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# MULTI-CRITERIA DECISION ANALYSIS: A FRAMEWORK FOR MANAGING CONTAMINATED SEDIMENTS

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**Abstract**

Decision-making in environmental projects can be complex and seemingly intractable, principally due to the inherent existence of tradeoffs between sociopolitical, environmental, and economic factors. One tool that has been used to support environmental decision-making is comparative risk assessment (CRA). Central to CRA is the construction of a two-dimensional decision matrix that contains project alternatives' scores on various criteria. The projects are then evaluated by either qualitatively comparing the projects' scores on the different criteria or by somehow quantitatively aggregating the criterion scores for each project and comparing the aggregate scores. Although CRA is laudable in its attempts to evaluate projects using multiple criteria, it has at least one significant drawback. That drawback is the unclear or unsupported way in which it combines performance on criteria to arrive at an optimal project alternative. In the case of qualitative comparison of project scores using CRA, it can be unclear why an alternative is chosen if it performs better only on some criteria compared to another alternative. Quantitative CRAs are often unsupported in how they determine the relative importance of each criterion in determining an aggregate score for each alternative.

Multicriteria decision analysis (MCDA) not only provides better-supported techniques for the comparison of project alternatives based on decision matrices but also has the added ability of being able to provide structured methods for the incorporation of project stakeholders' opinions into the ranking of alternatives. In this paper, we provide a brief overview of common MCDA techniques and their use in regulatory

agencies in the USA and EU. Then, we discuss existing literature in which MCDA techniques have been applied to decision-making involving aquatic ecosystems including decisions related to the remediation of contaminated sediments. Finally, we develop a straw man decision analytic framework specifically tailored to deal with decision-making related to contaminated sediments.

## 1. Current and Evolving Decision Analysis Methodologies

Environmental decisions are often multi-faceted, involving many different stakeholders with different priorities and objectives. These decisions present exactly the type of problem that behavioral decision research has shown humans are poorly equipped to solve unaided. Most people, when confronted with such problems, will attempt to use intuitive or heuristic approaches to simplify the complexity until the problem seems more manageable. In the process, important information may be lost, opposing points of view may be discarded, and elements of uncertainty may be ignored. In short, there are many reasons to expect that, on their own, individuals — including experts — will often experience difficulty making informed, thoughtful choices in a complex decision-making environment involving value tradeoffs and uncertainty (McDaniels et al., 1999).

Moreover, environmental decisions typically draw upon multidisciplinary knowledge incorporating the natural, physical, and social sciences, medicine, politics, and ethics. This fact and the tendency of environmental issues to involve shared resources and broad constituencies mean that *group* decision processes are often necessary. These may have some advantages over individual processes: more perspectives may be put forward for consideration, the probability of benefiting from the presence of natural systematic thinkers is higher, and groups often learn to rely upon more deliberative, well-informed members. However, groups are also susceptible to the tendency to establish entrenched positions (defeating compromise solutions) or to prematurely adopt a common perspective that excludes contrary information, a tendency termed "group think" (McDaniels et al., 1999).

For environmental management projects, decision makers may receive input classifiable into four broad categories: 1) the results of modeling/monitoring studies, 2) risk analysis, 3) cost or cost-benefit analysis, and 4) stakeholder preferences (Figure 1a). However, decision techniques currently in use typically offer little guidance on how to integrate or judge the relative importance of information from the categories. Some types of information — modeling and monitoring results — do not depend on much qualitative judgement, others — risk assessment and cost-benefit analyses — may incorporate a higher degree of qualitative judgment, while others — stakeholder opinions or concerns — may be presented in solely qualitative terms. Structured information about stakeholder preferences may not be presented to the decision maker at all. In cases where the decision maker does receive information on stakeholder preferences, the information may be handled in an *ad hoc* or subjective manner that exacerbates the difficulty of defending the decision process as reliable and fair.

