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REVIEW OF RISK BASED PRIORITIZATION/DECISION MAKING METHODOLOGIES FOR DAMS

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REVIEW OF RISK BASED PRIORITIZATION/DECISION MAKING METHODOLOGIES FOR DAMS

1. INTRODUCTION

1.1. Objective

This report is intended to meet the following deliverable requirements from two linked USACE contracts.

W91278-04-P-0180 17—Task 3

Outline a position paper on viable prioritization methodologies that could be used by USACE to prioritize O&M general funding between civil infrastructure protection and ongoing maintenance funds.

DACW72-00-D-001, Task Order 62—Assessment and Incorporation of Risk Management Principles into USACE Civil Works Infrastructure: Task 1

Conduct a review of academic and private sector literature, documents and research on multiple hazard decision making and develop a draft position paper, outline a multi attribute model and methodology based on available software to prioritize O&M general funding between civil infrastructure protection and ongoing maintenance investments.

This position paper provides a review of literature applicable to risk based prioritization and decision making relative to the operations and maintenance of dams and associated navigational locks. Particular attention is paid to methodologies developed or used by USACE. Various multi attribute decision modeling and analysis methodologies are summarized and a method is proposed for use in a USACE case study that focuses on the Columbia—Snake River system in the NW District.

1.2. Risk Based Approach to Dam Safety, Its Origins and Regulatory Perspectives

The origins and evolution of dam safety risk assessment can be traced back to a variety of engineering, societal considerations; and public policy and business issues. Bowles (1998) discussed why dam owners particularly in the U.S. have been led to take risk-based approaches, in the light of the following issues:

- The aging of dams that do not satisfy current flood and earthquake loading criteria and the current state-of-practice;
- Increased downstream development below dams coupled with society's becoming increasingly risk averse, expectations for greater protection from natural and man-made hazards and increased community involvement in decisions relating to safety;
- Government is placing greater emphasis on performance-based budget justification, the 'user pays' principle, diminished governmental funding, its shifting away from prescriptive regulation to 'lighter regulation and a governmental emphasis on risk-benefit justifications for health, safety, and environmental regulations;
- Deregulation of the electrical utility industry and other pressures on corporations to improve business performance of all assets, including dams, as indicated by the growing emphasis on asset management approaches; and
- Corporatization and privatization of dams, which were previously owned and operated by governmental agencies.

The 1972 failure of Buffalo Creek Dam¹ led to the National Dam Inspection Act and the authorization by the Congress of the USACE to inventory dams located in the U.S. This resulted in the identification of some 2,900 unsafe dams of which 2,350 were found out to have inadequate spillways. Thus the early interest in applying risk-based approaches dates back to the study of ASCE Task Committee on the ‘Reevaluation of the Adequacy of Spillways of Existing Dams’ in 1973. Then the Teton Dam failure and later Toccoa Falls Dam failure led to an Executive Order that instructed federal agencies to explore risk-based approaches in their process of site selection, design, construction, and operation. Appendix A provides a summary of major dam failure incidents that resulted in life loss and/or significant economic losses. The Committee on dam safety produced its first set of guidelines in 1979 and a later version in 1985 (NRC, 1985).

Later, the Water Resources Development Act of 1986 authorized USACE to maintain and periodically publish an updated National Inventory of Dams (NID)². The Water Resources Development Act of 1996 established a National Dam Safety Program and named FEMA as its coordinator. It also required the reorganization of the Inter-agency Committee on Dam Safety (ICODS).

Since then, FEMA has commissioned various research projects regarding dam safety. The priorities included outlets/gates, spillways, hydrologic model analysis, dam failure analysis, risk analysis, overtopping, and seismic analysis. The Research Subcommittee of FEMA also sponsored a series of workshops in these areas, and facilitated the integration of research results into training.

For federal agencies, the regulatory basis for the use of risk based prioritization decision methodologies was initiated with Executive Order 12866, “Regulatory Planning and Review” issued by the Office of the President on September 30, 1993, and its companion document, “Economic Analysis of Federal Regulations Under Executive Order 12866” issued by the Office of Management and Budget (OMB) on January 11, 1996. The Executive Order and the OMB implemented document, mandated promulgation of formal regulatory requirements by Government agencies and the encouragement of developing guidelines, and using risk based prioritization approaches in their investment decisions. With the encouragement of OMB, federal agencies developed guidelines using risk as a prioritization decision tool. Risk based guidelines developed by the Department of Transportation’s Federal Aviation Agency, and the Department of Energy for their acquisitions investment analysis procedures are useful documents and are relevant to the purposes of this project. They will be discussed in Appendix C.

Meanwhile, the use of risk analysis to evaluate proposals for any major rehabilitation of water resources was initiated within the USACE in 1991. Thus, the Corps adopted a more methodical risk analysis approach to the engineering and economic evaluation of all flood damage reduction projects it plans and builds. Later, with the encouragement of OMB, the USACE (1996) recognized that major rehabilitation is an investment to avoid future increased operating and emergency repair costs and losses, and thus developed an economic-based decision framework that borrows heavily from the methods of risk analysis combined with probabilistic benefit-cost analysis. For major rehabilitation programs, the Corps applied risk analysis principals to investment decisions about aging hydraulic structures. The current policy of Corps requires the use of risk analysis methods for all flood damage reduction projects to help improve decision-making. The policy emphasizes concentrating on the uncertainty in key variables, for example: discharge associated with exceedence frequency for hydrologic studies, reliability of the existing protective structure, and stage-damage function for economic studies. The approach considers project increments comprised of different risk management alternatives represented by the tradeoffs among engineering performance, and project costs. Moser

¹ A chronology of major dam safety incidents and the legislative actions can be found at the NPDP website at <http://npdp.stanford.edu/chronology.html>

² <http://crunch.tec.army.mil/nid/webpages/nid.cfm>

(2004) indicates specific applications of risk analysis within the Corps. One application involved estimating the reduction in vessel collision and grounding damages due to widening of the Houston Ship Channel (Moser et al 1995) and another one estimated the risk closure of the Poe Lock, Sault Ste. Marie, MI of which the particular interest was the likelihood of an extended lock closure from a vessel related incident. We have not located these two documents yet. However, for the purpose of completeness, relevant to our focus, a few risk-based condition indexing methodologies for dams and components of dams and locks will be discussed in the following sections.

In the early 1990's, the Australian Committee on Large Dams (ANCOLD 1994) published its first guidelines on dam safety. This and B.C. Hydro first explicitly addressed life loss tolerable risk criteria, which was based on nuclear power and industrial facility risk practices. Starting 1995, the US bureau of Reclamation (USBR) has developed risk assessment procedures and is currently the largest user of risk based methodology it has developed. This methodology called Risk based Profiling System will be analyzed in the later sections.

One of the workshops sponsored by FEMA named "the Association of Dam Safety Officials (ASDSO)/FEMA specialty workshop on risk assessment for dams", was conducted in March 2000 in order to 1) carry out a review of the state-of-the-practice of dam safety risk assessment; 2) to identify research needs; and 3) to recommend an approach for addressing those needs. The expert panel at the workshop included state and federal regulators, private owners, federal and local government owners, industry associations, consulting engineers and academics. The workshop identified information needs for dam safety evaluation and management. The workshop participants identified four risk assessment application areas ranging from quantitative to qualitative areas. The four application areas were:

1. Failure Modes Identification Approaches (Qualitative Approaches)
2. Index Prioritization Approaches
3. Portfolio Risk Assessment Approaches; and
4. Detailed Quantitative Risk Assessment Approaches.

The workshop participants identified strengths and weaknesses of each of the four approaches and suggested immediate and future research and application needs relating to each application. In the following section we will discuss specific methodologies that are currently being used and that fall under each of these categories, and will refer to the opinions of the ASDSO/FEMA expert panel where necessary.

2. SUMMARY OF METHODOLOGIES

Quite a few methodologies exist both in the U.S. and in the world that consider risk as part of assessing dam safety. We refer to risk as probability of occurrence of an unfavorable event multiplied by the consequences should such event occurs.

Risk = probability x consequence

Or in a more elaborate expression we define risk as follows:

Risk = threat³ x vulnerability x {direct (short-term) consequences + indirect (broad) consequences}

We have identified several tools pertaining to:

³ For our purposes threat means initiating event, a cause or a root cause

* USACE Condition Indexing Method using REMR software

** Andersen et al Condition Indexing Method for embankment dams (1995-2001)

- 1) dam safety risk assessment (RBPS);
- 2) dam safety priority indexing (TPR, CI);
- 3) dam safety risk assessment and priority indexing (PRA, CI); and
- 4) dam security risk (and vulnerability) assessment. (RAM-D, EPRI tool)

Not all of the methods incorporate uncertainty in their approach, however they are included here since they all have been either developed in cooperation with dam agencies or recognized worldwide or in the U.S. and are currently being used. Two of those methods look at dam security issues, in that they differ from the rest of the methods. The next section summarizes each methodology. We will begin with dam security risk assessment tools. Table 1 will provide a snapshot overview of the dam safety risk assessment and investment prioritization methodologies described here in a table format.

For the purposes of completeness, we have also provided an overview of general widely recognized risk analysis methods in Appendix D. Some of the dam safety risk assessment methodologies that we are about to discuss, draw upon these risk analysis methods.

2.1. RAM-D Risk Assessment Methodology for Dams

RAM-D is a risk assessment process developed to assess security risk at IFIP dams and to provide a systematic way to compare reduction in risk afforded by various risk reduction strategies, costs, and impacts of deploying specific security system upgrade packages or consequence-mitigation efforts. RAM-D was prepared by Sandia National Laboratories for the Interagency Forum for Infrastructure Protection (IFIP) – a consortium of hydropower generators, government dam owners, transmission system operators, and anti-terrorism experts- in 2001. RAM-D adapts the security principles, processes and procedures developed by Sandia to protect nuclear materials. RAM-D assumes the following risk equation:

$$\text{Risk} = (\text{Likelihood of attack}) \times (\text{Consequence}) \times (1 - \text{System Effectiveness})$$

Specifically designed for dam owners, operators and security managers, RAM-DSM takes the user through the facility's classification; evaluation of the consequences if the facility is attacked; definition of potential terrorist adversaries and their motives and resources; quantification of risk; detailed analysis of a facility's vulnerabilities; and cost-benefit analysis of possible upgrades. RAM-DSM, is used, for instance, to determine where to place sensors, cameras, or lights, or whether to invest in walls, barriers, higher fences, better doors, extra training, or improved policies. Currently RAM-DSM is a manual system with the documentation available in hardcopy and on compact disk. RAM-DSM publications include a field manual, training guide, exercise book and worksheets for evaluating existing security features, equations for calculating risk, and a proprietary fault-tree analysis tool for identifying vulnerabilities⁴.

RAM-D includes worksheets for evaluating existing security features, equations for calculating risk, and a proprietary fault-tree analysis tool for identifying vulnerabilities⁵.

In summary, the methodology considers the following issues: the missions of the dam in concern; identification of undesired events that prevent mission success; list and characteristics of the critical assets to be protected; analysis of potential adversaries and their characteristics; definition and analysis

⁴ Technical Support Working Group, Briefing on RAM-D at http://www.tswg.gov/tswg/ip/RAMD_TB.htm

⁵ Sandia Laboratories, Dec.2001 News Release: "Two New Methodologies can help owners improve security of nation's dams and power systems" accessed at <http://www.sandia.gov/media/NewsRel/NR2001/ramdramt.htm>

of credible threats to a dam; assessment of the level of risk that can be tolerated; optimal use of available technologies for security upgrades; identification of consequence mitigation options; identification of risk reduction alternatives; and operational and cost impacts. RAM-D methodology uses fault trees (starts with a generic and adapts to a specific dam); adversary sequence diagrams (ASD) and populates them with data obtained from subject matter experts, published information and data from site surveys. Dam layouts and sketches are also heavily relied upon.

