Risk Analysis, Vol. 26, No. 1, 2006 DOI: 10.1111/j.1539-6924.2006.00713.x

Multicriteria Decision Analysis: A Comprehensive Decision Approach for Management of Contaminated Sediments

I. Linkov,[1]* F. K. Satterstrom,[1] G. Kiker,[2] T. P. Seager,[3] T. Bridges,[4] K. H. Gardner,[5] S. H. Rogers,[5] D. A. Belluck,[6] and A. Meyer[7]

Contaminated sediments and other sites present a difficult challenge for environmental decisionmakers. They are typically slow to recover or attenuate naturally, may involve multiple regulatory agencies and stakeholder groups, and engender multiple toxicological and ecotoxicological risks. While environmental decision-making strategies over the last several decades have evolved into increasingly more sophisticated, information-intensive, and complex approaches, there remains considerable dissatisfaction among business, industry, and the public with existing management strategies. Consequently, contaminated sediments and materials are the subject of intense technology development, such as beneficial reuse or *in situ* treatment. However, current decision analysis approaches, such as comparative risk assessment, benefit-cost analysis, and life cycle assessment, do not offer a comprehensive approach for incorporating the varied types of information and multiple stakeholder and public views that must typically be brought to bear when new technologies are under consideration. Alternatively, multicriteria decision analysis (MCDA) offers a scientifically sound decision framework for management of contaminated materials or sites where stakeholder participation is of crucial concern and criteria such as economics, environmental impacts, safety, and risk cannot be easily condensed into simple monetary expressions. This article brings together a multidisciplinary review of existing decision-making approaches at regulatory agencies in the United States and Europe and synthesizes state-of-the-art research in MCDA methods applicable to the assessment of contaminated sediment management technologies. Additionally, it tests an MCDA approach for coupling expert judgment and stakeholder values in a hypothetical contaminated sediments management case study wherein MCDA is used as a tool for testing stakeholder responses to and improving expert assessment of innovative contaminated sediments technologies.

KEY WORDS: MCDA; multicriteria decision analysis; risk assessment

1. CURRENT AND EVOLVING DECISION ANALYSIS METHODOLOGIES

Management of environmental contamination requires making decisions while balancing scientific findings with multifaceted, values-laden input from many different stakeholders with different priorities and objectives. Typically, the information presented to environmental decisionmakers falls into one of four categories, ranging from highly quantitative to highly qualitative: modeling and monitoring studies, risk/impact assessments, cost or cost-benefit analysis, and stakeholder preferences. Structured information about stakeholder preferences, when presented

1 Cambridge Environmental Inc., 58 Charles Street, Cambridge, MA 02141, USA.
2 University of Florida, Gainesville, FL 32611, USA.
3 Purdue University, West Lafayette, IN 47905, USA.
4 U.S. Army Engineer Research and Development Center, Environmental Laboratory, 3909 Halls Ferry Rd., Vicksburg, MS 39180, USA.
5 Center for Contaminated Sediments Research, University of New Hampshire, Durham, NH, USA.
6 FHWA/USDOT, 400 7th Street, S.W., Washington, DC 20590, USA.
7 U.S. Army Corps of Engineers, Hazardous, Toxic and Radioactive Waste Center of Expertise, 12565 West Center Rd., Omaha, NE 68144, USA.
* Address correspondence to Igor Linkov, Cambridge Environmental Inc., 58 Charles Street, Cambridge, MA 02141, USA; Linkov@cambridgeenvironmental.com.

0272-4332/06/0100-0061$22.00/1

to decisionmakers at all, may be handled in an *ad hoc* or subjective manner that exacerbates the difficulty of defending the decision process as reliable, transparent, and fair. 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 method of combining quantitative and qualitative inputs from scientific studies of risk, cost and cost-benefit analyses, and stakeholder views has yet to be fully developed for environmental decision making. As a result, decisionmakers often do not fully use all available and useful information in choosing between identified management alternatives.

In response to these decision-making challenges, some regulatory agencies and environmental managers have moved toward more integrative decision analysis processes, such as multicriteria decision analysis (MCDA) or comparative risk assessment (CRA). These approaches are designed to raise awareness of the tradeoffs that must be made between competing project objectives, help compare technologies and alternatives that are dramatically different in their potential impacts or outcomes, and synthesize a wide variety of information. In the context of sediment management problems, while CRA can be viewed as part of a decision-making process that relies on estimated relative risks or impacts associated with each management alternative under consideration, its drawback is the unclear way in which it combines performance across criteria to arrive at an optimal project alternative (Linkov & Ramadan, 2004). MCDA, on the other hand, provides a systematic approach for integrating risk levels, uncertainty, and valuation—however, few MCDA approaches are specifically designed to incorporate multiple stakeholder perspectives or competing value systems.

