides a basis for decisions about the most appropriate risk management option to be used to treat the risks. Risk assessment outputs are to be used as inputs to the USACE decision-making processes (IEC, 2008). Risk assessment can be qualitative, quantitative or a blend (semi-quantitative) of both. Risk assessment is informally described by asking and answering the following questions that build on the Kaplan and Garrick triplet (1981):

1. What can go wrong?
2. How can it happen?
3. What are the consequences?
4. How likely is it to happen?

Risk assessment is the step that gathers the evidence, answers the risk manager's questions, and identifies and addresses the uncertainty that remains in the decision problem. It is the positive task of risk analysis whereas risk management is the normative task of risk analysis. Good risk assessment analyzes the causes of the risk to determine their contribution to the consequences and their likelihood of occurrence. This analysis provides valuable insight into the most effective ways to further treat unacceptable risks.

There are many risk assessment models found in the literature. This manual adopts a four-step model that is broad enough to cover both pure and speculative risks. The possibilities of loss and gain are evident in Figure 2.3.

Purposes of Risk Assessment

Risk assessment is to provide evidence-based information and analysis to make informed decisions on how to treat risks and how to choose risk management options. The benefits of performing risk assessment include:

- providing objective information for decision makers
- understanding the risk and its potential impact upon objectives
- identifying analyzing and evaluating risks and determining the need for their treatment
- quantifying or ranking risks
- understanding risks in order to assist in selection of treatment options
- identifying important contributors to risks and weak links in systems and organizations
- comparing risks in alternative systems, technologies or approaches
- identifying and communicating risks and uncertainties
- establishing priorities for life, health and safety
- rationalizing a basis for preventive maintenance and inspection
- post-incident investigation and prevention
- selecting different forms of risk treatment
- meeting regulatory requirements
- providing information that will help evaluate the tolerability of the risk when compared with pre-defined criteria

Adapted from IEC 31010 Ed. 1.0: Risk Management

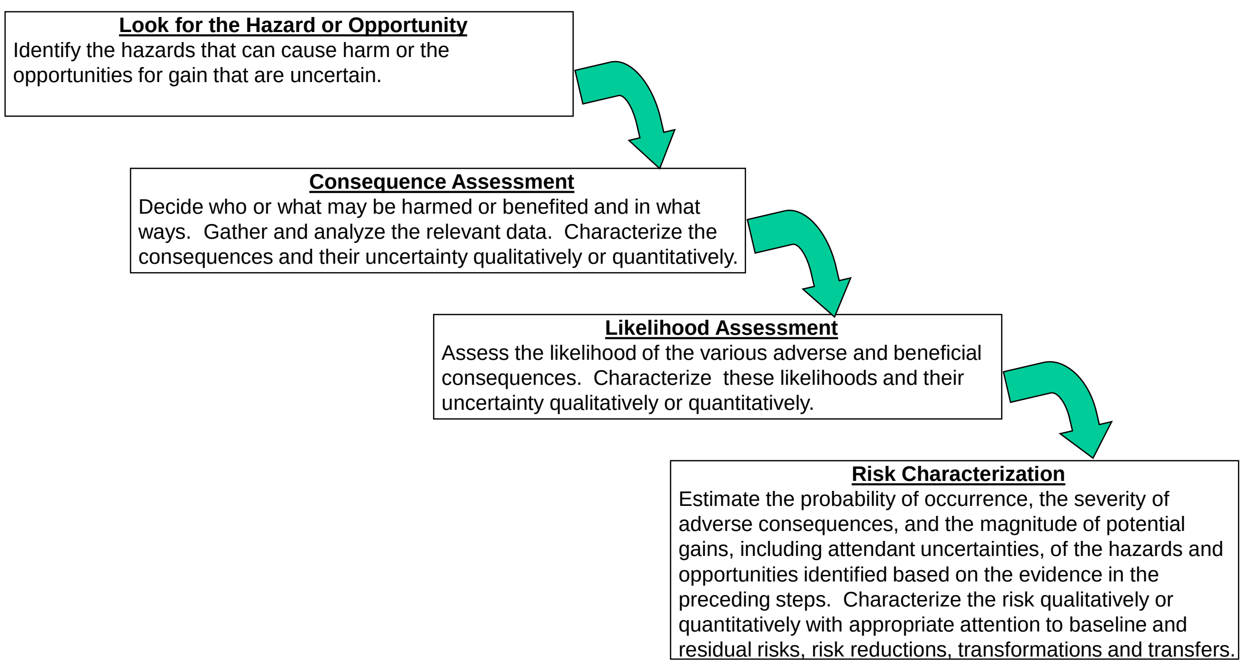

Figure 2.3: Four-step risk assessment process

Some version of each of these four steps is found in most risk assessment models. The first step simply requires a clear identification of the source and nature of the risk. What is the hazard that threatens a loss or the opportunity that promises a gain? The next two steps require the assessor to identify the consequences of the specific risk and the likelihood of those consequences occurring. The final step, risk characterization, is where the analysis of the three preceding steps is pulled together to characterize the risk qualitatively or quantitatively for the purpose of supporting decision making. Throughout this process the USACE analyst is to carefully consider and address the uncertainty at each stage of the assessment, most importantly in the characterization of the risk itself.

The specific manner in which these steps are executed varies from application to application. Some aspects of flood risk management assessments, for example, are well established. Expected annual damage calculations are typically done using the Hydrologic Engineering Center's Flood Damage Assessment Software. Navigation risk assessments are less standardized. Likewise the tools and methods for engineering, budgeting, ecosystem restoration and the wide range of risks USACE confronts differ in their state of development. For now it will suffice to differentiate between qualitative and quantitative risk assessments.

2.7.1 Qualitative Risk Assessment

Qualitative risk assessment is distinguished by its lack of reliance on numerical expressions of risk. Instead, qualitative risk assessment depends on risk descriptions, narratives, and relative values often obtained by ranking or separating risks into descriptive categories like high, medium, low and no risk. When the relative values are numeric but nominal or ordinal in character, such as when index numbers are used, the risk estimate is said to be semi-quantitative, but they remain more qualitative than quantitative in character.

2.7.2 Quantitative Risk Assessment

Quantitative risk assessment relies on numerical expressions of risk. Both the likelihoods and consequences of risk are expressed numerically in specific units defined by the needs of risk managers. A quantitative risk estimate can be a deterministic point estimate[4] or a probabilistic estimate, such as an interval or probability distribution. Quantitative analysis is preferred when it is possible. Full quantitative analysis may not always be possible or desirable due to insufficient information about the decision problem, lack of data, unclear social preferences and many other factors. In some instances the resources and effort needed for quantitative analysis may not be warranted or required, even though the analysis is possible.

2.7.3 Risk Estimate

A risk estimate is an estimate of the likelihood and severity of the adverse effects or opportunities that addresses key attending uncertainties. A risk estimate combines the estimate of the consequences and their likelihood to describe the overall level of risk. Quantitative estimates are numerical in nature and are preferred over narrative qualitative estimates. Risk estimates should include all relevant aspects of the risk, which may encompass existing, future, historical, reduced, residual, new, transformed or transferred risks.

[4] Recall, however, that risk can never be adequately described by a single value. The estimate must embody information about both the probability and the consequence.

2.7.4 Risk Description

A risk description is a narrative explanation and depiction of a risk that bounds and defines a risk for decision-making purposes. It's the story that accompanies the risk estimate that places it in a proper context for risk managers and others to understand.

2.8 Risk Communication

Risk communication is the open, two-way exchange of information and opinion between risk analysts and their stakeholders and various publics about risks. This exchange is intended to lead to a better understanding of the risks and better risk management decisions. It provides a forum for the interchange of information with all concerned about the nature of the risks, the risk assessment and how risks should be managed (Yoe, 2012). Risk communication may be informally characterized by asking and answering the following questions (Chess & Hance 1994):

- Why are we communicating?
- Who are our audiences?
- What do our audiences want to know?
- How will we communicate?
- How will we listen?
- How will we respond?
- Who will carry out the plans? When?
- What problems or barriers have we planned for?
- Have we succeeded?

Done well, risk communication helps stakeholders understand the nature and magnitude of the risk. It's essential to developing credible and acceptable risk management responses. It can enhance trust and confidence in the decision-making process while promoting the participation and involvement of interested parties.

Risk communication is needed to explain actions required to avoid or to take risks. It's needed to explain the rationale for the risk management option chosen. The effectiveness of specific options needs to be communicated so stakeholders understand their own risk management responsibilities and know what actions they must take to reduce the risk or realize the gain. The benefits of a risk management option, as well as the costs of managing the risk and who will bear them, are additional information conveyed by good risk communication.

Goals of Risk Communication
1. Promote awareness and understanding of the specific issues under consideration during the risk analysis process by all participants.
2. Promote consistency and transparency in arriving at and implementing risk management decisions.
3. Provide a sound basis for understanding the risk management decisions proposed or implemented.
4. Improve the overall effectiveness and efficiency of the risk analysis process.
5. Contribute to the development and delivery of effective information and education programs when they are selected as risk management options.
6. Foster public trust and confidence in the safety of the food supply.
7. Strengthen the working relationships and mutual respect among all participants.
8. Promote the appropriate involvement of all interested parties in the risk communication process.
9. Exchange information on the knowledge, attitudes, values, practices and perceptions of interested parties concerning risks associated with food and related topics.

Source: The Application of Risk Communication to Food Standards and Safety Matters, a Joint FAO/WHO Expert Consultation. Rome, Italy, 2-6 February 1998

Three common risk communication goals are (Food Insight. 2010):

1. Tailor communication so that it takes into account the emotional response to an event.
2. Empower the audience to make informed decisions.
3. Prevent negative behavior and/or encourage constructive responses to crisis or danger.

USACE risk communicators need to pay special attention to describing residual risks, i.e., risks that remain after the risk management option is implemented. The uncertainty that could affect the magnitude of the risk or the efficacy of the risk management option must be carefully communicated to stakeholders and the public. This should include the weaknesses, limitations of or inaccuracies in the available evidence. It should also include the important assumptions on which risk estimates are based so that stakeholders can understand the sensitivity of both risk estimates and the efficacy of risk management options to changes in those assumptions and how those changes can affect risk management decisions (Yoe, 2012).

Risk communication does not require consensus or an agreement. It should, however, provide people with meaningful opportunities for input before decisions are made and for feedback as evidence is accumulated and uncertainty is reduced. Risk communication requires listening to and understanding people's concerns about risks so that those concerns can be considered during decision making. This is essential if the public is to respect the process, even if they disagree with some of its decisions and outcomes.

2.8.1 Hazard and Outrage

Experts and the public interpret risk in very different ways; this complicates risk communication. Risk involves scientific facts and people's feelings in response to the manner in which the risk is perceived. That perception may or may not align well with the facts of the risk. These competing dimensions of risk, the objective vs. the subjective, create some unique communication challenges.

Peter Sandman (1999) said the technical side of risk, which is usually the concern of USACE, focuses on the magnitude and probability of undesirable outcomes. These technical concerns include: the size of a flow, its recurrence interval, the damages a flow can cause, the strength of a structure or component, the likelihood that load will exceed capacity, and the extent of failure if load does exceed capacity. He called these technical details and facts "hazard."

The public, by contrast, focuses on the non-technical side of the risk. This is the social context of the risk, which involves values and emotions. The public cares more about flood losses than they do about floods themselves. Losing a grandmother's rug, a pet or a place to live matters more than a recurrence interval. Concerns like whether the risk is voluntary or coerced, familiar or exotic, dreaded or not dreaded and whether USACE is considered trustworthy or untrustworthy, responsive or unresponsive are important to the public. Sandman called all this "outrage."

USACE experts are more occupied by and concerned with the hazard aspects of a risk. As experts they think about these problems and know things that others do not. The public is less concerned with the science, numbers and facts of the risk than they are with the outrage factors, i.e., the personal and social context of the risk. The public has feelings about the risk. They believe things to be true or not, often without respect to the facts of a situation. The public is less concerned with the probabilities of a flood than they are with the relative importance of what might be lost.

These two distinct dimensions of a risk can lead to a disconnect between USACE experts and the public. Planners, for example, may worry about how to explain a 1 percent annual exceedance frequency flow to a public that does not care about that aspect of the risk.

> In February, 2010 USACE labeled Addicks and Barker Dams in the Houston area as "extremely high risk" as part of the USACE National Dam Safety Program. This designation was a source of considerable concern to the public even though USACE told the public not to be alarmed.
>
> Source: Karen Zurawski February 19, 2010 blog for the Houston Chronicle

While experts tend to focus on what they know and think, the public focuses on what they feel and believe. Both dimensions of a risk are important but for different reasons. The public may worry about things USACE experts would say they need not worry about (See textbox). Other times they may not worry about things USACE experts think they should, e.g., the oncoming hurricane. Risk communication based on explaining the facts of the risk may well miss the greater concerns of the public, which tend to be the social and personal meaning of the risk.

2.8.2 Internal Risk Communication

The internal risk communication task ensures effective interaction between risk managers and risk assessors. Three rules of thumb for this task are:

- Collaborate early
- Coordinate often
- Cooperate always

2.8.3 External Risk Communication

External risk communication requires USACE risk managers, assessors and communicators to interact with their various publics and external stakeholders. The extent of this interaction will depend on how "public" the risk management activity is. Not every risk management activity will require external risk communication. Budget allocation decisions, for example, may be wholly contained within the USACE organization. When external communication is warranted, four broad categories of tasks can be identified. These are:

- Risk communication
- Crisis communication
- Public involvement
- Conflict resolution

2.9 Five Points To Take Away

Here are five things that summarize the key points in this chapter.

1. Risk = Probability x Consequence. There are two kinds of risk: pure risk (loss to avoid) and speculative risk (opportunity for uncertain potential gains).
2. Risk analysis comprises the tasks of risk management, risk assessment and risk communication.
3. Risk managers must avoid and take risks.
4. Risks can be assessed qualitatively or quantitatively.
5. The hazard and outrage dimensions of risk make risk communication challenging.

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Chapter 3: Uncertainty

3.1 Introduction

As introduced on Chapter 2, uncertainty reflects a lack of awareness, knowledge, data or evidence about circumstances relevant to a decision problem. Uncertainty is a state, even partial, of deficiency of information related to or understanding or knowledge of an event, its consequence, or likelihood. Risk analysis requires analysts to separate what we know from what we do not know. Then risk assessors and managers alike must intentionally address the potential effects of what we do not know on decision making. One of the fundamental principles of risk analysis is to base our assessment of risks on the best available science and evidence. A second foundational principle is to focus appropriate attention on those things we do not know that could affect decision-making outcomes.

If we are not sure about any aspect of our work, then we are uncertain. In general, uncertainty derives from one of two sources. There can be knowable facts that we, for any reason at all, may not know. This source of uncertainty is called knowledge uncertainty. Other times the natural variability in the universe may prevent us from knowing a value even when we have sufficient data and facts. This source of uncertainty is called natural variability.

Uncertainty occurs at two distinctly different levels of resolution. There is macro-level uncertainty that involves social values and micro-level uncertainty that occurs at the level of the analyst's desktop. These levels present distinctly different challenges to USACE.

The purposes of this chapter are three. First, the two levels of uncertainty must be distinguished. Second, the two sources of uncertainty must be distinguished. Third, the importance of addressing uncertainty in a rational and intentional manner to support good risk analysis must be emphasized.

3.2 Two Levels of Uncertainty

3.2.1 Macro-Level Uncertainty

Uncertainty is an emerging constant in modern decision making. We all operate in an uncertain environment. Growing social complexity and an increasingly rapid pace of change are now permanent parts of the decision-making landscape. The deterministic decision making of the past is giving way to risk analysis as a viable alternative decision-making paradigm.

When we say the world grows more complex, we should think of this complexity in a social sense. The size of a society, the number of its parts, the distinctiveness of those parts, the variety of specialized social roles that it incorporates, the number of distinct social personalities present, and the variety of mechanisms for organizing these into a coherent, functioning whole have grown immensely over the last century (Tainter 1996). We live now in societies with millions of different roles and personalities. Our social systems are so complex that they often defy understanding. One need only try to identify the USACE partners, stakeholders and publics to begin to understand the world's complexity. USACE no longer answers only to Congress. As a direct consequence of this complexity, the USACE problem solving methods have grown more complex.

Added to this complexity is the increasingly rapid pace of change in almost every arena. Scientific breakthroughs make things once impossible to conceive commonplace. Much of this change is driven by rapid advances in technology. Technology changes social values and beliefs as well as the way we live and work. The ways we communicate have changed forever and continue to change in ways that are difficult to forecast. Change is too rapid and at times too turbulent to be wholly understood or predicted by human beings. This challenges USACE and its traditional programs. Large public works projects built in decades past in response to values long since changed or evolved challenge USACE to keep pace with the changes that affect them, especially when national priorities have changed drastically since these projects were constructed.

Social, economic and technological connectivity around the globe accelerates at a dizzying pace. Social movements are often global in their pervasiveness. We are increasingly a global economy. Fashions are designed in New York and approved in London, patterns are cut in Hong Kong, clothes are made in Taiwan and shipped in containers on vessels that call around the world, and then the clothes are sold across Europe and North America. Computer viruses spread in hours; human viruses spread in weeks.

With government deficits and debts rising in the more established economies of the world, there is relentless pressure on costs in all public decision making. Patterns of competition are becoming unpredictable. Customer demands grow increasingly diversified. There is a growing role for one-of-a-kind production. Rapid sequences of new tasks in business and government are becoming more routine. Transportation patterns shift, modes of transport change, priority projects are quickly displaced and budget commitments are unpredictable.

These and other changes present USACE with a world where irreversible consequences unlimited in time and space are now possible. Many of the problems USACE risk managers face can have a long latency period. Many of our country's landscape scale ecosystem restoration problems like those in the Columbia River basin, Puget Sound, Florida Everglades, Coastal Louisiana and the Chesapeake Bay, as well as global concerns like greenhouse gases, climate change and sea level rise, provide clear examples of problems that took decades to emerge and be recognized. The implications of the solutions being formulated may likewise take decades to be understood.

Gradually we have become aware of the "unknown unknowns" Donald Rumsfeld first spoke of in November 2006. Events like Hurricanes Katrina and Rita and the Deepwater Horizon oil spill have helped the nation realize that despite all we know the unknown far outweighs the known in many of our most critical decision-making processes. We have begun to suspect that there are some risks, e.g. sea level change, for which there may be no narrative closure. That is, for the foreseeable future, there is not an ending by which the truth is recovered and the boundaries of the risk established. USACE is likely to continue to grapple with climate change, sea level change and uncertain budgets, for example, for decades to come.

Public perception is a palpable force. In some situations it is an irresistible one. Risks and uncertain situations have a social context. Without social and cultural judgments, there are no risks. Nonetheless, these social and cultural judgments are not always grounded in fact. Unfortunately, they are also not always adequately considered in decision-making processes. The public is fond of equating the possibility of an undesirable outcome with the probability of such an outcome. This makes conceivable risks seem very possible and it fuels our fears of the uncertain.

An oil spill in the Gulf of Mexico reverberates around the world. Flood problems grow worse, ecosystems degrade, ports compete with one another for survival and maintenance is deferred on critical infrastructure. Responsibility in this more connected world has become less clear. Who has to prove what and what constitutes proof under conditions of uncertainty? What norms of accountability are being used and to whom are we accountable? Who is responsible morally and who is responsible for paying the costs? These questions plague decision makers nationally and transnationally.

USACE lives and operates in this uncertain reality. Social values are formed, change and are re-formed against this backdrop of macro-level uncertainty. There are so many social relationships it is difficult to know what values the nation, a project area community or a stakeholder group holds dear at any one point in time. Into this changed and changeable environment the USACE decision-making processes intrude. A “culture of uncertainty” is required to survive in such an environment and risk analysis provides just such a culture.

3.2.2 Micro-Level Uncertainty

It’s not the macro-level priorities of Congress, global geopolitics, values of a city’s population or climate change that commands most of the attention in a risk analysis. Neither is the uncertain environment in which the Corps makes decisions the most pragmatic challenge for the Corps. Instead, it’s the uncertainty that Corps analysts and decision makers deal with every day on their jobs that most challenges decision making. It is lack of data, incomplete theory, imperfect models, unknown values, and the inherent variability of the universe that present the most immediate challenge to Corps analysts and decision makers.

Rarely does a Corps decision maker have all the information needed to make a decision that will yield a known outcome. There is always a “pile of the things” we know and a pile of the things we do not know. Risk analysis enables experts to sort through that pile of things we do not know to better understand the nature and causes of the uncertainties the Corps faces. The nature and cause of the uncertainty dictates the most appropriate way to address it in decision making. Therefore, the first, and most important, distinction to make in the pile of unknowns is that between knowledge uncertainty and natural variability.

3.3 Two Sources of Uncertainty

Uncertainty, as used in this manual, comprises knowledge uncertainty and natural variability.

3.3.1 Knowledge Uncertainty and Natural Variability Defined

Knowledge uncertainty is uncertainty attributed to a lack of knowledge on the part of the observer. It stems from a lack or incompleteness of information. It is reducible in principle, although it may be difficult or expensive to do so. Knowledge uncertainty arises from incomplete theory, incomplete understanding of a system, modeling limitations and/or limited data. Knowledge uncertainty has been called epistemic uncertainty in the literature.

Examples of knowledge uncertainty abound in USACE work. A U.S. Army Engineer Research and Development Center (ERDC) study of woody vegetation on levees (ERDC, 2011) found a great deal of knowledge uncertainty concerning the effects of woody vegetation on levee stability. For example, hydrologic data for small streams, such as those in the study, may not exist. There is a general lack of experimental data to characterize new engineering materials and processes. Sometimes there is a poor understanding of the linkages between inputs and outputs in an ecosystem restoration project. Cost estimators may not know the value of land or the mean structure value in a flood plain. In a reconnaissance study the number of utilities crossing a channel to be enlarged may be unknown. The value of Manning's roughness coefficient the mean high daily temperature of water, the presence of cracks or spalling concrete in a monolith, pH values in a stream, toxin concentrations in sediments to be dredged, the extent of hard bottom affected by a navigation channel enlargement and home owner preferences for relocation out of the flood plain are all examples of knowledge uncertainty. These all have an important characteristic in common. There is a true and constant value[5] for each of these examples. Other causes of knowledge uncertainty include dated, missing, vague or conflicting information, incorrect methods, faulty models, measurement errors and incorrect assumptions. Knowledge uncertainty is, quite simply, not knowing facts that are, conceptually, knowable. A most common example is not knowing a parameter or value we need to build a model or to make a decision.

Natural variability is uncertainty that deals with the inherent variability in the physical world. It refers to true differences in attributes due to heterogeneity or diversity. Natural variability is often attributed to a random process that produces variability of a quantity over time and/or space or among members of a population. It can arise because of natural, unpredictable variation in the performance of the system under study. In principle, it cannot be reduced or altered by obtaining more information, although more information may improve estimation of the natural variability that exists. For example, a larger sample will provide a more precise estimate of the standard deviation but it does not reduce variability in the population itself. Natural variability is called aleatory uncertainty in the literature. It is also called variability.

USACE works with complex natural and manmade systems that are rife with examples of natural variability. The time to complete a lockage cycle, the number of barges in a tow, the draft of a vessel, the peak annual flow on a stream, the price of a cubic yard of concrete, the size of a tow and the daily number of visitors to a lake are but a few examples. There is also

[5] True value as used in this chapter refers to a simple numerical fact. You may be unfamiliar with a specific dam and not know how many tainter gates it has. If, in fact, it has five tainter gates, five is the true value. A Corps lake has an average number of daily visitors in a year. You may not know that number. Even if the data have never been collected and the number has never been calculated there is still a true value for this statistic.

variability in any attribute of a population, like the strength of the rebar in a concrete dam or the life of a light bulb.

3.3.2 Distinguishing Knowledge Uncertainty and Natural Variability

It can be important to be able to distinguish between knowledge uncertainty and natural variability. The former can often be reduced by research, collecting data, taking a course, hiring an expert, and so on. The latter cannot be reduced by gathering more information. This can be very important when one chooses a strategy for addressing uncertainty in decision making. Figure 3.1 provides an example of how the things we don't know might be sorted. There are specific tools and techniques that are appropriate for each endpoint in the figure. Analysts who can identify the source of their uncertainty are much more likely to find an appropriate and effective way to address that uncertainty than are those who cannot.

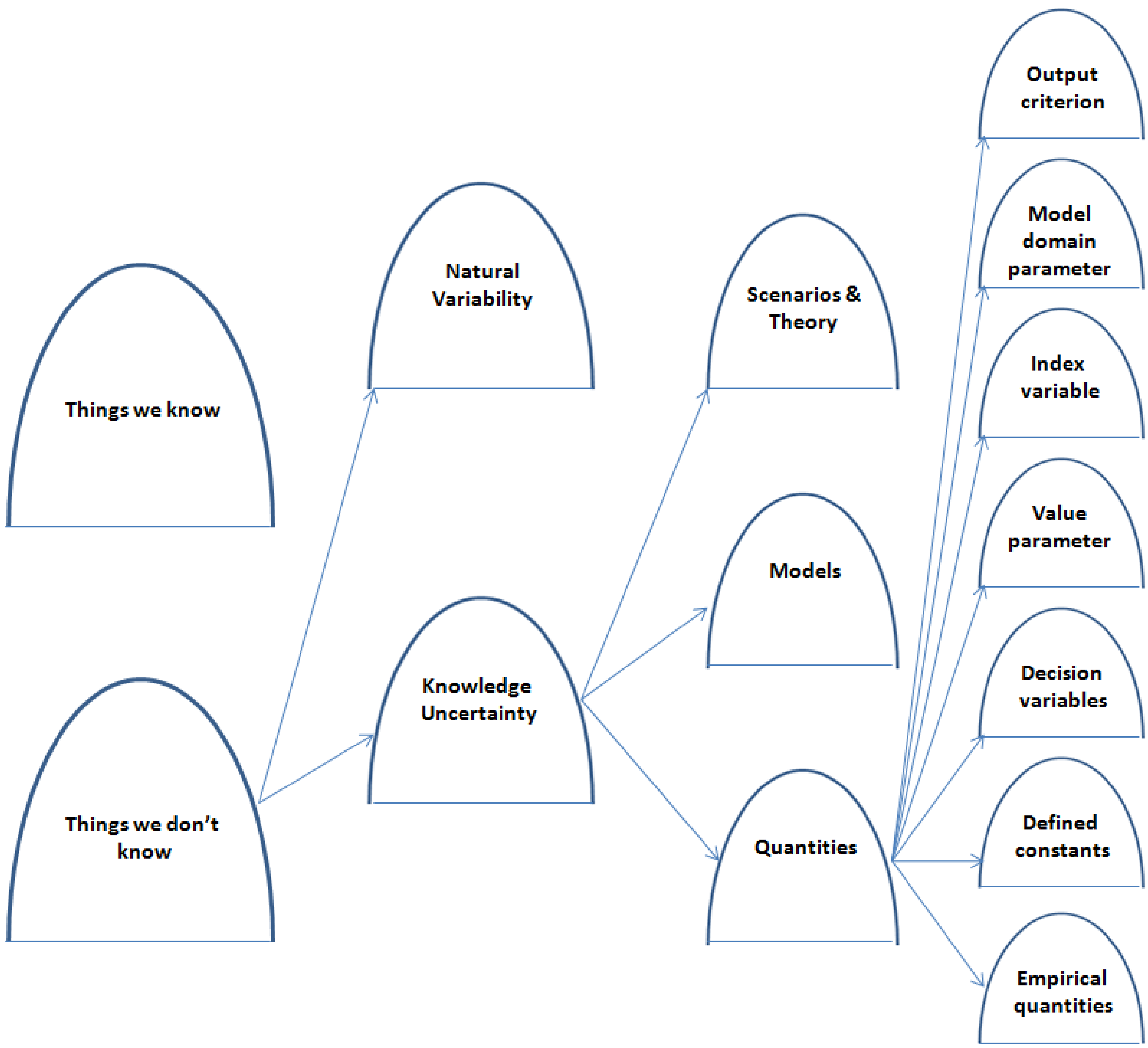

Figure 3.1: Separating what we know from what we don't know and sorting what we don't know

Consider a simple example of a community with 100 houses that must be purchased as part of a project cost. For simplicity, let's dispense with the complications of reality and assume the cost of the project is simply the cost of the 100 houses, each of which is different and does not change (see Table 3.1). We begin with no data and the cost of the plan is in the collection of things we do not know as a bit of knowledge uncertainty. The true cost is a fact that is "out there" and it is constant.

As an experiment, think about the value of an individual house. This is not a constant. Each house has a different value. So we begin this problem recognizing there is natural variability in the house values. Furthermore, because we have no data there is knowledge uncertainty about that natural variability. Thus, the uncertainty at the outset of this analysis is due to both knowledge uncertainty and natural variability.

$ 164,440	$ 142,096	$ 145,532	$ 177,127	$ 210,522	$ 60,093	$ 127,646	$ 128,727	$ 126,915	$ 106,376
$ 100,338	$ 103,326	$ 95,514	$ 72,080	$ 112,889	$ 171,822	$ 133,923	$ 116,687	$ 139,817	$ 124,073
$ 120,266	$ 155,576	$ 150,354	$ 142,339	$ 85,189	$ 172,617	$ 159,524	$ 115,638	$ 106,371	$ 203,075
$ 224,298	$ 161,243	$ 75,769	$ 174,455	$ 170,791	$ 97,741	$ 142,127	$ 141,764	$ 157,791	$ 173,773
$ 209,130	$ 105,239	$ 141,777	$ 114,693	$ 84,110	$ 188,728	$ 155,252	$ 233,973	$ 169,976	$ 130,085
$ 145,756	$ 152,926	$ 173,510	$ 222,267	$ 202,695	$ 160,931	$ 206,910	$ 209,136	$ 93,802	$ 104,709
$ 159,474	$ 80,379	$ 105,038	$ 110,281	$ 189,800	$ 203,081	$ 139,920	$ 96,868	$ 109,548	$ 142,553
$ 160,006	$ 216,130	$ 228,186	$ 134,182	$ 154,949	$ 181,276	$ 173,454	$ 177,881	$ 130,339	$ 204,240
$ 62,225	$ 172,778	$ 165,200	$ 194,453	$ 181,295	$ 71,542	$ 134,315	$ 181,183	$ 124,641	$ 253,245
$ 141,099	$ 207,225	$ 180,906	$ 143,332	$ 125,989	$ 231,911	$ 186,929	$ 169,933	$ 97,933	$ 164,969

Table 3.1 Natural variability in residential structure values

Knowledge uncertainty is reducible while natural variability is not. Let's examine those ideas from the perspective of an "omnipotent" (i.e., all-knowing) risk analyst who happens to know the true mean value of all 100 houses is $149,849 as shown in Table 3.2. Keep in mind that our USACE analysts do not yet know this value. Because a true and constant value, i.e., a fact, exists, we can gather some data to try to learn what it is. So, imagine we take a random sample and estimate the cost of 35 houses. This evidence reduces our knowledge uncertainty a great deal. It suggests the true value we seek is about $150,566[6], which is not a bad estimate at all.

Residential Structure Values		
	Mean	Standard Deviation
Sample	$ 150,566	$ 38,528
Population	$ 149,849	$ 42,975

Table 3.2 Summary statistics for structure values

The uncertainty has been reduced but not eliminated because we work with the sample value. Nonetheless we now assume an average value of about $150,000 per house. Our data collection has also produced some evidence about the natural variability in house prices. After a sample, the USACE analysts have an estimate of the true mean but they will not know, as we do, how close it is to the true mean. Eventually, estimates will be prepared for each house. At that time they will learn the true mean value is $149,849. At this point all knowledge

[6] This result is based on an actual random sample taken from the 100 values. The reader should not expect every such sample to yield such a good estimate.

uncertainty will have been eliminated and the true fact of the mean value of all houses will be known.

This analysis began with a large uncertainty due to knowledge uncertainty. In this instance it was possible to reduce knowledge uncertainty by conducting a sample and gathering some data. This effort greatly reduced the uncertainty. In this simplistic example it was possible to continue to reduce the uncertainty by gathering more data until the value of every house was estimated and the unknown value could be calculated with certainty.

It is not always possible to get to complete certainty, nor is it always necessary or desirable. In reconnaissance studies, for example, it is not unusual to work with large degrees of uncertainty. Cost estimates may be based on a 20 percent level of design detail or less, for instance. Moreover, it is not always going to be possible to gather data to reduce knowledge uncertainty at all.

The key idea to understanding if you are dealing with knowledge uncertainty is: ask yourself if a true value exists and if it is a constant. If the answers are both yes, then you are dealing with knowledge uncertainty. In our example there was clearly a true constant value.

Knowledge uncertainty is not confined to numerical values. Much of knowledge is unknown and thus the notion is extended to include all situations regarding factual matters that are in the collection of things we do not know. For example, we may not know whether providing water in a specific quantity and quality in a given place at a particular time will restore either the functionality or the morphology of an ecosystem.

So far we have neglected the standard deviation; let's consider it now. The USACE analysts know that houses vary in value. That variability is clouded by knowledge uncertainty at the beginning. Imagine standing in front of the houses and being asked the value of a specific house. You must say at that point that you do not know the answer. That answer would be the same for each house. Once the sample is completed, however, we have now reduced our knowledge uncertainty about the natural variability in structure values. The mean value is $150,566 with a standard deviation of $38,528.[7]

Now consider Table 3.1 again. Notice the variability in the house values. Consider this simple experiment. Imagine the value of each house on a lottery game ping pong ball. What will the value of the next ball be? If we repeat that experiment, is that value a constant? Clearly it is not. Each selection will produce one of 100 different values.

Does knowing the sample standard deviation help you predict the value on the next ball? Again the answer is no. Suppose we know the population standard deviation and the mean from Table 3.2. Will this help us predict the value of the next ball? No, it will not.

The value of the next ball is uncertain. Analysts new to this distinction between knowledge uncertainty and natural variability are sometimes tempted to reason that the value is going to be something and we do not know it now so that is knowledge uncertainty. This is wrong. The

[7] These two facts coupled with the knowledge that the sampling distribution of the sample mean is normal due to the large sample size equips the savvy Corps analyst with a great deal of useful information about the natural variability in housing prices. This is not the focus of this discussion, however.

value of the next ball is not a constant before it is chosen, it is a variable. It reflects natural variability. Spending more money to get the remaining 65 cost estimates after the initial sample provides a better estimate of the standard deviation. In fact it eliminates uncertainty about this measure of natural variability. But that data does absolutely nothing to reduce the variability itself. The houses still have 100 different values because of the "system"[8] that produced housing values in this community. It is important to understand that collecting more data, doing research, even conducting more analysis, will not reduce the natural variability that characterizes housing prices in the community.

Interestingly, once a ball is chosen its value does become a constant. At this point, we may have knowledge uncertainty about the house value on the last ball selected because it is now a true value or fact that can, conceptually, be discovered. The only way to change the existing variability to a more desirable variability is to alter the system that has produced the original variability. Let us suppose that the community decisions makers in our example have decided that a more egalitarian mix of housing is desirable. They intend to enact this decision by making improvements to every house below the average value to bring it up to the average value. This yields the population shown in Table 3.3.

$ 164,440	$ 149,849	$ 149,849	$ 177,127	$ 210,522	$ 149,849	$ 149,849	$ 149,849	$ 149,849	$ 149,849
$ 149,849	$ 149,849	$ 149,849	$ 149,849	$ 149,849	$ 171,822	$ 149,849	$ 149,849	$ 149,849	$ 149,849
$ 149,849	$ 155,576	$ 150,354	$ 149,849	$ 149,849	$ 172,617	$ 159,524	$ 149,849	$ 149,849	$ 203,075
$ 224,298	$ 161,243	$ 149,849	$ 174,455	$ 170,791	$ 149,849	$ 149,849	$ 149,849	$ 157,791	$ 173,773
$ 209,130	$ 149,849	$ 149,849	$ 149,849	$ 149,849	$ 188,728	$ 155,252	$ 233,973	$ 169,976	$ 149,849
$ 149,849	$ 152,926	$ 173,510	$ 222,267	$ 202,695	$ 160,931	$ 206,910	$ 209,136	$ 149,849	$ 149,849
$ 159,474	$ 149,849	$ 149,849	$ 149,849	$ 189,800	$ 203,081	$ 149,849	$ 149,849	$ 149,849	$ 149,849
$ 160,006	$ 216,130	$ 228,186	$ 149,849	$ 154,949	$ 181,276	$ 173,454	$ 177,881	$ 149,849	$ 204,240
$ 149,849	$ 172,778	$ 165,200	$ 194,453	$ 181,295	$ 149,849	$ 149,849	$ 181,183	$ 149,849	$ 253,245
$ 149,849	$ 207,225	$ 180,906	$ 149,849	$ 149,849	$ 231,911	$ 186,929	$ 169,933	$ 149,849	$ 164,969

Table 3.3 New natural variability in residential structure values due to a change in the system

The new mean is higher. The point of interest to us, though, is that there is now less natural variability in this community. The standard deviation has changed from $42,975 to $25,011. The natural variability has been reduced in this example[9] by changing the system. The new system still has natural variability, however, so it has not been eliminated.

3.3.3 Why Is It Important to Distinguish the Two Sources of Uncertainty?

There are some very practical reasons for distinguishing the nature of the uncertainty in a decision problem. The first of these is that the choice of the most appropriate tool or technique for addressing uncertainty depends very directly on the source and nature of the uncertainty. This is critically important for those who assess risks to understand.

When the effects of uncertainty in model outputs and decision criteria are characterized by intervals, probabilistic statements or probability distributions, it is useful for assessors to know

[8] That so-called system includes location, school district, size of house, construction material, wear and tear, landscaping and many other systematic factors and influences on house value.

[9] As a point of interest, note that reducing natural variability is not always an improvement. There may be many instances in USACE work where increasing natural variability is actually desired. Increased variability in stream flows is often considered a desirable feature of an urban ecosystem, for example.

how much of the variability in values is due to knowledge uncertainty and how much is due to natural variability. This information needs to be conveyed to decision makers so they can decide if additional effort to reduce uncertainty is warranted.

Consider Figure 3.2. It shows two hypothetical outcomes that measure a single decision criterion. The original estimate (dashed line) shows considerable variation in the values of the decision criteria. If the assessors of this value can attribute the variation to knowledge uncertainty and natural variability and communicate this to decision makers, they can then decide if it would be worthwhile to devote more resources to further reducing uncertainty.

Let us suppose the variation is due to both sources of uncertainty and decision makers want the best characterization of this decision criterion possible. They direct the assessors to gather the information needed to reduce the knowledge uncertainty as much as possible. After doing so, the decision criterion is re-estimated; imagine it is represented by the solid curve. Clearly the uncertainty has been reduced as the distribution is now tighter.

Pleased with this improvement, the decision maker might desire additional reductions in uncertainty. However, if the remaining variation is due to natural variability, then there are no options for further reducing the variation. The solid result may simply represent the true range of outcomes that is possible given the relevant natural variability in the system under consideration. It is impossible for either the assessor or the decision maker to know how much the decision criterion estimate can be improved unless the assessor can distinguish between the two sources.

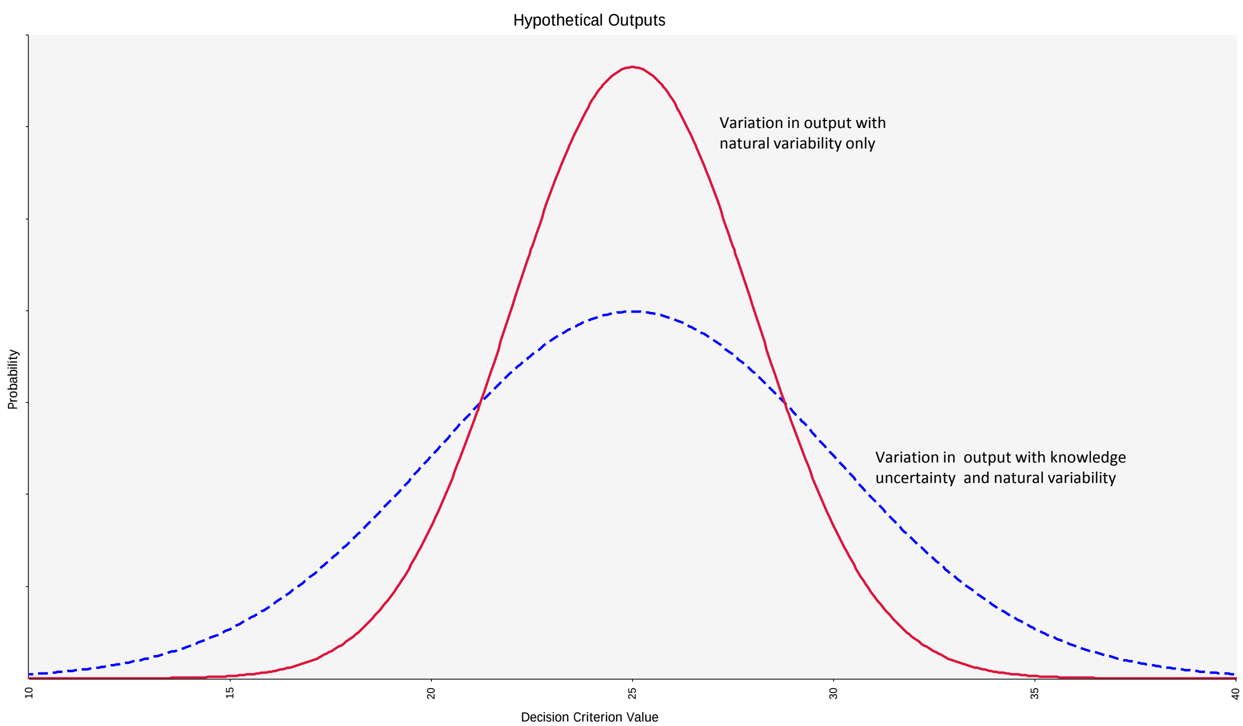

Figure 3.2: Two hypothetical distributions displaying uncertainty

3.4 Three Kinds of Knowledge Uncertainty

Natural variability occurs in systems and its effects are observed in variables that describe the workings and outcomes of those systems. If the knowledge uncertainty about the natural variability in a decision problem can be eliminated or reduced to a negligible level, then the remaining natural variability can often be addressed in a quite straightforward manner.

Figure 3.3 shows a hypothetical ecosystem restoration decision problem that illustrates three kinds of knowledge uncertainty that USACE employees are likely to encounter in their work. Knowledge uncertainty is found in scenarios, theories and knowledge, models, and quantities. Often our understanding of the systems we work with is incomplete. This is reflected in the theories of our disciplines and the scenarios we construct to describe a decision problem or analysis. We may not understand how the components of our scenarios (see figure 3.3) relate to one another or that our characterizations of these components may be incomplete or even incorrect. Finally, our knowledge of facts is often incomplete. For example, you may be unable to name the capitals of the 50 U.S. states. Another example is that there is knowledge uncertainty about the effects of woody vegetation on the strength and stability of levees.

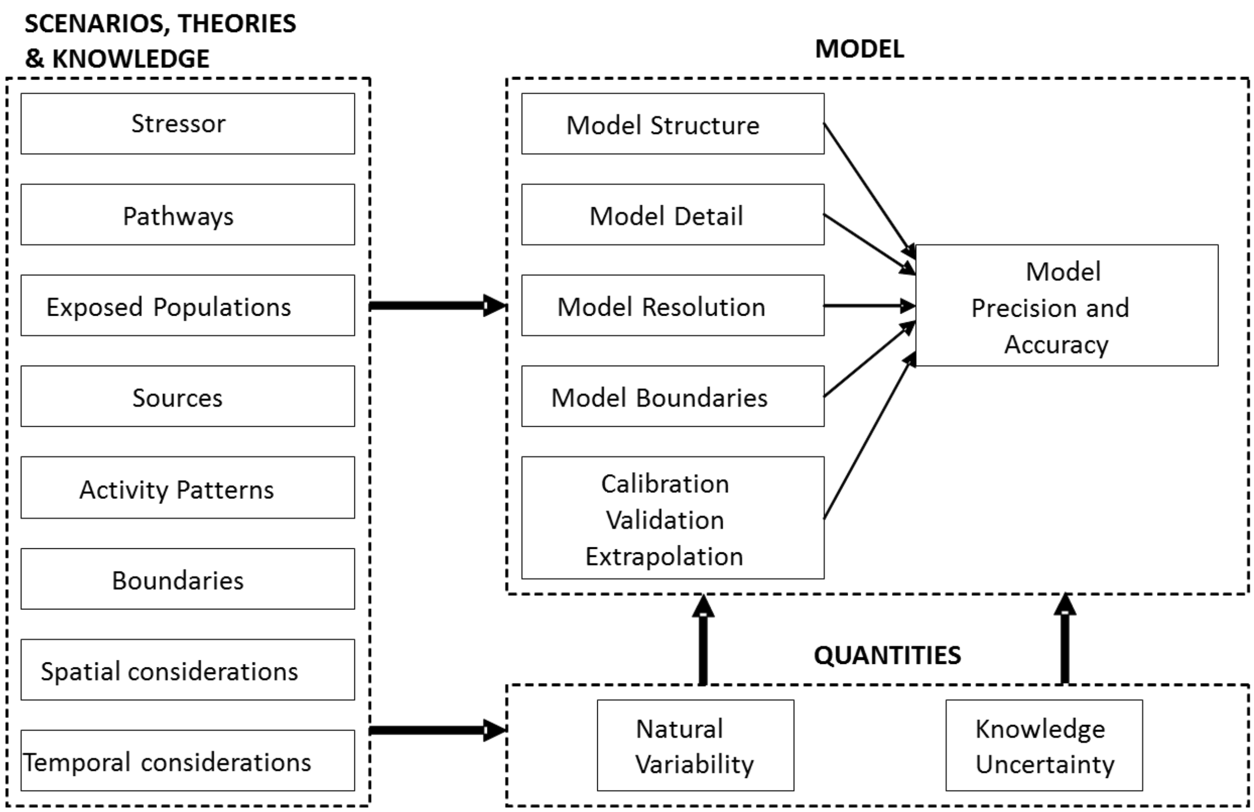

Figure 3.3: Ecosystem restoration decision problem illustrating three major sources of uncertainty

Model uncertainty is most assuredly one of the most common and persistent sources of knowledge uncertainty, as can be seen in figure 3.3. All of our models are more or less flawed simplifications of reality. Everyone who has built a model of even modest complexity has come face-to-face with knowledge uncertainty. As persistent as this source of uncertainty is, it is rarely addressed in a serious way in most analyses. Pragmatically speaking, it is so difficult to obtain even an imperfect model; effort to explore the significance of potential model uncertainty is rarely expended.

The most commonly encountered sources of knowledge uncertainty are found in the quantities with which USACE works. These quantities include inputs to models as well as the data used for day-to-day decision making. Notice that the quantities source in figure 3.3 includes reference to natural variability so that it does not get lost in the discussion.

3.5 Quantity Uncertainty

Uncertain quantities have received the most attention to date not only within USACE but in most risk assessments. A quantity can be a fact, a parameter in a model, a parameter of a population, a statistic, a variable, data or any other form of numerical information. Morgan and Henrion (1990) offer a taxonomy that is useful for considering the types of quantities that tend to be uncertain. Morgan and Henrion's (1990) classification of uncertain quantities includes:

- Empirical quantities
- Defined constants
- Decision variables
- Value parameters
- Index variables
- Model domain parameters
- Outcome criteria

True values

The population of a flood plain, the number of bridges crossing a waterway, the percentage of the channel bottom that is rock, the mean strength of materials in a structure, the mean daily stream flow, average weight of a miter gate, the current price of a yard of concrete, the beam width of a class of ships, and the number of tainter gates at a dam are all quantities that have a true value.

Best values

The discount rate, the value of a life, the money to be allocated for O&M, a design flow for a levee, the design vessel for a channel, the useful life of a project, a planning horizon, a mitigation goal, the length of levee to be blown up to protect a city are quantities that are not true values. An appropriate value must be determined by some degree of subjective judgment.

This discussion begins with an important distinction. Some quantities have a true or factual value while others do not. This is not the same distinction made earlier about knowledge uncertainty and natural variability. In the absence of a true value, assessors and decisions makers alike are more likely to seek the best or most appropriate value, one that reflects some degree of subjective judgment. Not all quantities have a true value. The search for a true value is an objective one while the search for a best value is subjective.

Analysts can generally look up, measure or estimate a true value. Generally, best or most appropriate values are varied systematically in some sort of sensitivity analysis to examine how model outputs, decision criteria and the like respond to different chosen values.

Each type of quantity in the Morgan and Henrion taxonomy is introduced below. Expanded discussion can be found in the original source as well as Yoe (1996, 1997, 2000, 2012).

3.5.1 Empirical Quantities

The most common quantities encountered in USACE analyses are empirical quantities. They have true values. Empirical quantities are things that can be measured or counted. This includes stream flows, pH, dissolved oxygen, number of native plant species, distances, times, sizes, statistics and every kind of count that can be imagined. An empirical quantity can have an exact value that is unknown but measurable in principle. An unknown empirical quantity is an example of knowledge uncertainty. A full range of tools and techniques from narrative descriptions through probabilistic methods can be used to address this uncertainty.

3.5.2 Defined Constant

Some quantities have a true value that is fixed by definition. These are defined constants. When they are unknown by the analyst, the solution is to look them up. Examples include pi, e, 43,560 square feet per acre, and 325,851 gallons of water per one acre-foot of water.

3.5.3 Decision Variables

USACE risk managers decide the Dam Safety Action Classification (DSAC) for a dam. Planners decide the depth for channel deepening. There are many quantities that an analyst must choose. Examples include a reasonable cost, a mitigation goal, a tolerable level of risk, and so on. Decision makers exercise direct control over decision variables, they have no true value. Decision variables are subjectively determined. Knowledge uncertainty about a decision variable is most appropriately addressed through parametric variation and sensitivity analysis.

3.5.4 Value Parameters

Some quantities express some aspect of the social values that emerge from the macro levels of uncertainty in USACE work. These values, such as discount rates, the value of a life, and the weights used in a multi-criteria decision analysis, represent aspects of the decision makers' preferences and judgments. They do not have true values; they are subjective assessments of social values. Parametric variation and sensitivity analysis are the most common means of addressing knowledge uncertainty about these quantities.

3.5.5 Index Variables

An index variable identifies an element of a model, a point in time, or a location within a spatial domain. More often than not they do not have true values. Random or representative choices of index variables are usually subjectively determined. Occasionally a very specific point in time or place is needed. When this happens there may be a true value. Examples of index values are project years 10, 20, and 30; a representative grid cell in a GIS model, the position of an object in a model where a sequence of events is initiated (e.g., the location of a vessel on a waterway when a lock begins to open). Index variable uncertainty is most often addressed through parametric variation and sensitivity analysis.

3.5.6 Model Domain Parameters

Some quantities specify and define the scope of the systems considered in a decision problem. For USACE these include definitions of study areas, impact areas, tributary areas to a port, regional sediment systems, and the like. On a smaller scale the domains of specific models are included: for example, flood plain delineations, land areas for habitat unit calculations, sea level change boundaries, and so on. These parameters often describe the geographic, temporal and conceptual boundaries (domain) of a model and define the resolution of its inputs (minutes, hours, days, weeks) and outputs. They may or may not have true values. They usually reflect judgments regarding the model domain and the resolution needed to assess risks adequately. Scale characteristics chosen by the modeler may have no true value in nature. Some analyses, however, may be restricted to specific facilities, towns, timeframes and so forth and may have true values. Knowledge uncertainty about domain parameters is a form of model uncertainty when such boundaries are built into the model structure. If the domain is the upstream miter gate at a specific lock, it is trivially specific and objective. The hinterland affected by economic activity at the Port of Los Angeles is a much more subjective determination. These kinds of quantity uncertainties are most appropriately addressed through parametric variation and sensitivity analysis.

3.5.7 Outcome Criteria

Outcome criteria are output variables such as benefit cost ratios, net benefits, habitat units, probabilities of unsatisfactory performance, and similar variables that are outputs of models and calculations. Their values are determined by the models used and the quality of the model's input quantities. Propagating the uncertainty about output criteria is the responsibility of the risk assessor addressing it, while decision making is the responsibility of the risk manager.

3.5.8 Causes of Uncertainty in Empirical Quantities

Of these different quantities, those with true values that are subject to knowledge uncertainty are by far the most important for USACE analysts. The vast majority of these quantities are empirical quantities. While the causes of empirical uncertainty discussed below are our primary focus in this section, this discussion is also applicable to any quantity that has a true value. The work of Morgan and Henrion (1990) provides the structure for this discussion.

Empirical quantities are most often measured, calculated or estimated. When good measurement data are available there may be little or no knowledge uncertainty about the true value of a parameter or variable. At the other extreme, knowledge uncertainty may be absolute and permanent[10] because the data have been lost to history. Even when there is no knowledge uncertainty, natural variability may remain to be addressed. It is essential to know the cause(s) of knowledge uncertainty if one is to address it appropriately in a decision problem.

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[10] We will never know the mean high temperature for the month of July, 1187 in Rome for example. Even so that quantity is a true value.

3.5.8.1 Random Error and Statistical Variation

Many data we have for empirical quantities are sample data. Not all samples are valid probability samples; those that are still yield parameter estimates that are subject to random error. Many measurements of physical quantities are inexact. Classical statistical techniques provide a wide array of techniques and tools for quantifying this kind of uncertainty including estimators, standard deviations, confidence intervals, hypothesis testing, sampling theory and probabilistic methods.

> Much data are collected outside a laboratory and under less than ideal conditions. Where in the stream does the investigator insert the meter to read dissolved oxygen? How do you estimate the percent of mid-day shade on a stream? How carefully does the inspector inspect?
>
> Subjective judgments like these are notoriously suspect under uncontrolled conditions. Although the methods discussed in this manual tend to be analytical ones, uncertainty can sometimes be addressed by very practical means. Calibrating all measurement devices, including the people taking the measurements, is often one of the best hedges for uncertainty. How good are your first floor elevations if estimated by interns using hand levels, a six-foot rule and topographic maps?

3.5.8.2 Systematic Error and Subjective Judgment

Systematic errors arise when the measurement instrument, the experiment or the observer are biased. Imprecise calibration of instruments and people is one cause of this bias. If the scale is not zeroed or the datum point is off, the solution is better calibration of the instrument or data. If the observer tends to over- or under-estimate values, then a more objective means of measurement is needed or the observer needs to be calibrated or recalibrated. The challenge to the USACE analyst is to try to reduce systematic error to a minimum. The best solution is to avoid, minimize or correct the bias. Using random sampling techniques to collect all data can eliminate or at least minimize many forms of bias. When a bias can be identified, e.g., the datum was off by a foot, allowances can sometimes be made for it, i.e., re-measure or adjust each measurement by a foot.

It is more difficult to correct for biases that are unknown or merely suspected. Bias in subjective human estimates of unknown quantities is a topic covered extensively in the literature; see, for example, O'Hagan (2009) or Yoe (2012).

> There was a meeting of USACE and resource agency personnel to discuss a project where dredged material was to be used to create wetlands. Early in the meeting someone said, "We will fill to -1." All nodded in agreement.
>
> As the meeting ended someone confirmed the fill to -1 MLW. Quickly others objected. "I thought it was -1 MSL/-1 NGVD/-1 MHW," they said in sequence. Everyone took a seat and the meeting began again with more clarity.

3.5.8.3 Linguistic Imprecision

Communication is still humankind's number one challenge, despite all our years on the planet. Because we so often use the same words to mean different things and different words to mean the same things, communicating about complex matters involving risk is especially challenging. If we say flooding occurs frequently or a risk of infrastructure failure is unlikely, what do these words really mean? Tasked with measuring the percentage of mid-day shade on a stream for a habitat suitability model, a group of environmentalists engaged in a lengthy discussion about when mid-day occurs and how dark a surface must be to be considered shade.

We do not want to run Monte Carlo simulations using different meanings of words. The most obvious solution to this kind of ambiguity is to carefully specify all terms and relationships and to clarify all language before or as it is used. Using quantitative rather than qualitative terms when possible can also help.

3.5.8.4 Natural Variability

This source of uncertainty warrants repeating. Many quantities vary over time, space or from one individual or object in a population to another. An oil spill kills some fish but not others. This variability is inherent in the system that produces the population of things we measure. Frequency distributions based on samples or probability distributions for populations, if available, can be used to estimate the values of interest. Other probabilistic methods may be used as well.

3.5.8.4 Randomness and Unpredictability

Inherent randomness is irreducible in principle. This cause of knowledge uncertainty identifies those events that are not predictable in practice at the current time. Examples include such things as where the next major flood will occur, when a lock gate will fail to operate, or how the next major marine casualty will occur. Such events can be treated as random processes. Uncertainty about such quantities can be addressed by a full range of methods from narrative descriptions through probabilistic methods.

Phenomena that appear random to one assessor may be the result of a process well known by a subject matter expert. Centers of expertise, strong interdisciplinary risk assessment teams, peer involvement and peer review processes provide a reasonable hedge against this sort of problem arising.

3.5.8.6 Disagreement

Experts do not always see eye-to-eye on matters of uncertainty. Neither do organizations. Planning studies are cost shared. There have been many spirited debates over whether to use the water authority's hydraulics and hydrology or that of USACE. There can be widely disparate views of the problem. Different technical interpretations of the same data can give rise to disagreements. There can also be the real possibility of conscious or unconscious motivational bias.

Disagreements are often resolved through negotiation and other issue resolution techniques. Allowing disagreements to coexist is another option. Sensitivity analysis can then use the different arguments in order to examine their effect on decision criteria.

3.5.8.7 Approximation

Ecosystem restoration in the Comprehensive Everglades Restoration Plan sought to restore the timing, quantity and quality of water closer to conditions that existed many decades before data were systematically collected. At best, they could approximate these conditions through the spotty data that were available. This knowledge uncertainty about unknown conditions is often manifested in model uncertainty when models are based on approximations.

Analysts are only able to approximate the function of complex systems due to these three kinds of uncertainty. Methods for dealing with this source of uncertainty will depend on the specific limitations of the approximation.

3.6 Being Intentional About Uncertainty

The one and only reason to expend so much effort on understanding the nature of the uncertainty about the things you do not know in your decision problems is so you can intentionally take effective steps to address that uncertainty. Here are nine steps to take to become intentional about uncertainty in decision making:

1. Recognize that uncertainty exists in your decision problem.
2. Identify the specific things that are uncertain and the sources of that uncertainty.
3. Identify those uncertainties that are important to your decision problem. These are the uncertainties that have the potential to have a significant effect on your decision criteria.
4. Acknowledge this significant uncertainty and make stakeholders aware of its existence.
5. Choose appropriate tools and techniques to address each significant source of uncertainty.
6. Complete your analysis incorporating these tools and techniques.
7. Understand the results of your analysis.
8. Identify any options for further reducing remaining uncertainty.
9. Convey your results, the significance of the uncertainty, and any options for reducing uncertainty to decision makers.

Rock in the channel

During one proof-of-concept, risk-based estimate of costs in the early 1990s, a design engineer was asked to estimate the percentage of rock in a channel bottom with an estimated interval. He declined to do so; when pressed, he refused. His justification was that he had much more and much better data than he normally has. He was offended by the notion that he might not know how much rock was actually in the channel bottom. His point estimate proved to be off by a significant amount. He has become a supporter of interval estimates.

The process begins by recognizing uncertainty when it exists and it almost always exists. It is not unusual for experienced professionals to underestimate the things they do not know or to overestimate the quality of their data. Experts are often confident, not so much because of what they actually know as what they believe to be true. Biases, mindsets and beliefs can prevent some people from recognizing that uncertainty exists. Experts are often correct in their intuitive judgments and this strongly reinforces those biases. Thus, the starting point for all risk work is to begin by recognizing the existence of uncertainty. This may, at times, require USACE analysts to challenge one another. To challenge false beliefs in certainty, ask: "What is your evidence for your beliefs about this problem?" When experts can produce evidence, it is reassuring. When they cannot, it can be enlightening.

Once uncertainty is recognized it is necessary to specifically identify what is known with certainty and what is not. The analyst's job is to identify those uncertain things that are most important to decision making. These would be scenarios, theories and knowledge, models or quantities that if not certain could affect the decision criteria. In planning, any source of uncertainty that could affect the estimation of net benefits significantly is a significant uncertainty. Clearly benefit estimates and costs estimates would be significant sources of uncertainty, if uncertain. Drilling down a little deeper into cost, one might find many potential sources of uncertainty. Many cost and quantity estimates will be uncertain. Some of these will be more important than others. Methods for identifying the most significant uncertainty can be found in Yoe (2012).

There are going to be people who need to know about the uncertainty even before you begin to address it. If design engineers do not yet have information about seismic zones in a project footprint, others need to know this. If economists do not have first floor elevations for floodplain structures, people need to know this. USACE partners are certainly going to need to know the limitations of the available data.

Matching an appropriate tool and technique to the uncertainty is an important analytical step. Some uncertainty can be addressed in a qualitative risk assessment. Other uncertainty may require a probabilistic risk assessment. Between and beyond these approaches lie many tools and techniques that are described in Chapter 7.

Characterizing the risks associated with the decision problem requires analysts to complete the analyses and to pull together the many and disparate approaches for addressing uncertainty that may have been used. It is important for the analysts to spend sufficient time with the results of their analyses to understand them and the uncertainty that attends them.

In best practice, analysts will be able to distinguish the effects of knowledge uncertainty from the effects of natural variability. This will enable the analyst to identify potential options for further reducing the uncertainty in the analysis. One of the greatest challenges, and an area of risk analysis that has not yet received sufficient attention, is to convey the results, the significance of the uncertainty and any options for reducing uncertainty to decision makers.

It is the USACE analyst's responsibility as risk assessor to address the most significant uncertainties in their decision problems. Some of the simpler tools available include narrative descriptions of the uncertainty, clarification of ambiguous language, negotiation for differences of opinion and confidence ratings for their analyses. When the relevant uncertainty could lead to dramatically different futures and a few key drivers of this uncertainty can be identified, scenario planning is a useful technique. In more quantitative analyses, assessors can use parametric variation, bound uncertain values, use sensitivity analysis or quantitative risk assessment, all of which can include both deterministic and probabilistic analysis. These and other techniques are reviewed in Chapter 8.

It is the USACE decision maker's role as risk managers to address uncertainty in their decision making. When the uncertainty is great and the consequence of making a wrong decision is a concern, adaptive management strategies may be implemented. Adaptive management strategies are designed to reduce key uncertainties (through research, experiments, test plots, trial and error, and so on) to provide information to better inform managers about the risks and the efficacy of the risk management options before they are irreversibly implemented.

The “precautionary principle” is favored in some circumstances as an approach to decision making under uncertainty. There are also a number of criteria that have been developed for choosing from among alternative risk management measures under uncertainty. They include the:

- Maximax criterion—choosing the option with the best upside payoff,
- Maximin criterion — choosing the option with the best downside payoff,
- Laplace criterion — choosing the option based on expected value payoff,
- Hurwicz criterion — choosing an option based on a composite score derived from preference weights assigned to selected values (e.g., the maximum and minimum) , and
- Regret (minimax) criterion – choosing the option that minimizes the maximum regret associated with each option.

Good risk analysis requires assessors, managers and communicators to be intentional about dealing explicitly with uncertainty when carrying out their responsibilities.

3.7 Five Points To Take Away

1. There are two levels of uncertainty: macro-level and micro-level uncertainty.
2. Uncertainty comprises knowledge uncertainty and natural variability.
3. Knowledge uncertainty can appear in our scenarios, theories and knowledge, models and quantities.
4. The thing that is uncertain and the cause of that uncertainty will largely determine which tools and techniques are best suited for addressing the uncertainty.
5. Risk analysis addresses uncertainty in decision making in a very intentional and systematic manner.

3.8 References

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Chapter 4: Risk Management

4.1 Introduction

Chapter One in this manual asserted that USACE is a risk management organization. Risk management is the cornerstone of the risk analysis process and the focus of this chapter, which has three primary parts. First, the importance of life cycle risk management for USACE projects is established. Risk management is not an add-on or a process that occurs sometimes; it begins with project conception in planning and extends through the final disposition of a project. Second, the risk manager's job is briefly considered. Third, the current risk management model for USACE is introduced and described.

4.2 Life Cycle Risk Management

In its Civil Works program USACE must manage risk over the entire life cycle of a project. Uncertainty is a ubiquitous dimension of the project life cycle. There will always be useful facts that are not available. Even when the necessary facts are available, natural variability assures that decision making under uncertainty remains a constant challenge over the entire life cycle of a project. Consequently, uncertainty must be addressed in an intentional manner, and risks both constant and changing must be managed from planning through the final disposition of a USACE project.

Project Life Cycle

For the purposes of this manual the stages of a project life cycle are:

- Planning
- Preconstruction engineering and design (PED)
- Construction
- Operation and maintenance, including replacement, rehabilitation and reconstruction
- Final disposition

The formal recognition of risk analysis as an effective discipline for guiding decision making under uncertainty is relatively recent. Moreover, the roots of this discipline are found in many fields and applications. This has led to a sometimes confusing proliferation of terminology. When one speaks about "risk management," for example, many people will understand that term but not all, and sometimes not many will understand it in the same way. As a result, it may be useful to say a little about what risk management is not.

Risk management is not an add-on or an afterthought. Analysts do not do what they have always done in the way they have always done it, then add something called risk management at the end just before calling their decision making complete. Risk analysis is a relatively new paradigm for making decisions under uncertain conditions. Risk management is the cornerstone of the risk analysis process. Risk management is practiced from the first day of a planning study through the stages of the life cycle (see textbox) to the final disposition of a project.

Risk management is not a process practiced sometimes;, i.e., it is not a tool or technique taken down from a shelf and practiced on special occasions. It is not something you practice only in selected stages of a project's life or at selected moments within those stages. Risk management is the USACE decision-making framework. It is to be applied to decision making vertically and horizontally throughout the organization and to all projects, all business lines and all functions.

Risk management is not just a planning practice or just a project management practice. Every office within USACE at every level that makes mission critical decisions under conditions of uncertainty must use the risk management framework.

Risk management is not a new process, but it is becoming a very formal process. Many different elements of USACE have been wittingly or unwittingly practicing risk management work since their inception. Different people are going to have different opinions and views about what it means to perform risk management. This manual is intended to aid a transition to a common, unified view of what it means to perform risk management within USACE. The model presented later in this chapter marks an important step in this direction.

4.2.1 Life Cycle Stages

Some of the risks to be managed over the life of a project are continuous, while some are resolved as new risks arise. If a feasibility study is initiated to address flood risks, those flood risks are going to persist in some form over the entire life cycle of the project. That form may change more than once, but some risks of loss and potential gain will persist. Others will be resolved. If a feasibility study assumes no Hazardous, Toxic, and Radioactive Waste (HTRW) problems and there are none, the risk of a mistaken assumption is favorably resolved. If assumptions made about subsurface geological conditions used to estimate a cost during a reconnaissance study prove wrong, the bust in the cost estimate will have its consequences but the risk will also be resolved long before construction.

Each stage of the life cycle presents its own unique risks and its correspondingly unique uncertainties. Risk managers in each stage make assumptions that kick the proverbial risk "can" down the life cycle road. As a result, risks comprise many of the threads that link the life cycles together. Some risk management tasks begun in planning will continue throughout the project life cycle. Some will end in later stages. New risks will arise in each life cycle stage along the way. Some will be resolved quickly within the same stage. Others may span several different stages.

Risk management is the continuous process that identifies and addresses all of these risks. The risk register (RR) is emerging as the most useful tool for documenting and managing the risks that arise throughout the project life cycle. The current vision is that a RR would be "born" during the planning stage of a project and this register would be used by USACE personnel throughout the project's life. There is some potential for developing a RR for existing projects that would accompany them from their current life cycle stage through their final disposition. Neither of these ideas is yet reality at the time this manual is written.

Figure 4.1 shows the stages of a project life cycle (not to scale) and how uncertainty decreases over time as knowledge uncertainty is reduced and natural variability is revealed. All of this comes at a cost. Risk management throughout the project's life cycle is essential for identifying and addressing uncertainty in decision making as well as for controlling the cost consequences of risks that arise in the course of the project's life.

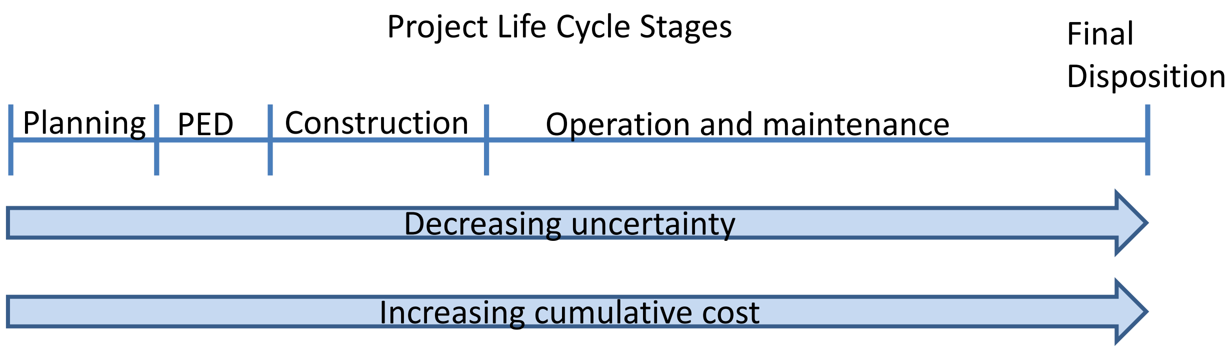

Figure 4.1: Project life cycle stages, uncertainty and cost

The risks over a project's life cycle can be categorized as:

- Risks in the community
- Study risks
- Implementation risks
- Operation risks
- Outcome risks

Figure 4.2 suggests the predominate risks encountered and managed in each project life stage. Uncertainty in decision making may be the greatest at the outset of the planning stage. It is reduced considerably during reconnaissance and feasibility studies as problems and opportunities are identified, verified and measured so that risks in the community are better understood. Study risks are introduced when planning studies are initiated. These are risks associated with the analytical and decision errors that USACE itself can make when dealing with the tradeoff between more uncertainty and lower study costs with shorter schedules. Implementation risks arise as proposed solutions are formulated, screened and compared culminating in the identification of a tentatively selected plan (TSP).

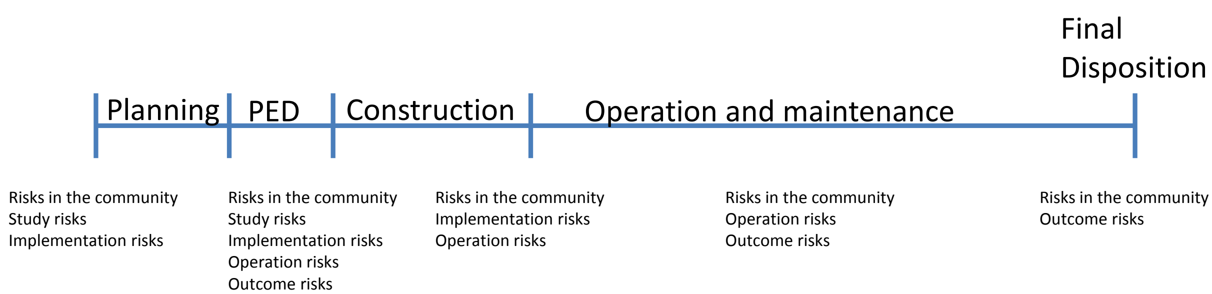

Figure 4.2: Predominant risks by project life cycle stage

Once a specific solution is identified the preconstruction engineering and design (PED) stage of the life cycle reduces uncertainty about project cost and design features and details. During that process it refines understanding of the risks the community faces, introduces new study risks with this new phase of study, and intensifies the focus on implementation, operation and outcome risks as the project moves toward reality. Design details introduce more tangible understanding of risks that might arise during project operation as well as a better understanding of how well the project will perform in reducing risks of loss or enhancing risks of potential gain. These are outcome risks. Outcome risks also include any new risks introduced by the project itself, such as levee overtopping, failure in flood risk projects or new kinds of environmental disasters made possible by channel deepening projects that might give rise to larger vessels or inherently dangerous cargo.

In each stage assumptions may be made to resolve issues of uncertainty. For example, Olmstead Lock and Dam's feasibility study made assumptions about project costs that were refined in the PED stage. The PED design and cost estimate assumed some project components could be pre-built and floated to the work site. When the project was to be built there was insufficient bidding interest to make the PED design work and the assumptions of PED were proven incorrect. This is normal for decision making under uncertainty. When things like project costs must be decided without all information, some of the assumptions made will inevitably be proven wrong. Risk management cannot end that problem but, performed well, it can limit it and provide contingency plans for avoiding or limiting the adverse consequences of risks that can be anticipated.

Once the construction stage begins study risks drop out of the picture and implementation risks take center stage as the primary concern. The risks in the community remain constant and operation risks begin to rise in importance. Outcome risks are temporarily diminished in importance.

In the O&M stage when the project lives its useful life, risks in the community and outcome risks come to the fore and are managed over decades. It is in this stage that much of the uncertainty of the earlier stages will be resolved as everyone learns if the losses are prevented and the gains realized. New operation risks arise with wear and tear on the project and this may include such things as periodic replacement of components that wear out, major rehabilitation of major project features, or even reconstruction of the project to meet the needs of changing values and physical circumstances.

Although most USACE projects continue to provide services to the community, some projects outlive their useful life. Some may be deauthorized, meaning federal money will no longer be spent on them. For example, a channel deepening project that is no longer funded will silt in. Most local flood risk management projects are turned over to local sponsors. In the future it may be necessary to walk away from, decommission or remove some projects. At this final stage of the life cycle the emphasis is likely to be on those original community risks that run throughout a project's life as well as the outcomes associated with the final disposition of a project.

Some risks exist at a point in time; some persist over the life of a project; and some fall in between these extremes. All of these risks need to be managed. Figure 4.3 illustrates this idea with a few examples. Notice that some risks persist throughout the entire life cycle. In fact, some of these risks, like flood losses, may even pre-exist the project. Others may be born with the project.

The risk register (RR) is a valuable risk management tool for following risk throughout the project life cycle. It provides not only a log but an ongoing record of all risks of concern. Thus, risks created in one stage of a project can be readily communicated to the next stage. Risks may persist for varying lengths of time as well. Note the occurrence of an extreme storm event during the useful life of the project in figure 4.3. This could have presented risks of sand boils, overtopping, disruption of traffic or many other possible losses. Other discrete event risks could include damage to a closure structure, failure of a pump station motor, a zoological disease outbreak or any number of events.

All of the risks that are the responsibility of USACE must be managed, and all need to be tracked in the project's RR. The RR is described in detail in Appendix D. The RR is a very valuable tool but it is a log for recording actions that give rise to risks, the nature of the identified risks, and the options for managing them. What the RR does not do is help us to think about the overall framework of managing risks. For that we need a risk management model. Such a model is presented in the next section.

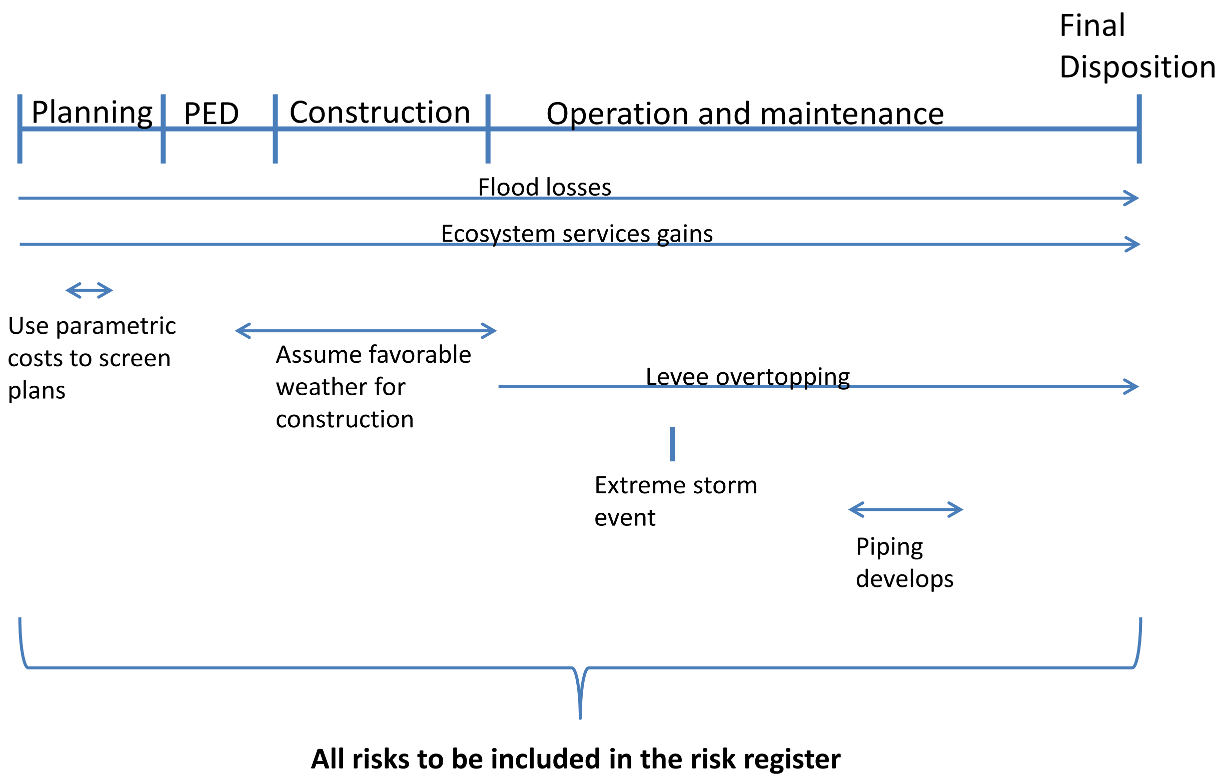

Figure 4.3: Examples of risks that occur over the project life cycle

4.3 Risk Management Model

Given the risk manager's job is to manage risk over the entire life cycle of a project, the question becomes how will USACE decide to implement these management tasks in its Civil Works program. What risk management model will USACE use? The model that seems to best suit the varied risk management needs of USACE at this point in time is a modification of the International Organization for Standardization's (ISO) risk management model. The model is presented in Figure 4.4.