Some of the suggested risk mitigation measures in this methodology include early warning, decreasing adversary success, and improved emergency evacuation.

One of the apparent issues in this type of methodology is the difficulty of quantifying terrorism risk. The probability of an adversarial attack is assumed to be constant throughout the entire method in the absence of data. However, as Matalucci (2002) points out, RAM-D is a living process that will require revisions and updates as the threat environment changes. Another concern is that the interdependencies of dams do not seem to be factored in to the analytical process. Two or more dams operating as a system downstream on the same river need to be analyzed interdependently. The methodology a dam safety assessment tool, described next, takes into account a system of dams rather than an individual dam itself only.

2.2. EPRI's Hydro Facility Vulnerability Assessment Tool

Since this tool has not been released yet, we are providing the following information from the Electric Power Research Institute's website:

“The Electric Power Research Institute (EPRI) is cooperating with the U.S. Federal Energy Regulatory Commission's (FERC) Division of Dam Safety and Inspections to develop a hydropower vulnerability and security assessment tool that can be used to conduct vulnerability studies of dams regulated by FERC. The intent is to cooperatively assist in the development of an engineering procedure on dam security by providing a model and appropriate guidance in conducting vulnerability studies and identifying countermeasures that dam owners can take to mitigate the risk from potential attacks. The project is aimed at developing a security-planning tool that can be used by facility owners to perform self-assessments, provide inspectable results for compliance purposes, and can be used with some expected level of standard application. Since September 2001, there has been a heightened awareness and concern for the vulnerability of hydroelectric facilities to potential acts of terrorism. FERC has responded to this heightened threat concern by working with other agencies and dam owners. The initial steps were to increase dam owners' awareness of the risk and to perform initial assessments of the level of vulnerability. These first steps have recognized that there are a number of approaches that can and have been taken to determine vulnerability and the appropriate responses. FERC is looking to create a tool that it can use as part of the annual inspection process to assess dam owners' vulnerability to acts of terror and their level of preparedness to either deter or respond to such acts. By creating an assessment tool and making it available to dam owners, the commission further hopes to give owners a uniform process to make their own judgments about vulnerability and necessary countermeasures or responses.”⁶

2.3. Portfolio Risk Assessment Methodology (PRA)

Portfolio Risk Assessment was developed by Bowles (1996) from the Utah State University and SMEC/RAC Engineers, and is still being modified. A portfolio refers to a group of dams, which are the responsibility of a single owner or regulator. PRA became a standard practice in Australia and has

⁶ Eprri Journal online: A new tool for Assessing Hydro Facility Vulnerability
<http://www.epri.com/journal/details.asp?id=635&doctype=projects>

recently begun to be used by US Dam agencies also. The underlying approach for PRA was initiated by the corporatization of Australian dam operating organizations and these organizations started to look at their dams from a business perspective. As Bowles (2003) states, this took place partly in response to the publication of the Australian National Committee on Large Dams Incorporated, ANCOLD's 1994 Dam Safety Management Guideline, which introduced using risk-based approaches for dam safety. This combined with the need for these new corporations to develop a portfolio-wide perspective of the business risks of dam ownership led to the development of PRA. Bowles (1998) states the purpose of PRA as follows: 'to provide basis for evaluating or establishing Integrated Dam Safety Management Program which includes reducing risks associated with a portfolio of dams to tolerable levels -where 'tolerable levels' may be defined using standards or risk-based criteria -; to prioritize structural and non-structural risk reduction measures; to identify the amount and disbursement of capital for risk reduction measures; and to understand business risks with dams.'

The overall process of PRA is conducted by a team of engineers, a PRA expert, the owner's dam safety manager, decision-makers and stakeholder representatives. The process includes: 1) identification of decision framework, 2) engineering assessment, 3) risk assessment, and 4) prioritization.

The decision framework is usually guided by the externally imposed requirements, together with the internal considerations such as business criticality or alternatives for replacing project functionality. A rating system is used which summarizes the results of engineering assessments of the dams, such as Pass (P), no Pass (NP) when there is enough information available about the condition of the dam parts, and Apparent Pass (AP) or Apparent no pass (ANP) when the information is insufficient. This simplified rating is suggested for ease of communicating with decision-makers. In addition, regional estimates for the likelihood and severity of floods and earthquakes are made, a 'reconnaissance' level risk assessment is conducted through which dams are assessed against engineering standards, and failure modes are identified using Failure Modes and Events Analysis (FMEA). Then reservoir relationships are developed, dam break modeling, inundation mapping, and finally the estimates of capital budget requirements for structural and non-structural risk reduction measures are produced. It should be noted that for evaluation and prioritization, SCUPS (separable construction upgrade packages) are used rather than failure mode by failure fixes.

For the consequence modeling, life safety tolerable risk and financial/economic risk guidelines are considered, including the ALARP (as-low-as-reasonably-practicable) principle. Life safety risk criteria are based upon ANCOLD guidelines and USBR (which will be discussed in the next section) depending on dam location. Occupational Health and Safety (OH&S) risks are not lumped with dam safety risks. For more detail on life safety criteria please refer to ANCOLD (1994) and USBR (1997). Unlike life safety criteria other financial losses and business criticality consequences differ from portfolio to portfolio. Total portfolio risk is usually calculated as the sum of annualized estimates of probability of failure and annualized life safety and economic/financial risks for all dams in the portfolio.

SCUPS are typically prioritized to maximize the rate of annualized life safety risk reduction until a point of diminishing returns is reached (Bowles et al 1996). This is based upon unadjusted cost per statistical life saved (CPSLS), meaning, without subtracting the economic benefits from the annualized cost of fix. When a point of diminishing returns is reached, the remaining fixes are prioritized based upon maximizing the rate of reduction of annualized financial or economic risks (risk costs). This can be categorized as 1) internal business considerations (e.g. loss of financing, business criticality, contractual obligations); and 2) external factors (e.g. public protection/tolerable risk criteria, regulatory requirements, public perception, and environmental issues). Some of the examples used are structural risk reduction measures (construction packages), relocating downstream residents, but also mentioned are operating level restrictions, increased monitoring and surveillance, emergency action planning,

early warning systems, and contingency planning. Practice has shown that one of the good characteristics of this approach is that very high probability risks are being addressed in the short term, in some cases very rapidly.

The results of the risk evaluation are summarized using risk ratings presented alongside engineering ratings for the existing dams and SCUPS.

In short, as Bowles (2003) summarizes, PRA involves the reconnaissance level application of the identification, estimation, and evaluation of steps of dam safety risk assessment to a group of existing dams and risk reduction measures. The outcomes include an engineering standards assessment and risk profile for the existing dams, and a basis for developing and prioritizing risk reduction measures and supporting investigations.

The US Society on Dams (USSD) (2003) considers PRA as a valuable and increasingly accepted approach for cost-effectively prioritizing dam safety remedial measures and further investigations of a group of dams, but points out the limitations of the approach and the need for frequent updating. The ASDSO/FEMA workshop pointed out those limitations as the danger of misusing the results, risk analysis being not in depth, lack of published guidance and the relatively high costs of using the PRA (Bowles and Johnson 2001).

To our knowledge, USACE conducted a demonstration of the Portfolio Analysis approach on a 283-ft high rolled-earthfill Alamo Dam in their LA District, as part of their Research and Development Program in 1999. The existing dam and 19 structural risk reduction alternatives were evaluated for flood, earthquake, and normal operating conditions and the findings were presented at an ANCOLD Annual meeting (Bowles et al 1999a). USACE also implemented pilot PRA demonstrations in their Baltimore District involving 15 dams in 1999. Between September 2000 and Sept.2001, likewise Huntington District initiated and completed a PRA on their 35 dams (USACE, 2001).

More in-depth explanations of PRA can be found at Bowles (1996); Bowles et al (1997); Bowles et al (1998); Swain et al (1998); Bowles et al (199?); Bowles et al (1999b); and Chauhan and Bowles (2003) (see references).

2.4. Dam Safety Risk Based Profiling System⁷:

Risk Based Profiling System, (RBPS) was developed, revised, and implemented by the Bureau of Reclamation (BOR) to improve its capability to prioritize dam safety activities and resources, and to identify those structures that represented the greatest risk to the public.

Before the RBPS, the Technical Priority Rating (TPR) method was developed in 1986, and was being used to prioritize a large number of potential engineering and construction projects with one set of technical criteria. The TPR however was not a risk-based system. After an independent peer review of the Dam Safety Program for the DOI in 1997, the Peer review Team recommended TPR to be replaced with a risk-based system due to concerns relative to TPR to identify and rank those dams with safety deficiencies.

The RBPS incorporates the following risk equation:

Risk = Probability of Load x Probability of Adverse Response x Consequences

⁷ summarized from BOR (2001) and BOR web site, SSLE page (2004)

RBPS is available on the Internet and the following paragraph is taken from the USBR website summarizing main points of the RBPS:

“The RBPS uses the risk associated with individual loading conditions such as hydraulic, seismic, or static (normal) loads, or sums the total risk imposed by a given structure. The foundation of RBPS is the ‘Failure Index’ (Load x Response) for hydrologic-hydraulic, seismic and static cases. These three cases are considered as being the primary factors that lead to dam failure together with O&M and Safety issues. The RBPS assesses a dam by assigning a maximum of 1000 points. The initial point distributions chosen for allocation between the four categories are as follows:

Category	Assigned Points
Static	300
Hydrologic	300
Seismic	300
Operation and Maintenance	100
TOTAL	1000

The higher the point total, the greater the potential risk associated with a given dam. By using readily available data and information, and engineering and scientific judgment, estimates of points distributions are made for a dam using these four categories. To determine the failure index, the evaluator completes a series of worksheets. These worksheets address the full range of loading conditions (where applicable) and physical condition of the dam. An additional step to further prioritize and compare dams on a common risk-based level is to multiply the Failure Index by a Loss of Life Factor which characterizes the consequences associated with a failure as is done when determining the annualized loss of life in a risk analysis. This product is called the “Risk Index.” The Loss of Life Factor is determined by a consideration of several factors including the total population at risk, the location of this population below the dam, the severity of the flooding expected should the dam fail, and the severity of the failure mode in question. This Risk Index is calculated separately for each category of Failure Index and then summed to represent the Total Risk Index. In addition to the Risk Index a measure of potential social and economic impacts are reflected through use of the Socio-Economic Index. For the purposes of the RBPS, the term “social” is assumed to grossly include cultural and environmental consequences. The Socio-Economic Index is determined by multiplying the Failure Index by the total population at risk and dividing by 1000. Specific and more refined factors that may enter significantly into the decision-making process related to social, economic, cultural and environmental consequences could be incorporated into the RBPS in the future by dam safety program managers. The final scoring for any particular dam is calculated by comparing its score to the highest score found for all the dams in Reclamation’s inventory, expressed as a percentage. This ranking is calculated for all the Failure Indexes, Risk Indexes, and Socio-Economic Indexes. This thus provides for consideration of risk in a variety of ways.”