This article employs an MCDA framework appropriate for contrasting the views of multiple decisionmakers (or stakeholder groups) and for guiding individual decisionmakers through problems that may have no single best solution. For individuals, the MCDA process quantifies value judgments (and the sensitivity of outcomes to those judgments), scores different project alternatives on the criteria of interest, and facilitates selection of a preferred course of action. For groups, 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, resulting in a more complete understanding of the values held by others.

2. INTRODUCTION TO MCDA METHODS

An ideal environmental management alternative might be viewed as minimizing human health and ecological risks while minimizing cost (Driscoll *et al.*, 2002). However, such an alternative rarely exists. Consequently, decisionmakers typically create a decision matrix to assess the performance of available alternatives relative to the criteria considered important. For example, this type of matrix is usually the product of Superfund feasibility studies as well as CRA. Each alternative is then evaluated by scoring it on each criterion, qualitatively or quantitatively combining these scores, and then comparing the aggregate scores for each alternative. CRA, however, does not address how the combination of criteria should be carried out. In the case of qualitative comparison of project scores using CRA, it can be unclear why an alternative is identified as optimal if it performs better only on some criteria compared to another alternative. Quantitative CRAs share the same problem, as they are often unsupported in how they determine the relative contribution of each criterion to the aggregate score (Table I).

MCDA methods, meanwhile, provides a more structured approach. A detailed analysis of the theoretical foundations of MCDA methods and their comparative strengths and weaknesses is presented in Belton and Stewart (2002) and Figueira *et al.* (2005). The common purpose of these methods is to evaluate and choose among alternatives based on multiple criteria using systematic analysis to overcome 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, much like CRA. However, 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.

Table I. Comparison of Decision Process Elements for *Ad Hoc* Decision Making, Comparative Risk Assessment, and Multicriteria Decision Analysis

Elements of Decision Process	*Ad Hoc* Decision Making	Comparative Risk Assessment	Multicriteria Decision Analysis
Define problems	Stakeholder input limited or nonexistent. Therefore, stakeholder concerns may not be addressed by alternatives.	Stakeholder input collected after the problem is defined by decisionmakers and experts. Problem definition is possibly refined based on stakeholder input.	Stakeholder input incorporated at beginning of problem formulation stage. Often provides higher stakeholder agreement on problem definition. Thus, proposed solutions have a better chance at satisfying all stakeholders.
Generate alternatives	Alternatives are chosen by decisionmaker, usually from preexisting choices with some expert input.	Alternatives are generated through formal involvement of experts in more site-specific manner.	Alternatives are generated through involvement of all stakeholders, including experts. Involvement of all stakeholders increases likelihood of novel alternative generation.
Formulate criteria by which to judge alternatives	Criteria by which to judge alternatives are often not explicitly considered and defined.	Criteria and subcriteria are often defined.	Criteria and subcriteria hierarchies are developed based on expert and stakeholder judgment.
Gather value judgments on relative importance of criteria	Nonquantitative criteria valuation weighted by decisionmaker.	Quantitative criteria weights are sometimes formulated by the decisionmaker, but in a poorly justified manner.	Quantitative criteria weights are obtained from decisionmakers and stakeholders.
Rank/select final alternatives	Alternative often chosen based on implicit weights in an opaque manner.	Alternative chosen by aggregation of criteria scores through weight of evidence discussions or qualitative considerations.	Alternative chosen by systematic, well-defined algorithms using criteria scores and weights.

Table II summarizes a number of MCDA methods. Multiattribute utility theory (MAUT), multiattribute value theory (MAVT), and the analytical hierarchy process (AHP) are more complex methods that use optimization algorithms, whereas outranking uses a dominance approach. The optimization approaches 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 is to find a simple expression for the net benefits of a decision. Through the use of utility or value functions, MAUT transforms diverse criteria into one common scale of utility or value. MAUT relies on the assumptions that the decisionmaker is rational (preferring more utility to less utility, for example), that the decisionmaker has perfect knowledge, and that the decisionmaker is consistent in his or her judgments. The goal of decisionmakers in this process is to maximize utility or 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 aggregates various facets of the decision problem using a single optimization function known as the objective function. The goal of AHP is to select the alternative that results in the greatest value of the objective function. Like MAUT, AHP is a compensatory optimization approach. However, rather than utility and weighting functions, AHP uses pair-wise comparisons of decision criteria to elicit decisionmakers' values. All individual criteria are paired against all others, and the results are compiled in matrix form. For example, in examining the choices in the remediation of contaminated sediments, AHP would require the decisionmaker to answer questions such as: "With respect to the selection of a sediment alternative, which is more important, public acceptability or cost?" The decisionmaker uses a numerical scale to compare the choices, and AHP moves systematically through all pair-wise comparisons of criteria and alternatives. AHP 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 and methodological weaknesses of these methods have been subject to multiple reviews (Barzilai, 2001, 2004).