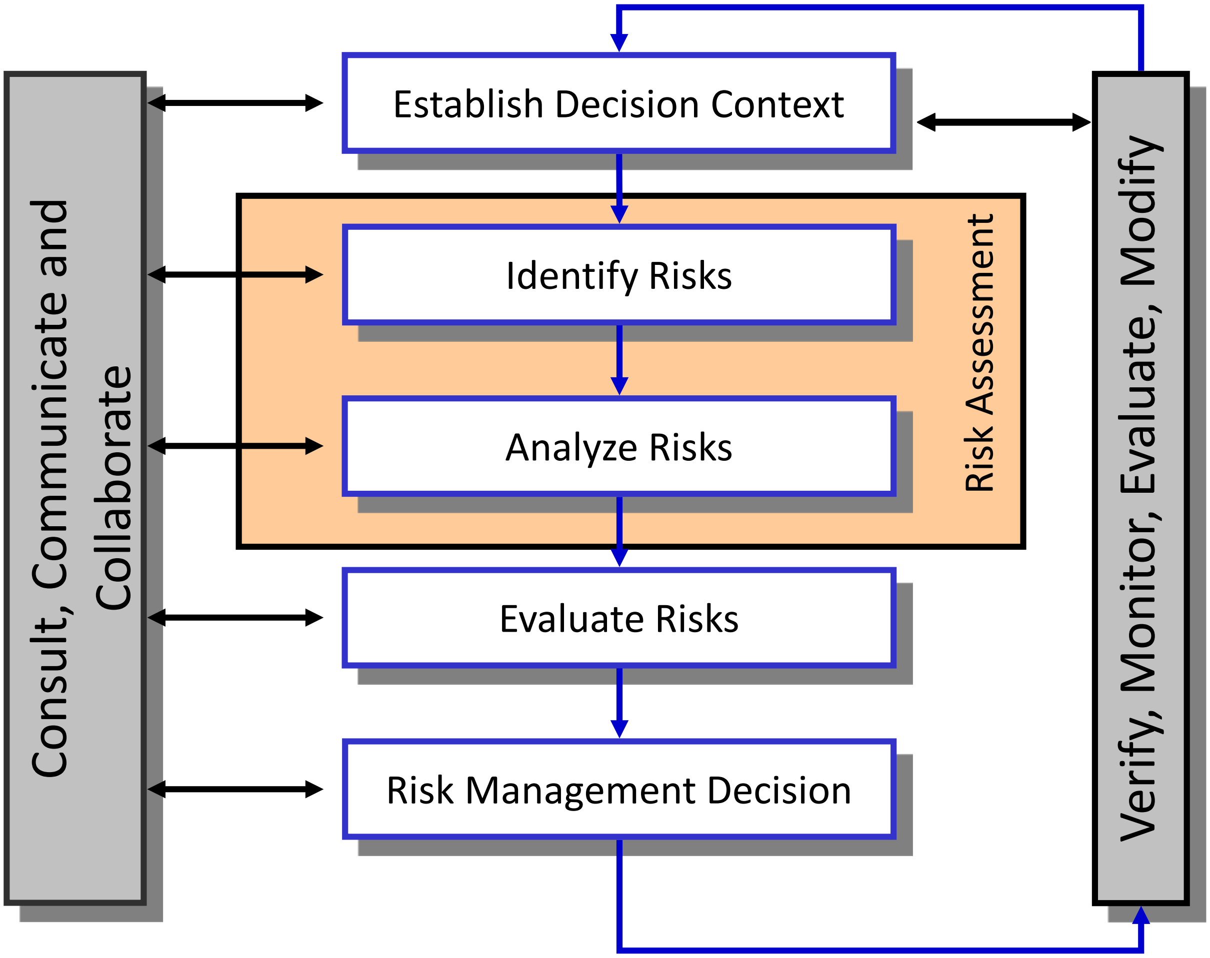

Figure 4.4: Risk-informed decision-making model.

This model represents a universally applicable approach to decision making that is systematic, scalable, simple and flexible. It focuses on the relevant uncertainties and remains reasonably transparent and open to interested parties. The discussion below presents the principles of the framework, which are considered to be firm. Importantly, the framework remains flexible in its details. It is also scalable and can be used for decisions large and small. It is neither prescriptive nor restrictive. It is an organizing framework that provides for consistency across all Civil Works risk management activities while allowing sufficient flexibility to meet the varying needs of the many decision-making entities in USACE.

The model incorporates the three tasks of risk analysis previously presented in Chapter Two: risk assessment, risk management and risk communication. Risk assessment is embodied in two tasks in the risk management model. The process of consultation, communication and collaboration shown on the left includes the risk communication task.

The tasks and processes of the risk management model are described generally in the sections that follow. A chapter on risk-informed planning serves as an example of how this risk model can be incorporated into Civil Works planning.

4.3.1 Five Tasks

The risk management model of Figure 4.4 identifies five risk management tasks. They are:

1. Establish the decision context,
2. Identify risk,
3. Analyze risk,
4. Evaluate risk, and
5. Risk management decision.

Decision making is the beginning and ending focus of the model. That decision making is especially challenging because it involves uncertainty. The tasks of the risk management model are discussed individually below.

4.3.1.1 Establish the decision context

Decision making begins by establishing the decision context. The primary elements of a decision context include:

- Defining the management problem or opportunity;
- Identifying the objectives of the risk management activity;
- Requesting specific information needed to make a decision;
- Identifying the decision criteria;
- Preliminary identification of the key decision uncertainties; and
- Initiate consultation, communication and collaboration activities.

> Defining a problem or opportunity consists of several specific tasks:
>
> - Identification-recognizing a risk problem exists and understanding what it is.
> - Acceptance-deciding to focus attention and resources on the problem.
> - Representation-articulating the risk problem in an evidence-supported narrative for USACE and others while linking the problem or opportunity to possible solutions.

Once a risk management activity has been initiated, the first task is to clearly identify the decision-making context and articulate it carefully so others will understand it. This begins with the problem and opportunity definition (see textbox). Identifying the problem to be solved or the opportunity to be pursued simply states where USACE currently is in the decision-making process. Problems and opportunities are the reason to conduct a risk management activity. For example, periodic damaging floods on Brown Sugar Creek is a problem. Reconnecting the urban community with the natural ecosystem is an opportunity.

Examples of objectives :

- Protecting human life, health and safety,
- Providing more reliable navigation services,
- Providing a more predictable flow of budget resources, and
- Minimizing the costs of facility operations subject to an acceptable level of service.

Objectives identify what USACE and its stakeholders would like to see happen and when. Identifying objectives is the next logical step in establishing the decision context. The objectives state, in broad and general terms, what the risk manager intends to do about the problems and opportunities faced. They are not solutions or risk management options. An objective is a clear statement of a desired outcome of a risk management option. Objectives should be specific and at least conceptually measurable.[11] They define what success will look like. The simple relationship between problems/opportunities and objectives should be such that when the objectives are realized, then the problems are solved and the opportunities are realized. Reducing flood damages to residential properties is an objective. Raising structures and levees are risk management options.

A good objective is:

Specific—it is clear and free from ambiguity
Flexible—it can be adapted to new or changing requirements
Measurable—its achievement can be documented by some objective means
Attainable—it can be reached at the end of a course of action
Congruent—it is in harmony with other objectives
Acceptable—it is welcome or pleasing to key stakeholders

A good objective is not:

Absolute targets—it does not specify a particular level of achievement
Management options—it does not prescribe a specific course of action
Government goals—it is not a political or governmental objective
Risk assessment tasks—developing a dose-response curve is not an objective
Resource constraints—it does not address time, money, or expertise

Once problems and opportunities are defined and good objectives are available, risk managers must identify the specific kinds of information they are going to need to know in order to best achieve their objectives. In USACE, well established programs and issues like flood risk management, inland navigation and reservoir reallocation are well-known and have long-established information. In these instances, risk managers need only identify any unique information requirements to their staff.

In unique situations risk managers may have to be extremely specific about the information they need to make a decision. Identifying these information questions may require considerable effort. The decision to blow up the Birds Point New Madrid levee in 2011 is a good example of a unique risk decision. The strategy that was employed was a risk control measure identified at the time the project was constructed.

These information requirements are often best conveyed in a list of questions. These are the specific questions that will guide subsequent analytical efforts. Consider them fact-oriented, information-gathering questions.

[11] Objectives will not be analyzed and measured in every decision making process. Emergency situations may not allow for it. Simple decisions may not require it. Every objective should be measurable in principle, whether it will be measured or not.

Examples of decision information questions might include:

- What are the District's dredging priorities?
- Which flood risk management measures will be most effective for this community?
- When should the engineering structure be rehabilitated?
- Which structures should we inspect first?
- Does the navigation channel need modification?
- Are there significant environmental impacts associated with this permit application?
- What is the community's current flood risk?
- What is our exposure to a construction cost overrun?
- What is the probability of a catastrophic loss of aquatic wildlife due to a marine casualty in the channel?
- What are the consequences of continued subsidence for the project's integrity?
- How much hard bottom is adjacent to the channel?
- What is the potential for improving this ecosystem?

Every risk management activity will ultimately require some sort of balancing of risks, costs, benefits, and other social and political values. This means the nature of the relevant benefits, costs and values, i.e., the decision criteria, must be explicitly identified early in the risk management process so appropriate information is gathered. The decision criteria chosen must be meaningful to the people with decision-making authority. This means a collaborative process of identifying them is required for decisions that involve non-USACE entities. The collaborative component of this model is discussed in a later section. Risk managers must anticipate the criteria upon which they will base their decision and assure these criteria are conveyed to staff.

Even routine maintenance can be risky

The *Idaho Mountain Express* on November 10, 2010 reported that about 1,000 steelhead trout died at the USACE Dworshak Dam on the North Fork of the Clearwater River in Idaho during routine maintenance. A generator was taken out of service and its draft tube was drained to allow routine maintenance, trapping hundreds of Steelhead. Although most were hatchery fish, some were wild fish protected under federal law. How might use of the risk management model have helped prevent this accident?

As the decision context is determined, risk managers should, with the help of their analytical staff, make a preliminary determination of the information they have and the information they need. Information needs are uncertainties at this point in the activity. Some will be successfully reduced during the analysis while others will not. In fact, new information needs and uncertainties may arise. The uncertainties of greatest potential concern for decision making, i.e., those uncertainties that can influence risk management outcomes and, consequently, decision making, need to be identified by decision makers and analysts at the earliest possible point in the process.

Documentation of every risk management activity is an important aspect of a transparent process. The suggested outputs of this step include:

- A written problem and opportunity statement,
- A written statement of the risk management activity's objectives,
- A written list of all the unique decision information questions,

- A written list of the decision criteria, and
- A written list of the key uncertainties.

4.3.1.2 Identify risk

The essence of risk management is recognizing and understanding the risks. The primary elements of this step are:

- Risk identification
- Risk profile
- Decision whether to complete the risk assessment

> A risk profile describes the risk with the data that are readily available. It might include such things as:
> •Latest statement of the problem
> •Description of the hazard or opportunity involved
> •How assets are exposed to the hazard
> •Frequency, distribution and levels of occurrence of the hazard
> •Identification of possible risks
> •Nature of values at risk (human health, economic, cultural, etc.)
> •Distribution of the risk and benefits from the risky activity
> •Characteristics of available risk management options
> •Current risk management practices relevant to the issue
> •Public perceptions of the potential risks
> • Information about possible risk management (control) measures
> •Preliminary identification of important scientific data gaps that may prevent or limit a risk assessment
> •International implications of risk management
> •Risk management objectives
> •Decision to pursue a risk assessment
> •Questions to be answered by risk assessment

Risk identification is the process of finding, recognizing and describing risks in a narrative fashion. Informally, this is done by asking and answering the question, “What can go wrong?” The purpose of risk identification is to identify what might happen or what opportunities might exist that may affect a USACE decision-making process. Risk identification includes identifying the causes and source of the risk, i.e., asking and answering the question, “How can it happen?” of each potential risk.

Risk identification requires assessors to identify but not yet quantify the relevant risk consequences (positive or negative) and their likelihoods. Figure 4.4 identifies this step in risk management as the first part of the risk assessment, described at length in the chapter that follows. This first risk assessment step identifies the hazards that can cause harm or the opportunities for gain that are uncertain.

It is critically important to carefully identify all the risks being addressed in the risk management activity. Some activities may involve both pure and opportunity risks. Risk identification should, as appropriate, include the following:

- Existing and emerging risks-current risks and risk that can reasonably be expected in the future;
- Risk reductions-reductions in risk expected to result from risk management strategies;
- Residual risks-risk remaining after risk management strategies are implemented;
- Risk transformations-any changes in the nature (i.e., consequence or probability) or source of the risk that results from a risk management strategy; and
- Risk transfers -any shifting of the burden of the risk from one group to another.

This step of the risk management process should produce a risk profile, i.e., a description of what is currently known about the risks identified. Significant data gaps or other uncertainties are identified in the profile. The profile clearly identifies what is and what is not known about the identified risks.

The profile provides the basis for deciding whether a full risk assessment is needed or not. There will be times when the risk profile provides the risk manager with all the information needed to make a decision. In these cases a full risk assessment is not needed and the "analyze risk" step that follows can be abbreviated. In general, once the assessors have enough information to answer the risk manager's information questions, the analytical process can stop. If that need is met by a profile, additional analysis is not needed. If the uncertainty prevents the profile from sufficing, the risk assessment process must be completed.

The suggested outputs of this step include:

- A narrative description of the risks identified,
- A completed risk profile, and
- A decision whether or not to pursue a risk assessment.

4.3.1.3 Analyze risk

The essence of a risk assessment is the analysis of the risks. The primary elements of this step include:

- A completed risk assessment,
- Characterizations of each risk,
- Written answers to the risk manager's questions, and
- Characterization of the decision-critical significance of relevant uncertainties.

If the risk profile does not provide sufficient information for risk managers to make a decision, then a risk assessment will usually be initiated. This is a formal analytical step intended to reduce the uncertainty that makes an early decision unwise or infeasible. The risk assessment characterizes the consequences of the risks that have been previously identified. It also characterizes the likelihoods of the various consequences. Finally, it integrates the consequence and likelihood assessments to characterize the risks and meet the risk manger's information needs. The "analyze risk" step answers the risk manager's questions and characterizes the uncertainty that remains.

The bulk of the data gathering and analysis are completed in this step. Subsequent iterations of this step may be required to analyze the effectiveness of risk management options under consideration. When options are identified in advance of the first iteration of this step, risks with a risk management option in place will usually be analyzed in the first iteration of this step. In other situations, risk management options are not identified until subsequent steps. Those situations require another iteration of this step.

As Figure 4.4 indicates, this step completes the risk assessment when an assessment is needed for decision making. The entire risk assessment may be qualitative, quantitative or some mix of the two. The purpose of the assessment is to characterize the risks identified in step two of the risk management process.

A completed assessment will present a characterization for each identified risk. The risk characterization includes:

- One or more estimates of each risk - this includes estimates of the magnitude of the adverse effects and/or potential gains as well as their likelihoods. These estimates must also identify and characterize the most significant uncertainties. Quantitative estimates are numerical in nature; qualitative estimates are narrative.
- A risk description-this is a narrative that bounds and defines a risk for decision-making purposes.
- Estimates of changes in risk attributable to the management options-these may not be possible to estimate in the first iteration of this step. Whenever they are performed, USACE bases these estimates on comparisons of without- and with- risk management option scenarios whenever possible.

In addition to completing a risk assessment and characterizing the relevant risks, there are two other important components of this step. One is answering the risk managers' questions. The other is addressing significant remaining uncertainty that remains in an intentional and effective way that informs the decision-making process. All the information that risk managers requested in the decision context step that is directly related to risk or decision making is gathered and analyzed in this task. That means pulling together all the necessary information from the other analytical tasks and formatting it so managers can use it for decision making. These data are used in the subsequent evaluation of the risk.

In well-established programs and more routine work, the critical questions may be well known. In feasibility studies, estimates of costs and benefits are going to be needed. Hydrologic analyses are required for a great many USACE efforts. Ordinarily, decision makers do not have to specifically request such information. In other unique decision contexts, however, the decision makers information needs will need to be clarified in the decision context step. Risk-informed estimates of all decision criteria should be produced by the final iteration of this step.

When the "analyze risk" step is completed, the bulk of the analytical work is done and the nature and extent of the uncertainty should be most clear. At this point, decision makers need to be fully informed about what is known and what is not known about the decision problem. The analyses in the risk assessment should identify all significant assumptions made in the analysis. Explicit assumptions can be readily identified by the analyst who made them. The more insidious implicit assumptions are usually best identified by a technical review process.

A comprehensive list of relevant sources of uncertainty should be prepared. A relevant uncertainty is one that could affect the decision-making process or a significant detail in the formulation or performance of a risk management option. The nature and cause of the uncertainty should be identified and any methods or techniques used to address the uncertainty should be described. Most importantly, the manner in which these uncertainties can affect the characterization of the risk itself or the decision criteria must be effectively communicated to decision makers.

The suggested outputs of this step include:

- A completed risk assessment if required;
- A characterization of each significant risk with a focus on relevant remaining uncertainties; and
- Written answers to the risk manager's questions with a focus on the decision critical significance of relevant uncertainties.

4.3.1.4 Evaluate risk

The emphasis in risk analysis shifts back to deliberation, discernment and decision making once the risks have been assessed. The primary elements of the risk evaluation step include:

- Judging risks acceptable or not,
- Formulating risk management options for unacceptable risks,
- Evaluating risk management options to determine which are viable solutions, and
- An adaptive management strategy when warranted.

> **Tolerable Risk**
> The notion of a tolerable risk differs for opportunity and pure risks. For pure risk, a tolerable risk is a non-negligible existing or residual risk. It is not acceptable but it is tolerated due to the risk manager's inability to reduce it further, the cost of doing so or the magnitude of the benefits associated with the risky activity. A tolerable opportunity risk is one in which the likelihood of the desirable consequences is sufficiently high or the magnitude of the desirable consequences is sufficiently large to justify tolerating the risk that the consequences will not be realized or their magnitude will be reduced.

The risk manager's first evaluation decision after the risk assessment is completed is to determine whether the characterized risks are acceptable or not. Risk managers must manage risks that are unacceptable to an acceptable level, if possible, and to a tolerable level if not. To do so, alternative risk management options must be formulated and evaluated. The second evaluation decision involves identifying which of the multiple risk management options considered are viable solution options. Both of these evaluation decisions require consideration of the risks, risk management objectives and decision criteria previously identified.

In this step, the focus of the risk management process turns from analysis toward decision making that explicitly considers the significant uncertainties that accompany the decision problem. Risk managers together with analysts determine which risks require management and then evaluate and compare the risk management options developed for the decision context.

Acceptable risks and tolerable risks are not the same thing. An acceptable risk is one that we are prepared to assume "as is" in order to live our lives and do our work. Acceptable risks are often negligible, and when they are not the benefits are large enough to make the non-negligible risk acceptable. Acceptable risks are not managed explicitly. An acceptable opportunity risk is one with a sufficiently large positive consequence to warrant assuming a non-trivial chance those gains will not be realized or one with a sufficiently low chance of the desired benefits not be obtained.

A risk worth taking?

The USACE issued a request for interes to develop a resort directly on the shoreline in the Frank Russell Recreation Area at Cannon Dam and Mark Twain Lake. The paper describes the desired resort as having a minimum of 100 rooms, dining facilities, 300-person capacity conference center/meeting facility. It could also offer other recreational opportunities including an indoor water park, golf and spa accommodations. About 500 acres of land will be used for development. This is a great example of an opportunity risk.

Source: http://www.mvs.usace.army.mil/Portals/54/docs/recreation/marktwain/RFI-Mark-Twain-concession-revised-FINAL.pdf accessed November 23, 2016

A tolerable risk exceeds what is acceptable. When an unacceptable risk is reduced to a tolerable level, it may be because we lack the technological means to reduce it further or the costs of doing so would outweigh the benefits of further risk reduction. A tolerable level of risk is one we grudgingly live with to secure certain benefits if we are confident the risk is being properly managed. It is not a negligible risk or something we might ignore. A tolerable risk is to be monitored, kept from increasing and reduced further if and as practicable.

Each identified existing risk is evaluated in light of the risk management objectives, decision criteria and other relevant social values to determine whether it is acceptable or not. The risk characterization developed in the previous step provides the basis for this evaluation. A risk is either acceptable, tolerable or unacceptable. Acceptable risks require no further management. Unacceptable risks must be managed and tolerable risks can be further managed or left as is.

When the existing or future risk is not acceptable it may be appropriate to formulate risk management options to manage the risk further. As noted in Chapter 2, the available risk management strategies vary for risk reduction and risk taking, as seen in Table 4.1.

Risk Management Strategies	
Risk Reduction	Risk Taking
Avoidance	Creation
Prevention	Enhancement
Mitigation	Exploitation
Transfer	Sharing
Retention	Ignoring

Table 4.1: Available risk management strategies

Risk management options are formulated in this step if they have not been identified earlier in the risk management process. Once a risk is found not acceptable, risk managers and assessors should identify and formulate risk management options that will meet the risk management objectives and, thereby, solve the problems and attain the opportunities identified in the decision context. The options in Table 4.1 provide symmetrical strategic approaches for risk reduction and risk taking.

Risk taking means to take an action and accept the risk that the opportunities will not be fully realized. Risk creation involves bringing opportunities that did not heretofore exist into being. It means creating opportunities. Risk enhancement means taking measures to increase the likelihood of desired outcomes. Risk exploitation options increase the desired consequences, increasing the potential gains. Risk sharing requires partners in the risk taking activities. Risk ignoring is to intentionally not consider potential risks.

Where bearing a risk means a potential loss, risk reduction means to take an action to lessen a potential loss. Risk avoidance options eliminate the risk by avoiding it altogether. If the dam is not built, then there is no risk of dam failure. Risk prevention options reduce the likelihood of the risk (reservoirs reduce flood risk probabilities) while risk mitigation options reduce the consequence of the risk (levees reduce flood risk consequences). Risk transfers outsource or insure the risk (as flood insurance transfers flood risk) and risk retention means managers accept and budget for the risk.

Cost of Risk Reduction

Managing risk, especially through risk mitigation or avoidance, can be costly. For risks of loss, a cost buy-down is a useful perspective. The risk assessment will characterize one or more levels of risk that can be reduced by risk management, each at some cost. Usually, the more the risk is reduced, i.e. the greater the buy-down, then the more costly the option. The challenge is to determine the desirable balance between residual risk and the incremental cost of additional risk reductions.

For risks of uncertain reward, a gamble for a gain is a useful perspective. In this case the presumption is that the more we spend the greater is our chance of realizing a gain. Thus, more costly "gambles for gain" should offer either a greater chance of gain (a more positive likelihood) or a greater return (a more positive consequence).

The general strategies for managing risks include identifying specific measures for reducing the likelihood or consequence of potential loss risks and increasing them for opportunity risks. When the likelihood and positive consequence of an opportunity risk are great enough, risk taking may be in order. Transference or risk sharing merely shares or shifts responsibility for the risk from one party to another; it does not diminish the total risk. The recipients of the transferred risk need to be party to the risk management decision. Most USACE risk preventions and mitigations will leave a residual risk. When stakeholders have options for managing the residual risk that USACE cannot recommend or implement, they should be considered as part of the risk management strategy.

Ideally, multiple risk management measures will be formulated for each risk identified. Measures can then be combined to create risk management options that treat the whole of the decision problem. A number of alternative risk management options should ordinarily be formulated to assure that the best option has been identified. Once the risk management options have been formulated, they need to be evaluated. This is done by estimating the effects of each risk management option on the relevant risk metrics, risk management objectives and the decision criteria identified in a comparison of without- and with- risk management scenarios.

Residual risk, the risk remaining after a risk management option is implemented, must receive special attention in the evaluation. If the residual risk is neither acceptable nor tolerable, additional risk management features need to be developed by USACE or other risk managers with the ability to enact the measures that USACE cannot. In a similar fashion, risks transferred to other parties need to be explicitly identified and the affected parties engaged in the evaluation and decision process. Transformed risks should, likewise, not be overlooked.

Uncertainty is presumed to be a major factor in every risk management activity. It is essential that risk managers and other decision makers be effectively informed about the nature and identity of key uncertainties as well as their effects on decision-making outcomes. This information should include a description of the possible range of critical decision variables, identifying the risk assessor's level of confidence in the various metrics to be considered in the decision making, and any options that might be effective in further reducing uncertainty.

Risk management options are evaluated by examining and weighing differences in risk and other important social values attributable to the options. Evaluation is restricted to a single option at a time. The outcome of this evaluation process is to judge each option's potential as a viable. All viable options are later compared to one another in the final risk management step. The nature and extent of the uncertainty attending the assessment of an option and the efficacy of its future performance are important considerations in this process.

Because both the risk and the efficacy associated with a risk management option are uncertain, it may not be possible to formulate options that assure successful management of the risk in the future. When the uncertainty is especially troublesome for decision making, it may make sense to formulate plans that incorporate adaptive management strategies.

When uncertainties are significant and to some extent controllable or measurable, risk managers can use adaptive management strategies in their risk management options. Adaptive management provides opportunities for learning about the remaining uncertainties that can be used to reduce the uncertainty and formulate more effective risk management responses (e.g., through research, experiments, or demonstration projects). When uncertainty is great enough to render a decision unacceptably risky, adaptive management strategies should be included in the risk management options.

The suggested outputs of this step include:

- Decide whether each identified risk is acceptable or not,
- Formulate alternative risk management options to address each risk that is not acceptable,
- Evaluate each alternative risk management option to determine if it is a viable solution or not, and
- Include an adaptive management strategy in the risk management option when warranted.

4.3.1.5 Risk management decision

When the analysis has been completed and the risk management options have been reduced to a set of viable options, it is time to make decisions. The primary elements of the risk management decision step include:

- Comparison of the viable options and selection of the best risk management option,
- Identification of measurable desired outcomes to monitor the option's efficacy,
- Formation of an adaptive management plan, when appropriate,
- Development of an implementation plan, and
- Implementation of a risk management option

Up until this point the risk management options have only been evaluated individually to assure that only viable options are considered for implementation. All viable options must be compared to one another in order to identify the best option from among them. This comparison of risk management options highlights the tradeoffs among competing objectives (e.g., residual risk and cost). Balancing tradeoffs in either an informal or a formal process is very often the essence of risk management decision making. To assure the selected risk management option is grounded in the best available evidence, uncertainty must be explicitly considered in the evaluation and comparison of risk management options.

Decisions of interest to external stakeholders, and even internal decisions with multiple USACE stakeholders, are best supported by displays that show the contributions of the risk management options to the risk management objectives, decision criteria and other social values considered in the decision process, an effective summary or display of the uncertainties most relevant to the risk manager's decision and support for how to make the decision under that uncertainty.

The risk manager's choice of a risk management option is tantamount to establishing a tolerable level of risk. As each option will have some degree of residual risk, best practice decision making will include specific reference to the level of residual risk that constituents of the decision process will have to tolerate.

Because there is almost always unresolved uncertainty attending a decision, risk managers also must identify one or more desired and measurable outcome of the risk management strategy. These outcomes provide the foundation for monitoring the success of the decision. The roles and responsibilities of everyone involved in managing the identified risk(s) are specified. To the extent that there is significant uncertainty in the analysis that could influence the formulation of the eventual risk management solution, the risk management strategy should include an adaptive management plan to reduce such uncertainties over time and, as needed, to modify the execution of the actions taken.

Risk management means reducing risks that are not yet acceptable to a new tolerable level of risk. This requires selecting the best risk management option from among those compared and implementing it. Implementation will differ from one USACE function to another. In time these implementation protocols may be defined as risk-informed standard operating procedures that incorporate the risk management model or its successor into each entity's decision-making processes.

Combinations of management treatments may be needed to achieve a tolerable level of risk. Risk management options will often comprise multiple risk management measures. Rarely will a single risk treatment completely eliminate a risk or reduce it to an acceptable level. For example, the risk of damage resulting from floods may be partially reduced by a levee. The remaining risk may be reduced to a tolerable level through the purchase of flood insurance, additional nonstructural measures, and an evacuation plan. Choosing the "best" risk management option requires a comparison of decision criteria like performance levels, levels of project outputs, National Economic Development benefits, costs, public safety, and the like. Multiple risk management measures, treatments, or features are sometimes available for the same risk.

When a risk management option is chosen, an implementation plan should be developed. In addition to the decision specific implementation details are some risk management considerations. These include: the risk management measures; the roles and responsibilities of Corps and non-Corps risk managers; schedules, expected outcomes, metrics for those outcomes, and a plan for monitoring them. The risk management strategy must, of course, be implemented, ideally, by those best equipped to manage the risk. Risk management responsibility in practice is often shared by USACE and its stakeholders. An implementation plan needs to be explicitly developed. When uncertainties are great it should include adaptive management strategies as appropriate.

The suggested outputs of this step include:

- A comparison of the pros and cons of all viable solutions that includes consideration of the relevant uncertainties;
- Selection of the best risk management option;
- Identification of a measurable desired outcome to monitor the option's efficacy;
- When appropriate, an adaptive management plan;
- An implementation plan; and
- An implemented risk management option.

4.3.2 Two Processes

The two processes, shown in Figure 4.4, weave their way through risk management in varying degrees of complexity. Risk-informed decision making, the heart of risk management, is a relevant concept at all level of the organization. There will be a wide variation in the extent to which the two ongoing processes are required. These two processes can be essential elements of each step. They have been separated out to

> Do you have a process? Did you follow your process?
>
> A plume of groundwater contaminated with trichloroethylene, or TCE, used to clean equipment at an Atlas Missile site has been flowing from an abandoned site west of Cheyenne, WY. Forty-five wells and eight years of preliminary work later USACE is moving forward to solve the problem. An appeal has been made for local residents to apply for appointment to a Restoration Advisory Board. In a public meeting residents asked questions of scientists who have been working on the project to receive information about what has been done so far and what options are available for future remediation. Ongoing consultation, risk communication and collaboration will clearly be an essential part of this risk management solution. Wouldn't a risk management model have been useful when this process began?
>
> Source: Billings Gazette November 17, 2010 http://billingsgazette.com/news/state-and-regional/wyoming/article_2dfa6cbf-ee3d-5dd4-a9da-7135eadda341.html Accessed November 19, 2010.

emphasize both their importance and their ongoing nature. The first of these, the "consult, communicate and collaborate" process, begins when a risk management activity is initiated. It can run continuously throughout the five steps described above and beyond. The other process, "verify, monitor, evaluate and modify" is usually initiated after a risk management option is implemented. It is the ongoing risk management process between re-iterations of the five steps described above. Unless all uncertainty has been resolved and the risk has passed or the opportunities are fully realized, there is an ongoing risk management function that, at a minimum, involves monitoring. These two processes are described below.

4.3.2.1 Consult, Communicate and Collaborate

Consultation with experts and interested parties, active risk communication, and appropriate levels of collaboration with agency partners and stakeholders are to be ongoing activities throughout the risk management process, as appropriate to the decision context. In some situations all the risk management activities in Figure 4.4 will be wholly contained within the USACE organization. In these instances there may be no need for stakeholder involvement as all coordination and communication will be limited to USACE itself. An example might include risk management activities dealing with the allocation of project resources within the District. In other situations there will be varying degrees of shared responsibility for conducting the risk management steps, the risk assessment, risk communication and decision making. The consultation, communication and collaboration processes will vary markedly between these two situations.

When there are shared risk management decisions, the decision participants should be identified and an agreement, documenting the shared responsibility for the assessment and the choice of the risk management alternative, should be prepared and agreed to by all responsible participants. When USACE practices risk management within its organization, standard operating procedures (to be developed) may be used to guide this ongoing process. Stakeholders, whether within or outside of USACE, must always be appropriately involved in a risk management activity.

Stakeholders are individuals or groups who are, or perceive themselves to be, affected by the decisions or activities being analyzed. Stakeholders may include individuals or groups. During the risk management process, it is important to keep all stakeholders engaged in two-way communication that both directs the problem identification and risk assessment while it communicates the results of that assessment. In addition, everyone involved with the risk management solution needs to agree and commit to their role in implementing the solution.

Asian Carp

The Asian Carp issue is custom made for risk management. The uncertainties are huge, the issue has high visibility and decision needs to be made. This fish may be the Corps best argument for a risk management process.

The Chicago Journal on October 27, 2010 said in part, "Since preliminary hearings on the potential invasion of Asian Carp began over a year ago, players on all sides of the issue have scrambled for theories on how to stem the possible migration of the fish into the Great Lakes…" A "potential" invasion cries for risk management. How are they likely to reach the Lakes? Will they survive once there? Will they colonize and reproduce? Will they effectively spread? Some people think it "could effectively wipe out other species in the lakes' ecosystem…" The uncertainties are significant and a risk management approach would be an invaluable aid to solving this problem.

Quotes taken from
http://www.chicagojournal.com/News/10-27-2010/New_ideas_on_Asian_Carp_control
Accessed November 19, 2010

Two-way risk communications are necessary to keep the decision-makers and stakeholders informed about progress as well as share concerns that arise during the risk management process. The views and input of stakeholders can have significant impacts on decisions made as part of the risk-management process. Communication and dialog among participants should provide continual input and feedback opportunities so that misunderstandings and surprises during the process are minimized. In best practice, stakeholders and the public engage in joint decision making. Processes to enhance communication, such as Shared Vision Planning, mediated collaborative stakeholder processes, or other similar communication approaches should be applied when applicable. Risks related to crisis situations warrant special risk communication attention. Risk Communication is the subject of Chapter Six.

The suggested outputs of this step include:

- Preliminary identification of internal and external stakeholders;
- Preparing and executing a public involvement plan including provisions for risk communication;
- Preparing and executing a formal agreement documenting the shared responsibility for this risk management process; and
- Standard operating procedures or memoranda of understanding for activities that do not involve a broader base of the public or stakeholders.

4.3.2.2 Verify, Monitor, Evaluate, Modify

There are several purposes of post implementation monitoring. One purpose is to verify that the risk management option has been implemented as intended and that all parties with a responsible risk management role are doing what they are required to do. Another purpose is to collect targeted data to assure progress is being made toward achieving the desired outcomes of the implemented risk management strategy. A related purpose might include collecting targeted data to test hypotheses required to reduce analytical uncertainties identified in the initial risk management process when adaptive management is needed. Another purpose is to scan the overall setting for the activity to identify opportunities, hazards or changes in socioeconomic preferences or conditions that may not have been recognized during the initial risk analysis process, or that may have changed in their significance. Monitored data should be evaluated on a regular basis and the risk management strategy should be modified in accordance with what is learned.

Can Safety Be Guaranteed?

The *Sun Times* in an October 21, 2010 article called the Greers Ferry Lake Dam and dikes "earthquake proof, according to the U.S. Army Corps of Engineers." A USACE spokesman is quoted as having said, "There are two types of earthquake classifications to consider. There is the operating basis earthquake (OBE) and the maximum credible earthquake (MCE). (Neither) the dam nor the dikes would sustain any damage with an OBE. There would not be a breach with the concrete dam or the earth dikes in the event of an MCE. There would possibly be damage, but not a breach." Is this what the public should be thinking about any dam?

An OBE was explained by USACE in the article as "the maximum vibratory ground motion that can be expected to occur at the site during the economic life of the project, usually 100 years". By contrast USACE described an MCE as "the earthquake that would cause the most severe vibratory ground motion or foundation dislocation capable of being produced at the site under the currently known tectonic framework." Are these definitions important to convey? If so, are they understandable? What are the three most important things the public ought to know about Greers Ferry Lake Dam and dikes in order to best manage their risk?

Source: http://www.thesuntimes.com/newsnow/x2030531066/Will-dam-break-in-earthquake Accessed November 22, 2010.

An implication of uncertainty and the risk analysis paradigm is that every decision is conditioned on the information available at the time it is made. As the world grows ever more complex, the pace of change increases, knowledge bases grow, values change and new events occur. As a direct consequence, fewer decisions are final. They are the best current decisions based on what we know and what we do not know with certainty. In a sense, risk management is adaptive decision making.

The verification, monitoring, evaluation and modifications described here are post-implementation activities. They are not to be confused with an adaptive management strategy, which may be an explicit feature of a risk management option when uncertainties are especially problematic. Monitoring for the purposes of adaptive management is considered an element of the risk management decision, which is different from this verification monitoring process that is intended to see if the decision is working.

Verification assures that a risk management option is being properly implemented. Monitoring assures that desired risk reductions are being attained. If the desired gains have not been realized, managers must decide whether a change is needed to help them be realized, or whether the activity should be abandoned or deauthorized. If the residual risk is greater than expected, a decision must be made as to whether to tolerate the residual risk or to reiterate the risk management process to lower the risk further.

Monitoring gathers information that measures progress toward the desired outcome(s) identified in the risk management decision step. The outcome is the desired result of implementing the chosen risk management option. An outcome (a consequence or result) is more than an output (something produced). It is a measure of the impact of the risk management option on people, public safety, the environment, the economy, the nation, USACE, and so on. Outcomes should be measurable to assure that they are realistic and meaningful. The measurable outcome that is used to verify success is to be identified in the last of the five risk management steps. The outcome may not always be measured in fact, but it should always be measurable in principle. Outcomes that are actually monitored should be monitored on a regular basis (e.g., annually) or as needed (e.g., following an event like a flood or storm).

Best practice risk management actively measures and evaluates the success of its decision(s), its implementation and outcomes. The sole purpose of doing so is to determine if changes in the risk management strategy are needed. If the desired risk reductions are not being achieved or if new information becomes available, then it may be advisable to modify the decision or exercise options of a risk management plan that includes this intentional flexibility. This may either be done in accordance with the adaptive management plan, if one exists, or by reiterating part or all of the risk management process.

The suggested outputs of this step include:

- Creating a plan for verifying, monitoring, reviewing and modifying the implemented solution, and
- Implementing that plan.

4.4 Risk Management: Occupation or Role?

Risk management is both an occupation and a role. There will be people with explicit risk management responsibilities and that is the occupation. Anyone who must handle uncertainty while performing their job will assume the role of a risk manager from time to time. In this sense, the responsibility for risk management is a bit fuzzy, in a fuzzy set way of speaking. That is, some people will be 100 percent members of the set of risk managers while other USACE employees may be only five percent members. Rarely will a USACE analyst have no risk management responsibility. Most often risk management will be a role that a person is required to assume.

The risk manager's job is to make effective and practical decisions under conditions of uncertainty. As long as there is any uncertainty at all, a risk management decision is conditional. It is based on what is known and not known at the time a decision is made. As uncertainty is reduced during the decision-making process through risk assessment, in the future as more information is accumulated, or as the outcomes of the original management decision become known. It may be prudent to revise the decision to reflect the new knowledge. Hence, the risk management process is an iterative one. Every decision is based on what is known at the time the decision is made and is subject to further revision in the future as long as uncertainty remains.

Let's call any new initiative or revisited issue undertaken by USACE a "risk management activity." There are five basic parts to a risk management activity. These parts define the risk manger's duties. They are:

1. Identifying problems and opportunities,
2. Estimating risk ,
3. Evaluating risk ,
4. Controlling risk,[12] and

[12] This is a term of art described later in this section. Not all risks can be controlled.

5. Monitoring risk.

Figure 4.5 shows the five tasks in a continuous loop to capture the iterative nature of the risk manager's job. As is true of any iterative process, the tasks, although presented in a sequential fashion, are not always executed sequentially. Activities in a later task may precede activities in an earlier task. Activities in different tasks may occur simultaneously. Many activities and tasks can be repeated more than once. The entire sequence may be completed several times.

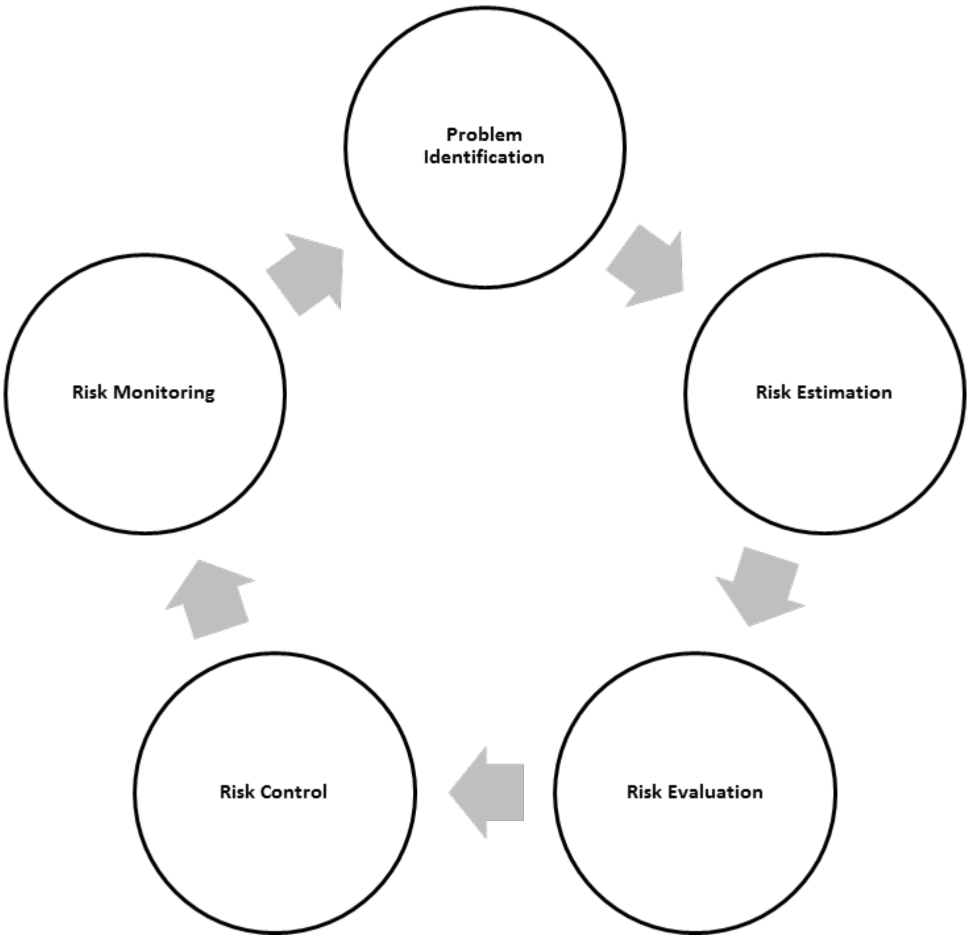

Figure 4.5: The risk manager's job in five tasks.

Risk management activities are triggered by some sort of event or initiated in response to accumulated information inputs. A problem needs attention or an opportunity presents itself. The risk manager's[13] first task is to recognize, accept and define the problems and opportunities on which to act.

Risk managers have an important, but limited, role in the risk estimation task. Estimating risks is the assessor's job; it is part of the evidence-based risk assessment process. Good risk assessment cannot be completed without direction and guidance from the risk manager. Risk

[13] At the present time USACE does not have any job position called risk manager despite the many risk management decisions it makes. Thus, risk management is more a role decision makers assume as part of their range of duties. Analysts assume this role but less frequently. To simply the narrative "risk manager" is used to describe anyone functioning in a risk management role.

managers are responsible for overseeing the USACE risk analysis process. They are its custodians. They also guide the risk assessment process by requesting the specific information needed to solve problems and realize the opportunities they identify.

Once the risk assessment is completed, the risk manager must evaluate the assessed risk. The USACE risk manager's first significant risk evaluation decision is to determine if the risk is acceptable. Any unacceptable risk must be managed. If possible, unacceptable risks will be managed to an acceptable level. When this is not feasible the risk should be managed to a tolerable level.

Risk managers do not have to evaluate the effectiveness of any specific risk management options until the fourth task, risk control. Risk control is a term of art, it may be misleading to suggest we can control some risks. Risk management options are identified or formulated, the options are evaluated and compared, the best risk management option is selected, conceptually measurable decision outcomes identified and the best option is implemented in this task.

Decisions made under uncertainty can be more or less effective in reducing risks. In the fifth task shown in figure 4.5, USACE risk managers monitor decision outcomes, evaluate them, and then modify the decision as necessary. Once an option is implemented USACE can monitor decision information (e.g., is sea level changing?), decision implementation (has the option been properly implemented and are all stakeholders cooperating), and decision outcomes (e.g., are desired risk reductions being realized?). Monitored information is evaluated and judged and risk managers either hold the course or modify the risk management decision.

Get the question(s) right

Risk managers want to make decisions that solve problems and realize opportunities. To do that, they need information. Risk managers have to ask for the specific kinds and forms of information they require to make decisions.

A significant proportion of USACE work is of a recurring nature. Flood risk management, inland navigation, deepwater navigation, and O&M issues, to name a few, are responsibilities where the information requirements have become relatively institutionalized and well known to all involved. In these situations risk managers have little explicit need to identify the information they require.

New and unique situations arise all the time, however. Woody vegetation on levees, blowing up the levee at Birds Point, and Asian Carp threatening indigenous ecosystems are just a few examples.

4.5 Five Points To Take Away

1. USACE must manage risk over the entire life cycle of a project.
2. USACE has a conceptual risk management model.
3. The model has five steps: identify decision context, identify risks, analyze risks, evaluate risks, and implement a risk management decision.
4. The model has two ongoing processes: (1) consult, communicate and collaborate and (2) verify, monitor, evaluate and modify.
5. The five basic parts of the risk manager's job are: identifying problems and opportunities, estimating risk, evaluating risk, controlling risk, and monitoring risk.

4.6 References

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Chapter 5: Risk Communication

5.1 Introduction

Risk communication may be the least appreciated and understood of the three risk management tasks. It has become a specialization in the field of communication. Risk is described as the product of probability and consequence. When it comes to risk communication, however, risk may be helpfully described by the following equation:[14]

Risk = Hazard + Outrage

This equation is used to describe the perception of risk, a perception that has two distinct components. Hazard refers to the technical side of the risk. It encompasses the magnitude and probability of undesirable outcomes like increases in the probability of a lock stall, ecological losses due to invasive species, declines in property values, and the like. Outrage refers to the non-technical side of the risk. Outrage often focuses on negative things about the situation itself as opposed to the "technical" outcomes. Is this a voluntary or coerced situation? Are people familiar with it or is it an exotic risk (like a levee being blown up)? Some risks, perhaps like dam failure or levee overtopping, may invoke dread while others do not. Outrage includes the emotional response to the risk.

These two very different components of a risk give rise to many of the things that make risk communication a unique communication challenge. Below is a quick survey developed by Food Insight[15] to test your risk communication instincts. Read each question and think about how much you agree or disagree with it. Answers appear in this footnote.[16]

- The primary purpose of risk communication is to reduce fear and panic.
- The key to successful pre-event planning is to develop risk communication messages prior to a crisis.

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[14] This equation is attributed to Peter Sandman and it is featured prominently on his homepage at http://www.psandman.com/ accessed February 28, 2012.

[15] Food Insight is the host site for some communication training materials. These materials are available at http://www.foodinsight.org/Resources/Detail.aspx?topic=Risk_Communicator_Training_for_Food_Defense_Preparedness_Response_Recovery accessed February 28, 2012.

[16] 1. Sometimes the purpose of effective risk communication is to increase fear. 2. Pre-scripted messages may be useful, but they are only one element of pre-event planning. 3. Risk perception is a combination of both outrage (emotion) and hazard (likelihood of negative consequences). 4.Communication also occurs internally (within the organization) as well as informally (interaction with customers, neighbors, families, etc.). 5. During high stress situations, empathy and caring has a greater impact on establishing trust than expertise and credentials.6. The media shouldn't be expected to do your job. They may have a different agenda.

- An individual's perception of risk is based on an understanding of possible negative consequences.
- During a crisis, risk communication should be limited to the organization's official spokesperson.
- During a high stress situation, the spokesperson can help build trust and credibility by demonstrating human qualities such as caring and empathy.
- The role of media during a crisis is to help the communicator deliver the message effectively.

This chapter defines risk communication and discusses what it is and what it isn't. Then it returns to the equation above to distinguish the effects of facts and feelings on risk perception and resulting risk communication strategies. The three M's of risk communication–message, messenger, and media–are then taken up briefly before the chapter turns to some of the challenges of explaining quantitative data to the general public.

5.2 Risk Communication Defined[17]

Risk communication has been defined as an open, two-way exchange of information and opinion about risk leading to better understanding and better risk management decisions. In a white paper called Transforming the Corps into a Risk Managing Organization, USACE has expanded that definition to say:

Risk communication is the open, two-way exchange of information and opinion about hazards and risks leading to a better understanding of the risks and better risk management decisions. Risk communication is integrated into the assessment and management processes. It is not a task that occurs only after decisions have been made. Risk communication ensures that the decision makers, other stakeholders, and affected parties understand and appreciate the process of risk assessment and in so doing can be fully engaged in and responsible for risk management.

The basic communication model many organizations use is a unidirectional model that employs a "we tell them" approach. That model focuses primarily on who says what, when, and to whom; through what channel; and with what effect. It is a very communicator-centric model.

The basic risk communication model is multidirectional. Not only is it a two-way exchange of listening and speaking, it is multidirectional because it recognizes the existence of many audiences in a given risk issue. Risk communication actively involves the audience as an information source, so information flows in both directions.

[17] Most of the information in this section is modified from the Risk Communicator Training for Food Defense Preparedness, Response & Recovery program materials found at http://www.foodinsight.org/Resources/Detail.aspx?topic=Risk_Communicator_Training_for_Food_Defense_Preparedness_Response_Recovery accessed February 28, 2012.

Experts in the field of risk communication have identified three risk communication goals that come up time and again in a crisis situation. These are:

- Tailor communication so that it takes into account the emotional response to an event;
- Empower stakeholders and the public to make informed decisions; and
- Prevent negative behavior and/or encourage constructive responses to crisis or danger.

We are emotional beings and must allow people to have an emotional response to the situations in which they find themselves. Sharing power with stakeholders and the public is an effective way to make them care about the information you have to convey to them. This is often best accomplished by empowering them to make informed decisions for themselves, their families and other interests in a risk situation. Good risk communication can help prevent negative behaviors like trying to ride out a severe hurricane on the coast. When people are not especially outraged in the face of a hazardous risk, risk communication may be strategically used to invoke fear and motivate people to make a more constructive response to their situation (see textbox).

> "Persons not heeding evacuation orders in singlefamily, one- or two-story homes will face certain death."
>
> National Weather Service, Hurricane Ike warning for Galveston, September, 2008

The desired outcomes of risk communication will vary with the circumstances, but they can include such things as:

- Decrease illness, injury and deaths;
- Reduce property and economic losses;
- Build support for the response plan;
- Assist in executing the response plan;
- Prevent misallocation and wasting of resources;
- Keep decision-makers well informed;
- Counter or correct rumors; and
- Foster informed decision making concerning risk.

Risk communication differs by context. Communication promoting preparedness before the event and supporting recovery after the event are quite different from communication in the midst of a crisis. Communication for preparedness and recovery can be planned, tested and strategic. Working on these communications are pre-event activities. They are multidirectional, proactive and certain. By contrast, crisis response is spontaneous; there is no planning or testing possible because the event circumstances are unknown until they occur. Crisis communication is unidirectional and reactive. The degree of certainty is substantially reduced, so these communications are more equivocal.

Risk communication is not:

- Spin;
- Public relations;
- Damage control;
- Crisis management;

- How to write a press release;
- How to give a media interview; or
- Always intended to make people "feel better" or reduce their fear.

Risk Communication is:

- Considerate of human perceptions of risk;
- Multidirectional communication among communicators, publics and stakeholders;
- Inclusive of activities before, during and after an event;
- An integral part of an emergency response plan; and
- Able to empower people to make their own informed decisions.

5.3 Perceptions of Risk[18]

People perceive risks differently. Engineers look at floods differently than do people who experience flooding. Wildlife managers are more willing to take a chance on ecological improvements than others are. Port stakeholders want 50-foot deep channels even if they may not be able to make full use of them. What shapes our perceptions of risk?

There are "thinking" aspects of risk and "feeling" aspects of risk. Thinking about risk leads to a different perception than feeling about risk. This is in part due to the nature of risk. A risk of loss involves a hazard (i.e., something that can go wrong) and its probability (i.e., the likelihood) of it happening. These are aspects of a risk that require thinking.

Risks also involve consequences, i.e., the personal or social implications of the hazard. These consequences affect people's values, i.e. the subjective evaluation of the relative importance of what might be lost. This is the outrage.

Psychometric research has identified a broad range of factors that affect the outrage, or the feeling dimensions, of risk. These factors can also affect the acceptability/tolerability of a risk. In general risks are less acceptable the more they include any of these factors:

- Catastrophic potential
- Familiarity
- Understanding
- Controllability
- Voluntary exposure
- Effects on children
- Disturbing manifestation of effects
- Specific identity of victims
- Dread
- Mistrust of institutions
- Media attention

[18] Much of the materials in this section are modified from the works of Peter Sandman found at his homepage http://www.psandman.com/ accessed February 28, 2012.

- Previous accident history
- Inequitable distribution of effects
- Low levels of offsetting benefits
- Reversibility
- Manmade origin

USACE has been involved in a number of situations that involve one or more of these outrage increasing factors. Perhaps you saw the outrage on the news or heard about the lawsuit to stop USACE when the levee at Bird's Point was blown up? All experts agree it was the correct decision. It was part of the risk management plan from the time the levee was built. Ms. Ellenann Howton, 59, was quoted in the April 30, 2011 New York Times as saying, "I've cried. I've thrown up. I don't eat because I'm so stressed."

When the Morganza floodway was opened, the May 14, 2011 edition of nola.com, the online site of the *Times-Picayune*, described about 25,000 people and 11,000 structures in harm's way. With up to 25 feet of flooding expected over a 3,000 square mile area of Cajun country stretching from Melville to Morgan City, outrage was high in affected areas, despite the obvious benefits of operating this project as it was designed to be operated.

It is not difficult to imagine the outrage some stakeholders and members of the public would feel if USACE were to build a new levee or deepen a navigation channel. Several districts know all too well the outrage that results when there is a drowning at a USACE managed lake. Asian carp headed from the Mississippi River basin toward Lake Michigan have millions of people in varying states of outrage. Of course not all outrage needs to be negative. Potential gains, such as improving fish habitat on a waterway, may garner positive emotional responses.

There is a fundamental disconnect in the ways people approach risk. Those focused on hazard perceive it one way; those focused on outrage see it another. Because of the different ways experts and the public perceive risk, there are some unique challenges for risk communication. The different ways we perceive risk lead to some very different risk communication strategies. The outrage and actual danger do not always align accurately, as the Figure 5.2 below suggests. Each quadrant warrants a different strategic approach to risk communication.

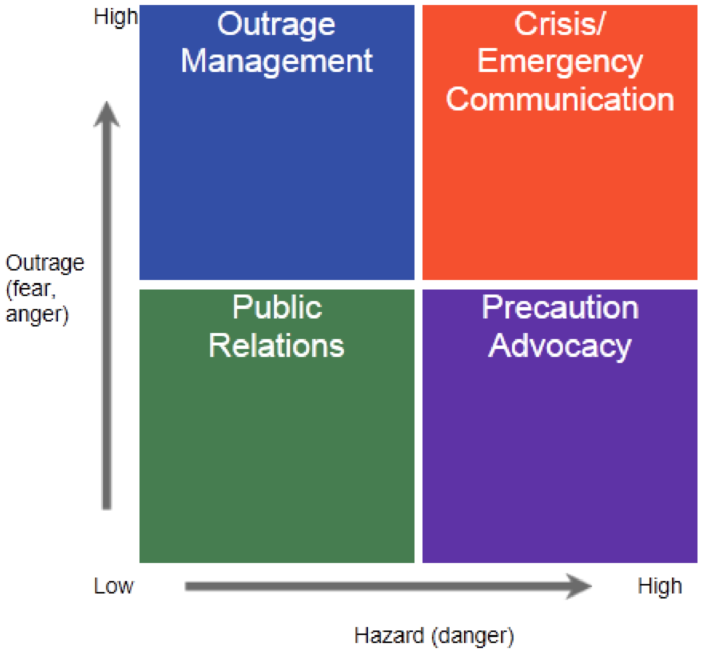

Figure 5.2. Peter Sandman's four risk communication approaches (NCFPD/IFICRC, 2009)..

There is no one-size-fits-all risk communication strategy. Figure 5.2 illustrates four basic risk communication strategies. Public relations is perhaps the best known strategy and requires no elaboration here. When the real danger is low and the outrage is low, risk communication requires nothing more than normal public relations work. When outrage rises in the absence of a real hazard, for example when a dam is rated DSAC 4, an "High Urgency" designation more likely for budgeting purposes than for describing the actual hazard, the strategy is outrage management. The goal of this strategy is to reduce outrage so people do not take unnecessary actions. You would not want people evacuating Houston because Addicks and Barker dams (ordinarily dry dams) were rated extremely high risk.

An opposite situation is found when there is real danger and people are not sufficiently outraged. The classic example is the approaching hurricane in an area where people feel experienced with hurricanes. The strategy in an instance like this is precaution advocacy. Its goal is to increase real concern about the hazard to motivate people to take preventive actions. The fourth strategy is crisis communication. This might be incurred when a community is taking a category 5 hurricane risk very seriously. The goal of crisis communication is to acknowledge a serious hazard, validate people's concern and give them effective ways to act in response to the hazard.

5.4 The Three M's of Risk Communication

There are three important elements for USACE to consider in any risk communication setting. These are the message to be delivered, the messenger to deliver it and the media by which it will be delivered.

5.4.1 The Message

Imagine it is your task to develop one key risk communication message for one of the following. How would you go about it?

- The presence of woody vegetation on levees
- Establishment of Asian Carp in Lake Michigan
- Opening Morganza floodway
- Blowing up the Bird's Point levee
- DSAC 4 rating for a local dam

Message development is a critical element in any effective risk communication. Message development has become a defined skill set for risk communicators. One technique begins by asking risk communicators to answer these three questions for each risk communication.

- What are the three most important things for your audience to know?
- What three things would your audience most like to know?
- What three points is the audience most likely to get wrong unless you emphasize and explain them?

These points then form the basis for your risk communication message. For each of the three messages three supporting facts are developed. These form the basis for each risk communication message. A hypothetical example is provided in Figure 5.3.

The 27/9/3 challenge is demonstrated in figure 5.3. This refers to the goal of developing a message that uses no more than a total of 27 words, that can be delivered in 9 seconds, and contains 3 key messages. The three key messages could be those in the top row or a message could be developed in support of any one of these messages. No matter which of these messages is chosen the 27/9/3 challenge is met (NCFPD/IFICRC, 2009).

The EPA has developed a useful guide for developing a message map, it is *Risk Communication in Action: The Tools of Message Mapping* and it is available at http://www.epa.gov/nrmrl/pubs/625r06012/625r06012.pdf (Accessed March 1, 2012). Additional message development tools are found in training module three of the Risk Communicator Training for Food Defense Preparedness, Response & Recovery resources available at http://www.foodinsight.org/Resources/Detail.aspx?topic=Risk_Communicator_Training_for_Food_Defense_Preparedness_Response_Recovery (Accessed March 1, 2012).

1. The dams present no risk to people.	2. The dams need some repair.	3. The dams will be repaired.
1a There is no water behind these dams	2a A highway could be damaged during an extreme storm	3a Money has been provided
1b They will not be filled	2b We know exactly how to fix the problem	3b Repair will take 18 months
1c They are not near residential neighborhoods	2c This is a routine adjustment	3c We will begin later this spring

Figure 5.3: Risk communication message development for a hypothetical situation with a DSAC IV dam designation

5.4.2 The Messenger

Once you have a message, what are the qualities needed in a messenger? The answer depends on the level of outrage that attends the situation. Would it surprise you to learn that caring and empathy may be more important than experience and competence? When stress is low, expertise is important. In fact, competence and expertise account for 80-85 percent of the trust in messengers during low-stress situations.

When stress is high, however, the messenger's competence and expertise are not nearly as important as the messenger's caring and openness. It may be wiser to select a messenger with a real connection to the audience (e.g., my family lives behind the Bird's Point levee). Someone that uses opening remarks that indicate active listening about people's concerns (e.g., I have heard some concerns and would like to hear directly from you) may be more effective than the world's foremost authority on levees or explosives. Competence and expertise shrink to 15-20% of the trust factors. Listening, caring and empathy account for 50%, with honesty and openness accounting for another 15-20%. A variety of other factors make up the difference (Covello, 2002).

The essential task is to carefully choose the right messenger for the right situation. Stress changes the way people process information. That means the message and the messenger must be chosen for the stress level. People process less information when stressed and they have a different focal point as well. For example, in low-stress situations people can process an average of seven bits of information (a telephone number). In high-stress situations they process an average of three bits of information, thus the emphasis on three's above.

In low-stress situations people process information linearly, i.e., in the order in which it is received (1, 2, 3). When stressed, people process information in primacy order (where importance is emphasized) or in recency order (3, 2, 1). When relaxed, people process information at an average grade level. Newspapers often write for a seventh- or eighth-grade reading level. During times of stress, information is processed at four grades below the average level. As suggested above, the focus is on competence, expertise and knowledge in low stress and on listening, caring, compassion and empathy when stress is high (Covello, 2002).

5.4.3 Media

There is no such thing as "the public." There are multiple publics, or audiences, for any risk communication message. Native speakers of English and non-native speakers may be different publics, as might those with children and those without children. Race, ethnicity, income, politics, age and life experience are some factors that can contribute to the existence of distinct publics. Be sure to use multiple channels of communication for your multiple audiences. Different groups get their information from different places. A strategy that relies on TV, radio and newspapers will miss those who Tweet, text and browse online for their information. It is important to become familiar with different means of communicating and to use them appropriately and effectively.

5.5 Explaining Technical Information to the Public

An Advisory Committee on Water Information webpage **http://acwi.gov/hydrology/Frequency/B17bFAQ.html** accessed March 1, 2012) poses these two questions:

Question: *What is the 100-year flood? Twice in the past 10 years, government officials have said that our river has had a 100-year flood? How can this be?*

Question: *What is a recurrence interval? My house was damaged by a flood last year, and I'm using my flood insurance payment to make some improvements as well as repairs. A government report said that the recurrence interval was 100 years, and my friend who's doing the work says that it's safe to make the improvements because another flood won't occur for 99 more years. Is that right?*

These questions present good examples of communication issues USACE has come up against from time to time in non-crisis communication situations. Talking about quantitative information and uncertainty are ongoing challenges to USACE analysts. There are three things to stress when communicating technical information to the public. They are:

- Motivation
- Simplification
- Orientation

5.5.1 Motivation

If people are outraged, it does not matter how you present the data to people. Numbers don't help or hurt in high-stress situations because outraged people do not want to hear or believe the data. It is irrelevant to them. Data is what experts rely on; the public relies on feelings and beliefs.

> **Upset and Risk Perception**
>
> Sandman and others suggest there is strong evidence that being upset is more likely a cause of risk perception than it is an effect of risk perception. The more upset people are about a risk, the more serious they tend to consider it. Changing how serious people think the risk is has relatively little impact on how upset they are. When people are very upset about objectively small risks, they will resist learning that the risk is small. If you somehow manage to force the data on them, they are likely to look for and find other reasons to remain upset. Likewise, people unconcerned about objectively serious risks will resist learning that the risk is serious. Faced with the facts of the situation, they will look for and find other reasons to remain unconcerned. This tends to hold for experts and lay publics. Experts tend to come up with more data-based rationales to justify their upset-based risk perceptions.

In high-stress situations you must begin by motivating people to want to hear what you believe they need to know. This begins by reducing their outrage; then you must make people want to hear the numbers. Reducing outrage relies a great deal on the skills of the messenger. Convincing people to want to hear the data can be helped by sharing power and giving people a decision to make that can be better made if they have the information you want to impart. It always helps motivation to ask people what they are interested in and want to know.

5.5.2 Simplify

To simplify the message, experts must often do the opposite of what they have been trained to do. Experts are trained to be complex, to think holistically, to think in terms of systems and to integrate knowledge. Professionals are advised to be impersonal and not show any emotions. Everyone can recall newsreel footage of the expert raising a hand to the microphone and saying, "I have no comment at this time." Truth be told, we love our data. We know how hard we worked to get it. We are justifiably proud of our efforts and mesmerized by the power of our numbers. These are the instincts you must work against in order to communicate effectively about technical information.

Simplification requires you to simplify your language, your graphics and your content. If you have succumbed to the temptation to use words to impress people, don't. Omit all those words. If you are going to use a word that must be defined, just use the definition, not the word. Do not say "hydrograph," talk about how fast the water rises or how long it stays high. If you must use jargon, always introduce the concept before you introduce the word. USACE rates its dams on a scale from I to IV with I being the least risky and IV the most risky. That's called its DSAC rating. You may see that term in our reports or in the newspapers.

Ask your audience to stop you immediately if you lapse into jargon, acronyms or any words that are not clear to them. Assure everyone you will restate in words that are clear. Be especially sensitive not to use jargon when stress is high. A simple sentence structure works best. When it is necessary to use difficult material, warn your audience. If you must speak about flood plains or exceedance frequencies, apologizing to your audience about the technical information you are going to talk about is better than just launching into the technical information without warning.

It is also wise to be careful about using technical terms that have different technical meanings. If you are a statistician and speak of significance and bias, you have different meanings in mind than a lay audience does. Using a readability index can also be helpful; remember the average grade level and the stress level when you do.

Simple graphics are best. When you are supporting decision making you are encouraged to show the data and to use multivariate relationships. In risk communication, limit yourself to one point per graphic. Bar charts and pie charts work better than the more complex decision support graphics you might be using. Put the conclusion you want the audience to draw right on the slide. Do not just say it or, worse, expect people to draw it. If you can use animation or a series of slides to simplify complex information, then do so.

The best way to simplify content is to stick to the most essential points. These include the things people want to know, things they need to know, and what they will get wrong if you don't tell them. A good test for including a detail is to ask:

1. Can the audience understand the main point without the detail?
2. If the detail is left out and they hear it later, will it seem to contradict what I have said?

If the answer to 1) is yes and the answer to 2) is no, then leave the detail out. If there is something that is true or interesting or something you worked really hard to find out but it is not necessary to your main point, then leave it out. Don't overlook non-technical details, especially if it is information the audience already knows. People know what happened in New Orleans; if that is part of the issue or history, then do not tiptoe around it.

Telling stories is a lot better than dumping data. Stories that make a specific point are best. If you can't tell a story, at least use concrete language. Letting people see pictures of you doing your job—inspecting the lockwall or conducting a damage survey, for instance —can help tell your story.

Be a person. Let people know a little about your background. If people are concerned about water quality, tell them you would drink the water but your spouse would probably prefer bottled water (or whatever the particular truth may be). Let people know you are human. Allow your emotions to show. It can be useful to express sympathy when it is felt. If you show you are human, people may be more respectful and understanding. If you are emotionless and respond in an impersonal manner, people may well treat you impersonally. However, you should never display anger toward your audience; that is a serious error.

If you ask if people understand, it will be unusual for anyone to say "no." Thus, you must learn to check people's non-verbal cues for understanding. Whose eyes are glazing over? Who is taking frantic notes in hopes of understanding later?

5.5.3 Orientation

Help people get properly oriented toward your message and also toward the uncertainty they need to understand. When you meet with people, help them understand your message. Tell people the structure of your presentation and always let them know where you are in the presentation. A simple way to do that is to list the topics on a flipchart and cross them off as you cover them.

> **Orienting People**
>
> We will look at five causes for the loss of wildlife…we will name four things you need to take with you in the event of an evacuation….we will examine three reasons for the recent increase in flooding…we will identify five negative consequences from deepening the channel.

As an expert you are far more familiar and comfortable with the material than your audience. There are three things you can do to help keep your audience focused on your main points. First, make sure the audience understands the logic of your argument. Logic and reasoning are far more important than data. Furthermore, if the logic is good, people are going to be better able to understand the data. Second, help the audience know why they need to know something before you give them the information, i.e., they should understand every piece of evidence. Third, remember to keep the audience oriented; make them aware of where you are in your story.

An audience will usually understand better if you start with the conclusions and then provide the data used to justify them. If you start with conclusions, then you need less data. Use more reasoning and less evidence, i.e. fewer numbers, but more concepts, conclusions and logical consequences. Help people see what is truly important and focus on the greatest concerns. (Remember your 3s!) Examples, anecdotes and quotes may be more effective than numbers. Test your technical explanations whenever you can with local folks. Focus groups can be very helpful. Ask your test subjects what they learned. If it is different from what you wanted them to learn, then your message needs work.

If the audience has any preconceptions, acknowledge them, especially if your information is going to conflict with them. We know most people think that global warming is the cause for the more frequent floods. Although climate change may be a contributing factor, we will present compelling evidence that new development around Voodoo Creek is a more direct cause of the problem.

To help the audience orient themselves properly about uncertainty, learn to use "confidence limits" in your language. This is not so much about statistical confidence limits as rhetorical ones. It is important to learn to say things like:

- This is what we are absolutely certain of
- This is what we think is likely but is by no means proven
- This is what we think is unlikely but is still possible

It is important to let people know your level of confidence. Explain uncertainty in ways they will understand. Don't sound more certain than you are.

When it is time to convey the truth of uncertainty to others, don't wait to be confronted but acknowledge uncertainty up front. Be sure to talk about it before people ask you about it. Do not put yourself in the position of sounding confident only to have to backtrack. Put bounds on the uncertainty. Do not use single numbers. Tell people the range of possibilities that is credible.

When you are communicating in a crisis situation, don't say anything that might not be true. If you guess wrong and lose credibility, that can become a communications and trust disaster. Never say that you're sure if you are not sure. This is not poker, it is risk communication. In the past we went too far and would say nothing (i.e., "no comment"). What you really is to find the middle ground with your audience. You need a way to say that we don't know for sure yet but that it is probably this or that based on what our experts are telling us. An important part of a risk communications message is to orient people to uncertainty.

Clarify to the audience that you're more certain about some things than others. We know one of the dam gates has become stuck in the up position and is now open. The water being released presents no danger to the community now or in the future. We do not yet know what caused the gate to get stuck but we have a crew working to close it and we have three inspectors examining the other gates. We will let you know why the gate got stuck and what the conditions of the other gates are as soon as possible.

It is important to explain what you have already done and what else you will do to reduce the uncertainty. Tell people what have you learned so far, what more you will learn, how it will be learned, when you will know it, and when you will pass the information along. When the remaining uncertainty is very small or is going to be very hard to reduce further, then say so. It is better to underpromise and overdeliver than to overpromise and underdeliver. It is okay to say that we're pretty certain but we're not going to get much more definite any time soon or that we're very uncertain now but we expect to have answers soon. When it comes to things like climate change and sea level change, it may be appropriate to say we're extremely uncertain and are going to remain extremely uncertain for a long time to come. Sometimes finding out for sure is less important than taking appropriate precautions now. We do not know if this is a serious problem or not, it would take us $3 million to find out and $2 million to just stop it, so we are going to just stop it.

When you are uncertain and everybody is making estimates, report everybody's estimates, not just your own in order to avoid more outrage. *We performed our risk assessment and got this answer; the university got a much lower value so we think the truth is somewhere between the two.* Convert disagreement to mere uncertainty. But, do not hide behind uncertainty and use it as a reason to not say anything. If it is more than likely that the problem is real, say so, even if there is lingering uncertainty. *It does look as if the levee is subsiding but we will need to confirm that with a survey.*

Organizations are often inclined to release uncertain good news and hold back uncertain bad news. They should do the opposite. Withholding bad news on the grounds that it is uncertain can come back to haunt you. It is not wise to perpetuate uncertainty. When there are ways to answer the questions you have, then pursue them. Be especially careful to never say, for instance, that there is no evidence that the levee is subsiding if you have not looked for evidence of subsidence.

A risk comparison can be one of the best ways to put numbers in context. Few people understand what 10^{-6} means in practical terms, even if they understand the number. So if you say a risk is bigger than this but smaller than that, it helps people understand what the number means. *This 1% exceedance frequency flood everyone has been talking about is worse than the flooding you get when the downtown intersection floods, but it is a little less than the flood you had three years ago.*

Many comparisons backfire and make people angry. This happens when people use two or more unrelated risks, i.e., the comparison risk is unrelated to the risk you're trying to explain. *You are more likely to fall in your own shower than that this levee will be overtopped, but it is more likely to be overtopped than it is we will be struck by a mile wide asteroid from space.* That kind of comparison is only going to make matters worse. If you must use different kinds of risk, be sure they do not evoke different levels of outrage. A small outrage and big risk (such as experiencing a car accident) is not good for a large outrage and small risk (e.g., the dam breaches). The example might be okay in technical terms, but it is mismatched with the outrage. Use comparisons wisely; they do not work with people who are already outraged or who will be outraged by your choice of bounds..

Make sure your organization maintains the right attitude. Do not give people too much guidance on what to think or feel. Don't criticize your audience's values. Let people decide for themselves what value judgments to make and which conclusions to draw from your data. You are the expert. These may just be numbers to you, so make sure you maintain appropriate feelings about the data. If you discuss the number of lives at risk or social vulnerability in a sterile and objective way, you will have problems conveying your message. If you do not express appropriate values, people will disqualify and ignore you.

5.6 Visualizing Data

Motivating the public to be interested in your data is more than just the presentation of your data. But once you have motivated the public to take an interest in your data, finding innovative ways to make the masses of data available to people is a looming challenge. The visualization of data is getting more attention in a wide variety of fields.

- Now is a good time to begin to consider new ways of presenting your information. A few websites that introduce you to this subject matter follow. These are not the kinds of displays you'd use for an emergency situation. They are displays that you might use to enable people to access the data in ways that are useful to them. **Many Eyes** (http://www-955.ibm.com/software/data/cognos/manyeyes/ accessed March 2, 2012) is an experiment by IBM Research that enables you to explore data using your eyes! The site allows the entire internet community to upload data, visualize it and talk about their discoveries with other people.

- **Gapminder** (http://www.gapminder.org/ accessed March 2, 2012) is an innovative project to bring a fact-based view of the world to the desktop. Multivariate, time-series cross-sectional data displays can be used to develop rich understanding of data.
- **The International Shark Attack File** (http://www.flmnh.ufl.edu/fish/sharks/statistics/statistics.htm accessed March 2, 2012) of the Florida Museum of Natural History site provides effective examples of some very traditional data presentations. This page with multiple-minis (http://www.flmnh.ufl.edu/fish/sharks/statistics/pop2.htm accessed march 2, 2012) provides a good example of multivariate data used to present a lot of information in a small space.
- **Riskometer.Org** (http://riskometer.org/ accessed March 2, 2012) is an American Council on Science and Health site that enables the user to access information in ways that are of the most interest to the user.
- The work of **Edward Tufte** (http://www.edwardtufte.com/tufte/ accessed March 2, 2012), the reigning guru on data visualization, is another good source of ideas.

5.7 Five Points To Take Away

1. Risk communication is the open two-way flow of information and opinion about risks and their management.
2. The perception of risk can be as important as the actual facts of the risk.
3. “Risk = Hazard + Outrage” is a useful way to think of risk for communication purposes.
4. The message, messenger and media are the three M’s of risk communication.
5. Three things to stress when communicating technical information to the public are: motivation, simplification and orientation.

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Chapter 6: Risk Assessment

6.0 Introduction

Risk assessment is the science-based component of risk analysis that answers the risk manager's questions about the risks. It is a set of logical, systematic, evidence-based analytical activities designed to provide risk managers with the best possible identification and description of the risk(s) associated with the decision problem. It provides the evidence base for decision making. Evidence can be considered to include anything that helps assessors discern the truth about a matter of concern to them. It includes data, knowledge, analytical results and information in all of its forms. A risk assessment includes the objective and subjective information needed for decision making as well as a careful characterization of the relevant uncertainty that could influence the decision. It is based on orderly reasoning.

USACE has been assessing risk throughout the life of its program. Its Flood Risk Management Program, which began as a National Flood Control Program in 1936, provides one of the earliest models of risk assessment available in the U.S. Government. For decades USACE analysts have been assessing and managing the risks of flood throughout the nation. Partial duration frequency curves and other distributions have been used to address the natural variability in floods. Knowledge uncertainty has in the past been addressed by levee freeboard and enhanced design features as well as by contingencies in cost estimates. Risks have been assessed quantitatively and probabilistically through measures such as expected annual damage estimates. The USACE large inventory of public works projects has necessitated a long and growing experience with risk assessment and management, long before these concepts matured into the disciplined approaches of today.