RBPS relies heavily on Failure Modes, Effects, and Criticality Analysis, FMCEA (general description of FMCEA given in Appendix C) for estimating the likelihood of adverse consequences from loads on dams. Two types of risk are defined in this methodology: 1) A Risk Index (=Failure Index * Loss of Life factor) and 2) a Socioeconomic Index (= Failure Index * Total PAR⁸/1000). However, it does not propose a prioritization scheme for risk reduction alternatives and apparently is only a scoring

⁸ Population at Risk

mechanism and an indexing method for ranking dams in accordance with weighted failure modes and consequences. It appears to be a deterministic model based on qualitative assessment rather than relating to absolute probabilities.

The RBPS falls under ‘index prioritization approach’ category meaning that the ranking is based on an index calculated from a combination of weights, which are assigned to capture various attributes of identified dam safety deficiencies. The attributes and ranking procedures are usually prescribed in order to form a common basis for ranking between dams. These approaches are appropriate for initial screening of a portfolio of dams, or a comparison to other forms of risk analysis. The ASDSO/FEMA workshop participants suggested that the index approaches are valuable for dam safety issues and investigations, whereas they should be calibrated and must incorporate a risk metric to be considered risk-based and that they are less costly to use than PRA, but are more limited in the scope of their outcomes.

The Colorado State Division of Water Resources adapted RBPS by revising some of the worksheets to fit its needs and simplified some of the concepts in the life loss aspects.

2.5. Condition Indexing Methods (developed with USACE’s REMR Program):

USACE developed a program for repair, evaluation, maintenance and rehabilitation (REMR)⁹ in the early 1980s. The need for REMR methodologies emerged from the fact that in a given fiscal year, there are many REMR needs distributed over a large number of facilities, but not enough resources to address each. Recognition of the REMR program grew out of USACE workshops devoted to design and construction of new hydraulic structures. In one of these workshops the Corps came to a conclusion that when a structure or a project reached the point of requiring drastic REMR measures to keep it functioning, it was generally also time to replace it with a larger project. However, it was also realized that the technology needed for designing and constructing new hydraulic structures is not the same technology needed for REMR activities for hydraulic projects. Thus the REMR program started with an aim of performing research on O&M activities. Benefits of the REMR program were summarized by Markow et al (1989) as follows:

- To permit more economical, rapid and quality-oriented performance of REMR activities,
- To increase the service life of facilities, so long as it remains reasonable and feasible to do so,
- To correct operational problems so that they do not recur within the near future,
- To modify, if appropriate, design and construction procedures to reduce later problems with facilities associated with REMR, and
- To disseminate knowledge to other agencies involved in REMR activities¹⁰

As part of the REMR program, a factor describing the physical condition of a facility has been developed to be used with funding priority given to those with the ‘worst’ condition. Thus, Condition Indexing (CI) is the process by which the current physical state of a facility or portion of a facility may be defined. Several CI systems have been developed and are still being developed by the USACE. The first such system was developed for pavements inroads and parking lots, and then revised later for roads, and streets, and later for the concrete in navigation lock monoliths (Bullock 1989), miter lock gates (Greimann et al 1990; 1993) and gates, walls and mechanical equipment (Markow et al 1989) and other structures. Although differing in specifics, each of these systems adopted the same general approach. As such, the condition indexing process involves dividing the facility into subunits, rating the condition of each of the subunits and then through field inspections measuring the facility condition. Indices to measure facility condition fall into one of three general classifications (Markow et al 1989):

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¹⁰ More detailed info on REMR program is given at www.cecet.army.mil/fl/remr/remr.html

1. Quantifying the amounts of damage or distress that have accumulated within the structure (e.g. fracture, corrosion etc),
2. Results of non-destructive tests (e.g. dynamic loading etc.) and
3. Developing indices relating to some aspect of the physical condition of a facility to its operational characteristics or serviceability – where serviceability is defined as the degree to which a facility fulfills its intended level of service to users).

These indices help determine the amount of REMR work required.

The REMR methodologies initially focused only on condition or physical state as determined through site-inspections rather than focusing directly on risk. However, later studies incorporated risk into their condition indexing formulation. For the purposes of consistency we will begin with the summary description of a recent study by Andersen and Torrey (1995; 2001) on Condition Indexes for embankment dams developed for the USACE and Hydro-Quebec, since this methodology looks at the overall dam's CI. Then we will discuss CI methods developed earlier for key components of inland waterway dams and locks systems which will provide a segue to the decision making prioritization methodology that we will propose and demonstrate on the Columbia River System. The summary of the risk-based decision methodologies are given in Table 1. Note that we did not include Greimann et al (1990; 1993) and Markow et al's (1989) CI methods in the table, since they look at components of a dam rather than rating the overall condition of a dam. Therefore they are complementary as opposed to the rest which are complete models used for dam safety.

2.6. Andersen and Torrey's Condition Indexing Method for Embankment Dams:

A rather recent study performed as a joint research project by Hydro-Quebec and the Corps of Engineers developed a decision analysis approach that bridges the gap between decision-making based solely on condition and decision-making based upon classical risk analysis. The theoretical underpinnings of this approach were developed and presented by Andersen and Torrey (1995), which proposes a total-systems approach for aging civil engineering facilities particularly embankment dams. Later, the methodology was called "risk indexing tool" and refined to assist in prioritizing maintenance, repair, and evaluation tasks on embankment dams that are less than 100 ft with little information concerning performance history (Andersen et al 2001). Developed for embankment dams, this methodology has the objective of developing a rating procedure that describes the current condition of embankment dams in a uniform manner. It includes a procedure for prioritizing O&M activities on embankment dams. The methodology covers a system for ranking the relative importance of different threats based on expert judgment. The risk-indexing tool is based upon identifying potential deficiencies to the safety of the structure. The risk index is not a direct measure of risk. Checklists are presented for onsite inspections to determine current physical condition. They define 3 factors that contribute to vulnerability. These are intrinsic and time-invariant characteristics (I) of the dam (I1= height; I2= dam type; I3= foundation type; and I4= storage capacity) and upon external time-variant factors (E) associated with dam (E1= age; and E2= seismicity). Additionally, design characteristics of the dam (D1= spillway capacity; and D2= mass movement factor of safety). Thus by taking the mean values, the overall vulnerability takes the following equation:

$$V = (I1 + I2 + I3 + I4)/4 + (E1 + E2)/2 + (D1 + D2)/2$$

Each of the above parameters can take the value of maximum 10, thus the maximum vulnerability score becomes 1,000. These vulnerability criteria are based upon guidelines developed by the Dam Safety Directorate of Hydro-Quebec and by FEMA (1998). Andersen et al (2001) indicates that Hydro-Quebec was at that time, in the process of developing a direct risk-based measure for dam importance to be used in conjunction with their existing condition measurement tool. For the hazard potential, a score of 1 to 10 is assigned depending on the potential for loss of life, possible economic losses, environmental

damage and/or disruption of lifeline facilities. The importance of the dam in an inventory then takes the following form: $I_{\text{dam}} = V \times H$

Accordingly, a dam possessing the highest scores in each category and having a high hazard potential will have an importance score of 10,000.

There are various physical conditions that can lead to failure of an embankment dam. Andersen et al. (2001) define condition in terms of a condition function that is based upon a condition indexing scale. They consider 4 potential failure modes: (1) overtopping; (2) external erosion; (3) piping; and (4) mass movement.

The analysis does not factor in absolute probabilities, The relative importance of various observable physical conditions that could lead to a failure is determined through a Bayesian updating procedure and a simplified failure criticality analysis based upon conditional probabilities of failure determined by expert elicitation. A simple failure criticality analysis is performed wherein specific changes in physical condition of the dam are considered to contribute to the probability of failure for each mode. From this, failure criticality analysis and the conditional probabilities of failure, the relative importance of various changes in physical condition is determined through the elicitation of expert opinion. When there is actual data available, then the probabilities are updated without the use of expert opinion. The physical condition and the relative importance are then combined for each observable deficiency to form a risk index. These risk indices are used to prioritize expenditures for improvements on the premise that actions to address the most significant physical deficiencies are preferred.

The reason why Andersen et al (2001) did not take into account the absolute probabilities is due to the fact that there is a disagreement within the dam safety profession as to whether or not it is possible to reliably determine the probability of failure of a dam and whether or not the probability of failure is of value for prioritization and maintenance, repair, and evaluation tasks in an inventory of dams.

Andersen et al field tested this risk indexing methodology in one of the management regions of Hydro-Quebec using 30 dams and then on another 300 dams. Andersen et al (2001) state that additionally, Hydro-Quebec, the USACE, and the BOR were working at the time that their article was written, in a joint research project to develop a condition indexing methodology for spillways and flood water discharge facilities based upon the same principles used in the methodology for embankment dams.

From this point on, it is important to note that the effort to develop decision analysis tools and the time required for their implementation has to be justified. One concern is that current budgets available to state and/or federal regulators may only enable a rapid walk-through inspection once every several years.

2.7. Markow et al's REMR methodology for Inland Waterways Locks:

Markow et al (1989) developed a REMR management system through the implementation of a life cycle analysis and costing methodology. In essence, they look at facility performance and the factors that influence costs throughout its service life. Markow et al call this approach as 'demand responsive' in that maintenance and rehabilitation are viewed as responses to the demand for repair or renewal of the facility. Treating REMR actions as demand responsive activities, they introduce 3 additional elements: 1. Estimates of future resource requirements and costs of managing facilities based on predictions of structural and operational deficiencies caused by use, environment and age; 2. REMR policy statements, defining the types of preventive or corrective actions to be taken, and when and where they are to start; 3. Relationships between the as-maintained state of the civil facility, and the impacts on both the Corps and the users of the facility (in terms of transportation service provided, safety, etc.) and providing a measure of the benefits (or disbenefits) of each policy at the costs computed in 1.

Based on above, Markow et al develop example models of facility performance for lock gates, walls and mechanical equipment; relate this performance to the costs and the impacts of different REMR policies; and build these into a prototype computer software. They also illustrate their methodology using a real case study.

Markow et al focus on locks used in inland waterway navigation and treat them as a network of transportation systems. Thus, they describe the importance of the inland transportation networks as 1) Responsiveness to defense mobilization, 2) Capacity to accommodate commercial traffic, and 3) Reliability, safety and efficiency of commodity transportation. By pointing at the then statistics of the locks and dams owned and operated by the Corps in terms of number, age distribution, size, purpose, traffic patterns, Markow et al discuss the issue of trade-off among evaluation, maintenance, repair, and rehabilitation over time, along with the trade-offs in distributing and allocating resources among competing needs throughout a network of facilities. They thus propose a life cycle costing approach for the analysis of REMR projects in order to help understand facility performance as well as to illuminate the long-term costs and benefits of different courses of action. For this purpose they treat REMR activities as demand-responsive actions in that, REMR activities are viewed as responses to the demand for repair and renewal of the facility. Markow et al's methodology consists of the following steps:

1. Define REMR policy (what work to do, when, where, how)
2. Assess facility's condition as a function of design, construction, loading, and REMR history
3. Feed the definition and the condition assessment to REMR requirements
4. Estimate REMR costs
5. Assess the consequences of REMR in terms of updated facility condition, structural integrity, level of service and costs, safety and reliability
6. Evaluate costs and consequences
7. Revise policy if necessary (go back to step 1)

Based on the Corps' REMR definition, Markow et al's study uses 4 basic REMR classes (repair, evaluate, maintain, rehabilitate) and differentiates between major versus minor REMR activities. They consider evaluation and maintenance as minor or periodic actions; and repair and rehabilitation as major actions that require different logistical requirements and funding sources. Thus major activities are assumed to create discontinuities or steps in the deterioration functions.