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. 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 overperformance 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 (Seager, 2004).

3. THE EMERGENCE OF MCDA WITHIN THE U. S. ARMY CORPS OF ENGINEERS

The U. S. Army Corps of Engineers (USACE), U.S. Environmental Protection Agency (USEPA), Department of Energy (DOE), and other federal agencies use a variety of modeling tools to support their current decision-making processes. The majority of these tools are based on physical modeling and engineering optimization schemes. Even though federal agencies are required to consider social and political factors, the typical decision process does not specifically provide for consideration of such issues. In these *ad hoc* environments, comparatively little effort is applied to engaging and understanding stakeholder perspectives or to providing for potential learning among stakeholders, often causing the decision process to become adversarial. However, our review of regulatory and guidance documents revealed several programs where agencies are beginning to consider formal decision tools like MCDA in environmental decision

Table II. Comparison of Critical Elements, Strengths, and Weaknesses of Several Advanced MCDA Methods: MAUT, AHP, and Outranking (after ODPM (2004) and Larichev and Olson (2001))

Method	Important Elements	Strengths	Weaknesses
Multiattribute utility theory	• Expression of overall performance of an alternative in a single, nonmonetary number representing the utility of that alternative • Criteria weights often obtained by directly surveying stakeholders	• Easier to compare alternatives whose overall scores are expressed as single numbers • Choice of an alternative can be transparent if highest scoring alternative is chosen • Theoretically sound—based on utilitarian philosophy • Many people prefer to express net utility in nonmonetary terms	• Maximization of utility may not be important to decisionmakers • Criteria weights obtained through less rigorous stakeholder surveys may not accurately reflect stakeholders' true preferences • Rigorous stakeholder preference elicitations are expensive
Analytical hierarchy process	• Criteria weights and scores are based on pair-wise comparisons of criteria and alternatives, respectively	• Surveying pair-wise comparisons is easy to implement	• The weights obtained from pair-wise comparison are strongly criticized for not reflecting people's true preferences • Mathematical procedures can yield illogical results; for example, rankings developed through AHP are sometimes not transitive
Outranking	• One option outranks another if: 1) "it outperforms the other on enough criteria of sufficient importance (as reflected by the sum of criteria weights)" and 2) it "is not outperformed by the other in the sense of recording a significantly inferior performance on any one criterion" • Allows options to be classified as "incomparable"	• Does not require the reduction of all criteria to a single unit • Explicit consideration of possibility that very poor performance on a single criterion may eliminate an alternative from consideration, even if that criterion's performance is compensated for by very good performance on other criteria	• Does not always take into account whether overperformance on one criterion can make up for underperformance on another • The algorithms used in outranking are often relatively complex and not well understood by decisionmakers

making (Stahl, 2003; Stahl *et al.*, 2002; USEPA, 2000, 2002; Baker *et al.*, 2001; DOE, 1998; Jenni *et al.*, 1995). Similarly, a detailed review of the regulatory background and use of decision analysis tools in the European Union (Bardos *et al.*, 2002) found that, although risk assessment and cost-benefit analysis remain the dominant decision support approaches, MCDA methods are more frequently used in European Union countries than in the United States.

The emergence of MCDA is illustrated here in the case of the USACE. The Corps of Engineers has used a single approach to 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. A complex analysis of each alternative is used to determine the benefits and costs in terms of dollars and other nondollar measures (environmental quality, safety, etc.), and the alternative with the highest net NED benefit (with no environmental degradation) is usually selected. The USACE uses a variety of mechanistic and deterministic fate and transport models to provide information for 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 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. Yet, the P&G approach is limited in that information on costs, benefits, and impacts is rarely precise. In addition, the P&G approach does not always satisfy the wants of key stakeholders.

In response to an 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). In addition, revised planning procedures have been proposed to formulate more sustainable options through "combined" economic development and 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 multicriteria or trade-off methodology (Males, 2002). This new USACE guidance and revisions on the application of MCDA techniques to environmental projects creates an opportunity to develop a systematic strategy to implement these methods within specific USACE mission areas (such as navigation and restoration) and to link these methods with existing risk analysis and adaptive management procedures.