This chapter provides an updated introduction to the use of risk assessment by USACE. It begins with the introduction of the current USACE conceptual risk assessment model. From there it proceeds to consider a number of the qualitative and quantitative tools, techniques and methods of potential value to USACE risk assessors.

6.2 Risk Assessment Model

To a great extent many USACE employees have been performing risk assessment for a long time. Now, however, the notion of risk analysis has evolved and matured to the point where it is possible to talk about the practice of risk analysis in a more formal way. It is timely for USACE to take advantage of the advances in the theory and practice of risk analysis in general and risk assessment in particular. Risk assessment is a continuously evolving process with a stable core that may best be described by the four questions introduced in Chapter One. Informally, risk assessment is a process that asks and answers these questions of the work to be performed:

What can go wrong?

How can it happen?

What are the consequences?

How likely is it to happen?

These informal questions are addressed in a vast array of definitions and models that describe how the core work of risk assessment is applied in a wide and growing variety of applications. Figure 6.1 repeats Figure 2.3 as a model that currently meets USACE needs for a more formal expression of the USACE risk assessment process.

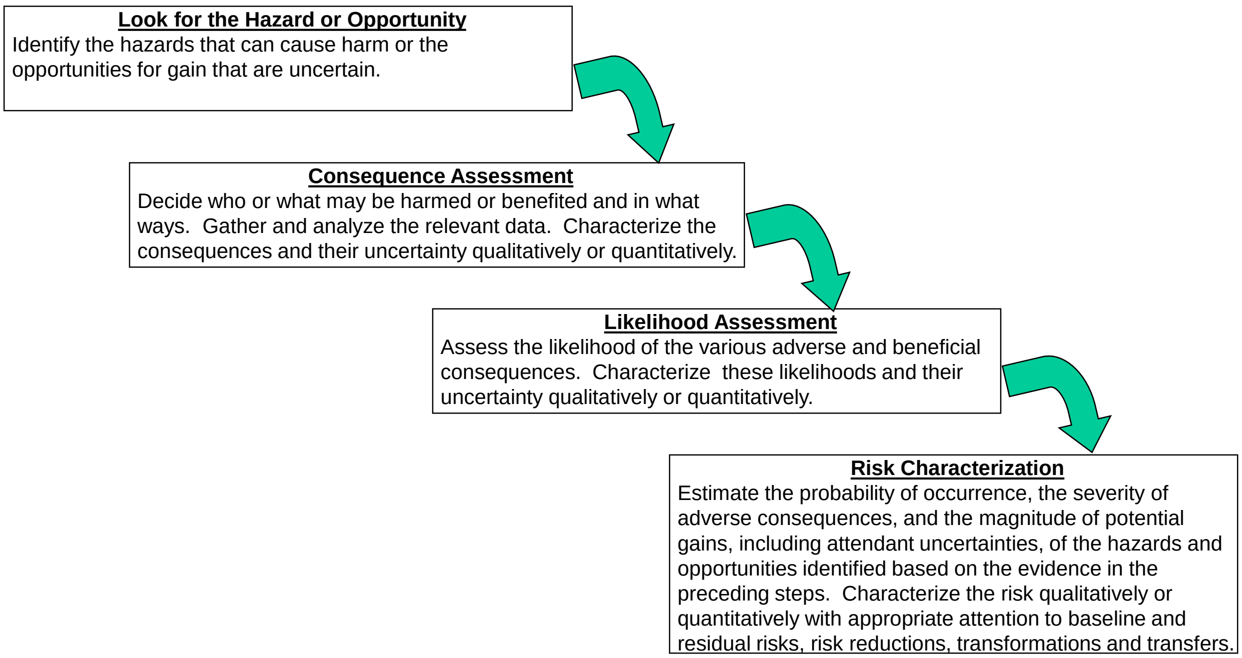

Figure 6.1: : Four-step risk assessment process

This is the same risk assessment that is conducted in the identify risk and analyze risk steps of the risk management model. The generic risk assessment concepts are identified more carefully in this conceptual model. Ideally, each specific risk assessment conducted by USACE will include each of these steps.

The first formal step in any risk assessment is to identify the risks of interest. This is done by looking for the hazards that can cause harm and the opportunities for potential gains that are uncertain. In a flood risk management example, this step is identifying the source of a flood problem.

Earlier risk was described by a simple equation: Probability x Consequence. These two elements comprise the next two steps in the risk assessment model: consequence assessment and likelihood assessment.

Assessors must identify and describe the consequences of the hazards and opportunities that have been identified. This activity might be described as the cause-effect link in the risk assessment. What undesirable effects do the hazards have? What desirable effects might the opportunities offer?

In a flood risk management planning study, the consequence assessment will include the estimation of a stage-damage curve as seen in Figure 6.2. This curve describes the consequences of various levels of flooding on property damage in a flood plain reach.

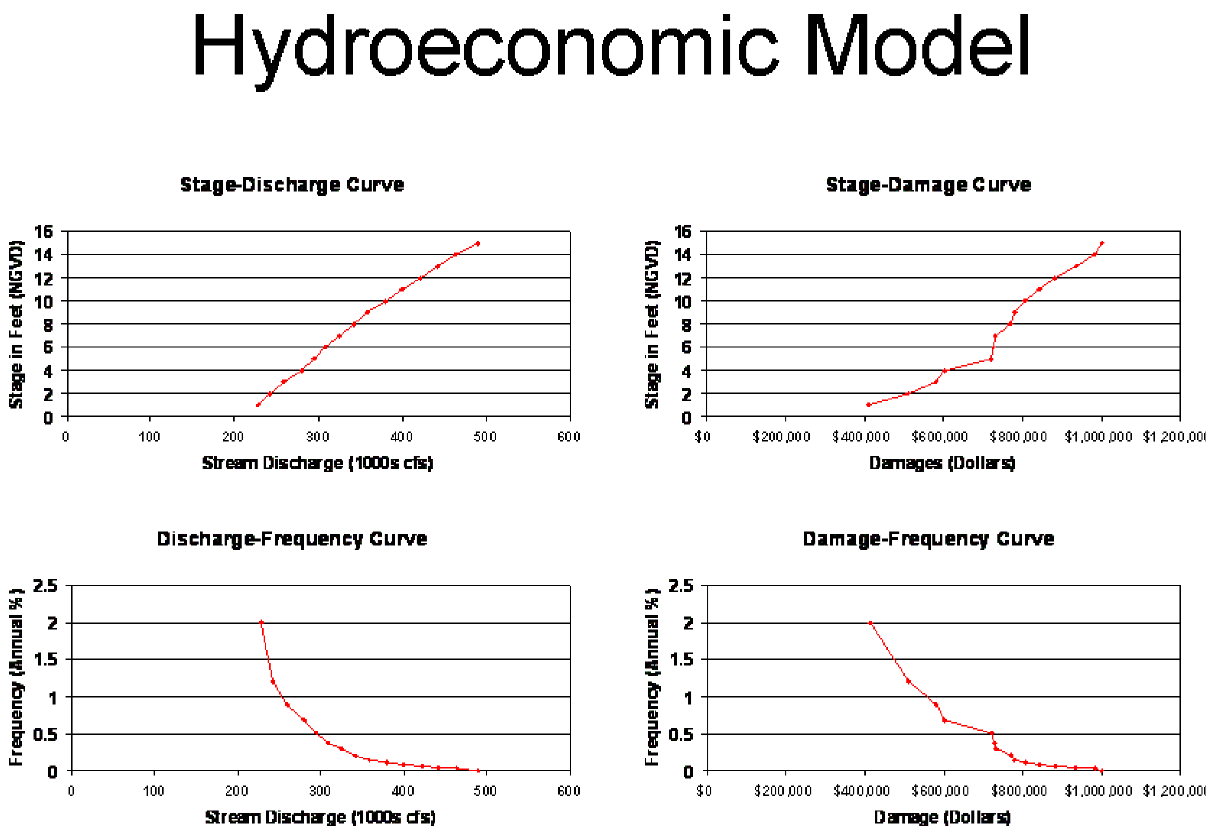

Figure 6.2: Consequence assessment, likelihood assessment and risk characterization in flood risk management

Concurrently, or sequentially, USACE analysts will be assessing the likelihoods of the various negative or positive consequences. This step is often called an exposure assessment in other risk assessment models. Risk assessors analyze how undesirable consequences of hazards or the desirable consequences of opportunities occur so that they can characterize the likelihoods of the sequences of events that produce these outcomes. Most risks can't be directly observed or measured because they are potential outcomes that may or may not occur. Uncertain occurrence is a necessary condition for risk. Certain events are not risks.

Probability is the language of uncertainty and qualitatively or quantitatively assessing the likelihoods of the various adverse and beneficial consequences associated with the identified risks is necessary for risk assessment. In a flood risk management study these likelihoods are captured in part by the stage-discharge and discharge-frequency curves. These two curves together enable assessors to estimate the likelihood that the varying levels of flooding and their associated damages will occur.

The fourth generic step in the risk assessment model is risk characterization. Characterizations include one or more estimates of risk and a narrative description of the risk. The risk estimate estimates the likelihood and severity of the adverse effects or the potential gains from opportunities. The estimate addresses key attending uncertainties. Quantitative estimates are numerical in nature and are preferred over qualitative estimates. Risk estimates should include all the relevant aspects of the risk, which may encompass existing, future, historical, reduced, residual, new, transformed and transferred risks. A risk description is a narrative explanation and depiction of a risk that bounds and defines a risk for decision-making purposes. It's the story that accompanies the risk estimate. It places each risk in a proper context for risk managers and others to understand.

A good risk characterization converts the scientific evidence base and the remaining uncertainty into a statement of risk that answers the manager's questions. During the risk characterization the overall importance of the various uncertainties encountered throughout the risk assessment are brought into focus. Risk characterization should include sensitivity analysis or formal uncertainty analysis commensurate with the nature of the risk assessment.

Characterization of risk draws on the analytical work done in the preceding steps. In the flood risk management example the damage frequency curve integrates the consequence and likelihood assessments and enables planners to use expected annual damages to estimate the risk of flooding.

The elements of the risk assessment model are not always easy to separate in every risk assessment. Every risk assessment will not include all four steps. In some instances it may be more efficient to conduct a detailed assessment of a likelihood, for example, if there is some evidence to suggest imaginable potential consequences may never occur. For example, demonstrating that a potential flood cannot reach a piece of critical infrastructure such as an airport obviates the need for a damage survey and a risk characterization.

6.3 Some Critical Risk Assessment Tasks

The four generic steps in the model above will look very different in different applications. Flood risk management assessments and budget risk assessments use very different models and techniques. The USACE risk assessments are distinguished by their differences. Nonetheless, there are some common tasks worth mentioning.

6.3.1 Create a Risk Profile

Some risk assessment tasks may be initiated in the risk profile, defined in Chapter 4 as a description of what is currently known and not known about the risks identified. A risk profile is essentially the first iteration of a risk assessment. Often the uncertainty in the first iteration is too great to support decision making and a risk assessment is done to reduce the uncertainty.

6.3.2 Understand the Questions

Risk assessors must understand what information they are being asked to provide for risk managers. In well-known or routine situations everyone understands what needs to be done without a formal process of producing a written list of questions to be answered. In all other decision-making situations, however, that list of questions is an essential first step. When a new program like the National Levee Safety Program is implemented, there is nothing more important than getting the questions right.

> Managers and assessors need to remain vigilant against imprecise language. It is easy to ask what is the risk associated with a non-federal levee, for example. But what are the consequences of concern to risk managers? *Is it substandard engineering design? Stability of the levee? Potential loss of life? Property at risk?*
>
> *Do they want estimates of the probability of failure? If so, should the estimates be for a selected event or annually?*

Assessors and managers should review the questions together to make sure they have a common understanding of the meaning of the questions and the information required to answer them. There will be times when the assessors know it is going to be impossible to answer some of the questions. Risk managers need to know this so that a revised set of questions can be negotiated and approved by the managers. Questions need not literally be questions. Information needs can be expressed in any number of ways. Whether routine or unique, however, these questions guide the risk assessment.

6.3.3 Identify the Risks

Data collection and analysis begin in earnest when you begin to identify the risks. The source of the risk may already have been identified as the decision context was established by the risk managers, with or without the assistance of the assessors. In many risk assessment models this step is called hazard identification.

Risk assessors should think comprehensively about risks and identify all of the decision-relevant risks. It is important to avoid the mistake of focusing too quickly and too narrowly on a single risk when there may be more than one. Not only the existing risk should be considered, but also residual, new, transformed and transferred risks. Risk identification is primarily a qualitative analysis that results in a narrative description of a risk. This is the stage when risk assessors begin to identify and separate what we know about a risk from what we do not know.

6.3.4 Assess the Effectiveness of Risk Management Options

In many USACE decision problems risk assessors will need to estimate risk reductions attributable to the risk mitigation options under consideration. Additional evaluations of the risk management options might include economic costs and benefits, environmental impacts, social impacts, legal ramifications, and the like. All of these evaluations should be conducted in a risk-informed manner that focuses on and appropriately addresses the uncertainty encountered in the evaluation.

It will likely be efficient to consider residual, new, transferred and transformed risks at the time risk reductions are estimated. Sometimes risk management options will be reasonably well known when the risk assessment is initiated. Other times risk management options will not be formulated until after risks are assessed and judged not acceptable. The assessment of risk management options is often considered an integral part of risk characterization in some models. Whenever they are ultimately assessed, uncertainty concerning the efficacy of an option should be investigated and documented so that risk managers and other interested parties may be made aware of them.

6.3.5 Communicate Uncertainty

Risk assessors can't just identify and investigate the significance of the uncertainty in risk assessment. They have to find ways to communicate its significance for decision making to risk managers and interested stakeholders. Characterizing the significance of the key uncertainties in a risk assessment is critical to informed decision making. The National Research Council (NRC) in 1994 said, "uncertainty forces decision makers to judge how probable it is that risks will be overestimated or underestimated" and to make decisions accordingly.

The informed consent of those affected by risk management decisions relies critically on the risk assessor's ability to communicate the nature and significance of the uncertainty that remains. When people are asked to live behind a levee or downstream from a dam, they have a right to know the limitations of the risk management measures taken on their behalf as well as the limitations of the information on which those measures were based. Characterizing uncertainty is essential to the transparency of the USACE risk management process.

> Multidisciplinary teams assure that needed expertise is available. Experts tend to function in isolation of one another's disciplines. Knowledge tends to be integrated by one or a few individuals. On an interdisciplinary team the experts integrate their knowledge with that of others. Engineers understand something about economics and economists understand a little engineering. The team itself integrates the knowledge of its member experts. Interdisciplinary teams work more efficiently and effectively than multidisciplinary teams. Transdisciplinary teams dissolve the boundaries among disciplines and move beyond integration to assimilation of perspectives. They are often able to construct knowledge and understanding that transcends the individual disciplines. Transdisciplinary teams are preferred but they are still rare.

6.4 What Makes a Good Risk Assessment?

If you're new to risk assessment, then there are some simple suggestions to follow that will help you perform a good risk assessment. They are presented below.

6.4.1 Frame the Questions that Need to Be Answered

First, a good risk assessment must begin with the questions that need to be answered by the risk assessment to support the risk manager's decision making. Get these questions right, then answer them clearly and concisely.

6.4.2 Separate Risk Assessment from Risk Management

Keep risk assessment functionally separated from the risk management task. Have different people perform these two tasks. Make sure they communicate early and often.

6.4.3 Make Risk Assessment a Team Effort

USACE risk assessment works best as a team effort. Evidence-based analysis requires subject matter experts. It is unusual for a single person to possess all the knowledge required to complete a risk assessment. Good teams are at least multidisciplinary. Better teams are interdisciplinary. The best teams are transdisciplinary.

6.4.4 Design the Magnitude of the Effort to Match the Risk and the Resources Available to Assess It

The magnitude of the effort is commensurate with the resources available and in proportion to the seriousness of the problem. Risk analysis in general and risk assessment in particular are perfectly scalable processes. Any risk assessment no matter how crude is generally better than no risk assessment. The process can be completed in an hour if that is all the time you have. However, a complete and thorough risk assessment may require a couple of years if the project is very large, is complex, and has very large risks.

6.4.5 Follow a Risk Assessment Process

The process is often as important as the result. Following a risk assessment process aids the understanding of the problem and its solutions.

6.4.6 Do Not Choose a Point of View

A good risk assessment assumes no point of view. It is not the assessor’s job to protect lives, save or create jobs, or to punish or reward anyone. Assessors only need to provide objective evidence-based answers to the questions they have been asked.

6.4.7 Use Science to Describe Uncertainty

Effective risk assessment separates what we know from what we do not know. It then focuses special attention on what we do not know. Effective risk assessment gets the right science into the assessment and then it gets that science right. Assessors use science to answer the risk manager’s questions. Honesty about uncertainty provides the confidence bounds on those answers.

6.4.8 Tie the Analysis to the Evidence

Good science, good data, good models and the best available evidence are integral to good risk assessment. The analysis must be tied to the evidence.

6.4.9 Identify Assumptions

. In an effective risk assessment all assumptions are clearly identified for the benefit of other members of the assessment team, risk managers and anyone else who will read or rely upon the results of the risk assessment.

6.4.10 Conduct Sensitivity Analyses

Sensitivity analysis should be a part of every risk assessment. Testing the sensitivity of assessment results is a minimum requirement for every assessment, qualitative or quantitative.

6.4.11 Consider Multiple Dimensions of Risk

We need to consider risk broadly and focus on the risks of interest in order to distinguish risk assessment from safety analysis. These may include:

- Existing risk
- Future risk
- Historical risk
- Risk reductions
- New risks
- Residual risk
- Transferred risk
- Transformed risk

It's not always necessary to consider each of these kinds of risk but it is rarely adequate to consider only one dimension of a risk.

6.4.12 Keep the Assessment Unbiased and Objective

Effective risk assessments are unbiased and objective. They tell the truth about what is known and not known about the risks. They are as transparent and as simple as possible but no simpler. Practicality, logic, comprehensiveness, conciseness, clarity and consistency are additional qualities desired in a risk assessment.

6.4.13 Keep Risk Assessment and Decision-Making Separate

Risk assessments usually produce more estimates and insights than scientific facts. The assessment provides information; it does not produce decisions. Risk managers make decisions.

6.4.14 Clearly Describe the Limits of Knowledge Discovered During an Assessment

Risk assessments can have educational value for use in future assessments. They often identify the limits of our knowledge and in doing so guide future research. Completed risk assessments may be conducive to learning about similar or related risks.

6.4.15 Document the Assessment

Documentation is an important part of the risk assessment process. Effective documentation tells a good story well. It lays out the answers to the risk manager's questions clearly, correctly and simply.

6.5 Qualitative and Quantitative Risk Assessment

Risk assessments can be qualitative or quantitative.

Qualitative risk assessment compiles, combines and presents evidence to support a non-numerical estimate and description of a risk. Numerical data and analysis may be part of the input to a qualitative risk assessment but they are not part of the risk characterization output.

Quantitative risk assessment relies on numerical expressions of risk in the risk characterization. Numerical measures of risk are generally more informative than qualitative estimates. When the data and resources are sufficient, a quantitative assessment is preferred. Nevertheless, quantitative risk assessment is not always possible or necessary, so qualitative risk assessment is often a viable and valuable option.

Qualitative risk assessment is especially useful:

- For routine noncontroversial tasks;
- When consistency and transparency in handling risk are desired;
- When theory, data, time or expertise are limited; or
- When dealing with broadly defined problems where quantitative risk assessment is impractical.

Qualitative assessment produces a descriptive or categorical treatment of risk information. Uncertainty in qualitative assessments is generally addressed through descriptive narratives.

Quantitative assessments can be deterministic or probabilistic. Quantitative risk characterizations address risk management questions at a finer level of detail and resolution than a qualitative risk assessment. This greater detail requires a more sophisticated treatment of the uncertainty in the risk assessment than is found with qualitative assessment.

The next two chapters provide an introduction to the risk assessor's toolbox. Chapter 7 presents qualitative risk assessment tools. Chapter 8 presents quantitative tools. Table 6.1 provides a summary of the tools presented and suggestions for the risk management and risk assessment tasks where they are likely to prove most useful.

Tools and Techniques	Identifying Risks	Consequence Assessment	Likelihood Assessment	Risk Characterization	Evaluating Risk	Evaluating RMOs	Knowledge Uncertainty	Natural Variability
Qualitative Tools								
Brainstorming	SA	NA	NA	NA	NA	NA	NA	NA
Delphi Techniques	SA	NA	NA	NA	NA	NA		
Interviews	SA	NA	NA	NA	NA	NA		
Expert Elicitation	SA	SA	SA	NA			SA	WA
Increase or Decrease Risk	WA	WA	WA	NA	NA	WA	NA	NA
Risk Narratives	SA	A	A	SA	NA	NA	A	WA
Evidence Mapping	SA	A	A	SA	NA	NA	SA	WA
Screening	SA	A	A	SA	WA	NA	WA	WA
Ratings	SA	A	A	SA	A	A	A	A
Rankings	SA	A	A	SA	A	A	A	A
Enhanced Criteria Ranking	SA	A	A	SA	NA	A	A	A
Operational Risk Management (Risk Matrix)	SA	SA	SA	A	A	NA	WA	WA
Develop a Generic Process	NA	SA	SA	A	A	A	A	A
Qualitative Assessment Models	NA	A	A	A	A	A	A	A
HACCP	A	A	WA	NA	WA	SA	NA	A
MCDA	WA	A	A	SA	A	SA	A	WA
Quantitative Tools								
Modeling and Model Building	NA	SA	SA	SA	NA	SA	A	SA
Event Tree	NA	SA	SA	SA	NA	SA	SA	SA
Fault Tree	SA	A	SA	SA	NA	WA	SA	SA
Monte Carlo	NA	SA	SA	SA	SA	SA	SA	SA
Sensitivity Analysis	WA	SA	SA	SA			SA	SA
Monolithic Scenario Analysis	NA	SA	SA	SA	NA	SA	NA	WA
Deterministic Scenario Analysis	NA	SA	SA	SA	NA	SA	A	A
Probabilistic Scenario Analysis	NA	SA	SA	SA	NA	SA	SA	SA
Uncertainty Decision Rules	NA	NA	NA	WA	SA	SA	NA	NA
Subjective Probability Elicitation	NA	NA	SA	NA	NA	A	SA	A
Multi-Criteria Decision Analysis	NA	A	A	A	SA	SA	SA	WA
Safety Assessment	NA	A	A	SA	SA	A	A	A
Scenario Planning	A	SA	SA	SA	SA	SA	SA	WA
Vulnerability Assessment	NA	WA	SA	A	SA	NA	A	WA
Fragility Curves							A	SA
HAZOP	SA	SA	NA	SA	?	?		
SWIFT	SA	SA	SA	SA	SA	SA	SA	SA
Business Impact Analysis	A	SA	A	A	A			
Fault Modes and Effects Analysis	SA	NA	NA	NA	NA	NA		
Root Cause Analysis	A	NA	SA	SA	NA			
Cause Consequence Analysis	A	SA	NA	NA	NA			
Layers of Protection Analysis	SA	NA	NA	NA	NA			
Human Reliability Assessment	SA	SA	SA	SA	A			
Bow Tie Analysis	NA	A	SA	SA	A			
Reliability Centered Maintenance	SA	SA	SA	SA	SA			
Markov Analysis	A	NA	SA	NA	NA			
Bayesian Statistics	NA	NA	SA	NA	SA		SA	A
Bayesian Networks	NA	NA	SA	NA	SA		SA	A

Table 6-1. Risk Assessment Tools and Techniques

The rows of the table show a variety of tools, techniques and methods available to risk assessors. They are grouped as qualitative or quantitative tools. Those that can function as either are first listed among the qualitative tools. Columns two through five identify specific risk assessment activities or qualities found in a generic risk assessment process. "Evaluating risk" refers to the judgment of a risk as acceptable or not. Tools with potential use for evaluating risk management options are also identified. The last two columns help identify tools known to be useful in addressing knowledge uncertainty or natural variability.

The subjective ratings provided by the author are as follows:

- SA = strongly applicable
- A = applicable
- WA = weakly applicable
- NA = not applicable

There is, naturally, a wide range of applications over which some of these tools can be applied. They will be more applicable for some applications than for others. To say a tool is strongly applicable generally means there are situations in which it would be strongly applicable. That does not mean it is strongly applicable in all situations. The ratings provide a preliminary relative guide to the tools. The descriptions in the chapters that follow will aid the assessor to choose the most appropriate tool.

6.6 Five Points To Take Away

1. Risk assessment is the science-based component of risk analysis that answers the risk manager's questions about the risks.
2. The USACE generic risk assessment model has four steps: hazard/opportunity identification, consequence assessment, likelihood assessment, and risk characterization.
3. Communicating uncertainty effectively is a critical task of risk assessment.
4. Good risk assessment begins with the questions risk managers need to have answered in order to support their decision making.
5. Risks can be assessed qualitatively or quantitatively.

6.7 References

National Research Council. 1994. Committee on Risk Assessment of Hazardous Air Pollutants. Science and judgment in risk assessment. Washington DC: National Academies Press.

Chapter 7: Qualitative Risk Assessment Tools

7.1 Introduction

This chapter introduces and briefly summarizes a range of qualitative risk assessment tools that may be suitable for the USACE Civil Works Program. The chapter begins with a few general and less structured tools suitable for filling information gaps and assessing risks at the most basic level. It proceeds through more structured approaches like screening, rating and ranking hazards, risks, solutions and the like. It ends while summarizing several more specific techniques. The discussion of each tool is adapted from the style of the International Electrotechnical Commission (2009) summary of risk assessment techniques. The flow of the discussion, in general, includes the following:

- Overview of the technique,
- How the technique is used,
- Inputs required,
- Process applied,
- Outputs produced,
- Strengths or limitations of the technique, and
- Examples of Use.

7.2 Brainstorming

7.2.1 Overview of the Technique

Brainstorming is a proven effective methodology for generating ideas. It is especially useful for generating unusual ideas. A common goal of brainstorming is to generate the greatest number of ideas in the least amount of time possible. Some brainstorming techniques include evaluation of ideas; others do not. Good brainstorming uses a particular technique and structure that ensures participants' imaginations are triggered by their own thoughts as well as the thoughts and comments of others. A great many such techniques are described in the literature and the worldwide web. Careful preparation and effective facilitation are two important elements in a successful brainstorming process.

7.2.2 How the Technique Is Used

Brainstorming can be used alone or in conjunction with other risk assessment methods. Its purpose is to encourage imaginative thinking at any stage of a risk management activity. It can be used for scoping activities (e.g., to identify risks and stakeholders). It can also be used at a detailed level for particular issues (e.g., to identify means of keeping specific aquatic nuisance species out of specific waterways). Because it relies so heavily on imagination, brainstorming can be particularly useful to identify the risks of new technology or novel solutions to new and old problems.

7.2.3 Inputs

The inputs for successful brainstorming include:

- a well-defined problem,
- a team of people with knowledge of the problem,
- a brainstorming technique,
- a facilitator, and
- the means to both record and disseminate the results of the process.

7.2.4 Process

The process itself can be formal or informal. Formal brainstorming is more structured. Facilitators prepare in advance and participants may be prepared as well. The session has a defined purpose, structure and outcome. Informal brainstorming is less structured. It may be represented by the “let’s go around the table and see what everybody thinks” method we have all experienced.

7.2.5 Outputs

The outputs depend on the purpose of the brainstorming session but you can expect a list of ideas. Most of the time the ideas will not be evaluated, although some brainstorming techniques provide for some degree of evaluation of the ideas. Most purists would argue that evaluation is a process separate from brainstorming.

7.2.6 Strengths and Weaknesses

Strengths:

- Encourages imagination
- Identifies new risks and novel solutions
- Involves key stakeholders and hence aids communication overall
- Relatively quick and easy to set up

Weaknesses:

- Failing to get the right mix of skills and knowledge in the group
- Group domination by one or more strong personalities or bosses
- Free-riding by group members
- Social phenomena like "groupthink" or "groupshift"
- Difficulty verifying that the effort is comprehensive

There are techniques designed to overcome these weaknesses.

7.2.7 Examples of Use

Brainstorming may be useful for identifying hazards, risks, stakeholders, decision criteria and risk management options. For a more complete discussion of brainstorming see Aiken et al. (1997), Isaksen (1998.), Mind Tools Limited (2007), Osborn (1963), and Yoe (2012), or simply do a web search on brainstorming.

7.3 Delphi Techniques

7.3.1 Overview of the Technique

The Delphi technique is an expert survey conducted in two or more rounds. It is designed to obtain a consensus of opinion from a group of experts. The most unique aspect of the Delphi technique is that it allows experts to express their opinions individually and anonymously while providing them with the views of other experts as the process progresses. Iterated rounds of input are used to focus the expert opinions and discussion until, ideally, a consensus among the experts is achieved.

7.3.2 How the Technique Is Used

The Delphi technique is an effective way to address uncertainty. It can be applied at any stage of the risk management process and at any stage in a project's lifecycle. It is most valuable when a consensus of experts' views is required. It is sometimes called a forecasting technique because it has, historically, been used for that purpose. It is most useful for problems plagued by uncertainty, especially knowledge uncertainty; otherwise, analytical solutions are more efficient. The experts in a Delphi process can only provide estimates of uncertain aspects of a decision process.

7.3.3 Inputs

The inputs for this process include a group of experts and a decision problem for which consensus is required. Experts may be asked to rank options or to fill in gaps in critical knowledge uncertainty. The process is designed for use with a group of experts that do not normally interact with one another. In other words, a Delphi process would not be used within an office of coworkers or other groups where all the participants know one another.

7.3.4 Process

The first step, once the purpose of the process is clearly identified, is to form a small team to facilitate and monitor the process. This team identifies and secures the participation of a group of experts. Initial phases sometimes allow experts to add pertinent information to the knowledge base and define relative terms to be used, such as "importance," "high risk," "unlikely," and similar words and phrases. The process is a combination of polling and conference, where much of the responsibility for communication is shifted from the members of the large group to the members of the facilitating team. The team develops the round one questionnaire, which is designed to elicit information relevant to the decision problem. The questionnaire should be pretested and then it is sent to the expert group members individually.

Information from this first round of responses is analyzed and summarized by the team. The summary is usually provided to the expert group without attributions. The group members are usually given one opportunity to revise their original responses based on this initial round of review of the original responses. The facilitators prepare a second questionnaire for the expert group. Experts respond to the second questionnaire and the process is repeated until consensus is reached.

7.3.5 Outputs

The desired output of this process is the expert group's convergence toward consensus on the decision problem.

7.3.6 Strengths and Weaknesses

Strengths (IEC, 2008):

- Easier to get the needed experts as experts do not need to actually assemble in one place at one time
- Anonymity helps to assure that any unpopular opinions will be more likely to be expressed
- There is no group dominance, all views have equal weight
- The process achieves ownership of outcomes

Weaknesses:

- Process is very labor intensive and time consuming for the facilitating team
- Experts must be able to express themselves clearly in writing

The Delphi technique is one of the more common techniques for eliciting expert opinion. It may be most valuable for reducing knowledge uncertainty about matters of subjective judgment or interpretation.

7.3.7 Examples of Use

One common example is classifying the condition of a structure or structural component based on limited physical evidence. A second common example is forecasting the efficacy of a risk management option with condition forecasts. For additional information see *The Delphi Method, Techniques and Applications* Edited by Harold A. Linstone and Murray Turoff, New Jersey Institute of Technology, 2002 http://is.njit.edu/pubs/delphibook/delphibook.pdf accessed October 16, 2011.

7.4 Interviews

7.4.1 Overview of the Technique

Conducting structured or semi-structured interviews can be an important and useful technique for addressing uncertainty. Using this technique, individual experts are asked a set of prepared questions. Structured interviews adhere to the prescripted questions while semi-structured interviews allow the conversation to explore issues and topics that arise during the interview.

Well-constructed interviews can encourage experts to see problems from new perspectives (IEC, 2008).

7.4.2 How the Technique Is Used

Interviews are most useful when it is impractical or undesirable to get people together for brainstorming or more formal processes, like a Delphi process. The structure of an interview usually assures more productive outcomes than a free-flowing discussion in a group. Interviews can be used to identify risks or to assess the efficacy of risk management options (IEC, 2008). The ease with which interviews can be conducted makes them useful tools for gathering stakeholder input to a risk management process.

7.4.3 Inputs

The inputs to an interview process include:

- clear articulation of the objectives of the interviews
- study design
- list of people to be interviewed
- set of questions to ask
- interview(s)
- transcription of interview results
- analysis of interview results
- report of interview process and results

7.4.4 Process

The set of questions to ask is a critical input. In qualitative research, open-ended questions are preferred when possible. The questions should be simple and each one should address a single topic or issue. The language should be appropriate to the interviewee. Use engineering jargon for engineers but not for the public, for example. Interview questions should include follow-up questions. In other words, the answer to one question may trigger a sequence of questions to follow. For example, if a person's home was flooded in the last flood, they will be asked different questions than a person that was not flooded. All questions should be pretested for clarity. The prepared questions are then asked of each interviewee. Care should be taken to use good interview techniques.

7.4.5 Outputs

The output of the interview process is a documented record of the interviewees' views on the interview's subject matter

7.4.6 Strengths and Weaknesses

Strengths:

- Useful for large groups
- Structure assures uniformity of coverage of an issue

- One-to-one communication allows conversation to meander (semi-structured)
- A record of information obtained

Weaknesses:

- Prior approval(s) may be required before conducting an interview survey
- Time-consuming and labor intensive
- Benefits of group interaction are absent (i.e., bias is more likely than in group discussion, imagination is not triggered)
- Interviews are underutilized in risk assessment

7.4.7 Examples of Use

It is common to use an interview process to speak to peers, stakeholders and experts about a wide variety of topics. It is routine practice to seek input and insight from the experience of others when faced with a novel situation. When those conversations seek information to use in a decision problem, it can help to conduct a structured or non-structured interview.

Partial Check List of Aquatic Nuisance Species
Gymnocephalus cernuus Eurasian ruffe
Hypophthalmichthys molitrix silver carp
Hypophthalmichthys nobilis bighead carp
Ictalurus furcatus blue cat
Lepisosteus platostomus shortnose gar
Lepomis auritus redbreast sun
Lepomis microlophus redear sun
Menidia beryllina inland silverside
Misgurnus anguillicaudatus Oriental weather
Morone americana white perch
Morone saxatilis striped bass
Mylopharyngodon piceus black carp
Neogobius melanostomus round goby
Notropis buchanani ghost shiner
Noturus insignis margined madtom

Individual analysts are often required to provide estimates of values ranging from budget inquiries to model inputs about which there may be uncertainty. It is often wise for the analyst to construct and complete a short interview of oneself to document potentially important thought processes.

An interview format can simultaneously reduce uncertainty and document efforts to do so when questioning experts, for example, on such uncommon concerns as the effects of blasting rock in a channel on marine wildlife, the effect of woody vegetation on levee stability, and the like,.

7.5 Checklists

7.5.1 Overview of the Technique

Checklists are useful tools. Lists of hazards, risks, failure modes, or risk management measures are sometimes developed during a risk assessment. The lists are usually based on experience or the work of others in similar situations. Checklists or protocols can be used at any stage of a project lifecycle.

7.5.2 How the Technique Is Used

Although a checklist can be used as a stand-alone technique, it is often used to check that everything has been covered when a more imaginative technique, such as brainstorming, has been applied.

7.5.3 Inputs

The inputs to a checklist include prior experience with an issue and documentation of that effort in a report or other format. In some instances a checklist may be developed by drawing on the expertise of a group that can use a technique like brainstorming to create a checklist for subsequent use.

After identifying the scope of the decision problem, the steps to develop checklists might include:

- Procuring or preparing a checklist that is adequate to the purpose,
- Identifying the expert or team to use the checklist, and
- Stepping through each aspect of the decision problem to decide whether items on the checklist are present.

7.5.5 Outputs

The outputs of this process depend on the nature of the decision problem. Normally a checklist will produce a subset of items that are considered relevant to consider for the situation at hand.

7.5.6 Strengths and Weaknesses

Strengths (IEC, 2008):

- May be used by non-experts
- Well-designed lists combine wide-ranging expertise into an easy-to-use technique
- Are fast and helpful when done well
- Help ensure common elements are not overlooked
- Compiling and publishing lists related to risk identification and risk management is an activity that yields high value to USACE and others
-

Weaknesses:

- Can inhibit imagination in unique situations, e.g., the identification of risks
- Address the ‘known knowns’ and may neglect the ‘known unknown’s’ or the ‘unknown unknowns’
- Can encourage ‘check it off ‘ types of behavior
- Tend to be based on what has been seen or done before

7.5.7 Examples of Use

The Great Lakes and Mississippi River Interbasin Study (GLMRIS) was faced with identifying aquatic nuisance species of concern. After reviewing about 625 publications and reports as well as other sources and personal communications, they identified a total of 253 alien aquatic species. Their work now represents a potentially useful checklist for others dealing with potential introduction of non-indigenous species into waterways.

Lists of nonstructural measures have been prepared to aid plan formulation. An example of one such list is found at http://www.corpsnedmanuals.us/FloodDamageReduction/FDRID094NonstrucFldDmgMeas.asp?ID=94 accessed October 20, 2011.

7.6 Expert Elicitation

7.6.1 Overview of the Technique

USACE is frequently required to make important decisions in the presence of uncertainty, and risk analysis seeks to increase understanding of the implications of uncertainty for decision making. Expert elicitation is a useful technique for improving the characterization of uncertainty. It is a systematic process of formalizing, and usually quantifying, often in probabilistic terms, expert judgments about uncertain quantities. It is discussed here among the qualitative methods because it has also been used to elicit qualitative judgments about matters of uncertain facts. The process frequently involves integrating empirical data with scientific judgment and identifying a range of possible outcomes and likelihoods. Thus, it can also be a quantitative technique. Documenting the underlying thought processes of experts is the essence of the process.

7.6.2 How the Technique Is Used

Many of the complex problems USACE faces are characterized by a lack of direct empirical evidence for some aspect(s) of the problem. Most of these situations require judgment to help bridge the gaps in data, knowledge or theory. Expert elicitation is used to make subjective judgments as objective as possible; It is defined more narrowly than expert judgment. It is a method limited to characterizing the science (state of knowledge) in a decision problem. Expert judgment, as defined here, refers to characterizing the decision-relevant values and preferences that lead up to decision making. Thus, estimating a roughness coefficient for a model is a matter of expert elicitation, while trading off national economic development effects for national ecosystem restoration effects is an expert judgment. Elicitations may be group or individual efforts.

7.6.3 Inputs

The inputs for an expert elicitation process include:

- Problem definition to include identification, selection and development of technical issues to be resolved,
- Formal elicitation protocol,
- Experts,
- Identification, summary and sharing of the relevant body of evidence with experts, and
- Formal elicitation to encode the experts' judgments.

7.6.4 Process

The elicitation process begins with problem definition and identification of technical issues. The elicitation process is facilitated according to the chosen protocol. A protocol provides for the elicitation of opinions, analysis and aggregation, the revision of those opinions, and the development of a consensus when one is needed. Experts need to be identified and relevant evidence shared. Formal elicitation – is the last step in the process. It is a normal process to conduct a facilitator/expert(s) discussion to refine the issues. The experts define the scope of the problem, clarify terminology, and clarify all contextual matters that will influence their ability to render judgment. Significant elicitations may include the calibration of experts. The best processes may include a peer review.

7.6.5 Outputs

The outputs of the process include the expressed consensus, judgment or degree of belief expressed qualitatively or, at times, quantitatively (typically probabilistically).

7.6.6 Strengths and Weaknesses

Strengths:

- Can provide carefully considered and fully described views of highly respected experts affiliated with diverse institutions and perspectives (such cross-institutional viewpoints may be preferable to relying on the views of an in-house expert)
- Can bound uncertainty and provide estimates of critical missing data and information
- Useful for addressing emerging science challenges and scientific controversies including such technical issues as model selection or use and data selection or use
- Deliberation by a group of experts can help render complex problems tractable

Weaknesses:

- Difficult to find informed experts
- Experts are not always well calibrated
- Problems can arise in combining expert judgments when consensus is not reached
- Potential for biased and imprecise estimates

7.6.7 Examples of Use

Experts are not always well calibrated . A well-calibrated expert is an individual that can consistently produce an estimate that is in agreement with the corresponding true value. Poorly calibrate experts occurs for a wide variety of commonly recognized reasons. Primary among these reasons are the heuristics people use to think about probabilistic information. In the case of qualitative elicitations, problems frequently arise because the same words can mean very different things to different people. The same words can also mean very different things to the same person in different contexts.

Figure 7.1 illustrates another potential weakness of this process. Because expert elicitations are based on subjective judgment, there is a concern that they may be considered arbitrary. Biased and imprecise estimates are limited in the information they shed (due to their spread) and are more likely to miss the true value within the estimated bounds of uncertainty. Biased and precise estimates are most likely to miss the true value in an interval estimate. Unbiased and precise estimates are most informative and have a significant probability of capturing the true value. Unbiased and imprecise estimates are most likely to capture the true value but they have less useful information content because of the spread.

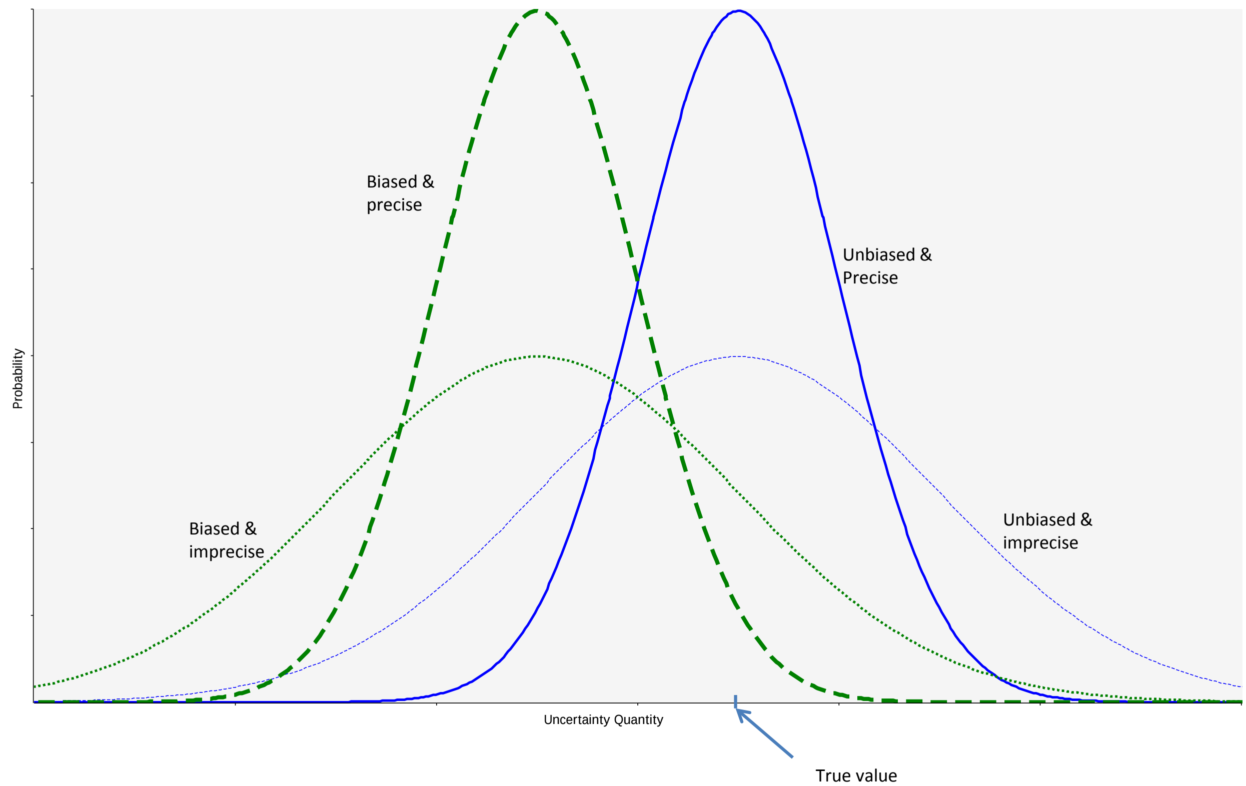

Figure 7.1: Probability distributions representing bias and precision possibilities for expert elicitations

For additional information on expert elicitations see the U.S. Environmental Protection Agency Draft Expert Elicitation Task Force White Paper (http://www.epa.gov/osa/pdfs/elicitation/Expert_Elicitation_White_Paper-January_06_2009.pdf accessed October 21, 2011), A Practical Guide on Conducting Expert-Opinion Elicitation of Probabilities and Consequences for Corps Facilities (http://www.iwr.usace.army.mil/docs/iwrreports/01-R-01.pdf accessed October 21, 2011), or O'Hagan et al. (2009).

7.7 Increase or Decrease Risk

7.7.1 Overview of the Technique

The simplest way to assess the effect of any change in conditions on an identified risk is to consider the available evidence and judge whether the risk has increased, decreased or remained unchanged.

7.7.2 How the Technique Is Used

For some simple decision problems it may be enough to know if things are getting more or less risky. What has the storm done to the dunes along the coast? How has the towboat affected lock operation after hitting the lock gates? How has the root network affected the levee's slope stability? Being able to say the risk has increased or decreased and to present the evidence or rationale for why we think so may be the simplest form of a qualitative risk assessment. This is not a technique used to evaluate changes in risk conditions. It is not a technique used to identify risks.

7.7.3 Inputs

The inputs include:

- An identified risk,
- A clearly identified change in conditions that could affect the risks, and
- A judgment of the effect of each changed condition as well as the evidence that judgment is based upon.

7.7.4 Process

Given a risk and a change in conditions, the task is to determine whether we now have more or less risk than we had before. It is helpful to use the "risk = Probability x Consequence" definition to do this. Think separately about the probability and consequence of the risk. What has happened to make the risk more or less likely to occur as a result of the changed condition? What evidence do you rely on to make that judgment? What uncertainty makes you unsure of your judgment? What has happened to make the consequences of the risk more or less severe? Again, marshal the supporting evidence and the most significant uncertainty. Assess the effects of each change in conditions and then consider the overall effects of all the changes in conditions on the identified risk. If you have reasons and evidence to support the notion that a risk is more likely to occur and the consequences may be more severe, it is easy to conclude the situation is more risky. Take care to identify the elements of your judgment that are uncertain.

7.7.5 Outputs

The outputs of this technique include:

- Enumerated changes associated with an identified risk,
- The effects of these changes on the risk,
- Identification of key remaining uncertainties, and, when possible,
- An overall assessment of all changed conditions on the risk.

7.7.6 Strengths and Weaknesses

Strengths:

- Evidence based
- Easy to apply

- Provides an initial characterization of an identified risk

Weaknesses:

- Not good for netting out changes in risk factors
- Substantial uncertainty usually accompanies characterization of risks

When some circumstances tend to increase a risk while others tend to decrease a risk, this technique will be of little value. When the impacts of events are cumulatively aligned, this technique can be a useful simple tool. Simply identifying the direction of change in a risk and the specific reasons for that change can be a positive step forward. The evidence and rationale that support the judgments made are the most critical parts of this method.

This method is useful for assessing changes in risk in the immediate aftermath of a change while uncertainty is greatest. It provides analysts with an opportunity to identify relevant risks and the likely changes in those risks while highlighting the critical uncertainties.

7.7.7 Examples of Use

This is a technique that may be immediately valuable in post-event assessments. If a tow boat has hit the gates of a lock, there are several risks that are immediately obvious including such things as loss of pool, interruption of navigation traffic, and costly gate repairs. It may be possible to assess each of these situations based on what was observed during the incident. Identifying critical uncertainties, like conditions beneath the low water line, help to identify the most fruitful first steps to further reduce uncertainty.

7.8 Risk Narratives

7.8.1 Overview of the Technique

A risk narrative is a simple story that characterizes and describes an identified risk. It includes a narrative description of each of the four generic risk assessment steps: identify hazard or opportunity, consequence assessment, likelihood assessment and risk characterization.

7.8.2 How the Technique Is Used

A simple narrative uses the available evidence to answer the following questions about an identified risk. What can go wrong? How can it happen? What are the consequences if it happens? How likely are the consequences to occur? A risk narrative answers these questions honestly and directly. Answering these four questions is a useful organizing technique. A narrative describes the risky situation and supports the description with the facts that are available while honestly communicating what remains uncertain. Think of this narrative as a risk hypothesis.

7.8.3 Inputs

The inputs to a risk narrative are answers to the four informal risk assessment questions arranged in an effective story form. The questions are:

- What can go wrong?
- How can it happen?
- What are the consequences if it happens?
- How likely are the consequences to occur?

7.8.4 Process

The best narratives tell the story of the whole of the risk. When appropriate, tell the risk story, the risk reduction story and describe the effectiveness of the risk management options. Then tell the story of the residual, transferred or transformed risks. In quantitative risk assessments a risk narrative should accompany every risk estimate. In qualitative risk assessment the narrative may provide all that is needed for a risk management decision. Risk narratives are robust and flexible tools that can be used for any of the risk assessment tasks.

7.8.5 Outputs

The outputs include:

- A qualitative assessment of the risk evident in the nature of the narrative description.

7.8.6 Strengths and Weaknesses

Strengths:

- A description of the risk as complete as possible given the available evidence;
- An accounting of the available evidence;
- A risk hypothesis that identifies the remaining uncertainty.

Weaknesses:

- Incomplete risk hypotheses when uncertainty is great
- Can discourage more complete quantitative risk assessments by appearing more complete than is true.

7.8.7 Examples of Use

Risk narratives are suitable as a first-step risk assessment in many situations. They can provide sufficient information for decision making and this makes them a valuable component of any risk profiling effort. A risk narrative is applicable to any stage of the risk assessment process and to any kind of risk. It is a versatile but limited tool.

7.9 Evidence Mapping

7.9.1 Overview of the Technique

Evidence maps have been proposed by Schütz et al. (2008) as a tool for summarizing the scientific data about a potential hazard. The method has been used primarily in situations when the evidence is unclear on the existence of a hazard or not. For example: *Is sea level change a hazard for a specific project or not? Does woody vegetation on levees weaken or strengthen the levee?* The notion can be readily extended to opportunity risks. *Will channel deepening result in a net increase in cargo?* Evidence maps summarize the information available on these uncertain issues in an easily accessible form.

7.8.2 How the Technique Is Used

Summarizing scientific evidence is a fundamental purpose of risk assessment. Evidence maps are useful when the data are incomplete, inconsistent or even contradictory on significant matters of uncertainty. Evidence maps are useful in these situations because they help assessors summarize what is certain about hazards, what is uncertain and why. The maps have been used most predominantly to help determine whether a situation represents a hazard or not. However, the technique can be readily adapted to other uncertain situations.

7.8.3 Inputs

The essential elements of an evidence map process are:

- A well-defined decision problem (usually a potential hazard),
- The evidence basis (i.e., the number and quality of relevant scientific studies),
- A panel of experts to review the evidence,
- The pro- and con-arguments for the existence of a hazard with supporting and attenuating arguments, and
- The conclusions about the existence of a hazard with remaining uncertainties identified.

7.9.4 Process

Figure 7.2 shows the template for an evidence map. Sponsors of the evidence map assemble the relevant studies from the available literature that are suitable for a risk evaluation with input from the expert panel. The experts then extract the arguments for a hazard or risk (pro-argument) and the arguments against a hazard or risk (contra-argument). They carefully document evidence that attenuates or supports these arguments and then draw some tentative conclusions about the hazard or risk while carefully noting the uncertainties that still attend the issue.

7.9.5 Outputs

The process output is a map of the pro- and con- arguments along with the remaining uncertainties. The summaries are entered into a single-page template like that shown in the figure. The map and its accompanying summary document summarize what is and is not known about a hazard, risk or other topic being mapped.

7.9.6 Strengths and Weaknesses

Strengths:

- Summarizes the current state of the scientific evidence
- Provides an unbiased summary of what is and is not known about the issue
- Presents evidence-based arguments for all sides of an issue and notes evidence that either attenuates an argument or supports it
- Well-suited to situations where contradictory views on an issue exist

Weaknesses:

- Cannot be applied unless a reasonable evidence base exists.

7.9.7 Examples of Use

For more information on evidence maps, see Schütz, et al. (2008).

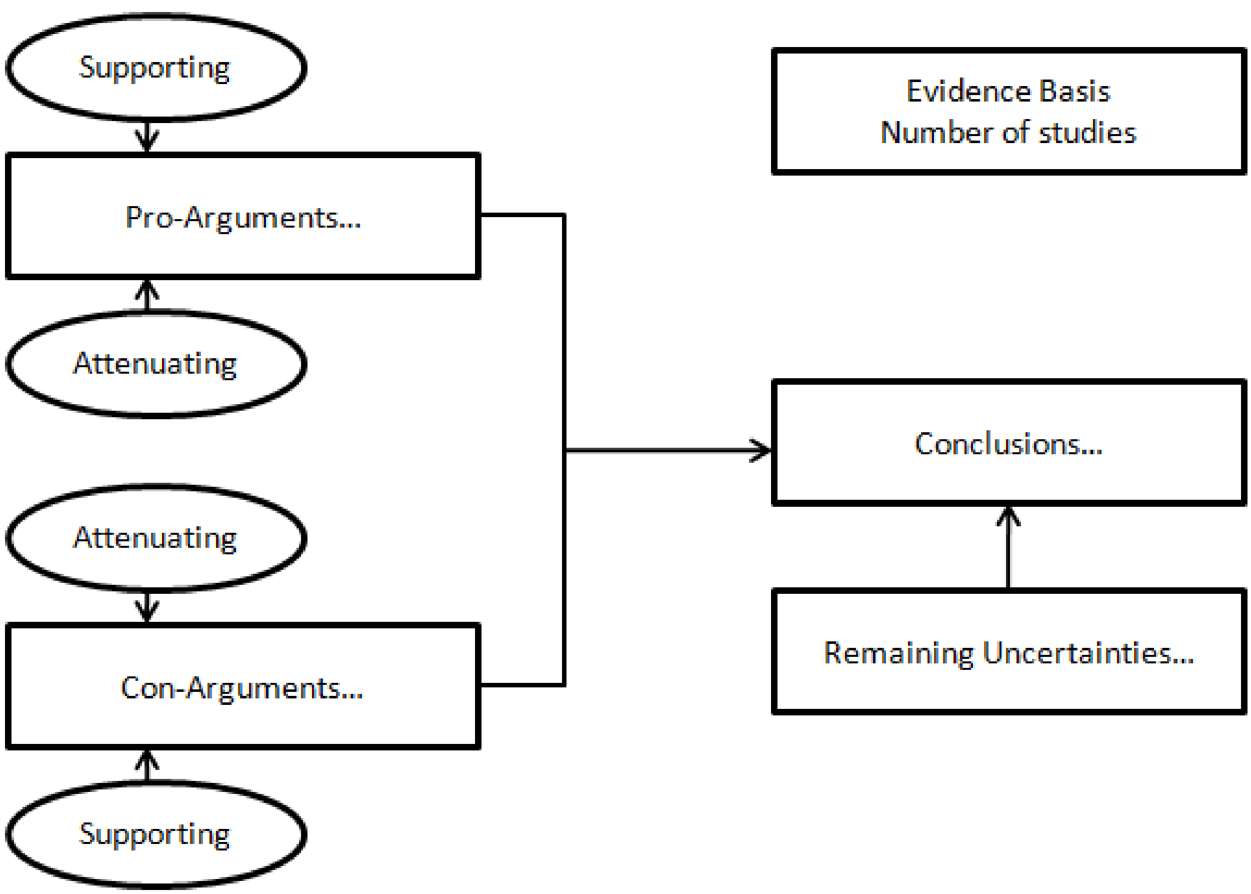

Figure 7.2: Template of the Schütz, Wiedemann, and Spangenberg evidence map

7.10 Screening

7.10.1 Overview of the Technique

Screening, or sorting, is the process of separating elements into one or more categories of interest through a systematic evidence-based process.

7.10.2 How the Technique Is Used

Usually there are two screening categories which are some versions of "in" or "out." Screening criteria can be chosen to either screen items onto the short list of interest (in) or to screen items off of the long list (out). Screening can be used to identify hazards of potential concern or of no concern. For example, screening techniques can be used to say which concrete monoliths, rumble mound jetties or tainter gates are of potential concern. O&M projects can be screened for funding this year or not. It is the tool to use to create collections of things. It is not the tool to use to find the best item among the collections.

Things that can be screened, rated or ranked

The sorting techniques discussed in this section on screening are useful anytime analysts need to reduce a long list of things to a shorter list of things. This is often done when the need for action exceeds the resources available for taking action and decision makers have to make risk-based choices. Rating and ranking have the additional benefit of sorting the things into ever finer categories. Sorting can be used to assess potential hazards (ANS of potential concern, stone rubble breakwaters in most need of repair), risks (risk of non-federal levees overtopping, pump motors failing, tainter gates not operating), risk management options (final array of alternative plans, O&M strategies, technology to use to control ANS, budget strategies), or virtually any other set of "things."

7.10.3 Inputs

Inputs for screening include:

- Items to be screened,
- Carefully defined categories ,
- Evidence-based criteria to use for separating items into categories,
- Evidence, and
- A synthesis algorithm for using measurements and criteria to separate a long list of items into discrete and separate categories of items.

7.10.4 Process

Given a list of items to be screened and categories, measurements of the screening criteria are obtained for each item to be screened. If there is more than one criterion, an algorithm for considering the evidence and sorting the items is needed. The domination procedure requires an item to be better or worse over all criteria than all other items. This could be used to separate the best or worst from the rest of a population of items. A conjunctive procedure requires an item to meet all predetermined criteria thresholds for inclusion in a category. A disjunctive procedure requires an item to meet at least one criterion threshold to pass on to the category of interest.

Elimination by aspects begins by identifying the most important criterion from your set of criteria. A cut-off value is then set for it. All items that do not meet the cut-off value are eliminated or screened out. You next identify the next most important criterion, set a cut off for it and eliminate all items that do not meet it. This process continues until you have the desired subset of screened in items.

7.10.5 Outputs

The output of a screening process is a list of elements that has been successfully sorted into the mutually exclusive and collectively exhaustive categories of interest.

7.10.6 Strengths and Weaknesses

Strengths:

- Reliance on evidence
- Ease of documentation

Weaknesses:

- Items in categories cannot be differentiated from one another
- Only the categories are differentiated

7.11 Ratings

7.11.1 Overview of the Technique

Rating is an activity that individually scores or rates each item of interest to the decision maker. It systematically separates elements into multiple categories of varying degrees of interest.

7.11.2 How the Technique Is Used

Items with like ratings are gathered into like groups where the groups usually, but not always, have an ordinal logic to them. The National Dam Safety Program's dam safety action classes (DSAC) I through V provide a handy example of a rating system. Ratings can be used for a wide variety of risk elements. For example, hazards may be rated high, medium or low. Probabilities of risks may be rated from rare to common. Consequences could range from negligible to catastrophic.

7.11.3 Inputs

The inputs for a rating system are essentially the same as those for a screening system, they include:

- Items to be rated,

- Carefully defined rating categories,
- Evidence-based criteria to use for rating,
- Evidence, and
- A synthesis algorithm for rating the items.

7.11.4 Process

The ratings process is to compile the list of elements to be rated, and then carefully define the rating categories. This means more than simply saying items will be rated high, medium or low. It means objectively defining the criteria for rating an item high, medium or low. This, of course, requires analysts to identify the evidence-based criteria that will be used in the rating. This is a critical step. If the rating of high, medium or low cannot be determined on the basis of objective evidence, then the rating system will be of limited utility in risk assessment. Once the criteria are established, objective measurement of each criterion is estimated for each item. These measurements are combined via a synthesis algorithm and an overall rating is assigned. An example of an algorithm is found in Appendix A.

7.11.5 Outputs

The output is a rating for each item in the list of things to be rated.

7.11. 6 Strengths and Weaknesses

Strengths:

- Flexibility,
- Evidence-based,
- Reproducibility,
- Finer degree of discernment than a simple screening provides

Weaknesses:

- Process is sometimes abused
- Ratings are assigned subjectively without tying the rating explicitly to any objective evidence

7.12 Rankings

7.12.1 Overview of the Technique

Ranking distinguishes differences among individual items and assigns a position to one thing relative to other things.

7.12.2 How the Technique Is Used

It is a systematic process used to put items in an ordinal sequence when used in a qualitative setting. Ranking can also be a cardinal or scalar ranking when data are available. Ranking requires essentially the same elements as a screening or rating process, but it may also include weighting the importance of the various criteria. Ranking is a simple process when objective criteria measures are available. A ranking process is described in detail in Appendix A.

7.13 Risk Indices

7.13.1 Overview of the Technique

A risk index is a semi-quantitative measure of risk. The riskiness of an event or situation is represented by a number generated using a scoring approach that relies on ordinal scales. Risk indices are used to compare and rate a set of risks using similar criteria. A risk is broken down into a small number of components (e.g., probability and consequence; hazard, exposure and consequence; contaminant characteristics (sources), range of possible exposure pathways, impact on the receptors). Scores are applied to each component of the risk and aggregated to an overall risk score that, though numeric, is qualitative in nature.

7.13.2 How the Technique Is Used

Indices are used as a scoping or priority-setting device for many different types of risk. They are used to identify risks that require a more detailed, and possibly quantitative, assessment. When based on evidence and validated, indices are useful as a comparative tool as long as the underlying models are understood.

7.13.3 Inputs

The inputs for a risk index are derived from the system, situation or set of risks under study. A good understanding of the sources of risk, the possible pathways and the range of consequences is needed. Because the choice of ordinal scales for the index is arbitrary, sufficient evidence is required to validate the index. It is neither sufficient nor acceptable to simply assign a number to a risk or a risk component.

7.13.4 Process

Step one when using a risk index is to understand and describe the system or set of risks of interest. When the system is defined, the components of the system or the set of risks can be developed in a way that provides a composite index. For an ecological risk, for example, the index components might include sources, pathways and receptor(s) to be scored. A navigation example might have hazard, exposure and consequence components.

Suppose the interest is identifying the riskiest locations in a waterway segment, where the risk is defined as a marine casualty (i.e., a grounding, allision or collision). An index can be defined using the following underlying risk model:

Risk index = Probability the hazard is present x Probability the asset(s) at risk come in contact with the hazard x the adverse results of an exposure

The ordinal scales might look like those below. Let’s define the hazard as other vessels. The probability the hazard is present:

1 = very unlikely (once a year)
2 = unlikely (once a month)
3 = likely (weekly)
4 = very likely (daily)
5 = inevitable (several times a day)

Let the probability the asset(s) at risk comes in contact with the hazard be defined as:

1 = rare/never
2 = infrequent (monthly)
3 = frequent (weekly)
4 = high (daily)
5 = constant

The consequences or adverse results of an exposure may be defined as:

1 = minor damage to vessels
2 = serious damage to vessels
3 = major damage to vessels
4 = multiple casualties or serious environmental damage
5 = at least one fatality or major environmental damage

Each location on the waterway is rated for each component based on the available evidence. Thus, the number assigned to the component is not as important as the evidence upon which that numerical judgment is based. The individual scores are combined multiplicatively. The maximum risk index is 125. A subjective judgmental interval scale may be defined as follows:

High Risk >=75: top priority, action is required now
Medium Risk >=27 and <75: deal with this risk over the next few weeks/months
Low Risk <27: deal with this risk if attention is warranted

The scores must be internally consistent and relative. Scores may be added, subtracted, multiplied and/or divided according to the high-level model adopted at the outset of the exercise. Cumulative effects can be taken into account by adding scores. For example, scores can be added for multiple locations on a waterway segment in order to compare the relative risks of waterway segments. Remember, it is not valid to apply mathematical formulae to ordinal scales.

A location with an index of 75 is not 50% worse than one with an index of 50. All we can say is that a 75 indicates a greater risk than a 50. Uncertainty can be addressed by sensitivity analysis. Scores can be varied or even entered as a range to reflect uncertainty.

7.13.5 Outputs

The output of the risk index technique is a series of indices that establish the relative order of a set of risks. Risk indices, though numerical, are essentially a qualitative approach. Numerical indicators of qualitative risks are called semi-quantitative risks.

7.13.2 Strengths and Weaknesses

Strengths:

- a good scoping tool for ranking different risks associated with a similar problem, activity or location
- allow for multiple evidence-based components that affect the level of risk

Weaknesses:

- The results may be meaningless if the process and its output are not evidence based
- Numerical values for risk may be misinterpreted
- Numerical values used to compile the risks are likely to lack consistency if not defined.

7.13.7 Examples of Use

Risk indices are used primarily for risk ranking, a component of risk evaluation.

7.14 Operational Risk Management (Risk Matrix)

7.14.1 Overview of the Technique

The risk matrix, sometimes known as operational risk management (ORM), is another qualitative technique based on the simple equation, "Risk = Probability x Consequence." It is often used as a screening/rating tool to identify which risks need more detailed analysis or need to be treated first.

7.14.2 How the Technique Is Used

The probability dimension of a risk forms one dimension of the matrix and is broken into qualitative segments or categories. Although the segments could be defined quantitatively, they are usually not. Categories like improbable, remote, occasional, probable and frequent (USDOD, 2003) are used and they are usually defined in a narrative manner. When constructing the probability scale, remember that the lowest likelihood should be acceptable for the highest defined consequence, otherwise all elements with the highest consequence may be identified as unacceptable and the matrix will fail to discern among the many elements. Likewise, the continuum of consequences is broken into a number of qualitative categories such as negligible, marginal, critical and catastrophic. These categories should extend from the maximum credible consequence to the lowest consequence that is of concern. The categories comprise the other dimension of the matrix. It is usual to identify three to five categories for each risk dimension, although the scale may have any number of categories. Definitions for probability and consequence categories need to be as clear and unambiguous as possible. A sample is shown in Figure 7.3.

	Improbable	Remote	Occasional	Probable	Frequent
None					
Negligible					
Marginal					
Critical					
Catastrophic					

Figure 7.3: Blank sample risk matrix

When the probability and consequence categories are given evidence-based narrative or quantitative definitions, it is possible to examine the evidence and assess the risk of a list of items based on the available evidence. For example, the risk of levee failure can be assessed for a list of non-federal levees. Each levee would be slotted into the matrix cell based on the definitions of the probability and consequence categories and the available evidence for an individual levee.

7.14.3 Inputs

This technique requires a well-defined risk to be assessed (i.e., a specific question to answer) and the following:

- A list of items to assess,
- Carefully constructed evidence-based definitions of a limited number of probability categories,
- Carefully constructed evidence-based definitions of a limited number of consequence categories, and
- Evidence for categorizing each item by probability and consequence.

7.14.4 Process

The process is critical to this technique. Carefully defining sets of mutually exclusive and collectively exhaustive evidence-based probability and consequence categories is the most critical aspect of this process. Then, gathering evidence to support the rating for the probability and consequence of each potential risk becomes the basis for this evidence-based assessment technique. It is common practice to begin by selecting the consequence category that best fits the situation, then identifying the likelihood with which those consequences will occur.

7.14.5 Outputs

The output of this process is a list of potential risk items, each of which has a probability and consequence rating that has been documented on the basis of the available evidence.

Every item on the list of risks to be assessed will have been placed in one of the cells of the risk matrix. Usually the cells are grouped into subjective ordinal clusters of cells. Imagine the 25 cells above being coded red, yellow or green, where red indicates an unacceptable risk, yellow identifies items to be carefully monitored and green indicates items of no immediate concern. That is one potential output of this process.

The Department of Defense has also attempted to number the cells from least to most risk and then assigned risk management decision-making authority based on the level of risk. Low levels of risk are handled at the lower end of the decision chain and the greatest risk decisions are made by upper management.

7.14.6 Strengths and Weaknesses

Strengths:

- Systematically addresses both the consequences of a potential risk and its probability of occurring based on the available evidence
- Technique is easy to explain and understand
- If uncertainty or confidence ratings accompany the analysis it is possible to convey the remaining levels of uncertainty

Weaknesses:

- One of the most easily abused risk assessment tools
- Use is subjective
- Ratings can vary among raters
- Ratings of consequence and probability are often assigned arbitrarily and without direct regard for the available evidence

7.14.7 Examples of Use

Consider a hypothetical case where the risk matrix is used to establish budget priorities. If items with frequent and catastrophic consequences are the items most likely to be funded, then the “winning strategy” may become assigning the highest possible rating to each potential budget item rather than objectively assessing the evidence. This destroys the value of the technique and the integrity of the decision-making process and produces junk analysis along the way.

A second common abuse is to define subjective clusters of cells to different categories of risk such as high, medium and low. The abuse begins when the clusters are defined arbitrarily and in ignorance of or disregard for the desirable properties of the clusters.

Appendix B provides an example of a risk matrix and additional discussion of these issues.

7.15 Develop a Generic Process

7.15.1 Overview of the Technique

A generic process begins with the familiar conceptual model, “Risk = Probability x Consequence.” Each of these two factors are individually decomposed into the critical elements that explain the probability and the consequence for a specific risk issue. The elements that that comprise it. The probability may be multiplicative when a series of independent elements must all be present for a non-zero probability of the risk to exist, or they could be additive when they represent separate exposures or pathways. The elements of the consequences tend to be additive (±) if multiple consequences are relevant.

7.15.2 How the Technique Is Used

This technique is one of the most flexible techniques and it can be adapted to a wide variety of uses. The Great Lakes and Mississippi Rivers Interbasin Study (GLMRIS) identified in excess of 200 aquatic nuisance species (ANS). To identify which of these species of concern represents an unacceptable risk of establishment of a non-indigenous aquatic species, a generic process was used. This process is described in Appendix C. A generic process is best suited to risks that are routine in the sense of being numerous and repetitive. A generic process, once developed, can be used repeatedly to qualitatively assess the level of risk based on consideration of both the probability and the consequences associated with a potential risk.

7.15.3 Inputs

The inputs to this process include the well-defined decision problem that identifies a specific question to answer and a systematic method to decompose a potential risk into the key probability elements and the most critical consequence elements. Each element identified in this manner will be rated qualitatively. Evidence to support the qualitative ratings for each element is also needed. An algorithm for synthesizing the element ratings into an overall probability rating, an overall consequence rating and, ultimately, an overall risk potential rating is also required.

7.15.4 Process

The process is best explained with an example. Imagine a process that could be used to estimate the risk potential of hundreds of ANS becoming established in a new waterway. The basic risk of establishment of an ANS is represented as:

$Risk = P_{establishment} \times C_{establishment}$

Furthermore, the probability an ANS is established in a new waterway is given by:

$P_{establishment} = P_{arrive} \times P_{survive} \times P_{colonize} \times P_{spread}$

Where P_{arrive} is the probability an ANS arrives via a pathway; $P_{survive}$ is the probability it survives in its new environment once it gets there; $P_{colonize}$ is the probability it establishes a reproducing colony; and P_{spread} is the probability it is capable of spreading throughout the new basin from its colony in this new environment. The relationship is multiplicative because if any one of those probabilities is zero then the overall probability of establishment is zero and there is no risk.

The consequence elements for ANS establishment might be as follows:

$C_{establishment} = C_{economic} + C_{environmental} + C_{other}$

Consequences can be economic, environmental or other. They are considered additive because even if one kind of consequence is absent others may be present.

High, medium, low and no risk scenarios are defined clearly and unambiguously for each of the seven elements in the example above. Using available facts and evidence, each of these seven elements is then rated a high, medium, low or no risk. The rating is based on the definition and is supported by the available evidence. An uncertainty rating can accompany each element rating. For example, assessors could rate the uncertainty for each of their seven element ratings from very uncertain to very certain.

The element ratings are aggregated up into an overall probability and an overall consequence of establishment. These two ratings are then used to develop a risk potential rating for the organism of concern. Appendix C provides an example of this process.

7.15.5 Outputs

The outputs of this process include individual risk ratings for each of the x elements identified in the generic process (there were seven elements in this example), an overall risk rating (in this example, a rating for the ANS), an uncertainty rating for each risk element and the overall risk rating, and the ability to combine individual risk ratings to develop pathway ratings. For the given example there could be multiple ANS risk ratings for any given aquatic pathway, and these could be combined to develop an overall risk for the pathway.

7.15.6 Strengths and Weaknesses

Strengths:

- Comprehensive
- Can be applied to a wide variety of situations
- Almost any risk can be decomposed into a reasonable number of probability and consequence elements
- Logically sound when key elements are identified and the process is supported by evidence
- Can be performed with varying levels of resources and degrees of uncertainty
- Conducive to learning
- Repeated applications of a generic model result in a better understanding of the problems and their potential solutions
- Easily documented and readily open to evaluation

Weaknesses:

- Once developed there may be a tendency to rely on this qualitative method when a quantitative assessment is possible

7.15.7 Examples of Use

For more on the generic process see Yoe (2012).

7.16 Semi-Quantitative and Qualitative Assessment Models

7.16.1 Overview of the Technique

Semi-Quantitative and Qualitative Assessment modeling techniques are actually a variation on the generic process model. Qualitative methods that make limited use of numerical estimates of risk are sometimes called semi-quantitative assessments. Instead of using qualitative ratings, the technique produces semi-quantitative estimates of risk that require careful interpretation.

7.16.6 Strengths and Weaknesses

Strengths:

- Index number results support a finer level of discernment and differentiation of the risks

Weaknesses:

- Genesis of the semi-quantitative values is poorly understood and the index numbers are often accorded more credibility than they deserve

7.16.7 Examples of Use

Consider a conceptual example focused on levee safety. The input to this process includes a risk question to be answered, a levee inventory (i.e., a list of things to assess) and a generic model that uses an algorithm that converts qualitative judgments to numerical estimates. With thousands of levees to consider it may be useful to first screen the levees using a semi-quantitative method. As usual, a well-defined problem and a specific question or two are needed. Let us suppose the questions are: Which non-federal levees present the greatest potential risk to life and property? Which levees should be the first to be subjected to a complete technical risk assessment?

Using the "Risk = Probability x Consequence" model as our starting point, the challenge is to identify criteria that aid assessment of the probability of an unsatisfactory performance as well as an assessment of the consequences. Suppose the criteria and potential scenarios (or ratings) developed for this purpose are the following:

A. How old is the levee?

1. Unknown
2. 10 years or under
3. Over 10 and up to 25 years
4. Over 25 and up to 50 years

B. Who owns the levee?

1. Unknown
2. More than one owner
3. Private levee

4. State or local ownership
5. Federal ownership

C. How well is it maintained?

1. Unknown
2. Regular maintenance by known authority
3. Periodic maintenance by known authority
4. Irregular maintenance
5. No maintenance

D. Construction quality?

1. Unknown
2. State-of-the-art engineering design and construction
3. Standard engineering design and construction
4. Substandard design and construction

E. Number of flows confined in the last ten years?

1. Unknown
2. None
3. One
4. Two or more

F. Any known problems?

1. Unknown
2. Yes
3. No

These criteria capture the essence of the probability element.

To capture the consequence the following criteria are considered:

G. How vulnerable is the population?

1. Unknown
2. Highly vulnerable (low income, elderly, low education, minority)
3. Moderately vulnerable (housing close to levee, much housing in flood plain)
4. Low vulnerability (housing removed from the levee, less housing in flood plain)

H. How large is the population at risk?

1. Unknown
2. Less than 1,000

3. 1,000 to 10,000
4. 10,000 to 100,000
5. 100,000 to 1,000,000
6. Over 1,000,000

Evidence is gathered to rate each levee against each criterion. The selected answer for each criterion is converted to an order of magnitude.[19] The "riskiest" response is rated a 1, the second riskiest 0.1, the third riskiest 0.01, etc. An unknown entry is rated a 0. The product of all eight entries is calculated. The range between the largest and smallest possible products is normalized over the [0,100] interval. The calculated product is interpolated from this range and the normalized value is the levee's rating.

For example, consider the hypothetical levees in Table 7.1. This is a semi-quantitative method. Although the rating is numerical it remains qualitative in information content. The numerical ratings have only ordinal level information content.

A	B	C	D	E	F	G	H	RISK SCORE
2	3	3	4	3	2	3	4	45
5	4	2	2	4	3	4	4	35
5	2	5	4	4	2	2	2	75

Table 7.1: Semi-quantitative risk scores for three hypothetical levees

All the levees in the region are assessed and their semi-quantitative ratings enable assessors to answer the risk manager's questions. The levees with the highest numerical ratings have the greatest risk potential. It is understood that this assessment proceeds under conditions of considerable uncertainty. When the very rudimentary data of this tool are not available it is acknowledged that the levee cannot even be ranked. Presumably such an assessment would highlight the need for additional data at some sites, while enabling risk managers to identify those levees that should be subjected to a more rigorous technical risk assessment first.

7.17 Hazard Analysis and Critical Control Points (HACCP)

7.17.1 Overview of the Technique

Hazard Analysis and Critical Control Points (HACCP) is a risk management tool that incorporates risk assessment practices. The Pillsbury Corporation and NASA developed the HACCP control system in the 1960s to ensure food safety for the first manned space missions. A HACCP plan provides a structure for identifying hazards in a process and putting controls in place at critical control points to protect against the hazards and to maintain the quality, reliability and safety

[19] The algorithm described here is not critically important. Any number of algorithms could be used to produce an index number. Do not be concerned if you find insufficient detail to reproduce the method.

of the system's outputs. HACCP seeks to minimize risks by controlling the process rather than by end product inspection.