Markow et al developed 3 types of deterioration models: 1) expected value of the gate or wall condition indices, 2) standard deviations of these indices over time, and 3) probability of failure of mechanical equipment. The expected value of the condition index is a function of the initial condition index, and an exponentiation of time elapsed since the initial condition was assessed. Time is assumed to be a surrogate for several factors that affect lock damage and deterioration; quality of design and initial construction (or of subsequent reconstruction or major rehabilitation); the type and extent of lock usage; aging and time-dependent changes in material properties; and environmental effects (temperature, water intrusion, and chemical attack). The standard deviation of the CI was assumed to vary with time as well as the policy governing routine maintenance and rehabilitation, and the performance of repair and rehabilitation activities. Markow et al use a Markov process in which the standard deviation of the CI in any given time period is assumed to be a function solely of the standard deviation in the preceding time period. Thus Markow et al assume that evaluation and routine maintenance affect only the standard deviation of the expected value of the CIs and major actions affect the expected value of the CI. Additionally the probability of failure of mechanical equipment is assumed to be an increasing exponential function of time also. For the CI, Markow et al use a 0 to 10 scale for convenience. The CI encompasses a number of attributes of routine maintenance and evaluation policy (frequency, quality of work performed, completeness, intensiveness etc.) and the better the maintenance policy, the less likely premature deterioration or failure of the facility will occur.

Markow et al then look at the historic data for costs of operation, inspection, and routine maintenance of locks. They found out that operational costs are correlated with lock use and routine maintenance costs with the size of the lock chamber. They obtained expenditure data for repair and rehabilitation from the Pittsburgh District for the Emsworth, Montgomery, and Dashields locks and dams on Ohio River going back approximately 50 years. However, Markow et al cautioned against applying the models developed based on this data to other management systems since these data do not extend over a sufficiently long analysis period. Nevertheless, what the data demonstrated was that a consistent pattern of expenditures exists for each of the locks. On the other hand, lock damage costs appeared to be random based on the fact that lock gates and walls can be damaged by impacts from barges. Barge impacts are somewhat different from natural mechanisms that deteriorate facilities gradually; they are uncertain in terms of location, timing and severity, thus requiring a stochastic treatment in terms of modeling. This was modeled by looking at the statistics of occurrences and average costs per incident. The cost models that Markow et al developed will not be discussed here. The interested reader can refer to the technical report itself. However, it is important to note that the cost models presented in the technical report were preliminary, and the calibration of the effects of REMR policy on costs required further research.

Lastly, Markow et al develop models for estimating the benefits of REMR policies on inland navigation. Referring to the Water Resources Council, Markow et al state the benefits of navigation projects as: 1) cost reduction benefit (reduction in costs incurred from trip delays, reductions in costs because larger or longer tows can use the waterway, and reduction in costs by permitting barges to be fully loaded (e.g. by channel deepening); 2) shift of mode benefit (same origin-destination; different mode); 3) shift of origin-destination benefit; and 4) new movement benefit. The capacity of the waterways system is generally limited by the capacity of navigational locks. Lock capacity is a function of lock size, lock service time, and lock downtime. For trip delay costs, Markow et al assume that REMR actions would only affect link travel time, lock service time, and lock delay time, the three components which contribute to both towboat and barge operation time, through its effect on lock closures for inspection, routine maintenance, major rehabilitation and emergency repair. For estimating trip delay times, Markow et al propose the use of models developed earlier and that draw on queuing theory. They emphasize that if small increases in service rate can be affected by changes in REMR policy, then substantial savings in shipping times could result. They define lock capacity as a linear function of downtime among other things. Markow et al assert that REMR policy can affect service time in a number of ways. For example, the condition of lock valves and lock gates influence chamber filling and emptying time; and approach and exit times depend on the maintenance of the channel depth, as well as the level of maintenance performed. Thus, any reduction in service time or waiting time resulting from improved REMR performance leads to a reduction in shipping cost. They also suggest the use of models that take into account the fact that the change in service parameters of one lock has an effect on the performance of nearby locks (network effect). Earlier studies suggest that the effect of congestion at a lock seems to be transferred only to one lock upriver and one lock downriver. Markow et al also discuss potential impacts of REMR policy on shippers' costs through its effects on reliability. For example the shipper who requires certain level of reliability in the travel time of a particular commodity could suffer economic loss as a result of uncertainty in predicting arrival time of that commodity. Inadequate reliability may lead the shipper to an alternate transportation mode. Markow et al also discuss the effects of maintenance on accomplishing the Army's mission of deploying military equipment and supplies, as well as the impacts of maintenance on safety by decreasing the number of collisions, rammings, groundings, etc. They also suggest a framework for cause and effect relationships of the components of a lock and dam system.

Markow et al's model is a comprehensive approach in terms of identifying and estimating the cost, benefit and trade-offs of alternative REMR policies, yet it appears some areas needed further research

to make the model beneficial to use. Yet we do not know if Markow et al.'s method and software has been updated and whether it is being used or not. However, we think it is a good starting point for our purposes in terms of identifying the O&M policy requirements for inland waterway locks and dams.

2.8. Greimann et al's methodology for condition indexing of sector gates:

Greimann et al (1993) propose an inspection and rating methodology for sector gates. The entire inspection and rating process is based on a field inspection of the sector gate structure. During the inspection, current physical attributes of the systems are obtained and pertinent data are recorded on an inspection form. The data include gate location, inspection and maintenance histories, and historical water level. The form also includes space for entering field measurements (anchorage movements, elevation changes, gate deflection, cracks, dents, and corrosion), which are used directly to rate the condition of the gate. The CI is a scale from 0 to 100 that indicates the current state of the structure. CI is meant to focus management attention to those structures most likely to warrant immediate repair. CIs below 40 indicate an immediate need for repair or further inspections to assess the condition. In Greimann et al's method, a CI is based on 1) serviceability, or how a structure performs its function on a day to day basis, and 2) subjective safety, or how, in the judgment of engineers, the safety of the structure has been degraded by various distresses. When Greimann et al developed their inspection and rating procedure for sector gate structures in 1993, it had sufficient development and testing to warrant its distribution on a wider basis but was still in its developmental stage. Greimann et al's CI methodology can be considered as 'risk' based in the sense that the CI is based on the expert opinions on the deterioration limits that would be hazardous together with the current condition assessment through field tests.

Table 1- Summary Comparison List of Dam Safety/Security Risk Analysis Methods

Name of Tool	Stands for	Type of Tool	Infra-structure type	Developed by	Used by	Purpose	Approach	Data sources	
RAM-D	Risk Assessment Methodology - Dams	Dam security risk assessment software	Dams	Sandia Lab/IFIP (2001)	IFIP Dam owners/ ops and USACE	to assess security risk at IFIP dams and to provide a systematic way to compare reduction in risk afforded by various risk reduction strategies, costs, and impacts of deploying specific security system upgrade packages or consequence-mitigation efforts	missions of dam, undesired events that prevent mission success, critical assets to be protected, potential adversaries and their characteristics, credible threats to dam, level of risk that can be tolerated, optimal use of available technologies for security upgrades, consequence mitigation options, risk reduction alternatives, operational and cost impacts	Expert judgment, project interviews, published info, observation, site surveys	Generic Dam Fault Tree adapted to specific dam, Dam layout sketches, Adversary sequence diagrams (ASD), project-specific check sheets, worksheets for critical assets
An EPRI dam security planning tool (no name yet)	Hydro Facility Vulnerability Assessment Tool	Dam security risk assessment software	Dams with hydroelectric facilities	EPRI w/FERC's Division of Dam Safety and Inspection (tool development started 2003)	Dams regulated by FERC	as part of the annual inspection process, to assist dam owners and regulatory officials in assessing the vulnerability of hydro facilities to catastrophic consequences due to deliberate acts, and their level of preparedness to either deter or respond to such acts, and give them a uniform process	conducting vulnerability studies and identifying countermeasures		

PRA	Portfolio Risk Assessment Tool	Risk-based dam safety investment decision tool	Dams	Engineering rating system by Bowles, Anderson, Glover, Utah State Univ., RAC Engineers (1998)	Australian Dam Agencies	to provide basis for evaluating or establishing Integrated Dam Safety Management Program (i.e. reduce risks associated with a portfolio of dams to tolerable levels -where 'tolerable levels' may be defined using standards or risk-based criteria -; to prioritize structural and non-structural risk reduction measures; to identify the amount and disbursement of capital for risk reduction measures; and to understand business risks with dams)	Reconnaissance' level risk assessment, 'living document', conduct engineering assessment of dams, make regional estimates for floods, earthquakes, assess dams against engineering standards, identify failure modes, develop reservoir relationships, dam break modeling, inundation mapping, estimate capital budget requirements for structural and non-structural risk reduction measures. SCUPS (separable construction upgrade packages) rather than failure mode by failure fixes suggested for evaluation and prioritization.	site visits, engineering standards/codes, historical flood and non-flood failure data	FMEA, simplified event tree risk models, interim risk-based dam safety criteria developed by ANCOLD (1994), the US. Bureau of reclamation (USBR 1997) and B.C. Hydro (1993), for engineering assessment a rating system developed by SMEC/RAC (1995), cascade failure modes (Bowles 1987)
RBPS	Risk Based Profiling System	Deterministic dam safety assessment method	Dams	BOR	DOI dams	to improve BOR's capability to prioritize dam safety activities and resources, and to identify those structures that represent the greatest risk to the public	Deterministic: For each loading condition (static, hydrologic, seismic, and O&M + safety), score for Failure Index, Risk Index and Socio-Economic Index. Then compare the score to the highest score found for all dams in BOR's inventory and expressed as percentage.	engineering and scientific judgment, past examination reports, reports of findings, performance parameters, population at risk estimates (www.census.gov), Emergency Action Plan, identification of the 100-year flood event and related hydrologic data, seismic loads available on the Internet (peak horizontal acceleration that has a 2% chance of occurring in 50 years) from the National Seismic Hazard Mapping Project.	Decision trees-logic trees for determination of seismic response factor for embankment dams, and for computation of life loss, worksheets filled for physical condition of the dam and full range of loading conditions, Wayne Graham's procedure (DSO-99-06) for loss of life calculations
Condition Rating Procedure (need to get 1999 version) uses REMR software	Function-Based Condition Indexing	Condition	Embankment Dams	Andersen and Torrey (1995)	USACE	to develop a condition indexing system that meets REMR objectives for embankment dams that can be generalized for other civil infrastructure	condition index vectors developed with each element corresponding to the condition index of the facility for each objective.	expert panel to define ideal and failed condition, historical prioritization data	