4. MCDA APPLICATIONS IN THE MANAGEMENT OF CONTAMINATED SEDIMENTS AND RELATED AREAS

MCDA has been used to support decision making in contaminated sediment management and related areas (Table III). We describe 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. MCDA techniques have been applied to optimize policy selection in the remediation of contaminated sites, the reduction of contaminants entering aquatic ecosystems, the optimization of water and coastal resources, and the management of other resources. In some of these studies, the researchers have explicitly taken into account the opinions of local community groups and other stakeholders through focus groups, surveys, and other techniques and formally integrated these opinions into the decision process. Many papers reviewed in this section conclude that application of MCDA methods provides a significant improvement in the decision process and public acceptance of the suggested remedial or abatement policy.

Table III. MCDA Applications for Sediment Management and Related Areas

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)
	Outranking (PROMETHEE)	Selecting novel technological alternatives for sediment management	Dartmouth College; University of New Hampshire	Rogers *et al.* (2004)
	MAUT	Identifying radioactive waste cleanup priorities at DOE sites	DOE/NSF	Arvai and Gregory (2003)
	AHP, MAUT	Questionnaires	DOE	Apostolakis (2001); Bonano (2000); Accorsi *et al.* (1999a,1999b)
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 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	Kholghi (2001)
	Outranking (ELECTRE), distance (compromise programming)	Wastewater recycling and reuse in the Mediterranean	Aristotle University, Greece	Ganoulis (2003)
	Fuzzy outranking (NAIADE)	Choosing a sustainable wastewater treatment system in Surahammar, Sweden	Swedish Foundation for Strategic Environmental Research	van Moeffaert (2003)
	Outranking (PROMETHEE)	Prioritization of wastewater projects in Jordan	Staffordshire University, UK	Al-Rashdan *et al.* (1999)
	Elicitation of criteria from stakeholders	Determing the effects of a proposed 30% reduction in nitrogen loading to the Neuse Estuary in North Carolina	University of North Carolina	Borsuk (2001)

(*continued*)

Table III. (*continued*)

Area	Method	Decision Context	Funding Agency	Citation
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	Özelkan and Duckstein (1996)
	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 of 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 for 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)
	Outranking (PROMETHEE)	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	Water use planning	University of British Columbia, Compass Resource Management	Gregory and Failing (2002)
	MAUT+AHP	Regulation of water flow in a lake-river system	Academy of Finland	Hämäläinen *et al.* (2001)
	AHP & MAUT/SMART	Environmental impact assessment of two water development projects on a Finnish river	Finnish Environmental Agency, Helsinki University of Technology	Marttunen and Hämäläinen (1995)
	MAUT	Consensus building for water resource management in Oregon	NSF, USEPA, Carnegie Mellon University	Gregory and Wellman (2001)
	Committee consensus	Water management in British Columbia	B.C. Hydro, Social Sciences and Humanities Research Council of Canada, NSF	McDaniels (1999); Gregory *et al.* (2001)

(*continued*)

Table III. (*continued*)

Area	Method	Decision Context	Funding Agency	Citation
Management of other resources	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)
	AHP	Developing better management strategies for the Wonga Wetlands on the Murray River in Australia	La Trobe University, Australia	Herath (2004)
	AHP	Managing a coral reef	East West Center and WWF, The Netherlands	Fernandes *et al.* (1999)
	Trade-off analysis	Choosing among four development scenarios for the Buccoo Reef Marine Park in Tobago	U.K. Deparment for International Development	Brown *et al.* (2001)
	AHP	Analyzing priorities in fishery management	European Commission	Mardle *et al.* (2004)
	AHP	Fishery management in Trinidad and Tobago	Food and Agriculture Organization of the United Nations	Soma (2003)

4.1. Remediation of Contaminated Sediments and Aquatic Ecosystems

MCDA has rarely been applied to the remediation of sediments and aquatic systems. However, a few studies can be found in the literature. Toll *et al.* (1997) provide a guide for using decision analysis in the management of contaminated sediments, describe the history of decision analysis, and go through modeling, alternative comparison, and alternative choice for a particular test case. 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 trade-off 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.

Several studies also deal with stakeholder involvement for other types of contaminated sites, both terrestrial and aquatic. 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, USEPA, and other federal programs and (2) a value-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. The authors concluded that the incorporation of value-based tradeoff information leads stakeholders to making more informed choices. Apostolakis and colleagues (Apostolakis, 2001; Bonano *et al.*, 2000; Accorsi *et al.*, 1999a, 1999b) 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 elicit stakeholder input and select a suitable technology for the cleanup of a contaminated terrestrial site.

Many contaminated aquatic sites are on the USEPA 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—cost, implementability, short-term effectiveness, long-term effectiveness, and reduction of toxicity, mobility, or volume through treatment—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 the Idaho National Environmental Engineering Laboratory (INEEL).