7.17.2 How the Technique Is Used

HACCP plans are used primarily by food companies to ensure food safety. It is used anywhere within the food chain to control risks from physical, chemical or biological contaminants of food. HACCP operates on the principle of identifying things that can influence system output quality and identifying points in the process where critical parameters can be monitored so that these hazards can be controlled. This is a principle that can be generalized to other technical systems.

7.17.3 Inputs

HACCP begins with a flow or process diagram that reveals the system or process of interest. An example for a fish stocking exercise is shown in Figure 7.4. Potential hazards that can affect the quality, safety or reliability of the system output or process need to be identified. Information about these hazards, their risks and the ways in which they can be controlled are also inputs to a HACCP plan.

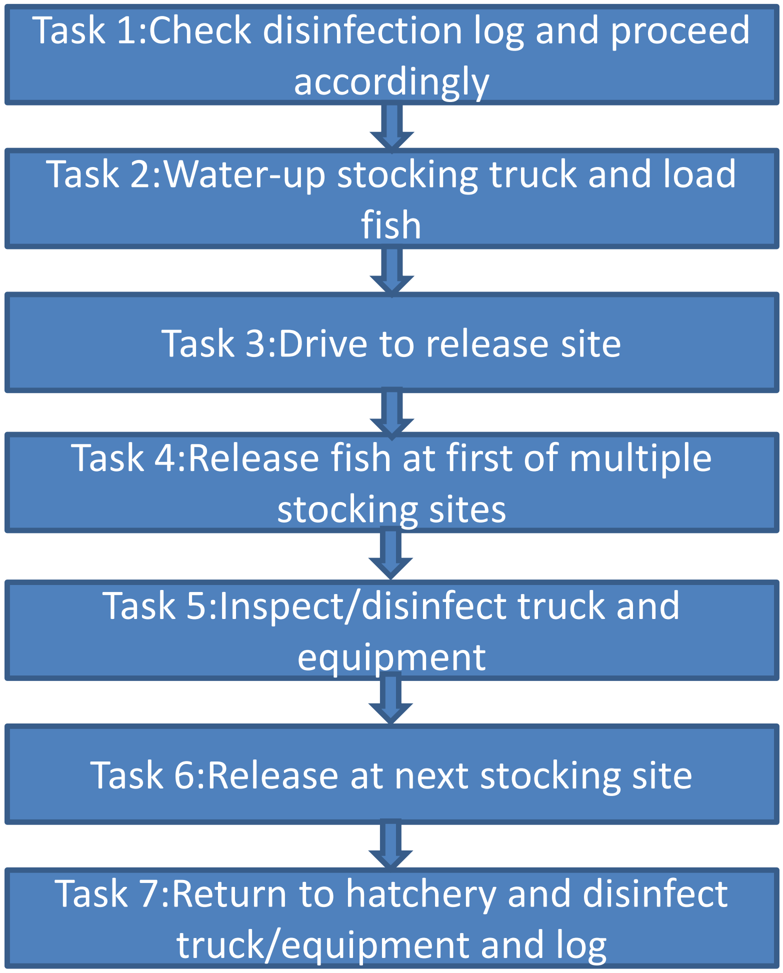

Figure 7.4: HACCP process diagram for a hypothetical fish stocking exercise[20]

7.17.4 Process

A HACCP plan is based on the following seven steps:

1) Conduct a hazard analysis that identifies hazards and ways to prevent them. The hazards for the fish stocking example include vertebrates, invertebrates, plants and other biologics that could be moved or introduced during the stocking operation.

2) Identify critical control points so that hazards are prevented, eliminated or reduced to an acceptable level. *Tasks 1, 5, and 7 in Figure 7.4 are critical control points for this process.*

3) Establish critical limits for each critical control point, so each critical control point can be operated within maximum or minimum parameters to ensure the hazard is controlled;

[20] This diagram is adapted from a fish stocking HACCP plan for Fort Richardson found at http://haccp-nrm.org/Plans/AK/haccpstocking-1.pdf accessed December 28, 2012.

4) Monitor the critical limits for each critical control point at defined intervals;

5) Establish corrective actions to be taken when monitoring indicates a deviation from an established critical limit;

6) Implement record keeping and documentation procedures for each corrective action;

7) Establish procedures for verifying the HACCP system is working as intended; this v*alidation* is to ensure the plan does what it was designed to do and verification is to ensure is working as intended.

Figure 7.5 shows part of a hazard analysis worksheet. A complete worksheet would address each task in the HACCP process diagram. Figure 7.6 show steps 3 through 7 can be followed.

1 Tasks from HACCP Flow Diagram	2 Potential hazards identified in HACCP step 2	3 Are any potential hazards significant?	4 Justify evaluation for column 3.	5 What control measures can be applied to prevent undesirable effects?	6 Is this task a CCP?
Task 1:Check disinfection log and proceed accordingly	Vertebrates	yes	Disinfection was necessary	Check log and verify disinfection	yes
	Invertebrates	yes	“	“	
	Plants	yes	“	“	
	Other biologics	yes	“	“	

Figure 7.5: Hazard analysis worksheet

			Monitoring					
CCP	Significant Hazard(s)	Limits for each control measure	What	How	Frequency	Who	Evaluation & corrective action(s)	Supporting documentation
Check logs inspect/ disinfect	Potential contamination of invasive species	Check inspect	Disinfection	Log	Between sites and hatchery	Driver	Loss of fish stocking privileges	Disinfection log

Figure 7.6: HACCP work plan

7.17.5 Outputs

The outputs of a HACCP process include:

- a process diagram,

- a hazard analysis worksheet, and
- a HACCP plan.

The hazard analysis worksheet lists the hazards that could be introduced, exacerbated, or controlled at each step in the process. The worksheet also identifies whether a hazard presents a significant risk and provides evidence for the judgment. Potential risk management measures are identified for each hazard. Process steps where monitoring or control measures can be applied are identified as critical control points. The HACCP plan identifies the procedures to be followed to control a specific design, product, process or procedure.

7.17.6 Strengths and Weaknesses

Strengths (IEC, 2008)

- Structured process that provides documented evidence for quality control as well as identifying and reducing risks
- Focuses on practical means of preventing and controlling hazards
- Encourages risk control throughout the process rather than relying on final product inspection
- Can identify hazards introduced through human actions a s well as means to control them at the point of introduction or subsequently

Weaknesses:

- Requires that hazards are identified and their significance understood as inputs to the process
- Requires risk definition of hazards .
- Appropriate controls need to be defined in order to specify critical control points and their control parameters.
- Action is only taken when the control parameters exceed defined limits.
- Gradual changes in the process that are statistically significant and need correction could be missed

7.17.7 Examples of Use

A HACCP plan could be developed to help assure water quality levels, for repeated physical processes like lockages, or to control processes comprising a sequence of events.

Food Safety applications of HACCP are easily found on the Internet and in ISO 22000 Food Safety Management Systems.

Natural resources examples can be found at the Planning Is Everything website, see for example http://haccp-nrm.org/listplans.asp accessed December 28, 2012.

7.18 Preliminary Hazard Analysis (PHA) [21]

7.18.1 Overview of the Technique

The objective of Preliminary Hazard Analysis (PHA) is to identify hazards and events that can cause harm for a given activity, facility or system. This technique is most useful for new systems and new technologies for which there is little information on design details or operating procedures. The aquifer storage and recovery systems planned for the restoration of the Everglades provide a good example of such a system.

7.18.2 How the Technique Is Used

PHA is not a true risk identification; it focuses only on identifying the thing or event that might cause harm. It makes little effort to estimate the probability or consequences of that harm. PHA is rarely the only attempt to assess risks but it can be a useful first attempt. It is also used to prioritize hazards for existing systems, such as identifying tainter gates in a USACE Division that are most prone to malfunction. This technique is generally used when more rigorous techniques are either not possible or not necessary.

7.18.3 Inputs

The inputs for a PHA include:

- Understanding the intended purpose of the system being assessed, and
- Consideration of appropriate details of the system design.

7.18.4 Process

The process is simple. It produces a list of hazards and potential harmful events or risks that could occur. This list is compiled by considering such design details and characteristics as:

- Materials used or produced
- Equipment employed
- Operating environment
- Layout
- Interfaces among system components
- Effects on natural systems

Part of the value of PHA is its simplicity. A PHA should be updated as design detail is increased as well as during construction, testing and operation. The emergence of new hazards and correction of identified hazards is the goal of these ongoing updates. The results of a PHA can be described in a simple narrative or in tables and trees.

[21] The information for this method is summarized from a 2009 draft of the International Standard IEC/FDIS 31010 Risk Management — Risk Assessment Techniques

7.18.5 Outputs

The output of this technique is a list of hazards or risks when they can be identified. This list is expected to lead to recommendations for accepting the potential risk, recommending control measures, creating design specifications or conducting more detailed and sophisticated risk assessments.

7.18.6 Strengths and Weaknesses

Strengths:

- Can be used when there is limited information about risks
- Early identification of potential risks

Weaknesses:

- Limited by its reliance on preliminary information
- Does not help risk managers know how to manage a risk.

7.19 Hazard Operability Study (HAZOP)[22]

7.19.1 Overview of the Technique

Hazard Operability Study (HAZOP) is the structured and systematic examination of a planned or existing product/project, process, procedure or system. Its purpose is to identify risks to people, equipment, the environment and/or organizational objectives. A good HAZOP eliminates risks when and wherever possible. It is a qualitative technique that was originally developed to analyze chemical process systems. It has since been extended to use in other systems and complex operations that include electrical and mechanical systems, complex procedures, software systems, organizational change, and even legal contract design and review.

7.19.2 How the Technique Is Used

The technique uses guide-words to question how the design intention or operating conditions may not be achieved at each step in the design, process, procedure or system. A multidisciplinary team usually conducts a HAZOP in a series of meetings. It is especially useful for identifying and dealing with deviations from a design intent due to deficiencies in the design, component(s), planned procedures or human actions. It has been widely applied to software design review. A HAZOP study is usually not done until the detail design stage when a full plan/understanding of the intended process is available but while design changes are still practical. HAZOPs can be conducted during operations but required changes can be costly.

[22] The information for this method is summarized from a 2009 draft of the International Standard IEC/FDIS 31010 Risk Management — Risk Assessment Techniques

7.19.3 Inputs

Essential inputs to a HAZOP include current information about the system, process or procedure being reviewed as well as the intention and performance specifications of the design. Specific inputs might include blueprints, drawings, specification sheets, flow sheets, process control and logic diagrams, layout drawings, operating and maintenance procedures, and emergency response procedures. For procedures and software HAZOP inputs include documents that describe the elements of the procedure and their functions.

7.19.4 Process

HAZOP reviews each part of the design and specification of the process, procedure or system to learn what deviations from the intended performance can occur. It then considers their potential causes and likely consequences. This is usually done by using guidewords to systematically examine how each part of the system, process or procedure will likely respond to changes in key parameters. Guidewords can be customized or generic words can be used that encompass all types of deviation (see textbox).

Sample Guide Words

No or not, Other than, More , Early, Less, Late, As well as, Before, Part of , After, Reverse (of intent), Other terms can be crafted as needed…

The usual steps in a HAZOP include:

- Identify team leader
- Define objectives and scope of effort
- Establishing a set of guidewords
- Convene the HAZOP with appropriate knowledge of system and requisite expertise (should not be the same as the design team)
- Collect required documentation
- Split the system, process or procedure into smaller tangible elements
- Agree on design intent for each element
- Apply guidewords one after the other to identify possible deviations which will have undesirable outcomes
- Identify the cause and consequences of each undesirable outcome
- Identify treatment to prevent undesirable outcomes from occurring or to mitigate the consequences if they do
- Document the discussion and specific actions to treat the risks

7.19.5 Outputs

The primary output is the HAZOP meeting documentation or minutes. This should include the guide words used, the deviation(s) identified, their possible causes, actions to address the identified risk, and identification of the person responsible for the action.

7.19.6 Strengths and Weaknesses

Strengths:

- Ability to systematically and thoroughly examine a system and generate solutions to identified risks while involving a multidisciplinary team
- Can be applied to a wide range of systems
- Can accommodate human error as well as system failures
- Written record of the process can demonstrate due diligence

Weaknesses:

- Time consuming and expensive
- Requires a high level of system specification
- Major modifications can be expensive or untenable if performed too late in the design process
- Process can bog down if it focuses on detailed issues of design rather than broader risk issues
- Tend to rely heavily on the expertise of designers who may lack the objectivity to see problems in their designs

7.20 Structured What-if (SWIFT)[23]

7.20.1 Overview of the Technique

Structured What-if (SWIFT) was originally designed for chemical and petrochemical plant hazard studies. It is a simpler alternative to a hazard operability study (HAZOP). Like HAZOP, it is a systematic, team-based assessment that relies on the use of a set of ”prompt” phrases to stimulate the team to identify risks. It is used to explore how a system, plant item, organization or procedure will be affected by deviations from normal operations and behavior. More specifically, SWIFT is used to examine the consequences of changes in operations and the risks that can be altered or created by these changes. This makes it a useful tool for examining changes in the way things are done. SWIFT is applied at considerably less detail than a HAZOP study.

7.20.2 How the Technique Is Used

This technique requires careful definition of the procedure, project, plant item and/or change that is being investigated. The external and internal contexts of the proposed changes or deviations are usually established through interviews and the study of documents, plans and drawings by the facilitator. Usually, the process or change is subdivided into its key elements. A successful process requires an experienced and expert study team of from 4 to 20 people .

7.20.3 Inputs

Before the study begins a suitable list of prompt words or phrases must be developed to assure a comprehensive consideration of the potential risks. As with many group processes, it is

[23] The information for this method is primarily summarized from a 2009 draft of the International Standard IEC/FDIS 31010 Risk Management — Risk Assessment Techniques

essential that all participants share a common understanding of the system or change and both its external and internal context. The workshop usually begins by asking the study team to identify and discuss each key element and:

- Known risks and hazards,
- Previous experience and incidents,
- Known and existing controls and safeguards, and
- Regulatory requirements and constraints.

7.20.4 Process

This discussion is enhanced by having a facilitator expand the questions being considered using a ”what-if” phrase and a prompt word that is related to the decision context. ”What-if” phrases include: “what if…”, “what would happen if…”, “how could…..”, “could someone or something…”, “has anyone or anything ever….” and the like. These prompts are combined with prompt words that are either prepared in advance or that arise during the course of the discussion. These prompts are intended to help the team explore the causes, consequences and likelihoods of potential risk scenarios. Risks identified in this process are summarized so the team can consider whether they have adequate controls in place.

Additional iterations of the what-if questions are used to identify further risks until no new risks are identified. The prompt list should be prepared in advance and added to as the workshop progresses. The list is used to motivate discussion and to suggest additional issues and scenarios for the team to discuss. SWIFT may be combined with other risk ranking techniques to determine the priority of risks identified in the process.

7.20.5 Outputs

The principle output of this process is a register with suggested risk management treatments identified and ranked by priority. These treatments form the basis for a risk management plan.

7.20.6 Strengths and Weaknesses

Strengths:

- Wide application to many kinds of physical plant, systems, situations, circumstances, organizations and activities
- Not data intensive
- Requires relatively little time to prepare
- Effective in identifying major hazards rapidly
- Helps identify opportunities for improving processes and systems
- Usable outputs

Weaknesses:

- Requires experienced and knowledgeable team members as well as an effective facilitator
- Preparation must be carefully undertaken

- Preparing a set of prompt phrases is a critical task
- Less than comprehensive prompt lists will not reveal complex or hidden risks

7.20.7 Examples of Use

SWIFT is most likely to be used with engineering and infrastructure systems, but it may also be useful when examining any potential changes in the way things are done. SWIFT might be a useful first iteration tool to examine potential unintended consequences of changes in any aspect of a project's life cycle from planning through deauthorization.

7.21 Five Points To Take Away

1. Brainstorming, Delphi techniques, interviews and expert elicitations can be effective methods for addressing uncertainty by filling in data gaps.
2. Evidence maps are a new tool that can be very helpful in sorting out the disparate opinions about the existence of a hazard or risk found in the literature.
3. Sorting tools that include screening, rating and ranking methods are among the most frequently used and robust qualitative risk assessment tools.
4. Developing a generic risk assessment process is a valuable approach to problems that recur or for risk issues where many different assessments will have to be conducted.
5. There is a growing number of specialty qualitative risk assessment tools like HACCP, PHA, HAZOP, and SWIFT that rapidly expand the set of qualitative tools available to risk assessors.

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(USDOD 2003) …details missing

Chapter 8: Quantitative Risk Assessment Tools

8.1 Introduction

This chapter introduces and briefly summarizes a range of quantitative risk assessment tools that may be suitable for the USACE Civil Works Program. The discussion of each tool is adapted from the style of the International Electrotechnical Commission (2009) summary of risk assessment techniques. The flow of the discussion, in general, includes the following:

- Overview of the technique,
- How the technique is used,
- Inputs required ,
- Process applied ,
- Outputs produced, and
- Strengths or limitations of the technique.

A number of the techniques found in this chapter can be applied qualitatively or quantitatively.

8.2 MCDA

8.2.1 Overview of the Technique

Multi-Criteria Decision Analysis (MCDA) is a well-established operations research technique used for making tradeoffs of quantitative or qualitative information that involves the personal preferences of decision makers. It is designed for decision problems that involve multiple criteria. Many different decision algorithms or methods of weighing and combining the criteria and decision-maker preferences are included in the MCDA toolbox. Among the more common methods are the analytic hierarchy process (AHP), ELECTRE (Outranking), multi-attribute utility theory (MAUT), PROMETHEE (Outranking), and Simple Multi-Attribute Rating Technique (SMART), among others. [Note: Simple Multi-Attribute Rating Technique is also known as SMART. This is NOT the same process as the USACE SMART planning process.]

8.2.2 How the Technique Is Used

MCDA has proven to be especially useful for group decision-making processes. Rather than identify the best solution, MCDA helps decision makers find a solution that best suits their goals/preferences and their understanding of the problem they seek to solve. It has proven to be especially useful in establishing priorities, reducing a long list of things of concern to a short list, and in establishing a ranking among alternative solutions. Thus, MCDA might be used to help rank a number of potential O&M activities where the decision may be based on costs, essential services produced, public perception or systems considerations. It can also be used to help identify the best plan from among an array of alternative plans, or to identify the riskiest levee, miter gate or stone rubble breakwater from among a set of such structures.

8.2.3 Inputs

The inputs to a MCDA process include:

1. Problems,
2. Alternative solutions to the problems,
3. Criteria upon which a decision will be based,
4. Evidence (i.e., measurements of the criteria for each alternative),
5. Decision matrix of alternative and criteria measurements,
6. Subjective weights for the criteria,
7. Synthesis algorithm, and
8. A decision.

8.2.4 Process

Using the inputs described above, the first step is to develop a simple hierarchical model as seen in Figure 8.1. For this example, Criterium DecisionPlus[24] Software was utilized to analyze a multipurpose planning problem.

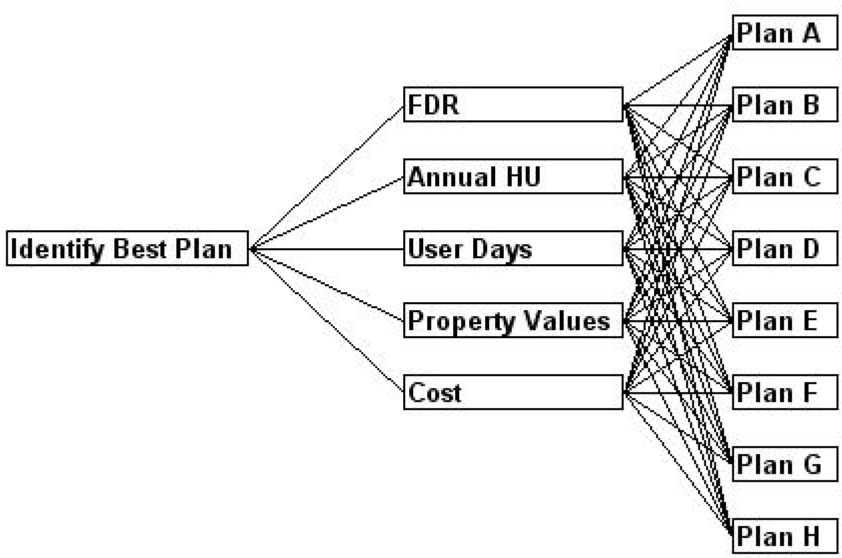

Figure 8.1: Hierarchical MCDA model for choosing the best plan

There are eight alternative plans, Plan A through Plan H, from which the best plan was to be selected. The criteria for plan selection were:

- Flood damage reductions in thousands of expected annual damage dollars;
- Annual habitat units;
- Annual user days of recreation;

[24] Criterium DecisionPlus is a trademark of InforHarvest Inc.

- Effects on property values (Maximum, high, moderate, low, minimum); and
- Cost in millions of dollars.

Numerical estimates for all criteria except effects on property values were generated for the investigation. The effects were subjectively categorized as seen in the list above. The decision matrix was constructed internally by the software based on data entry as shown in Figure 8.2.

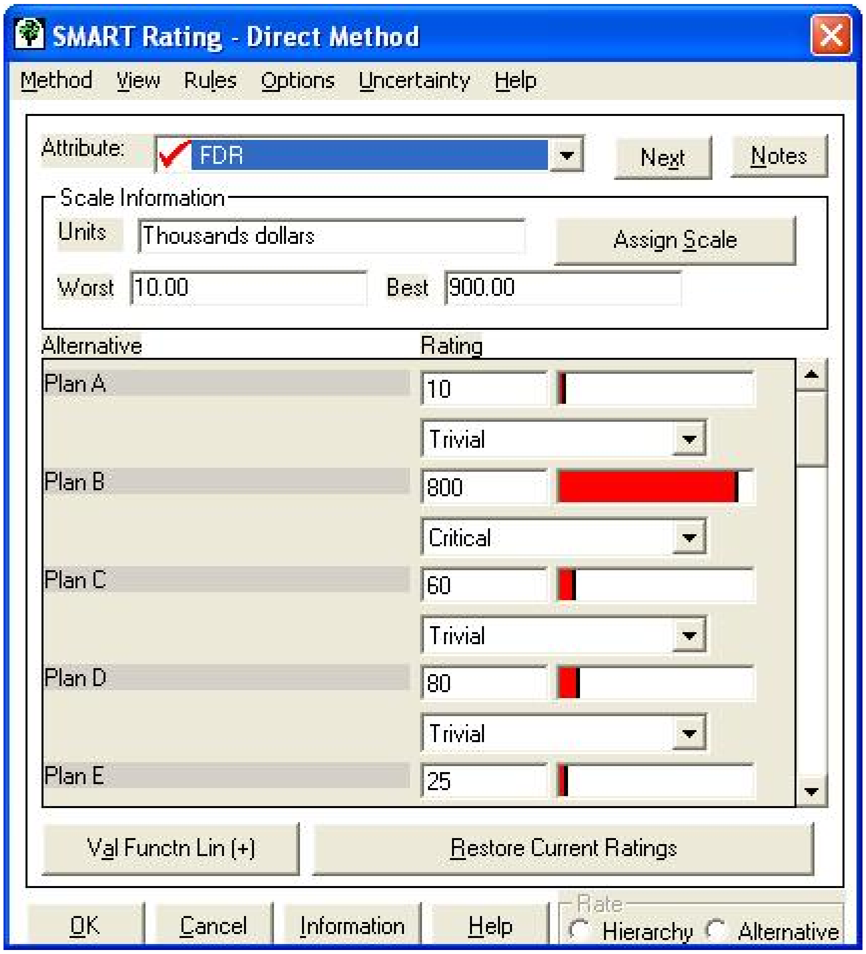

Figure 8.2: Direct data entry for MCDA criterion flood damage reduction

Subjective weights must be established for the criteria. Figure 8.3 shows the weights for this example. In this instance costs and benefits were assumed to be equally important. Using a 200 point total, 100 points were allocated to costs and 100 points to benefits. Because there were four equally important benefit categories, each criterion received 25 points.

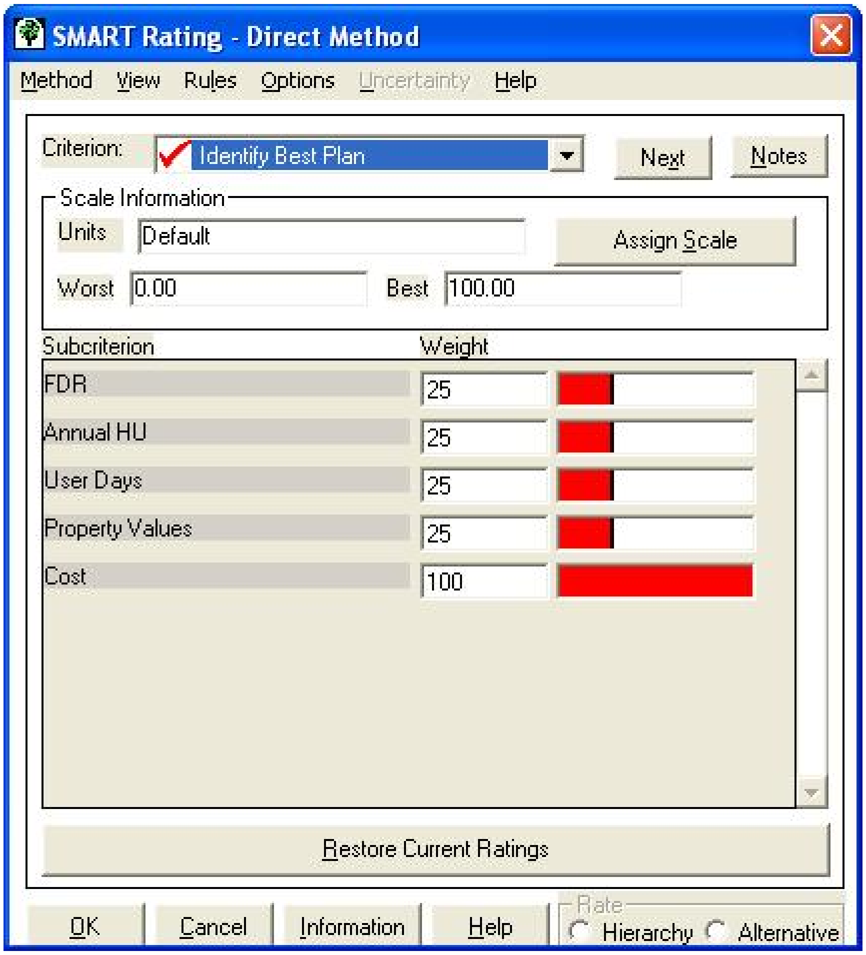

Figure 8.3: direct entry of subjective weights for MCDA criteria

Criterium DecisionPlus provides the capability to use the Analytical Hierarchy Process (AHP) or the Simple Multiattribute Rating Technique (SMART) to combine preferences and evidence to assist the decision process. SMART originates from multi-attribute utility theory and was used for this example.

8.2.5 Outputs

A variety of outputs van be produced from an MCDA analysis. Figure 8.4 shows the most basic output, which calculates a score for each plan. The largest score indicates the best plan based on the criteria identified, their measurements and weights. In this example, Plan B with a score of .736 is the best plan, based on the weights assigned and the evidence entered for each criterion.

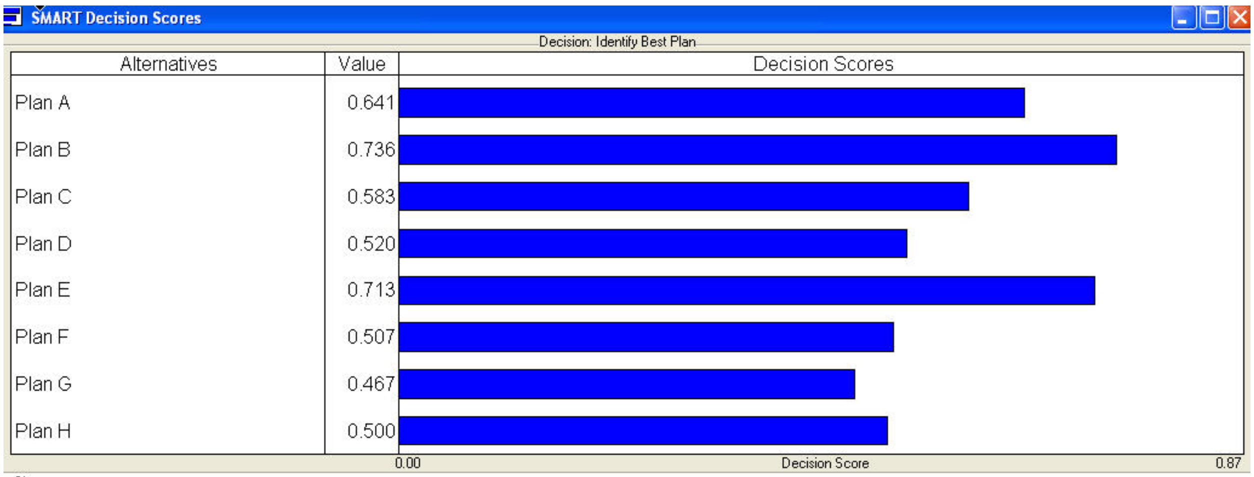

Figure 8.4: MCDA decision scores for individual plans

Many MCDA methods offer a variety of options for sensitivity analysis or other means for exploring the potential effects of uncertainty on the decision. Figure 8.5 presents one example of such a sensitivity analysis. The position of the vertical line represents the current weight of the habitat unit's criterion. The horizontal lines represent the top five alternative plans. The intersection of the vertical line with the horizontal lines represents the relative rankings of the alternative plans at the current weight. At the current weight, Plan B (blue) is the highest ranked. However, if the importance of habitat units is increased, i.e., the vertical red line shifts right, Plan E (green) would be a more desirable plan. If habitat units continue to increase in importance, Plans H and G become more desirable than Plan B. Thus, as the importance of habitat units increases, i.e., as the vertical line moves to the right, the relative rankings of the plans change, clearly revealing the subjective nature of the decision process. Uncertainty about social values is a common source of significant uncertainty in decision making.

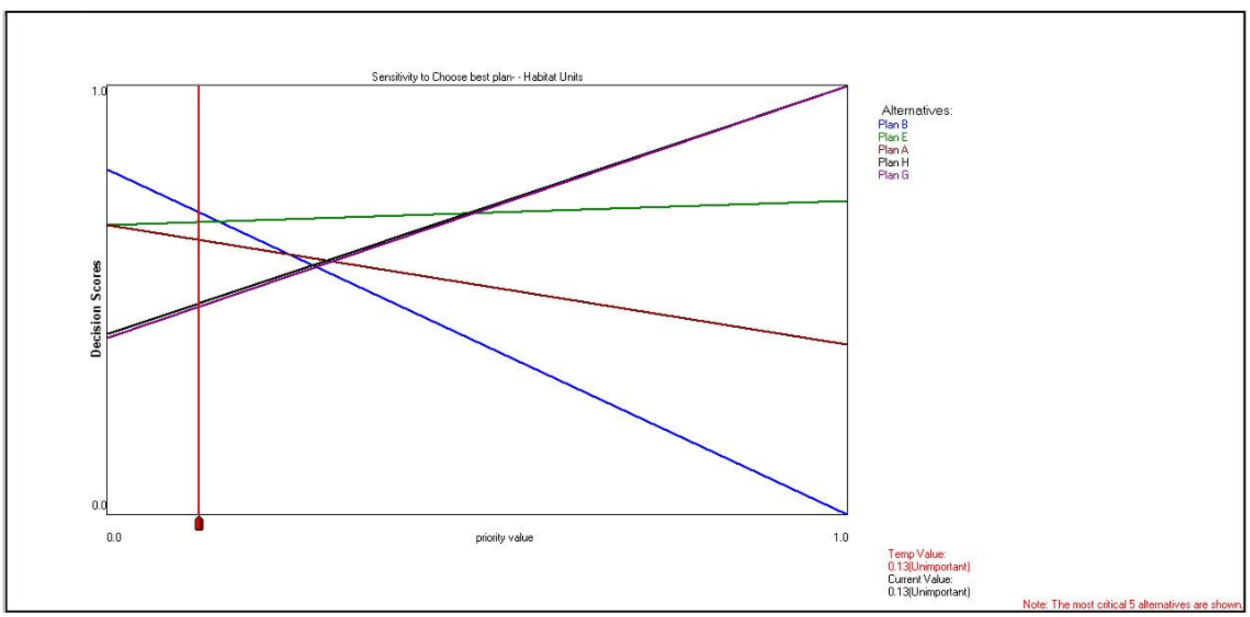

Figure 8.5: Sensitivity of best plan to importance of habitat units

8.2.6 Strengths and Weaknesses

Strengths:

- Ability to answer a multiple criteria decision question
- Enables decision makers to explore the sensitivity of the solution to different weights and, in some methods, to a range of uncertain criteria values

Weaknesses:

- Require a subjective assignment of weights
- Most appropriate set of weights is often difficult to discern and attain agreement of the team
- Different synthesis algorithms can yield different rankings of alternatives

8.3 Modeling and Model Building

8.3.1 Overview of the Technique

A model is a device, demonstration, equation, explanation, picture or replica of something else. Models are used to describe how actual things behave. USACE makes extensive use of quantitative models in many of its areas of responsibility. There are physical models, mathematical models, statistical models, computer models, blueprints, maps and drawings that function as models.

8.3.2 How the Technique Is Used

Models are used by USACE to understand stream flows, storm paths, the transport and fate of substances in water, ecological responses to changes in the environment, and economic responses to new infrastructure. Risk-based models are used to explore the effects of uncertainty on model outputs and real-world outcomes. Models are also used to achieve goals like maximizing net economic development or efficiently allocating O&M resources. Simulation models are routinely used to explore the effects of channel improvements on navigation. Some of the USACE models are used repeatedly and throughout the organization. Other models are developed for one-time use in a unique analysis. Models can be used in every stage of a project's life cycle, in every business line, and in every functional area of responsibility.

8.3.3 Inputs

All models require knowledge, theory, data and information in many forms. Other inputs to a model depend on the nature of the model.

Physical models are built as replicas of some real thing. Usually, a physical model is a scaled-down version of reality, like the USCE Waterways Experiment Station (now the Engineer Research and Development Center-ERDC) physical model of Niagara Falls that delighted visitors for many years. Sometimes a scaled-up version of a smaller reality is depicted, like the DNA molecules used in schools. Physical models are expensive and their relative inflexibility limits their usage.

Mathematical equations are flexible and relatively cost-effective models. Systems of equations and mathematical relationships are common inputs to these models. USACE also makes extensive use of statistical models. Risk analysis requires models that enable analysts to explore “what if” questions. These models often require probability distributions among their inputs.

8.3.4 Process

Modeling may be the most idiosyncratic part of the risk assessment process. It can be helpful to have a process in mind. The 13 steps that follow describe a model building process offered by Yoe (2012).

1. Get the question right. The first step in developing any model is to understand the question(s) the model needs to be able to answer. Know what information the model needs to produce. Different questions can lead to very different models, requiring different data and a different model structure.

2. Know how your model will be used. Understand how the model is expected to be used. Know what the model can and cannot do. Anticipate as many potential uses of the model before you begin to build it as possible. Will it be used to identify research needs, develop a baseline risk estimate, or to evaluate risk management options? Will it be shared with others or used again? Will it be added to over time or is it to be completed once and for all? Who will use it?

3. Build a conceptual model. Building a conceptual model is where a model building effort is most likely to succeed or fail. Models do not fail as much due to data and parameter value issues as they do because of faulty conceptualization of the problem to be represented. This step takes you from abstract ideas and notions to the hard reality of details. The best modelers include the important processes and exclude unimportant ones. This step is a combination of both science and art.

The typical conceptual risk model will identify the sequence of events necessary to lead to an undesirable consequence. It will lead to an answer to the specific questions that have been asked. A conceptual model is well-served by a risk narrative that answers the four basic questions:

1. What can go wrong?
2. How can it happen?
3. What are the consequences?
4. How likely are the consequences?

Transform your narrative answer to these questions to a sketch, for example, one could develop an influence diagram to show how the problem will be modeled.

4. Specify the model. The specification model defines the calculations and other inner workings that will make the model run. It may help to think of it as the paper-and-pencil exercise of figuring out the calculations that will be needed to make the conceptual model produce answers that are useful to you. It is more than this, but that provides a good mental image of the essence of this task. The functional form of all relationships and the model logic are built in this step. Placeholders and dummy values can be used in lieu of data.

5. Build a computational model. The output of this step is a fully functional model. In this step you complete the computer program needed to run the model you have specified. To complete a computational model you'll need to collect the data you need to make the model operational.

6. Verify the model. The equations, calculations, logic, references and all the details need to be just right. Verification assures that the computational model is consistent with the specification model and that the specification model is correct. It is important to be sure the model is built correctly. The model must be debugged, reviewed and tested to ensure the conceptual model and its solution are implemented correctly and that the model works as it is intended to work.

7. Validate the model. Does the model represent reality closely enough to provide information that supports decision making? One can validate model outputs, model inputs or the modeling process. Historical data validity uses historical inputs to see if the model reproduces historical outputs. When the outputs cannot be validated, it may help to validate the input data. Data validity means the data is clean, correct, useful, and truly representative of the system modeled. When neither the inputs nor the outputs can be validated the best remaining option may be to try to validate the reasonableness of the process. A model has face validity when it appears that it will do what it is supposed to do in a way that accurately represents reality.

8. Design simulation experiments. If you sit down with your model and just start making runs, it is likely that, sooner or later, you will get what you need. It is also likely you'll waste a lot of time making runs you did not need. Carefully identifying the various conditions for the scenarios or simulations to run is essential to an efficient modeling process. Arrange your series of experiments efficiently. It may make sense to do them in a specific order if significant adjustments must be made to the model for different conditions. Write down the runs in the order they will be completed. Take care to verify all alterations to a model and save significantly different versions of the model as separate files.

9. Make production runs. Be systematic in making your runs. Carefully record the nature and purpose of the run (e.g., existing risk estimate to establish a baseline measure of the risk) and make note of your model's initial conditions, input parameters, outputs, date, analysts and so on. Enter this information into a log kept for the model. Keep it up to date. Take special care to save all outputs from a production run and to carefully identify them. Unless you are absolutely sure about the outputs you will and will not need to complete a risk assessment, save all simulation outputs, if possible. It is far better to save outputs you will never need than to need outputs you never saved.

10. Analyze simulation results. Analyzing simulation results is about getting useful information from data. Analyze the results and learn what the simulations have taught you about the problem. The analysis of simulation results will provide information needed to answer the questions. Always take care to characterize the remaining uncertainty in useful and informative ways.

11. Organize and present results. The information gleaned from the model runs needs to be organized and presented to decision makers in a form that is useful. You'll find more on this topic in Chapter 9.

12. Answer the question(s). Answer each question specifically. Do it in a question-and-answer format. To the extent that lingering uncertainty affects those answers, take care to portray those effects. Once you have adequately answered the questions, summarize the insights you have gained, offer specific observations, and conjecture in a responsible way.

13. Document your model and results. You must carefully document the results. The model must be documented as well. Explain the structure of the model, including relevant descriptions of the preceding steps, the conceptual and specification models, the source and quality of the data, the results of the verification and validation efforts, as well as the history of production runs. Provide enough user instruction that another person can run the model if there is a chance the model will be used again. As familiar as you are with the model today, there is a good chance it will look like someone else's work in six months' time.

8.3.5 Outputs

The outputs of models are even more varied than the models themselves. Some produce insights, some provoke discussion, some provide numerical estimates of values of interest for decision making, while others produce distributions of possible outcomes or extensive databases. The substance of these model outputs can touch on any subject matter. It may be useful in risk analysis to distinguish between deterministic and probabilistic models. The former tend to produce point estimates or a single output (which may be more complex than a single point), while the latter produce probabilistic outputs.

8.3.6 Strengths and Weaknesses

Strengths:

- Allow analysts to conduct controlled experiments
- Can reveal new facts about problems
- Broad range of applications
- Effective training tools
- Mathematical and statistical modeling tools are flexible
- Can often be built in a modular or patchwork approach that enables analysts to re-use parts of models in new applications and to add to an existing model when new features or capabilities are desired

Weaknesses:

- Models can be costly or time-consuming to build
- Model results are very sensitive to model formulation
- No guarantee a model will produce an optimal solution
- Models have been found to produce incorrect outputs

A significant USACE initiative to improve model outputs and the quality of the decisions they inform is found in EC 1105-2-412 Assuring Quality of Planning Models issued in 2011.

8.4 Event Tree

8.4.1 Overview of the Technique

An event trees is a qualitative or quantitative analytical technique for modeling a system or sequence of events. It is a sequence of nodes and branches that describe the possible outcomes of an initiating event. Each unique pathway through the tree describes a unique sequence of events that could result from the initiating event. An example is shown in Figure 8.6.

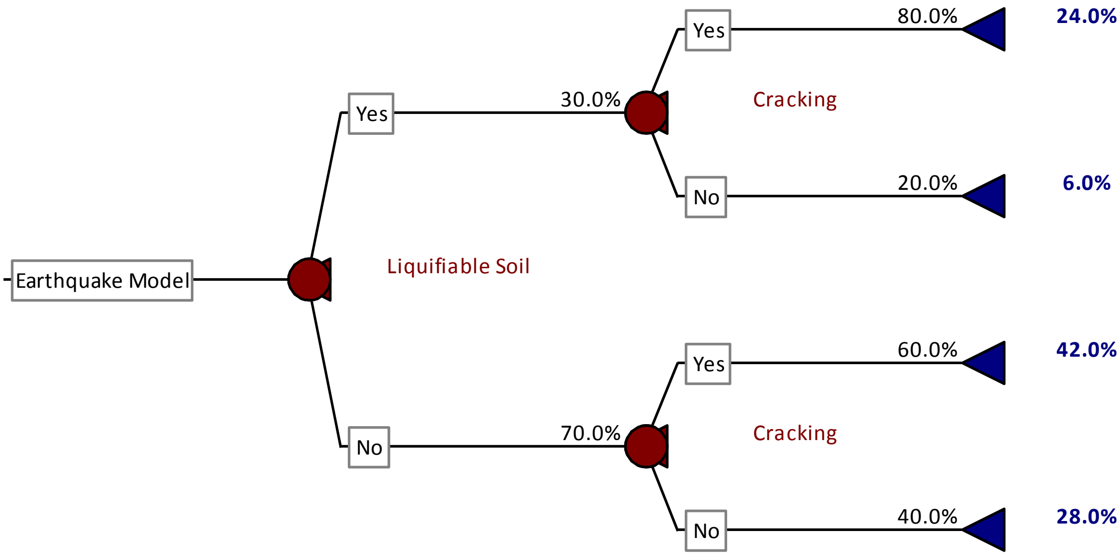

Figure 8.6: Simple event tree of earthquake effect on a concrete monolith

Decision Tree

A decision tree may begin with a decision or a chance event. A single stage decision tree requires one decision then the tree defines how it can play out. Multi-stage decision trees are a mixed pattern of chance-decision-chance-decision-chance events. A decision tree enables managers to examine how different decisions made at various points in the model could turn out.

A decision tree model is a predictive tool that shows the ultimate consequences of the various decision choices. Each consequence is represented by a pathway through the tree. A decision that puts one on the path that leads to the most desired value (e.g., highest benefit, lowest probability of adverse outcome) is the decision that is typically chosen.

A distinguishing characteristic of the event tree is that all the events or nodes are assumed to be determined by chance. There are no decisions to be made along any of the pathways. When decisions points are added to an event tree it is more appropriate to call the technique a decision tree. Event trees that only assess the frequency of the various possible outcomes are sometimes called probability trees.

The event tree is an inductive logic technique that answers the basic question "what happens if...? " by fanning out like a tree (IEC 2009). An event tree is useful for identifying both aggravating and mitigating events that might follow the initiating event.

8.4.2 How the Technique Is Used

Event trees can be used at any stage in the lifecycle of a project or process. It has value as a qualitative tool because the process of developing a tree aids the understanding of a risk situation by identifying the potential scenarios and sequences of events that can lead to undesirable or more desirable outcomes. Quantifying the tree with probability and consequence information enables the risk assessor to characterize the risk numerically. A quantitative model can be very useful in evaluating the efficacy of different risk control strategies. The trees are most often used to model failure modes where there are multiple safeguards and/or multiple modes of failure.

8.4.3 Inputs

A tree model requires an explicit understanding of the process that is being modeled. The initiating events, sequences of follow-on events, and outcomes or endpoints must be known. A quantitative event tree requires sufficient data to numerically describe the function and failure of the system under consideration. One of the critical inputs to an event tree is a clearly and concisely defined initiating event. A new tree is required for each distinct initiating event.

8.4.4 Process

An event tree begins with an initiating event. Events are represented by nodes. Chance events are represented by circles, decisions by squares and endpoints by triangles. The initiating event may be a natural event, an infrastructure failure, an operator error or any other causal event. A chance event will have more than one potential outcome. Each potential outcome is represented by a branch emerging from the preceding node. Subsequent events that may aggravate or mitigate the outcome are listed in sequence from left to right. Each event outcome is represented by a chance node. The potential outcomes of each are represented by branches. This node-branch sequence continues until an endpoint is reached. An endpoint represents the point at which the sequence of events from the initiating event is concluded for the purposes of the decision problem at hand.

> **"Tree Time"**
>
> Nodes represent points in logical time. The position of a decision node marks the time in a sequence of events when the decision maker makes a decision. A chance node shows the "logical" time when the result of an uncertain event becomes known. An endpoint denotes the time when process is ended or problem is resolved.
>
> Time (logic) flows from left to right. Branches leading into a node have already occurred. Branches leading out of or following a node have not occurred yet.
>
> When a chronologic order exists it should be reflected in the model. When the order is driven by the modeler's logic there is more flexibility and art in how events are sequenced. However, once the model is constructed a logical tree time is established.

In quantitative event trees probabilities are estimated for each branch emerging from a node. These probabilities are usually listed above the branch. If additional consequences are quantified (dollars, lives lost, people affected, and so on) these are listed below the branch. Each probability is a conditional likelihood predicated on the nodes and branches that preceded it. Consider Figure 8.6 again. Each path through the tree represents the likelihood that all of the events in that path will occur. There is often art involved in defining the sequence of events on the paths. This enables assessors to calculate the likelihood of any identified outcome by the product of the individual conditional probabilities and the frequency of the initiating event. Conditional probabilities give them the quality of independent events.

8.4.5 Outputs

A good event tree model provides a qualitative description of a potential risk. It fleshes out problems and their consequences as different combinations of events are shown to produce variations of the problem and a range of outcomes that can result from an initiating event. Figure 8.6, for example, suggests the different ways damage to a concrete structure may occur as a result of an earthquake. Quantitative estimates of event consequences and their likelihoods can be obtained when the tree model is quantified. The best models can help assessors understand the relative importance of different sequences of events and failure modes. The efficacy of different risk management options can often be tested and quantified by changing critical model inputs to reflect the function of the risk management options. Event trees can be used to examine part of a risk, for example the likelihood assessment, and its outputs may become inputs to other risk assessment models. Event trees provide an effective visual map of risks.

8.4.6 Strengths and Weaknesses

Strengths:

- Able to display potential scenarios following an initiating event
- Can account for timing, dependence, and domino effects that are cumbersome to handle in verbal descriptions and other models

Weaknesses:

- Require analysts to be able to identify all relevant initiating events
- May require a separate model
- Difficult to represent delayed success or recovery events when nodes are constructed with dichotomous branches
- Any path is conditional on the events that occurred at previous branch points along the path
- Models can quickly grow very large

8.4.7 Examples of Use

Event trees are useful for helping USACE analysts anticipate the range of effects associated with natural disaster events or infrastructure failures.

8.5 Fault Tree

8.5.1 Overview of the Technique

Fault tree analysis is almost the mirror image of event tree analysis. While an event tree uses forward logic to proceed from a single initiating event to a number of potential outcomes, a fault tree begins with a single outcome and uses backward logic to proceed to a number of potential initiating events or causes. This technique is for identifying and analyzing factors that can contribute to a specific undesired outcome or fault, also called the top event. Causal factors are deductively identified, organized in a logical manner and usually represented from top to bottom, rather than horizontally as an event tree is. The pathways through the tree show causal factors and their logical relationship to the top event. A simple fault tree is shown in Figure 8.7. It shows four possible causes of a pump failure.

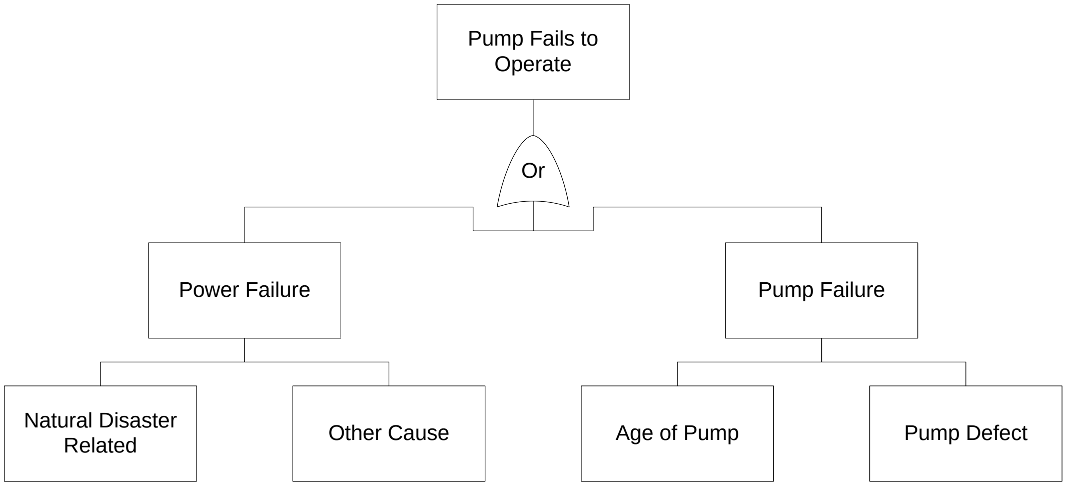

Figure 8.7: Fault tree showing sources of pump failure

Each unique pathway through the tree describes a unique sequence of events that could have caused the fault. Thus, each pathway provides a visual depiction of a risk hypothesis.

8.5.2 How the Technique Is Used

Murder investigations and epidemiological outbreak investigations are good examples of fault tree applications. Qualitative fault trees identify potential causes and pathways to a failure. Quantitative fault trees can be used to calculate the likelihood of the fault having been caused by any particular sequence of events, provided that you know the probabilities of causal events.

Fault trees are often used during the design stage of a system to identify potential causes of failure and to inform the ultimate choice of the design options. They are used during operations to identify the relative importance of different pathways to major failure events. A fault tree can be used to analyze the causes of an unexpected failure by showing how different events could have come together to cause the failure.

8.5.3 Inputs

An understanding of the system under study and a technical knowledge of the causes of failure are required for either a qualitative or quantitative tree. Conventional fault tree symbols, including input and output events, gates (e.g., and, or), and the like should be used. A quantitative analysis requires failure rates for all the basic events in the fault tree.

8.5.4 Process

The basic steps are to define the top event or failure/fault of concern. This may be an actual failure, like a dam failure, or a broader outcome of that failure, like catastrophic loss of life due to a dam failure. Beginning with the top event, all the possible immediate causes or fault modes leading to the top event are identified. Each of these fault modes is, in turn, analyzed to identify the means by which it could have occurred. This process continues in a stepwise manner to successively lower system levels until further decomposition of the failure mode ceases to be productive. In a structural project this may occur at the component fault level. Events and causal factors at the lowest level of the model are called base events.

When probabilities can be assigned to base events and the events that follow them, the probability of the top event, given a specific pathway, can be calculated. “And” and “or” gates as well as duplicate failures modes can complicate the estimation of probabilities using event trees. Even when quantification of probabilities is not feasible the trees are often useful for displaying causal relationships.

8.5.5 Outputs

The most useful outputs of a fault tree analysis include the visual depiction of how the top event can occur. The trees are especially useful for showing interacting pathways where two or more simultaneous events must occur. They can also provide overall estimates of the probability of failure as well as the probabilities of individual pathways to failure (also called minimal cut sets) when likelihood information is available and the model is not too complex.

8.5.6 Strengths and Weaknesses

Strengths:

- Can analyze a wide variety of factors including physical phenomena, human responses and interactions of all these factors
- Top down approach focuses attention on those causes of failure that are directly related to the top event
- a good model for water and infrastructure systems with many interfaces and interactions
- System behavior can be readily understood by the visual depiction of failure modes
- Can identify combinations of events that could lead to failure
- often useful in decomposing events so probabilities can be estimated
- may not be possible to estimate the probability of a dam failure all at once; but after the chain of necessary and sufficient events is identified it may be feasible to estimate the probabilities of these events

Weaknesses:

- Can become quite large for complex systems
- Usually a high level of uncertainty in the calculated probability of the top event
- For some situations causal events are not bounded and it is hard to know if all important pathways to the top event are included

8.5.7 Examples of Use

Fault trees are useful for considering risks associated with complex systems or new technologies. They can be useful for identifying the sources of infrastructure or other system failures.

8.6 Monte Carlo

8.6.1 Overview of the Technique

The Monte Carlo process is a numerical technique used to replace uncertain parameters and values in models and calculations with probability distributions that represent the natural variability and knowledge uncertainty in those inputs. The Monte Carlo process samples an individual value from each probability distribution in the model. These values are then "plugged in" to the model's equations and calculations so that the model's calculation can be completed and outputs can be produced. This process is repeated the desired number of times to generate a distribution of output values.

8.6.2 How the Technique Is Used

The Monte Carlo process is a popular simulation technique that enables analysts to propagate the uncertainty in a decision problem and produce a numerical description of the range of potential model outputs. These output distributions can be subjected to statistical analysis to inform decision making. When the Mont Carlo process is included in a simulation model, the model is often called a Monte Carlo simulation.

This process can be used to replace point estimates in any kind of model. Easy-to-use commercial software has made the method popular to use in spreadsheet models. Thus, the process can be used in any spreadsheet model that USACE uses where one or more model inputs are uncertain, i.e., subject to natural variability or a matter of some knowledge uncertainty. This makes it a widely applicable tool for assessing risks. Its use is not restricted to spreadsheet models, however. It can be employed in virtually any quantitative model. Several of the models developed corporately by USACE employ this technique. HEC-FDA, Beach-fx and HarborSym are certified planning models that use the Monte Carlo process.

8.6.3 Inputs

Inputs for this method include a clear understanding of the model and its inputs, the sources of uncertainty and the required output(s).

8.6.4 Process

Imagine estimating the number of containers offloaded at a port in a month. Clearly this is a variable. It can be calculated simply by multiplying the number of vessels calling at the port by the average number of containers offloaded per vessel. The number of vessels calling at a port will vary naturally with the state of the economy, weather conditions and the like. Suppose the average is known to be 38 and calls have a Poisson distribution as shown on the left of Figure 8.8. Suppose we have no data about the average number of containers offloaded but estimate the average to be between 40 and 65, as seen in the middle distribution. We have a simple multiplication that uses two probability distributions rather than two point estimates. Arithmetic operations with distributions is complex and often has no closed form. Consequently, it is convenient and useful to estimate this model using the Monte Carlo process.

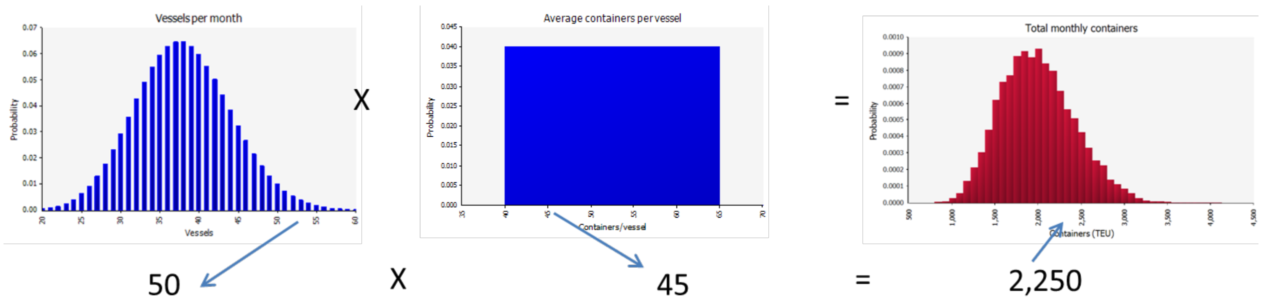

Figure 8.8 An illustration of the use of the Monte Carlo process

In this example random values 50 and 45 were selected from the two input distributions via the Monte Carlo process. These values were handled according to the structure of the model, in this case a simple multiplication. They yielded an estimate of 2,250 containers per month. This is one iteration of the Monte Carlo process. The process is repeated 10,000 times and it yields the distribution on the right that characterizes the uncertainty about how many containers are offloaded in a month. The output distribution reflects the natural variability and knowledge uncertainty in the model.

The Monte Carlo process, itself, consists of two steps. The first step is to generate a simple random number between 0 and 1. A number of efficient algorithms for generating simple random numbers are well known. The second step is to transform that number into a value useful for a specific probability distribution. A number between 0 and 1 is not useful to estimate a mean number of containers believed to be between 40 and 65. The transformation step is a mathematical calculation that is more or less difficult depending on the distribution used.

Consider the uniform distribution, U(a,b), used above where the minimum a = 40 and the maximum b = 65. To obtain a value, x, from this distribution use the function:

$x_i = a + (b - a)r_i$

where r_i is a simple random number between 0 and 1. Thus, $x = 40 + 25r_i$. Suppose we have r_i values of .6198, .1127, and .4009, derived from a random number generator. Substituting we would obtain the following estimated values of the mean number of containers offloaded per vessel sampled from the distribution U(40,65).

$x = 40 + 25(.6198) = 55.5$

$x = 40 + 25(.1127) = 42.8$

$x = 40 + 25(.4009) = 50.0$

8.6.5 Outputs

The outputs of the Monte Carlo process are distributions of values calculated in the models. These distributions can include the actual input values used in the calculations, intermediate calculations or model outputs. These distributions can be analyzed using statistical techniques to support decision making. For example, a close-up view of the output in the simple model above is shown in Figure 8.9.

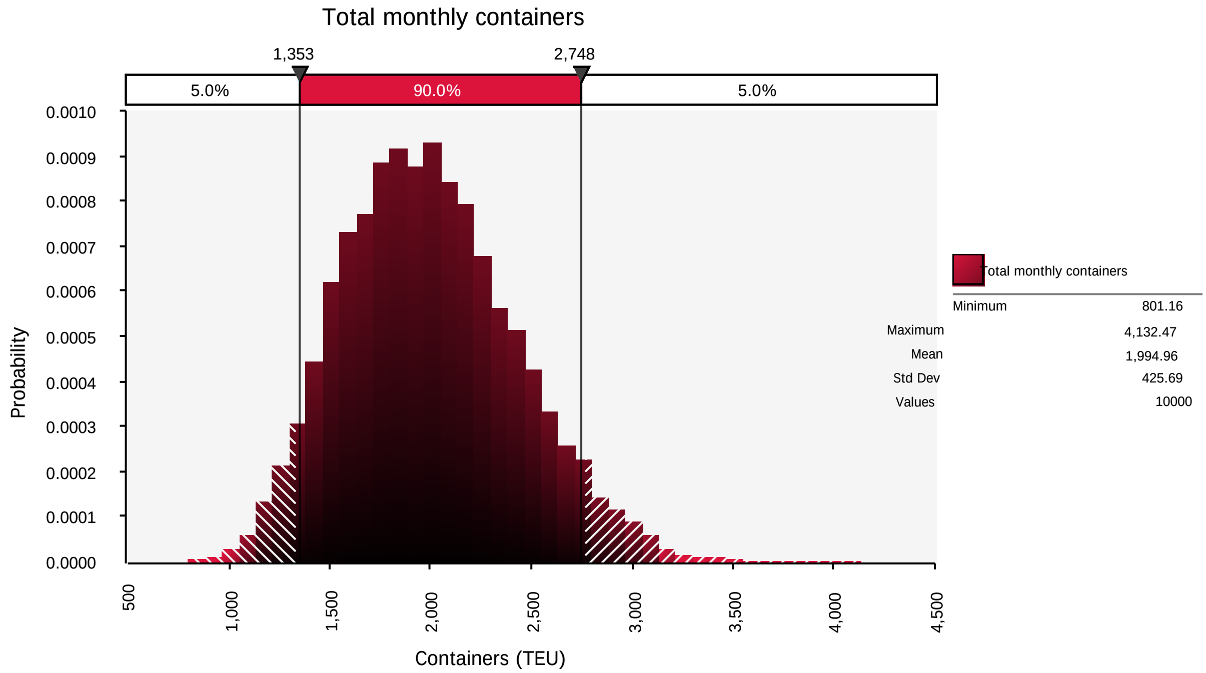

Figure 8.9: Monte Carlo process simulation results

The monthly total number of containers is an uncertain value. It is uncertain because there is natural variability in the number of vessel calls and because the mean number of containers offloaded is an uncertain parameter. The estimate above shows this value is between 801 and 4,132 containers with an expected value of 1,995 per month. Based on this analysis we can be 90% confident the actual total will be between 1,353 and 2,748 containers (see the delimiters). The probability of a specific outcome can be identified. There is a 5 percent chance there will be more than 2,748 containers per month. Additional statistical analyses are also possible.

8.6.6 Strengths and Weaknesses

Strengths

The strength of this technique is its widespread applicability. Many of the natural and physical systems USACE deals with are too complex to assess the effects of uncertainty using

analytical techniques. These effects can, however, often be assessed by describing input uncertainties and running simulations that sampled the inputs to represent possible outcomes. This method enables analysts to examine complex situations that are difficult to understand and solve by other means.

Substituting distributions for uncertain point estimates enables USACE analysts to honestly represent the uncertainty in a model and to explore its potential effects on model outputs. Models are relatively simple to develop and they can represent virtually any influences or relationships that arise in reality. The method can accommodate a wide range of distributions in an input variable, including empirical distributions derived from observations of real phenomena. The large amounts of data that can be generated lend themselves readily to sensitivity analysis to identify strong and weak influences on outputs. As noted previously, commercially available software makes it relatively easy to apply this numerical technique to any spreadsheet model.

Weaknesses

The Monte Carlo model's limitations include the fact that the solutions are not exact and their usefulness may depend on the number of iterations or simulations completed. It is not a transparent process. Using the "uncertain numbers" represented by distributions makes it difficult for stakeholders to understand the process.

8.6.7 Examples of Use

This technique is already widely used in USACE benefit and cost estimation. It has great potential for application in program management, budgets and the preparation of estimates of any kind that require working with uncertain values.

8.7 Sensitivity Analysis

8.7.1 Overview of the Technique

Sensitivity analysis is used to systematically investigate how the variation in a risk assessment output can be apportioned, qualitatively or quantitatively, to different sources of knowledge uncertainty and natural variability. This may be accomplished by varying an assumption to see how a point estimate output responds to a change in the assumption, by sophisticated analysis of probabilistic outputs, or by any number of methods between these extremes. Some risk assessment outputs and the decisions that rely on them may be sensitive to minor changes in assumptions and input values. When assessment outputs and the decisions that may be made based upon them are sensitive to changes in assumptions, scenarios, models or inputs of all kinds, it is critically important that that information be effectively conveyed to risk managers and other decision makers.

Sensitivity analysis provides the point in a risk management activity when attention is focused intentionally on better understanding the things that are not known and their importance for decision making. The results of the sensitivity analysis will provide insight into the importance of different sources of uncertainty.

Sensitivity analysis is sometimes called 'what if' analysis. It may be the single best way to increase both the assessor's and manager's confidence in the results of a risk assessment or other risk-based analysis. It provides an understanding of how analytical outputs respond to changes in the inputs. Because risk assessments can be qualitative or quantitative, sensitivity analysis can likewise be qualitative or quantitative. To conduct a sensitivity analysis assessors need a completed risk assessment or other risk-informed analysis and an awareness of the most significant sources of uncertainty. These uncertainties provide the avenues to investigate in the sensitivity analysis.

Qualitative sensitivity analysis is used to identify the sources of uncertainty that exert the most influence on the risk assessment outputs. A basic methodology for qualitative sensitivity analysis includes:

- Identifying specific sources of uncertainty
- Ascertaining the significant sources of uncertainty
- Qualitatively characterizing the significant uncertainty.

Examples of such methodologies can be found in Yoe (2012) and WHO (2006).

Making assumptions about uncertain values is one of the most common and expedient ways of addressing uncertainty. To the extent that assumptions are used to address uncertainty one should routinely test the sensitivity of assessment outputs to those assumptions. The simplest way to do this is to first construct a list of the key assumptions of your risk assessment. There are two kinds of assumptions, those we know we make, i.e., explicit assumptions, and those we do not know we are making, i.e., implicit assumptions. Explicit assumptions should be identified and preserved for the attention of assessors and managers. Peer review by multidisciplinary reviewers is often needed to identify implicit assumptions that become embedded in the way that disciplines or organizations function.

Challenge each assumption. Do the outputs change? Do the answers to the risk manager's questions change? Can any of these changes affect the risk management decision? If so, that information needs to be conveyed to the risk managers.

There are four classes of quantitative sensitivity analysis tools (Yoe, 2012). These are scenarios, mathematical, statistical and graphical analysis. Some of the more common tools from these groups include:

- Nominal range sensitivity (one-at-a-time analysis)
- Difference in log-odds ratio
- Break even analysis
- Automatic differentiation technique
- Regression analysis
- Analysis of variance
- Scatter plots
- Tornado plots
- Spider plots

The purpose of sensitivity analysis is to understand the uncertainties that could influence decisions and to develop appropriate strategies to address those uncertainties.

8.7.6 Strengths and Weaknesses

Strengths:

Structuring Scenarios

Informal scenarios can be as simple as a narrative sequence of plausible events. Formal scenarios may depend on complex models like event trees, decision trees, process risk models, and the like. If probabilistic methods are used the team must possess skill in the use of these methods. Scenario construction, especially in planning, can require the imagination to think about the future without necessarily extrapolating from the past. Other times, for example when constructing fault tree scenarios, scenario construction can require intimate knowledge of complex systems.

- Easy to run the sensitivity analysis
- Simple methods can reveal sensitivities that are useful to decision making
- Commercially developed software and several USACE certified planning models support useful sensitivity analysis techniques.

Weaknesses:

- Limited by the assessor's awareness of uncertainty
- Some tools are quite sophisticated and require quantitative skills that are not always found on staff

8.8 Scenario Analysis

8.8.1 Overview of the Technique

When the future is very uncertain, scenarios can be used to describe the most significant ways the future might evolve. Scenarios are coherent narratives created to describe uncertain conditions, usually found in the future. Scenario analysis enables assessors to identify a limited number of futures in order to explore how different risks might unfold in the future.

8.8.2 How the Technique Is Used

Scenario analysis is used extensively in planning studies and it can be successfully adapted to operations and regulatory functions to support policy and other decisions, plan future strategies and courses of action and consider existing activities. It can be a valuable tool to anticipate how risks of all kinds might develop in the short- and long-term time frames.

8.8.3 Inputs

The inputs for scenario analysis include:

- A well-defined question to be answered or problem to be examined,
- An interdisciplinary team of people that can identify the appropriate number of scenarios and an appropriate level of detail for each,
- A scenario structuring tool, which may be informal or formal, and
- Analysts to do the appropriate analysis within each scenario identified.

8.8.4 Process

Scenarios are the stories we tell about how a situation arises or is resolved in the future. A scenario is best described in a narrative similar to a newspaper article written about a specific future condition. Significantly, a scenario is different from the analysis that can be done within a scenario. Once a future, or other, scenario is defined, it can be constructed and analyzed in a wide variety of ways. Scenario analysis is the name given to the development of this broad array of stories about the future, descriptive models and the analysis that can be done with them (Yoe, 2012).

8.8.5 Outputs

The outputs of a scenario analysis include a discrete number of clearly defined and well-articulated scenario narratives and the requisite analyses that are conducted within that scenario. For example, hydraulic and hydrologic analyses for a specific location may be conducted for existing conditions (a no-change scenario), a scenario with maximum development in the watershed, and a scenario with significant climate change and sea level rise. This would result in three sets of analytical results that can be expected to differ significantly from one another.

Monolithic scenario analysis relies on the development of a single unchallenged scenario to describe an uncertain situation or future. The most likely future condition in a planning area without a federal project is a good example of how USACE has used monolithic scenarios in the past. Unfortunately, a single scenario forces analysts to ignore significant sources of uncertainty.

Deterministic scenario analysis (DSA) defines and examines a limited number of discrete and specific scenarios. This tends to rely on a small number of possible future states of the system being modeled. Scenario planning relies on the development of a limited number of with and without project conditions and is a good example of DSA. This approach has limitations too. Only a limited number of scenarios can be considered and the likelihoods of these scenarios cannot be estimated with much confidence. This approach is also inadequate for describing the full range of potential outcomes. So although it can be very useful for planning and strategic decision making when there are a few very significant sources of uncertainty, it is less useful when there is more uncertainty with few if any most significant sources.

Probabilistic scenario analysis (PSA) can overcome these limitations by combining probabilistic methods, for example the Monte Carlo process, with a scenario generation method like event tree models. Many of the USACE planning models produced by the Hydrologic Engineering Center could be consider PSA tools. PSA's are useful for exploring the range of potential outcomes that may be encountered in the future.

8.8.6 Strengths and Weaknesses

Both deterministic and probabilistic scenario analysis take a range of possible futures into account. This is usually going to be preferable to considering a single scenario in an uncertain situation. It is also preferable to the traditional approach of relying on high-medium-low forecasts that assume future events will follow past trends. This is especially important for situations where there is little current knowledge on which to base predictions (e.g., the effectiveness of large scale aquifer storage and recovery in Florida) or where risks are being considered in the longer term future (e.g., sea level change).

An associated weakness is that some of the scenarios may be unrealistic and unrealistic results may not be recognized as such. The availability of data and the ability of the analysts and decision makers to be able to develop realistic scenarios are the two most common constraints of this method.

8.9 Uncertainty Decision Rules

8.9.1 Overview of the Technique

Risk managers must address uncertainty in their decision making, especially when the consequence of making a wrong decision is a concern. A number of decision rules have been developed for making decisions under uncertain conditions. Some of the more common ones include:

- Maximax criterion—choosing the option with the best upside payoff
- Maximin criterion — choosing the option with the best downside payoff
- Laplace criterion — choosing the option based on expected value payoff
- Hurwicz criterion — choosing an option based on a composite score derived from preference weights assigned to selected values (e.g., the maximum and minimum)
- Regret (minimax) criterion – choosing the option that minimizes the maximum regret associated with each option.

8.9.2 How the Technique Is Used

These are rules that can be used in lieu of deterministic decision rules like choosing the plan with maximum net National Economic Development benefits, although deterministic rules can sometimes be modified to accommodate these rules.

8.9.3 Inputs

The inputs required for uncertain decision rules include:

- Uncertainty estimates for the risk manager's decision criteria,
- Alternative decision choices, and
- Knowledge of the mechanics of the rule used to address the decision uncertainty.

8.9.4 Process

Imagine that a new strategy for operating and maintaining projects across a division is being considered and the accumulated present value of the difference in O&M costs over a decade are summarized in Table 8.1. A pessimistic view of the uncertain future will result in greater O&M expenditure while the most likely and optimistic view will produce net savings as shown.[25] Table 8.1 will be used to illustrate the use of the decision rules.

[25] Not every decision problem involves different future states of the world. It is conceivable that three different strategies might result in a distribution of possible outcomes because of the uncertainty attending their estimation. If you think of the pessimistic state as the minimum value, the most likely as the mean and the optimistic as the maximum the application of these rules across a distribution of possibilities is little changed.

State of the World	Strategy 1	Strategy 2	Strategy 3
Pessimistic	-$8,876,515	-$12,451,560	-$10,578,176
Most Likely	$7,028,208	$130,636	$817,531
Optimistic	$12,767,740	$97,733,095	$11,559,042

Table 8.1: Hypothetical savings for three O&M strategies under three different future states of the world

The maximin criterion chooses the alternative that yields the "best" of the worst outcomes. In this case, it maximizes the pessimistic outcome with Strategy 1. Maximin is often favored by those who have a pessimistic outlook on the future and who are risk averse. Under the maximin, or Wald, decision criterion, only the minimum payoffs of each strategy are considered. Relying on a single value like this is a weakness of this rule. Its strength is its risk adverse bias.

The maximax criterion is the opposite of the maximin criterion. It would lead to the selection of Strategy 2 because it is based on an optimistic outlook , i.e. risk preferring behavior. This criterion also uses one value by focusing on the "best" of the best outcomes, or the maximum of all maximum payoff. Both of these criteria could be easily applied using the results of a probabilistic risk assessment.

Unlike the maximin criterion, which appeals to the cautious, and the maximax criterion, which appeals to gamblers, the Laplace criterion appeals to the risk neutral. The Laplace criterion is based on expected values. If each of the values in Table 8.1 represents a point estimate from a deterministic scenario analysis, then the expected value is the weighted sum of the three states of the world. Absent a more objective set of probability estimates to attach to the different states of the world that could be realized, the Laplace criterion assigns equal probabilities to all states and their outcomes.

Strategy 1's expected value is $3.6 million, strategy 2 is $28.2 million and strategy 3 is $0.6 million, making strategy 2 the preferred approach. However, had these been the results of a probabilistic risk assessment where the most likely value was the mean, Strategy 1 would be the preferred decision.

The Hurwicz criterion is a compromise between the maximin and maximax criteria. It relies on a coefficient of optimism (α) that ranges from 0 to 1 to represent the decision maker's optimism. An α = 0 indicates total pessimism (equivalent to the maximin criterion) and α = 1 indicates total optimism (equivalent to the maximax criterion). The coefficient of pessimism is defined as 1-α. This weighted payoff is defined:

Hurwicz payoff = α(maximum payoff) + (1-α)(minimum payoff)

Suppose $\alpha = .4$, the Hurwicz payoffs (HP) of the three alternatives in millions are: -$0.2 million, $31.6 million, and $2.7 million, making Strategy 2 the preferred strategy.

The regret, or minimax, criterion is based on the economic concept of opportunity cost. The opportunity cost of a strategy for a particular state of the world is the difference between its payoff and the payoff of the highest-yielding alternative for that state of the world. Let the pessimistic view represent the minimum and the optimistic view the maximum payoff as shown in Table 8.2; all values are in millions of dollars.

Alternatives	States of the World		
	Pessimistic	Most Likely	Maximum
Strategy 1	-$8.9 M	$7.0 M	$12.8 M
Strategy 2	-$12.5 M	$0.1 M	$97.7 M
Strategy 3	-$10.6 M	$0.8 M	$11.6 M

Table 18.2. Inputs for developing a regret matrix

Using the inputs of Table 8.2, the regret matrix of Table 8.3 can be prepared. If strategy 1 is chosen and a pessimistic state of the world occurs, there is no regret because strategy 1 yields the best possible outcome in a pessimistic state. It also yields the best result in a most likely state. If the optimistic state is realized, however, the gain is $84.9 million less than it could have been had you picked strategy 2. The regret matrix is completed by examining the regret of each choice under each possible state of the world. Once the maximum regret column is completed the task is simply to choose the strategy that will minimize the maximum regret experienced by a wrong choice. In this case, choosing Strategy 2 could mean no more than a $3.6 million regret so it is the best choice using the regret criterion.

	Regret Matrix (Millions $)			
	Minimum	Most Likely	Maximum	Maximum Regret
Strategy 1	$0	$0	$84.9	$84.9
Strategy 2	$3.6	$6.9 M	$0	$3.6
Strategy 3	$1.7	$6.2 M	$86.1	$86.1
			Minimax	$3.6

Table 8.3 Regret matrix and the minimax

Each of these rules produces a decision based on a defined set of preferences.

8.9.5 Outputs

The outputs usually include a ranking of alternative solutions to the decision problem.

8.9.6 Strengths and Weaknesses

Strengths:

- use of rules lead to a decision

Weaknesses:

- rules rely on a limited amount of information when applied to a probabilistic risk assessment

8.9.7 Examples of Use

These rules would most likely be used in situations where USACE exercises some discretion over decision making, such as in allocating resources at the program and budget levels as opposed to planning, where National policy guides the decision-making process.

8.10 Subjective Probability Elicitation

8.10.1 Overview of the Technique

Subjective probability elicitation can be considered a special case of expert elicitation where the specific purpose of the elicitation is to capture an expert's knowledge about the uncertain probability of some event. This situation arises often enough to warrant separate consideration.

8.10.2 How the Technique Is Used

Probability is the language of uncertainty. The variability in the world can often be well described by frequency data when they are available. Knowledge uncertainty, however, is usually better described by the belief type of probability most often called subjective probability. Subjective probabilities are also useful for describing natural variability when data are insufficient for doing so.

> Experts can be expected to vary in their judgments about the subjective probability of an event. Consequently, there are no 'correct' subjective probabilities. The quality of a subjective probability estimate will always depend on the knowledge and experience a person has and the process used to elicit that information in a useful format.