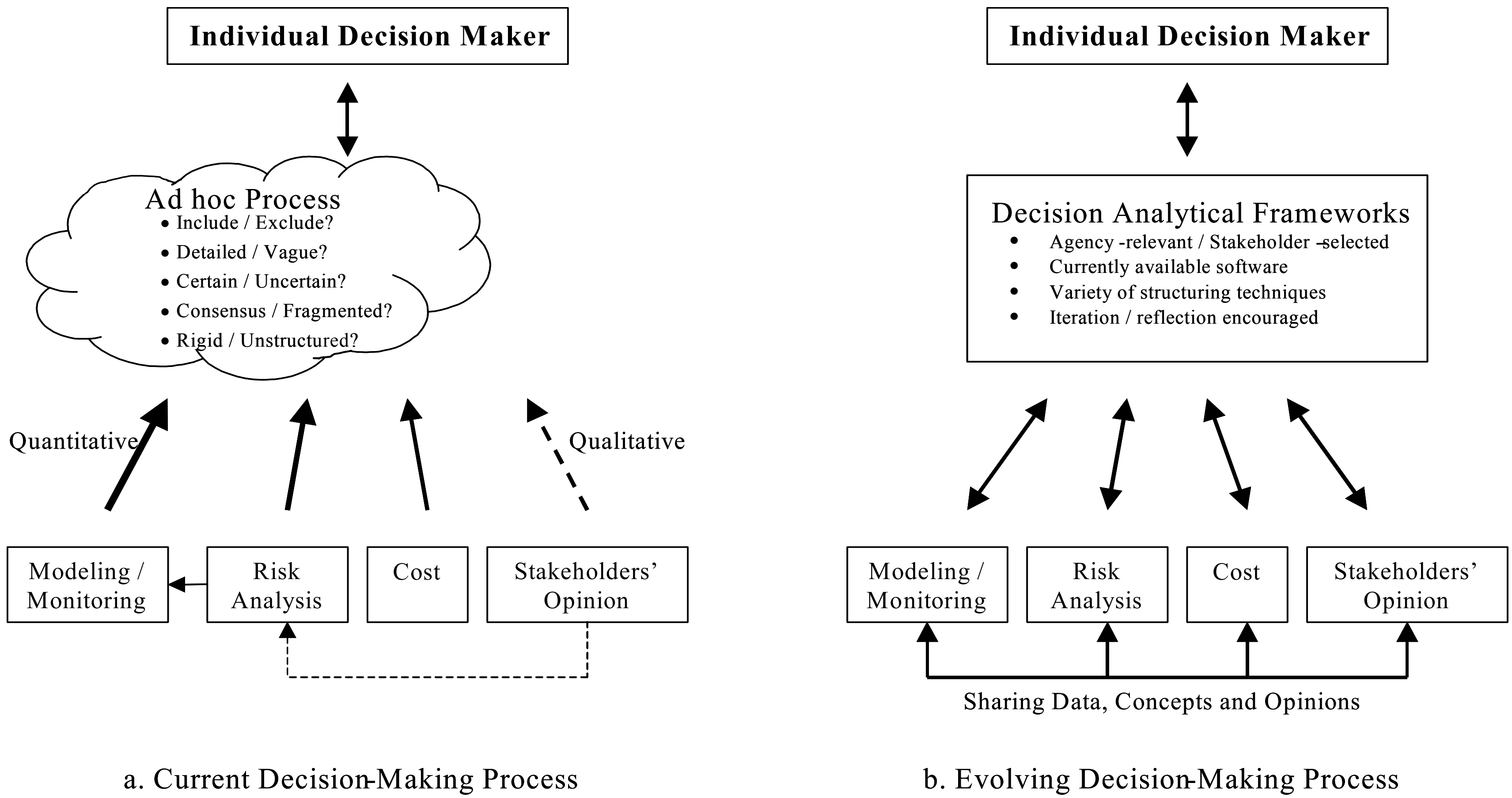


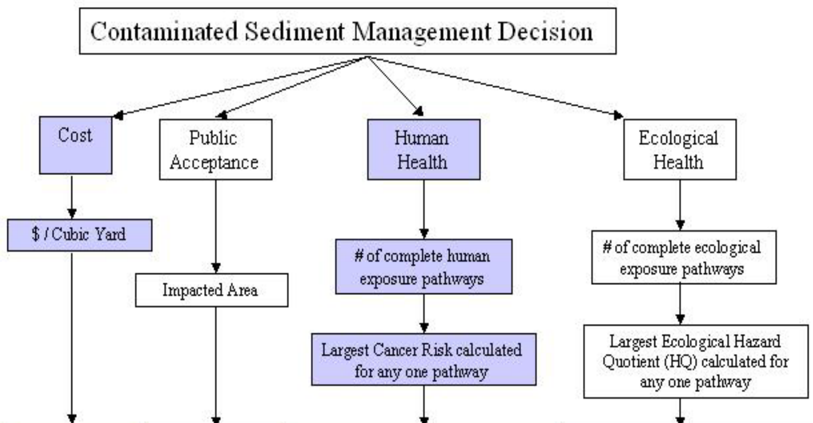

Figure 1: Current and evolving decision -making processes for contaminated sediment management.

Moreover, where structured approaches to combining the four categories of information *are* employed, they may be perceived as lacking the flexibility to adapt to localized concerns or faithfully represent minority viewpoints. A systematic methodology to combine quantitative and qualitative inputs from scientific studies of risk, cost and benefit analyses, and stakeholder views to rank project alternatives has yet to be fully developed for environmental decision making. As a result, decision makers often do not optimally use all available and necessary information in choosing between identified project alternatives.

In response to these decision-making challenges, this paper reviews the efforts of several government agencies and individual scientists to implement new concepts in decision analysis for complex environmental projects. The decision analytic approaches reviewed here are applicable to a range of environmental projects, but subsequent discussion focuses on decision making involving contaminated sediments and aquatic ecosystems. Recent literature on environmental applications of multi-criteria decision theory and regulatory guidance developed by US and international agencies is summarized, and the general trends in the field are reflected in Figure 1b. MCDA tools can be applied to assess value judgments of individual decision makers or multiple stakeholders. For individuals, risk-based decision analysis quantifies value judgments, scores different project alternatives on the criteria of interest, and facilitates selection of a preferred course of action. For group problems, the process of quantifying stakeholder preferences may be more intensive, often incorporating aspects of group decision-making. One of the advantages of an MCDA approach in group decisions is the capacity for calling attention to similarities or potential areas of conflict between stakeholders with different views, which results in a more complete understanding of the values held by others.

## 2. MCDA Methods and Tools

Figure 2 illustrates decision dilemmas for a contaminated sediment management project discussed in Driscoll *et al.* (2002). The decision-makers seek to select a management alternative that minimizes human health and ecological risks, minimizes cost, and maximizes public acceptance. Three remediation alternatives (A, B and C) are identified for consideration by stakeholders and/or the project team. Criteria are established to aid decision-makers in judging the relative strengths of the alternatives. To evaluate ecological risk, two criteria are selected: the number of complete exposure pathways and the maximum calculated hazard quotient from all the pathways. To evaluate human health risk, two similar criteria are selected: the number of complete human exposure pathways and the maximum cancer risk calculated from all the pathways. The cost in dollars per cubic yard of sediment is used as a cost criterion. The impacted area (*i.e.* the amount of land required to manage the sediment) is used as a measure of public acceptance. Quantitative estimates for these criteria are developed through research, monitoring, and survey studies or through expert judgment elicitation. The resulting data are used to parameterize the decision matrix depicted in Figure 2.




| | Cost | Public Acceptance | Human Health | | Ecological Health | |
|---|---|---|---|---|---|---|
| | $ / CY | Acres | pathways | Max. Cancer Risk | Pathways | Max. HQ |
| Choice A | 20 | 1000 | 24 | $1.0 * 10^{-3}$ | 38 | 1800 |
| Choice B | 40 | 200 | 18 | $1.0 * 10^{-4}$ | 23 | 1500 |
| Choice C | 60 | 5 | 12 | $1.0 * 10^{-6}$ | 14 | 10 |

*Figure 2: Example decision criteria and matrix.*

A decision matrix in a form similar to Figure 2 is usually the final product of feasibility studies for Superfund projects or similar investigations. Decisions are typically based on an informal, *ad hoc* comparison of the alternatives. MCDA methods have evolved as a response to the observed inability of people to effectively analyze multiple streams of dissimilar information. There are many different MCDA methods and a detailed analysis of the theoretical foundations of these methods and their comparative strengths and weaknesses is presented in Belton and Stewart (2002). The common purpose of MCDA methods is to evaluate and choose among alternatives based on multiple criteria using systematic analysis that overcomes the limitations of unstructured individual or group decision-making.

Almost all decision analysis methodologies share similar steps of organization in the construction of the decision matrix. Each MCDA methodology synthesizes the matrix information and ranks the alternatives by different means (Yoe, 2002). Different methods require diverse types of value information and follow various optimization algorithms. Some techniques rank options, some identify a single optimal alternative, some provide an incomplete ranking, and others differentiate between acceptable and unacceptable alternatives.

Within MCDA, elementary methods can be used to reduce complex problems to a singular basis for selection of a preferred alternative. However, these methods do not necessarily to weight the relative importance of criteria and combine the criteria to produce an aggregate score for each alternative. For example, an elementary goal aspiration approach may rank the dredging alternatives in relation to the total number of performance thresholds met or exceeded. While elementary approaches are simple and can, in most cases, be executed without the help of computer software, these methods are best suited for single-decision maker problems with few alternatives and criteria, a condition that is rarely characteristic of environmental projects.

Multi-attribute utility theory (MAUT), also known as multi-attribute value theory (MAVT), and the analytical hierarchy process (AHP) are more complex methods that use optimization algorithms. They employ numerical scores to communicate the merit of each option on a single scale. Scores are developed from the performance of alternatives with respect to individual criteria and then aggregated into an overall score. Individual scores may be simply summed or averaged, or a weighting mechanism can be used to favor some criteria more heavily than others. The goal of MAUT/MAVT is to find a simple expression for decision-makers' preferences. Through the use of utility/value functions, the MAUT method transforms diverse criteria, such as those shown in Figure 2 into one common dimensionless scale of utility or value. MAUT relies on the assumptions that the decision-maker is rational (preferring more utility to less utility, for example), that the decision-maker has perfect knowledge, and that the decision-maker is consistent in his judgments. The goal of decision-makers in this process is to maximize utility/value. Because poor scores on criteria can be compensated for by high scores on other criteria, MAUT is part of a group of MCDA techniques known as "compensatory" methods.