CI	Risk Indexing tool		Embankment Dams	Andersen, Chouinard et al (2001)	USACE	to develop a simplified "indexing type" tool that can be used to help prioritize maintenance and repair tasks for large inventories of dams for safety officials, practicing engineers, and owners/operators of inventories of dams for which no or limited modern engineering analysis has been performed, for which there is little or no instrumentation, and for which there is little or no information available on as-built conditions or performance history.	4 internal, 2 external time variant and 2 design factors incorporated into vulnerability portion, multiplied by hazard (susceptibility of failure and downstream damage to the built environment). Relative importance of physical conditions assessed using Bayesian prior and posterior probability estimates. then with on-site inspections, actual condition is assessed. Then a risk index of the sum obtained by summing risk index over all potential failure modes	Dam Safety Directorate of Hydro-Quebec Guidelines developed by Dascal (1991) for vulnerability and hazard potential measures, FEMA (1998) guidelines for intrinsic and extrinsic characteristics, reported dam incidents and accidents data, national averages for prior conditional probabilities for failure modes by USCOLD (1998) and expert judgment for Bayesian posterior prob.	Criticality Analysis, Bayesian Theorem
TPR	Technical Priority Rating (TPR) System	Dams	Interior Dam Safety Task Force (1986)	BOR and DOI	to prioritize a large number of potential engineering and construction projects with one set of technical criteria				

Table 1- Summary Comparison List of Dam Safety/Security Risk Analysis Methods (continued)

Name of Tool	Assumptions	Risk		Output Consequences		Risk reduction measures	Notes on Outcome/Significance
		Threat	Vulnerability	Immediate (direct) consequences	Indirect (broad) consequences		
RAM-D		probability of occurrence of terrorism, sabotage and assumed a constant value	considered	Costs, disruption of operations	Public opinion	Early warning, decreasing adversary success, improved emergency evacuation etc	threat level assumed constant, does not take into account a system of dams - checks security on a case by case basis
PRA	Risk matrices developed and evaluated: life safety risk matrix, economic/ financial loss risk matrix, F-N charts, F-\$ charts	probability of occurrence of natural hazards (flood and earthquake), and (seemingly) aging	Quantitative probability of failure (/year), and qualitative engineering assessment ratings (P, AP, ANP, NP) for each dam and its physical subsystems (e.g. emergency spillway, gate system, embankment, outlet works, and reservoir rim).	Incremental loss of life ((lives) [until diminishing returns] , incremental economic damages (financial liability in \$), incremental risk cost in \$/yr (?)	third party economic damages	Prioritizing RRM (maximizing rate of risk reduction through 1)internal business considerations (e.g. loss financing, business criticality, contractual obligations); 2) external factors (e.g. public protection/tolerable risk criteria, regulatory requirements, public perception, and environmental issues). Examples include EWSs, structural risk reduction measures (construction packages) costed, relocating downstream residents, but also mentioned are operating level restrictions, increased monitoring and surveillance, emergency action planning, early warning systems, contingency planning, ALARP analysis of options to reduce risk (probability of failure).	Total portfolio risk calculated as sum of annualized estimates of probability of failure and annualized safety and economic/financial risks for all dams in the portfolio. For cascade case, the consequences of downstream failure included in the upstream failure. Valuable and increasingly accepted approach for cost-effectively prioritizing dam safety remedial measures and further investigations for a group of dams. It provides insights that can better inform owners about the business and liability implications of dam ownership. PRA outcomes must be used with regard for the limitations of the approach

							and be periodically updated. Also, existing risk-base dam safety criteria focus on public safety (e.g. ANCOLD for societal risk), still additional criteria needs to be developed for business implications
An EPRI dam security planning tool (no name yet)	not known yet	prioritizing potential terrorism threat scenarios	?	?	?	security and mitigation upgrades	is in the progress of being development. Very low budget \$6500. No deliverables yet.
RBPS	FAILURE INDEX =Load Factor x Response Factor RISK INDEX= Failure Index x Loss of life Factor, SOCIO-ECONOMIC INDEX= Failure Index x Total Pop.@risk/1000 Time it would take for dam to breach = f(size, erodability, failure mode, construction materials, dam design, reservoir storage), all fatalities occur within 90 min. of flood wave travel time so Warning Time = f(distance PAR, dam breach formation time)	4 categories: 1)hydraulic/hydrologic; 2)seismic; 3)static loads; and 4)O&M and safety cases	dam failure, PAR (population at risk)	Loss of life	Socio-economic	No	Deterministic methodology. Two types of risk defined: Risk Index (=Failure Index*Loss of Life factor) and Socio-Economic Index (failure Index*Total PAR/1000), a bit confusing, no risk reduction alternatives explicitly stated, just a scoring mechanism

Condition Rating Procedure uses REMR software	dam importance factor	static loads, weather and ?	4 failure modes: overtopping, surface erosion, piping, mass movement, 8 adverse conditions: cause or location of failure mode, 10 defense (component) groups based on ICOLD. CI obtained between 0-100 based on a rating procedure obtained through expert judgement	loss limited to owner	no loss of life but some damage to third parties, loss of one or more lives	monitoring devices	not probabilistic, based on expert judgement
CI	Dam Importance Factor = Vulnerability x Hazard, $V = (I1+. +I4)/4 \times (E1+E2)/2 \times (D1+D2)/2$ where V_{max} is 1000. And Using Bayes Theorem conditional posterior and prior probabilities of failure for four major failure modes (see next columns)	static loads and weather	Intrinsic factors, time-invariant (I1=height, I2= dam type, I3= foundation type, I4= storage capacity), External time-variant factors (E1=age; and E2=seismicity), Design Characteristics (D1=spillway adequacy; and D2= mass movement of safety) 4 failure modes: 1) overtopping, 2) external erosion, 3) piping, and 4) mass movement	loss limited to owner, and loss of life	downstream economic losses, disruption of life-line facilities, environmental damage	left for further research	no absolute probabilities, based on expert judgement

Table 2- Comparison Matrix of Dam Safety/Security Risk Analysis Methods

Name of Tool	Condition Assessment	Security	Indexing (prioritization)	set of dams (system approach)	single dam (non-systems) approach	deterministic risk component	probabilistic risk component
RAM-D	X	X			X	X	X
EPRI Tool	?	X	?	?	?	?	?
PRA	X		X	X		X	
RBPS	X		X		X	X	
CI (function-based)	X		X			X	
CI (risk-based)	X		X	X		X	X
TPR			X		X		

3. OVERVIEW OF DECISION ANALYSIS TECHNIQUES

The assessment and modeling of catastrophic risk (e.g. security, safety) and the evaluation of more routine maintenance and repair requirements provides the input for risk based decision making. The decisions to reduce risk are based upon evaluation of potential alternatives with respect to multiple criteria. The field of decision analysis has evolved a set of multicriteria decision making methods designed to improve both the decision making process and the quality of decisions made. According to the Hobbs and Meier (2000, p. 6), decision analysis has six basic functions:

1. To structure the process.
2. To display the tradeoffs among criteria.
3. To help people reflect upon, articulate, and apply value judgments concerning acceptable tradeoffs, resulting in recommendations concerning alternatives.
4. To help people make more consistent and rational evaluations of risk and uncertainty.
5. To facilitate negotiation.
6. To document how decisions are made.

Decision analysis methodologies include:

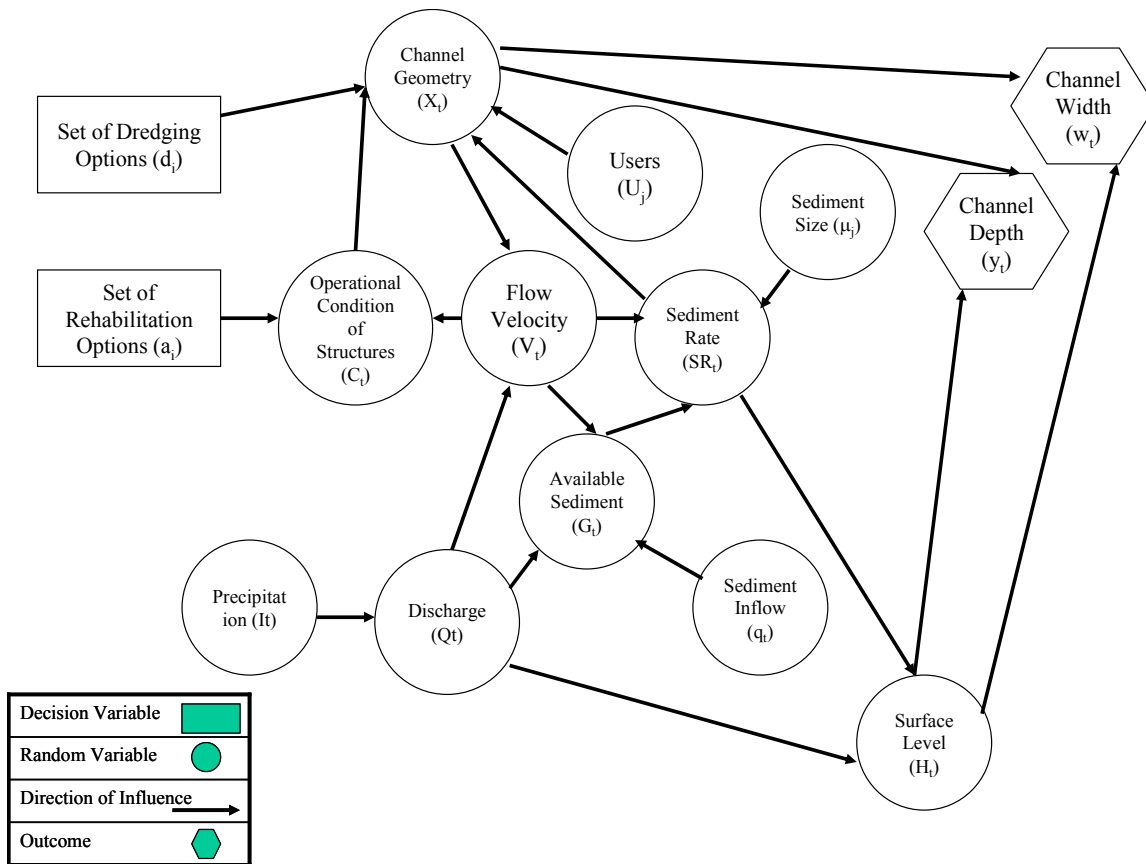
- Decision Trees
- Influence Diagrams
- Surrogate Worth Trade off Method (SWT)
- Multi Attribute Utility Theory (MAUT)
- Analytical Hierarchy Process (AHP)

3.1. Decision Trees:

Decision trees are a graphical and analytic method of capturing the probabilistic nature of decision making. Decision trees combine decision nodes (choice of decision alternatives) with chance nodes (alternative states or outcomes from each decision). The modeler specifies the decision alternatives, the potential outcome states for each alternative, and the value or consequence of each outcome. If the probability of each outcome can be estimated, the decision tree can be “rolled back” and the expected value of each decision alternative can be calculated. The preferred decision is the alternative with the highest expected value. This methodology is appropriate when (a) limited set of alternative decisions and outcome states are present, (b) the probabilities of outcomes and their value can be estimated, and (c) decisions will be made on an expected value basis. As pointed out by Haimes (2003, p. 144), decision trees are very useful in representing sequences of decisions and decision outcomes.

3.2. Influence Diagrams:

Influence diagrams are a graphical alternative to decision trees. Decision nodes are represented by squares, chance nodes by circles, and outcomes by other shapes (typically octagons). Influence diagrams may be used to identify and to evaluate very complex decision networks. Figure 1 illustrates the use of influence diagrams by the USACE to evaluate channel projects that involved two sets of decisions: choosing a dredging option and choosing a rehabilitation option.