Subjective probabilities are not pre-existing numbers waiting within us to be revealed to the world. According to the subjectivist view, the probability of an event (including an event such as P(X)>x) is a measure of a person's degree of belief that it will occur. Thus, probability is not a property of the event but a property of the expert's judgment (Morgan and Henrion, 1990). These are values that must be carefully constructed when needed and they are best constructed through a rigorous elicitation process. The elicitation technique matters because expert's statements of probability are likely made in response to the question asked rather than based on pre-analyzed and pre-formed coherent beliefs. The purpose of elicitation is to represent the expert's knowledge and beliefs accurately in the form of a good probability distribution (O'Hagan et al., 2006).

A formal elicitation process is not necessary for every uncertain probability for which data are lacking. Uncertainties that occur routinely should be treated routinely. Much of the time these uncertain probabilities will be described using uniform, triangular, pert or other nonparametric distributions for which the individual assessor will estimate the defining values.

Summarizing Yoe (2012), a formal elicitation process should be used when a problem is complex, highly visible, involves a controversial issue, or trust in the analytical work is an issue. This need is amplified uncertain values provided by USACE, which has stewardship responsibilities for water resources, form the basis for public decision. The number of stakeholders and diversity of their views along with media scrutiny and likelihood of a court challenge will also increase the need for a formal elicitation.

To develop useful elicitations procedures and to obtain useful probability estimates it helps to understand the heuristics and other experts used in forming judgments about uncertain quantities (Tversky and Kahneman, 1974). The most common heuristics include:

- Availability
- Representativeness
  - Conjunctive failure
  - Base rate neglect
  - Law of small numbers
  - Confusion of the inverse
  - Confounding variables
- Anchor and adjust
- Motivational bias

8.10.3 Inputs

The inputs to a subjective probability elicitation include:

- a well-defined elicitation problem,
- a group of experts,
- an expert facilitator, and
- an elicitation protocol that includes training the experts.

It may include a calibration process and an actual elicitation.

8.10.4 Process

The process is somewhat variable; but once the problem, the experts and the facilitator are identified an elicitation protocol best describes the process. A five-step protocol for elicitation developed by O'Hagan et al. (2006) is shown below.

1. Background and preparation: the client identifies variables to be assessed.
2. Identify and recruit experts: the choice may be obvious or it may require some effort. Six criteria for experts:
   a. Tangible evidence of expertise

b. Reputation
c. Availability and willingness to participate
d. Understanding of the general problem area
e. Impartiality
f. Lack of economic or personal stake in the potential findings

3. Motivating and training the experts: assure experts uncertainty is natural. Training should have three parts:
   a. Probability and probability distributions
   b. Introduction to most common judgment heuristics and biases as well as ways to overcome them
   c. Practice elicitations with true answers unlikely to be known by the experts
4. Structuring and decomposition: spend time exploring dependencies and functional relationships that meet agreement by experts; precisely define quantities to be elicited.
5. The elicitation: an iterative process with three parts:
   a. Elicit specific summaries of expert's distribution
   b. Fit a probability distribution to those summaries
   c. Assess adequacy: if adequate stop; if not, repeat the process with experts making adjustments

The duration of disruption to navigation from an emergency loss of the navigation pool behind a dam is a continuous random variable. Imagine a need to elicit the expert's cumulative distribution function for the duration of the disruption. The goal is to elicit information about a relatively few number of individual (p,x) pairs that enable us to reproduce the expert's beliefs in the form of a probability distribution. The data points or summaries we seek can be based on probabilities or on quantity values, although probabilities may be the most common form of elicitation. One strategy is to seek specific quantiles (points taken at regular intervals) that can be used to construct a cumulative distribution function (CDF), beginning with the median, p = .5, value to divide all possible values in half. The expert is then asked to find the midpoint of each remaining range. This method produces the median, then the quartiles, then the 12.5, 37.5, 62.5, and 87.5 percentiles, etc. Examples of questions adapted from O'Hagan et al. (2006) follow. Bear in mind the context is an emergency that causes loss of pool.

Can you determine a navigation disruption duration such that any disruption is as likely to be longer than this duration as it is to be shorter than this duration?

For contrast, an alternative formulation of the second question might be, "Give a navigation disruption duration such that you think an actual disruption has a 50% chance of being less than it." Although there can be many formulations of the specific questions, none of them are transparently simple to comprehend. However, a distribution can be elicited in this fashion.

Fixed value methods work a little differently. For this approach we might ask, "What is the probability that a navigation disruption will be 21 days or less?" Different duration lengths can be used to flesh out the shape of the CDF.

It is widely reported in the literature that most people, including experts, are poorly calibrated and tend to be over or under confident (Morgan and Henrion, 1990). If we conduct a formal subjective probability elicitation, it would be nice to have some confidence in its results. The catch is our expert says there is a .95 chance navigation will be disrupted for less than 45 days. If it is disrupted for 60 days, does that mean our expert is wrong? The answer, of course, is no. Only statements of absolute certainty, i.e., p = 0 or p = 1, can be proven right or wrong by subsequent observations. That means the strength or weakness of an elicitation more or less rises and falls with the process and the calibration of the experts.

Experts can be calibrated if the elicitation is important enough. This enables you and the experts to learn how well they tend to recognize and evaluate their uncertainty. The most common calibration method is to ask a series of questions with factual answers that are unlikely to be known by the expert. The questions might include such things as: what is Avogadro's number, where is Timbuktu located, or how long is a U.S.$20 bill? Experts can be asked to express the likelihood their answer is correct. With enough such questions one would expect a well-calibrated expert to get about 60% of the questions she said she was 60% confident in to be correct, and so on.

Binary calibrations are another common technique. A third technique asks experts to estimate quantitative questions with 90% confidence intervals. The calibration process prior to an elicitation is one of the most effective ways to make an expert aware of their estimation bias. Once aware, many educated experts are able to neutralize that bias.

8.10.5 Outputs

The actual elicitation itself can vary but it is likely to be seeking one of three kinds of information: a point estimate of some sort, a probability distribution, or the parameters of a specific probability distribution.

8.10.6 Strengths and Weaknesses

Strengths:

- Can produce estimates of probabilities that are otherwise unavailable
- Rigor of the process can be adjusted to the needs of the assessment

Weaknesses:

- Experts are poorly calibrated and are well known to produce poor estimates of subjective probabilities absent training to offset the heuristics people rely on and calibration to help them recognize their bias
- Unacceptable non-rigorous protocols may be accepted

8.11 Safety Assessment

8.11.1 Overview of the Technique

A safety assessment seeks to determine whether a situation meets or fails to meet a specific safety requirement rather than to try to identify a specific level of risk. A safety assessment usually consists of some form of a ratio of an actual value compared to a standard or value considered to be safe for the population.

8.11.2 How the Technique Is Used

This method requires some authority to make a specific determination of a level of performance that will be considered safe. The denominator contains the safety standard and the numerator contains the measurement. The most familiar examples may be from the food safety arena where the quotient is $\frac{Estimated\ daily\ intake}{Acceptable\ daily\ intake}$ for a given food substance of concern. Similar quotients are used for exposure to toxins in the environment. In engineering, safety analyses might compare $\frac{demand}{capacity}$ for a structural component like a rebar, a concrete monolith, electrical component and the like. When the quotient exceeds one, the situation is considered less safe than when the quotient is one or less. Conversely, a factor of safety might be defined with a ratio. Assume for simplicity a limit state or factor of safety for a tension bar defined as $\frac{F_t A}{P}$, where F_t is ultimate tensile strength in ksi, A is area in square inches, and P is load measured in kips. Let the arguments for this factor of safety be as defined below, where F_t and P are described by normal distributions with the parameters shown in Table 8.4. A sample calculation of the factor of safety is shown below. However, there are two random variables whose precise values are uncertain.

Random Variables	Mean	Std Dev	Distribution
Ultimate Tensile Strength, F_t (ksi)	40	4	40
Load, P (kips)	15	3	15
Constant			
Area, A (in^2)	0.5		
Limit State			
Factor of Safety FS = $F_t A/P$	1.33		

Table 8.4: Sample factor of safety analysis for a tension bar

A Monte Carlo process was used to generate 100,000 separate estimates of the factor of safety. The results are shown in Figure 8.10. Notice that 8.3% of the calculations resulted in a factor of safety less than one. In this instance values less than one are undesirable. This is the probability of an unsatisfactory performance P(u) and reliability is defined as:

R = 1 - P(u) thus, the tension bar reliability is 91.7%.

It is important than a safety assessment is based on populations; it is usually not considered as reliable for any one member of a population. In other words, reinforcing bars with a quotient greater than one fail more often than those with a quotient less than one. Not every bar with a value greater than one will fail and failures can be observed in bars with values less than one.

8.11.3 Inputs

The inputs for this tool require:

- A population of things to be evaluated,
- A well-defined numerator and denominator for the quotient, and
- Measurement data for the quotient.

8.11.4 Process

The process is to calculate the value of the numerator and the value of the denominator and to compare the two. Ratio values that exceed the safety threshold (often a value equal to one) are considered less safe and in need of risk management action.

8.11.5 Outputs

The output is a so-called determination of "safe" or "not safe." We say "so-called" because such a bright line determination of safety requires a standard for determining safety. Standards require someone to make a value judgment about the level of performance that is considered safe.

8.11.6 Strengths and Weaknesses

Strengths:

- Can be used relatively quickly to screen whether a situation could result in adverse consequences
- Much of the data, presumably including the standard, are already available
- Method is consistent in its data requirements and the calculation of safety factors
- Method has a conservative bias that is sometimes favored by decision makers

Weaknesses:

- May not use all available study data because it focuses on a ratio of values
- Conservative bias is also a weakness

8.12 Scenario Planning

8.12.1 Overview of the Technique

Scenario planning relies on the use of alternative plausible scenarios to describe uncertain futures. More traditional planning processes, by contrast, have relied on a single future scenario to describe an uncertain future condition. The failure of such traditional planning methods along with the growing emphasis on the need to address uncertainty in a more intentional manner have given rise to the use of scenario planning in an increasing number of applications.

> Example: Ecosystem Restoration
>
> Consider an ecosystem restoration project where new legislation reducing phosphorous loading in the watershed has been passed. How does one forecast the future performance of the project when it is unknown how successful the law will be in reducing phosphorous loads and it is unknown whether the future will comprise relatively dry or relatively wet years?
>
> These two uncertain variables create four rather distinct future scenarios: high phosphorous and wet years, low phosphorous and wet years, high phosphorous and dry years, and low phosphorous and dry years. Each of these could be a significantly different future scenario.

The first use of scenarios in a planning context is thought to have been in the military strategy studies done by the RAND Corporation for the U.S. Government in the 1950s. The theoretical foundations of scenario forecasting, an important component of scenario planning, were principally developed in the 1970s. Royal Dutch Shell is regularly credited with popularizing and modernizing the use of scenario planning for strategic planning in the early 1970s (Wack, 1985a, 1985b). Scenario planning was developed into its current state during the second half of the 20th century primarily in Europe.

8.12.2 How the Technique Is Used

The USACE planning process compares the most likely alternative condition for the study area without a project in place to the most likely alternative future condition with a project in place in order to estimate the effects of a plan that will be used to decide which is the best plan. Scenario planning would be used when it is not possible to identify any one of the possible without- or with- condition scenarios as most representative of the future.

Scenarios are not predictions or variations around a theme. Neither are they alternative forecasts of a key variable. Scenarios are narratives that describe distinctly different alternative plausible views of the future. Once described, the analytical work required for decision making is completed consistent with the assumptions and framework of each scenario. Thus, scenario planning is to be used when a single without condition scenario cannot adequately characterize the potential shape of a very uncertain future. Typically, this will occur when there exist one or more critical uncertain quantities or conditions that could alter the shape of the future in significantly different ways.

8.12.3 Inputs

The inputs for scenario planning include:

- A well-articulated planning problem,
- A need for alternative views of the future (i.e., significant uncertainties that cannot be resolved in the planning process), and
- A planning team with knowledge of the scenario planning process.

8.12.4 Process

Scenario planning produces a small number (usually two to four) of future scenarios, as seen in Figure 8.11. Technical analyses are conducted under each of the alternative scenarios. Referring to the preceding textbox example (Ecosystem Restoration), water quality analyses, for example, would be completed for each of the four phosphorous/runoff scenarios.

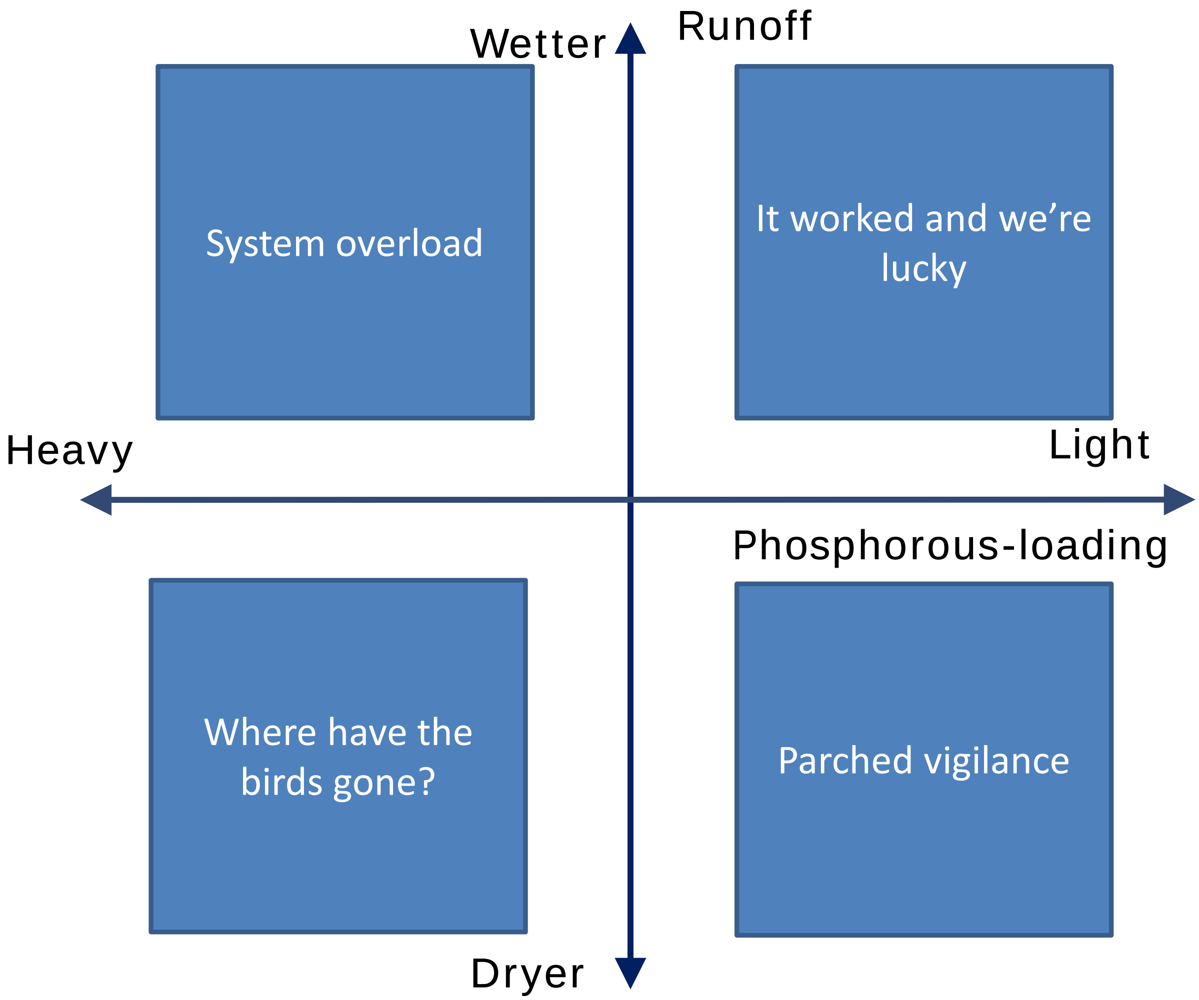

Figure 8.11: Four different scenarios considering runoff and phosphorous loading as the axes of uncertainty

Ralston and Wilson (2006) describe the scenario planning process in 18 steps arranged in four major tasks as follows:

I. Getting Started

1. Develop case for scenarios
2. Get executive support and participation
3. Define decision focus
4. Design process
5. Select facilitator
6. Form scenario team

II. Laying Environmental-Analysis Foundation

7. Gather data and view
8. ID key decision factors

9. ID critical forces and drivers
10. Conduct focused research on key issues, forces, & drivers

III. Creating the Scenarios

11. Assess importance and predictability/uncertainty of forces/drivers
12. ID key axes of uncertainty
13. Select scenario logics to cover uncertainties
14. Write stories for scenarios

IV. Moving from Scenarios to Decisions

15. Rehearse future with scenarios
16. Decision recommendations
17. Identify signposts to monitor
18. Communicate results

8.12.5 Outputs

This scenario planning approach will typically result in the identification of four different scenarios. Narratives are written for each one. In the traditional practice of scenario planning, each of the four scenarios would be quantified similar to the way it is done for the single future scenario planning in use today. These multiple analyses would more fully characterize the range of potential effects of a project so that more robust solutions could be identified. Scenario planning would, therefore, produce solutions that will be effective no matter which view of the future is ultimately realized.

8.12.6 Strengths and Weaknesses

Strengths:

- All involved in the planning process must challenge own world view
- Exposes blind spots about existing uncertainties
- Planners are better able to address the uncertainty in a planning effort using these techniques or those described in the preceding chapter

Weaknesses:

- Effort required
- Technical complexity of conducting analyses under multiple sets of assumptions

8.13 Vulnerability Assessment

8.13.1 Overview of the Technique

Vulnerability assessment identifies a system’s vulnerabilities to specific threats that could result in adverse consequences. These systems include, but are not limited to, information technology systems, energy supply systems, water supply systems, transportation systems, communication systems and infrastructure systems of all kinds. They could, under some circumstances, include natural systems as well. In practical terms, a system is often a facility or process. Threats have a broad spectrum and include natural, criminal, terrorist and accidental threats for a given system. In the case of USACE, these systems include projects or facilities at a specific location. The adverse consequences can be economic, environmental, political, social or other consequences.

8.13.2 How the Technique Is Used

Vulnerability implies the presence of a threat. Vulnerability assessment is used to identify elements of a system that are most vulnerable so that vulnerability can be reduced through risk management measures. Since the events of 911, vulnerability assessment has tended to focus more frequently on terrorist threats. Consequently, vulnerability, as used here, means that a person intent on doing harm to others can recognize the desired target, gain access to it, complete the attack undetected and withdraw from the target. One's vulnerability is enhanced if the attack has the desired effect and is difficult from which to recover.

8.13.3 Inputs

Inputs required for a vulnerability assessment include:

- A well-defined risk management problem,
- A vulnerability assessment team,
- A vulnerability assessment methodology, and
- An intimate understanding of the system to be assessed.

8.13.4 Process

The Department of Defense (DoD) has long used the CARVER method as an offensive target analysis tool. Since 911, it has become a very effective defensive tool for critical infrastructure protection known as CARVER + Shock.

CARVER is an acronym for the following six attributes used to evaluate the attractiveness of a target for attack:

- *Criticality* - measure of the adverse impacts of a successful attack
- *Accessibility* - ability of attacker to physically access and egress from target
- *Recuperability* - ability of the system to recover from an attack
- *Vulnerability* - ease of accomplishing attack once the target is accessed
- *Effect* - amount of direct loss from an attack as measured in appropriate units (lives lost, production lost, service disruption, and so on)
- *Recognizability* - ease of identifying the target

A seventh attribute, Shock, has been added to the original six to assess the combined health, economic and psychological impacts of a successful attack on the target.

The attractiveness of a specific target can be ranked for each of the seven attributes on a scale from one to ten on the basis of scales developed for the specific vulnerability assessment. Conditions that are associated with lower attractiveness (or lower vulnerability) are assigned lower values (e.g., 1 or 2), whereas, conditions associated with higher attractiveness as a target (or higher vulnerability) are assigned higher values (e.g., 9 or 10). Once all seven elements of a target have been assessed, the total score is calculated and targets can then be ranked based on their individual vulnerability.

The steps in a CARVER + Shock vulnerability assessment (FDA, 2007) are summarized below.

- Establish Parameters: Answer the question of what you are trying to protect and from what you are trying to protect it.
- Assemble Experts: Convene a team of subject matter experts to conduct the assessment.
- Detail System Assessed: Develop a description of the system under evaluation including any subsystem, complexes, components and nodes (its smaller structural parts) that could be a specific target.
- Assign Scores: Once the infrastructure has been broken down into its smallest parts, these are ranked or scored for each of the seven CARVER-Shock attributes to calculate an overall score for that node. Examples can be found at http://www.vet.utk.edu/cafsp/resources/pdf/CARVER%20plus%20Shock%20Primer.pdf accessed December 31, 2012.

Apply What Has Been Learned: Once the critical nodes of the system have been identified, develop a plan to put countermeasures in place that minimize the attractiveness of the nodes as targets.

8.13.5 Outputs

After an assessment is completed, every potential target identified in the process will have an overall vulnerability score that can be used to identify targets that need to be hardened against attack.

8.13.6 Strengths and Weaknesses

Strengths:

- The CARVER+Shock method is well established and tested methodology.
- Software tools have been developed to conduct these analyses for food production infrastructure. See http://www.fda.gov/Food/FoodDefense/ToolsResources/ucm295900.htm accessed December 31, 2012.
- Additional adaptations of such software tools are possible if warranted.

Weaknesses:

- CARVER+Shock is based on the assumption that ‘good guys’ can look at a system and see what ‘bad guys’ see.
- Vulnerability assessments are limited by their focus on known vulnerabilities.

8.14 Fragility Curves[26]

Fragility curves are becoming increasingly common components of flood risk assessments. A report published by USACE (ERDC, 2010) describes the concept of the fragility curve and shows how fragility curves are related to more familiar reliability concepts, such as the deterministic factor of safety and the relative reliability index. Examples of fragility curves are identified in the literature on structures and risk assessment to identify what methods have been used to develop fragility curves in practice. Four basic approaches are identified: judgmental, empirical, hybrid, and analytical. Analytical approaches are, by far, the most common method encountered in the literature. This group of methods is further decomposed based on whether the limit state equation is an explicit function or an implicit function and on whether the probability of failure is obtained using analytical solution methods or numerical solution methods. Advantages and disadvantages of the various approaches are considered.

8.15 Environmental Risk Assessment

8.15.1 Overview of the Technique

Environmental risk assessment (ERA) is a process that was developed in the U.S. by the Environmental Protection Agency (EPA) to address risks to ecosystems, plants, animals and humans as a result of exposure to a range of environmental hazards, including chemicals, anthropogenic activity, microorganisms and the like. The basic approach begins with the hazard or source of harm and the pathways by which the hazard can affect a susceptible target population. It culminates in an estimate of the likelihood and consequences of that harm. The models have evolved and are sometimes called ecological risk assessment, although that term tends to be reserved by EPA for assessing the risks of pesticides in the environment. These ERA models are not suitable for estimating habitat units but they are valuable for consideration of broader scope environmental and ecological risks.

8.15.2 How the Technique Is Used

Early risk assessment models were geared toward the estimation of cancer risks in humans. As risk assessment progressed, the need to address a wider array of risk assessment endpoints became evident and the ERA model was initially developed. This was one of the first assessment models to rely heavily on pathway analysis. Pathway analysis explores the different routes by which a target endpoint might be exposed to a source of risk. Pathway analysis has since been adapted and used in many different risk applications. It has proven especially useful for identifying risk management options to reduce unacceptable risk.

[26] This is abstract from USACE ERDC, “Beyond the Factor of Safety: Developing Fragility Curves to Characterize System Reliability,” Martin T. Schultz, Ben P. Gouldby, Jonathan D. Simm, and Johannes L. Wibowo, ERDC SR-10-1, July 2010.

8.15.3 Inputs

ERA inputs (EPA, 1997) include:

- Overall purpose and general scope of the risk assessment ;
- Products needed by management for risk decision making ;
- Approaches, including a review of the risk dimensions and technical elements that may be evaluated in the assessment ;
- Relationships among potential assessment end points and risk management options;
- Analysis plan and a conceptual mode;
- Resources (for example, data or models) required or available;
- Identity of those involved and their roles (for example, technical, legal or stakeholder advisors); and
- Schedule to be followed (including provision for timely and adequate internal and independent external peer reviews).

8.15.4 Process

The ERA process is summarized in Figure 8.12. The main steps of the process are problem formulation, analysis and risk characterization. Data are collected and analyzed throughout the process. Critical tasks in the process include selecting the data that will be used and determining its strengths and weaknesses, an analysis of stressors and their distribution in the environment, and potential and actual exposure to the stressors.

8.15.5 Outputs

Stressor-response relationships, exposure and effects profiles, and a risk characterization are primary outputs of the process. The EPA website for Ecological Risk Assessment http://www.epa.gov/pesticides/ecosystem/ecorisk.htm (Accessed December 31, 2012) provides access to a wealth of related resources.

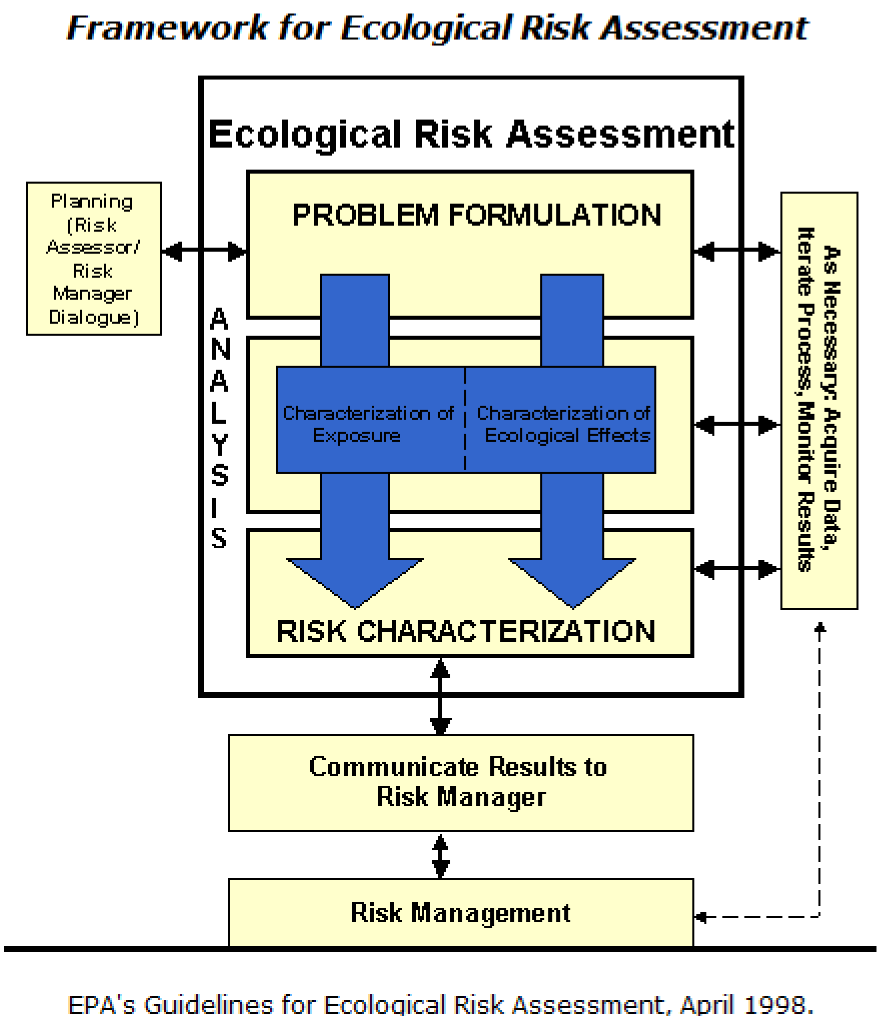

Figure 8.12: EPA's Ecological Risk Assessment Model

8.15.6 Strengths and Weaknesses

Strengths:

- Detailed understanding and presentation of the nature of the problem and the factors that contribute to environmental risk(s)
- Pathway analysis can identify critical points in the chain of risk events that show how and where it may be possible to improve risk controls or introduce new ones

Weaknesses:

- Relatively extensive data requirements
- Without extensive data, ERA can have a high level of uncertainty associated with it

8.16 Dose-Response Curve

8.16.1 Overview of the Technique

A Dose-Response Curve is the primary model used to characterize the adverse human health effects of chemicals, toxins and microbes in the environment. The curve shows the relationship between the dose (magnitude and frequency) of a stressor (e.g., concentration of a pollutant, number of microorganisms, intensity of radiation) to the response of the receptor organism (often a human) under study. A chemical dose may be measured in mg per kg of bodyweight daily for a lifetime. A microbial dose may be the number of organisms consumed or absorbed. The response is generally some measure of an adverse health effect. It may be the probability of an illness, cancer or death; the number of excess tumors produced by such a dose; blood pressure increases; organ atrophy; or any other of a large number of adverse effects.

8.16.2 How the Technique Is Used

Dose-response relationships are used in consequence assessments to characterize the harm that can result from exposure (likelihood assessment) to the hazardous dose. Doses are typically shown on the X axis and responses on the Y axis. Figure 8.13 shows a stylized dose-response curve.

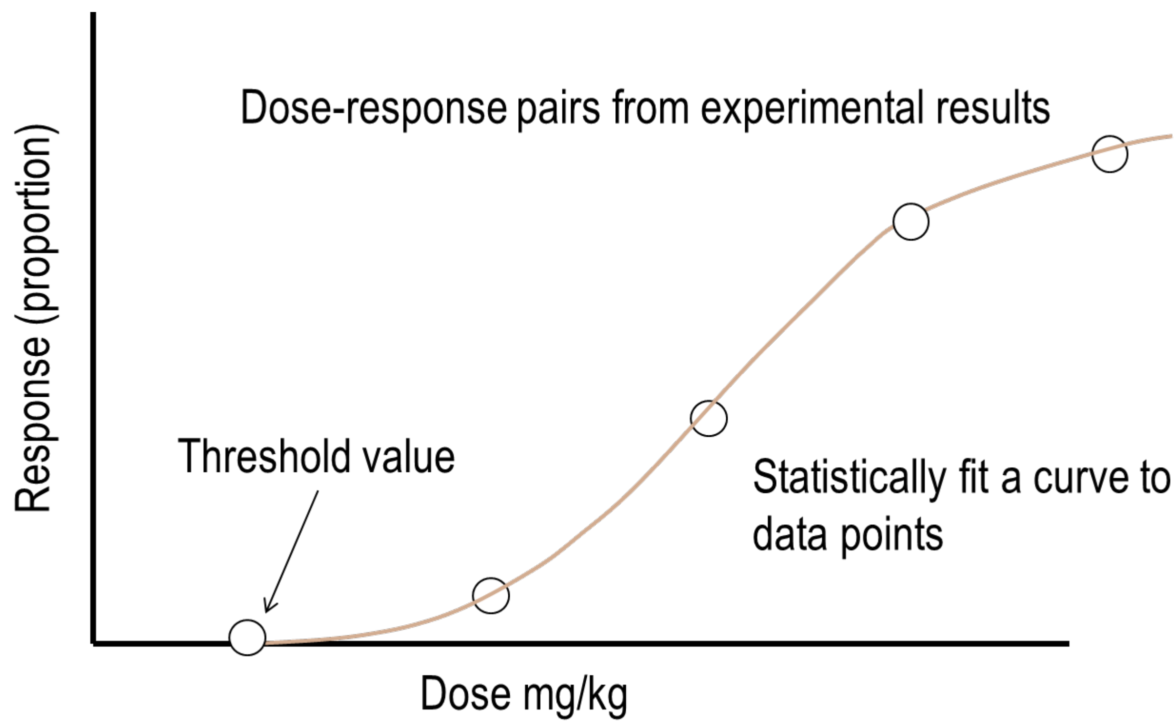

Figure 8.13: Stylized dose-response curve

8.16.3 Inputs

A relationship requires:

- A clearly identified hazard,
- A defined dose, and
- A defined adverse effect (response).

8.16.4 Process

The data must come from valid scientific experiments or epidemiological studies that produce a dose-response data point. These points are collected from the available data and a curve is fit to the points. The first point above zero on the curve is called the threshold dose. Doses below the threshold are assumed to have no adverse effects.

8.16.5 Outputs

Dose-response curves are part of a risk assessment. They help answer the "what can go wrong" question. It is still necessary to describe how the receptor organism may become exposed to the hazard and at what dose. A dose-response and exposure assessment are usually sufficient to develop a risk estimate for this class of hazards.

8.16.6 Strengths and Weaknesses

Strengths:

- Widely accepted technique with well-known data requirements
- Successfully used in decision making for many years

Weaknesses:

- Lack of data in the low dose ranges (hence an inability to establish a threshold that has led to the widespread use of no threshold models)
- Available data are frequently for a species other than the receptor species, leading to extrapolation issues (e.g., many human dose-response curves are based on animal feeding data)

8.16.7 Examples of Use

Dose-response relationships can be used to investigate the risks associated with dredge material and sediments as well as for ground water pollution, oil spills and other situations where toxic contaminants have been introduced to a natural environment. The concept is rather flexible and depth-damage functions routinely used in flood risk management studies are themselves dose-response curves.

8.17 Root Cause Analysis

8.17.1 Overview of the Technique

Root cause analysis or root cause failure analysis is used to identify what, how and why something happened, so that recurrences can be prevented. It is often used to analyze major asset losses and it is conducted after a failure event. When the process is applied to economic or financial losses it is called loss analysis.

When a problem occurs, if you only fix the symptoms you can expect to have to fix it again and again. Looking deeper to figure out why the problem occurs enables one to fix the underlying systems and processes that cause the problem.

8.17.2 How the Technique Is Used

Root cause analysis is used for accident investigations and to enhance occupational health and safety. It's also used to improve reliability and maintenance of technological, engineering and infrastructure systems, as well as for quality control.

8.17.3 Inputs

Because root cause analysis usually is used in relation to a system failure, evidence gathered from the failure or loss is a critical input. Evidence from similar failures may also be useful. Additional information may be required to test specific hypotheses about the causes of a failure.

8.17.4 Process

The essential logic of root cause analysis relies on the assumption that systems and events are interrelated. An action or event in one area triggers an action or event in another until it results in the observed failure. Root cause analysis traces back these sequences of events to discover where the problem started and how it grew into the loss under investigation. Experts are also needed for a root cause analysis.

Mind Tools[27] identifies three groups of causes. Physical causes involve tangible, material items that failed in some way. For example, a gate chain breaks. Human causes result when people do something wrong or fail to do something that was needed. Human causes can lead to physical causes. For example, the chain may have failed because it was not maintained or inspected for wear and tear. Organizational causes reflect faulty systems, processes or policies used to make decisions. For example, gate chain inspections are eliminated because gate chains rarely fail.

The process begins by establishing the scope and objectives of the root cause analysis. This is followed by gathering data from the failure or loss. Next, a structured analysis is conducted to determine the root cause. Solutions are developed and recommendations are made, implemented and monitored. MindTools (undated) identifies a simple five-step process.

Step One: Define the Problem

- What do you see happening?
- What are the specific symptoms?

Step Two: Collect Data

- What proof do you have that the problem exists?
- How long has the problem existed?

[27] http://www.mindtools.com/pages/article/newTMC_80.htm, Accessed October 12, 2016.

- What is the impact of the problem?

Step Three: Identify Possible Causal Factors

- What sequence of events leads to the problem?
- What conditions allow the problem to occur?
- What other problems surround the occurrence of the central problem?

Step Four: Identify the Root Cause(s)

- Why does the causal factor exist?
- What is the real reason the problem occurred?

Step Five: Recommend and Implement Solutions

- What can you do to prevent the problem from happening again?
- How will the solution be implemented?
- Who will be responsible for it?
- What are the risks of implementing the solution?

8.17.5 Outputs

The outputs of a root cause analysis include the data and evidence gathered, hypotheses considered, conclusions about the most likely root causes for the failure or loss, and recommendations for corrective action.

8.17.6 Strengths and Weaknesses

Strengths:

- Experts are involved in a structured analysis conducted in a team environment
- Can consider all likely hypotheses and documents the outputs

Weaknesses:

- Required expertise is difficult to find
- Critical evidence may be destroyed during the failure or removed during cleanup
- Danger exists that the team may not allow enough time or resources to fully evaluate the situation

8.17.7 Examples of Use

This technique is most likely to be used to examine and reduce the risks of infrastructure and equipment failures by USACE.

8.18 Fault Modes and Effects Analysis (FMEA) and (FMECA)[28]

8.18.1 Overview of the Technique

Fault Modes and Effects Analysis (FMEA) and Fault Modes and Effects and Criticality Analysis (FMECA) are techniques used to ask: what could go wrong. Both techniques identify the ways components or systems can fail to measure up to design levels of performance. These techniques identify (IEC, 2009):

- All potential failure modes of the various parts of a system,
- The effects these failures may have on the system,
- The causes of failure, and
- How to avoid the failures, and/or mitigate the effects of the , on the system.

8.18.2 How the Technique Is Used

Unlike root cause analysis, these techniques try to predict failures before they occur. FMECA extends an FMEA by ranking each fault mode by its combined likelihood of occurrence and the severity of its consequences. Although this is usually a qualitative or semi-quantitative assessment, it can be quantitative when actual failure rates are available.

These techniques can be applied during the design, construction or operation of a system. They have been used to help select design alternatives with high reliability/dependability and to ensure that all failure modes and their effects on operational success have been considered. They are also useful for developing lists of potential failures as well as the severity of their effects. Both techniques have been used to improve testing and maintenance as well as providing a basis for quantitative reliability and availability analyses. They have been used for component faults in physical systems but also to identify human failure modes and effects. These techniques produce outputs that can become inputs to other techniques such as fault tree analysis.

8.18.3 Inputs

The critical input for FMEA is detailed information about the components of the system. This information must be in sufficient detail to enable experts to analyze the ways each component can fail. Information inputs may include design drawings of the system or component being analyzed along with details about the process and its operating environment that might affect its operation. Historical data on failure rates is essential for a quantitative analysis.

8.18.4 Process

The steps of a FMEA process are shown below and in Figure 8.14

[28] The information for this method is primarily summarized from a 2009 draft of the International Standard IEC/FDIS 31010 Risk Management — Risk Assessment Techniques

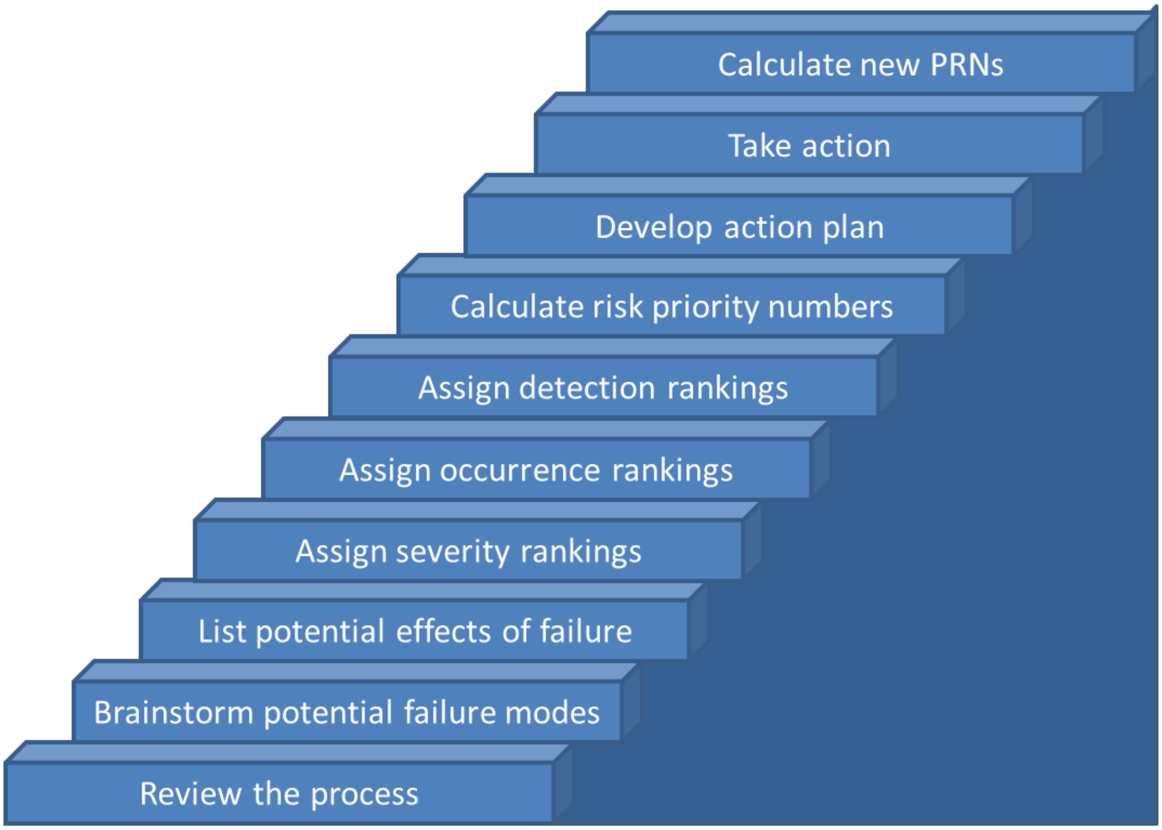

Figure 8.14: Steps of an FMEA analysis

FMEA Analysis Process Steps

1. Calculate new RPNs
2. Take action
3. Develop action plan
4. Calculate risk priority numbers
5. Assign detection rankings
6. Assign occurrence rankings
7. Assign severity rankings
8. List potential effects of failure
9. Brainstorm potential failure modes
10. Review the process

Each process requires a definition of the scope and objectives of the study and commissioning a team that understands the system to be analyzed. This usually includes breaking the system down into its components or steps. Then for each component the team identifies:

- How each component can conceivably fail
- Mechanisms that can produce these modes of failure

- What the effects will be if the failures occur
- If the failure is a safe or unsafe one
- How the failure can be detected
- What provisions can be made to compensate for the failure

Risk Priority Numbers

An FMEA identifies opportunities for failure or "failure modes" in each step of a process. Each failure mode gets a numeric score that quantifies (a) the likelihood that the failure will occur, (b) the likelihood that the failure will *not be* detected, and (c) the amount of harm or damage the failure mode may cause to a person or to equipment. The product of these three scores is the Risk Priority Number (RPN) for that failure mode. The sum of the RPNs for the failure modes is the overall RPN for the process.

For FMECA, the study team classifies each failure mode according to the combined influence of the severity of its consequences, its likelihood of occurring and its detection possibility. In Figure 8.14 this is done with a risk priority number (see textbox). Risk management actions are defined to reduce the effects or their likelihood of occurrence or to increase the delectability of the failure mode before it occurs. These actions should minimize the occurrence of the more significant failure modes. A without- and with-comparison of the RPN provides a semi-quantitative to quantitative basis for assessing the action plan.

8.18.5 Outputs

The primary output is a list of failure modes and their effects for each component. This list may or may not include an estimate of the likelihood of failure. Causes of failure are also provided along with the criticality of each failure mode.

8.18.6 Strengths and Weaknesses

Strengths:

- Ability to identify component fault modes, their causes and their effects on the system
- Can avoid the need for costly equipment, component and project modifications in service by identifying problems early in the design process
- System reliability and redundancies can be improved by the process
- Process is helpful in designing testing protocols when modes of failure have been anticipated

Weaknesses:

- Not useful when considering combinations of failure modes
- Can become costly and time consuming and are frequently difficult and tedious when applied to complex multi-layered systems

8.19 Cause Consequence Analysis[29]

8.19.1 Overview of the Technique

The Cause Consequence Analysis (CCA) technique was invented by RISO Laboratories in Denmark to conduct risk analysis of nuclear power stations. Cause-consequence analysis combines fault tree and event tree analysis. It blends cause analysis (described by fault trees) and consequence analysis (described by event trees). CCA has the ability of fault trees to show the different ways factors can combine to cause a risky event and the ability of event trees to show the many possible outcomes. By combining deductive and inductive analysis, CCA can identify chains of events that can result in multiple undesirable consequences. When probabilities can be estimated for the various events in a CCA diagram, the probabilities of the various consequences can also be calculated. The technique has been adapted by other industries to estimate the safety of protective systems. It has subsequently been extended to the assessment of risks in other systems as well.

8.19.2 How the Technique Is Used

CCA has been used primarily as a reliability tool for safety critical systems to provide a more thorough understanding of system failures. It enhances the failure logic of fault trees by supporting the analysis of time sequential failures. Time delays can also be incorporated into the consequence analysis, a refinement over event trees.

The method can be used to examine the various paths a system could take following a critical event that depend on the behavior of particular subsystems. For example, the deployment of critical personnel or the performance of emergency response systems can be modeled. If these elements are quantified, the model can then yield estimates of the probabilities of different potential consequences following the critical event.

Because the diagrams are complex, they tend to be used when the magnitude of the potential consequence of failure justifies this intensive effort. The failure of major levees systems in urban areas like New Orleans or Sacramento might warrant such an effort, for example, as might consideration of climate change scenarios.

8.19.3 Inputs

The primary inputs to this technique include:

- An understanding of the system being modeled,
- The events that threaten its function,
- Its failure modes, and
- Failure scenarios.

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[29] The information for this method is primarily summarized from a 2009 draft of the International Standard IEC/FDIS 31010 Risk Management — Risk Assessment Techniques

8.19.4 Process

CCA steps mirror those for fault tree and event tree analysis. Analysts must identify the critical event(s) and their subsequent pathways and then develop a fault tree for causes of the initiating event. Figure 8.15 presents a simplified conceptual CCA diagram. The details have been omitted to simplify the example. The figure shows an initiating event that has a fault tree (details of the fault tree analysis are suggested rather than shown) exploring how it could have come about. The event may or may not lead to a specific condition (this event box would include the various pathways of an event tree), which itself may have contributing factors explained by a fault tree. If the event fails to lead to the condition of interest, a set of consequences will then be realized. If the condition does occur, then there may be a time delay before another potential condition's occurrence is determined. Even absent specific detail, the potential richness and complexity of CCA is evident. The same set of consequences can be reached by multiple pathways.

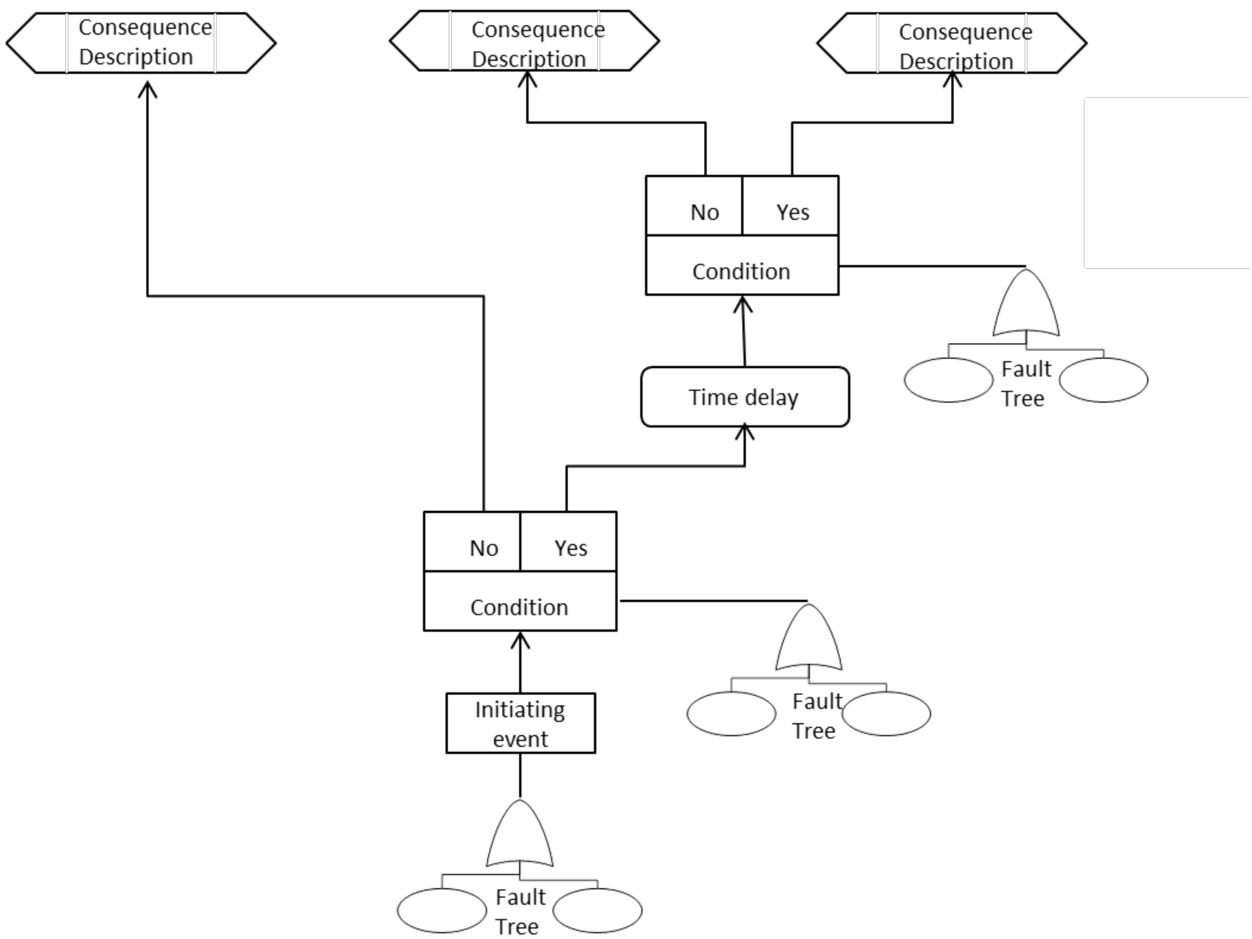

Figure 8.15: Cause Consequence Analysis Conceptual Diagram

8.19.5 Outputs

The primary output is the diagram. A CCA diagram shows both how a system can fail as well as the consequences of the failure. The probability of occurrence of each potential consequence can be estimated based on an analysis of the probabilities of particular conditions that can follow the initiating event.

8.19.6 Strengths and Weaknesses

Strengths:

- Able to display potential scenarios following an initiating event
- Can account for timing, dependence, and domino effects that are cumbersome to handle in verbal descriptions and other models
- Provides a more comprehensive view of a system
- Can show events that develop over time (see the time delay in Figure 8.15)

Weaknesses:

- Complex
- Quantification of probabilities dependencies can be challenging

8.20 Cause-and-Effect Analysis

8.20.1 Overview of the Technique

Cause-and-effect analysis helps the assessor to think through causes of a risk (i.e., a problem or opportunity). This structured method pushes the team to consider all the possible causes of the risk, not just the obvious ones. Figure 8.16 provides a sample cause-and-effect diagram, also called a fishbone or Ishikawa diagram. The problem, shown on the right, is explained first by potential contributory factors grouped into broad categories. Factors contributing to each of these broad categories are identified and then another level of contributory factors are identified. A completed fishbone diagram details a number of testable hypotheses. The diagram can point to potential causes, but only evidence and empirical testing of these hypotheses can determine real causes.

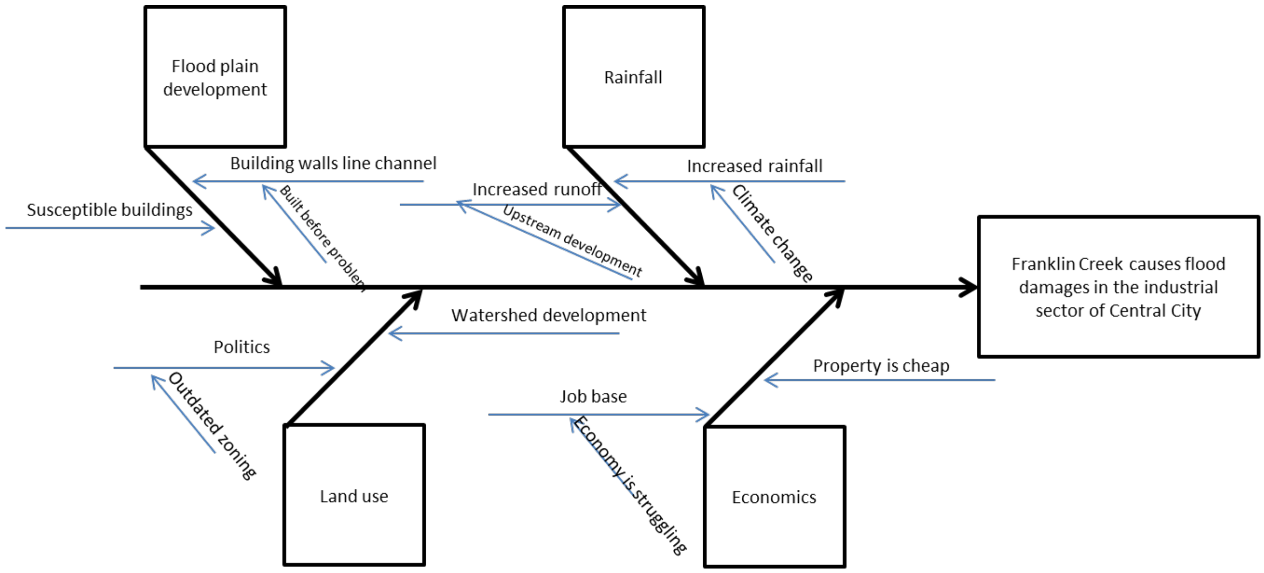

Figure 8.16: Simplified example of a cause-and-effect diagram

The completed diagram provides a visual display of the causes of a specific effect. The effect displayed can be a problem (negative) or opportunity (positive). Cause-and-effect analysis enables analysts to consider a broad range of both causes and scenarios that lead to them. The diagram is generated by a team of experts. Once completed it often helps support development of a consensus view of the most likely causes, which can then be tested empirically or evaluated with available data.

8.20.2 How the Technique Is Used

A fishbone diagram may be most useful at the beginning of a risk assessment. It helps the team think more broadly about possible causes and it can help guide the collection of data, especially if the analysis will involve formal hypothesis testing. Cause-and-effect analysis can be used as part of a root cause analysis.

8.20.3 Inputs

The critical inputs, as with many of these techniques, include:

- The expertise and experience of the team, and
- A good understanding of the effect (problem, opportunity) that is being explained.

8.20.4 Process

The basic steps in performing a cause-and-effect analysis consist of:

Identify the problem,

Work out the major factors involved (the boxes in Figure 8.16),

Identify possible causes and sub-causes (the 'fishbone' lines of Figure 8.16), and

Analyze your diagram.

The major factors or main causes of an effect might include people, equipment, environmental factors, processes, events, situations, and the like. The next task is to fill in the possible causes for each major factor with branches and sub-branches (the fishbones) to further describe the cause. It can help to keep asking "why?" or "What caused that?" in order to understand the causes and develop the diagram.

At this point the diagram should show all the possible causes of your effect. When the problem lends itself to further investigation, the team can establish formal hypotheses, set up investigations, carry out surveys, conduct analysis, and so on, to test the accuracy of your assessment of the causes.

This is usually a qualitative assessment. To quantify it, analysts sometimes assume the probability of the problem or opportunity occurring is one and assign probabilities to the major factors, which can subsequently be broken down to the causes and sub-causes based on expert opinion and the degree of belief about their relevance. This is very difficult to do in a valid way because the contributing factors often interact in ways that are difficult to account for in subjective probability estimates.

8.20.5 Outputs

The primary output is the fishbone diagram that shows possible and likely causes. Such a diagram should be verified and tested empirically before risk management recommendations are made.

8.20.6 Strengths and Weaknesses

Strengths:

- Structured team approach to identify and consider all hypotheses
- Outputs are easy to read and understand
- Technique can guide data collection and analysis

Weaknesses:

- Not a complete risk assessment
- Not a true analysis, but rather a brainstorming tool used at beginning of an assessment
- Separating factors and causes may mask important interactions among the elements of the diagram

8.20.7 Examples of Use

This is a valuable tool to use when defining the decision context.

8.21 Layers of Protection Analysis (LOPA)[30]

8.21.1 Overview of the Technique

Layers of Protection Analysis (LOPA) is an engineering tool used to ensure that the risk associated with a process is successfully managed to a tolerable or acceptable level. It was developed as a more rational and objective alternative to subjective engineering judgment. It is a simplified semi-quantitative risk assessment method for evaluating the risk of specific hazard scenarios and comparing it with risk tolerance criteria to decide whether existing safeguards are adequate or more safeguards are needed (PrimaTech, 2005). A variety of LOPA methods are available.

LOPA analyzes whether there are sufficient measures to control or mitigate the risk associated with individual hazard scenarios, i.e., specific cause-consequence pairs associated with a process. An individual protection layer (IPL) is analyzed for its effectiveness. The combined effect of the IPLs associated with a hazard scenario are compared against risk tolerance criteria to determine if additional risk reduction measures are required to reach a tolerable level of risk.

There are three issues for IPLs (PrimaTech, 2005). First, how safe is safe enough? Second, how many protection layers are needed? Third, how much risk reduction should each layer provide? Risk tolerance criteria are needed to answer the first question. LOPA answers the next two.

8.21.2 How the Technique Is Used

When used qualitatively, LOPA reviews the layers of protection between a hazard or causal event and an outcome. The semi-quantitative application adds some rigor to the screening processes. LOPA can be used to help allocate risk reduction resources effectively by analyzing the risk reduction produced by each layer of protection.

[30] The information for this method is primarily summarized from a 2009 draft of the International Standard IEC/FDIS 31010 Risk Management — Risk Assessment Techniques

Sample Customized Guidewords

Mix up of components
Contamination of components
Dosing quantity too high
Dosing quantity too low
Mass flow too high
Mass flow too low
Too early (point of time)
Too late (point of time)
Wrong sequence
Temperature too high
Temperature too low
Pressure too high
Pressure too low
Insufficient mixing
Wrong conveying route
Wrong conveying direction
Outward leak
Internal leak
Leaking valve
Wrong proportions of substances
Wrong particle size
Wrong state of aggregation
Concentration too high
Concentration too low
Catalytic effects
Inhibitory effects
Catalyst activity too low
Viscosity too high
Viscosity too low
Index of pH too low
Index of pH too high
Loss of heating
Heating too high
Prevented liquid expansion
Loss of agitation
Agitator too slow
Loss of vacuum
Intake of air
Pump failure
Wrong impeller
Agitator breakage
Filter breakage
Break of column trays
Gasket leakage
External corrosion
External fire

Source: http://bgc-formulare.jedermann.de/?selectedMenuId=bgi_r
Accessed December 23, 2011

8.21.3 Inputs

LOPA inputs include basic information on risks including hazards, causes and consequences. A process hazard analysis can provide useful input. LOPA also requires information on proposed or in place controls. Probabilities for initiating events, protection layer failures, measures of consequence and a definition of tolerable risk are also required for best practice LOPA. The risk tolerance criteria are necessary because without them there is a tendency to keep adding safeguards in the belief that the more safeguards the safer the process. This can be a false assumption that leads to unnecessary investment in safety.

8.21.4 Process

LOPA is conducted by a team of experts. The process includes the following steps:

- Clarify initiating events, i.e., causes of hazard scenarios
- Provide sufficient scenario detail
- Express consequences in a form compatible with LOPA
- Record and identify candidate safeguards (i.e., IPLs)
- List all safeguards before deciding if they are IPLs
- Consider identifying enabling events/conditions and conditional events
- Rank hazard scenarios so they can be screened for LOPA
- Flag recommendations for additional IPLs

LOPA requires the team to identify initiating causes for an undesired outcome in the process under study. Data on the probabilities and consequences of these events are generated. A single cause-consequence pair is selected and the scenario risk is estimated. Layers of protection that can prevent the cause from proceeding to the undesired consequence are identified and analyzed for their effectiveness. Independent protection layers are identified from among all the layers. Not all layers of protection are IPLs.

Using orders of magnitude estimates for probabilities and consequences, the probability of the initiating event and the probabilities of failure of each IPL are analyzed and compared with risk tolerance levels to determine whether additional protection is required. A simple example is found in Summers (2002).

An IPL is a device, system or action that is capable of preventing a scenario from proceeding to its undesired consequence independent of the initiating event or any other layer of protection associated with the scenario, as suggested in Figure 8.17. Examples include design features, physical protection devices, interlocks and shutdown systems, critical alarms and manual intervention, post event physical protection, and emergency response systems (procedures and inspections are not IPLs).

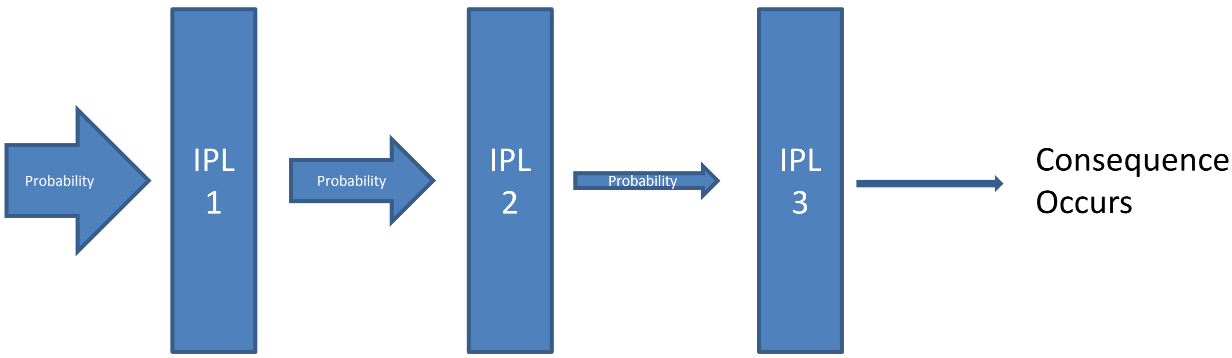

Figure 8.17: IPLs reduce the likelihood of an adverse consequence

8.21.5 Outputs

The outputs of a LOPA are recommendations for where additional risk reduction controls are required. The effectiveness of the recommended controls in reducing risk should be described.

8.21.6 Strengths and Weaknesses

Strengths:

- Takes less time than a fault tree analysis or fully quantitative risk assessment while remaining more rigorous than qualitative subjective judgments
- Helps identify and focus resources on the most critical layers of protection while identifying operations, systems and processes for which there are insufficient safeguards
- Focuses on the most serious consequences

Weaknesses:

- focus on a cause-consequence pair and one scenario at a time
- Complex Interactions among risks or risk controls are not considered
- Quantification relies on the assumption that the layers of protection are independent from each other and the initiating event, i.e., there are no common mode failures.

8.21.7 Examples of Use

LOPA is not useful for very complex scenarios where there are many cause-consequence pairs or where there are a variety of consequences affecting different stakeholders. LOPA may be useful for addressing situations where catastrophic failure of infrastructure and protection systems are possible.

8.22 Human Reliability Assessment (HRA)[31]

8.22.1 Overview of the Technique

Human Reliability Assessment (HRA) is designed to estimate the likelihood that particular human actions that may prevent hazardous events will not be taken when needed and that other human actions that may cause hazardous events by themselves or in combination with other conditions will occur. These are examples of "human errors." They do not imply that people are necessarily personally responsible or culpable in some way, just that an action was omitted (or taken) that adversely influenced safety.

8.22.2 How the Technique Is Used

HRA deals with the impact of humans on system performance and it can be used to evaluate human error effects on a system or process. The potential for human error in a process is especially great when the time available to make decisions is short. Although the consequences of many human errors are small, there are times when human action is the only defense against an initial fault progressing towards an accident. Critical human errors have frequently contributed to a catastrophic sequence of events. These accidents warn us against risk assessments that focus solely on the hardware and software in a system. The dangers of ignoring possible human error are often too great to ignore.

HRA can be qualitative or quantitative. Qualitative analysis can identify the potential for human error and its causes so the likelihood of error can be reduced. Quantitative analysis can produce data on human failures that can be used with other techniques.

8.22.3 Inputs

HRA inputs include definition of the tasks that people must perform, knowledge of the kinds of errors that occur in practice, and the potential for new errors. Expertise on human error and its quantification is also needed and it is not often a staff area of expertise for USACE. Potential human error is especially important during emergency responses, for navigation casualties, and in operations of complex systems.

[31] The information for this method is primarily summarized from a 2009 draft of the International Standard IEC/FDIS 31010 Risk Management — Risk Assessment Techniques

8.22.4 Process

The International Electrotechnical Commission identifies the following steps for a general HRA process (IEC):

- Problem definition: identify the types of human involvement that will be included in the analysis
- Task analysis: identify how the task be will performed and the type of resources needed to support safe performance of the task
- Human error analysis: how can task performance fail? What errors can occur? How can they be recovered?
- Representation: how can these errors or task performance failures be integrated with other hardware, software and environmental events to enable overall system failure likelihoods to be calculated?
- Screening: are there any errors or tasks that do not require detailed quantification?
- Quantification: how likely are individual errors and failures of tasks?
- Impact assessment: which errors or tasks are most important, i.e. which ones have the highest contribution to reliability or risk?
- Error reduction: how can higher human reliability be achieved?
- Documentation**:** what details of the HRA need to be documented?

Limitations and gaps in relevant data sources can be expected. Expert elicitation processes are likely to be useful in overcoming these uncertainties.

8.22.5 Outputs

The output of the analysis is a list of errors that can occur and the identification of methods by which they can be reduced, preferably through redesign of the system. The analysis will include identification of error modes, error type causes and consequences. A qualitative or quantitative estimate of the risk posed by the different errors is the end product.

8.22.6 Strengths and Weaknesses

HRA provides a formal mechanism to include human error in consideration of risks associated with systems where humans play an important role, for example in the operations of locks and dams. It provides formal consideration of human error modes and risk management options for reducing the likelihood of failure due to human error. It is limited in its utility by the complexity and variability of humans. It is difficult to anticipate all the ways that humans can err. This makes defining simple failure modes and estimating their probabilities difficult. HRA though good with pass/fail tasks has trouble addressing partial failures, quality failures, and poor decision making.

8.22.7 Examples of Use

Wreathall, et al. (2003) provides an HRA example in rail transportation.

8.23 Bow Tie Analysis

8.23.1 Overview of the Technique

Bow Tie Analysis is a simple diagram used to help conceptualize the interaction of causes, controls and consequences of a risk. Although it reflects elements of both event tree and fault tree logic, it differs by its focus on the barriers between the causes and the risk and between the risk and consequences. Figure 8.18 provides an example of a generic bow tie diagram.

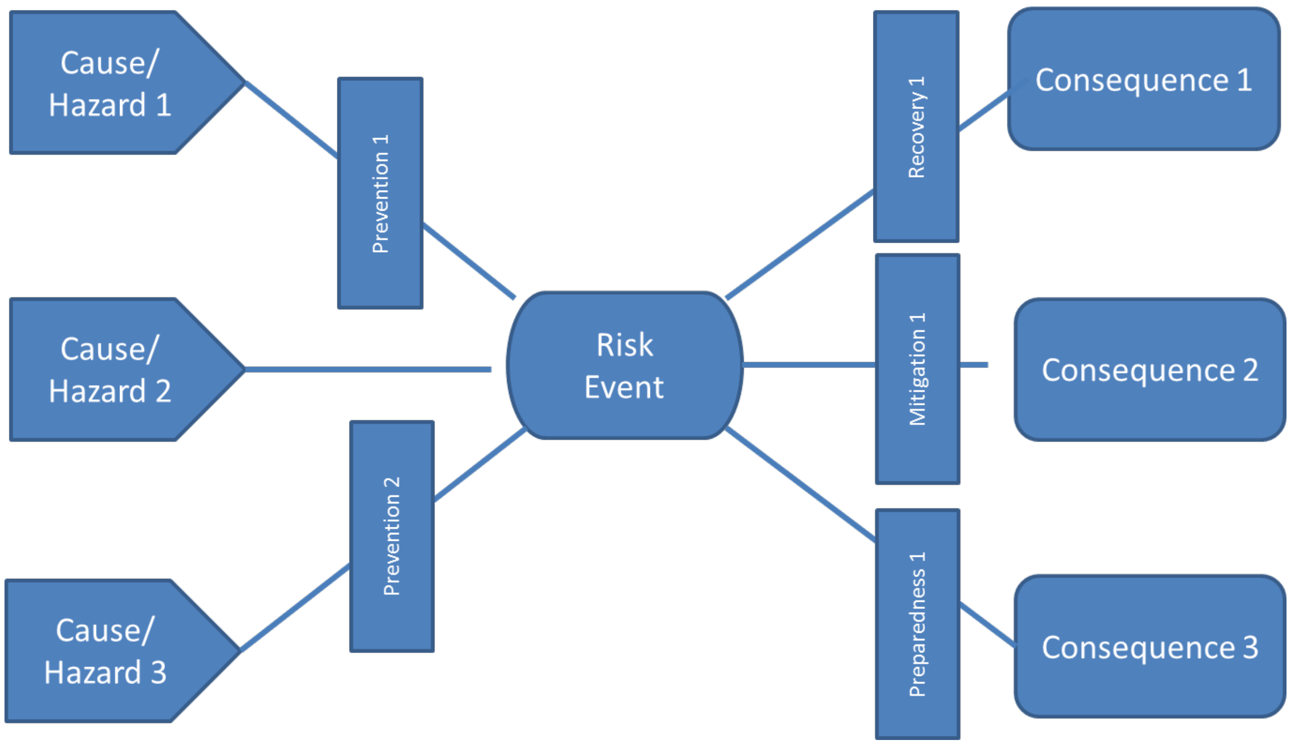

Figure 8.18: A generic bow tie diagram

8.23.2 How the Technique Is Used

The bow tie analysis is useful when the decision problem does not require more complex methods and when there are clear independent pathways leading to failure. It is usually easier to understand than fault and event trees and is therefore a more useful communication tool.

8.23.3 Inputs

Inputs to a bow tie analysis include:

- Causes and consequences of risk
- Factors that may prevent or mitigate problem risks
- Factors that may stimulate or promote desirable consequences

8.23.4 Process

The process begins by identifying a specific risk or event that becomes the knot in the bow tie. Causes that can lead to consequences are listed on the left and connected to the knot via lines that form the left side of the bow tie. Escalation factors (not shown in the figure) can be added between the lines on the left when they can be identified.

Barriers that can prevent a cause from leading to an unwanted consequences can be shown as vertical bars across the lines. Bars on the left side of the bow tie generally prevent the risk from occurring. The prevention measure is placed on the line it disrupts. If there are barriers to escalation, they can also be shown on the escalation lines when they are used. When the risk is a potential gain, the bars represent stimulation measures on the left side of the diagram.

The right side of the bow tie shows the potential consequences that can result from the risk. Although the conceptual figure is symmetrical, an actual bow tie need not be. The consequences are also connected to the risk by lines. Barriers to the consequence are shown as bars across the radial lines that represent preparedness, mitigation and recovery options that can prevent or reduce specific consequences. When the consequences are positive the bars reflect promotion options that support the generation of positive consequences.

The bow tie diagram may be quantified to some extent when the pathways are Independent and the likelihood of a particular consequence or outcome is known, so long as the effectiveness of a control can be estimated. Generally, quantification is more appropriate with event and fault trees.

8.23.5 Outputs

A simple diagram is the output of a bow tie analysis. It shows the main failure pathways and the risk management measures in place to prevent or mitigate the undesired consequences or to stimulate and promote desired consequences.

8.23.6 Strengths and Weaknesses

Strengths:

- Simple to understand
- Presents a clear picture of the problem
- Focuses attention on measures that are supposed to be or can be in place to prevent and mitigate risks
- Can be used for desirable consequences
- Does not require a high level of expertise to use

Weaknesses:

- Limited by its simplicity
- Does not address situations where multiple causes must occur simultaneously
- Could over simplify complex situations, especially when the model is quantified

8.24 Reliability Centered Maintenance[32]

8.24.1 Overview of the Technique

Reliability Centered Maintenance (RCM) is designed to produce the least maintenance costs for low operational risk and high equipment reliability. It was initially developed for the commercial aviation industry in the late 1960s, but it has since been adapted for use by other industries. It provides a process to identify applicable and effective preventive maintenance requirements for equipment in accordance with the safety, operational and economic consequences of identifiable failures considering the degradation mechanism responsible for those failures. The process supports decision making about the necessity of performing a maintenance task. As such, it may be useful to a wide range of USACE operation, maintenance, replacement and rehabilitation issues.

8.24.2 How the Technique Is Used

RCM is used to make decisions about safety based on consideration of personnel, the environment, and operational or economic concerns. The criteria considered depend on the nature of the problem. For planning, a process may be required to be economically viable and sensitive to environmental considerations. For dam safety, an item of equipment should be operationally successful and may have less stringent economic and environmental criteria. The analysis should be targeted to equipment where failure would have serious safety, environmental, economic or operational effects. RCM is generally applied during the design and development phase and implemented during operation and maintenance.

8.24.3 Inputs

Best practice RCM requires a good understanding of the equipment and structure, the operational environment and the associated systems, subsystems and items of equipment, together with the possible failures and the consequences of those failures.

8.24.4 Process

The basic steps of an RCM program include:

- Initiation and planning
- Functional failure analysis
- Task selection
- Implementation
- Continuous improvement

[32] The information for this method is primarily summarized from a 2009 draft of the International Standard IEC/FDIS 31010 Risk Management — Risk Assessment Techniques

RCM is risk-based. It focuses on situations where potential failures may be eliminated or reduced in frequency and/or consequence by carrying out maintenance tasks.

It is performed by identifying required functions and performance standards. Functional failures that may result are then identified for equipment and components associated with those functions. Figure 8.19 shows a degradation curve. The interval P-F shows the time between when a budding failure reveals itself (point P) and when the equipment can no longer be used because its performance has degraded to an unacceptable level (point F). Consider the example of a pump designed to pump a specific flow. When wear and tear degrades the pump's performance, point P occurs when a lower flow is first noted. When the pump cannot produce an adequate flow, point F has been reached. The pump still operates. It has not broken down, but it is no longer meeting its minimum functional duty.

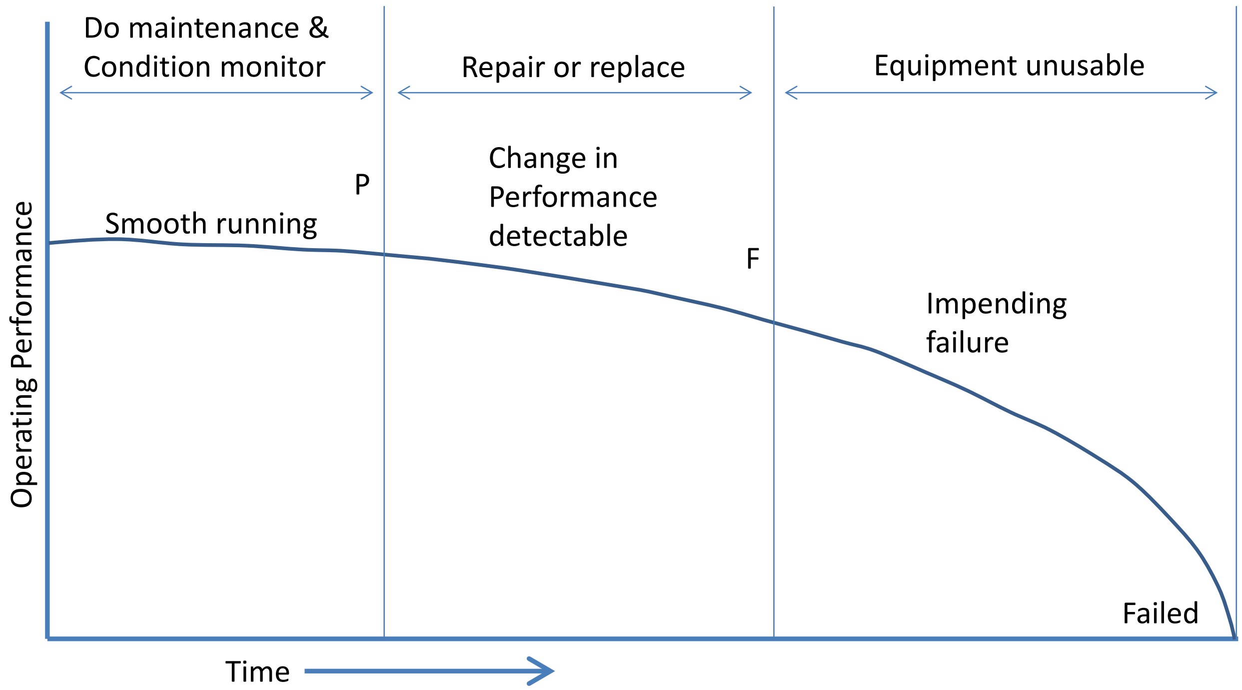

Figure 8.19: Hypothetical degradation curve

This degradation curve concept applies to every part of a project, i.e., every part has its own P-F interval. Condition monitoring is used to observe the P. Usually, only the vital parts that lead to a breakdown are monitored. The P-F interval is identified based on the worst case failure suffered on-site with the equipment item, by using the failure history from comparable operations, or by making a reliability failure assessment of the item. The goal is to avoid breakdown maintenance and to minimize reactive maintenance in favor of predictive maintenance.