4.2. Reduction of Contaminants Introduced into Aquatic Ecosystems

In addition to being used in the remediation of contaminated sites, MCDA techniques have been used in attempts to reduce 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 affect groundwater. Specifically, they use cost-benefit analysis to evaluate two emission control scenarios and their effects on aluminum and nitrate levels in groundwater. Kholghi (2001) and Ganoulis (2003) apply MCDA to decide how to manage wastewater in North America and the Mediterranean, respectively. Kholghi uses MAUT to decide among alternatives, while Ganoulis illustrates the use of a distance technique through a case study.

Van Moeffaert (2002) 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. 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.

4.3. Allocation of Water and Coastal Resources

MCDA techniques have been extensively used to help balance the sometimes conflicting demands of environmental conservation and business development with regards to water allocation and coastal development. 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 plan that incorporates adaptive management, increased drought conservation measures, and changes in dam releases. In two papers, Ni, Borthwick, and Qin (Ni *et al.*, 2002; Qin *et al.*, 2002) describe their use of AHP in determining the optimal length and location of 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.

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 & Sawalhi, 2003) attempts to optimize the allocation of water from the river to countries that border it using a distance technique. Other analyses of water bodies in the United States (Bella *et al.*, 1996), Europe (Özelkan & Duckstein, 1996), and South Africa (Joubert *et al.*, 1997) have examined various uses for water bodies such as consumption, recreation, conservation, and power generation.

Many MCDA applications 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. 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 & Failing, 2002; Hämäläinen *et al.*, 2001; Marttunen & Hämäläinen, 1995; Gregory & Wellman, 2001; McDaniels, 1999; Gregory *et al.*, 2001; Whitaker & 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.

4.4. Management of Other Resources

MCDA has also been used to manage wetlands, coral reefs, and fisheries. Herath (2004) uses AHP to decide how many wetlands in Australia should be created to increase nature-based tourism. When faced with deciding whether to increase tourism at coral reefs, Fernandes *et al.* (1999) also use AHP techniques while Brown *et al.* (2001) use stakeholder workshops to elicit stakeholder opinions and a less-quantitative trade-off 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. 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.

5. APPLICATION OF MCDA METHODS FOR CONTAMINATED SEDIMENT MANAGEMENT: COCHECO RIVER CASE STUDY

No matter the context, stakeholder involvement is increasingly recognized as being an essential element of successful environmental decision making. Kiker *et al.* (2005) proposed a generalized method for capturing and organizing that involvement as structured input to the decision-making process, alongside the results of scientific and engineering studies. While the current environmental decision-making context often limits stakeholder participation, Kiker *et al.* propose an alternative process that iterates between stakeholder engagement and expert assessment. For example, stakeholders may provide the criteria by which alternatives should be judged; the primary role of experts is then to develop and assess technological alternatives in relation to these criteria.

While the actual membership and function of stakeholder, expert, and decision-making groups may overlap, the roles of each are essential in maximizing the utility of human input into the decision process. Each group has its own way of viewing the world, its own method of envisioning solutions, and its own societal responsibility. Policymakers and decisionmakers spend most of their effort in 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 provide input for defining the problem, formulating 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, to the best of their abilities, 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 decisionmakers, their primary role is to provide the technical input necessary in the decision process.

This general approach was applied to the problem of managing approximately 75,000 cubic yards of sediment contaminated with polycyclic aromatic hydrocarbons and heavy metals removed from the Cocheco River in Dover, NH, during 2005 (Rogers *et al.*, 2004). Motivation for this dredging project included maintenance of a navigable channel, considered essential to long-term economic development plans to return Dover to its historical status as an inland port. Because the Cocheco is a navigable waterway and is thus under federal jurisdiction, the USACE helped Dover coordinate the process and performed the dredging. Although there has been much debate in the community over the dredging decision, the focus of this case study is solely on the disposal of the contaminated sediments, rather than on dredging operations themselves.

5.1. Problem Definition and Alternative Generation

The original list of decision alternatives was constructed by technical experts from the City of Dover and the USACE, and it included ocean dumping, an upland disposal cell, and three possible landfill sites. After a process of elimination that limited stakeholder engagement to the involvement of elected representatives and public hearings, the city settled on disposal at a riparian site that had been a repository for contaminated sediments in previous dredging operations. This decision process did not consider a broad range of stakeholder groups or novel technological alternatives, and three beneficial reuse alternatives were subsequently devised by experts at the Center for Contaminated Sediments Research (University of New Hampshire): cement manufacture, immobilization in flowable cementatious fill, and construction of new wetlands area. These three hypothetical alternatives and the consensus disposal site actually selected were tested in an MCDA process, which engaged the stakeholders and decisionmakers who participated in the actual management problem.