Similar to MAUT, AHP completely aggregates various facets of the decision problem into a function which determines how good a solution is(objective function). The goal is to select the alternative that results in the greatest value of the objective function. Like MAUT, AHP is a compensatory optimization approach. However, AHP uses a quantitative comparison method that is based on pair-wise comparisons of decision criteria, rather than utility and weighting functions. All individual criteria must be paired against all others and the results compiled in matrix form. For example, in examining the choices in the remediation of contaminated sediments, the AHP method would require the decision-maker to answer questions such as, "With respect to the selection of a sediment alternative, which is more important, public acceptability or cost?" The user uses a numerical scale to compare the choices and the AHP method moves systematically through all pair-wise comparisons of criteria and alternatives. The AHP technique thus relies on the supposition that humans are more capable of making relative judgments than absolute judgments. Consequently, the rationality assumption in AHP is more relaxed than in MAUT.

Unlike MAUT and AHP, outranking is based on the principle that one alternative may have a degree of *dominance* over another (Kangas et al., 2001). Dominance occurs when one option performs better than another on at least one criterion and no worse than the other on all criteria (ODPM, 2004). However, outranking techniques do not presuppose that a single best alternative can be identified. Outranking models compare the performance of two (or more) alternatives at a time, initially in terms of each criterion, to identify the extent to which a preference for one over the other can be asserted. The criteria are not necessarily compared on a single scale. Outranking techniques then aggregate the preference information across all relevant criteria and seek to establish the strength of evidence favoring selection of one alternative over another. For example, an outranking technique may entail favoring the alternative that performs the best on the greatest number of criteria. Thus, outranking techniques allow inferior performance on some criteria to be compensated for by superior performance on others. They do not necessarily, however, take into account the magnitude of relative underperformance in a criterion versus the magnitude of over-performance in another criterion. Therefore, outranking models are known as "partially compensatory." Outranking techniques are most appropriate when criteria metrics are not easily aggregated, measurement scales vary over wide ranges, and units are incommensurate or incomparable.

## 3. Governmental/Regulatory Uses of MCDA

Decision process implementation is often based on the results of physical modeling and engineering optimization schemes. Even though federal agencies are required to consider social and political factors, the typical decision analysis process does not provide specifically for explicit consideration of such issues. Comparatively little effort is applied to engaging and understanding stakeholder perspectives or to providing for potential learning among stakeholders. One result of this weakness in current and common decision models is that the process tends to quickly become adversarial where there is little incentive to understand multiple perspectives or to share information. However, our review of regulatory and guidance documents revealed several programs where agencies are beginning to implement formal decision analytical tools (such as multi-criteria decision analysis) in environmental decision-making.

### 3.1. U.S. ARMY CORPS OF ENGINEERS

Historically, the U.S. Army Corps of Engineers has used essentially a single measure approach to civil-works, planning decisions through its Principles and Guidelines (P&G) framework (USACE, 1983). The Corps has primarily used net National Economic Development (NED) benefits as the single measure to choose among different alternatives. The P&G method makes use of a complex analysis of each alternative to determine the benefits and costs in terms of dollars and other non-dollar measures (environmental quality, safety, *etc.*); the alternative with the highest net NED benefit (with no environmental degradation) is usually selected. The USACE uses a variety of mechanistic/deterministic fate and transport models to provide information in quantifying the various economic development and ecological restoration accounting requirements as dictated by P&G procedures. The level of complexity and scope addressed by these models is determined at the project level by a planning team. Issues such as uncertainty and risk are also addressed through formulation at the individual project management level.

While the P&G method is not specifically required for planning efforts related to military installation operation and maintenance, regulatory actions, or operational and maintenance dredging, it is a decision approach that influences many USACE decisions. The USACE planning approach is essentially a mono-criterion approach, where a decision is based on a comparison of alternatives using one or two factors (Cost Benefit Analysis, as commonly used, is an example of a mono-criterion approach). The P&G approach has its challenges in that knowledge of the costs, benefits, impacts, and interactions is rarely precisely known. This approach is limiting and may not always lead to an alternative or decision process satisfactory to key stakeholders.

In response to a USACE request for a review of P&G planning procedures, the National Research Council (1999) provided recommendations for streamlining planning processes, revising P&G guidelines, analyzing cost-sharing requirements, and estimating the effects of risk and uncertainty integration in the planning process. As an integration mechanism, the National Research Council (1999) review recommended that further decision analysis tools be implemented to aid in the comparison and quantification of environmental benefits from restoration, flood damage reduction, and navigation projects. In addition, new USACE initiatives such as the Environmental Operating Principles within USACE civil works planning have dictated that projects adhere to a concept of environmental sustainability that is defined as "a synergistic process whereby environmental and economic considerations are effectively balanced through the life of project planning, design, construction, operation, and maintenance to improve the quality of life for present and future generations" (USACE 2003a, p. 5). In addition, revised planning procedures have been proposed to formulate more sustainable options through "combined" economic development/ecosystem restoration plans (USACE, 2003b). While still adhering to the overall P&G methodology, USACE (2003b) advises project delivery teams to formulate acceptable, combined economic development and ecosystem restoration alternatives through a multi-criteria/trade-off methodology (Males, 2002). Despite the existence of new guidance and revisions on the application of MCDA techniques to environmental projects, there remains a need for a systematic strategy to implement these methods within specific USACE mission areas (navigation, restoration) as well as linkage with existing risk analysis and adaptive management procedures.

### 3.2. U.S. Environmental Protection Agency

Stahl (2002, 2003) has recently reviewed the decision analysis process in U.S. Environmental Protection Agency (EPA) and observed that EPA could improve its decision processes to more effectively encourage stakeholder participation, integration of perspectives, learning about new alternatives, and consensus building. According to Stahl, the decision-framing process usually conforms to EPA's mission but does not always recognize different stakeholder perspectives. The problem formulation process may be influenced explicitly and implicitly by political factors which create a barrier to the integration of physical science concerns and relevant social science concerns. Stahl concludes that this approach can compromise the cohesive analysis of human and ecological impacts of a project and may result in decisions unfairly supportive of the interests of some stakeholders at the expense of others.

Similar to the USACE, the EPA uses a variety of modeling tools to support its current decision-making processes. The majority of these tools are "quantitative multimedia systems that assess benefits and risks associated with each proposed alternative with the objective of selecting the "best option" " (Stahl, 2003). Our review has identified several EPA guidance documents that introduce decision-analytical tools and recommend their use. Multi-criteria Integrated Resource Assessment (MIRA) is being proposed as an alternative framework to existing decision analytic approaches at the U.S. EPA (Stahl et al., 2002, Stahl, 2003, USEPA, 2002). MIRA is a process that directs stakeholders to organize scientific data and establishes links between the results produced by the research community and applications in the regulatory community. MIRA also encompasses a tool that utilizes AHP-based tradeoff analysis to determine the relative importance of decision criteria. MIRA was developed by EPA Region 3's Air Protection Division as an effort to link its decisions to environmental impacts.