8.24.5 Outputs

RCM risk assessment consists of estimating the frequency of each failure without maintenance being done. The definition of maintenance tasks such as condition monitoring, scheduled restoration, scheduled replacement, failure-finding or no preventive maintenance are the outputs of RCM. Other risk management actions that can result from RCM analysis include redesign, changes to operating or maintenance procedures or additional training for personnel. Task intervals and the required resources are identified for each risk management response.

8.24.6 Strengths and Weaknesses

Strengths:

- Lowest cost/low risk/high reliability payoff comes with effective preventive maintenance

Weaknesses:

- Reliance on performance data
- Data are frequently missing and expert elicitations are used to fill data gaps

8.25 Markov Analysis

8.25.1 Overview of the Technique

Markov analysis provides a means of analyzing the reliability and availability of systems whose components exhibit strong dependencies, as befits many of the engineering and even natural systems with which USACE works. A critical insight for Markov analysis is that in the present moment the future is independent of the past. Thus, older information produces less accurate predictions and the future is best predicted by the information known now. This conditional independence is deceiving because we experience the future as dependent on the past. However, if we view time as a chain of events, such that one moment is only dependent on the previous moment and independent of the next (after all, it hasn’t occurred yet) and all other previous moments, we have the basis for the simplest Markov model, called a Markov chain.

8.25.2 How the Technique Is Used

Markov analysis is often used to analyze repairable systems that can exist in multiple states including:

- Independent components in parallel;
- Independent components in series;
- Load-sharing system;
- Stand-by system, including the case where switching failure can occur; and
- Degraded systems.

Navigation systems are a good example of repairable systems amenable to Markov analysis that can be used for calculating availability and taking into account the spare components for repairs.

8.25.3 Inputs

The IEC identifies the essential inputs to a Markov analysis as:

- A list of various states that the system, sub-system or component can be in (e.g., fully operational, partially operation (i.e. a degraded state), failed state, and so on);
- A clear understanding of the possible transitions that are necessary to be modeled; for example, failure of a lock gate needs to consider the state of any spare gates as well as the frequency of inspection;
- Rate of change from one state to another, typically represented by either a probability of change between states for discrete events, or a failure (λ) or repair (μ) rate for continuous events.

8.25.4 Process

Markov analysis centers around the concept of "states" (e.g., available, partially available or failed) and the transition between these states over time based on a constant probability of change. A stochastic transitional probability matrix is used to describe the transition

between each of the states to allow the calculation of the various outputs. Consider a

navigation system that can be in only three states; functioning, degraded or failed. Call these states S_1, S_2, and S_3, respectively. Each day, the navigation system exists in one of these three states. Table 8.5 shows the probability that the navigation system will be in state S_i tomorrow, where i can be 1, 2 or 3.

		State Today		
		S_1	S_2	S_3
State Tomorrow	S_1	0.95	0.3	0.2
	S_2	0.04	0.65	0.6
	S_3	0.01	0.05	0.2

Table 8.5: Markov transition matrix for a navigation system

The sum for each of the columns in the transition matrix is 1. If the system is in state S_1 today there is a 95% chance it will be in S_1 tomorrow, with a 4% chance it will be in S_2 tomorrow and a 1% chance it will be in S_3. It is also possible to represent the system by a Markov diagram, shown in Figure 8.20, where the circles represent the states and arrows represent the transition with the transition probability indicated.

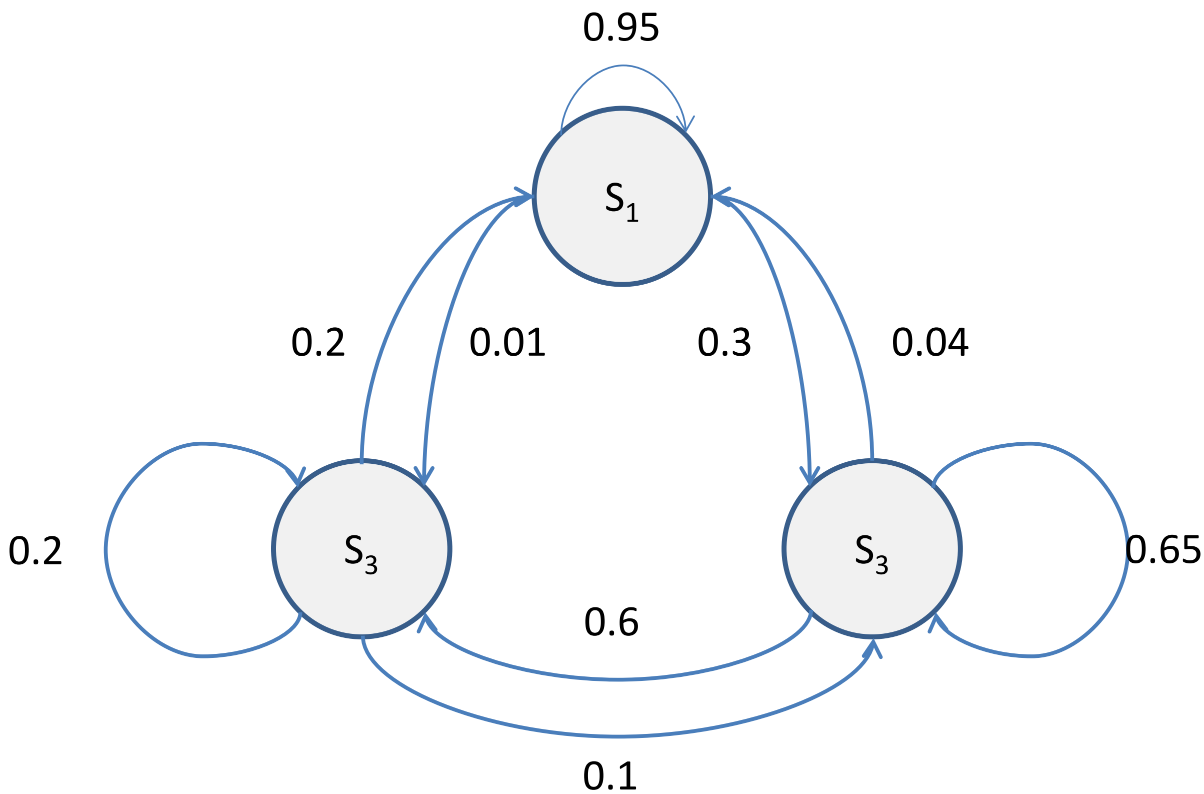

Figure 8.20: Markov diagram for navigation system

Usually the state to itself arrows are omitted. They are shown here to complete the concept.

Now we define P_i to represent the probability of finding the navigation system in state i. This spawns three simultaneous equations to be solved. They are:

$P_1 = 0.95P_1 + 0.30P_2 + 0.20\ P_3$

$P_2 = 0.04P_1 + 0.65P_2 + 0.60P_3$

$P_3 = 0.01P_1 + 0.05P_2 + 0.20P_3$

Because these three equations are not independent, they cannot be solved for the three unknowns. Using what we know about the dependency, the following equation can be substituted for any one of the above equations:

$1 = P_1 + P_2 + P_3$

The solution for this set of equations reveals $P_1 = 0.85$, $P_2 = 0.13$, and $P_3 = 0.02$. Thus, the system is fully functioning 85% of the time, in the degraded state 13% of the time and failed 2% of the time.

For continuous events the mathematics are a bit more complex, but the principle is the same.

8.25.5 Outputs

The outputs from a Markov analysis are the probabilities of being in the various states. These probabilities provide one of the essential components of a risk.

8.25.6 Strengths and Weaknesses

Strengths:

- Enables analysts to calculate the probabilities for systems with a repair capability and multiple degraded states

Weaknesses:

- Assumes all events are statistically independent since future states are independent of all past
- Requires knowledge of all probabilities of a change state

8.26 Bayesian Statistics and Bayes Nets

8.26.1 Overview of the Technique

The premise of Bayesian statistics, attributed to Thomas Bayes, is that any already known information (the prior) can be combined with subsequent information (the Posterior) to establish an overall probability. The simplest expression of Bayes Theorem is:

$$P(A|B) = \frac{[P(A)P(B|A)]}{P(B)}$$

Classical statistics assumes that all distribution parameters are constants. Bayesian statistics views them as random variables. Probability, in the Bayesian sense, is easier to understand if it is considered as a person's degree of belief in a certain event as opposed to the classical sense that is based upon physical evidence. The Bayesian approach is based on this subjective interpretation of probability. It has proven useful for decision thinking and the development of Bayesian Nets also called Belief Nets, Belief Networks, or Bayesian Networks.

These nets use graphical models to represent probabilistic structures. The network comprises nodes that represent a random variable and arrows that link a parent node to a child node to show how variables influence one another. A simple example of a network is shown in Figure 8.21.

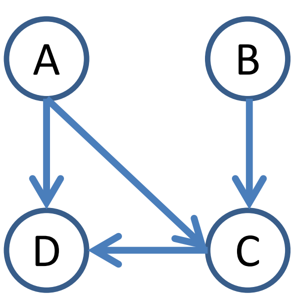

Figure 8.21: A simple Bayes network

8.26.2 How the Technique Is Used

Intuitive appeal and user friendly software have resulted in widespread use of Bayes' theory and nets in recent years. Nets are used for medical diagnosis, image modeling, genetics, speech recognition, economics, space exploration, and in the powerful web search engines used today (IEC). They are useful in any application where analysts must find out about unknown variables using structural relationships and data.

8.26.3 Inputs

The inputs for a Bayes Net include:

- The definition of system variables and causal links between the variables,
- Specified conditional and prior probabilities,
- Evidence to be added to the net, and
- Updated beliefs.

8.26.4 Process

The process can be best demonstrated with an example. Consider Table 8.6 where an inspection is used to determine if a structural component is in a failed condition. The belief before the inspection is that 99% of the components are not failed (NF) and 1% have failed (F). This is the prior information. Inspection accuracy shows that if the component has failed, the inspection result is positive (I+, i.e., failure is judged to have occurred), 98% of the time. If the component has not failed, the inspection result is positive 10% of the time. These two pieces of information comprise the likelihood information. They are not summed in the table because they represent different probability concepts and are not complements.

	Prior	Likelihood	Product	Posterior
Component is failed	P(F)=.01	P(F|I+)=.98	P(F)P(F|I+)=.0098	.0901
Component is not failed	P(NF)=.99	P(NF|I+)=.1	P(NF)P(NF|I+)=.0990	.9099
Total	1	NA	.1088	1

Table 8.6: Bayes table data

Using Bayes rules, the products are determined by multiplying the prior and likelihood values. Notice that these two probabilities product values do not sum to 1. The next step is to normalize them. The Posterior is found by dividing the product value by the product total (e.g., .0098/.1088=.0901). The output shows that a positive test result (indicated by the likelihood) shows that the Prior has increased from 1% to 9% . Thus, a random component has a 1% chance of being failed.

However, information changes probability in the Bayesian approach. Knowing the component has been judged to have failed during inspection increases the likelihood that it is in fact failed to 9%. Notice that there is a strong chance that even with a positive inspection the result of a failed component is unlikely. That is, 91% of all components judged to have failed will in fact not have failed.

Examining the equation for the first row Posterior P(F)P(F|I+)/(P(F)P(F|I+)+ P(NF)P(NF|I+)) = (.01*.98)/((.01*.98)+(.99*.1)) shows that the false positive response (i.e., identifying failure 10% of the time on the 99% of components that have no failure) plays a major role in the Posterior values.

Now consider the Bayes Net of Figure 18.20 once more. Let's generalize the example now. Let the Prior probabilities be as defined in Table 8.7. For the two events A and B let there be a yes/no condition. These are both independent events, i.e., their probabilities do not depend on any other event in the net.

P(A) = Y	P(A) = N	P(B) = Y	P(B) = N
.9	.1	.6	.4

Table 8.7 Prior probabilities of nodes A and B

Node C's value depends on both events A and B, so Table 8.8 shows the conditional Prior probability for node C.

A	B	P(C) = Y	P(C) = N
Y	Y	.5	.5
Y	N	.9	.1
N	Y	.2	.8
N	N	.7	.3

Table 8.8: Conditional probabilities for node C with node A and node B defined

Node D depends on nodes A and C. Its conditional Prior probabilities are given in Table 8.9.

A	C	P(D) = Y	P(D) = N
Y	Y	.6	.4
Y	N	1	0

N	Y	.2	.8
N	N	.6	.4

Table 8.9: Conditional probabilities for node D with node A and node C defined

If we'd like to determine the Posterior probability of P(A|D=N,C=Y), it is first necessary to calculate P(A,B|D=N,C=Y). P(A|D=N,C=Y) says if D is no and C is yes what is the probability that A is yes. Using Bayes' rule, the value P(D|A,C)P(C|A,B)P(A)P(B)[33] is determined as shown in table 8.10, where the last column shows the normalized probabilities that sum to 1 as derived in the inspection example above (result rounded).

A	B	P(D|A,C)P(C|A,B)P(A)P(B)	P(A,B|D=N,C=Y)
Y	Y	.6 x .5 x .9 x .6 = .162	.445
Y	N	.6 x .9 x .9 x .4 = .194	.533
N	Y	.2 x .2 x .1 x .6 = .002	.007
N	N	.2 x .7 x .1 x .4 = .006	.015

Table 8.10: Posterior probability for nodes A and B with node D and node C defined

To get the desired value it is necessary to group all the A=Y probabilities and Y=N probabilities, as is done in Table 8.11.

P(A=Y|D=N,C=Y)	P(A=N|D=N,C=Y)
.978	.022

Table 8.11: Posterior probability for node A with node D and node C defined

The Prior for P(A=N) has decreased from .1 to a Posterior of .022. Meanwhile, P(B=N|D=N,C=Y) has changed from .4 to .548.

8.26.5 Outputs

The outputs of Bayes Nets are derived Posterior distributions and a graphical model that explains the relationships among variables. This abstract example shows how the Bayesian approach can use information, e.g. that D=N and C=Y, to update probability estimates based on a degree of belief.

[33] This formula will not be obvious based on the simple Bayes equation shown above.

8.26.6 Strengths and Weaknesses

Strengths:

- Knowledge on the Priors and Bayes rule are all that is required
- Subjective beliefs can be used in a problem

Weaknesses:

- Inferential statements are often difficult for people to understand
- Knowledge of priors is essential

8.27 Risk Control Effectiveness[34]

8.27.1 Overview of the Technique

When talking about Risk Control Effectiveness analysis, we need to ask: Are existing risk management measures adequate? To answer that question one must know:

- What the existing (or proposed) management measures are for a particular risk.
- If those controls are capable of adequately reducing the risk to a tolerable level of residual risk.
- If the risk management measures are operating in the intended manner.
- If the controls can be demonstrated to be effective when required.

8.27.2 How the Technique Is Used

Residual risks are important. A risk assessment should always estimate and communicate them. This can be done for existing risk management measures by considering the existing (or proposed) risk management measures' effectiveness in reducing an existing (or future) risk in order to estimate the level of residual risk.

To answer the questions above with confidence, proper assurance processes, such as an audit or a risk control self-assessment must be undertaken. Risk control effectiveness analysis can be used to provide a relative assessment of the actual level of risk control that is currently present and effective. This is then compared to the level of risk control that is reasonably achievable for a particular risk.

8.27.3 Inputs

The inputs for an risk control effectiveness analysis include:

- Intimate knowledge of the existing risk management measures, and

[34] The information for this method is primarily summarized from a 2009 draft of the International Standard IEC/FDIS 31010 Risk Management — Risk Assessment Techniques

- An effective qualitative or quantitative means for rating or ranking their effectiveness.

8.27.4 Process

Assessing the effectiveness and adequacy of risk controls is difficult unless the performance of the risk controls is adequately documented. This documentation must include a description of the control, its purpose and its design intent. Validating its effectiveness requires evidence of the operation of the control, which should also be documented. In private industry it is usual for assurance providers to conduct audits of the risk control, which will include such documents and other evidence of the operation of the control.

It is not always easy to accurately express the level of effectiveness for a particular risk management option, but it is valuable to do so as part of the risk management monitoring, evaluation and modification process. It is important to know when risk management efforts can be improved through further or different risk treatment. A measure of RCE can serve this purpose and a qualitative rating for RCE has proven useful at times. The IEC offers examples of qualitative ratings presented below:

- Fully effective: Nothing more to be done except review and monitor the existing controls. Controls are well designed for the risk, address the root causes and management believes that they are effective and reliable at all times.
- Partially effective: Most controls are designed correctly and are in place and effective. Some more work to be done to improve operating effectiveness or management has doubts about operational effectiveness and reliability.
- Ineffective: While the design of controls may be largely correct in that they treat most of the root causes of the risk, they are not currently very effective. Or, some of the controls do not seem correctly designed in that they do not treat root causes, those that are correctly designed are operating effectively.
- Totally ineffective: Significant control gaps. Either controls do not treat root causes or they do not operate at all effectively.
- Not effective: Virtually no credible control. Management has no confidence that any degree of control is being achieved due to poor control design and/or very limited operational effectiveness.

8.27.5 Outputs

The output of an RCE is a documented rating of each individual risk control and the overall risk management option.

8.27.6 Examples of Use

This method is easy to do qualitatively. Quantitative monitoring can be a valuable part of the verify, monitor, evaluate modify process of the USACE risk management model. This is not likely to be possible until quantitative measures of success are identified earlier in the risk management process and methods are set in place to collect and monitor these data.

8.28 Frequency Number (FN) Curves

8.28.1 Overview of the Technique

Frequency Number (FN) curves graphically present the frequency of a given number of casualties occurring for a specified hazard. They show the likelihood of a risk causing a specified level of harm to a specified population. Most often they show the cumulative frequency (F) at which N or more members of the population will be affected. High values of N that occur with a high frequency F are likely to be unacceptable risks. A flood risk damage frequency curve is an example of an FN curve. An example is seen in Figure 8.22. The number of lives exposed to a flood risk by exceedance frequency is another example of an FN curve.

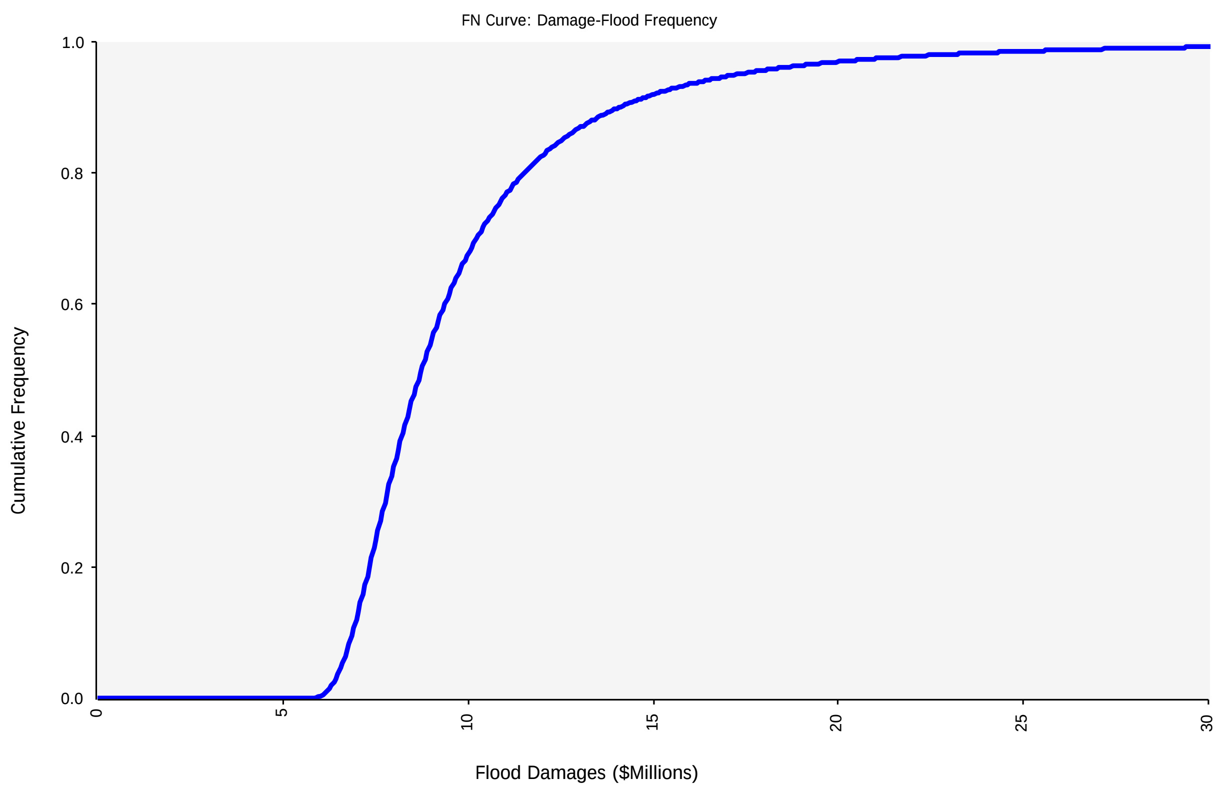

Figure 8.22: FN curve example using flood damages and flow exceedance frequency

8.28.2 How the Technique Is Used

FN curves are one way of representing the outputs of a risk assessment. It is common for most risk profiles to have a high likelihood of a low consequence outcome and a low probability of a high consequence outcome. An FN curve is a line describing this range of probability-consequence pairs rather than a single point representing one consequence likelihood pair.

8.28.3 Inputs

The required inputs usually come in one of three general forms. Sets of likelihood-consequence pairs over a given period of time will yield a curve. The data from a quantitative risk assessment estimating the likelihoods of specified numbers of casualties is a second way to generate a curve. Historical data can also be used to derive an FN curve.

8.28.4 Process

The process is quite simple. The available data are plotted onto a graph with the number of casualties forming the x-axis and (usually) the cumulative likelihood of N or more casualties forming the y-axis. Logarithmic scales are often used when the ranges of values are large.

FN curves have been generated using actuarial data and simulation model estimates. Generally, statistical curves are used to manage an existing system while theoretical curves are used to design or model a system. When the existing data are insufficient, it is not unusual to use a mixture of statistical and theoretical data to derive a curve. For example, actual flood events provide statistical data for a damage frequency curve and extrapolated or interpolated data points may be used to fill in data points that have never been observed in practice. It is important to carefully construct data for low-frequency, high-consequence events to assure their reasonableness.

8.28.5 Outputs

The output is a simple line graph like that shown in Figure 8.22, which represents the risk across a range of consequences. FN curves are a useful way of presenting risk information.

8.28.6 Strengths and Weaknesses

They can be used by managers and system designers to help make decisions about risk and safety levels. They provide a useful way to present both frequency and consequence information that allows for comparisons between different types of risk. It is common, for example, to present damage-frequency curves for the without and with project conditions when evaluating flood risk management measures.

While FN curves make effective comparisons of risks from similar situations where sufficient data are available, they should not be used to compare different types of risks, especially when the quantity and quality of data varies. FN curves are not a risk assessment method so much as one way to present the results of risk assessment. They can be difficult for the lay public and other non-experts to interpret and evaluate.

8.29 Cost Benefit Analysis

8.29.1 Overview of the Technique

USACE has a long history of using cost benefit analysis (CBA) to assist decision making. Cost benefit analysis is also a well-established method used to evaluate risks and risk management options. Comparing the costs of risk management to the benefits of the treatment is, at least, an implicit part of risk evaluation. Cost benefit analysis has also been used to identify the ”best” risk treatment for a risk management activity.

8.29.2 How the Technique Is Used

In most cases, existing USACE policy will dictate the nature of the benefits and costs to be identified and assessed for decision making. Usually this will include both the direct and indirect benefits and costs associated with a risk management action. Direct benefits are those that flow directly from the risk management action; for example, flood damage reductions or increases in ecosystem services. Indirect benefits are those that are coincidental to the risk management action. Examples include peace of mind that comes with flood damage reductions and regional economic activity that benefits from the increase in ecosystem services. Direct costs are directly associated with the risk treatment and its implementation. The costs of constructing levees or of changing the quantity and quality of water available at a specific time and place are examples of direct costs. Indirect costs are additional or ancillary costs associated with the risk management activity. Examples of indirect costs include loss of a direct sightline to the river because of levee construction or the diversion of land development capital away from the restored ecosystem.

8.29.3 Inputs

Inputs include:

- A clear description of the risk issues,
- The risk management options, and
- Estimates of the direct and indirect benefits and costs associated with these issues and options.

8.29.4 Outputs

The output is an estimate of the net benefits or benefit-cost ratio associated with the risk management options under consideration.

8.29.5 Strengths and Weaknesses

Strengths:

- provides a powerful tool for evaluating risks when all benefits and costs can be reliably monetized

Weaknesses:

- controversy about the reliability and appropriateness of reducing some risk management effects to dollar terms

8.30 Five Points To Take Away

1. Quantitative risk assessment can be deterministic or probabilistic.
2. There are a large and growing number of quantitative tools available to aid the assessment of risk.
3. Not all of the quantitative tools perform complete risk assessments; many of them have specialized and narrowly focused uses.

4. Probabilistic scenario analysis tools are a bundle of quantitative risk assessment tools that combine the power of the Monte Carlo process with the utility of scenario creating techniques, like event and fault trees, to support probabilistic risk assessment.
5. The best quantitative risk assessment methods include sensitivity analysis or some other means of addressing the significance of uncertainty on the assessment results.
6.

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Chapter 9: Making Decisions With Risk Information

9.1 Introduction

Successful risk management requires USACE decision makers to be able to make good decisions based on an accurate understanding of the relevant information under conditions of uncertainty. Because risk information deals with the probability and consequences of risks as well as uncertainty, it is essential that decision makers be able to understand and use probability information to make good decisions.

There are two broad categories of decisions within the USACE Civil Works mission that are affected by a risk approach. The first and most obvious category includes decisions made about explicit and specific risks that USACE must manage. The second category includes a far more numerous group of decisions that do not bear directly on explicit risk issues but which must be made under conditions of uncertainty.

The first of these includes those decisions that deal explicitly with risks that USACE is tasked to manage in the conduct of its Civil Works mission. These are flood risks; storm damage risks; erosion risks; risks of infrastructure underperformance, malfunction or failure; risks that navigation or ecosystem improvements will not produce the expected benefits; and the like. Some of these decision problems have been coalescing into new focus areas over the last couple of decades. Examples of these explicit risks include the USACE major rehabilitation program, the national dam safety program, the national levee safety program, the flood risk management program, SMART planning, and other initiatives not addressed in a formal program. This latter category includes a wide range of engineering risk and reliability issues, risks associated with invasive species, risks associated with accelerating the planning process, and the like.

The second and larger category includes all the familiar kinds of project lifecycle and programmatic decisions that are not associated with an explicit risk issue that USACE has been accustomed to making with less than complete information. These decisions include the usual range of planning, construction, operation and maintenance questions that arise with projects. They affect all functional areas within USACE, such as engineering, real estate, regulatory, planning, and the like. In addition to these project lifecycle questions there are programmatic issues that touch on policy, budgets, strategies, and the like. Risk analysis enables USACE to intentionally address the knowledge uncertainty and natural variability in these familiar decision contexts. Let’s call this first category of decisions risk-informed decision problems because risk analysis requires USACE to explicitly account for the uncertainty in the decision-making process. This was not often done in the past.

Two categories are identified to make sure that no one thinks the notion of risk-informed decision making is restricted to decisions made about risks. It applies to any decision that is significantly affected by uncertainty, no matter what the subject matter of the decision is. Uncertainty has a significant effect if the nature of the decision in any way depends on the actual truth of the remaining uncertain factors. Consider the very simple example of estimating a commute time by automobile. It is 10 minutes if you catch the traffic light green and 12 minutes if you catch it red. If minutes matter then the status of the traffic light is a significant uncertainty. If two minutes is unimportant there is no significant uncertainty.

Costs

Project cost estimates prepared by USACE during planning studies and even during more advanced engineering and design have been notoriously underestimated over the agency's lifetime. They provide an excellent example of the illusion of certainty for many reasons. Let's consider two of them.

Precision often supports the illusion of certainty. When project costs can be estimated to dollar and cents many people are inclined to equate this kind of precision with accuracy when that is simply not the case. Precision ≠ accuracy.

Complexity also encourages the illusion of certainty. Consider that in any cost estimate there can be thousands of inputs. Even if every person involved is 95% confident in their most likely estimate that means 50 of every 1,000 estimates are going to be off the mark. It only takes one unlikely result to tip the scales.

Decision making under conditions of uncertainty is both more honest and more challenging than making decisions under the illusion of certainty. In the past, many businesses and government organizations simply ignored uncertainty. Analysts developed their best estimates for every input and calculated their best estimate of the answer. The entire organization committed to believing the numbers they generated, conveniently forgetting how shaky some of their original parameter estimates really were. Once these numbers found their way into the plan, report, memo, or budget, they were treated as truths. The best estimate we have has often been falsely equated with the truth. If risk analysis and decision making under uncertainty have taught us nothing else, it is that there is no such thing as "the number." For risk management to succeed, organizations must learn how to present and use information that most accurately captures and displays the importance of the uncertainty for the information that will be used to make a decision.

This chapter takes some initial steps in that direction by discussing how to use the information developed in risk-based analysis to make better decisions. The chapter begins in the next section with a trivially simple illustration of a risk-informed decision that makes a few fundamental points and clarifies some meanings before strategies are presented for using risk information. These strategies are developed first by understanding the quantities in the risk information and then by considering the probabilities of these quantities. Suggestions for examining relationships between variables are offered before the chapter closes with a reminder to be sure to answer the risk manager's questions with the risk information that is developed.

9.2 Risk-Informed Decisions

To support the discussion that follows let's consider an oversimplified example that enables us to focus on a few important points. These points include:

- USACE work has always been fraught with uncertainty,
- In the not too distant past it was not practically feasible to intentionally and explicitly address this uncertainty in sophisticated ways, and
- As a consequence many uncertain values were treated as if they were known quantities.

Risk management requires that analysts and decision makers alike understand and break with these simple propositions.

Consider the trivially simple model below that estimates the cost of light bulbs for the year at a gatehouse on a lock. Each value is presented as a point estimate and the total cost is the simple product of two numbers. Before decisions were informed by risk this total cost estimate would have been accepted as a gospel truth.

	Quantity	Unit Price	Total Cost
Light bulbs	100	$ 1.00	$ 100.00

Table 9.1: A simple cost estimation example

Risk-informed decision making requires analysts to be honest about the things they know and do not know and to be intentional in addressing the things they do not know. They need to find effective ways to present and summarize the importance of this uncertainty to decision makers and decision makers are bound by the integrity of the risk management process to consider the effects of uncertainty appropriately when they make decisions.

We know a lot of light bulbs will be needed through the year based on past experience as well as the number of bulbs found around the gatehouse. What we don't know for sure is how many bulbs will be needed; that is a matter of natural variability. The life of a bulb, the number of bulbs broken, the number of lamps requiring bulbs, the time each lamp is on--these are all factors that contribute to the number of bulbs needed and they change from year to year. Furthermore, the nature of that variability is a mystery. We do not know the mean life of a bulb or its standard deviation, nor do we know the numerical parameters that describe those other conditions either, so we have knowledge uncertainty about the natural variability.

Now, imagine this estimate is being prepared as the gatehouse transitions to the use of LED bulbs. Let us further imagine the procurement officer does not know the price of LED bulbs. The unit price of these bulbs is an example of knowledge uncertainty; the price is a fact we simply do not know. In a risk-informed decision process we need to account for these uncertainties. One way to do that is to say we do not know how many bulbs we are going to need or what they will cost so we are guessing $100 ought to cover us for the year. This is honest about the ignorance but it does nothing to address it. The following decision is simply whether to allocate $100 or not.

Now consider Figure 9.1 where the uncertain inputs have been replaced with probability distributions that represent the uncertainty about the input values. The knowledge uncertainty and natural variability about the number of bulbs required is addressed by estimating the number of light bulbs to be somewhere between 85 and 110 with 100 bulbs being the most likely required number of bulbs. These values are shown as a triangular distribution. The price of this new item is unknown and is estimated to be somewhere between $3 and $6. The uniform distribution addresses the knowledge uncertainty and suggests there is no best guess value in that range. The input distributions quantitatively and probabilistically represent the analyst's uncertainty.

Allowing inputs to vary according to the input distributions produces a wide range of possible total cost estimates. With the numbers provided it is rather easy to estimate the total cost will be between $255 (85 x $3) and $780 (130 x $6). Using the Monte Carlo process the total cost calculation was repeated 5,000 times with random input values each time.

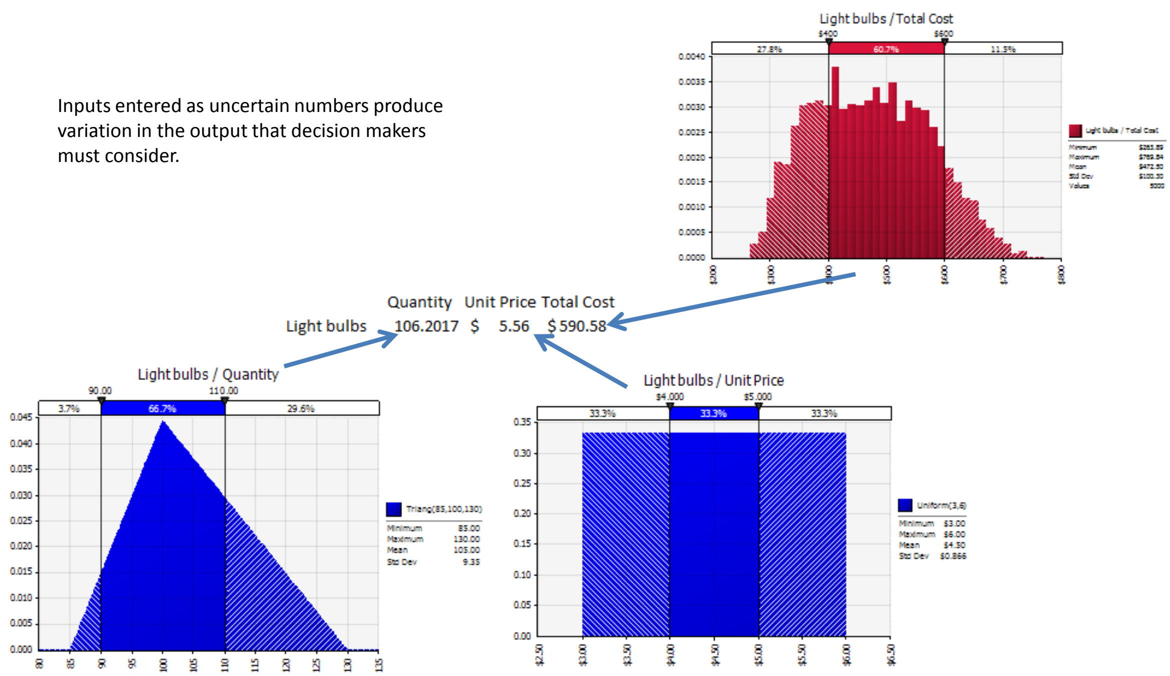


Figure 9.1: Using probability distributions to capture knowledge uncertainty and natural variability in calculating the costs of light bulbs for a hypothetical gatehouse

Notice that with this more honest approach, there is no such thing as "the answer." There is no longer a number that serves the purpose of the $100 estimate in an initial naïve formulation of the problem. The simulation results enable assessors to present decision makers with risk information to consider in the decision-making process. Table 9.2 provides some sample statistics culled from the output distributions. Any number of statistics could have been identified. If a decision maker focuses on a single value they would likely budget $472.50. This number is, however, likely to be wrong.

	Minimum	Mean	Maximum	P(>$600)	P(<$400)
Total Cost	$263.89	$472.50	$769.84	11.5%	27.8%

Table 9.2: Sample statistics from an output distribution

Notice the actual minimum and maximum values were not observed in 5,000 iterations of the model. Suppose $600 is the cutoff for this budget item. If the new bulbs cost more than $600 the transition will be postponed. Risk information enables decision makers to see that there is an 11.5% chance this value will be exceeded. If a low cost, say less than $400, frees up some funds for other purchases, we can see there is a 27.8% chance some funds will be freed up. The choice of values to display depends very much on the nature of the questions risk managers would like to have answered in order to provide them with the information they need to make a decision.

If risk assessors generate information like this and decision makers make decisions based only on means, two things happen. First, assessors waste time and resources doing risk-based analysis that addresses decision uncertainty because the additional information is ignored. Second, nothing is changing to improve the quality of decisions under conditions of uncertainty. Thus, it is essential to the success of risk management that USACE, as an organization, learns how to make better decisions with risk information.

9.3 Confidence in Decision Making

How much information is enough to make a decision or to feel confident in the decision that has been made? In a world of risk analysis, this is the $64,000 question. There will never be a foolproof answer to this question as long as human beings are both performing the work and reviewing the work. The IPCC (2010) provides a solid starting point for thinking about how much information is enough. They suggest that that any decision made under conditions of uncertainty should be accompanied by one of two metrics. These are either: a) a quantified measure of uncertainty, or b) a qualitative expression of the decision maker's confidence in the validity of the decision.

9.3.1 Quantified Measures of Uncertainty

Quantified measures of uncertainty include probability distributions of outcomes, such as a distribution of cost estimates and other quantitative measures. The statement "there is a 60% chance the gate chain will fail to function at some point this year" provides an example of another quantified measure of uncertainty. Some of the more common ways of quantifying measures of uncertainty are:

- Show the data,
- Never report a single value,
- Make probabilistic statements about uncertain values, and
- Bound uncertain values.

Examples of these approaches are presented below using a frequency of 10,000 estimates of a benefit-cost ratio from a hypothetical project.

9.3.1.1 Show the Data

The simplest way to quantify uncertainty when the data are available is to show the data. An example is shown in Figure 9.2. To provide the reader with options for interpreting a distribution it is recommended that the frequency distribution (or density function) be shown above the cumulative distribution function (CDF). They should use the same horizontal axis to better facilitate comparisons.

The CDF provides the reader the opportunity to estimate the frequency with which values less than or equal to any chosen benefit-cost ratio (BCR) value occurs. The frequency distribution conveys both the spread and shape of the data reasonably well. However, it is important to use alternative views to make sure the number of bins in the histogram is not influencing the reader's impression of the shape of the distribution. Figure 9.3 shows the same data with two different numbers of bins selected. Skew and peakedness can, in particular, be distorted by the choice of the number of bins used to display the data.

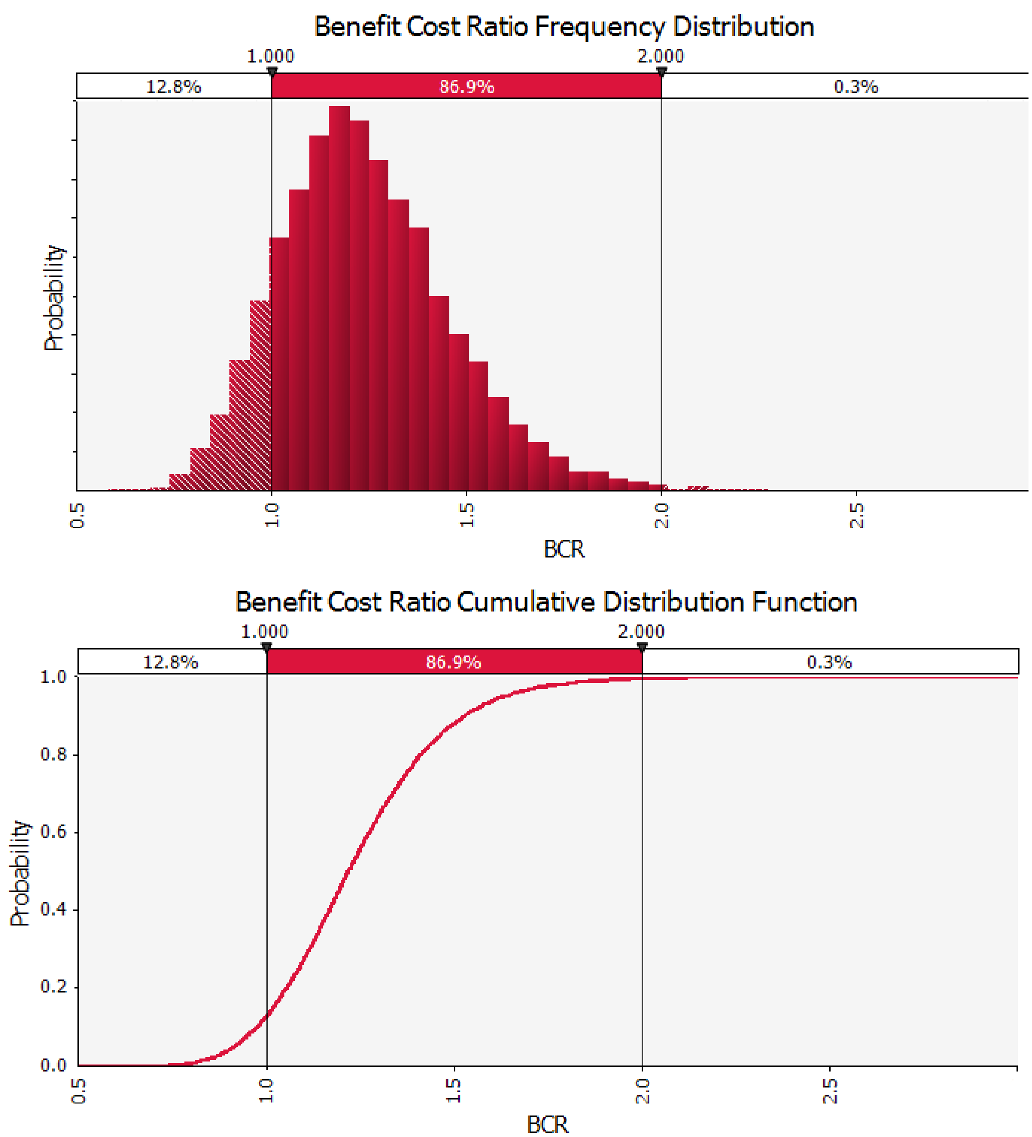
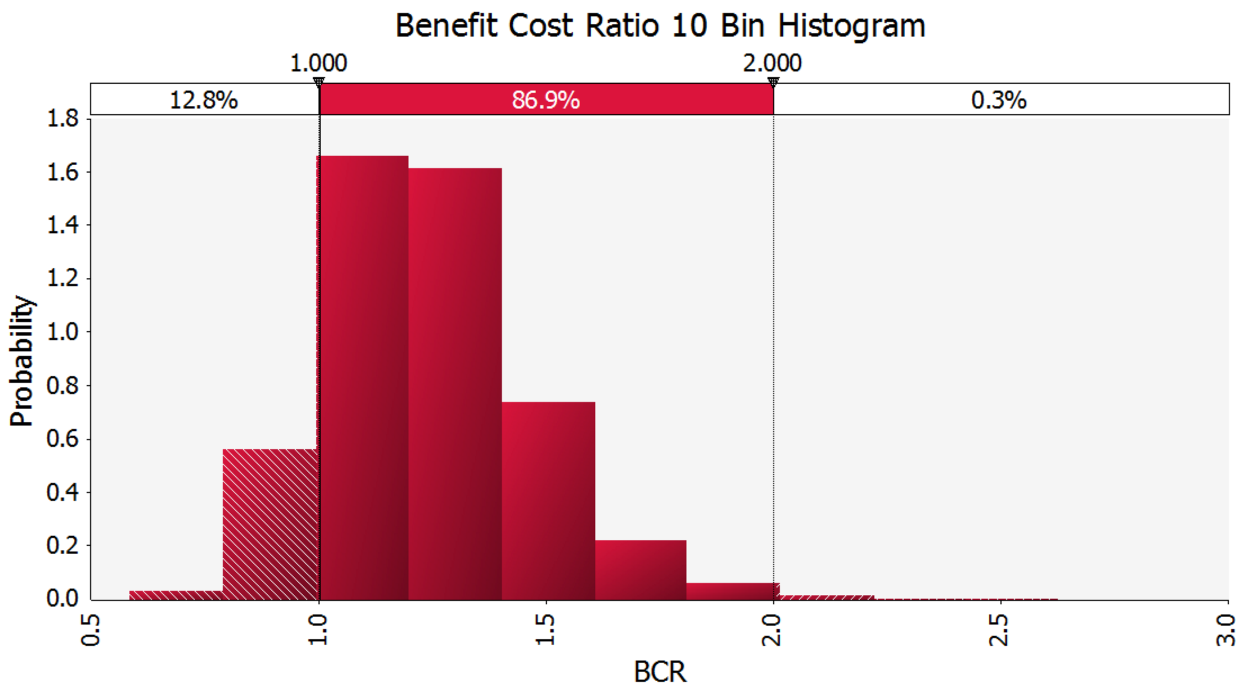


Figure 9.2: Histogram and CDF of BCR data



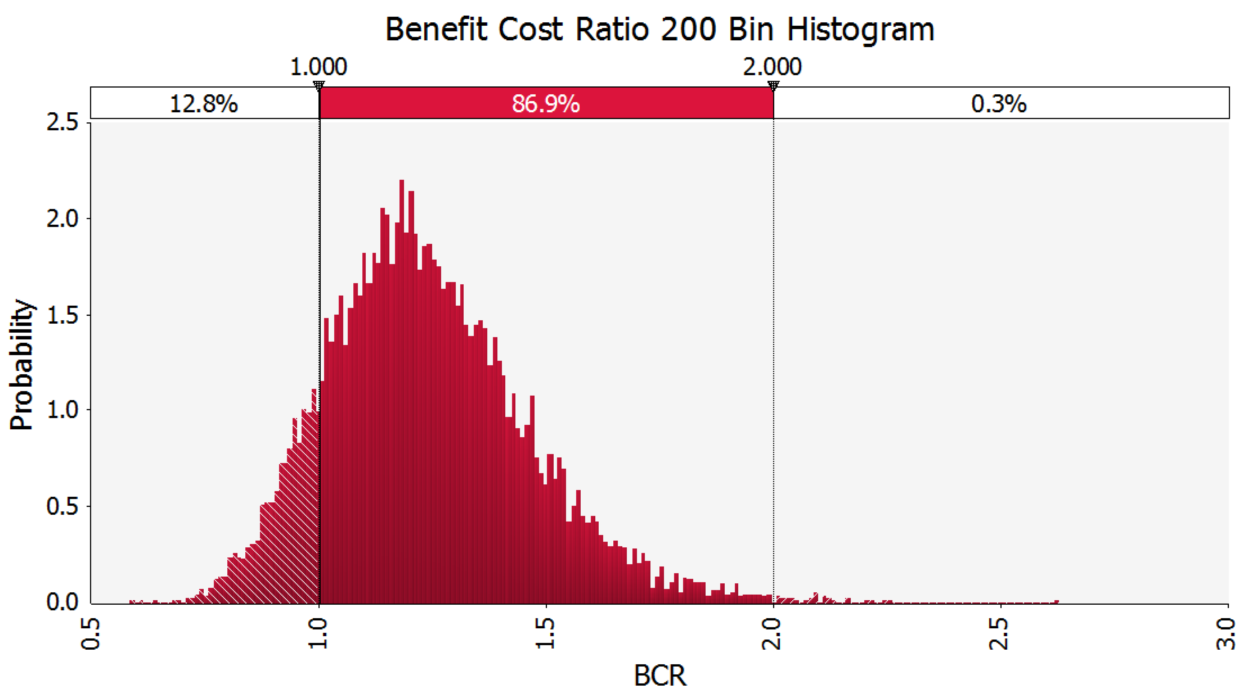
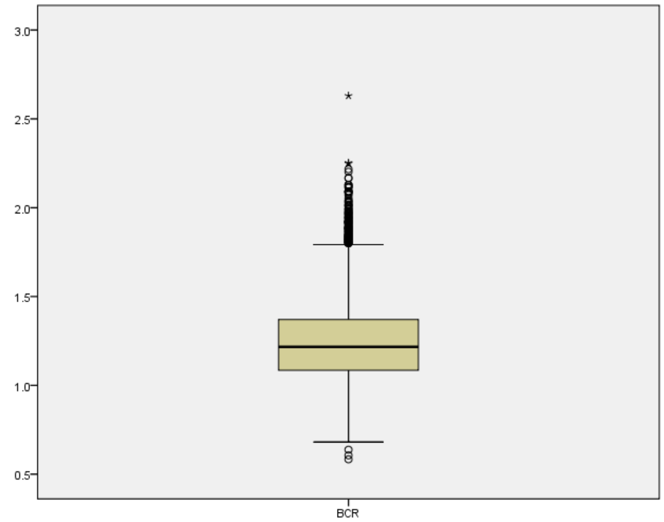
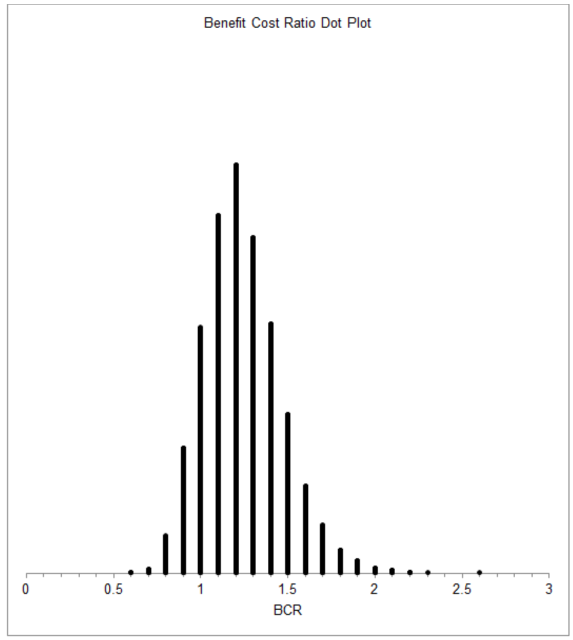


Figure 9.3: Benefit cost ration histograms with different numbers of bins

Figure 9.4 presents several alternative methods for showing the data. At the bottom is a horizontally oriented box plot or box and whisker plot. The vertical line in the middle of the box






```
Benefit Cost Ratio Stem-and-Leaf Plot

 Frequency    Stem &  Leaf

     3.00 Extremes    (=<.64)
     2.00        6 .  &
    16.00        7 .  34&
    53.00        7 .  6789&
   123.00        8 .  0011223344
   217.00        8 .  5556667777888899999
   379.00        9 .  0000011111222222333333333444444444
   485.00        9 .  55555556666666667777777788888888888999999999
   683.00       10 .  00000000001111111111111222222222222233333333333333444444444444
   785.00       10 .  55555555555555666666666666667777777777777888888888888888899999999999999
   917.00       11 .  00000000000000001111111111111111222222222222222222333333333333333334444444444444444
   986.00       11 .  555555555555555555666666666666666667777777777777777777888888888888888888899999999999999999
   956.00       12 .  000000000000000000001111111111111111122222222222222222333333333333333334444444444444444
   847.00       12 .  55555555555555566666666666666667777777777777778888888888888888999999999999999
   750.00       13 .  00000000000000111111111111112222222222222233333333333333444444444444
   678.00       13 .  55555555555555566666666666667777777777788888888888889999999999
   508.00       14 .  0000000000011111111222222222223333333344444444
   414.00       14 .  5555555666666666777777778888888999999
   341.00       15 .  0000001111111222223333333444444
   234.00       15 .  5556666667777788889999
   180.00       16 .  00001111122233444
   136.00       16 .  55566778899
    91.00       17 .  00112234
    54.00       17 .  55678&
   162.00 Extremes    (>=1.80)

 Stem width:  .1000000
 Each leaf:       11 case(s)
```

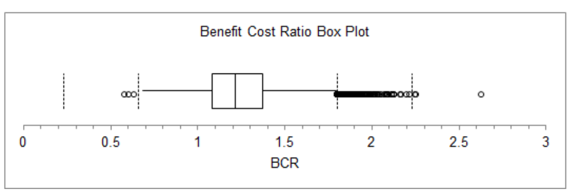


Figure 9.4: Alternative graphics to display the data

shows the location of the median value. The box itself shows the interquartile range, i.e., the middle 50% of the data. The left border of the box is the first quartile value, the right border is the third quartile. The whiskers extending horizontally from the box show values below (to the left) the first quartile less any outliers and values above (to the right) the third quartile less any outliers. Outliers can be defined somewhat differently in different software applications. The figure here shows vertical dashed lines or fences that indicate where outlier values begin. Outliers are defined as values that are 1.5 times the length of the interquartile range (0.29) or 0.43 or more points below the first quartile value or 0.43 points or more above the third quartile value. The minimum value is shown as a vertical line, the maximum as a dot. The box plot is best for showing how the data are dispersed around the median value. There is more spread in the highest 25% of all values than in the lowest 25%. We also see more outliers among the high values. Outliers could be the result of somewhat unusual circumstances in the calculation of the benefit cost ratio.

Above the box plot is a stem and leaf plot. Think of this as a histogram turned onto its side. The length of the lines reveal the relative frequency with which different ranges of values occur. Instead of bins we have a stem and leaf structure. At the bottom of the graphic notice a stem width is 0.1 and each leaf is 11 cases. Now look at the values in the Stem column and focus on the first row that has 17 as a stem entry. This is telling the reader the values in this row are BCR's that begin at 1.7 (this is 17 times the stem width). Next to the Stem column is the Leaf column. Notice 0 appears twice as a leaf. The leaf value is added to the stem value to get 1.7 + 0 or a BCR of 1.70. Because there are two leaves labeled 0 and each leaf is 11 cases, then we know there were 22 BCR values that round to 1.70. There were 22 each of 1.71 and 1.72 with 11 each of 1.73 and 1.74. Thus, the stem and leaf plot not only reveal the spread and shape of the data, it reveals the actual data points as well. Notice from the frequency column there are 91 data points in this row instead of the 88 we would expect (11 x 8 leaves), so the stem and leaf plot is not an exact representation of the data.

In the upper right of the figure is a dot plot; a dot is entered for each data point. In the figure shown here all data points were rounded to the nearest tenth in the BCR. The upper left shows a vertical box and whisker plot. The point to showing the data is to prove there is no such thing as "the number." What is the BCR? We don't know, but it is something like the numbers presented above show.

9.3.1.2 Never Report A Single Value

This segues to the second point, never report a single value. If uncertainty is important there is no such thing as a single number, so one should never be reported. Not even to summarize the results not even for convenience or shorthand. Once you have said the mean or best estimate, or whatever other words one chooses, is 1.24 that number takes on an aura of precision, accuracy, certainty, permanence, respect and magic that it does not deserve. The mean is simply what you get when you add 10,000 estimates of the BCR and divide by 10,000. It could be entirely possible, in some instances that there is not even a single occurrence of the mean value in an output distribution.

BCR Five Number Summary				
Minimum	1Q	Median	3Q	Maximum
0.58	1.09	1.22	1.37	2.63

Table 9.3: Five number summary for benefit cost ratio data

At an absolute minimum analysts should never present less numerical information than the five-number summary. Table 9.3 shows the five-number summary for the BCR data. The numbers are the minimum, first quartile, median, third quartile and maximum values of the uncertain output. If an effort is made to assure that these values become the standard reporting format, it will not prevent people from using the media but it should assure that everyone understands there is no such thing as the number. The five-number summary says the true BCR is uncertain but is likely to be somewhere between 0.58 and 2.63. There is a 50% chance it is less than 1.22 and a 50% chance it is more than that. In fact there is a 50% chance it is between 1.09 and 1.37.

The key to communicating uncertainty to decision makers and the public is to help them realize there is no such thing as "the number." One of the most effective ways to do this is to use the five-number summary when reporting on the output, decision criterion, variable or value of interest to people. A simple introductory sentence to place the five-number summary in context can be helpful: *"Taking into account the uncertainty that has resulted from the lack of sufficient data about subsurface conditions and future development in the watershed as well as the natural variability in precipitation, it is impossible to estimate the benefit cost ratio with certainty. Consequently, potential value of the benefit cost ratio is summarized by the following five-number summary…"*

9.3.1.3 Make Probabilistic Statements About Uncertain Values

Simple probabilistic statements can be used to highlight the uncertainty attending specific values of interest. When considering a benefit-cost ratio, people will be interested in the likelihood that this value falls below one; they may also be interested in the likelihood it takes a larger value like two or more. Examples of probabilistic statements from the data presented in the preceding discussion include:

- There is 12.8% chance the benefit-cost ratio will fall below one.
- There is a 0.3% chance the benefit-cost ratio will exceed two.
- There is an 86.9% chance the benefit-cost ratio will fall between one and two.

Notice there is a probability value and a second value of interest in each of these statements.

> You may have different degrees of confidence in different point estimates. These differences ought to be conveyed to risk managers. The WHO (2006) provides examples of how to do this. Following their guidance would produce statements like, "Taking into account the uncertainty that results from a lack of geotechnical data, we assume Plan X will cost $77 million or less with about 50% confidence."

9.3.1.4 Bound Uncertain Values

Uncertain values of interest can be expressed as bounded values. For example, one could say:

- The benefit- cost ratio is somewhere between 0.6 and 2.6 (feasible bounds).
- Ninety percent of all BCR estimates fall between 0.9 and 2.0 (confidence level).

Identifying a lower and upper bound is all that is required to bound an uncertain value. In some instances it may be sufficient to provide a single bound (the benefit cost ratio is below one). It is always advisable to define the nature of the bounds.

Do you offer absolute minimums and maximums, observed minimums and maximums? Do you bound specific percentile values? Are they the result of classical interval estimates or do they represent the strength of your belief in the likely value of an uncertain number?

9.3.2 Qualitative Expression of Decision Makers' Confidence

The first way to help instill a proper level of confidence in a decision that has to be made under uncertainty is to offer a quantitative expression of the uncertainty. Bear in mind that doing so may reduce the confidence a decision maker has in the decision made as compared to the days when uncertainty remained hidden to decision makers. This is a good thing. It is preferred that decision makers be transparent about the quality of the decision they are making rather than to maintain the illusion of certainty. True confidence, even if it is shaky, is preferred to steadfast false confidence.

The second way to help instill a proper confidence level in a decision is for the decision maker (or analyst) to offer a qualitative expression of their confidence in the validity of the decision. In a world of limited budgets and shortened study schedules the description of uncertainty will often come down to an expression of the decision makers' (or analysts') confidence in the validity of their decision (or analysis). Confidence in the validity of a finding is, in turn, based on the type, amount, quality and consistency of the evidence, which includes such things as mechanistic understanding, theory, data, models and expert judgment as well as the degree of

High agreement Limited evidence	**High agreement Medium evidence**	**High agreement Robust evidence**
Medium agreement Limited evidence	**Medium agreement Medium evidence**	**Medium agreement Robust evidence**
Low agreement Limited evidence	**Low agreement Medium evidence**	**Low agreement Robust evidence**

Agreement ↑

Confidence Scale

Evidence (type, amount, quality, consistency) →

Source: Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties, IPCC Cross-Working Group Meeting on Consistent Treatment of Uncertainties , Jasper Ridge, CA, USA, 6-7 July 2010

Table 9.4: A depiction of evidence and agreement statements and their relationship to

agreement that exists for the decision (analysis results). This confidence is expressed qualitatively. The IPCC (2006) has suggested the taxonomy found in Table 9.4. Confidence increases as one moves from the lower left corner northeast toward the upper right corner. Shading is used to convey increasing levels of confidence. Evidence is considered most robust when there are multiple sources of high quality, consistent evidence from independent sources. High levels of agreement suggest that most parties agree on the significance and meaning of the evidence.

Using this table we might delineate three tiers of decision quality for making decisions under uncertainty. These tiers are characterized, somewhat arbitrarily here, based on confidence levels.

High confidence decisions are those characterized by:

- High agreement and robust evidence,
- Medium agreement and robust evidence, or
- High agreement and medium evidence.

Medium confidence decisions are those characterized by:

- Medium agreement and medium evidence,
- Low agreement and robust evidence, or
- High agreement and limited evidence.

Low confidence decisions are those characterized by:

- Medium agreement and limited evidence, or
- Low agreement and medium evidence.

No confidence decisions are those characterized by:

- Low agreement and limited evidence.

Individual communities of practice within USACE must decide how decisions of varying degrees of confidence will be regarded. For example, high and medium confidence decisions may be sufficient for planning decisions, while medium confidence decisions may be insufficient for emergency operations. Low confidence decisions, when made, must be carefully managed to avoid unacceptable outcomes. No confidence decisions are normally unacceptable in anything but the most dire of circumstances.

9.4 Understand Risk-Informed Outputs Before Deciding

In order to make quantitative statements about uncertainty or to offer qualitative statements about one’s confidence in the validity of a decision or piece of analysis, it is absolutely essential that analysts and decision makers both understand the full information content of all risk-informed outputs. Analysts and decision makers must learn how to analyze a distribution so they can extract and effectively display managerial insights. Risk data, at a minimum, include the two dimensions of consequence and probability or, said differently, both the quantities in the distribution and their probabilities of occurring. It is often easier to get a good sense of the data by focusing on each in turn.

Here are three simple considerations to aid assessors and decision makers in their efforts to understand the information they get from risk-informed analysis:

1. Examine the quantities (consequences)
2. Examine the probabilities
3. Examine relationships between variables

Each is considered in turn in the sections to follow.

9.4.1 Examine the Quantities

For simplicity, let's continue to use the benefit cost ratio (BCR) data. When working with probabilistic data there are quantities and the probabilities associated with those quantities; e.g., the probability of a benefit cost ratio less than one is 12.8%. There are two dimensions to these data. The BCR values are called the quantities. The probability of these values occurring are called the probabilities. Our goal in this discussion is to simply understand the quantities. The way to begin is, as stated above, to look at the data. How do the data look? Is there a recognizable shape to the data or does it appear random? Is there one big cluster or several smaller ones? Is the cluster single peaked? Are the data symmetrical or skewed? How tight is the distribution? What values occur? Which values occur most? Which values do not occur often or at all? How are the data alike? Where do they tend to cluster? How are the data different? How spread out are they? Look at points when you can. Use a scatter plot or a time trend when it makes sense to do so, but do not automatically connect the points, if you connect them at all. Suppress grids and use only a few numbered ticks while you get a feel for your data. Let the evidence speak!

Graphs can be both useful and friendly. When well chosen, they can force us to note the unexpected; and little is more important to understanding one's data. There is no more reason to expect one graph to reveal all of your data's secrets than there is reason to expect one number to reveal all. Plan on using multiple graphs. Harris (1999) provides an excellent reference for choosing innovative graphics in his book *Information Graphics: A Comprehensive Illustrated Reference.*

The figures presented earlier in the chapter are not usually well suited to the needs of the general public. However, when communicating complex information to risk managers it is always useful to show the data if we are to help move decision making away from overreliance on a single value. Look at the data to understand its location, spread or scale, the shape of the data and tendencies to cluster or not. This helps experts notice the unusual when it exists. They also can show outliers that we need to understand and explain. What conditions must prevail for the BCR to exceed two, for example?

Once you have a feel for the data, numerical summaries can be useful for communicating that feel. Begin with the five-number summary. Take care not to anchor your own or anyone else's understanding of the data to its mythical average value. This can seriously impede a decision maker's ability to consider realistic extremes in the data. If we want decision makers to move away from single-point decision making, then we must begin to present risk managers with information that discourages that kind of thinking. Don't be too quick to reveal, much less emphasize, the mean value.

The five-number summary, repeated in Table 9.5, helps people to avoid anchoring to a mean and focusing on any one number. It is useful because it provides information about the location of the data with the median while describing the data's spread with quartiles and extreme values. The data range and interquartile range (middle 50% of all observations) are easily calculated from this summary. Each of the five numbers is an order statistic. Order statistics make it easier to visualize data sets. The median and quartile values are resistant statistics, i.e., they are not much influenced by outliers. Nonresistant statistics, like the mean and standard deviation, are heavily influenced by outliers. These five numbers constitute the values needed to define a box plot, as shown in Figure 9.4.

BCR Five Number Summary				
Minimum	1Q	Median	3Q	Maximum
0.58	1.09	1.22	1.37	2.63

Table 9.5: Five number summary for benefit cost ratio data

Understanding what your data have in common, e.g., their general location on the number line, is helpful. The mean, median and mode (see Table 9.6) are the most popular measures of your data's central tendency. Try not to use the mean; encourage the five-number summary.

BCR Measures of Central Tendency	
Statistic	Measure
Mean	1.24
Median	1.22
Mode	Multiple

Table 9.6: Measures of central tendency for benefit cost ratios

After understanding how your data are alike (they all tend to cluster around 1.24), it is important to understand how they differ. Measures of dispersion are used for this purpose. Table 9.7 shows some of the more common measures of dispersion. Of all of these, the standard deviation may be the most useful for helping the reader understand your data and what constitutes an unusual value for your output of interest. Adding ± 2 standard deviations to the mean provides a first cut at identifying unusual values for a bell-shaped distribution; ± 3 standard deviations defines a rough cut-off for identifying very unusual

Chebyshev's Theorem and the Empirical Rule

Theorem: The fraction of any data set lying within k standard deviations of the mean is at least

$$1 - \frac{1}{k^2}$$

where k = a number greater than 1.
This theorem applies to all data sets, which includes samples and populations.

The empirical rule gives more precise information about a data set than Chebyshev's Theorem, but it only applies to a data set that is bell-shaped. The empirical rule says:

68% of the observations lie within one standard deviation of the mean.
95% of the observations lie within two standard deviations of the mean.
99.7% of the observations lie within three standard deviations of the mean.

values. Calculate these values and use them to examine and explain your data.

BCR Measures of Dispersion

Statistic	Measure
Standard deviation	0.22
Variance	0.05
Minimum	0.58
Maximum	2.63
Range	2.05
1st Quartile	1.09
2nd Quartile	1.22
3rd quartile	1.37
Interquartile range	0.29

Table 9.7: Measures of dispersion for benefit cost ratios

Significant thresholds are another set of values an assessor must understand and identify. What they are and whether they even exist will depend on the individual value and the question one is trying to answer with the data. Separating good/desirable values from bad/undesirable values will always be important. Minimums and maximums are likely to be important. Values set in policy, zeros, BCRs less than one or more than a specific value of interest (perhaps to OMB), unusually large or unusually small values may all be important. In the BCR example, one and two are two significant thresholds. Values below one are more common than values above two.

Using z-scores (a number of standard deviations measured by $z = \frac{x-\mu}{\sigma}$) to measure distances between points in your data can sometimes be revealing. For example, a BCR of 1 is 1.1 standard deviations below its mean. Using 2 standard deviations as a rule of thumb threshold for unusual values it would not be unusual to see a BCR below one. OMB prefers a BCR above two. This value is 3.5 standard deviations above the mean and it would be a very unusual value to observe in reality. Using the mean ±1.96 standard deviations along with an assumption of a single-peaked and roughly symmetrical distribution, we can say 95% of all BCRs are expected to fall between 0.8 and 1.7.

9.4.2 Examine the Probabilities

Once you understand the quantities, you are ready to tackle their probabilities. The simplest way to begin is by dividing your data in half. This is what the median value does. Half the BCRs are 1.22 or below so there is a 50% chance the BCR will be 1.22 or less and a 50% chance it will be greater. The two halves can, in turn, be divided in half to yield quartiles. Using the quartiles developed for the five-number summary is a good place to begin. Table 9.5 above provides all four quartile values and these four values represent four standard points on the cumulative distribution function as seen in Figure 9.5. One-fourth (2,500) of the observations fall in each quartile. There is a 25% chance the BCR will be 1.09 or less; a 50% chance it will be below 1.22; and a 75% chance it will be below 1.37.

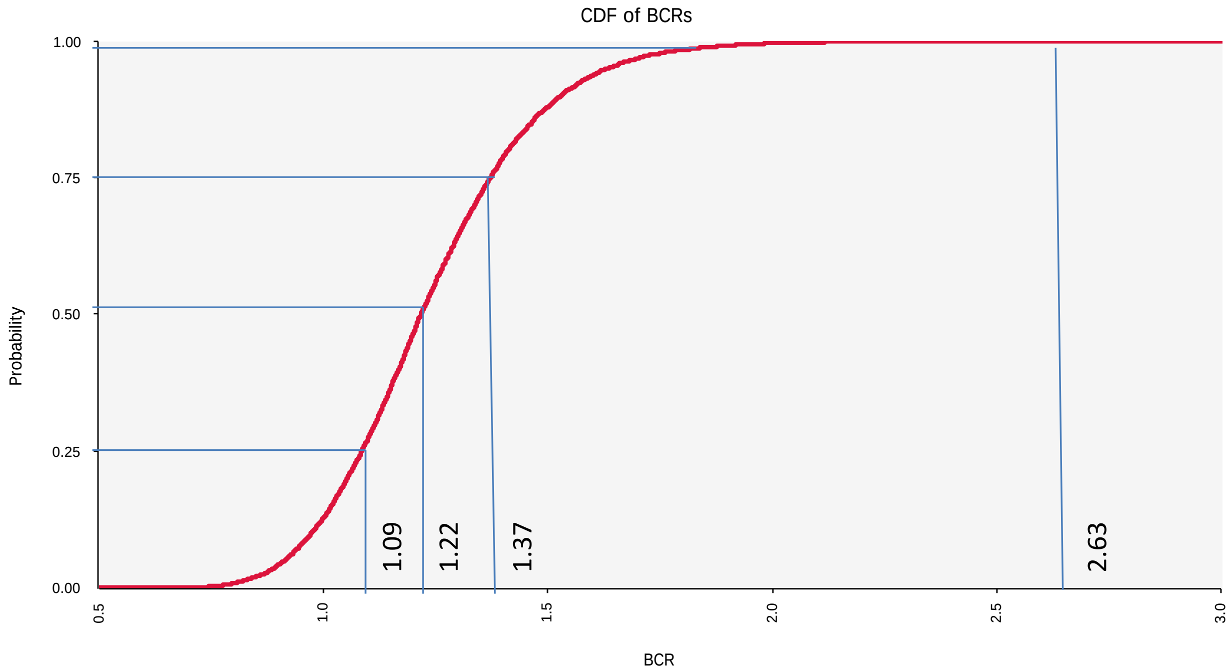


Figure 9.5: Four quartiles marked on the cumulative distribution function for benefit cost ratios

The more sharply the CDF rises, i.e., the steeper the slope, the more densely concentrated the values are. When the CDF flattens out, the spread of the distribution is greater. Imagine that the CDF casts a shadow on the horizontal axis. The shorter the shadow, the more concentrated the distribution.

Thresholds are specific quantity values that we do not want to exceed or fall below ranges of values we need to hit. Thresholds can be missed, attained or exceeded and the probabilities of doing so may be important to know. With probabilistic risk assessment it is relatively easy to estimate these values. An obvious threshold for the example is a BCR less than one. We have already seen that probability is 12.8%. Likewise the probability of a BCR in excess of two is 0.3%.

Probabilistic risk assessment techniques enable analysts to make quantitative statements about uncertainty. Information like that in Table 9.8, for example, enables risk assessors to tell risk managers we are 90% sure the eventual benefit cost ratio lies between 0.97 and 1.63.

Minimum Percentile	Maximum Percentile	Confidence Interval	Minimum Value	Maximum Value	Confidence Range
1	99	98%	0.811	1.861	1.05
2.5	97.5	95%	0.867	1.724	0.857
5	95	90%	0.972	1.63	0.658

Table 9.8:. Confidence statements for benefit cost ratios

Alternatively, we are 95% sure the true value of the BCR will lie between 0.87 and 1.72. This gives the risk manager a much more vivid understanding of the effects of uncertainty than if you begin by saying that our best estimate of the BCR is 1.22. Confidence ranges are probabilistic statements that help diminish overreliance on a single estimate of the output.[35] If the confidence range is too broad for the decision makers comfort level, there should be a discussion of practical options for further reducing the existing uncertainty.

Although it is not evident from the current example, tail probabilities and extreme events may be of more interest to decision makers than the probabilities discussed thus far. There are several options for discussing and presenting tail values. Deciding how to define the tails is the starting point. Above we discussed the importance of threshold quantity values, whether high or low. Here we define the tails by percentages and suggest the highest and lowest five percent as a starting point. The fifth and ninety-fifth percentiles for the example are 0.97 and 1.63. Using the filter feature of your spreadsheet software, it is a simple matter to isolate the tail of a distribution or any individual cluster of data, like the lowest 5% of all values as shown in Figure 9.6.

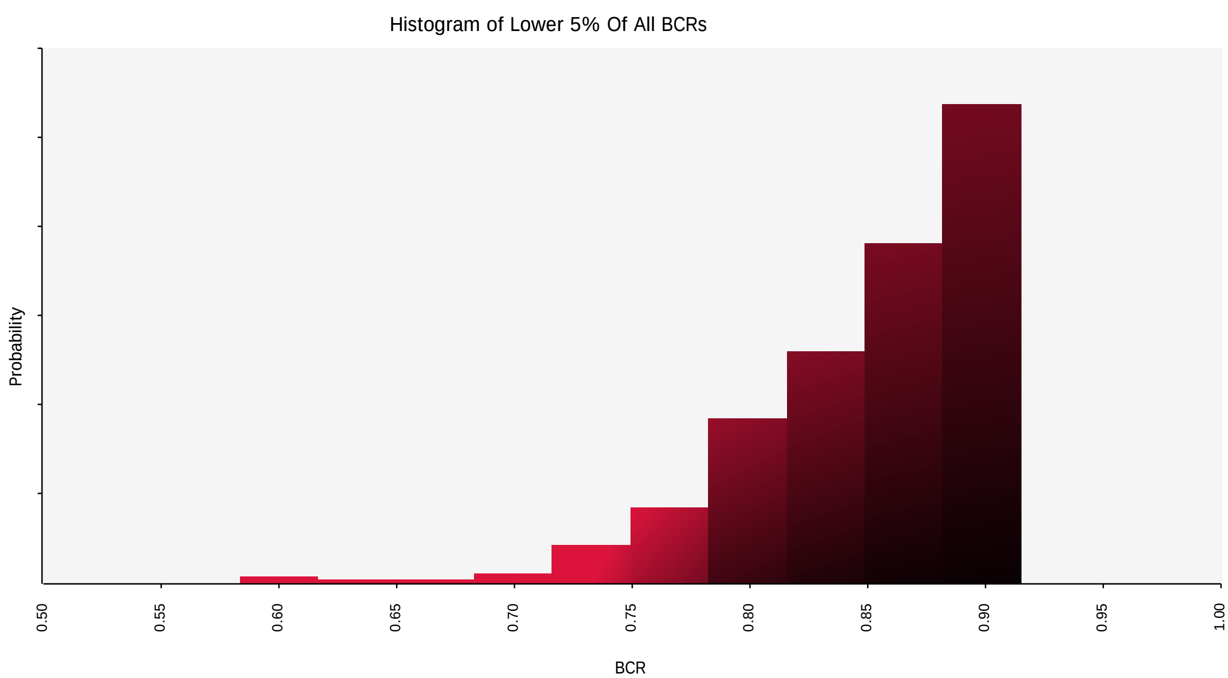


Figure 9.6: Histogram of the benefit cost ratios of projects for the fifth percentile BCR and lower

If the BCR does turn out to be in the lowest five percent, its mean will be 0.85. This sort of information is conditional on the fact that BCR is in the bottom five percent. The distribution of Figure 9.6 is a new conditional distribution, which itself can be subjected to as much analysis as

[35] The confidence ranges described here are not the same as the confidence intervals calculated for sample statistics. When we speak of being 'sure' as we do here, this is used in a rather loose sense. It literally means 90% (or 95%, etc.) of our results fell between these two numbers.

decision-making information needs warrant. This kind of partitioned analysis can be done for any size left or right tail. Conditional information can be informative for risk managers when tail values are important to the decision context. That, however, is not the case for the BCR example.

Extreme values can also be important to risk managers, especially in cases where loss of life, human health and safety are among the outputs of concern. For the BCR estimate the extremes are not quite so compelling as they might be for human life and safety. However, it is a relatively simple matter to explore the potential extremes of any given situation with a probabilistic risk assessment model.

9.4.3 Examine Relationships

Examining and explaining relationships between variables is sometimes more important than examining individual variables. To examine the relationships between variables, a new example is needed. Property damages are a major consequence for flood risks. Damage to residential structures and the contents of those structures are typically estimated as a percentage of the total value of the structure and the total value of the contents, where contents are often estimated as some percentage of the structure value. We'll use structures and content values for a hypothetical flood plain of 1,000 residential structures. Figure 9.7 presents histograms of both variables. This shows the shapes of the data. Figure 9.8 shows the data in a box and whisker format to reveal the spread and relative locations of the two datasets. Although the graphs are individually informative, they do little to help the reader understand anything about a possible relationship between the two variables.