5.2. Identification of Criteria

Using a semi-structured reflective interview, representatives from different stakeholder groups were interviewed personally or on the phone to identify key decision criteria and project objectives. In general, "semi-structured interviews have some degree of predetermined order but still ensure flexibility in the ways issues are addressed by the informant" (Dunn, 2000). A sample interview centered on some of the following questions:

1. What has been your level of involvement with the Cocheco River Dredge and Disposal Project?
2. What concerns do you have with the disposal/management options for the contaminated sediment?

3. How did you participate in the decision-making process? What were your perceptions of the process?
4. When it comes to the management of contaminated sediments in general, what are your biggest concerns, most important values and/or guiding principles for evaluating the situation?

Among the concerns voiced during the initial interviews were four recurring themes: economics, environmental quality, human habitat, and ecological habitat. Although stakeholders differed in emphasis, each of these qualities was mentioned during most of the interviews. At this stage, stakeholders helped to characterize the major decision criteria by discussing how they could be measured or manifested in specific attributes. For example, economics was identified as an important decision criterion, but economic considerations may have facets differing in importance to different stakeholders. Project costs (80% of which were slated to be paid from federal sources), maintenance costs, and community economic development (e.g., jobs) all were identified as driving the overall economic assessment

5.3. Gathering Value Judgment on Relative Importance of the Criteria

Value judgments were gathered in a two-step process. A written survey of 15 stakeholders was used to measure preferences for the four main criteria (economics, human habitat, environmental quality, and ecological habitat). Stakeholders were asked to assign percentage weights for each of the four major decision criteria, and were encouraged to answer the questions based on their values in general.

In addition, each of the major criteria was defined by a set of underlying attributes. While respondents were asked to rank all attributes in order of importance in several different groupings of four to eight, in each case respondent profiles emerged from the attribute rankings that were consistent with the directly elicited percentage weightings. In the end, the direct percentage weightings of the top-level criteria were sufficient to facilitate MCDA.

5.4. Determining Performance of Alternatives on Criteria

The four top-level criteria identified in the interviews were reported to the sediment management technology expert group to define and estimate specific measures that could be incorporated into a decision model. In many instances, the measures identified could be interpreted as relating to more than one of the top-level decision criteria, suggesting that the criteria are not completely independent—a quality typical of real-world environmental decision problems (Lahdelma *et al.*, 2000). Also, several of the measures identified proved difficult to quantify. For example, although experts agreed that air and water quality measures could be an important aspect of how stakeholders interpret overall environmental quality, devising comprehensive metrics for air and water that could be accurately and economically estimated and easily communicated to stakeholders proved challenging.

Expert assessment determined the alternatives' performance on each of the four criteria that stakeholders identified as important, and the results are summarized in Table IV.

5.5. Rank/Select Final Alternatives

In MCDA, alternatives may be judged against one another by comparing their performance on each criterion. For example, experts expected cement manufacture to be the least expensive dredged material management option—consequently outranking (or "dominating") all three other alternatives with respect to cost. Moreover, cement manufacture is tied with wetlands restoration for the highest environmental quality assessment, with both outranking the other alternatives. Wetlands restoration dominates all the others in the creation of ecological habitat, whereas the upland capped cell dominates in human habitat, chiefly due to the city's plan to turn the disposal site into recreation area following capping of the cell. One finding apparent from Table IV is that flowable concrete fill is inferior to one or more alternatives in all respects for this site. Nonetheless, we left this alternative for the quantitative assessment presented below.

Survey results in this case study were analyzed using the PROMETHEE method of pair-wise comparison embodied in *Decision Lab 2000* software (Visual Decision Inc. 2000). In PROMETHEE, rankings are based on calculation of positive and negative "flows," which are measures of the weighted average ranking of each alternative according to the performance table. For example, in an equal-weighting (or balanced scenario), the positive flow for cement manufacture is calculated as the sum of positive rankings +3.0 (from economics), +2.0 (from environmental quality), 0,

Table IV. Expert Performance Assessment of Alternatives

Alternative	Cost ($/cy)	Environmental Quality	Ecological Habitat (Acres)	Human Habitat (Acres)
Cement manufacture	$30	High	0	0
	+3.0	*+2.0*	*−1.0*	*−1.0*
Flowable fill	$55	Medium	0	0
	+1.0, −2.0	*−2.0*	*−1.0*	*−1.0*
Wetlands restoration	$75	High	+10	0
	−1.0	*+2.0*	*+3.0*	*−1.0*
Upland disposal cell	$40	Medium	0	+4
	+2.0, −1.0	*−2.0*	*−1.0*	*+3.0*

Note: The actual alternative planned for use in the Cocheco River project is the upland disposal cell. Dominance rankings are given in italics according to the number of clearly inferior (positive) or superior (negative) alternatives.

and 0 (from both human and ecological habitat), divided by the total number of spaces in the matrix made up of competing alternatives (in rows) and criteria (columns), which is 12. The result is 5 divided by 12, or 0.42. Negative flows are computed on the basis of negative rankings. Lastly, overall comparison of positive flows, negative flows, or the sum of these may determine alternative orderings. Often, the alternative orderings provided by the positive and negative flows are identical. When they are not, PROMETHEE may have identified alternatives that are incomparable. In this case, one alternative may exist that has both outstanding strengths and serious shortcomings. Selecting this alternative may reflect a strongly held preference for the criteria assessed as strengths—a position that may generate controversy.