Multi-attribute product evaluation is inherent in the nature of Life Cycle Assessment (LCA) that has been rapidly emerging as a tool to analyze and assess the environmental impacts associated with a product, process, or service (Miettinen and Hamalainen, 1997; Seppala *et al.* 2002). The EPA developed the *Framework for Responsible Environmental Decision-Making* (FRED) to assist the Agency's Office of Pollution Prevention and Toxics in their development of guidelines for promoting the use of environmentally preferable products and services (USEPA, 2000). The FRED decision-making method provides a foundation for linking life cycle indicator results with technical and economic factors for decision-makers when quantifying the environmental performance of competing products.

### 3.3. U.S. Department of Energy

Similar to the USACE and USEPA, the U.S. Department of Energy (DOE) uses a variety of models to support its decision-making process. A recent review (Corporate Project 7 Team, 2003) concluded that even though there are a significant number of guidance documents, systems, and processes in use within the DOE to determine, manage, and communicate risk, there is a great need for comparative risk assessment tools, risk management decision trees, and risk communication tools that allow site managers to reach agreement with their regulators and other stakeholders while achieving mutual understanding of the relationship between risk parameters, regulatory constraints, and cleanup. Because of DOE mandates, many DOE models are developed specifically for dealing with radiologically contaminated sites and sites with dual (chemical and radiological) contamination. Many models are deterministic, although probabilistic models are also used (U.S. DOE, 2003).

Our review has identified several guidance documents produced by DOE that introduce decision-analytical tools and recommend their use. Generic guidance developed for a wide variety of DOE decision needs (Baker *et al.*, 2001), breaks the decision process into eight sequential steps: 1) defining the problem, 2) determining the requirements, 3) establishing the goals of the project, 4) identifying alternative methods or products, 5) defining the criteria of concern, 6) selecting an appropriate decision-making tool for the particular situation, 7) evaluating the alternatives against the criteria, and 8) finally validating the solution or solutions against the problem statement. This guidance then focuses on how to select a decision-making tool — it recommends five evaluation methods and analyzes them. These methods are: 1) pros and cons analysis, 2) Kepner-Tregoe (K-T) decision analysis, 3) analytical hierarchy process, 4) multi-attribute utility theory , and 5) cost-benefit analysis.

The DOE produced a standard for selecting or developing a risk-based prioritization (RBP) system, entitled "Guidelines for Risk-Based Prioritization of DOE Activities", in April 1998. The standard describes issues that should be considered when comparing, selecting, or implementing RBP systems. It also discusses characteristics that should be used in evaluating the quality of an RBP system and its associated results. DOE (1998) recommends the use of MAUT as an RBP model since it is a flexible, quantitative decision analysis technique and management tool for clearly documenting the advantages and disadvantages of policy choices in a structured framework. MAUT merits special consideration because it provides sound 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. MAUT allows full aggregation of performance measures into one single measure of value that can be used for ranking alternatives. However, DOE (1998) cautions that the results of MAUT analysis should not normally be used as the principal basis for decision-making, as decision making will generally require taking into account factors that cannot be readily quantified, e.g. equity. Furthermore, the guidance states that no technique can eliminate the need to rely heavily on sound knowledge, data, and judgments or the need for a critical appraisal of results.

The DOE used a multi-attribute model as the core of its Environmental Restoration Priority System (ERPS) for prioritizing restoration projects developed in the late 1980's (Jenni et al., 1995). Although ERPS was designed to operate with any specified set of values and trade-offs, its use was limited to values that were elicited from DOE managers, including values based on risk analysis. DOE headquarters decided not to apply ERPS because of stakeholder opposition, although similar decision support systems have since been adopted for use at various DOE sites (CRESP, 1999). DOE has also attempted to use simple weighting to aid program planning and budget formulation processes (CRESP, 1999).

### 3.4. EUROPEAN UNION

A detailed review of the regulatory background and use of decision analytical tools in the European Union was recently conducted within the EU-sponsored Contaminated Land Rehabilitation Network for Environmental Technologies project (CLARINET) (Bardos *et al.*, 2002). The review found that environmental risk assessment, cost-benefit analysis, life cycle assessment, and multi-criteria decision analysis were the principal analytical tools used to support environmental decision-making for contaminated land management in sixteen EU countries (Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, and the United Kingdom). Similar to the U.S., quantitative methods like ERA and CBA are presently the dominant decision support approaches in use while MCDA and explicit tradeoffs are used less frequently.

Pereira and Quintana (2002) reviewed the evolution of decision support systems for environmental applications developed by the EU Joint Research Center (JRC). The concept of environmental decision support has evolved from highly technocratic systems aimed at improving understanding of technical issues by individual decision makers to a platform for helping all parties involved in a decision process engage in meaningful debate. Applications developed in the group include water resources management, siting of waste disposal plants, hazardous substance transportation, urban transportation, environmental management, and groundwater management

## 4. MCDA Applications in the Management of Contaminated Sediments and Related Areas

Our non-exhaustive review of recent literature shows that MCDA has been used to support decision-making related to contaminated sediment management and related applications in aquatic ecosystem management. We summarize in this section decision analysis applications published in English language journals over the last 10 years that were located through Internet and library database searches. Each identified article is classified based on whether it depends solely on technical data and expert evaluations or whether it incorporates stakeholder preferences. The articles are summarized in Tables 1 and 2.

### 4.1. APPLICATIONS OF MCDA BASED SOLELY ON TECHNICAL CRITERIA AND EXPERT EVALUTATIONS

MCDA techniques based solely on technical criteria and expert evaluations have been applied to optimize policy selection in the remediation of contaminated sediments and aquatic ecosystems, the reduction of contaminants entering ecosystems, the optimization of water and coastal resource management, and the management of fisheries (Table 1).

Table 1 MCDA applications based solely on technical criteria and expert evaluations

| Application Area | Method | Decision Context | Funding Agency | Citation |
|---|---|---|---|---|
| Remediation of contaminated sediments and aquatic ecosystems | Risk-cost trade-off analysis, fuzzy set theory, composite programming | Disposal of dredged materials | USACE and University of Nebraska | Stansbury *et al.*, 1999 |
| | Risk-cost trade-off analysis | Disposal of dredged materials | URS Greiner Inc.; University of Nebraska-Lincoln | Pavlou and Stansbury, 1998 |
| | SMART | Choosing a remedial action alternative at Superfund Site | USACE | Wakeman, 2003 |
| | MAUT | Remediation of aquatic ecosystems contaminated by radionuclides using MOIRA | EC projects | Rios-Insua *et al.*, 2002; Gallego, 2004 |
| | MAUT | Remediation of mixed-waste subsurface disposal site | DOE | Grelk, 1997; Grelk, 1998; Parnell *et al.*, 2001 |
| Reduction of contaminants introduced into aquatic ecosystems | Cost-effectiveness analysis | Optimizing method to reduce nitrogen discharge to the Potomac River by 40% | SAIC | Doley *et al.*, 2001 |
| | Cost-benefit analysis | Protection of groundwater through choosing from among various alternatives for reducing sulfur dioxide, nitrogen oxides, and ammonia airborne emissions | Environment and Climate Program, European Union | Wladis *et al.*, 1999 |
| | MAUT | Wastewater planning management. | Agricultural University of Tehran, Iran | Kholgi, 2001 |
| | Outranking (ELECTRE), distance (compromise programming) | Wastewater recycling and reuse in the Mediterranean | Aristotle University, Greece | Ganoulis, 2003 |
| Optimization of water and coastal resources | Outranking (PROMETHEE-I, II; GAIA; MCQA-I, II, III), distance (compromise programming; cooperative game theory) | Pick optimal use of Danube region between Vienna and Slovakian border from choices like hydroelectric station and a national park | NSF and USACE | Ozelkan and Duckstein, 1996 |