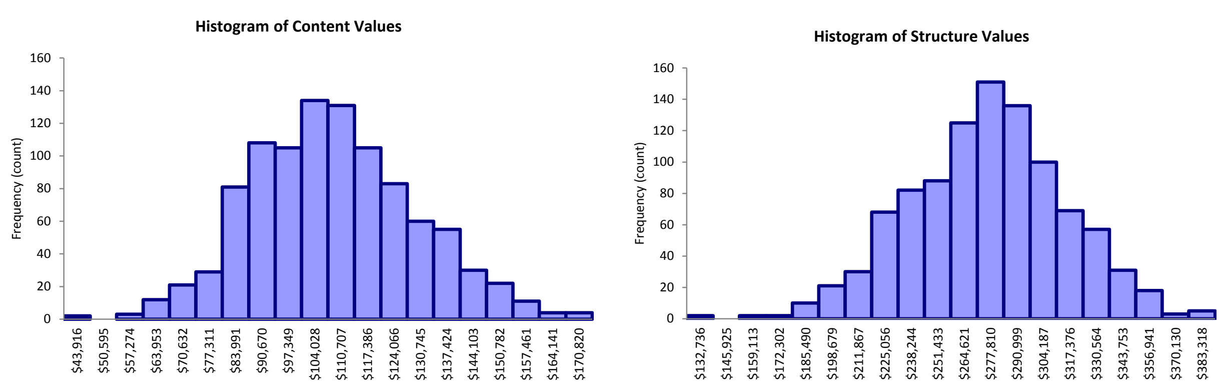


Figure 9.7: Histograms of residential property content and structure values

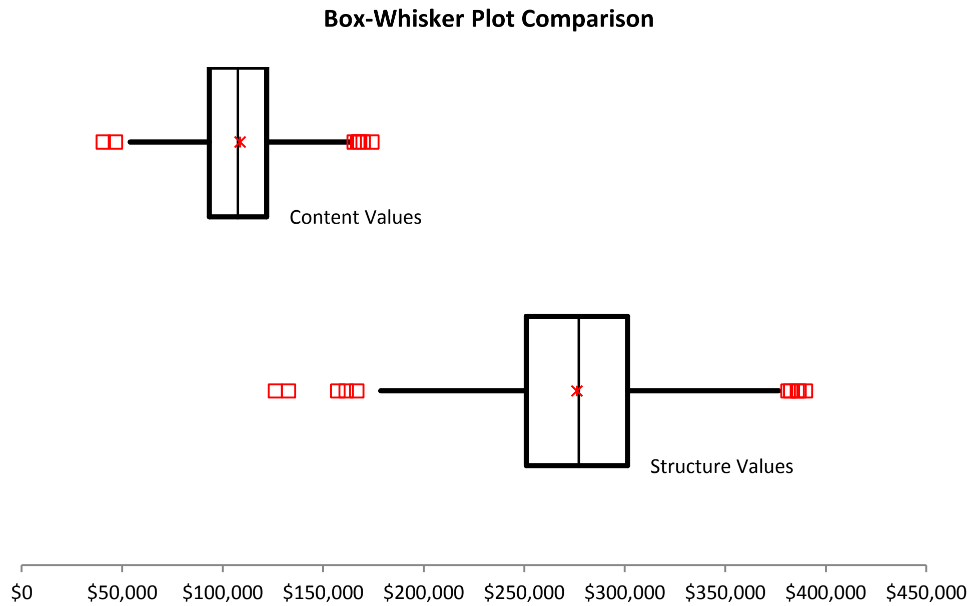


Figure 9.8: Box and whisker plots of residential structure and content values

The single best simple graphic device for exploring relationships between variables is the scatterplot. Figure 9.9 presents a scatterplot of content and structure values.

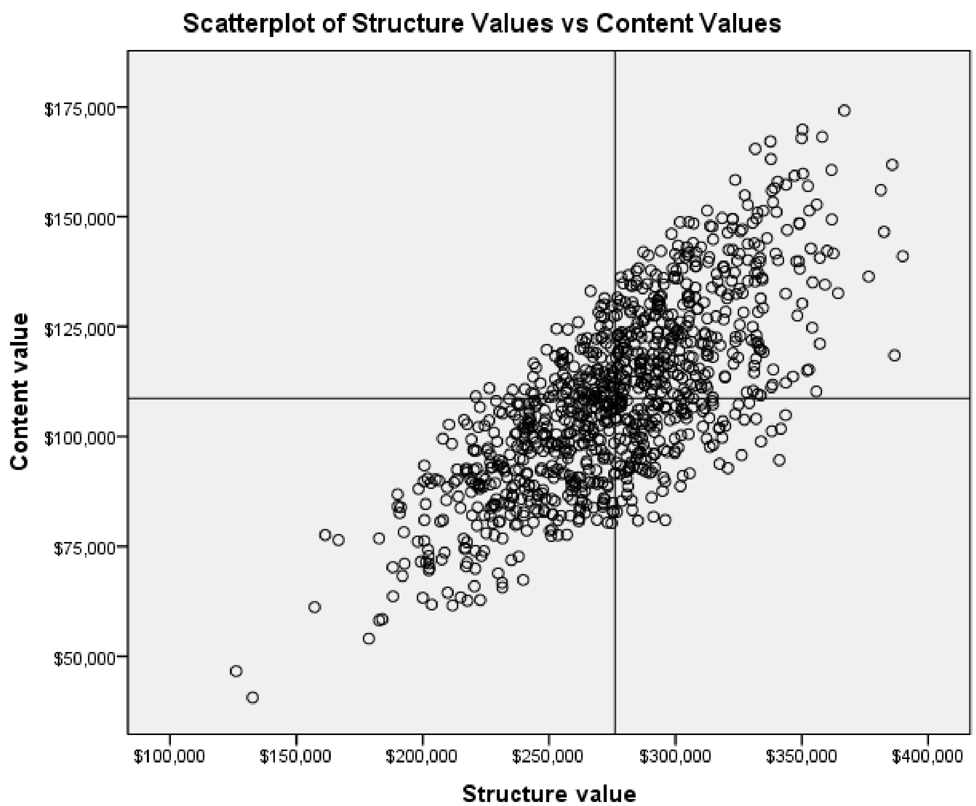


Figure 9.9: Scatterplot of residential structure and content values (N=1000)

Remember, scatterplots do not reveal cause and effect but simple correlation. The plot here, with means marked by indicator lines, reveals a distinct positive association between structure values and the values of their contents. As structure values increase so do content values. Structures above/below average in structure value tend to be above/below average in content value. The relationship is also relatively tight, i.e., the cloud of points is rather dense rather than widely spread.

Two commonly used coefficients are the Pearson and Spearman rank correlation coefficients. The Pearson coefficient is based on the differences from means between paired raw data values, this is 0.74 for the example. The Spearman rank coefficient is based on differences between the ranks of paired raw data values, this is 0.72 for the example.

These two variables are both inputs to a risk assessment. It can often be helpful to produce scatterplots of outputs to see how decision variables may be related to one another. Scatterplots of an output and an input upon which it depends can also be useful in sensitivity analysis to identify uncertain inputs that may influence the variation in an output. Examining the scatter plots of simulation results (inputs and outputs) can provide a good reality check for any risk assessment.

Scatterplots help reveal overall patterns of relationship between variables. Lines and curves, their tightness and direction, quickly reveal facts about relationships. It is easy to see how individual points differ from the averages when the averages are identified on the graphs. Unusual points and subclusters are also easy to identify, although none jump out in the current example. When clusters of points are found this invites the assessor to explore what "membership" in the group may be based upon. Use scatter plots to explore and then explain relationships to risk managers.

Correlation coefficients measure the strength of a relationship between a pair of variables; the two variables in this example have a correlation coefficient of 0.74. The positive value confirms that an increase in one variable tends to be associated with an increase in the other variable. The size, .74, indicates a relatively strong positive relationship. Correlation coefficients range from -1 for perfect linear negative relationships to +1 for perfect linear positive relationships. Values close to zero indicate the lack of an association between the values of the two variables.

Re-expressing the data in different ways can sometimes help you to see relationships. It is usually easier to see what is going on in linear relationships, so straightening out a curvilinear point scatter using logarithms or roots may be helpful.

The reason for understanding the results of any risk-informed analysis is to answer the questions risk managers have about a decision problem in a way that provides useful information for decision making. To make decisions with risk-informed information, it is absolutely essential that analysts answer the questions that were posed in the decision context framing step of the risk management model. The techniques described above will aid that process.

9.5 Communicating Uncertainty[36]

Explaining uncertainty to an audience with a wide range of scientific and mathematical expertise presents a serious challenge. This audience can include USACE decision makers and risk managers in and outside USACE as well as the public. Advances in data visualization techniques are well worth keeping abreast of to support the most effective displays of information for these varied audiences. Spiegelhalter (2012) suggests the primary purpose of a visualization may be to grab an audience's attention. Once you succeed in getting their attention you may inform them, alter their feelings, change their behavior or encourage them to weigh the possible benefits or harms of different actions. It may be important to communicate detailed numerical information to some audiences or it may be sufficient to just convey the essence of a message. If risk management is to include a public involvement component, ethical practice may require USACE to provide transparent information (Nelson, et al, 2009).

In general, people are uncomfortable using quantitative probabilities to make decisions because the everyday decisions, with which they are most familiar, are not guided by this kind of information. The danger in this is that when uncertainty information is presented in this way it can cause people to ignore the information entirely (Edwards, et al., 2012). Communicating uncertainty to decision makers is a significant challenge but communicating it to the public is an even greater challenge. Recent research by Edwards, et al. has suggested that the manner in which probability data are presented has had only equivocal effects on understanding, although graphical displays do seem to work better than verbal ones under some circumstances.

Uncertainty and probabilities can be described using language that appeals to people's intuition and emotions but this process fails when we want to convey precise information because of the ambiguity of words. Unlikely, probable, rare, and similar probability words are not interpreted consistently. Efforts to standardize language for decision-making purposes have not been successful (Yoe, 2012).

When precision is required, numerical probabilities are the most succinct and accurate way to convey that information. This becomes a difficult problem when any audience has low numeracy[37]. The format for presenting probability is itself a problem. Using odds or decimals compounds the effects of low numeracy and makes it more difficult for people to distinguish absolute risks from relative risks. Conditional probabilities, which are common in engineering problems, present additional difficulty (Spiegelhalter, 2012).

The manner in which a problem is framed can have an effect on the way the data are perceived. For example, the United States tends to favor the use of mortality rates (negative framing) for many purposes while the United Kingdom tends to use survival rates (positive framing). Ideally, there would be no framing effect as the data should provide the useful information. One way to

[36] The author gratefully acknowledges the influence of David Spiegelhalter, Mike Pearson, and Ian Short on the structure and content of this section. Their article provided the framework for this section as well as much of the content.

[37] Numeracy is the ability to reason and to apply simple numerical concepts such as comprehending fundamental mathematics like addition, subtraction, multiplication, and division.

avoid biases from framing is to use frequencies, e.g., *“Out of 50 years living here we expect 5 of them to have floods and 45 of them to be flood free.”* This wording tries to avoid framing bias by describing both positive and negative outcomes.

Fractions are sometimes used to convey probabilities. For example, a flood risk may be described as 1/10 in any year or using natural frequencies one might say a flood is expected to occur 1 in 10 years. These formats can lead to ratio bias or denominator neglect (Reyna, 2008). The perception of probability tends to be influenced by the ratio of the specific frequencies depicted. This perception is particularly sensitive to the numerator. For example, a flood risk of 1 in 10 years may be perceived as smaller than 5 in 50 or 10 in 100. Denominator neglect tends to not take the size of the population into account (10, 50, 100 in the preceding example) while focusing on the number of events (1, 5, 10). This is especially problematic when the denominator changes as when describing a flood risk of 1 in 10 or 2 in 100. The latter may well be regarded as the greater risk. Thus, if these kinds of ratios will be used it is important to use the same denominator for all values. Also, note that powers of 10 are easier to understand.

This chapter has argued the value of representing probabilities with graphics. Spiegelhalter’s (2012) summary of the literature finds a graphic can:

- Summarize data concisely,
- Illuminate hidden patterns,
- Gain and hold attention,
- Enliven information,
- Inspire the viewer,
- Help people with low numeracy,
- Arouse emotion, and
- Overemphasize negative consequences leading to risk aversion.

For communicating information about discrete events to the public, standard graphical tools like pie charts, bar charts and icon arrays are recommended. Pie charts, in particular, are useful for exhibiting single proportions, in part because they are usually familiar and acceptable to a general public audience. Figure 9.10 provides a view of the probability that a person living 75 years in a 1% exceedance frequency floodplain will be flooded one or more times versus remaining flood free. Using areas to represent probabilities in pie charts makes it difficult to compare multiple charts.

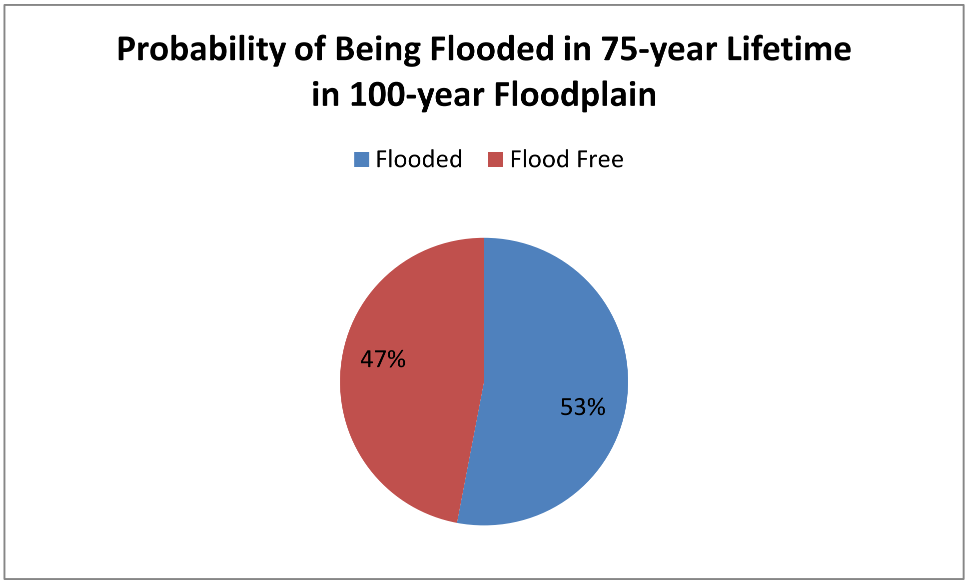


Figure 9.10: Pie chart probability of one or more floods in 75 years in a .01 exceedance frequency floodplain

Bar charts like the one in Figure 9.11 are useful for conveying the magnitude of events and they can sometimes be helpful for making comparisons.

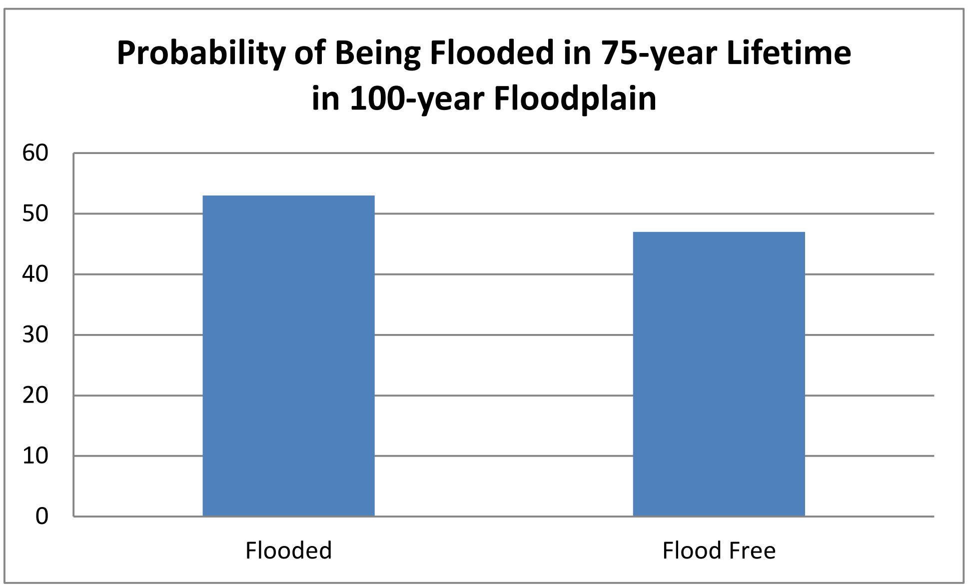


Figure 9.11: Bar chart probability of one or more floods in 75 years in a .01 exceedance frequency floodplain

Medical risk communication has used icon arrays with reasonable success since the 1990s. An icon array is a matrix of icons (usually 100 or 1000 icons) that represents an at-risk population. It uses natural frequencies and simultaneously shows both the number of expected events (e.g., years with floods) and the number of expected non-events (flood-free years). Their advantages over other visual displays include (Icon Array, http://www.iconarray.com/why accessed January 5, 2013):

- Icon arrays can be read simply by counting icons.
- Icon arrays show the part-whole relationship clearly in both relative count and relative area.
- Icon arrays are inherently a frequency-based representation of risk.

Figure 9.12 shows an icon array showing the expected number of flood events with an exceedance frequency of 0.1 that will occur in a 100-year period. On the left is an array without scattering. On the right is an array with scattering.

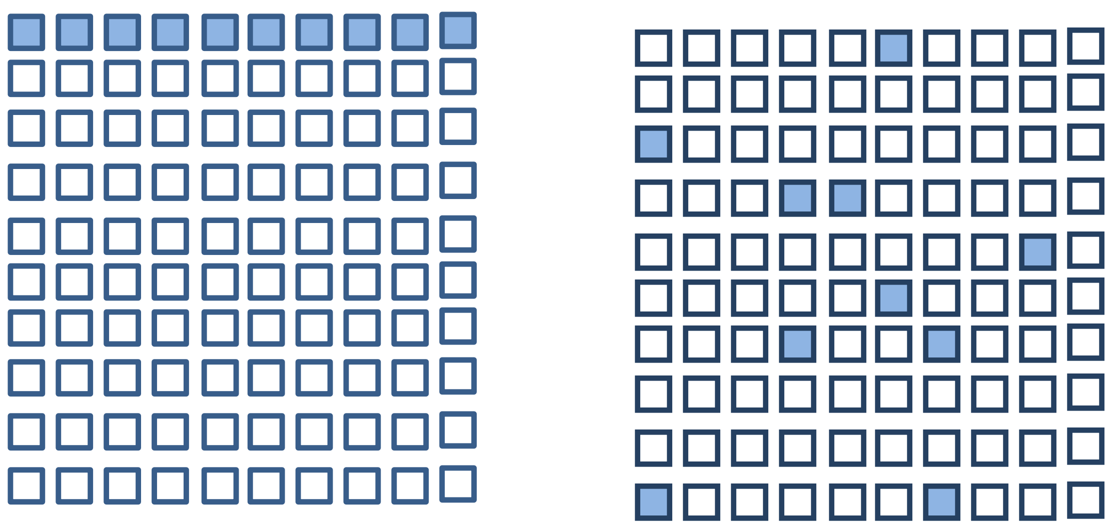


Figure 9.12: Icon arrays with and without scattering showing the number of years with a flood in a floodplain with an 0.1 exceedance frequency

Although scattering conveys the randomness with which floods occur better, it can be difficult to assess magnitudes and make comparisons in arrays with scattering. It is probably better to use arrays without scattering when the audience has low numeracy.

Risk ladders have been useful for contrasting risks over different orders of magnitude. Spatial or geographic uncertainty has been represented by using hue and saturation of color, blurring, symbols and other techniques (MacEachren, 2005). Recent innovations in infographics can be adapted to communicate uncertainty. Word clouds and font sizes have been proportioned to probabilities, for example. The potential for infographics with interactive features is, perhaps, one of the most promising areas for new and effective means of conveying uncertainty. Rosling's Gapminder (http://www.gapminder.org/ accessed January 5, 2013) is an excellent example of the ability of interactive infographics to tell a coherent story (Yoe, 2012). Interactive infographics promote understanding and retention by actively engaging the user with the content. There is some evidence to suggest this can minimize individual differences in numeracy.

Spiegelhalter, et al. (2012) conclude their informative review with some advice about how best to visualize probabilistic uncertainty. Ultimately, the approach will depend on the communication objectives of the presenter, the context of the communication and the audience. If understanding is an objective then they offer these suggestions:

- Use multiple formats: no single representation will satisfy everyone
- Illuminate graphics with words and numbers
- Use graphics that allow part-to-whole comparisons
- Avoid framing bias by using frequencies with a clearly defined denominator of constant size
- Use helpful narrative labels
- Use narratives, images and metaphors that are sufficiently vivid to gain and retain attention without arousing undue emotion
- Assume low numeracy of a general public audience
- Interactivity and animations provide opportunities for adapting graphics to user needs and capabilities
- Acknowledge the limitations of the quality and relevance of information
- Avoid chart junk and obvious manipulation through misleading chart features
- Assess the needs of the audience, experiment, and test and iterate toward a final design.

9.6 Five Points To Take Away

1. Risk-informed decision problems include any problems where USACE must explicitly account for the uncertainty in their decision-making process.
2. Decision making under conditions of uncertainty is both more honest and more challenging than making decisions under the illusion of certainty.
3. If risk managers do not use risk-informed information for decision making, then assessors waste time and resources doing risk-based analysis that addresses decision uncertainty because the additional information is ignored and nothing is changing to improve the quality of decisions under conditions of uncertainty.
4. Any decision made under conditions of uncertainty should be accompanied by either a quantified measure of uncertainty or a qualitative expression of the decision maker's confidence in the validity of the decision.
5. The potential for infographics with interactive features is, perhaps, one of the most promising areas for new and effective means of conveying uncertainty.

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APPENDICES

Appendix A: Ranking Techniques

A.1 Introduction

Ordering techniques have been very useful in qualitative risk assessment. Two techniques are described in this appendix. The first is informally called enhanced criteria-based ranking. The second is the analytical hierarchy process (AHP). The former is almost exclusively a qualitative ranking technique. AHP can be used with either qualitative or quantitative evidence.

A.2 Enhanced Criteria-Based Ranking

This eight-step process is based on qualitative criteria grounded in evidence. It is enhanced by its structure and a built-in "sanity check." The steps follow:

1. Criteria
2. Evidence-Based Ratings
3. All Possible Combinations of Ratings
4. Ranking
5. Evaluate Reasonableness of Ranking
6. Add Criteria
7. New Combinations of Ratings
8. New Ranking

As with all risk assessments this one begins with a clearly defined decision problem, i.e., a well-focused question to be answered. Ordering techniques are used when you have a list of items to be ranked. These could be projects to fund, non-federal levees, tainter gates in a district, dams in the nation, stone rubble breakwaters, and so on. The example that follows answers the hypothetical question, "Which lock gates in the USACE division present the greatest potential risk to health and safety and therefore should be repaired first?"

A.2.1 Step 1: Criteria

Begin by identifying a few science-based criteria that reflect the most important aspects of the risk you are evaluating. These should be chosen to enable you to answer the question. Using the familiar product definition of risk, probability times consequence, it is often useful to develop a criterion or two for each of these attributes of a risk. The number of criteria used for this methodology is usually limited to five or less. If you need more criteria perhaps it would be wise to use a more sophisticated technique.

Once the criteria have been identified, the most critical task is to define mutually exclusive and collectively exhaustive evidence-based scenarios for each criterion. High, medium, low or no risk potential scenarios are pretty standard for this method. Carefully defining these scenarios is the key to a substantial and transparent science-based method. The definitions must support ratings of the lock gates that can be based on evidence. Criteria and scenarios[38] for this example follow, note the no risk rating is not used.

Criteria #1: Age of gates

- H = High; twenty or more years old
- M = Medium: over ten years old and up to 20 years old
- L = Low; zero to 10 years old

Criteria #2: Frequency of use

- H = High; daily use year round
- M = Medium; more than once a year but less than daily usage
- L = Low; once a year or less

Criteria #3: Consequence of failure

- H = High; loss of life and/or property and/or navigation pool
- M = Medium; damage limited to the navigation structure itself
- L = Low; not much more than emergency repair costs

The first two criteria capture aspects of the probability of a risk occurring. Age and frequency are surrogate indicators of gate "failure." Criterion 3 clearly captures aspects of the consequence of failure. Data for each criterion ought to be available for each lock.

Alphabet ratings are used rather than numerical values to discourage people from doing math with numerical ratings. An H is a greater risk potential than an M or an L. If 3, 2, 1 are used instead people tend to think a 3 is three times worse than a 1. That is not the case. Math is not appropriate with a qualitative approach like this. Letters discourage the math.

The criteria chosen must enable the assessor to discriminate among the lock gates. Therefore, a criterion that results in all gates receiving the same rating is not a useful criterion and should be dropped, no matter how important it is. It is sufficient to note the criterion was considered but was not used in the assessment because it did not help to separate or rank the items.

If the criteria are to receive different weights, the weights should be determined in this step. For simplicity equal weights are used for this example.

A.2.2 Step 2: Evidence-Based Ratings

With a list of lock gates to rank and the criteria for ranking it's time to gather the evidence needed to rate each item for each criterion. Data to rate age and frequency of use ought to be relatively easy to obtain. The consequence of a failure may require a bit of judgment to go along with the evidence used to support the qualitative judgments of the risk assessors. The priority order for evidence is data or other objective evidence, expert elicitation, and expert judgment. When judgment replaces objective evidence, that judgment must be documented as carefully as evidence would have been.

[38] The example presented here is a heuristic presentation. No attempt is made to suggest the criteria used here or the scenarios defined for them are appropriate for anything more than a teaching example.

Table AA.1 presents the hypothetical results of this step. The facts, evidence, and judgments used to make these ratings would be referenced and included in the documentation of the process.

Gate	Criterion 1	Criterion 2	Criterion 3
Knightsbridge	H	L	M
Steadly	H	M	M
Redwood	M	H	L
Jackflash	M	H	L
Cantget	L	L	L
Roughjustice	H	M	L
IORR	L	M	H
19	L	H	L

Table AA.1: Lock gate ratings for each criterion

A.2.3 Step 3: All Possible Combinations of Ratings

This step is largely determined by the subjective weights assigned to the criteria. Before the ratings can be used to determine the ranking, the hierarchy of risk potential must be made explicit. For equal weights all the possible combinations of ratings result in the ranking hierarchy shown below.

Greatest Risk	HHH
	HHM, HMH, MHH
	HHL, HLH, LHH, HMM, MMH, MHM
	HLM, MHL, HML, LMH, MLH, MMM, LHM
	HLL, LHL, LLH, MML, LMM, MLM
	MLL, LML, LLM
Least Risk	LLL

Despite the “no math” caveat earlier, these ranks were determined by letting H=3, M=2, and L=1. The highest ranking risk sums to nine, the second row of risks sum to eight, etc. If analysts had decided that criterion 1 is more important than criterion 2 or 3 an HMM would be a higher ranked risk than MHM or MMH and the groupings would look different. The assigned weights will determine the combinations of ratings that receive the same ranking.

A.2.4 Step 4: Ranking

Using the results of steps 2 and 3 you rank the lock gates in order of descending relative risk as shown in the Table AA.2. Grouping the gates into subjective clusters of relative risk or concern is a judgment step that ought to be documented. The order of similarly rated items is arbitrary.

Gate	Rating	Ranking
Steadly	HMM	Greatest Risk
Roughjustice	HML	Moderate Risk
Jackflash	MHL	
Knightsbridge	HLM	
Redwood	MHL	
IORR	LMH	
19	LHL	
Cantget	LLL	Least Risk

Table AA.2: Subject ranking clusters of lock gates

The greatest and least risk lock gates are trivial to identify. The distinctions among the six pairs of gates ranked as risks of moderate potential were not sufficient to separate them further in the judgment of the analysts.

A.2.5 Step 5: Evaluate Reasonableness of Ranking

This is the sanity check step. Do the rankings make sense? If not, why not? What is missing? This step exists solely to minimize errors due to overlooking some important criterion. Analysts pause here to evaluate their thought process before finalizing the rankings.

Suppose the Jackflash and Knightsbridge locks were generally regarded as greater risks than Roughjustice lock. What might explain the fact that this judgment is not evident from the process so far? A conversation with the experts might reveal that if emergency repairs are needed the cost of that repair, in terms of disrupted navigation, would be greater at some locks than others. That consequence is not adequately picked up by the original criteria. The solution is to add a criterion to pick up this important factor. Imagine the following criterion is added to the analysis.

Criterion 4: Cost of emergency repair

H = High: major disruptions to navigation or power, much higher costs to repair
M = Medium: much higher costs to repair
L = Low; same as scheduled repair

Now the process better reflects the potential risk posed by the locks. This step often makes people uncomfortable because it is misunderstood. Its purpose is not to get the answer you want. Its purpose is to get the logic and the evidence right for a qualitative assessment. It reveals and documents the evolutionary thinking about the question at hand for the sake of transparency. A new criterion will not always be added. In fact, criteria can be dropped as redundant or non-discriminating. A criterion may at times be replaced by a better criterion. If the criteria change in any way steps 2 and 3 are repeated. If no new criteria are added the process is complete at this point.

A.2.6 Step 6: New Combined Rating

A new set of all possible combinations that reflects the weights of the new and old criteria will also be needed. Each pair of lock gates is rated against the evidence for the new criterion. A new set of combined ratings, shown in Table AA.3, is obtained.

Gate	Criterion #4 Rating	New Combined Ranking
Steadly	H	HMMH
Jackflash	H	MHLH
Knightsbridge	H	HLMH
Redwood	M	MHLM
IORR	M	LMHM
19	H	LHLH
Roughjustice	L	HMLL
Cantget	H	LLLH

Table AA.3: Lock gate ratings with four criteria

A.2.7 Step 7: New Ranking.

The new ratings and the revised list of all possible combinations provides a new ranking as shown in Table AA.4. The lock gates are again grouped into subjective clusters of designated risk potential. The fourth criterion provides an effective explanation for the perceived differences among the gates at Roughjustice, Jackflash, and Knightsbridge locks. Clearly, the lines separating the risk categories are subjective, but ideally it is not arbitrary. Decision makers will now decide how best to manage the greatest risks. In some instances a qualitative assessment may provide sufficient justification for taking action. In other instances a qualitative assessment is done to identify those risks that merit a quantitative assessment.

Gate	New Combined Ranking	Ranking
Steadly	HMMH	Greatest Risk
Jackflash	MHLH	Greatest Risk
Knightsbridge	HLMH	Greatest Risk
Redwood	MHLM	Moderate Risk
IORR	LMHM	Moderate Risk
19	LHLH	Moderate Risk

Roughjustice	HMLL	Moderate Risk
Cantget	LLLH	Least Risk

Table AA.4: Final ranking of lock gates

The tables provide effective documentation of the decision process. They identify the criteria, ratings and rankings. This transparency enables others to challenge any part of the evidence or judgment and to present alternative evidence for doing so. Focusing on the criteria and evidence that underlies the rankings are strengths of the process.

A.3 Analytical Hierarchy Process

The Analytic Hierarchy Process (AHP) was created by Thomas Saaty in the 1970s. It is a second example of criteria ranking process that can be used to order lists of things. In this example we assume the beneficial uses of dredged material program provides a clean source of dredged material that will be used to establish wetlands in a national wildlife preserve along the Chesapeake Bay that has been experiencing severe erosion in part because of its exposure to waves generated by deep draft navigation vessels. To keep the example simple assume there are three alternative sites for constructing wetlands and we want to know which sites are the riskiest. In other words, where is the establishment of a wetland most likely to fail. Figure A.1 shows a simple tree diagram representing the problem.

The discussion proceeds in two parts. First, we'll examine how to derive subjective weights for the different criteria. Next, we'll see how rankings can be established using a paired ranking technique.

A.3.1 Deriving Subjective Weights (Analytical Hierarchy Process Part I)

To identify the most promising sites for establishing a wetland we'll use three criteria. These are: water depth, wave action, and accessibility. The Analytical Heirarchy Process (AHP) can use tangible and intangible criteria as well as quantitative and qualitative information. Figure A.1 shows the relevant hierarchical model that summarizes the decision problem and the question to be answered.

The AHP process provides a simple way to derive weights to reflect the decision makers' preferences. For simplicity let's assume only one decision maker. She must rate the relative importance or her preference for each criterion using a pairwise comparison approach. This begins with the 3x3 matrix of Table A.4.

	Water Depth	Wave Action	Accessibility
Water Depth			
Wave Action			

Accessibility			

Table A.4: 3X3 criteria ranking matrix for determining the decision maker's criteria weights

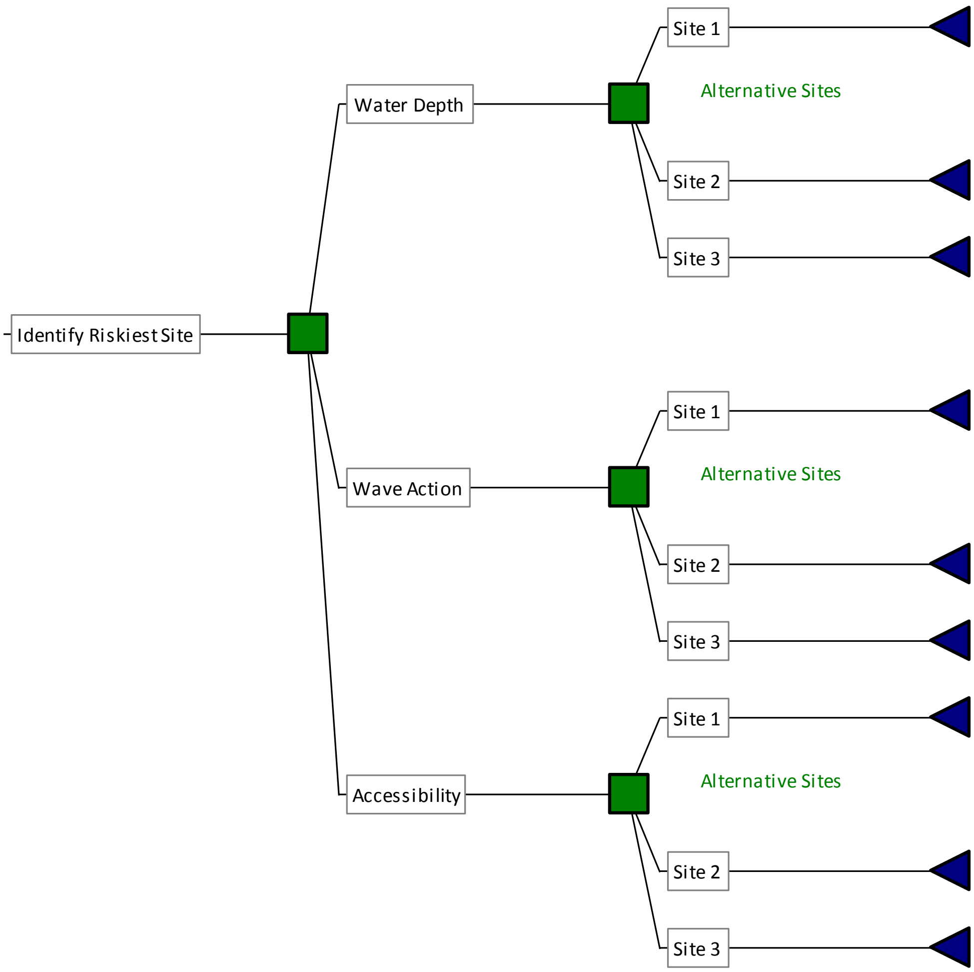

Figure A.1: Simple hierarchical model for three criteria and five alternatives

The AHP enables the decision maker to rank the importance of each criterion relative to the others, using the scale shown in Table A.6. The even numbers 2, 4, 6, and 8 provide the halfway positions for these values. Thus, a 4 is halfway between somewhat more important and definitely more important.

Relative Importance	Value
Equal importance/quality	1
Somewhat more important/better	3
Definitely more important/better	5
Much more important/better	7
Very much more important/better	9

Table A.6: Saaty's AHP scale for determining the relative importance of criteria in a pairwise ranking

Suppose the comparison for the decision maker in this case is as follows:

- Water depth is [much MORE important] than wave action[39]
- Water depth is [somewhat MORE important] than accessibility
- Accessibility is [extremely MORE important] than wave action
- Wave action is [extremely LESS important] than accessibility
- Wave action is [much LESS important] than water depth
- Accessibility is [somewhat LESS important] than water depth

The preferences/judgments are shown in Table A.7.

	Water depth	Wave action	Accessibility
Water depth	1	7	3
Wave action	1/7 = .14	1	1/9 = .11
Accessibility	1/3 = .33	9	1
Total	1.47	17	4.11

Table A.7: Completed criteria ranking matrix for a hypothetical decision maker

[39] This means water depth is more important in determining the risk of losing a wetland than wave action is for this particular assessment. A similar logic applies for all judgments that follow.

Here is how to read the table. The number entered in the cell is based on the row as compared to the column value. A 7 means the row criterion (water depth) is much more important than the corresponding column value (wave action). When the row value is less important than the column value the reciprocal is used. Thus, a 1/7 means the column value (water depth) is much more important than the corresponding row value (wave action). The last row shows the sum of the weights. From these values we can obtain an estimate of the overall weighting for each criterion for a given decision maker.

In order to derive the weights we normalize the weights by dividing each cell entry in Table A.7 by its column total. Thus, the weight for water depth is 1/1.47 = .68 as seen in Table A.8.

	Water depth	Wave action	Accessibility	Priority Vector
Water depth	0.68	0.41	0.73	0.61
Wave action	0.10	0.06	0.03	0.06
Accessibility	0.22	0.53	0.24	0.33
Sum	1.0	1.0	1.0	

Table A.8: Normalized weights

Inconsistencies can arise when people describe their subjective ratings. To smooth them out the average of each row is calculated as seen in the priority vector column of Table A.8. This is the final weight for each criterion. These weights suggest water depth carries a weight of 61% in the ranking process, wave action accounts for 6%, and accessibility represents about 33% of the ranking priority. Subcriteria can be considered if risk assessors want to break water depth, wave action and accessibility down into finer elements. Subcriteria are not used in order to avoid complicating the example unnecessarily.

Subcriteria

Imagine that water depth was divided into maximum and minimum depth. Weights would be determined for the subcriteria in a similar fashion. Suppose the ranking matrix looked like this.

	Min	Max
Min	1	3
Max	0.33	1
Total	1.33	4

The normalized weights become Max = 0.75 and Min = 0.25. Water depth was 0.61 so Max = 0.75 x 0.61 = 0.46 and Min is 0.25 x 0.61 = 0.15.

When comparison of alternatives begins it would begin at the DO and pH levels and aggregate upward, consistent with the methodology shown in AHP Part II.

A.3.2 Analytical Hierarchy Process Part II: Getting to a Decision

With subjective weights in hand the next step is to compare the alternative plans using criteria evidence and the weights. If there are subcriteria in your model the process begins with the subcriteria, i.e., the lowest level in the hierarchy of decision criteria.

First, prepare a Site Comparison matrix for each criterion. Next, use a pairwise comparison method[40] to complete the matrix. We'll do that qualitatively, using the same 1-9 rating scale presented above. Assessors must determine how each site compares to the others, based on water depth, for example. Suppose the following is true for water depth.

- Site 1 is somewhat better than Site 2.
- Site 1 is very much better than Site 3.
- Site 2 is much better than Site 3.

These judgments and the mathematical process described previously yield the results in Table A.9.

Water depth	1	2	3
1	1	3	9
2	0.33	1	7
3	0.11	0.14	1
Total	1.44	4.14	17

Water depth	1	2	3	Priority Vector
1	0.69	0.72	0.53	0.65
2	0.23	0.24	0.41	0.29
3	0.08	0.03	0.06	0.06

Table A.9: Water depth comparison matrix and calculation of normalized weights for Water depth contribution of each plan

Repeating the process for wave action and accessibility we obtain the values in tables A.10 and A.11.

Wave action	1	2	3
1	1	0.14	0.14
2	7.00	1	0.2
3	7.00	5	1
Total	15	6.14	1.34

Wave action	1	2	3	Priority Vector
1	0.0.7	0.02	0.11	0.07
2	0.47	0.16	0.15	0.26
3	0.47	0.81	0.74	0.68

[40] If actual data are available they can be used in lieu of the subjective comparisons, the math gets a bit more involved than we want to be here, however.

Table A.10: Wave action comparison matrix and calculation of normalized weights for wave action contribution of each plan

Accessibility	1	2	3
1	1	4	7
2	0.25	1	3
3	0.14	0.33	1
Total	1.39	5.33	11

Accessibility	1	2	3	Priority Vector
1	0.72	0.75	0.64	0.70
2	0.18	0.19	0.27	0.21
3	0.10	0.06	0.09	0.09

Table A.11: Accessibility comparison matrix and calculation of normalized weights for Accessibility contribution of each plan

Now we can combine the various weights and calculate the plan final scores for the three potential wetland sites. Figure A.2 provides the structure for these steps. The calculated criteria weights are entered above the criteria branches. The calculated plan weights follow on the node behind each weighted criterion. The triangle end points show how the criterion

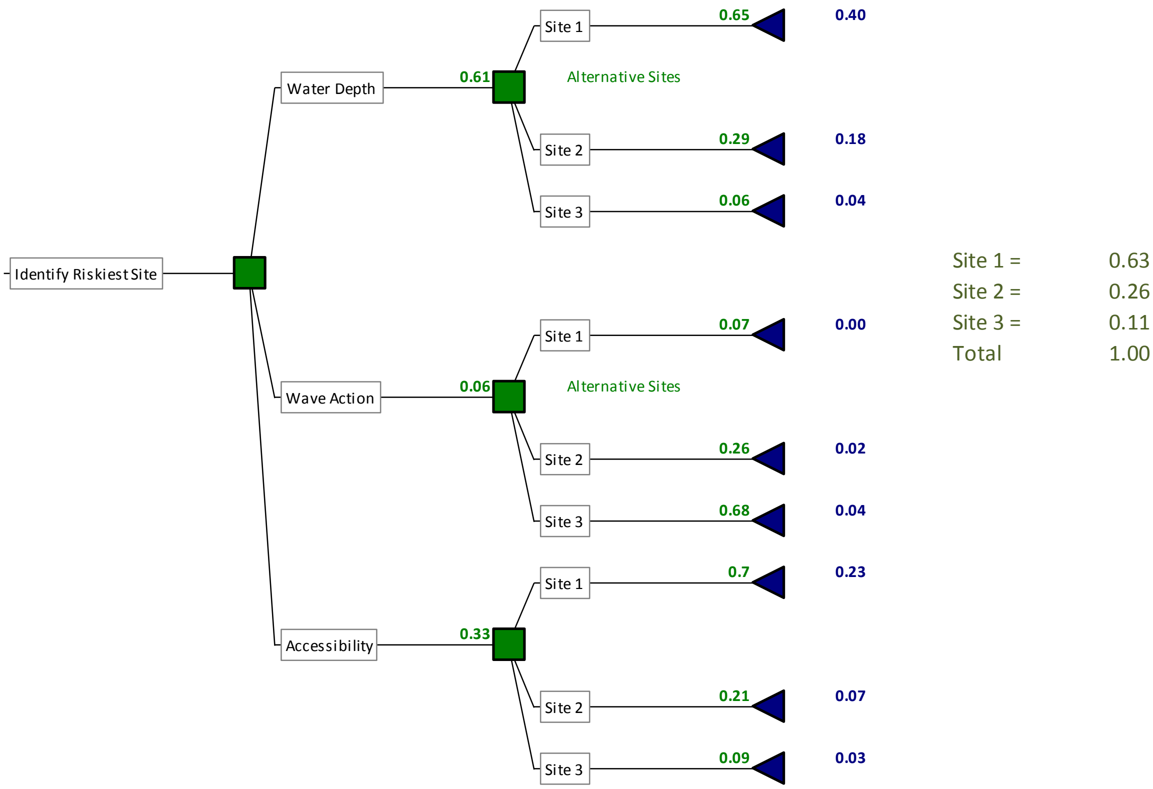

Figure A.2: Simple hierarchical model with AAHP determined weights

weight is distributed among the plans. When it comes to water depth site 1 is riskiest with a .4 score. Site 3 is the riskiest as far as wave action, but this pales next to the water depth scores. Site 1 is also riskiest when it comes to accessibility to the sites.

Summing the scores for the three criteria by site we see site 1 is the riskiest site with a score of .63. This is significantly more risky than the other sites based on the judgments entered. Thus, site 3 is the best, i.e., least risky, place to try to establish a wetland.

Here is a nontechnical, soft interpretation of this process. Note the criteria weights sum to 1. These weights are measures of the importance of each criterion. Accessibility captures 33% of the importance in this decision process. Each node following a criterion has values for the three sites that sum to 1. This shows each site's share of the total criterion importance. Thus, Site 1 captures 70% of the importance of the accessibility criterion. Multiplying the criterion weight by the node share produces a weighted contribution of the overall importance. So 0.33 x 0.7 = 0.231. Notice all the values following the triangle end points sum to 1. When we add each site's contributions to the individual criteria we obtain the final scores.

Appendix B: Risk Matrix

B.1 Introduction

Constructing, using and institutionalizing a risk matrix within an organization requires no special expertise in quantitative risk assessment methods or data analysis. That is both the advantage and the curse of the risk matrix. A risk matrix, also called a risk map, a heat map or, in Department of the Army jargon, "operational risk management" is based on the simple conceptual model of risk:

Risk = probability x consequence

The matrix itself is a table with several categories of probability along its rows (or columns) and several categories of consequences along its columns (or rows). The matrix associates a level of risk with each row-column pair, i.e. Each cell in the matrix. The matrix functions as a two-dimensional map and color-coding of risks is a common practice[41]. The highest risks are usually colored red and the lowest risks are usually green. Intermediate risks are often amber, but it is not uncommon to find matrices that use more than four colors. There is no standardized risk matrix and they are frequently colored to reflect the "risk appetite" of its creator. There is also a lot of ambiguity and ignorance about what any given risk matrix represents and this can lead to problems. Hubbard (2009) has called these simple stratification methods flawed and possibly "no better than astrology." Cox (2008) has undertaken a much more systematic look at the mathematical properties of risk matrices and found them lacking under a broad range of circumstances. Therefore, if USACE is to make use of the risk matrix as a risk rating tool it is critically important to be aware of their strengths and weaknesses so they can be used appropriately.

> Risk matrices are believed to have their roots in the system safety programs of the U.S.aerospace and military programs of the 1960s. For example, MIL-STD-882A, *Standard Practice for System Safety*, 1969 has evolved into MIL-STD-882D, *Standard Practice for System Safety*, February 2000 which describes the use of a risk matrix

A literature or web search on the term "risk matrix" or its variants reveals they are in popular use for a wide variety of applications. Including enterprise risk management, mishaps on military bases, manufacturing plant risk analysis, climate change risk management, terrorism, and airport operations to name a few examples. The risk matrix does not provide for a rigorous assessment of risks and is not well suited to decision making that requires a careful delineation of or distinction between risks. They are, however, easy-to-use and they have intuitive appeal. They have been defended as an avenue of

[41] In some instances a point scale (e.g., 1-5) is assigned to the probability category and the consequence category so the two may be multiplied together to obtain a risk score. This practice is noted but will not be further addressed in this appendix.

approach when quantitative information is scarce or nonexistent. They have been used at times to do the following:

- Identify risks in need of risk management
- Setting priorities among competing risks
- Allocating resources for risk assessment or risk management.

If a risk matrix is used as a proper qualitative tool its real function is to help a decision maker order his thinking and perceptions about risk. In other words, the matrix reveals what its makers think about the risks and this does not necessarily conform to the reality of the risks themselves. Thus, a risk matrix constructed and used in this fashion may or may not reveal anything objective about the risks themselves. When a risk matrix is used this way there is a wide degree of latitude in how the risk map is colored.

Unfortunately, this is not a widely held understanding of what a risk matrix is. Often there is a supposition on the part of its creators, others that use it, and occasionally its critics in the literature that the risk matrix roughly approximates some sort of underlying quantitative model of the risks themselves. Viewed this way the matrix is imbued with powers to differentiate risks that may not be present. When it is assumed or presumed that such a model exists the structure and usage of the risk matrix is much more circumscribed than many risk matrices are in practice. Dangerously, when these two views of a risk matrix are blurred or not even recognized the use of a risk matrix for decision making can be troublesome, sometimes leading to errors in judgment.

This chapter is predicated on the belief that a risk matrix can be a useful tool for organizing one's thought process and perceptions about risks but this should not be confused with objective knowledge of the risks themselves. Knowing how one perceives and thinks about risks is, undeniably, a useful starting point for risk assessment. The matrix itself, which is often presented as a risk management tool,[42] is, in fact, a risk assessment tool capable of producing useful information for consideration by risk managers under certain circumstances. The reader is cautioned against treating the results of any risk matrix assessment as the final say on a risk it is a ranking tool that reflects the views and perceptions of those who use it. Nonetheless, this quality of information can be very useful for some decision-making contexts.

> What kinds of things might a risk matrix be used to rank? In reality the list is almost limitless. It might be used to rank operation and maintenance needs at a project, within a District, or throughout USACE. One might use it to identify lock gates, rubble mound breakwaters, tainter gates, gate chains, lock chamber valves, generators, pump motors, or virtually any list of structure components in a District or across USACE, At a more micro scale different components at a single project might be ranked.

In this appendix you will find a description of how to build a risk matrix in the next section. That is followed by an example taken from MIL-STD-882D, which is also critiqued. The appendix ends by considering some of the technical problems that can arise with risk matrices as well as some discussion about how to address those weaknesses.

[42] Viewing a risk matrix as a risk management tool has led to some of the criticism of this tool.

B.2 Building A Risk Matrix

The risk matrix builds on the simple conceptual definition of risk as the product of a consequence and its probability. As with all other risk assessment tools the starting point is a good understanding of the decision context, specifically, know what question(s) are to be answered through the use of a risk matrix, i.e., understand how the matrix will be used. This context, of course, includes a well described list of “things”[43] to be rated or ranked.[44] Constructing the matrix itself is conceptually simple, pragmatically speaking, it is a lot harder than it looks to do it well.

First, one must determine the nature of the consequences of interest are. These can include such things as loss of life, public safety, workplace safety, environmental impacts, property damage, impacts on project implementation, costs of operating or maintaining a project, trust of USACE, legal consequences, social consequences, and the like. Ideally, these consequence categories will be defined in quantifiable or at least subjectively measurable ways.[45] Thus, the number of lives loss, hospitalizations, and injuries might be measures for public safety consequences. Trust of USACE may sound like a compelling consequence to consider in some circumstances but if that impact cannot be practically defined in a manner that lends itself to assessment, it is not going to work well.

Once the nature of the consequences have been determined categories that capture the range of severity of the consequences in a collectively exhaustive and mutually exclusive manner must be defined. There are usually three to five categories in number and they often cover a range from negligible to catastrophic, or some subset of this range. It is often useful to provide a category of “none” when no consequence is a distinct possible outcome. The names of the categories are somewhat arbitrary as the examples below suggest:

- Low, medium, high
- Negligible, marginal, critical, catastrophic
- Insignificant, minor, moderate, major, catastrophic

Although the names of the categories are flexible, their definitions should not be. This is a critical step in the development of a risk matrix because it defines the evidence that will be used to rate each item. Any process that simply assigns a consequence rating to the element to be rated without basing that rating on well-defined and, at least conceptually, measurable definitions is not an evidence-based risk methodology and it is to be avoided. Consensus is not an acceptable basis for a rating. Documented evidence is the only appropriate basis for a rating. Ratings are often described in the literature as being provided by subject matter experts (SME).

[43] These things can include physical objects, activities, events, hazards, risks, or any other risk-related elements.
[44] Although the risk matrix is widely called a risk ranking tool it is more appropriately called a rating tool as it puts the things to be rated in cells (that may or may not be ranked) that can include groups of things that are not further rated.
[45] The chances are if these consequences could be reliably quantified there would be no reason to use a risk matrix.

Even consensus among SME's is an insufficient basis for a rating unless it is based on documented[46] evidence.

The definitions may be simple as Table B1 suggests. Or they may be more complex as the example of the next section will illustrate. The key is not so much the simplicity or complexity as it is the ability to develop evidence that is capable of supporting a rating for each element. In the example below it is presumed that SME's would be capable of providing evidence for arguing that an element under consideration might result in one or more fatalities or multiple serious injuries. That evidence could be provided in a narrative form.

High consequence	May cause fatality or multiple serious injuries.
Medium consequence	May cause single serious injury.
Low consequence	May cause consequences other than death or injury.

Table B.1: Example of simple definitions for consequence categories

Once the consequences have been defined it is necessary to consider the frequency or likelihood with which the consequences can occur. It is important to restrict the consideration of the probability of occurrence only to those specific consequences identified. This step requires the assessor to define likelihood ranges for the consequences. It is usual to have the same number of probability categories as there are consequence categories, thus producing a square matrix. However, if a matrix is being used in an appropriate qualitative manner it is not compulsory to do so. The categories of probabilities usually cover a range from rare to frequent, or some subset of this range. With probability ratings it may be especially useful to include a category of "none" to cover circumstances when it may be impossible for the identified consequence to occur. The names of these categories are likewise flexible as the examples below suggest:

- Low, medium, high;
- Rare, unlikely, likely, almost certain;
- Improbable, remote, occasional, probable, frequent.

The definitions of these categories is, once again, critically important. It is also usually much more difficult to define these categories in a satisfactory way because the common usage meanings of the words chosen are so subjective and imprecise. An example set of definitions are found in Table B.2. Notice that the definitions provided are far from irreproachable in meaning.

[46] The standard for documentation for a qualitative method may, of course, fall well short of peer review. A documented thought process may suffice in the most data poor environments.

Rare	May only occur in exceptional circumstances
Unlikely	Could occur at some time
Likely	Will probably occur in most circumstances
Almost certain	Can be expected to occur in most circumstances

Table B.2: Example of simple definitions for probability categories

It is fairly common to find numerical definitions of the probability ratings. These are far more precise than the narrative definitions above but the problem is such data are usually not available. It is precisely because of the lack of data that one is likely to want to use a risk matrix. Regardless of the definitions that are used the key point is that the actual rating shall be based on documented evidence. Thus, is SME's describe an element's probability rating as "likely" using the definitions of Table B.2 they will be required to say precisely why they think the consequence associated with that element will "probably occur." It is to be hoped that explanation will reveal more about the meaning of "will probably occur" than the simple words say. For a brief history of the use of words to measure probability see Yoe (2012).

Once the categories have been defined in an operational way the next task is to take that list of things you are rating and rate each one of them. To successfully use the matrix it is critically important that everyone share a common understanding of the matrix's row and column dimensions. Spend some time discussing and clarifying those meanings before you begin to rate elements. Suppose, for example, we are considering the storage and use of toxic chemicals at a reservoir project with recreational features. If one such element is gasoline we would rate its potential consequences for accidental ingestion and then rate its probability. It is usually best to begin by rating the consequence. If probability is assessed first and an element is rated to be impossible or unlikely to occur some may think the risk is zero or low, then when the individual or team considers the consequence it may result in a downgraded rating of the consequence. For example, if most people believe the likelihood of a person ingesting gasoline at a USACE facility is very small, they may be influenced by this and call the consequence low.

Beginning with the consequence, suppose the team decides gasoline ingestion could cause a fatality so it is rated as a high consequence (per the preceding table), citing as evidence some science from a poison control site that says gasoline can be fatal if swallowed in sufficient quantity. Now imagine the team rates the chance of this as rare citing as evidence the facts that gasoline is always kept under lock and key and the only way a person would come in contact with it is to remove it from a gas powered appliance or tool and those circumstances are considered highly unlikely. Now the team has a hazard rated high-rare. Whereas, if the team had begun with a rare event they may have been influenced by that fact and decided the consequence was lower. Begin the rating for each element to be rated by assessing the consequence and then the probability.

In a similar fashion every other element in our list of things would be rated. There may be a gasoline spill hazard, for example. This would be rated independently from the ratings of gasoline ingestion. In the process of doing this for a long list of hazards it is not difficult to imagine that a few errors may be made. Thus, the ratings reveal less about the objective truth of the risks at the project site than they do about the team's perceptions of these risks. The output of a risk matrix is a consequence-probability rating pair for every element in the list of things to be rated. A risk matrix example follows.

B.3 Two Risk Matrix Examples

B.3.1 DoD Standard Practice for Safety System

The example presented below is from MIL-STD 882D (2000) Department Of Defense (DoD) Standard Practice For System Safety.[47] This example is chosen because it is a realistic example, not because it is an especially good or bad example. Let's begin by briefly considering the decision context. The Foreword of the standard says in part:

"The DoD is committed to protecting: private and public personnel from accidental death, injury, or occupational illness; weapon systems, equipment, material, and facilities from accidental destruction or damage; and public property while executing its mission of national defense. Within mission requirements, the DoD will also ensure that the quality of the environment is protected to the maximum extent practical. The DoD has implemented environmental, safety, and health efforts to meet these objectives. Integral to these efforts is the use of a system safety approach to manage the risk of mishaps associated with DoD operations."

Thus, the risk matrix that follows was developed to assess the mishap risk. A mishap is defined as an unplanned event or series of events resulting in death, injury, occupational illness, damage to or loss of equipment or property, or damage to the environment. To begin the process, it is necessary to identify and then define the consequence categories. Table B.3, taken from the MS, shows four defined categories of consequences. The descriptions are, as noted before, somewhat arbitrary. Note that these words on their own have ambiguous meanings. It is only possible to know what is meant by them once they are defined.

[47] Henceforth, this document is referred to as the military standard or MS.

Description	Category	Environmental, Safety, and Health Result Criteria
Catastrophic	I	Could result in death, permanent total disability, loss exceeding $1M, or irreversible severe environmental damage that violates law or regulation.
Critical	II	Could result in permanent partial disability, injuries or occupational illness that may result in hospitalization of at least three personnel, loss exceeding $200K but less than $1M, or reversible environmental damage causing a violation of law or regulation.
Marginal	III	Could result in injury or occupational illness resulting in one or more lost work days(s), loss exceeding $10K but less than $200K, or mitigable environmental damage without violation of law or regulation where restoration activities can be accomplished.
Negligible	IV	Could result in injury or illness not resulting in a lost work day, loss exceeding $2K but less than $10K, or minimal environmental damage not violating law or regulation.

Table B.3: Suggested mishap severity categories

Source: MIL-STD 882D (2000) Department Of Defense Standard Practice For System Safety

A good exercise to test the quality of your definitions is to first ask if they are mutually exclusive. In other words, can you think of a realistic situation that might impel you to give two or more different ratings to the same element? The definitions here include three kinds of consequences: environmental, safety, and health.[48] Let's consider the storage of toxic chemicals on a military installation for this discussion. How would a gasoline spill be rated? A first reaction is that most likely there would be minimal environmental damage not violating the law or regulation if one's image is a five gallon can tipping over. But suppose a storage tank ruptures underground, how would that be rated?

If the category definitions lead to situations where a single element can be described by more than one category the solution is to refine the definitions to make the categories mutually exclusive. Here if the consequences could include a fatality or minor environmental damage how would it be rated? Such questions simply need an application rule to prescribe how to handle such cases. Usual practice is to rate a hazard according to its greatest potential consequence. In the case raised above in which the element would get a negligible rating for a five gallon can and a critical rating for an underground storage tank the solution is to define the hazards more carefully. Instead of a "gasoline spill" hazard that carries everything from a five gallon can to an underground tank you should identify as many different hazard scenarios as necessary to clarify the rating. To solve problems of no mutual exclusivity the solutions are:

[48] Given these three criteria, in which category do the dollar losses fall? It is not clear to me. This may suggest the need for another criterion of dollar damages. Neither do I clearly see the safety criterion in evidence in these definitions. These are issues that should be raised and resolved during the development of your matrix.

better definitions of consequence categories, application rules, and finer delineation of hazards.

Next, test your definitions to assure they are collectively exhaustive. In this exercise you try to identify consequences that do not neatly fit into any of the categories. Consider a situation that could result in permanent partial disability, injuries or occupational illness that may result in hospitalization of one or two personnel. How would that be rated? It seems to fall between the cracks of critical and marginal. What if the damages are under $2,000? This seems to be less than negligible. The solution to such problems is to either add more categories or redefine the categories to include all possible cases.

Mutually exclusive and collectively exhaustive become considerably more difficult to define when multiple criteria are used. For example, it is not difficult to imagine an element that could have negligible environmental impacts, critical dollar damage levels and catastrophic health impacts. These sorts of conflicts are usually resolved by carefully articulated application rules. Note how these sorts of subjective decisions have the potential to remove the ratings from a risk matrix away from the rankings that a more objective quantitative risk assessment might produce. Thus, we repeat that the risk matrix is a good tool for expressing what the assessors believe to be true about the risks.

Once consequence categories are defined it is time to identify relevant and useful categories for the probability of the consequences you define. It may be useful to bear in mind that this is not necessarily an exercise to split the probability space [0,1] into equal categories it is an exercise to identify meaningful categories for the kinds of consequences you identify. Thus, if you have no extremely rare (say 1-in-a-million) consequences then you need not address probabilities of 10^{-6} in your categories, for example. Consider the five categories in Table B.4.

Description	Level	Specific Individual Item	Fleet or Inventory
Frequent	A	Likely to occur often in the life of an item, with a probability of occurrence greater than 10^{-1} in that life.	Continuously experienced
Probable	B	Will occur several times in the life of an item, with a probability of occurrence less than 10^{-1} but greater than 10^{-2} in that life.	Will occur frequently
Occasional	C	Likely to occur some time in the life of an item, with a probability of occurrence less than 10^{-2} but greater than 10^{-3} in that life.	Will occur several times
Remote	D	Unlikely but possible to occur in the life of an item, with a probability of occurrence less than 10^{-3} but greater than 10^{-6} in that life.	Unlikely, but can reasonably be expected to occur.
Improbable	E	So unlikely, it can be assumed occurrence may not be experienced, with a probability of occurrence less than 10^{-6} in that life.	Unlikely to occur, but possible.

Table B.4: Suggested mishap probability levels

Source: MIL-STD 882D (2000) Department Of Defense Standard Practice For System Safety

Notice first that this is not going to produce a square matrix. There are more probability categories than consequence categories. It is okay to use as many categories of each as you like as long as everyone knows the matrix is not intended to convey objective truths about risks so much as it is to represent the perception of the risk based on as much evidence as can be brought to bear.

The next thing to notice is that there are two sets of definitions for probabilities. This is a very cogent recognition of the essential difference in population probabilities and individual probabilities. Events that are very rare for any individual, e.g., getting struck by lightning, may happen several times a year in the population. This table explicitly recognizes this fact and provides two sets of definitions. Imagine a list of potential hazards associated with Humvees. As an individual you may be concerned with the risk associated with your vehicle. As the manager of a fleet of Humvees you have a very different focus.

The place to begin is the same as for consequences. Does everyone have the same understanding of the words? Are these categories mutually exclusive and collectively exhaustive? If not these issues need to be addressed before rating begins.

Consider the definition of "Frequent." It is, "Likely to occur often in the life of an item, with a probability of occurrence greater than 10-1 in that life." There is a mixed message in this definition. The quantitative definition says there is better than a 10% chance this hazard, let's say it is running out of motor oil, will occur to a specific Humvee at some point in its lifetime. An 11% chance qualifies. Do you consider something that has an 11% chance of occurring to be frequent? The answer need not concern us if frequent is defined in this manner and everyone understands this simply represents the perceptions of the creators of this matrix and it is not intended to be an objective definition of a frequent risk. Where the problems with this definition really begin, however, is with the narrative definition. A reader might assume a narrative definition was added in recognition of the fact that one will not always have quantitative information to make a numerical estimate of a probability. However, does something that could happen 11% or even 50% of the time over a lifetime sound like an event that occurs often? Would we equate an 11% chance of running out of motor oil over the lifetime of a Humvee with the statement, running out of motor oil is likely to occur often with this Humvee?

It seems the creator of this matrix fell prey to that difficult problem of defining probability words for instances where little or no data are available. The intervals were not defined uniformly as Figure B.1 shows. The mutually exclusive, collectively exhaustive nature of the quantitative scale is very obvious in the figure. However, if the data required to use this scale were available there is a good chance the risk assessment could use a more rigorously objective technique. Nonetheless, a numerical scale may convey a better sense of what the words mean than the narrative descriptions provided. Make sure your definitions avoid some of the mixed message found in these definitions.

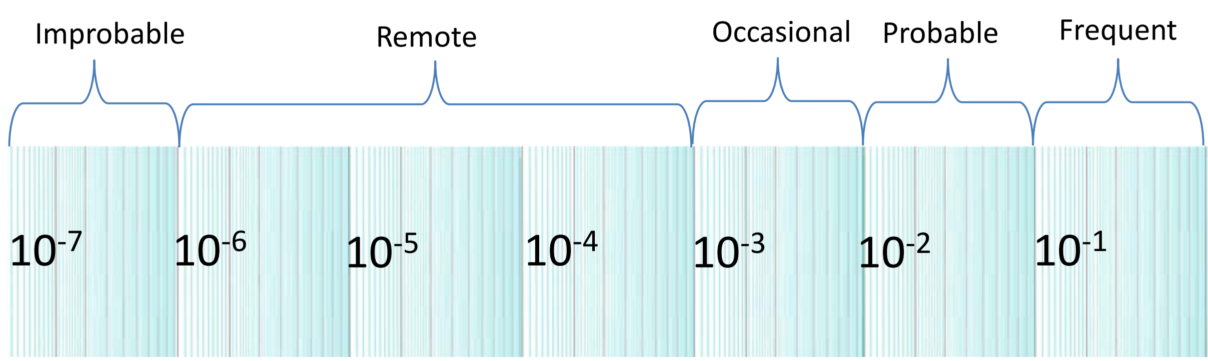

Figure B.1: Categories along a quantitative probability scale.

Now notice the fleet or inventory definitions to understand the challenge of remaining objectively accurate when rating probabilities. Imagine that Humvee fleet, does running out of motor oil happen all the time? That seems to better describe changing motor oil. Mutual exclusivity and collective exhaustion are difficult qualities to capture with narrative definitions of probability. What is the difference between frequent and several? These definitions seem to cry for numerical bounds but when there are no data how useful are numerical bounds? What is necessary is that those who will use such a matrix to support decision making have a common understanding of what the words mean and a common understanding that the matrix is not producing objective risk ratings that reflect the quantitative universe.

Figure B.5 shows the risk matrix produced by these consequence and probability values. The MS then ranks the 20 resulting cells from the greatest perceived risk (1)to the least perceived risk (20). There is nothing that is objectively true about the rankings provided in this matrix other than that cells to the northwest represent greater risks than cells to the southeast.

Consequence Probability	Catastrophic	Critical	Marginal	Negligible
Frequent	1	3	7	13
Probable	2	5	9	16
Occasional	4	6	11	18
Remote	8	10	14	19
Improbable	12	15	17	20

Table B.5: Example mishap risk assessment values

Source: MIL-STD 882D (2000) Department Of Defense Standard Practice For System Safety

Why is a catastrophic-probable hazard riskier than a critical-frequent hazard? The only reason is that the creators of the matrix said so. That is their prerogative to do so long as everyone understands that an objective quantitative assessment of catastrophic-probable and critical-frequent risks could result in the opposite ranking. The assignment of numerical ranks to the cells is arbitrary and subjective and entirely lacking in objective grounds for the order.

An alternative to numbering the cells is to use a color map to group risks in similar categories. Figure B.2 provides an example. This example uses a 5 x 5 matrix, without naming the rows or columns in order to demonstrate the subjective notion of risk appetite. Earlier we noted that

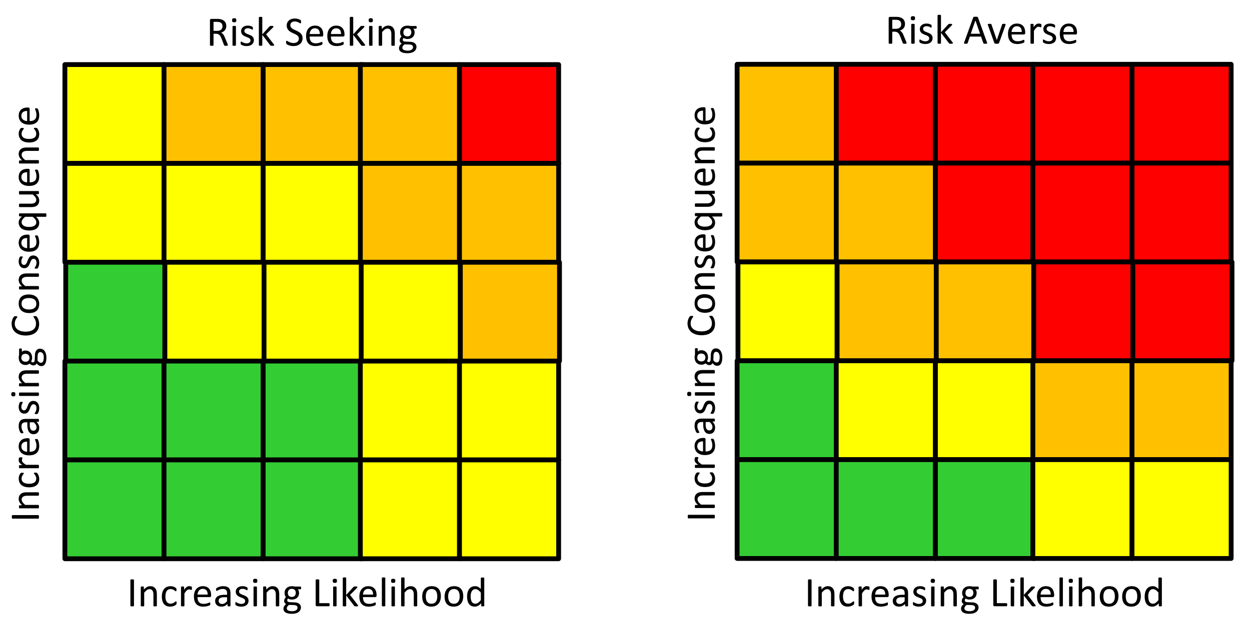

Figure B.2: Colored risk matrices showing different subjective appetites for risk

it is common to see these matrices colored in a variety of ways. Red are high risks, green are the lowest. Amber is second highest. In this instance the greatest risk are to the northeast. The figure on the left conceptually represents a risk seeking appetite for risk. It has subjectively decided that only consequence-probability pair represents a high risk, while eight pairs represent low risks. Assuming the exact same matrix on the right the different coloring reflects a different subjective appetite for risk. This risk manager is risk averse and considers nine consequence-probability pairings to be high risk with only four low risk pairings. There is no difference between the two matrices in this example other than the subjective weights attached to each cell. There is no objective truth about risk if maps can be colored this way to reflect an organization or team's risk perceptions. This discussion will serve shortly as our segue to the last section of this chapter.

At this point, once the map has been numbered or colored it is time to rate each individual element in the list of things to be rated. Once more, for emphasis, these ratings ought to be based not on SME's opinions but on the best available objective evidence that can be brought to bear. If an SME wants to rate an element "occasional" in frequency it is essential that the evidence (or at least the reasons absent objective evidence) for that rating be elicited from the SME and then documented to assure transparency in use of the results.

Table B.6 shows how the MS risk matrix was intended to be used. This is a responsibility-based risk matrix described in the MS. It basically shows that any risky action rated from one to five can only be authorized by the highest ranking official, the Component Acquisition executive. At the other extreme actions rated 18-20 can be authorized by anyone so designated. It is entirely reasonable, if not always entirely objective, to construct a risk matrix in this manner.

Mishap Risk Assessment Value	Mishap Risk Category	Mishap Risk Acceptance Level
1 – 5	High	Component Acquisition Executive
6 – 9	Serious	Program Executive Director
10 – 17	Medium	Program Manager
18-20	Low	As directed

Table B.6: Example mishap risk categories and mishap risk acceptance levels

Source: MIL-STD 882D (2000) Department Of Defense Standard Practice For System Safety

B.3.2 Navigation Budget Guidance

A second Corps example is taken from Part B of the EC 11-2-193 Navigation appendix found in U. S. Army Corps of Engineers Inland Marine Transportation System Improvement Report of 2008. This dated reference has been chosen intentionally, it does not necessarily reflect budget guidance at the time this is read. Paragraph V-9, Risk Assessment of Navigation Assets, of this document says in part: **"…** budget will achieve a significant milestone in USACE asset management efforts with the Navigation, Hydropower and Flood Damage Reduction business lines using a common format to address risk. … There will be five levels of Probability/Condition and five levels of Consequences/Economic Impact associated with each of the Navigation asset groups. These will be used to develop a Relative Risk Ranking Matrix shown in Table V-3. The Relative Risk Ranking Matrix values will be applied to each budget work package." Table V-3 is reproduced as Figure B.3. Note the example discussed here is for inland navigation, only one of for such navigation asset groups using such a method for operation and maintenance funding.

	Probability / Condition				
Consequence / Economic Impact	F	D	C	B	A
1	Extreme Risk 1	Extreme Risk 2	High Risk 5	High Risk 10	Moderate Risk 15
2	Extreme Risk 3	Extreme Risk 4	High Risk 7	Moderate Risk 11	Low Risk 19
3	High Risk 6	High Risk 8	Moderate Risk 12	Low Risk 16	Low Risk 20
4	High Risk 9	Moderate Risk 13	Low Risk 17	Low Risk 21	Negligible Risk 23
5	Moderate Risk 14	Low Risk 18	Low Risk 22	Negligible Risk 24	Negligible Risk 25

Figure B.3: Navigation relative risk ranking matrix

The numerical ranking for each cell has been added to the risk map to reveal the wholly subjective nature of the risk ranking. There is no reason cell D-1 is ranked higher than F-2, this cannot be determined objectively. F-1 is objectively riskier than D-2, even though they are placed in the same color code. Likewise D-1 is riskier than D-2 and F-2 is riskier than D-2, but it is easy to see that risks on northeast to southwest diagonals cannot be objectively ranked. Bear in mind, subjective is not a denigrating term, it just falls short of objective reality. It is entirely appropriate for USACE to choose its own risk appetite.

The budget guidance suggest this “ranking” process begins with a determination of which components are critical (i.e., have the potential to halt navigation) and which are non-critical (i.e. have limited potential to halt navigation). Perhaps the reader can appreciate the burden of distinguishing potential from limited potential?

The guidance suggests component conditions[49] be assessed by a review of multi-disciplined inspection reports, on-site reviews, rating criteria, and/or FEMS operations and maintenance records when available. This condition of the component may be viewed as a proxy measure for the probability of an unscheduled closure at an inland navigation lock chamber. Using proxy measures, however, can be expected to widen the gap between the subjective results obtained

[49] Notice that this model adapts the language of the risk matrix and uses condition as a measure of probability.

from using this matrix and the objective reality of the risk. Figure B.4 reproduces definitions of condition found in table V-5.

Condition Level		Probability / Condition
GOOD	A	ADEQUATE (Failure unlikely within budget cycle)
MODERATE	B	PROBABLY ADEQUATE (Less than 50% probability of failure within budget cycle)
POOR	C	PROBABLY INADEQUATE (Failure could occur within budget cycle)
FAILING	D	INADEQUATE (High probability for failure within budget cycle)
FAILED	F	FAILED (Already failed or failure will occur within budget cycle)

Figure B.4: Inland navigation probability/condition

Suppose you had an objective estimate of a component failure of 1%. How would you rate it? Either A or B seem reasonable, thus the categories are not yet mutually exclusive. They do however seem to cover, conceptually at least, the probability interval from 0 to 1. The consequence of categories defined in this manner is that the evidence used for rating a component must be explicitly identified and documented. Opinions are not evidence.

The consequences of diminished navigation feature performance are also to be assessed for each budget line item that could result in an unscheduled closure or diminished channel depth and/or width. Figure B.5 reproduces Table V-6, which defines the consequence ratings.

Table V-6 Inland Navigation Consequence/Economic Impact	
Consequence Level	**Consequence Description**
1	Maximum risk to mission Highest economic loss; Over __ B ton miles (OR TONS?) *Economic level thresholds are in development.* Probable life safety impact Minimum Acceptable Operations Service Level (see definitions) Court Decree Mandated Action Shutdown of energy generation or distribution facilities for national public use with no alternative modes of transportation (e.g. power plants and oil distribution facilities)
2	High risk to mission No life safety impact High economic loss; Over 1B ton miles *Economic level thresholds are in development.* Diminished cost efficiency of energy generation or distribution facilities for national public use with higher cost alternative modes of transportation (e.g. power plants and oil distribution facilities)
3	Moderate risk to mission No life safety impact Moderate economic loss; Between 500 and 1B ton miles *Economic level thresholds are in development.*
4	Low risk to mission No life safety impact Low economic impact; Under 500M ton miles *Economic level thresholds are in development.*
5	Negligible risk to mission No life safety impact Least economic; *Economic level thresholds are in development.*

Figure B-5: Inland navigation consequence/economic impact

The five consequence categories are not named and they are defined based on criteria that are not clearly articulated but which can be inferred from the table. The ultimate utility of these consequence levels will depend on the ability to develop subjective application rules economic in the form of threshold levels and service level definitions.

B.4 Weaknesses Of Risk Matrices

Douglas Hubbard (2009) and Louis Anthony Cox (2008) together offer very different but together rather scathing criticism of the manner in which risk matrices and some qualitative risk assessment techniques have been used. That critique can be fairly, yet inadequately, summarized by saying that risk matrices are not based on an objective quantitative assessment of the risks and therefore are prone to errors. If a risk matrix is being used for substantive decision making, for example, allocating budget resources to achieve mission objectives there could be underachievement of objectives for a given cost or failure to achieve least costly achievement of a targeted level of objectives. This conclusion, however, requires some assumptions about what the risk matrices are intended to represent. The greater part of these criticisms can be adequately addressed by keeping in mind that a risk matrix at best provides a subjective perception of an objective reality. To the extent that the subjective risk matrix relies on evidence and some of the suggestions offered above it can limit the distance between perception and reality, but it cannot eliminate it.