Source:

Figure 1 - Sample Influence Diagram

3.3. Multi Attribute/Multi Criteria Decision Models

Multi attribute modeling techniques all provide a method of evaluating decisions based upon multiple criteria. The simplest technique is a straightforward rate and weight exercise using a spread sheet. The criteria are assigned weights and alternative decisions are scored for each criterion. The resulting aggregate score for each alternative is the sum of the weights x score for each criteria. The alternative with the highest score “wins”. More complex techniques like multi attribute utility analysis and the analytic hierarchy process make the comparison of alternatives explicit and may be used to evaluate nested hierarchies of criteria. The application of MCDM/MAUD involves the following steps (Hobbs and Meier, p. 15):

- Select and Define attributes or criteria that reflect the dimensions on which the decision is to be evaluated
- Define alternatives to be analyzed
- Quantify levels of attainment for attributes
- Scale attributes
- Selection of weights for attributes
- Conduct trade off analysis
- Amalgamate results to single value function
- Resolve differences between and among stakeholders

3.4. Example of AHP

The USACE recently used the Analytic Hierarchy Process to prioritize a selection of a project from the O&M backlog. The Hierarchy used is shown in figure 2 below. The overall objective was to select highest value maintenance projects. The criteria used were benefit measures: Return on Investment, Public Safety and Health, Reliability, Environmental Sustainability, and System Criticality. Using the AHP tool Expert Choice, USACE managers calculated relative weights for each of these criteria, and scored all projects for each of the five criteria using the AHP technique of pair wise comparison. The Expert Choice tool amalgamated the scores, provided overall ranking, and sensitivity analysis.

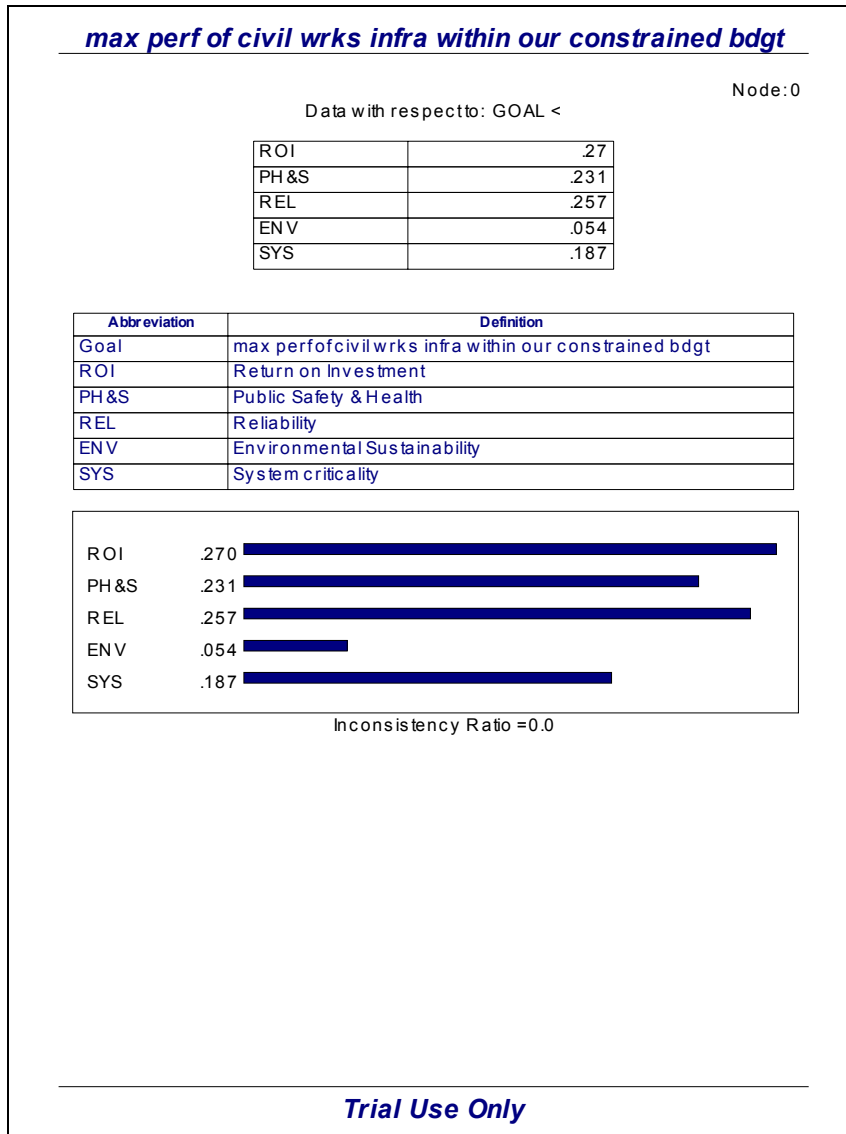


Figure 2- USACE's AHP model for O&M Backlog

3.5. Examples of other Decision Analysis Techniques

Here we provide a short summary of two decision methodologies that appeared in the Operations Research Literature. The first one by Keeney and McDaniels (1992) that describes the use of value focused thinking to structure and quantify basic values for the British Columbia Hydro and Power Authority (BC Hydro) in the context of strategic planning. The second is also by Keeney and

McDaniels (1999) that structures values of multiple stakeholders to help BC Gas develop an integrated resource plan required by the BC Columbia Utilities Commission.

A third method was also developed by Keefer et al (2001) that uses multiobjective decision analysis by the Office of Science and Technology (OST) within DoE to rank environmental cleanup work packages to aid in allocating a limited budget among competing R&D projects. The work package ranking system is implemented on database software to facilitate managers' access to several databases in scoring the proposed work packages. As Keefer et al (2002) indicates, OST has successfully used this system for three years (FY 2000 through FY 2002), and its development and use have been noted in DoE testimony in Congress.

3.5.1. Keeney and Daniels' Value-Focused Thinking about Strategic Decisions at BC Hydro

British Columbia Hydro and Power Authority (BC Hydro) is a large hydroelectric-based, publicly owned, integrated electric utility providing power to over 90 percent of the British Columbia population. For the purpose of structuring and quantifying basic values of the BC Hydro, Keeney and Daniels (1992) elicited strategic objectives for the organization from three senior executives, then refined and structured them into a hierarchy. Keeney and Daniels developed attributes and elicited a utility function to illustrate trade-offs at the strategic level. The results have been used to guide senior planners at BC Hydro in addressing a range of strategic issues. The initial discussions with the three senior executives generated two products: 1) a preliminary hierarchy of strategic objectives, and 2) a network of preliminary objectives that relates all the fundamental objectives to the means objectives defined for BC Hydro. Then, for each of the lowest level objectives in the hierarchy, an attribute was specified to measure the degree to which the objective was achieved. After having defined the objectives and attributes, the next step was to specify a range for each of the attributes, over which the utility function was to be assessed. The resulting strategic utility function had the form of an additive function, and had six major components concerning 1) economics, 2) environment, 3) health and safety, 4) equity, 5) service, and 6) public interest perception. The utility functions for sub objectives were also determined to be additive with a few exceptions. For example, a multiplicative utility function was found to be more appropriate for the sub objectives of the economy objective. Note that the utility function being multiplicative implies that the attributes are utility independent of each other. Once the form of the utility functions was determined, value trade-offs were quantified using pairwise comparison method, in order to calculate the scaling constants in the overall utility function. These 6 scaling constants obtained for the overall strategic utility function were then multiplied by the individual scaling constants, to determine priorities for the corresponding strategic objectives. Keeney and Daniels argue that the assessed utility function and its potential insights promise a future use in a variety of strategic decision contexts at BC Hydro for the next decade, with examples ranging from selecting new supply sources to siting facilities, to determining the roles of independent power producers or demand-side management, to setting policies regarding the environmental effects of projects, to making investments in health and safety including dam safety. According to Keeney and Daniels (1992), BC Hydro used versions of this multiobjective decision structure in various contexts such as, allocating percentage reduction in capital expenditures across the range of capital expenditures planned for coming years, in developing the utility's integrated electricity plan to clarify how electrical loads would be served over the then-coming decade, and in electric supply reliability planning.

3.5.2. Keeney and Daniels' Structuring of Values to Guide Integrated Resource Planning at BC Gas

The British Columbia Gas, a major utility, was required by the British Columbia Utilities Commission (BCUC) to develop an integrated resource plan that addressed multiple objectives and involved the participation of stakeholders. Keeney and Daniels (1999) assisted BC Gas by the elicitation of values

separately from most of the senior executives at BC Gas, members of the BCUC, and representatives of several stakeholder groups. Based on these values, Keeney and Daniels structured a set of objectives and associated performance measures for integrated resource planning (IRP) at BC Gas. A multistakeholder process provided judgments about appropriate value tradeoffs among these objectives. Multiattribute value elicitation was applied to obtain viewpoints about appropriate value tradeoffs among multiple views on relevant objectives for the planning process. The responses were structured into categories, differentiating between fundamental ends and means to achieve those ends. Again, developing measures (also called 'attributes') was a crucial step in making a set of objectives directly useful for planning purposes. For this purpose, a workshop was held with members of the IRP group at BC Gas, as well as other specialists in technical and regulatory issues. Then, the value tradeoffs were assessed using a workbook questionnaire during a one-day stakeholder meeting. Again, the assessment resulted in a linear overall utility function.

Keeney and Daniels argue that this information fostered improved communication, served as a guide for designing more attractive plans and identifying future information needs, and provided the basis for a quantitative evaluation of alternative plans and resources. Then, an evaluation function was constructed to be used to evaluate IRP alternatives. Using the value tradeoffs, this function converted all possible impacts into their 'equivalent cost.' Combining all the equivalent costs associated with any IRP plan provided an index for the total equivalent cost of that plan. The IRPs that had higher adverse environmental impacts, less desirable socioeconomic impacts, or greater cost to customers would all result in higher equivalent cost, and thus be viewed as less desirable than the other plans. The value of Keeney and Daniels' effort is that the measures they identified through this process were new to BC Gas, as such BC Gas did not have a clear statement of the range of possible socioeconomic impacts that it should consider in comparing alternatives. Later, a formal BCUC hearing process was conducted in which the objectives, value tradeoffs, and stakeholder process were subjected to intense scrutiny and were cross examined by the representatives of interested parties (e.g. lawyers for environmental organizations). The result was encouraging: the BCUC accepted the fundamental IRP objectives and value-oriented approach of the BC Gas IRP, but indicated that measures need to be refined over time and that future efforts should involve more time for participants to consider value tradeoffs. This study was important in the sense that, to our knowledge, it is the first analysis requiring regulatory approval where values were explicitly elicited from the top management of the firm being regulated, from members of the regulatory body, and from several stakeholders concerned with the impacts of choices made.

4. CASE STUDY AND PROPOSED METHODOLOGY

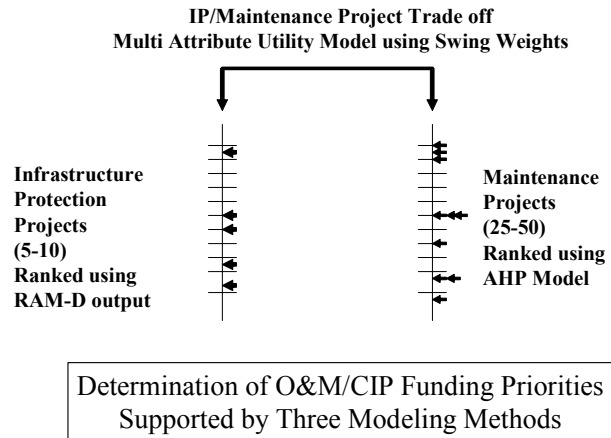
The objective of the PMCL/GWU task order is to demonstrate a methodology for creating a prioritization method that will allow the USACE to integrate the competing critical infrastructure protection (security) requirements and maintenance requirements that must be funded out of the USACE O&M budget. The geographical domain selected for testing this integrated prioritization methodology is the Columbia/Snake River system. The security and maintenance projects considered in the case study will be those associated with the nine¹¹ USACE operated PCNA dams with navigational locks. This case study will require the prioritization of 5 to 10 security projects and 25 to 50 maintenance projects. As shown in figure 3 below, these will require separate prioritization methods.