| Application Area | Method | Decision Context | Funding Agency | Citation |
|---|---|---|---|---|
| | Distance (compromise programming) and outranking (ELECTRE III) | Water allocation in the Upper Rio Grande | USACE, NSF, US-Hungarian Joint Research and Technology Fund | Bella *et al.*, 1996 |
| | Distance | Allocating waters of Jordan River basin to bordering nations | Birzeit University, Palestine | Mimi and Sawalhi, 2003 |
| | MAUT | Consideration expansion of water supply to Cape Town, South Africa, at the expense of regional mountain flora | University of Cape Town | Joubert *et al.*, 1997 |
| | MAUT | Selection of management alternative Missouri River | University of Missouri-Columbia | Prato, 2003 |
| | AHP, sensitivity analysis, MAUT | Optimizing the extent and location of a reclaimed coastline | Chinese government, John Swire and Sons, University College Oxford | Ni *et al.*, 2002; Qin *et al.*, 2002 |
| | MAUT | Designing a water quality monitoring network for a river system | National Cheng-Kung University, Taiwan | Ning and Chang, 2002 |
| Fishery management | AHP | Determining how to allocate funds for research into fisheries | Alaska Department of Fish and Game | Merritt, 2001 |
| | MAUT | Fisheries management | Fisheries and Oceans Canada | McDaniels, 1995 |
| | Fuzzy set theory and if-then rules | Analyzing plan to increase salmon population in Columbia River | Washington State University | Gurocak and Whittlesey, 1998 |
| | MAUT | Estimating fishery fleet size for the North Sea | EU | Mardle and Pascoe, 2002 |

Table 2 MCDA applications with stakeholder involvement

| Application Area | Method | Application Format | Decision Context | Funding Agency | Citation |
|---|---|---|---|---|---|
| Remediation of contaminated sites | Outranking (PROMETHEE) | Interviews and surveys | Selecting novel technological alternatives for sediment management | Dartmouth College and the University of New Hampshire | Rogers *et al.*, 2004 |
| | MAUT | Individual surveys | Identifying radioactive waste cleanup priorities at DOE sites | DOE/NSF | Arvai and Gregory, 2003 |
| | AHP, MAUT | Questionnaires | Ranking of remedial alternatives at hazardous waste sites | DOE | Apostolakis, 2001; Bonano, 2000; Accorsi *et al.*, 1999a&b |
| Reduction of contaminants introduced into aquatic ecosystems | Fuzzy outranking (NAIADE) | Interest groups | Choosing a sustainable wastewater treatment system in Surahammar, Sweden | Swedish Foundation for Strategic Environmental Research | van Moeffaert, 2003 |
| | Outranking (PROMETHEE) | Workshop | Prioritization of wastewater projects in Jordan | Staffordshire University, UK | Al Rashdan *et al.*, 1999 |
| | Elicitation of criteria from stakeholders | Surveys, meetings, interviews | Determing the effects of a proposed 30% reduction in nitrogen loading to the Neuse Estuary in North Carolina | University of North Carolina | Borsuk, 2001 |
| Optimization of water resources | Outranking (PROMETHEE) | Interviews, discussions, committees | Choosing the extent of groundwater protection versus economic development in an area of Elbe River in Germany | UFZ Center for Environmental Research, Germany | Klauer *et al.*, 2002 |
| | MAUT | Individual surveys | Water use planning | University of British Columbia, Compass Resource Management | Gregory and Failing, 2002 |
| | MAUT+AHP | Questionnaires, interviews, surveys | Regulation of water flow in a Lake-River system | Academy of Finland | Hamalainen *et al.*, 2001 |

| Application Area | Method | Application Format | Decision Context | Funding Agency | Citation |
|---|---|---|---|---|---|
| | AHP & MAUT/SMART | Interview | Environmental Impact Assessment of 2 water development projects on a Finnish river | Finnish Environmental Agency, Helsinki University of Technology | Marttunen and Hamalainen, 1995 |
| | MAUT | Small-group sessions | Consensus building for water resource management in Oregon | NSF, EPA, Carnegie Mellon University | Gregory and Wellman, 2001 |
| | Committee consensus | Stakeholder committee | Water management in British Columbia | B.C. Hydro, Social Sciences and Humanities Research Council of Canada, NSF | McDaniels *et al.*, 1999; Gregory *et al.*, 2001 |
| | Mental modeling | Individual surveys, workshop | Watershed management | EPA | Whitaker and Focht, 2001; Focht *et al.*, 1999 |
| Management of other resources | AHP | Interviews | Developing better management strategies for the Wonga Wetlands on the Murray River in Australia | La Trobe University, Australia | Herath, 2004 |
| | AHP | Survey | Managing a coral reef | East West Center and WWF The Netherlands | Fernandes *et al.*, 1999 |
| | Trade-off analysis | Focus groups, surveys, interviews | Choosing among four development scenarios in for the Buccoo Reef Marine Park in Tobago | UK Deparment for International Development | Brown *et al.*, 2001 |
| | AHP | Completed by individuals representing stakeholder groups | Analyzing priorities in fishery management | European Commission | Mardle *et al.*, 2004 |
| | AHP | Completed by individuals representing stakeholder groups | Fishery management in Trinidad and Tobago | Food and Agriculture Organization of the United Nations | Soma, 2003 |

4.1.1 Remediation of Contaminated Sediments and Aquatic Ecosystems Only a few papers have been written that directly apply MCDA techniques to the remediation of aquatic systems. In a series of papers (Gallego *et al.*, 2004; Rios-Insua *et al.*, 2002), Gallego, Rios-Insura, and colleagues describe and apply the MOIRA system for the analysis of remedial alternatives for lakes contaminated by radionuclides. MOIRA is a MAUT model tailored to take into consideration criteria — environmental, economic, and social — associated with radiological contamination. Wakeman (2003) uses the simple multiattribute rating technique (SMART) to analyze alternatives for dredging contaminated sediments at a Superfund site in Montana. Factors considered in the study include the availability of materials and services, the ability to construct alternatives, and reliability. Pavlou and Stansbury (1998) apply a formal analysis of the tradeoff between environmental risk reduction and cost to contaminated sediment disposal. They evaluate cost, risk reduction, and potential beneficial uses of fill materials associated with three alternative methods of sediment remediation. Stansbury *et al.* (1999) augment the use of risk-cost tradeoff analysis with fuzzy set theory and composite programming in another paper examining contaminated sediment management. The use of fuzzy set theory formalizes the treatment of uncertainty in the analysis, while composite programming is used to find the optimal remediation strategy.