> Cox in his 2008 article includes the following among the reasons risk matrices are used:
>
> ●they provide a clear framework for systematic review of individual risks and portfolios of risks
> ●convenient documentation for the rationale of risk rankings and priority setting
> ●relatively simple-appearing inputs and outputs, often with attractively colored grids
> ●opportunities for many stakeholders to participate in customizing category definitions and action levels
> ●opportunities for consultants to train different parts of organizations on "risk culture" concepts

One of the most common abuses of the risk matrix is to use a poorly constructed matrix. This would violate mutual exclusivity and collective exhaustion of categories and/or rely on poorly defined categories that are not jointly understood by creators and users of the matrix. A second common abuse is to assign ratings based on a gut feeling that is often dressed up as professional judgment or expert opinion without reference to any evidence for the judgment. Another version of this abuse is more damaging, however. Consider a situation that is created by the use of a risk matrix to guide resource allocation as is the case for the USACE operation and maintenance budget decisions. One possibility is that people would "game" the system. This means the budget game is won by obtaining money for an inland navigation budget line item. Money is most likely awarded to items with higher numerical rankings (see Figure B.3). Thus, the desire to win the game provides an incentive to seek the worst condition and the greatest consequences rating for a component possible. That the incentives align in this manner does not suggest anyone will play the game but the possibility exists and the value of the risk matrix quickly disintegrates if the strategy of those providing ratings is to win the game and obtain funding.

Accepting the inevitable subjective nature of ratings without strong data is a starting point. Evidence-based ratings are a necessity. Current practice at the time of this guidance was to have experts in each District complete the assessments. The process would likely be aided by having a team assess the available evidence for all competing line items to assure consistency among users of the definitions. It is very difficult to verify the assumptions used by different assessors and so comparing ratings across different Districts can be plagued by inconsistencies even if when there is no attempt to game the system.

Another problem associated with a risk matrix like the navigation one presented is that subjective ratings can result in inadvertent errors when resources are allocated to line items that though ranked higher by the matrix are actually lesser risks in reality. This latter problem cannot be solved with a subjective tool, but the work of Cox (2008) can help limit the damage.

Cox uses the risk product (consequence x probability) to argue that the relative ranking of some diagonally adjacent cells cannot be known with confidence. He also posits that some quantitative interpretation of risk categories in a matrix exists. He shows mathematically that risk matrices fail to discriminate correctly far more often than most people realize, moreover, their performance depends on the joint distribution of consequence and probability. He finds the matrices can be useful when consequence and probability are positively correlated but says they can be worse than useless when these attributes are negatively correlated. Many of the risks USACE deals with exhibit negative correlations where consequences rise as probability falls.

Cox rigorously explores the compatibility of risk matrices with quantitative risks. He found the following limitations:

- *Poor Resolution*. Risk matrices correctly and unambiguously compare maybe less than 10% of randomly selected pairs of hazards. They can assign identical ratings to quantitatively very different risks, a problem called "range compression".
- *Errors*. Risk matrices have assigned higher qualitative ratings to quantitatively smaller risks sometimes leading to worse-than-random decisions.
- *Suboptimal Resource Allocation*. Allocating resources decisions cannot be based on the categories provided by risk matrices.
- *Ambiguous Inputs and Outputs*. It is difficult to provide objective categories of consequences when there are significant uncertainties. Risk matrix inputs, i.e. probability and consequence categorizations, and resulting risk rating outputs require subjective interpretation. Different users can obtain opposite ratings of the same quantitative risks.

These limitations suggest that risk matrices should be used with caution, and only with careful explanations of embedded judgments.

His mathematical examination of matrices develops three desirable properties: weak consistency, betweenness, and consistent coloring as well as a fully quantitative interpretation of the two axes of the matrix, whose product provides a quantitative measure of the risk. These properties yield the color patterns shown in Figure B.6

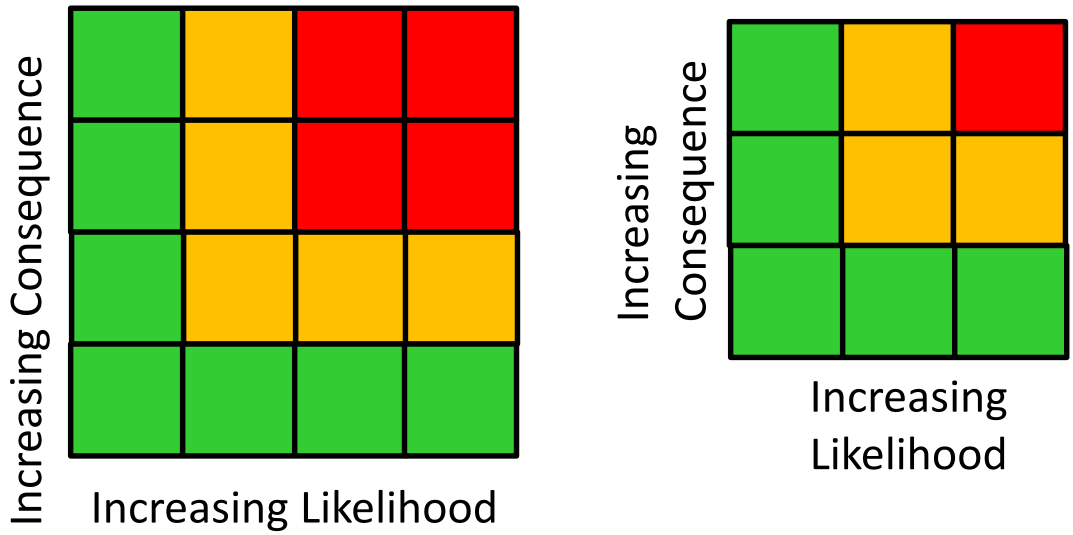

Figure B.6: Uniquely colored 4x4 and 3x3 matrices that satisfy the properties of weak consistency, betweenness, and consistent coloring

Although other color patterns can be chosen to represent the risk appetite of the organization any other pattern will result in more limited risk matrices. There is not a single unique color pattern for a 5x5 matrix but two possible coloring presented by Cox convincingly show, for example, that the matrix in Figure B.3 does not satisfy the three properties or a pattern consistent with a quantitative risk.

B.5 Evolution of a Risk Matrix

At the time this appendix was written, RiskAnal, an Internet mailing originally set up by the Pacific Northwest National Laboratory and the Society for Risk Analysis' Columbia-Cascades Chapter as a service to the international risk analysis community, was conducting a discussion of risk ranking tools. During that discussion Peter Lindstrom posted a link to a set of figures that summarized a discussion that took place in January , 2013 (http://spiresecurity.com/presentations/Spire%20-%20Risk%20Matrix%20Maturity%20Model.pdf accessed January 11. 2013). That discussion is summarized below and the figures that follow are based on Lindstrom's work.

There is a general recognition of risk matrices' failure to provide an accurate representation of the objective nature of a risk in many applications. One of the ideas surfaced in the discussion was to try to evolve the risk matrix toward a quantitative tool along the lines described below. Each step described would be considered an improvement in the risk matrix. However, it needs to be noted that this discussion interprets the risk matrix as more than its creators' perceptions of the risks. Figure B.7 begins by presenting a fairly standard risk matrix. Categories are very low, low, medium, high, and very high. Five hypothetical hazards have been mapped into their rated cells. The greatest risk is located in the upper right cell.

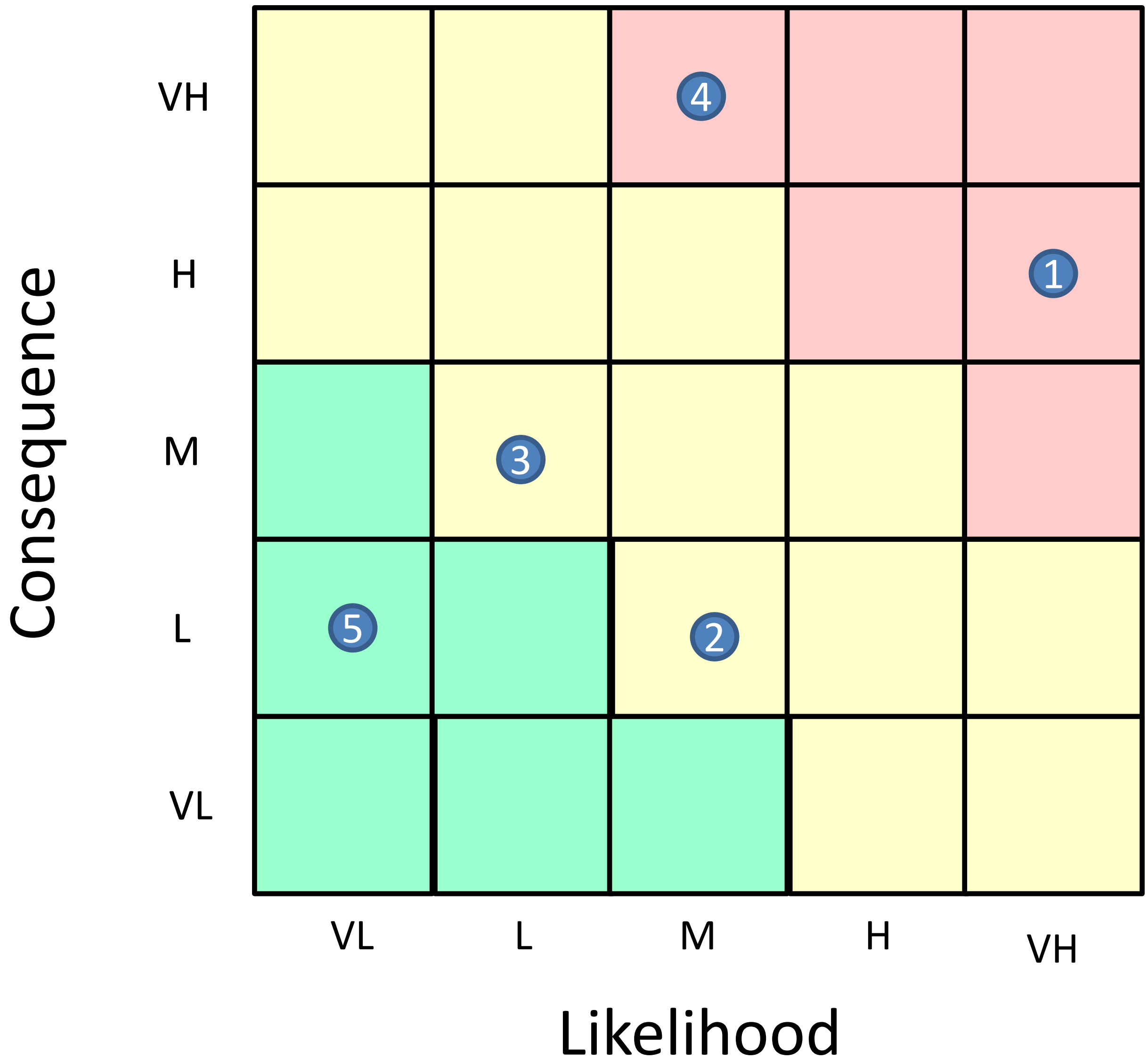

Figure B.7: A standard risk matrix mapped with hypothetical hazards

One of the first improvements suggested would be to add weights to the cells to differentiate the six greens, six reds and thirteen yellow cells. Figure B.8 add weights.

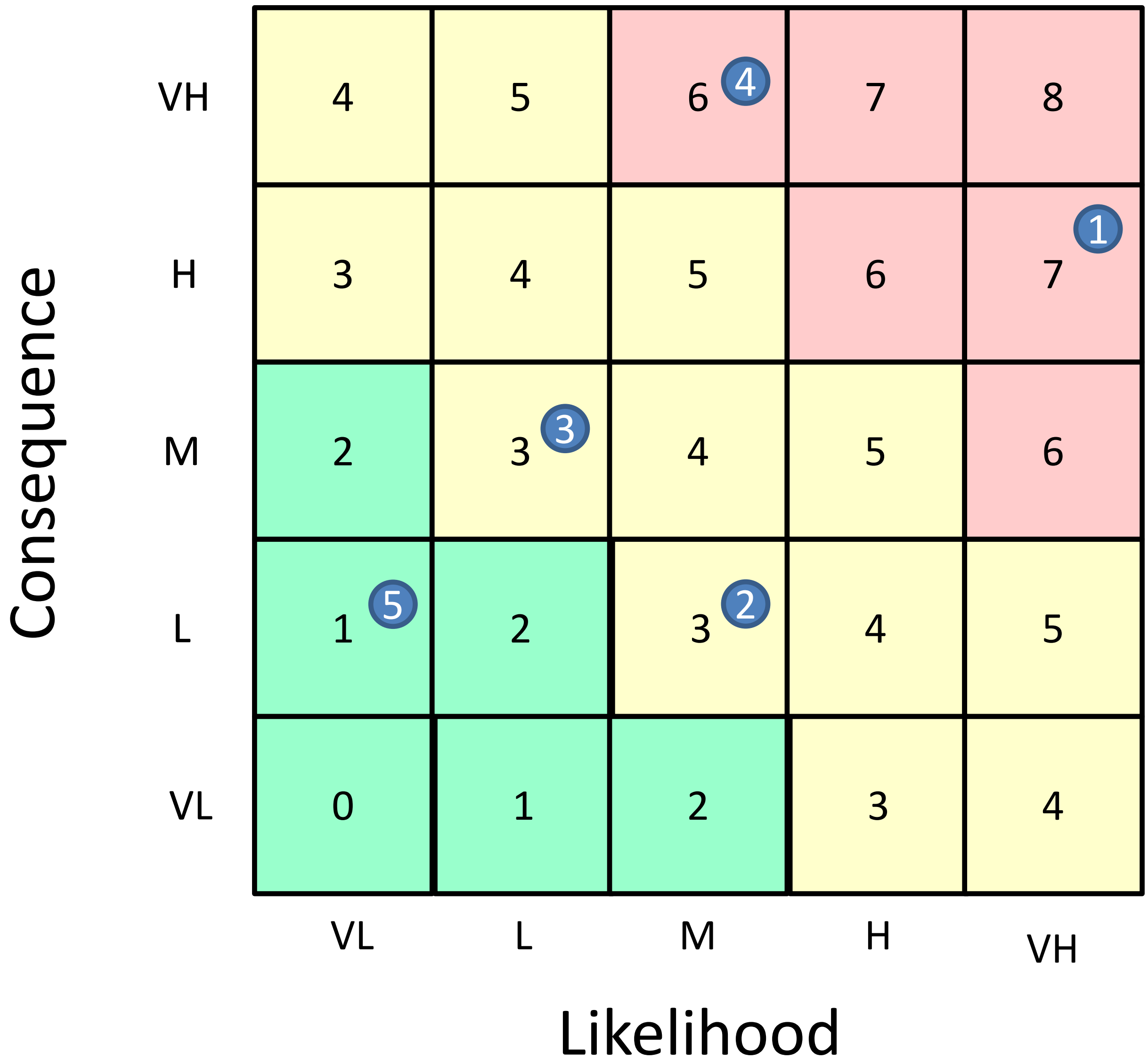

Figure B.8: Standard risk matrix with weights added

The cells are now grouped along diagonals that extend northwest to southeast. The lowest weighted risk is at the bottom left opposite the highest rated risk. Notice this weighting is a bit of a compromise between the weighting of each cell seen in the MIL-STD-88D and the color coded weighting of the standard risk matrix.

If the concerns of Cox (2008) are addressed some of the ambiguity of the borders (where the colors change) is addressed as shown in Figure B.9. The matrices shown to this point are

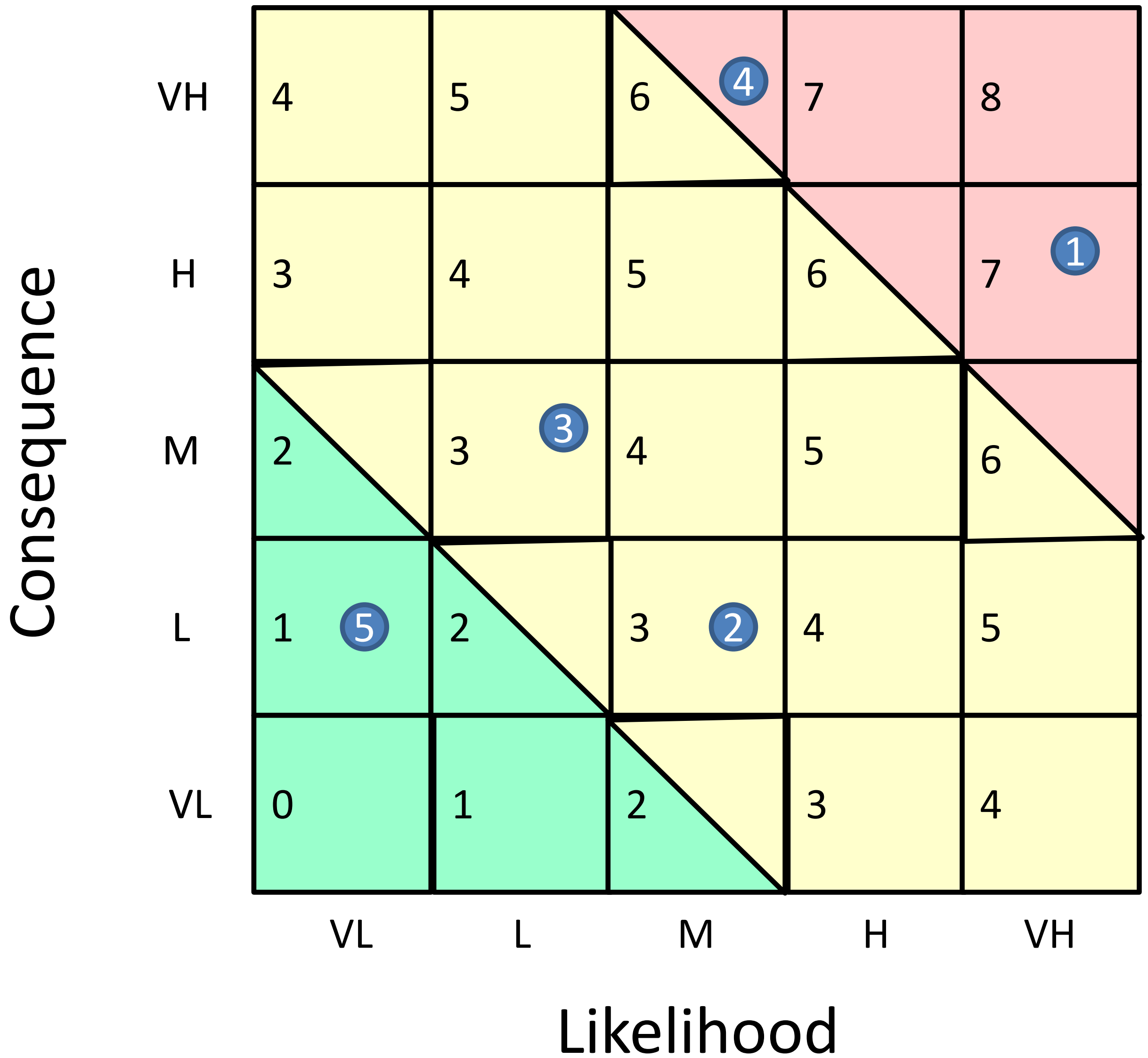

Figure B.9: Standard matrix adjusted to address Cox (2008) concerns for a 5 x 5 matrix

considered semi-ordinal because it is not possible to clearly say which cell weighted a 3 represents a greater risk among the 3's. Thus, the next step in the evolution of the risk matrix is to develop interval measures to replace the semi-ordinal cells that result from nominal categories. Figure B.10 shows an example of a matrix with interval measures. Adding

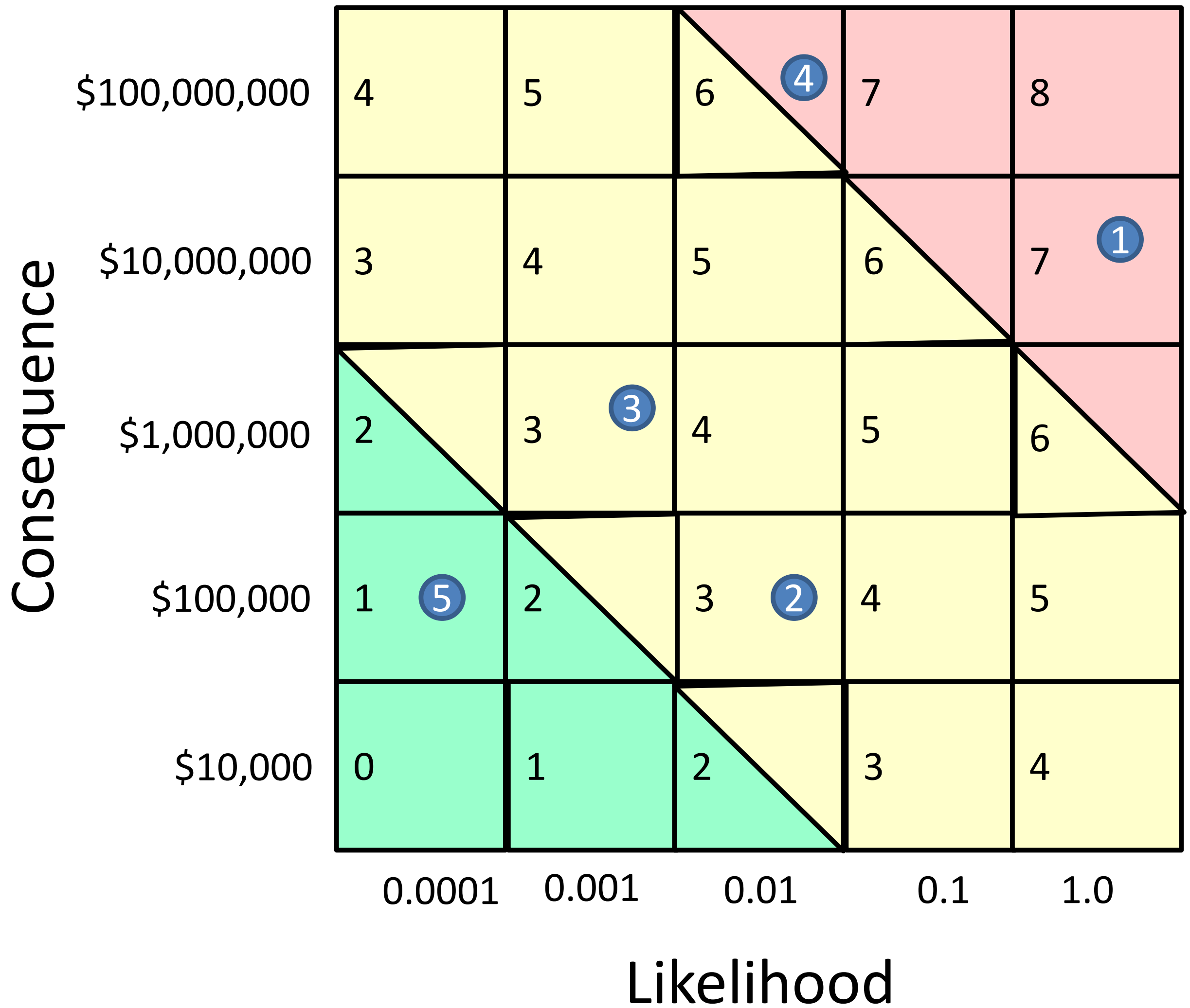

Figure B.10: Risk matrix delineated by interval level data

quantitative data to a matrix is a significant step forward and one that requires a leap of faith because matrices are often used precisely because there is a lack of quantitative information. Although it is rather simple to draw a figure with order of magnitudes probabilities and dollar values in reality it is often a) difficult to estimate those values, or b) consequences are often multi-faceted and not readily amenable to quantification.

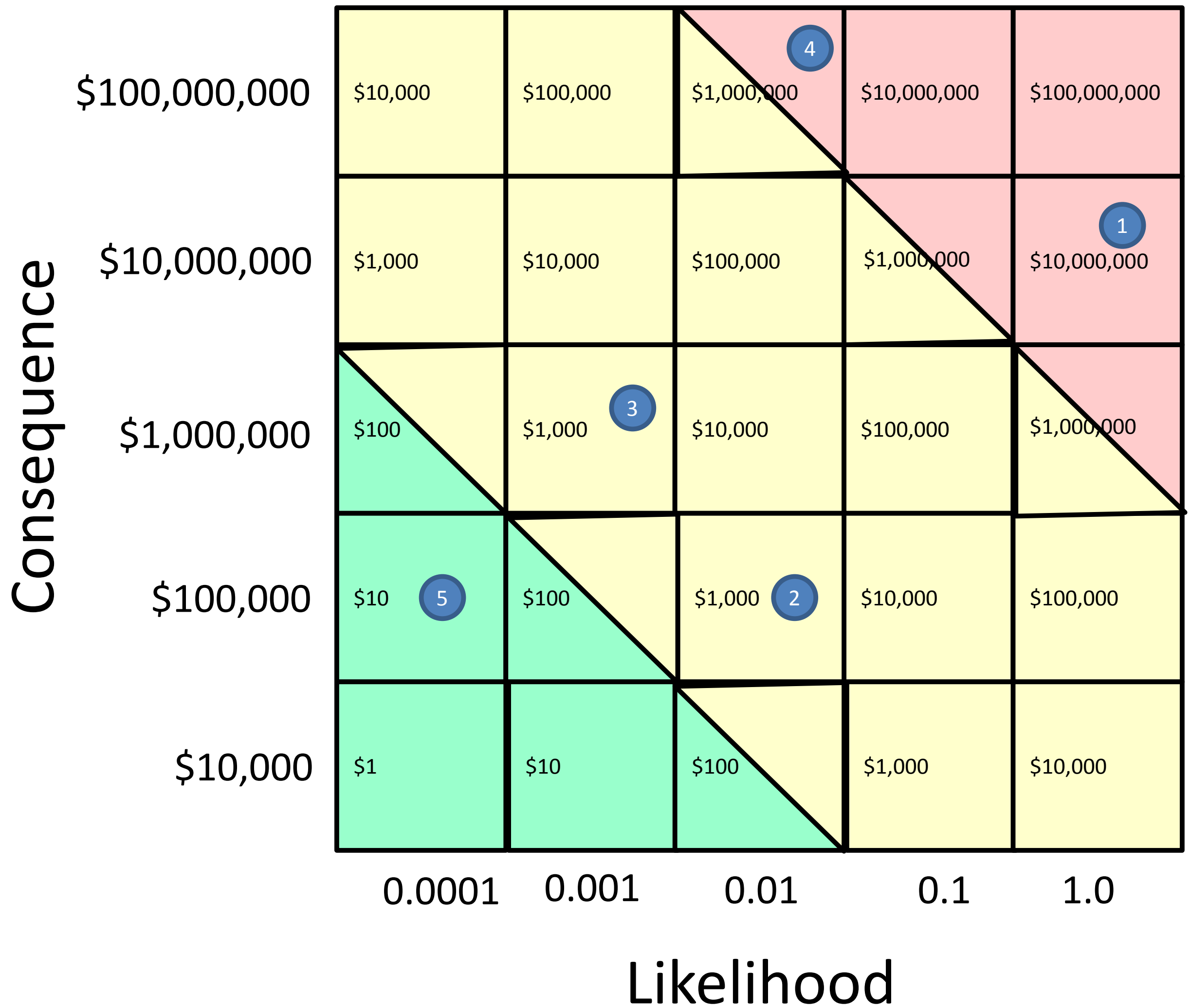

Figure B.11 Risk matrix that replaces the weights with quantitative estimates of the risk.

Figure B.11 shows the next evolutionary step, which includes replacing subjective weights with quantitative estimates of risk. Figure B.12 replaces the point estimates of individual hazards with distributions for the quantitative risk estimates.

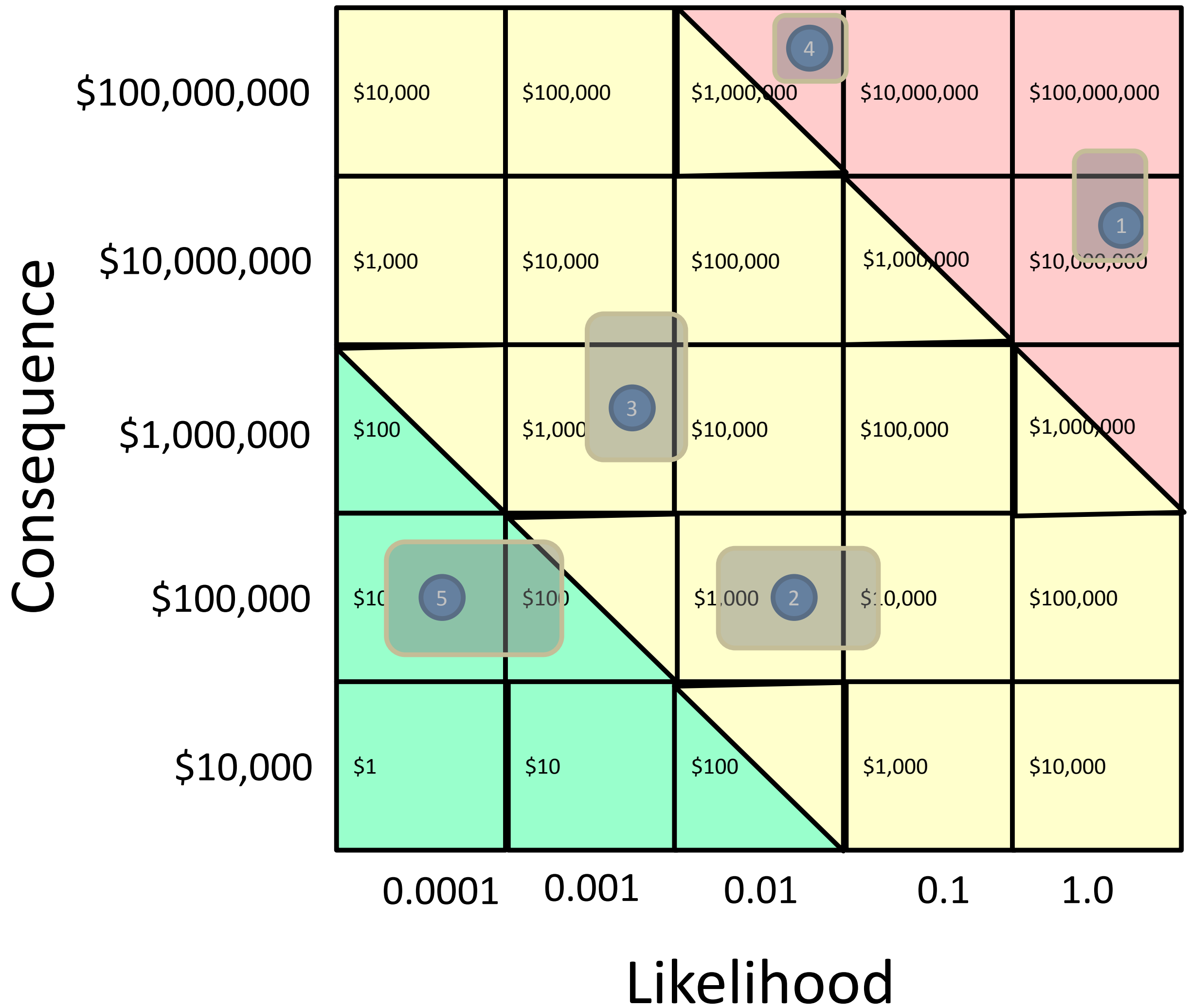

Figure B.12: Risk matrix with quantitative risk estimates represented by distributions

The distributions provide a means of addressing the issues of uncertainty in the overall risk matrix ratings. The ability to provide such advanced quantitative estimates of the risk associated with any given hazard goes well beyond the capability of those who use the risk matrix because it is a qualitative tool. Nonetheless, it is difficult to argue with the assertion that evolving the risk matrix in this direction is desirable.

Figure B.13 shows the next step in the evolution of the risk matrix with the addition of iso-risk lines that show changes in risk. At this point, placement of a risk in the cell becomes meaningful.

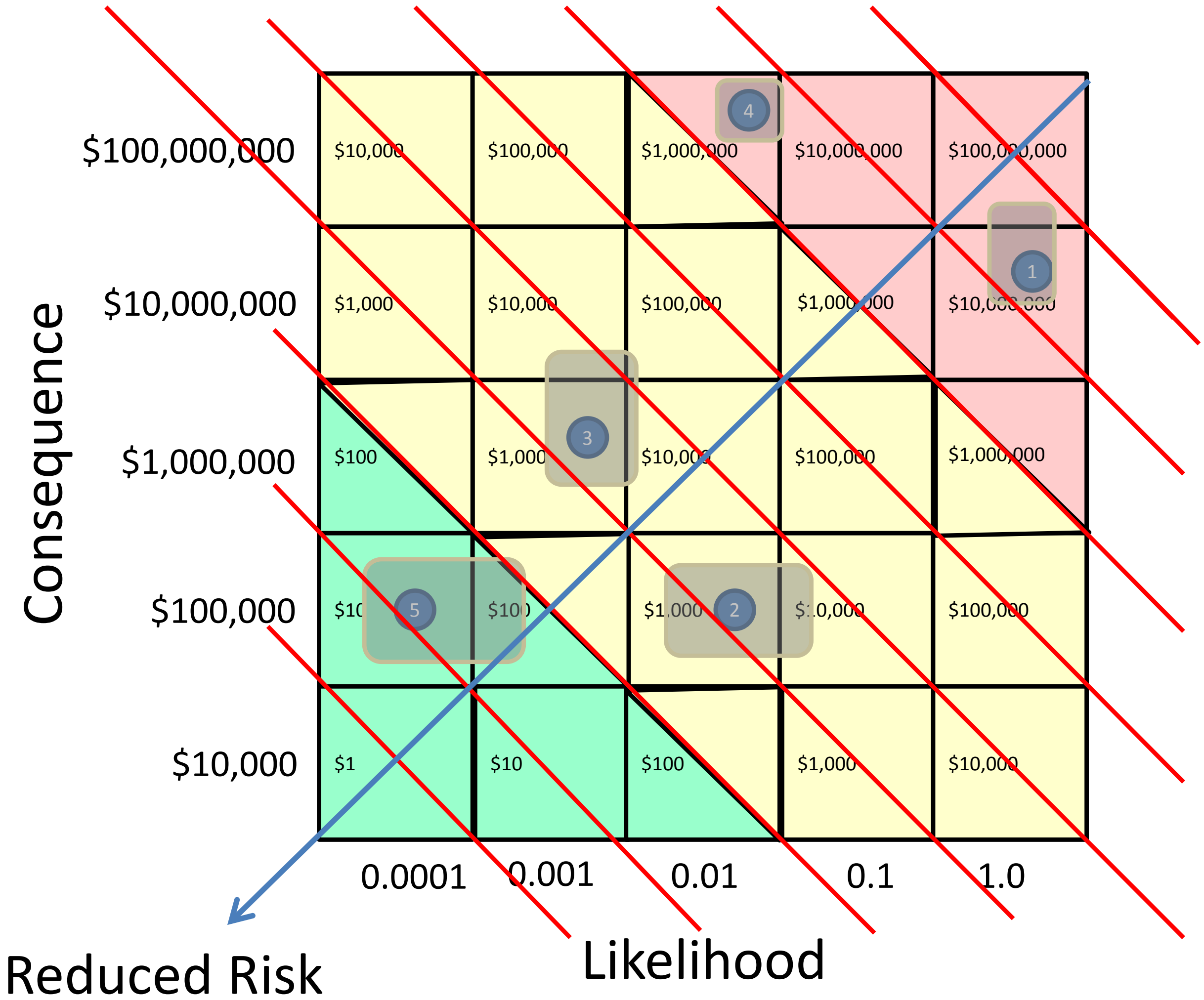

Figure B.12: Risk matrix with iso-risk lines to show changes in risk

This appendix begins with the premise that a qualitative risk matrix can be a useful tool if its creators and users clearly understand it to represent the views and perceptions of its creators and not an objective view of the actual risk. It is at that point that risk managers must carefully weigh the need for additional clarification, discussion, and information before using a matrix for significant decision making. The literature shows that when risk matrices are taken as a more objective view of the actual risk it can lead to decisions that are, at times, even worse than random decisions. The important point is to not place too much faith in the results of risk matrices, especially those prepared by one group for use by a second group.

One of the obvious solutions to the potential problems of risk matrices would be to avoid the use of the matrices. The problem with that solution is that people like the matrices, they are easy to use. If we assume matrices are here to stay for some time, another option is to try to evolve the risk matrix in the direction of quantitative estimates of risk as described in the figures preceding.

B.6 References

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Appendix C: Generic Qualitative Risk Assessment Process

C.1 Introduction

One approach to qualitative risk assessment presented in Chapter Six was to develop a generic process. A generic process builds on the simple definition of risk as:

Risk = Probability x Consequence

If either of these elements equals zero there is no risk. Either or both of the right hand side elements can be decomposed into its necessary component parts. The probability that something will or will not happen can often be broken down into a series of necessary components. When each component must occur in order for a risky event to be possible the events can be modeled as a cumulate product such as this sequence of "i" events:

Probability = P_1 x P_2 x … x P_i

Likewise, the consequence term can be decomposed into the sequence of consequences of relevant concern for the risk under consideration. When there is a variety of potential consequences some of which may or may not be present the decomposed consequence term is additive as shown here for j consequences:

Consequence = C_1 + C_2 + … + C_j

Thus, a generic process requires risk assessors to decompose a risk into its component parts. In a qualitative assessment these components are rated based on the evidence and an aggregation algorithm is used to combine the evidence and ratings for the individual probability and consequence components into an overall assessment of the risk. This chapter uses the experience gained by USACE conducting qualitative risk assessments of aquatic nuisance species (ANS) for the Great Lakes and Mississippi River Interbasin Study (GLMRIS) to demonstrate the development of a generic process to address a risk for which a pre-existing assessment model does not exist.

C.2 GLMRIS Background

The Water Resources Development Act of 2007 (WRDA 07) directed the U.S. Army Corps of Engineers (USACE) to conduct a feasibility study to determine the range of options and technologies available to prevent (ANS) transfer through aquatic pathways between the Great Lakes Basin and the Mississippi River Basin. The GLMRIS study split the divide between these two basins into two geographic regions. The first of these, shown in Figure C.1, is the Chicago Area Waterway System (CAWS), which is characterized by permanent an year round hydrologic connections between the two basins. Ten such connections are shown in the figure.

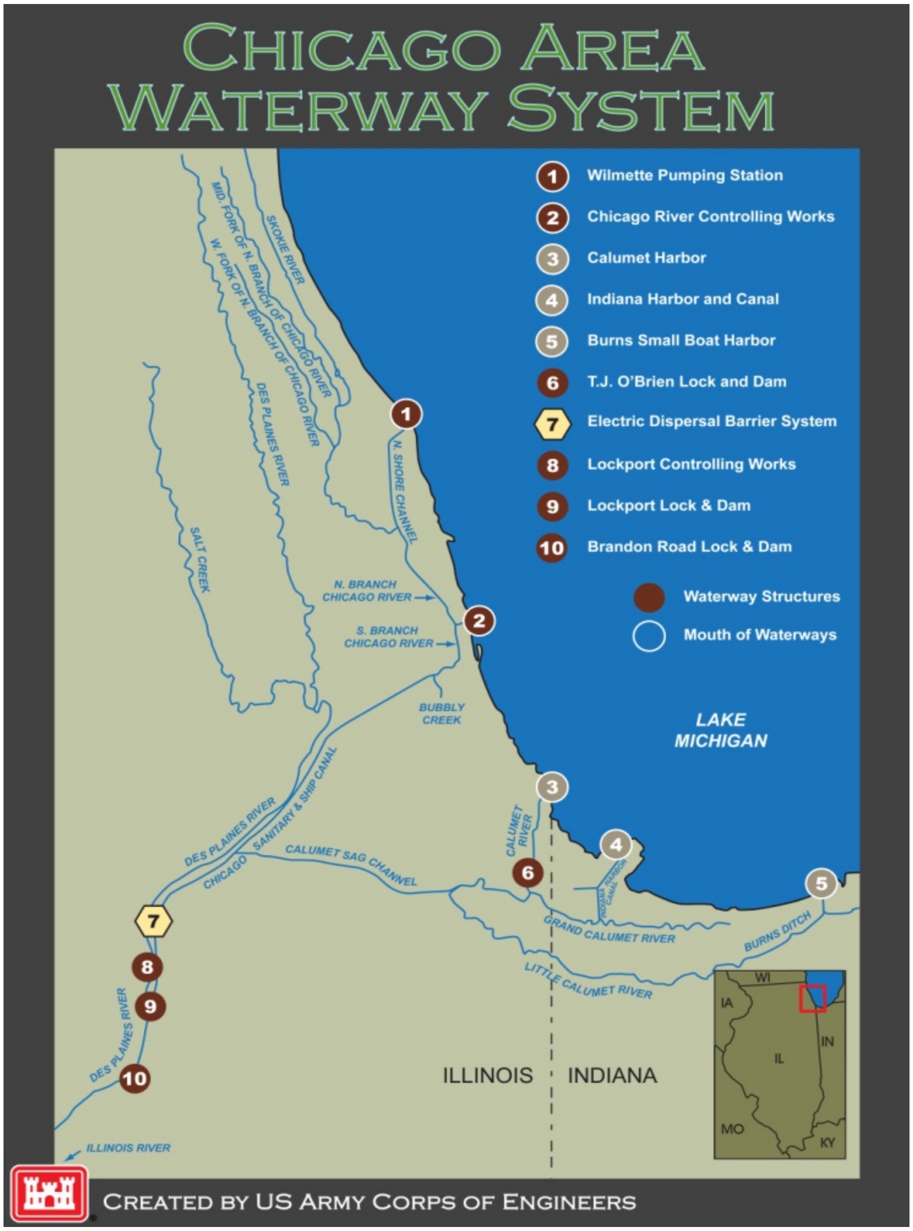

Figure C.1: Hydrologic pathways between the Great Lakes and Mississippi River basins in the Chicago Area Waterways System

Pathways to the east of this region, called Focus Area II, are more ephemeral and even speculative in some instances. Eighteen hydrologic pathways of potential concern are identified in Figure AB-2 where the pathway of greatest potential concern is indicated by a star.

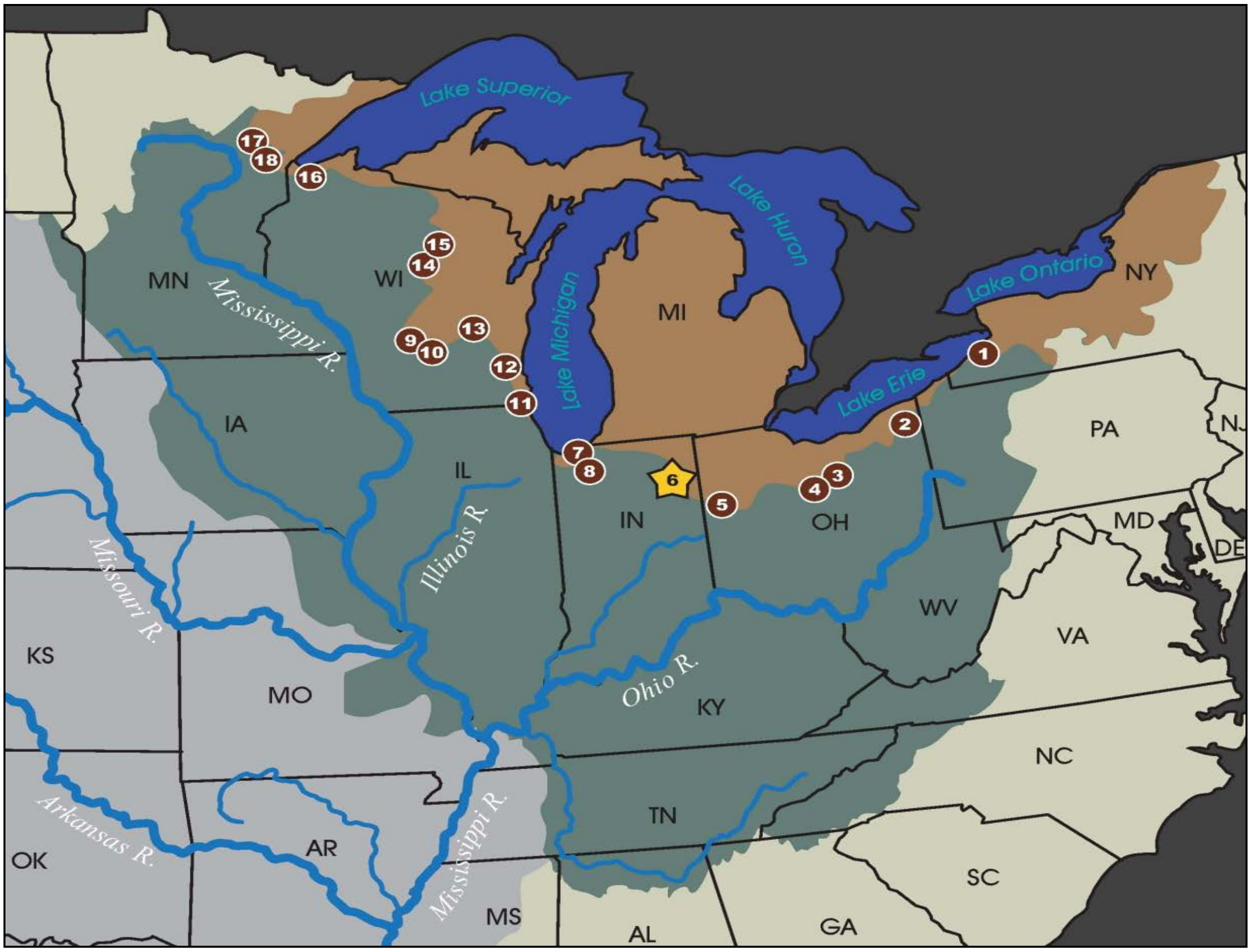

Figure C.2: Potential hydrologic pathways between the Great Lakes and Mississippi River basins in Focus Area II

In these two basins well over 200 aquatic species were identified in one or the other but not both basins. This initial list of species was screened down to a list of 33 ANS that were present in only one of the two basins. Ten of these are of concern for moving into the Great Lakes, the other 23 could potentially move into the Mississippi River. The task was to conduct individual risk assessments for each of the 33 species and each of the pathways. The number of risk assessments was too large and the data gaps were too significant for quantitative risk assessments to be conducted. Thus, qualitative risk assessments were conducted. The two different areas, CAWS and Focus Area II, were assessed by different teams using a common risk assessment model and some shared personnel and other resources.

C.3 Risk Assessment Method

The simple risk equation above was rearticulated as follows:

Risk of adverse impacts occurring as a result of the establishment of ANS X in Basin Y	=	Probability of ANS X becoming established in Basin Y	+	The consequences of ANS X becoming established in Basin Y

The probability of establishment ($P_{establishment}$) was decomposed into five necessary probability elements. They are:

Probability of ANS X becoming established in Basin Y = $P_{path} \times P_{arrival} \times P_{passage} \times P_{colonize} \times P_{spread}$

P_{path} = Probability that a complete aquatic pathway is available for interbasin transfer;

$P_{arrival}$ = Probability that the ANS will arrive at the pathway from its current distribution within a specified time;

$P_{passage}$ = Probability that the ANS can successfully move through the aquatic pathway from one basin to the other;

$P_{colonize}$ = Probability that the ANS can establish a colony in the newly invaded basin; and

P_{spread} = Probability that the ANS can spread to elsewhere in the new basin.

If any one of these elements is missing, i.e., if the probability of any one of these events is zero, the probability of establishment is zero and there is no risk. Each of these probabilities is conditional and is estimated based on the assumption that all preceding elements have occurred. Each of the five probability elements was assigned one of four qualitative likelihood ratings based on the best available evidence. The overall $P_{establishment}$ takes on the lowest probability rating from among the probability elements. Table C.1 provides four hypothetical examples.

	Probability Element					
ANS	Probability of Pathway	Probability of Arrival	Probability of Passage	Probability if Colonization	Probability of Spread	Probability of Establishment
A	M	L	H	H	L	L
B	H	H	H	L	H	L
C	M	H	H	M	M	M
D	H	L	M	M	L	L

Table C.1: Estimates of the probability of establishment for four hypothetical species

> Probability Element Ratings
>
> The rating for each probability element was based on the evaluation of information regarding the current distribution, life history, habitat requirements, physiology, and potential for human-mediated transport of each as well as information regarding the physical and environmental conditions of each pathway. When ANS-specific information was unavailable, information on similar (taxonomically related) species was evaluated. Sources of information included the open scientific literature, agency reports, and personal communications with subject matter experts.

The probability ratings used for this process are:

High = The event (e.g., successful passage through a pathway) will almost certainly occur;
Medium = The event is likely to occur but it is not certain;
Low = The event will likely not occur but is possible; and
None = The event is certain not to occur (it is impossible).

The consequence assessment considered three categories of consequences: environmental, economic, and social/political. The overall consequence from ANS establishment was estimated as:

Consequences = $C_{Economic} + C_{Environmental} + C_{Social/political}$

Environmental Consequences are effects on ecosystem structure and function, including effects on resident species, populations, and communities, habitats, and ecological services. Economic Consequences are *e*ffects on economic activities, such as changes in employment, unemployment, and earnings; changes in labor force, property values, and income. Social/Political Consequences are effects on human services and activities such as recreation and subsistence, as well as changes in regulatory requirements. Overall Consequences is the sum of all environmental, economic, and social consequences.

For the consequence assessment it is assumed the ANS has become successfully established in the new basin. The characterization of potential consequences also considered whether consequences would be "localized" or "widespread" in spatial extent. Each of the three consequence categories was assigned one of the following ratings based on the best available evidence:

High (H) = The magnitude and severity of the consequence is considered unacceptable.
Medium (M) = The magnitude and severity of the consequence is considered tolerable but not desirable.
Low (L) = The magnitude and severity of the consequence is considered acceptable.
None (N) = No undesirable consequences are anticipated.

The overall consequence level is basically the higher rating of the economic and environmental consequences. For example, if economic consequences are high and all other consequences are low, overall consequences are high. IF Environmental consequences are medium and all others consequences are none, the overall consequences are medium.

To establish an overall risk potential for a specific ANS on a specific pathway one takes the overall probability rating and the overall consequence rating and using Table C.1 the overall risk potential is obtained.

Probability of Establishment	Consequence of Establishment	Risk Level
H[a]	H	H
M	H	H
H	M	M
M	M	M
L	H	M
H	L	L
M	L	L
L	M	L
L	L	L
H, M, or L	N	N

[a] H = High; M = Medium; L = Low; N = None.

Table C.1: Determination of overall ANS risk

C.4 Different Approaches

Although both risk assessment teams used the same methodology they used it in different ways, consistent with the principles of SMART planning. In CAWS the team conducted both a probability and a consequence assessment in order to complete the risk assessment. An example of one of these risk assessments is included in the addendum to this appendix.

Focus Area II used a different approach. They focused on the probability of establishment first because there was considerable uncertainty about whether pathways even existed in some of these areas before the risk assessment was begun. In order to make good decisions, to minimize the collection of unnecessary data, and to limit superfluous analysis this team did not conduct any consequence assessments. In instances where the probability of establishment was low or none, no consequence assessment would be conducted because these would not lead to risks that would be managed. For higher probabilities of establishment consequence assessments would be conducted at a later point in the study process.

C. 5 Addendum: Example

The following example is offered to illustrate the extent to which evidence is used to document the qualitative ratings. The materials presented here were taken from a draft of *Risks of Adverse Impacts from the Movement and establishment of Aquatic Nuisance Species between the Great Lakes and Mississippi River Basins, Volume II: Appendix E*, dated September 2012.

C.5.1 ANS Potentially Invading the Great Lakes Basin

The ANS-pathway pair for this risk assessment is the plant, Cuban Bulrush (*Oxycaryum cubense) on* Pathway 1 Brandon Road Lock and Dam to Wilmette Pumping Station [WPS]. The risk assessment is summarized for existing conditions in Table C.3.

	T_0	
Probability element	P	U
P(pathway)	High	None
P(arrival)	Low	Low
P(passage)	Low	Low
P(colonizes)	Medium	High
P(spreads)	Low	Medium
P(establishment)	Low	High

Table C.3: Assessment of probability of establishment of Cuban Bulrush in the Great Lakes basin

The evidence used as the basis for the qualitative risk assessment ratings is far more important than the ratings themselves. In the pages that follow examples of evidence used to complete an assessment are presented.

C.5.2 Probability of Establishment

C.5.2.1 Evidence for P(pathway)=HIGH

Pathway is visible and confirmed and present year round. No activities or events are anticipated that would reduce or eliminate the hydrologic connection between WPS and Brandon Road Lock and Dam over the next 50 years.

C.5.2.2 Evidence for Uncertainty Rating=None

The existence of the pathway has been confirmed with certainty.

C.5.2.3 Evidence for P(arrival)=LOW

In determining the probability of arrival, the pathway is assumed to exist. Factors that influence the arrival of the species include:

a. *Type of Mobility/Invasion Speed*
   Cuban bulrush is a floating, epiphytic perennial herb. It is thought to be extremely invasive in appropriate conditions (Bryson et al. 2008). The corky, buoyant achenes of Cuban bulrush are adapted to dispersal by moving water (Bryson et al. 2008). Its mat forming, floating

habit facilitates asexual reproduction and transport of vegetative fragments by moving water (Haines & Lye 1983). The species appears to be expanding in the Mid-South region of the United States (McLaurin & Wersal 2011). However, the species has been in the U.S. for a century and has not moved to the upper Midwest.

b. *Human-Mediated Transport through Aquatic Pathways*
Cuban bulrush was likely introduced via ship ballast from the West Indies or South America (Bryson et al. 1996). There is heavy vessel traffic between the lower MRB and Brandon Road Lock and Dam.

c. *Current Abundance and Reproductive Capacity*
The Cuban bulrush reproduces by rhizomes/stolons and by the production of achenes (seeds) (NBII). Asexual reproduction by fragmentation occurs (Bryson et al. 2008).

d. *Existing Physical Human/Natural Barriers*
The three Illinois River locks located south of Brandon Road Lock and Dam have the potential to act as temporary barriers, because of the associated shoreline modifications. However, the Cuban bulrush can be carried by boats for short distances, which could allow it to transfer through the locks.

e. *Distance from Pathway*
Cuban bulrush is native to the New World tropics, from the southern United States through northern South America (NBII). The species has been in the southeastern United States for more than a century (Bryson et al. 2008) and is found sporadically throughout Florida, Louisiana, southern Georgia, southern Alabama, Mississippi (Galvao et al.) and coastal Texas. Populations have recently been found in Aliceville Lake in Pickens County, Alabama and in Aberdeen Lake and the Tennessee-Tombigbee Waterway in east-central Mississippi. Cuban bulrush was observed in the Ross Barnett Reservoir, MS for the first time in 2009 (McLaurin & Wersal 2011).

f. *Suitable Habitat (Physical, Structural, Hydrologic, Hydraulic, Chemical, and Climatological)*
Cuban bulrush is a perennial, rhizomatous, emergent sedge of littoral regions (NBII). It is found in free-floating mats and rafts that vary greatly in size (Bryson et al. 2008). It appears to be more of a tropical or subtropical species based on its native distribution. This species commonly establishes in freshwater ditches, marshes, ponds, lakes, rivers, and swamps (Bryson et al. 2008). It may be on the water's edge (up to 50m (164 ft) from the coast) or may detach from the land and float freely (NBII). It is unclear if this species requires other vegetation for establishment and mat formation, but it appears that the epiphytic form of Cuban bulrush prefers areas of dense floating aquatic vegetation (McLaurin & Wersal 2011). Suitable emergent wetland habitat is present in the vicinity of Brandon Road Lock and Dam. However, based on the native species distribution it may not tolerate extended freezing temperatures.

The evidence used to determine the probability rating considering all life stagesis: Suitable habitat exists from the current location of this species to Brandon Road Lock and Dam (f). The Mississippi River is poorly connected to the floodplain in many areas and marsh habitat is highly fragmented in the MRB (f), so upstream movement toward Brandon Road Lock and Dam may be slow. Cuban bulrush has been in the southeastern United States for a century and has not spread beyond the southern states so it may not be likely to move to the WPS pathway in the near term (e). The cold climate of the Midwest may prevent the spread of this species to Brandon Road Lock and Dam. Therefore, the probability of arrival is low.

C.5.2.4 Evidence for Uncertainty Rating=LOW

In order to better understand its dispersal and potential to invade wetland habitats, additional research is needed on both its reproductive biology, to determine the extent to which Cuban bulrush reproduces sexually and spreads from achenes, and its association with other aquatic weeds (Bryson et al. 2008). It is not documented how far north Cuban bulrush will be able to disperse or if the species will be able to survive the region's conditions. However, it has not spread very far north in decades. It is unlikely at this time step for the Cuban bulrush to travel the far distance to arrive at the pathway, therefore uncertainty for arrival is low.

C.5.2.5 Evidence for P(passage)=LOW

In determining the probability of passage, the species is assumed to have arrived at the pathway. Factors that influence the passage of the species include:

a. *Type of Mobility/Invasion Speed*
Cuban bulrush is a floating, epiphytic perennial herb. It is thought to be extremely invasive in appropriate conditions (Bryson et al. 2008). The corky, buoyant achenes of Cuban bulrush are adapted to dispersal by moving water. Its mat forming, floating habit facilitates asexual reproduction and transport of vegetative fragments by moving water (Haines & Lye 1983).

b. *Human-Mediated Transport through Aquatic Pathways*
Cuban bulrush was likely introduced via ship ballast from the West Indies or South America (Bryson et al. 1996). There is no cargo vessel traffic to the WPS (USACE 2011a) from Brandon Road Lock and Dam. Commercial vessels could transport the Cuban bulrush as far as the south branch of the Chicago River. There is small boat recreational use in the North Shore Channel.

c. *Existing Physical Human/Natural Barriers*
The sluice gate at the WPS separates the CAWS from Lake Michigan. However, occasionally flow is reversed back into Lake Michigan.

d. *Suitable Habitat (Physical, Structural, Hydrologic, Hydraulic, Chemical, and Climatological)*
Cuban bulrush is a perennial, rhizomatous, emergent sedge of littoral regions (NBII). It is found in free-floating mats and rafts that vary greatly in size (Bryson et al. 2008). This species commonly establishes in freshwater ditches, marshes, ponds, lakes, rivers, and swamps (Bryson et al. 2008). Much of the CAWS is a heavily modified channel with little floodplain connection or shallow marshy areas**.** Overall, there is low macrophyte cover in all

areas of the CAWS channel (LimnoTech 2010). There is some shallow shoreline with and without canopy cover in the Chicago Sanitary and Ship Canal (CSSC) that may be suitable. Cuban bulrush may be on the water's edge (up to 50m (164 ft) from the coast) or may detach from the land and float freely (NBII). This species is not likely to survive in near shore non-vegetated areas with manmade structures, like harbors, consisting of stone blocks and steel sheet piling. Much of the CSSC is vertical limestone or man-made walls. Virtually all (>90%) of the Chicago River and the Lower North Branch of the Chicago River is vertical wall (LimnoTech 2010). The North Shore Channel contains suitable habitat for the Cuban bulrush*.* Macrophytes are documented to exist in the North Shore Channel (LimnoTech 2010). It is unclear if this species requires other vegetation for establishment and mat formation, but it appears that the epiphytic form of Cuban bulrush prefers areas of dense floating aquatic vegetation (McLaurin & Wersal 2011). Based on the native species distribution it may not tolerate extended freezing temperatures.

The evidence used to determine the probability rating considering all life stages follows. There is low macrophyte cover in most areas of the CAWS channel, suggesting that the CAWS is generally not suitable habitat for aquatic macrophytes like Cuban bulrush (d). The Cuban bulrush spreads by floating and must move upstream to reach the WPS (a). Vessels could potentially transport this species upstream from Brandon Road Lock and Dam to the Chicago River. However, the vertical walls of the Chicago River would likely prevent this species from invading and moving further upstream to the North Shore Channel and the WPS (d). There is suitable habitat on the banks of the North Shore Channel, and if established near the WPS, Cuban bulrush could spread by achenes (a) into the GL when the sluice gate is open (c). Overall, this species is unlikely to spread throughout the CAWS during this time step due to habitat limitation and the need for upstream movement through the CAWS channel. Therefore, Cuban bulrush has a low probability of passing through the pathway.

C.5.2.6 Evidence for Uncertainty Rating=LOW

The lack of suitable habitat in the CAWS is documented, although the North Shore Channel may be suitable. The potential for vessels to transport the Cuban bulrush upstream through the CAWS is uncertain. The only chance for the species to move upstream into the GLB is to float through the sluice gate when it is open. The uncertainty of this species passing through this pathway is considered to be low.

C.5.2.7 Evidence for P(colonizes)=MEDIUM

In determining the probability of colonization, the species is assumed to have passed through the pathway. Factors that influence the colonization of the species include:

a. *Suitable Habitat (Physical, Structural, Hydrologic, Hydraulic, Chemical, and Climatological)*
   Cuban bulrush is commonly established in freshwater ponds and lakes (Bryson et al. 2008). It may be on the water's edge (up to 50m (164 ft) from the coast) or may detach from the land and float freely (NBII). It is unclear if this species requires other vegetation for establishment and mat formation, but it appears that the epiphytic form of Cuban bulrush prefers areas of dense floating aquatic vegetation (McLaurin & Wersal 2011). Based on the species' native distribution, it may not tolerate extended freezing temperatures. Wilmette

Harbor contains no emergent wetland habitat and the adjacent near shore areas of Lake Michigan are sandy beach and rip rap. Emergent wetlands can be found scattered inland of the Lake Michigan shoreline and associated with tributaries to Lake Michigan (USACE unpublished data). Illinois Beach State Park, located approximately 50 km (31 mi) north of WPS contains emergent wetlands near the shoreline of Lake Michigan. There is little emergent wetland habitat between the WPS and the Indiana border (USACE unpublished data) due to human modification of the shoreline. East of Indiana Harbor where the shoreline is more natural, there are scattered emergent wetlands but they are likely to be too far inland from Lake Michigan for the Cuban bulrush to colonize from Lake Michigan. There are small tributaries and large rivers in Indiana that have emergent wetlands. This species could form populations along the shoreline of Lake Michigan in calm areas with an accumulation of organic matter.

b. *Ability of the Species to Reach Suitable Habitat by Natural or Human-Mediated Dispersal* The Cuban bulrush invades new locations when floodwaters transport seed, roots and stem fragments. Overall, the ability of the Cuban bulrush to reach marsh habitat after exiting Wilmette Harbor is severely restricted by urbanization, harbors, and the lack of marsh and natural floodplain along the shoreline of Lake Michigan. Potential dispersal mechanisms via aquatic pathways that would allow Cuban bulrush to colonize suitable habitat include transport by boats and drift along the Lake Michigan Shoreline. Seeds or fragments of Cuban bulrush passing from the North Shore Channel into the Wilmette Harbor and Lake Michigan could be transported by vessels. Water circulation in Lake Michigan is typically counterclockwise (Beletsky & Schwab 2001) so drift to the emergent wetlands in Illinois Beach State Park is unlikely. The counterclockwise flow could carry the Cuban bulrush seeds or fragments to Indiana where there are emergent wetlands scattered inland of the shoreline of Lake Michigan and associated with rivers and tributaries (USACE unpublished data). Most emergent wetlands are not hydrologically connected to Lake Michigan, but Cuban bulrush could colonize tributaries if transported up river by flooding or wind driven currents. However, such tributaries are greater than 96 km (60 mi) from the WPS.

The evidence used to determine the probability rating considering all life stages follows. Recreational boat traffic from Wilmette Harbor could potentially assist in the dispersal of Cuban bulrush. However, the Cuban bulrush is not likely to colonize Wilmette Harbor, making vessel transport less likely (b). Cuban bulrush is also not likely to grow on the non-vegetated shoreline or rocky shoals that are in the vicinity of the WPS, or the sandy, higher energy shoreline of Lake Michigan (a). Suitable habitat is present in emergent wetlands associated with tributaries to Lake Michigan. However, these areas are primarily found in Indiana and are not located near the WPS (a). In addition, the Cuban bulrush is a warm climate species and the GLB may be too cold for this species to establish. Therefore, the probability of this species colonizing in Lake Michigan after exiting the WPS is considered to be medium.

C.5.2.8 Evidence for Uncertainty Rating=HIGH

There is a documented lack of suitable habitat along much of the shoreline of southern Lake Michigan. The distance that boats could transport seeds or adult fragments is uncertain. It is uncertain if the species will be able to reach to suitable habitat after exiting the WPS by drift alone. The climatological suitability of the GLB is uncertain. Therefore, the uncertainty of this species colonizing in the GLB is high.

C.5.2.9 Evidence for P(spreads)=LOW

In determining the probability of spread, the species is assumed to have colonized in the new basin. Factors that influence the spread of the species include:

a. *Suitable Climate in New Basin*
   Based on the species' native distribution it may not tolerate extended freezing temperatures. The Cuban bulrush appears to be more of a tropical or subtropical species.

b. *Type of Mobility/Invasion Speed*
   Cuban bulrush is a floating, epiphytic perennial herb. It is thought to be extremely invasive in appropriate conditions (Bryson et al. 2008). The corky, buoyant achenes of Cuban bulrush are adapted to dispersal by moving water (Bryson et al. 2008). Its mat forming, floating habit facilitates asexual reproduction and transport of vegetative fragments by moving water (Haines & Lye 1983). However, the species has been in the U.S. for a century and has not moved to the upper Midwest.

c. *Fecundity*
   The Cuban bulrush reproduces by rhizomes/stolons and by the production of achenes (seeds) (NBII). Asexual reproduction by fragmentation occurs (Bryson et al. 2008).

d. *History of Invasion Success*
   Cuban bulrush can exist at high density where established. The species has been spreading throughout the Southeastern United States for a century (Bryson et al. 2008).

e. *Human-Mediated Transport through Aquatic Pathways*
   Cuban bulrush was likely introduced via ship ballast (Bryson et al. 1996). The WPS is not a port; therefore there is no commercial vessel traffic to the WPS.

f. *Suitable Habitat (Physical, Structural, Hydrologic, Hydraulic, Chemical, and Climatological)*
   The Cuban bulrush is a wetland obligate. Cuban bulrush is commonly established in freshwater lakes (Bryson et al. 2008). It may be on the water's edge (up to 50m (164 ft) from the coast) or may detach from the land and float freely (NBII). It is unclear if this species requires other vegetation for establishment and mat formation, but it appears that the epiphytic form of Cuban bulrush prefers areas of dense floating aquatic vegetation (McLaurin & Wersal 2011). There is marsh habitat throughout the Great Lakes. There are areas of near shore emergent herbaceous habitat in tributaries and rivers feeding into the Great Lakes that would be suitable for the species (USACE unpublished data) , but they may not be hydrologically connected. However, there is floodplain habitat associated with tributaries of the Great Lakes through which the Cuban bulrush could spread (USACE unpublished data). Based on the species' native distribution, it may not tolerate extended freezing temperatures.

The evidence used to determine the probability rating considering all life stages follows. The abundant beach habitat in the GLB is likely unsuitable due to the high energy shoreline of Lake Michigan (f). It is not likely to grow near shore on non-vegetated areas like a harbor or rocky shoals. However, suitable wetland habitat is present in marsh and riverine habitats in the GLB and human and natural mechanisms of spread are possible (b,e,f). However, the native range of the Cuban bulrush suggests it is a tropical species and it has not spread very far north in a century suggesting climate is unsuitable in the GLB. Therefore, the probability of spreading in the Great Lakes is low.

C.5.2.10 Evidence for Uncertainty Rating=MEDIUM

There is suitable habitat found in the GLB, but the climate is potentially unsuitable, although this has not been tested. Therefore the uncertainty associated with the spread of the Cuban bulrush in the GLB is medium.

C.5.3 Consequences of Establishment

The consequences of establishment of the Cuban bulrush are summarized in Table C.3. Environmental and economic consequences are estimated to be low and the social/political consequences are medium. This leads to an overall consequence of low.

Consequences of Establishment				
Environmental Consequences	Economic Consequences	Social/Political Consequences		Total Overall Consequences
L	L	M		L

Table C.3: Consequence ratings for Cuban bulrush

C.5.3.1 Evidence for Environmental Consequences=LOW with Uncertainty = MEDIUM

Appendix A: The Cuban bulrush is found in the littoral zone of lakes, ponds, and streams, forming large monotypic floating mats that can shade out other species of aquatic macrophytes or outcompete them for space (Bryson et al. 2008; McLaurin & Wersal 2011), potentially resulting in alteration of plant community structure in wetland habitats in the GLB. It is slowly spreading northward in the southeastern United States (Bryson et al. 2008). There are also multiple ESA-listed wetland plant and invertebrate species that could potentially be adversely affected by the spread of Cuban bulrush. The Cuban bulrush also has the potential to generate adverse ecosystem-level effects. Hypoxic conditions can develop beneath the floating mats of Cuban bulrush (McLaurin & Wersal 2011), reducing habitat quality for aquatic organisms and affecting sediment biogeochemical processes. However, the Cuban bulrush is found only sporadically in the Southeast, and it is typically a tropical and subtropical species (Bryson et al. 2008); therefore, impacts on ecosystem in the GLB may be localized to areas of suitable temperature. Overall, the consequences of this species establishing in the GLB are low. It is uncertain whether the productivity of this species in the GLB will be high enough to generate significant ecological consequences. Therefore, there remains a medium degree of uncertainty regarding environmental consequences of the Cuban bulrush.

C.5.3.2 Evidence for Economic Consequences=LOW with Uncertainty = MEDIUM

Widespread establishment of Cuban bulrush would produce economic consequences in a number of categories, including loss of consumer surplus, reductions in recreational boating and fishing would adversely impact employment, income and tax revenues. For each of these consequence categories, the magnitude of economic consequences would depend on the extent of species establishment, the resulting impact on existing fisheries resources, and the consequent impact on recreational activity and fishing. The economic consequence of Cuban bulrush is low with medium uncertainty.

C.5.3.3 Evidence for Social/Political Consequences=MEDIUM with Uncertainty = MEDIUM

The Cuban bulrush has the potential to affect recreational and subsistence fishing by reducing habitat quality. The formation of large floating mats could also affect swimming and recreational boating. However, the Cuban bulrush is primarily a tropical and subtropical species. Therefore, it is expected to have a limited area of impact. Overall, social/political consequences could be medium. Although suitable habitat is present throughout much of the MRB, the realized spread, and with it the extent of social/political consequences, is uncertain. Therefore, uncertainty is medium.

C.5.4 Overall Risk of Adverse Impacts

The probability of establishment is low for existing conditions. The Cuban bulrush is not expected to reach the CAWS over the 50-yr time horizon. In addition, if it were to establish in the GLB, the consequences of establishment would be low, because this is primarily a tropical and subtropical species and is therefore unlikely spread widely in the GLB. Therefore, the overall risk associated with the establishment of Cuban bulrush is low for all pathways and time steps. The uncertainty associated with this risk level is also medium because of the uncertainty about the consequences.

Pathway	Probability of Establishment	Consequences of Establishment	Risk of Adverse Impacts
CAWS 1	L	L	L

C.6 References

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IWR Institute for Water Resources

The Institute for Water Resources (IWR) is a U.S. Army Corps of Engineers (USACE) Field Operating Activity located within the Washington DC National Capital Region (NCR), in Alexandria, Virginia and with satellite centers in New Orleans, LA; Davis, CA; Denver, CO; and Pittsburgh, PA. IWR was created in 1969 to analyze and anticipate changing water resources management conditions, and to develop planning methods and analytical tools to address economic, social, institutional, and environmental needs in water resources planning and policy. Since its inception, IWR has been a leader in the development of strategies and tools for planning and executing the USACE water resources planning and water management programs.

IWR strives to improve the performance of the USACE water resources program by examining water resources problems and offering practical solutions through a wide variety of technology transfer mechanisms. In addition to hosting and leading USACE participation in national forums, these include the production of white papers, reports, workshops, training courses, guidance and manuals of practice; the development of new planning, socio-economic, and risk-based decision-support methodologies, improved hydrologic engineering methods and software tools; and the management of national waterborne commerce statistics and other Civil Works information systems. IWR serves as the USACE expertise center for integrated water resources planning and management; hydrologic engineering; collaborative planning and environmental conflict resolution; and waterborne commerce data and marine transportation systems.

The Institute's Hydrologic Engineering Center (HEC), located in Davis, CA specializes in the development, documentation, training, and application of hydrologic engineering and hydrologic models. IWR's Navigation and Civil Works Decision Support Center (NDC) and its Waterborne Commerce Statistical Center (WCSC) in New Orleans, LA, is the Corps data collection organization for waterborne commerce, vessel characteristics, port facilities, dredging information, and information on navigation locks. IWR's Risk Management enter is a center of expertise whose mission is to manage and assess risks for dams and levee systems across USACE, to support dam and levee safety activities throughout USACE, and to develop policies, methods, tools, and systems to enhance those activities.

Other enterprise centers at the Institute's NCR office include the International Center for Integrated Water Resources Management (ICIWaRM), under the auspices of UNESCO, which is a distributed, intergovernmental center established in partnership with various Universities and non-Government organizations; and the Conflict Resolution and Public Participation Center of Expertise, which includes a focus on both the processes associated with conflict resolution and the integration of public participation techniques with decision support and technical modeling. The Institute plays a prominent role within a number of the USACE technical Communities of Practice (CoP), including the Economics CoP. The Corps Chief Economist is resident at the Institute, along with a critical mass of economists, sociologists and geographers specializing in water and natural resources investment decision support analysis and multi-criteria tradeoff techniques.

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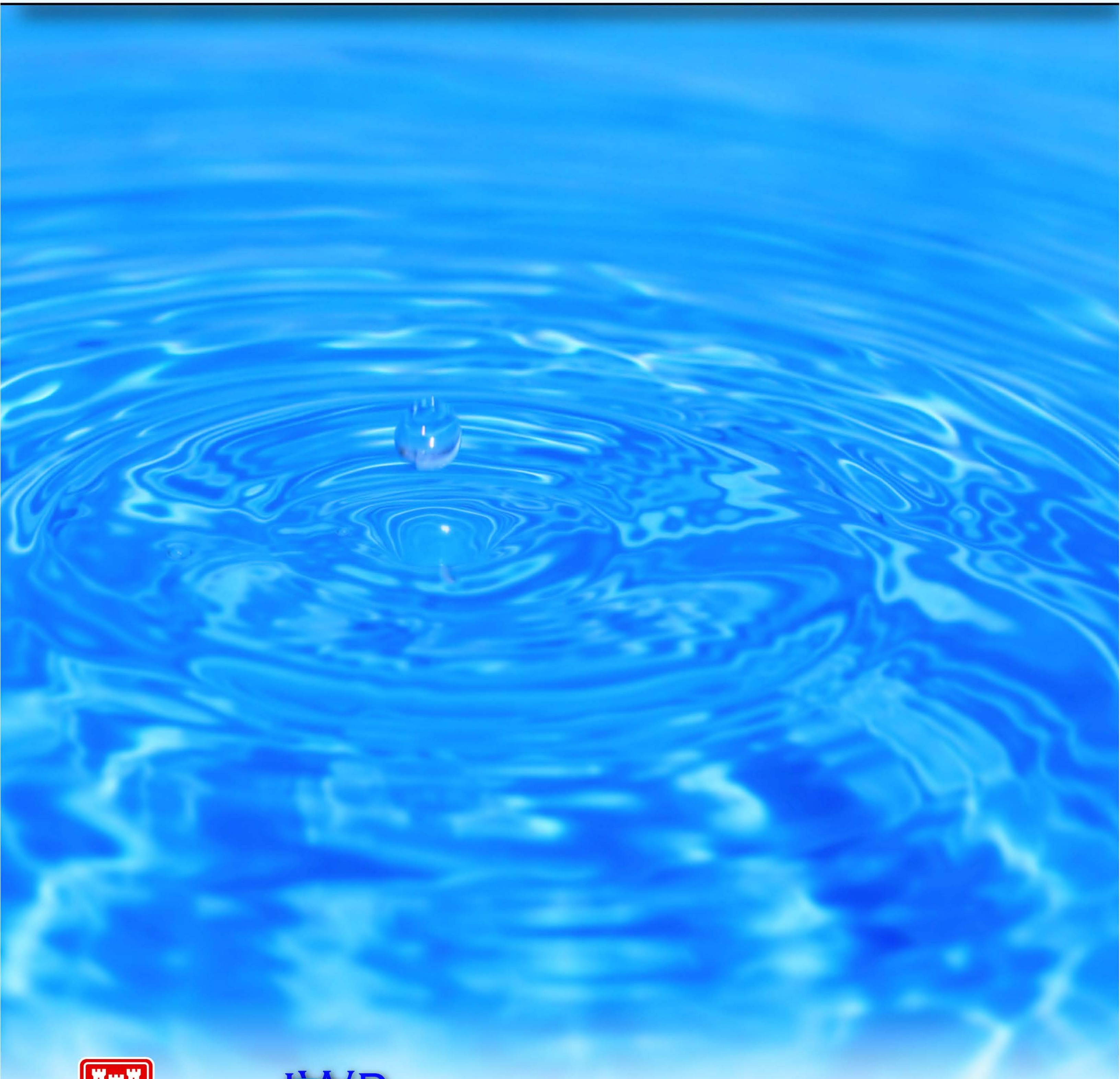

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