An example ordering is shown in Fig. 1, with positive flows reported in a small box above negative flows. Of the seven stakeholders that participated in the ordering of preferred alternatives, the decision analysis correctly predicted the elicited ordering of all four alternatives for three of the stakeholders. In the other four cases, the stakeholders' first and second choices matched exactly. These results suggest that researchers can rely on stakeholder value elicitation instruments to communicate a reasonably well-quantified expression of values that can prioritize development of the current alternatives or screen new alternatives. Moreover, while the decision matrix in this case was fairly simple for stakeholders to analyze heuristically, the consistency between predicted and elicited results suggests that decision analysis may be a valuable tool to assist decisionmakers in evaluating more complex situations.

Considerable uncertainties are built into both the value elicitation and performance assessment instruments. Therefore, it is important to investigate the stability of the alternative orderings (i.e., the sensitivity of the ordering to the criteria weightings). When small changes in criteria weights result in a change in preference ordering, decisionmakers may surmise that the preferences are weakly held, and that opportunities for compromise may exist. Alternatively, when the preference orderings are quite stable, they may be the result of strongly held views. Two or more such groups with different preferences may be in conflict.

To simplify the analysis, like-minded stakeholders were placed into four general groups according to the criteria, that they held to be most important. Groups

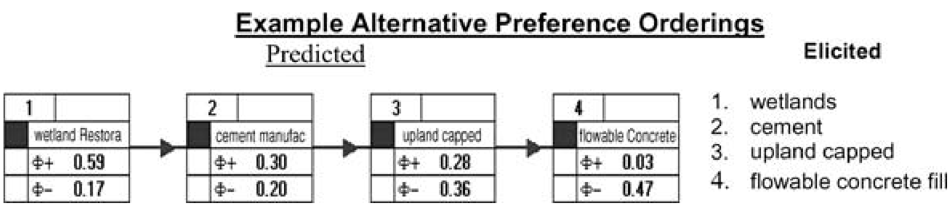

Fig. 1. Based on individual preference functions, *Decision Lab* can predict the order in which any stakeholder would prefer available alternatives using PROMETHEE. Predicted results for all stakeholders were compared to the actual ordering of alternatives elicited from stakeholder inspection of the performance table given to stakeholders during the verification process.

Table V. Criteria Weightings of Typical Stakeholder Groups

	Human Habitat	Ecological Habitat	Environmental Quality	Cost	1st Choice	2nd Choice
Human health (3)	0.5	0.1	0.25	0.15	Upland cap +0.6, −0.25	Cement +0.32, −.20
Eco/Env (6)	0.2	0.3	0.4	0.1	Wetland +0.57, −0.17	Cement +0.37, −0.17
Balanced (2)	0.25	0.25	0.25	0.25	Cement +0.42, −0.17	Upland cap +0.42, −0.33 Wetland +0.42, −0.33
Cost group (1)	0.25	0.05	0.1	0.6	Cement +0.67, −0.10	Upland cap +0.65, −0.28

Note: The numbers in parentheses indicate the number of respondents in each group. Positive and negative flows are separated by commas below the name of the preferred alternatives.

were differentiated as those most concerned with human health, with ecology and the environment, with a balance of factors, and with costs. The criteria weights used to represent each group are presented in Table V, and the first two preference alternatives are predicted for the group. Note that in some cases, the ranking of alternatives would change subject to whether the most positive, least negative, or best combination of flows is used as the basis of the ordering. In these cases, the alternatives may not be directly comparable, and a strict preference may not be completely expressed. Also, the balanced group presents an interesting case in which two alternatives are equally preferred (in both positive and negative flows) as second best.