Many contaminated aquatic sites are on the EPA National Priorities List and thus go through the Superfund cleanup process. Grelk (1997), Grelk *et al.* (1998), and Parnell *et al.* (2001) have developed a CERCLA-based decision analysis value model. The model incorporates five criteria — implementability; short-term effectiveness; long-term effectiveness; reduction of toxicity, mobility, or volume through treatment; and cost — that are further subdivided into a set of 21 measures. MAUT was used to determine weights associated with each individual measure. The model was used to perform analysis of remedial alternatives for a mixed-waste subsurface disposal site at Idaho National Environmental Engineering Laboratory (INEEL).

4.1.2 Reduction of Contaminants Introduced into Aquatic Ecosystems In addition to being used in the remediation of aquatic ecosystems, MCDA techniques have been used in attempts to reduce of the amount of pollution entering those ecosystems. Doley *et al.* (2001) use cost-effectiveness analysis to find an optimal way to reduce nitrogen discharge into the Potomac River. They couple a water quality model with an optimization model to assess the best way to reduce nitrogen discharges from various land use types. Wladis *et al.* (1999) evaluate alternative emission control scenarios for $NO_x$, $SO_2$, and $NH_3$, considering how these pollutants effect groundwater. Specifically, they use cost-benefit analysis to evaluate two emission control scenarios and their effects on aluminum and nitrate levels in groundwater. Kholgi (2001) and Ganoulis (2003) apply MCDA to decide how to manage waste water in North America and the Mediterranean, respectively. Kholgi uses MAUT to decide among alternatives, while Ganoulis illustrates the use of a distance technique through a case study.

4.1.3 Optimization of Water and Coastal Resources MCDA techniques have also been used to help balance the sometimes conflicting demands of environmental conservation and business development with regards to water allocation and coastal development. Analyses of water bodies in the United States (Bella *et al.*, 1996; Prato, 2003), Europe (Ozelkan and Duckstein, 1996), and South Africa (Joubert *et al.*, 1997) have examined various uses for water bodies such as consumption, recreation, conservation, and power generation.

A MAUT-based method was applied to compare current and alternative water control plans in the Missouri River (Prato, 2003). Structural modifications to the river have significantly altered its fish and wildlife habitat and thus have resulted in the need for careful ecosystem management. The following criteria were considered: flood control, hydropower, recreation, navigation, water supply, fish and wildlife, interior drainage, groundwater, and preservation of historic properties. The analysis supported the implementation of a modified plan that incorporates adaptive management, increased drought conservation measures, and changes in dam releases. Ni, Borthwick, and Qin in two papers (Ni *et al.*, 2002; Qin *et al.*, 2002) describe their use of AHP in determining the optimal length and location for a coastline reclamation project considering both developmental and environmental factors. In one of their studies, AHP is used to determine preference weights, while in the other study a specially developed questionnaire is used. The objectives are then optimized using the preference weights. Ning and Chang (2002) use MAUT to optimize the location of water quality monitors in a water quality monitoring system in Taiwan. Other MCDA methods (such as distance techniques like compromise programming and game theory) have also been used. For example, a study of the Jordan River (Mimi and Sawalhi, 2003) attempts to optimize the allocation of water from the river to countries that border it using a distance technique.

4.1.4 Fishery management Many studies have been completed using MCDA techniques to optimize fishery management. Most studies attempt to find an optimal level of fish use versus conservation. For example, McDaniels (1995) uses a MAUT approach to select among alternatives for a commercial fishery in the context of conflicting long-term objectives for salmon management. Similarly, Mardle and Pascoe (2002) use MAUT in fishery management while Gurocak and Whittlesey (1998) use a combination of fuzzy set theory and if-then rules. Merritt (2001) uses AHP to optimally allocate funds for research into fish stocks.

### 4.2 APPLICATIONS OF MCDA THAT INCORPORATE STAKEHOLDER VALUE JUDGEMENT

MCDA tools have been used to explicitly incorporate and sometimes quantify stakeholder values in deciding among cleanup and management alternatives (Table 2). These analyses have used a variety of techniques to elicit stakeholder opinion including focus groups, surveys, meetings, interviews, discussions, workshops, and questionnaires. The stakeholder opinions have then been integrated into numerous MCDA methods. Stakeholder values are often considered as one attribute among many such as costs and risk reduction. In addition to having the advantage of providing decision-makers with stakeholder input, MCDA can also have the benefit of providing a framework that permits stakeholders to structure their thoughts about the pros and cons of different remedial and environmental management options. Often, MCDA applications incorporating stakeholder opinions focus on the same issues addressed in the MCDAs reviewed in section. MCDA applications for group decision-making in other areas were also reviewed by Bose et al. (1997) and Matsatsinis and Samaras (2001).

4.2.1 Remediation of Contaminated Sites Our review has identified only one study dealing with the application of decision-analytical tools to include stakeholder involvement at contaminated sediment sites. However, we have identified several studies dealing with stakeholder involvement for contaminated terrestrial sites (Table 2). Rogers *et al.* (2004) employ a PROMETHEE outranking method to incorporate stakeholder values into the process of selecting one of a group of novel technological alternatives for sediment management. The authors found systematic outranking analysis to be effective at sorting out complex trade-offs. They identified dominated alternatives and studied the sensitivity of second-best alternatives to preference weightings. The stakeholders involved were eager to have their values heard and incorporated into the management decision process.

Arvai and Gregory (2003) compared two approaches for involving stakeholders in identifying radioactive waste cleanup priorities at DOE sites: 1) a traditional approach that involved communication of scientific information that is currently in use in many DOE, EPA, and other federal programs and 2) a values-oriented communication approach that helped stakeholders in making difficult tradeoffs across technical and social concerns. The second approach has strong affinity to the MAUT-based tradeoffs discussed earlier in this chapter. The authors concluded that the incorporation of value-based tradeoff information leads stakeholders to making more informed choices.

Apostolakis and his colleagues (Apostolakis, 2001; Bonano *et al.*, 2000; Accorsi *et al.*, 1999a&b) developed a methodology that uses AHP, influence diagrams, MAUT, and risk assessment techniques to integrate the results of advanced impact evaluation techniques with stakeholder preferences. In this approach, AHP is used to construct utility functions encompassing all the performance criteria. Once the utility functions have been constructed, MAUT is applied to compute expected utilities for alternatives. The authors used this approach to elicited stakeholder input and select a suitable technology for the cleanup of a contaminated terrestrial site.