- The infrastructure protection projects will use the results of the RAM-D evaluation, as interpreted by local USACE security experts, to produce an interval scale of Critical Infrastructure Protection (CIP) projects. These projects will be compared and evaluated based on the attributes identified in the RAM-D methodology. The interval scale requirement means that intervals have defined and constant meaning. For example, the interval between a score of “4” and a score of “6” is the same as the interval between a score of “6” and a score of “8”
- The maintenance projects will be separately evaluated by USACE maintenance experts based on the Analytic Hierarchy Process (AHP) as implemented in the tool *Expert Choice*. The attributes selected in this model will be based on a review of the AHP demonstration project used by USACE HQ to prioritize maintenance backlogs, and on a review of the attributes used in the condition indexing methodologies described above. (e.g. REMR). The AHP ranking produces an interval scale of measures. This scale will not be the same scale as that used for the CIP evaluation.
- The third step of the methodology will be a trade off analysis relying on the judgment of USACE divisional managers, using a multi attribute utility methodology. The swing weight multi attribute methodology provides a means for experts to identify the trade off between levels of achievement of competing goals without requiring that both goals be measured on the same scale. The trade off analysis focuses on how much of an interval a decision maker is willing to give up on one achievement scale to gain a defined increase on the competing scale.

The swing weight methodology will allow decision makers to start with a financial constraint (the projected O&M budget), and compile an integrated, prioritized listing of CIP and maintenance projects. The process may also be used to support future budget requests by providing integrated CIP/Maintenance project budget packages for various budget levels.

¹¹ Bonneville, The Dalles, John Day, McNary, Ice harbor, Lower Monumental, Little Goose, Lower Granite, and Dworshak

Figure 3- Proposed scheme



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Appendix A- Overview of Widely Recognized Risk Analysis Methods

<i>Hazards Risk Analysis Methods</i>	<i>Summary of Method</i>	<i>More Common Uses</i>
Preliminary Hazards Analysis (PrHA)	The PHS technique is a broad, initial study that focuses on (1) identifying apparent hazards, (2) assessing the severity of potential mishaps that could occur involving the hazards, and (3) identifying means (safeguard) for reducing the risks associated with the hazards. This technique focuses on identifying weaknesses early in the life of a system, thus saving time and money, which might be required for major redesign, if the hazards are discovered at a later date.	<ul style="list-style-type: none"> • Most often conducted early in the development of an activity or system where there is little detailed information or operating procedures, and is often a precursor to further hazard/risk analyses. • Primarily used for hazard identification and ranking in any type system/process.
Preliminary risk analysis (PRA)	PRA is a streamlined mishap-based risk assessment approach. The primary objective of the technique is to characterize the risk associated with significant loss scenarios. This team-based approach relies on subject matter experts systematically examining the issues. The team postulates combinations of mishaps, most significant contributors to losses and safeguards. The analysis also characterizes the risk of the mishaps and identifies recommendations for reducing risk.	<ul style="list-style-type: none"> • Primarily used for generating risk profiles across a broad range of activities (e.g., a port-wide risk assessment.)
What-if/checklist analysis	What-if analysis is a brainstorming approach that uses loosely structured questioning to (1) postulate potential upsets that may result in mishaps or system performance problems and (2) ensure that appropriate safeguards against those problems are in place. Checklist analysis is a systematic evaluation against pre-established criteria in the form of one or more checklists.	<ul style="list-style-type: none"> • Generally applicable to any type of system, process or activity (especially when pertinent checklists of loss prevention requirements or best practices exist). • Most often used when the use of other more systematic methods (e.g., FMEA and HAZOP analysis) is not practical.
Failure modes and effects analyses (FMEA)	FMEA is an inductive reasoning approach that is best suited to reviews of mechanical and electrical hardware systems. The FMEA technique (1) considers how the failure modes of each system component can result in system performance problems and (2) ensures that appropriate safeguards against such problems are in place. A quantitative version of FMEA is known as failure modes, effects and criticality analysis (FMECA).	<ul style="list-style-type: none"> • Primarily used for reviews of mechanical and electrical systems (e.g., fire suppression systems, vessel steering/propulsion systems). • Often used to develop and optimize planned maintenance and equipment inspection plans. • Sometimes used to gather information for troubleshooting systems.
Hazard and operability (HAZOP) analysis	The HAZOP analysis technique is an inductive approach that uses a systematic process (using special guide words) for (1) postulating deviations from design intents for sections of systems and (2) ensuring that appropriate safeguards are in place to help prevent system performance problems.	<ul style="list-style-type: none"> • Primarily used for identifying safety hazards and operability problems of continuous process systems (especially fluid and thermal systems). Also used to review procedures and other sequential operations.
Fault Tree Analysis (FTA)	FTA is a deductive analysis technique that graphically models (using Boolean logic) how logical relationships between equipment failures, human errors and external events can combine to cause specific mishaps of interest.	<ul style="list-style-type: none"> • Generally applicable for almost every type of analysis application, but most effectively used to address the fundamental causes of specific system failures dominated by relatively complex combinations of events. • Often used for complex electronic, control or communication systems.

Event tree analysis (ETA)	ETA is an inductive analysis technique that graphically models (using decision trees) the possible outcomes of an initiating event capable of producing a mishap of interest.	<ul style="list-style-type: none"> • Generally applicable for almost every type of analysis application, but most effectively used to address possible outcomes of initiating events for which multiple safeguards (lines of assurance) are in place as protective features. • Often used for analysis of vessel movement mishaps and propagation of fire/explosions or toxic releases
Relative ranking/risk indexing	Relative ranking/risk indexing uses attributes of a vessel, shore facility, port or waterway to calculate index numbers that are useful for making relative comparisons of various alternatives (and in some cases can be correlated to actual performance estimates).	<ul style="list-style-type: none"> • Extensively used to establish priorities for boarding and inspecting foreign flagged vessels. • Generally applicable to any type of analysis situation (especially when only relative priorities are needed) as long as a pertinent tool exists.
Coarse Risk Analysis (CRA)	CRA uses operations/evaluations and associated functions for accomplishing those operations/evolutions to describe the activities of a type of vessel or shore facility. Then, possible deviations in carrying out functions are postulated and evaluated to characterize the risk of possible mishaps, to generate risk profiles in a number of formats and to recommend appropriate risk mitigation actions.	<ul style="list-style-type: none"> • Primarily used to analyze (in some detail) the broad range of operations/evolutions associated with a specific class of vessel or type of shore facility. • Analyses can be performed for a representative vessel/facility within a class or may be applied to specific vessels/facilities. • Especially useful when risk-based information is sought to optimize field inspections for classes of vessels/facilities.
Pareto Analysis	Pareto analysis is a prioritization technique based solely on historical data that identifies the most significant items among many. This technique employs the 80-20 rule, which states that ~80 percent of the problems (effects) are produced by ~20 percent of the causes.	<ul style="list-style-type: none"> • Generally applicable to any type of system, process or activity (as long as ample historical data is available). • Most often used to broadly characterize the most important risk contributors for more detailed analysis.
Root cause analysis <ul style="list-style-type: none"> • Event charting • 5 Whys technique • Root Cause Map 	Root cause analysis uses one or a combination of analysis tools to systematically dissect how a mishap occurred (i.e., identifying specific equipment failures, human errors and external events contributing to the loss). Then, the analysis continues to discover the underlying root causes of the key contributors to the mishap and to make recommendations for correcting the root causes.	<ul style="list-style-type: none"> • Generally applicable to the investigation of any mishap or some identified deficiency in the field. • Event charting is most commonly used when the loss scenario is relatively complicated, involving a significant chain of events and/or a number of underlying root causes. • 5 Whys is most commonly used for more straightforward loss scenarios. • Root Cause Map is used in conjunction with any root cause analysis to challenge analysts to consider a range of possible root causes.
Change Analysis	Change analysis systematically looks for possible risk impacts and appropriate risk management strategies in situations in which change is occurring (e.g., when system configurations are altered, when operating practices/policies changes, when new/different activities will be performed).	<ul style="list-style-type: none"> • Generally applicable to any situation in which change from normal configuration/ operations/ activities is likely to significantly affect risks (e.g., marine events in ports/waterways). • Can be used as an effective root cause analysis method as well as a predictive hazard/risk analysis

<p>Common cause failure analysis (CCFA)</p>	<p>CCFA is a specialized approach for systematically examining sequences of events stemming from the conduct of activities and/or operation of physical systems that cause multiple failures/errors to occur from the same root causes, thus defeating multiple layers of protection simultaneously.</p>	<p>method.</p> <ul style="list-style-type: none"> • Exclusively used as a supplement to a broader analysis using another technique, especially fault tree analyses. • Best suited for situations in which complex combinations of errors/equipment failures are necessary for undesirable events to occur.
<p>Human error analysis</p> <ul style="list-style-type: none"> • Error-likely situation analysis • Walkthrough analysis • Guide word analysis • Human reliability analysis 	<p>Human error analysis involves a range of analysis methods from simple human factors checklist through more systematic (step-by-step) analyses of human actions to more sophisticated human reliability analyses. These tools focus on identifying and correcting error-likely situations that set people up to make mistakes that lead to mishaps.</p>	<ul style="list-style-type: none"> • Generally applicable to any type of activity that is significantly dependent on human performance. • Error-likely situation analysis is the simplest approach and is used as a basic level of analysis for human factors issues. • Walkthrough and guide word analyses are used for more systematic analyses of individual procedures. • Human reliability analysis is used for special application in which detailed quantification of human reliability performance is needed.