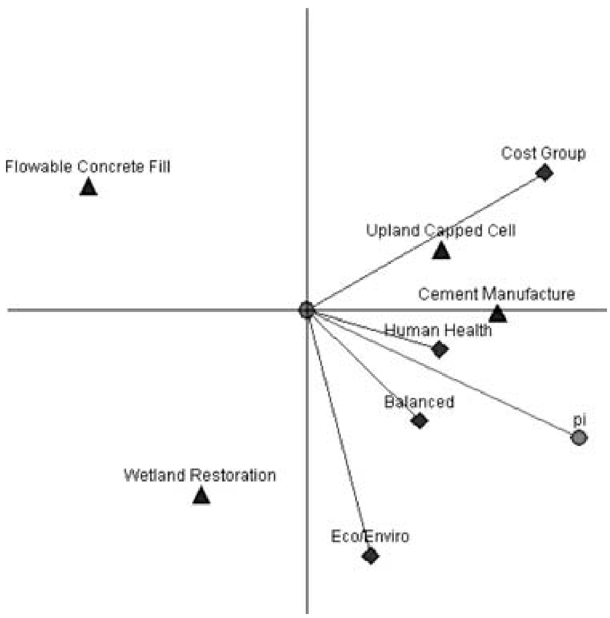

Fig. 2. Graphical analysis depicts the relation between different stakeholder groups (diamonds) and the alternatives they are expected to prefer (triangles). In general, the groups that have the greatest potential for disagreement are represented by axes that are pointing away from one another. The "pi" axis is an average of all groups, representing the consensus if all groups are counted equally.

Using principal components analysis, *Decision Lab* is capable of graphical analysis of the preferences of each different group relative to one another. Fig. 2 depicts each group on separate axes. In general, the axes point toward the preferred alternatives and away from the least preferred. The length of the axes is indicative of the conviction with which the group view is held. The graph is most useful at identifying potential conflicts between different groups. Although all parties can agree that flowable concrete fill is not appropriate for this site, the Cost group and Eco/Environmental group are at obtuse angles to one another, and thus they are likely to be at odds. In this case, agreement between these groups may be difficult or impossible to achieve. However, a consensus satisfying to the majority of the groups may be reached through a compromise solution.

To investigate the possibility that one of the alternatives may emerge as a consensus choice, the strength of conviction of each group must be investigated. One approach is to estimate the minimum change in expressed criteria weighting required to effect a change in the preference ordering. This approach may obviate the need to reliably and precisely establish exact criteria weights (Lahdelma & Salminen, 2001). Instead, the rankings may be interpreted more as one of many likely (or unlikely) outcomes. For example, a slight overweighting of any one criterion for the Balanced group would break the tie for second place between wetlands restoration and upland capped cell. The likelihood must be considered that, on further reflection, the Balanced group might change its views.

5.6. Case Study Conclusions

The principal purpose of the MCDA approach employed is not necessarily to find the "best" decision, but to improve the understanding of different stakeholder values. The approach of eliciting these values in parallel to development and assessment of the alternatives at hand is unusual, but it may allow for smoother introduction of new technological alternatives (such as beneficial reuse of contaminated sediments) at a more fully developed point in the decision process. So long as expert assessments of the new technologies are consistent with the criteria and metrics established in conjunction with stakeholders, the outranking methods presented may provide an effective tool for assessment of which stakeholder groups may be most likely to support the new alternative, or where potential compromises (or opposition) may be discovered. In progressing this research, the following general observations were made:

1. The stakeholders involved were eager to have their values heard and incorporated into the management decision process, but critical of written survey methods (although they did confirm the effectiveness of the survey at conveying a simplified, basic message).
2. The research experts recognized the importance of stakeholder values to management of environmental problems, but were especially challenged by the process of devising measurable, quantitative metrics that would faithfully reflect the decision criteria expressed.
3. The systematic outranking analysis is more effective at identifying dominated alternatives (such as flowable fill in this case), discovering the sensitivity of second-best alternatives to preference weightings, and in general sorting out complex tradeoffs than are stakeholder or expert heuristic processes.

The stakeholder value elicitation/public participation and decision analysis process studied may have potential for other environmental managers as a guideline on how to cost-effectively incorporate the public and affected parties into the decision process in a meaningful way.

ACKNOWLEDGMENTS

This article is partly the result of a Society for Risk Analysis workshop held in Palm Beach, FL, from June 22 to 24, 2004. The work presented by the authors was performed in their private capacities and does not reflect the policies or views of their parent institutions. The authors are grateful to Drs. Ganoulis, Cooke, Small, Valverde, Yoe, Sullivan, and Dortch, for useful suggestions. The authors are grateful to Shai Sahai for excellent technical assistance. Support for this study was provided by the USACE Hazard/Risk Focus Area of the Environmental Quality Technology Program (IL, FKS), the USACE Dredging Operations and Environmental Research (DOER) Program (GAK), and the USACE Center for Contaminated Sediments (IL, TSB). Additional support was provided by NOAA through the Cooperative Institute for Coastal and Estuarine Environmental Technology (KHG, IL, TPS, SR). Permission was granted by the Chief of Engineers to publish this material.

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