4.2.2 Reduction of Contaminants Introduced into Aquatic Ecosystems We located multiple MCDAs involving stakeholders that analyze ways to reduce contaminants entering aquatic ecosystems. van Moeffaert (2003) attempts to find the optimal wastewater treatment system among alternatives considered in Surahammar, Sweden. He uses a fuzzy outranking technique and combines the rankings with the opinions of various interest groups to choose " 'the best defendable' alternative." Al Rashdan *et al.* (1999) use outranking to prioritize wastewater projects in Jordan. They select criteria to judge the projects with the help of stakeholders through a brainstorming session. The methodology was found to be very useful in solving problems with conflicting criteria. Borsuk *et al.* (2001) examine the effects of a proposed 30% reduction in nitrogen loading on the Neuse River estuary in North Carolina. They elicit stakeholder opinion to determine which criteria should be examined in analyzing the effects of the reduction.

4.2.3 Optimization of Water Resources Many MCDAs involving stakeholder opinion seek to improve resource allocation and management. Klauer *et al.* (2002) attempt to use outranking to optimize groundwater protection strategies in an area of the Elbe River in Germany. Through interviews, discussions, and committees, Klauer uses stakeholder opinion to develop alternatives and criteria to rank them with. Unfortunately, the decision-making body in Germany decided to withdraw from Klauer's MCDA process and make a decision without considering its results. A number of other analyses (Gregory and Failing, 2002; Hamalainen *et al.*, 2001; Marttunen and Hamalainen, 1995; Gregory and Wellman, 2001; McDaniels *et al.*, 1999; Gregory *et al.*, 2001; Whitaker and Focht, 2001) seek to optimize water use planning using MAUT, AHP, and other MCDA techniques eliciting user opinions to determine alternatives, criteria, and criteria values. In the management of the Illinois River basin in eastern Oklahoma, a novel technique called Mental Modeling was used (Focht et al., 1999, Whitaker and Focht, 2001). Mental Modeling (Morgan *et al.*, 2002) is a promising tool for assessing individual judgments. It involves individual, one-on-one interviews leading participants through a jointly determined agenda of topics.

4.2.4 Management of Other Resources MCDAs involving stakeholder involvement are also used to manage wetlands, coral reefs, and fisheries. Herath (2004) uses AHP to incorporate stakeholders' opinions in deciding how much a wetland in Australia should be developed to increase nature-based tourism. When faced with the same choices as Herath (2004) except regarding coral reefs, Fernandes *et al.* (1999) also use AHP to incorporate stakeholder opinions while Brown *et al.* (2001) use stakeholder workshops to elicit stakeholder opinions and a less-quantitative tradeoff analysis to select a management option for Buccoo Reef Marine Park in Tobago; criteria evaluated included ecological, social and economic factors. In two papers (Mardle *et al.*, 2004; Soma, 2003), MCDA analysis involving stakeholder opinion is applied to fishery management. In both of these analyses, stakeholders value the importance of criteria through AHP.

## 5. Straw Man Application Framework of MCDA Methods and Tools for Sediment Management

Successful environmental decision-making in complex settings will depend on the extent to which three key ingredients are integrated within the process: people, process and tools. Based on our review of MCDA concepts and applications, we have synthesized our understanding into a systematic decision framework (Figure 3). This framework is intended to provide a generalized road map to the environmental decision-making process.

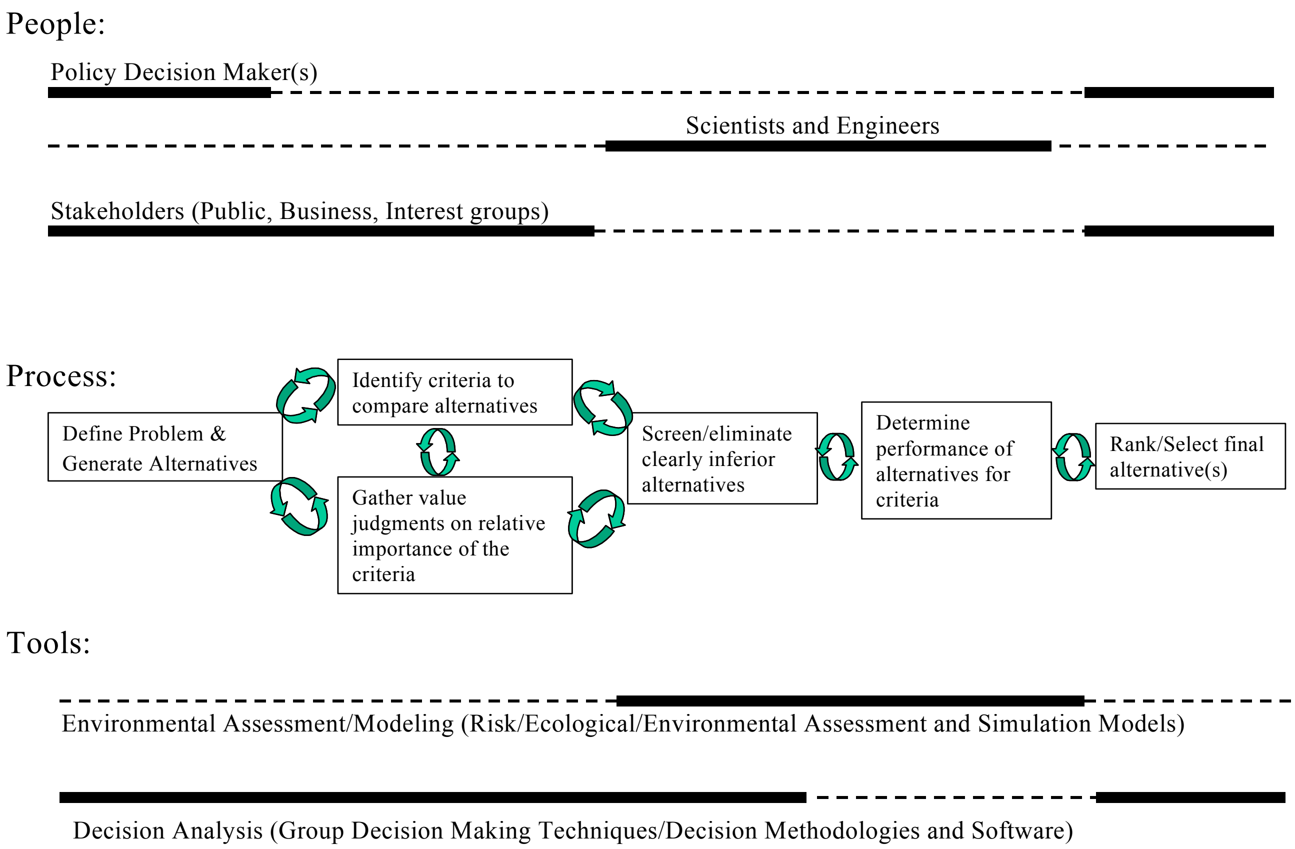



Figure 3: Straw man framework

Having the right combination of *people* is the first essential element in the decision process. The activity and involvement levels of three basic groups of people (decision-makers, scientists and engineers, and stakeholders) are symbolized by dark lines for direct involvement and dotted lines for less direct involvement. While the actual membership and the function of these three groups may overlap or vary, the roles of each are essential in gathering the most utility from human input to the decision process. Each group has its own way of viewing the world, its own method of envisioning solutions, and its own societal responsibility. Policy- and decision-makers spend most of their effort defining the problem context and the overall constraints on the decision. In addition, they may have responsibility for the selection of the final decision and its implementation. Stakeholders may provide input in defining the problem but contribute the most input into helping to formulate performance criteria and contributing value judgments for weighting the various success criteria. Depending on the problem and regulatory context, stakeholders may have some responsibility in ranking and selecting the final option. Scientists and engineers have the most focused role in that they provide the measurements or estimations of the desired criteria that determine the success of various alternatives. While they may take a secondary role as stakeholders or decision-makers, their primary role is to provide the technical input as necessary in the decision process.