Source: American Bureau of Shipping 2000

Appendix B: Examples of Federal Guidelines for Risk Based Investment Prioritization

B1. Department of Energy’s Guidelines for Risk-Based Prioritization

Department of Energy released its updated set of guidelines for its risk-based prioritization of activities in April 1998, in addition to the January 25, 1995 dated “Risk Principles: Risk Assessment, Management, and Communication and Priority Setting” issued by the Undersecretary of DoE. These risk principles are based on precepts generally applicable across Federal agencies and were modified to apply more specifically to DoE programs and processes. The 1998 DoE guidelines have the purpose of providing guidance for selecting and developing a risk-based prioritization (RBP) system. They define RBP as a “structured decision process to prioritize alternatives that compete for limited resources.” The possible context and application areas of RBP are stated as: “(1) cases where many projects are competing for limited funding; (2) the preparation and justification of budgets; (3) the prioritization of remediation initiatives; (3) the selection among competing designs for fulfilling a particular mission; (4) the regulatory analysis of proposed major Federal rules as mandated by E.O. 12866; (5) the allocation of staff resources; (6) the allocation of time to activities, such as the development of ‘living schedules’ for complex facilities or enterprises; and (7) selecting among many suggestions for upgrading troubled facilities, operations, or organizations.” (p.5)

The entire document consists of the definitions, explanation and discussion of 8 characteristics that help evaluate the quality of a RBP system. These are (1) logical soundness; (2) completeness; (3) accuracy; (4) acceptability; (5) practicality; (6) effectiveness; (7) defensibility; and (8) quantification of costs and benefits. The following table shows the discussion headings of each of the guidelines that help determine whether an RBP system meets the 8 specific characteristics:

Table B1- DoE Guidelines for an effective RBP System (discussion headings)

Characteristic	Guidelines
Logical Soundness	<ul style="list-style-type: none"> • Verify decision objectives; the set of decision objectives should be: <ul style="list-style-type: none"> • comprehensive, • relevant, • mutually exclusive, • independent, and • minimal in number • Performance measures should be: <ul style="list-style-type: none"> • unambiguous and clear • consistent with principles of rationality
Completeness	<ul style="list-style-type: none"> • Identification of decision objectives: High-level objectives for DoE (candidates for RBP implementation) are: <ul style="list-style-type: none"> • maximize accomplishment of mission • minimize adverse effects upon public health and worker safety • minimize adverse effects upon the environment • maximize compliance with regulations • minimize adverse/maximize desirable socioeconomic impacts • maximize safeguards and security integrity • maximize cost effectiveness • maximize public trust and confidence • Statement of decision objectives (should specify the object of value, context, and direction of preference) • Statement of performance measures (e.g. health and safety, mission impact. Efficiency. Societal impact, environmental impact) • Risk measures: the following parameters should be considered:

Characteristic	Guidelines
	<ul style="list-style-type: none"> • Relevant hazards • Likelihood and severity • Timing and duration • Treatment of uncertainty: RBP should include a means to address uncertainties in the prioritization results. 4 aspects of uncertainty in prioritization are: <ul style="list-style-type: none"> • Variability and uncertainty • Types of uncertainty • Assessing the impact of uncertainty using: <ul style="list-style-type: none"> • Sensitivity analysis • Uncertainty analysis • Developing data and information about uncertainties • Development of performance measurement scales (each performance measure should reflect either a benefit increase or a benefit decrease)
Accuracy	<ul style="list-style-type: none"> • Establishment of baseline • Establishing decision options • Aggregating performance measures • Consistency in scoring <ul style="list-style-type: none"> • Scoring teams • Judgment and biases • Facilitator • Training of participants
Acceptability	<ul style="list-style-type: none"> • Establishing weights and other value parameters (e.g. using swing weights as a ratio-scaled weights) • Fairness • Stakeholder involvement
Practicality	<ul style="list-style-type: none"> • Timeliness • Flexibility • Applicability • Adaptability • Graded Approach (i.e. to recognize that only in unusual circumstances will it be necessary to rigorously implement all of the guidelines)
Effectiveness	<ul style="list-style-type: none"> • Decision options definition (e.g. decision options might be specified as “yes-or-no decisions for all independent, separately costed activities proposed in the coming year.) • Decision options size (activities should not be defined so large as to provide insufficient advice for fine-tuning decision making, nor should they be so small and detailed that they force an overly burdensome and costly evaluation. • Cardinal measure of preference (i.e. performance measures should not produce and ordinal measure of preference)
Defensibility	<ul style="list-style-type: none"> • Qualification of participants • Level of detail • Defining acceptance criteria • Assuring quality • Documentation to support decision makers and to promote communication
Quantification of Costs and Benefits	<ul style="list-style-type: none"> • Units of value (see MAUT below) • Ranking decision options

B1.1. DoE Guidelines for the use of Multi-Attribute Utility Theory (MAUT)

These guidelines (DOE 1998) place a greater emphasis on Multi-Attribute Utility Theory (MAUT) as a tool for decision making in RBP. The reason for the greater emphasis is stated as “providing rigorous, sound, and demonstrated ways to combine quantitatively dissimilar measures of costs, risks, and benefits, along with decision maker preferences, into high-level, aggregated measures that can be used to evaluate alternatives.” The goals of MAUT are summarized as “to provide a defensible framework for identifying, organizing, and displaying information needed to support complex policy issues and/or technical decisions; deriving logical implications of such information; and providing insights and

recommendations for decision making.” The benefit of using MAUT is stated as: “ MAUT allows full aggregation of performance measures into one single measure of value that can be used for ranking alternatives. MAUT techniques can provide a mechanism to facilitate constructive discussion and mediate potential conflict.” However also warns that “the results of a MAUT should not normally be used as the sole or principal basis for decision making” and that “it will always be necessary to take into account factors that cannot be readily quantified or monetized, for example factors like equity.” (Doe 1998, p.3-4)

RBP systems usually generate a composite value for each decision option that indicates the net effect of implementing that decision option, and in MAUT, this composite measure is termed the “utility” and is usually expressed in dollars. Utility represents a combination of associated costs and benefits. With the Executive Order 12866, the OMB encourages monetization and the “willingness to pay” as an aggregate measure of what individuals are willing to forgo to enjoy a particular benefit. Therefore the DoE adopted the approach for “value of statistical life” as the “willingness to pay for reductions in risks of premature deaths.”

B2. Federal Aviation Administration’s Guidelines for the Investment Analysis Team’s Alternatives Risk Assessment

These guidelines were developed originally by the Volpe National Transportation Systems Center of the Department of Transportation for the Federal Aviation Administration’s Investment Analysis and Operations Research Division in 1995 and further updated in 1998, 1999, 2002, and 2003. They prescribe a semi-structured risk assessment approach for the investment management team as well as the project management team to follow throughout the entire life cycle of the acquisition program. It describes a process to assess the Risk evaluation factor for each alternative. FAA defines risk as the probability of an undesirable event occurring combined with the consequence of occurrence. The life cycle risk assessment refers to the assessment of the probability that an alternative will fail to deliver the projected benefits and consequences of such a failure. The guidelines thus consider the risks associated with the design, development, implementation, and operation phases of an alternative. The life cycle risks are broken down into 13 components as: technical; operability; producibility; supportability; benefit estimate; cost estimate; schedule; management; funding; stakeholder; information security; human factors; and safety. The idea behind this is that all 13 risk facets are thought to ultimately affect the successful completion and implementation of any alternative and, hence affect the final benefits and cost.

The significance of these guidelines is that they try to detect and reduce risks early to avoid greater cost of risk consequences later in the life cycle. FAA’s Acquisition Management System applies throughout the following phases of a program: 1) mission analysis; 2) investment analysis; 3) program implementation; and 4) in-service management. The guidelines address the risk issues associated with each phase of the life cycle of a program within the body of the FAA.

First, during the mission analysis phase, the risk management basically deals with identifying and characterizing risks to the FAA’s ability to execute its legislated responsibilities and satisfying customer demands for service. Typically, these risks arise from changes in the operational environment and shortfalls in operational capability. During this phase, risks associated with candidate solutions are identified, money and time are recommended to be included for each candidate solution in the acquisition program baseline (APB) to mitigate risk and achieve program success. Newly the Air Traffic Systems begun to explore *Portfolio management approach* for selecting among many candidate solutions.

Second, after the mission phase is complete, for the investment analysis phase, the guidelines suggest ensuring that primary risks associated with candidate solutions are fully identified and evaluated. It is recommended that sufficient money and time be included for each candidate solution in the APB to mitigate risk and achieve program success. Discussion with program staff, users, stakeholders, security, human factors, and safety helps identify risks and mitigation options. The investment analysis team formulates estimates of likelihood of the issue, severity and preliminary mitigations by techniques such as double-blind voting and justification discussions with stakeholders, investment and program analysts, and union reps. At the end of these discussions, least risk alternative emerges. The analysis team then coordinates with the cost, benefit, and other analysts to link the impact of the risks and their mitigation on the cost and/or the benefit estimate of the recommended alternative. This impact contributes to developing ranges around the most likely cost or benefit element in the respective Work Breakdown Structure (WBS). Details are recorded on a Risk Issues (Checklist) Database. Then the life cycle risks of preferred alternatives are funneled into 4 baseline parameters: 1) cost, 2) benefits, 3) schedule, and 4) performance. Investment Analysis Team's life cycle risk assessment involves the following: Technical description of each risk; likelihood of occurrence¹²; consequence of occurrence¹³; quantification¹⁴ of the impact on 4 baseline categories (cost, schedule, benefit, and performance); reasons for expected change and estimated funding need using Subject Matter Experts (SMEs); and matching the type of risk with functional responsibility of the organization within FAA. The guidelines suggest medium and high risk levels be identified and mitigation actions be implemented with milestones. The guidelines suggest that the rating scheme for risk should be simple (high, medium, and low), and using expert interviews, analogy comparisons, evaluation of program plans, and Delphi methods to estimate the probability of occurrence and severity of impact.

Thirdly, when the program implementation phase begins, a *programmatic risk assessment approach* is suggested to be adapted. A Risk Management Plan or Risk Planning Section is developed and Risk Mitigation Plans are documented and updated throughout the entire program implementation and in-service phase.

¹² A qualitative measure: Level A-not likely, B-low likelihood, C- likely, D- Highly Likely, E- Near Certainty

¹³ qualitative measures given as Level 1, 2, 3, 4, and 5, to a 5-scale measure Consequence Levels

¹⁴ Quantitative analysis is implemented by the risk lead and involves combining risk facet prioritizations and risk scores to develop a single score for each alternative. It requires documentation of differences and logic behind preferred alternative (Risk Assessment for Investment Analysis, 2003, p.4-32)

Appendix C – List of Acronyms

AHP	Analytical Hierarchy Process
ALARP	As Low As Reasonably Practicable
ANCOLD	Australian Committee on Large Dams
ANP	Apparent No Pass
AP	Apparent Pass
ASCE	American Society of Civil Engineers
ASD	Adversary Sequence Diagrams
ASDSO	Association of Dam Safety Officials
B.C. Hydro	British Columbia Hydro and Power Authority
BCUC	British Columbia Utilities Commission
BOR	Bureau of Reclamation
CCFA	Common Cause Failure Analysis
CI	Condition Index
CIP	Critical Infrastructure Protection
CPSLS	Cost Per Statistical Life Saved
CRA	Coarse Risk Analysis
DOE	Department of Energy
DOI	Department of Interior
EPRI	Electric Power Research Institute
ETA	Event Tree Analysis
FEMA	Federal Emergency Management Agency
FERC	Federal Energy Regulatory Commission
FMCEA	Failure Modes, Effects, and Criticality Analysis
FMEA	Failure Modes and Events Analysis
FTA	Fault Tree Analysis
ICODS	Inter-agency Committee on Dam Safety
IFIP	Interagency Forum for Infrastructure Protection
IRP	Integrated Resource Planning
MAUT	Multi Attribute Utility Theory
MCDM	Multiple Criteria Decision Making
NID	National Inventory of Dams
NP	No Pass
O&M	Operations and Maintenance
OH&S	Occupational Health and Safety
OMB	Office of Management and Budget
OST	Office of Science and Technology
P	Pass
PAR	Populations at Risk
PCNA	Pacific Northwest Coordination Agreement
PRA	Portfolio Risk Assessment
PrHA	Preliminary Hazards Analysis
RAM-D	Risk Assessment Methodology for Dams
RBPS	Risk Based Prioritization System
REMR	Repair, Evaluation, Maintenance, and Rehabilitation
RRMs	Risk Reduction Measures
SCUPS	Separable Construction Upgrade Packages
SME	Subject Matter Expert
SWT	Surrogate worth Trade off method
TPR	Technical Priority rating

USACE
USBR
USSD

United States Army Corps of Engineers
United States Bureau of Reclamation
United States Society On Dams