The framework (Figure 3) places *process* in the center of the overall decision process. While it is reasonable to expect that the decision-making process may vary in specific details among regulatory programs and project types, emphasis should be given to designing an adaptable structure so that participants can modify aspects of the project to suit local concerns, while still producing a structure that provides the required outputs. The process depicted in Figure 3 follows two basic themes: 1) generating management alternatives, success criteria, and value judgments and 2) ranking the alternatives by applying the value weights. The first part of the process generates and defines choices, performance levels, and preferences. The latter section methodically prunes non-feasible alternatives by first applying screening mechanisms (for example, overall cost, technical feasibility, general societal acceptance) followed by a more detailed ranking of the remaining options by decision analytical techniques (AHP, MAUT, Outranking) that utilize the various criteria levels generated by environmental tools, monitoring, or stake-holder surveys.

As shown in Figure 3, the *tools* used within group decision-making and scientific research are essential elements of the overall decision process. As with *people*, the applicability of the tools is symbolized by solid lines (direct or high utility) and dotted lines (indirect or lower utility). Decision analysis tools help to generate and map preferences of stakeholder groups as well as individual value judgments into organized structures that can be linked with the other technical tools from risk analysis, modeling and monitoring, and cost estimations. Decision analysis software can also provide useful graphical techniques and visualization methods to express the gathered information in understandable formats. When changes occur in the requirements or decision process, decision analysis tools can respond efficiently to reprocess and iterate with the new inputs. The framework depicted in Figure 3 provides a focused role for the detailed scientific and engineering efforts invested in experimentation, environmental monitoring, and modeling that provide the rigorous and defendable details for evaluating criteria performance under various alternatives. This integration of decision and scientific and engineering tools allows each to have a unique and valuable role in the decision process without attempting to apply either tool beyond its intended scope.

As with most other decision processes reviewed, it is assumed that the framework in Figure 3 is iterative at each phase and can be cycled through many times in the course of complex decision-making. The same basic *process* is used initially with rough estimates to sketch out the basic elements and challenges in the decision process with a few initial stakeholders and screening-level analysis or models. A first-pass effort may efficiently point out challenges that may occur, key stakeholders to be included or modeling/analysis studies that should be initiated. As these challenges become more apparent one iterates again through the framework to explore and adapt the process to address the more subtle aspects of the decision with each iteration giving an indication of additional details would benefit the overall decision.

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## 6. Conclusion

Effective environmental decision-making requires an explicit structure for coordinating joint consideration of the environmental, ecological, technological, economic, and socio-political factors relevant to evaluating and selecting among management alternatives. Each of these factors includes multiple sub-criteria, which makes the process inherently multi-objective. Integrating this heterogeneous information with respect to human aspirations and technical applications demands a systematic and understandable framework to organize the people, processes, and tools for making a structured and defensible decision.

Stakeholder involvement is increasingly recognized as being an essential element of successful environmental decision making. The challenge of capturing and organizing that involvement as structured inputs to decision-making alongside the results of scientific and engineering studies and cost analyses can be met through application of the tools reviewed in this paper. The current environmental decision-making context limits stakeholder participation within the "decide and defend" paradigm that positions stakeholders as constraints to be tested, rather than the source of core values that should drive the decision-making process. Consequently, potentially controversial alternatives are eliminated early and little effort is devoted to maximizing stakeholder satisfaction with either the decision process or outcome. Instead, the final decision may be something to which no one objects too strenuously. Ultimately, this process does little to serve the needs or interests of the people who must live with the consequences of an environmental decision: the public.

The increasing volume of complex and often controversial information being generated to support environmental decisions and the limited capacity of any one individual decision maker to integrate and process that information emphasize the need for developing tractable methods for aggregating the information in a manner consistent with decision makers' values. The field of MCDA has developed methods that can help in developing a decision analytical framework useful for environmental management, including the management of contaminated sites. The purpose of MCDA is not always to single out the "correct" decision, but to help improve understanding in a way that facilitates a decision-making process involving risk, multiple criteria, and conflicting interests. MCDA visualizes tradeoffs among multiple, conflicting criteria and quantifies the uncertainties necessary for comparison of available remedial and abatement alternatives. This process helps technical project personnel as well as decision makers and stakeholders systematically consider and apply value judgments to derive a favorable management alternative. MCDA also provides methods for participatory decision-making where stakeholder values are elicited and explicitly incorporated into the decision process.

Different MCDA methods have their associated strengths and limitations. No matter which analytical decision tool is selected, implementation requires complex tradeoffs. This complexity is probably one of the main reasons why MCDA is still not widely used in practical applications. However, explicit, structured approaches will often result in a more efficient and effective decision process compared with the often intuition- and bias-driven decision processes that are currently used.

Formal applications of MCDA in management of contaminated sites are still rare. Applications in related areas are more numerous, but to date they have remained largely academic exercises with some exception in the use of AHP-based methods in natural resources planning. Nevertheless, the positive results reported in the studies reviewed in this paper as well as the availability of recently developed software tools provides more than an adequate basis for recommending the use of MCDA in contaminated site management.

Environmental decision-making involves complex trade-offs between divergent criteria. The traditional approach to environmental decision-making involves valuing these multiple criteria in a common unit, usually money, and thereafter performing standard mathematical optimization procedures. Extensive scientific research in the area of decision analysis has exposed many weaknesses in the cost-benefit analysis (Belton and Steward, 2002). At the same time, new methods that facilitate a more rigorous analysis of multiple criteria have been developed. These methods, collectively known as MCDA methods, are increasingly being adopted in environmental decision-making. This paper surveyed the principal MCDA methods currently in use and cited numerous environmental applications of these methods. While MCDA offers demonstrable advantages, choosing among MCDA methods is a complex task. Each method has strengths and weaknesses; while some methods are better grounded in mathematical theory, others may be easier to implement. Data availability may also act as a constraint on applicable methods. It is therefore unavoidable that the decision-maker will have to choose, on a case-by-case basis, the most suitable MCDA technique applicable to each situation. This paper has set out a decision analytic framework to facilitate such a selection process and thereafter provides guidance on the implementation of the principal MCDA methods within a larger context of the people, processes, and tools used in decision-making . The extensive growth over the last 30 years in the amount and diversity of information required for environmental decision-making has exceeded the capacity of common, unstructured decision models. Focused effort directed at integrating MCDA principles and tools with existing approaches, including the use of risk and cost/benefit analysis, will lead to more effective, efficient, and credible decision making.

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