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From comparative risk assessment to multi-criteria decision analysis and adaptive management: Recent developments and applications

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Abstract

Environmental risk assessment and decision-making strategies over the last several decades have become increasingly more sophisticated, information-intensive, and complex, including such approaches as expert judgment, cost–benefit analysis, and toxicological risk assessment. One tool that has been used to support environmental decision-making is comparative risk assessment (CRA), but CRA lacks a structured method for arriving at an optimal project alternative. Multi-criteria decision analysis (MCDA) provides better-supported techniques for the comparison of project alternatives based on decision matrices, and it also provides structured methods for the incorporation of project stakeholders' opinions in the ranking of alternatives. We argue that the inherent uncertainty in our ability to predict ecosystem evolution and response to different management policies requires shifting from optimization-based management to an adaptive management paradigm. This paper 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 CRA, MCDA, and adaptive management methods applicable to environmental remediation and restoration projects. We propose a basic decision analytic framework that couples MCDA with adaptive management and its public participation and stakeholder value elicitation methods, and we demonstrate application of the framework to a realistic case study based on contaminated sediment management issues in the New York/New Jersey Harbor.

Keywords: Comparative risk assessment; Decision analysis; Adaptive management; Risk analysis; Sediments

1. Introduction: comparative risk assessment and evolving decision analysis methodologies

Risk management of environmental projects requires balancing scientific findings with multi-faceted input from many stakeholders with different values and objectives. In such instances, systematic decision analysis tools are an appropriate method to solve complex technical and behavioral issues (McDaniels, 1999). Regardless of the specific project, risk managers typically have four types of information that are used to make decisions: 1) the results of modeling and monitoring studies, 2) risk analysis, 3) cost or cost–benefit analysis, and 4) stakeholder preferences (Fig. 1a). These four types of information range from extremely quantitative to extremely qualitative, and structured information about stakeholder preferences may not be presented to decision-makers at all. In cases where the decision-maker does receive information on stakeholder preferences, the information may be handled in a subjective manner that exacerbates the difficulty of defending the decision process as reliable or 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, decision-makers often do not optimally use all available and useful information in choosing between identified project alternatives.

In response to these decision-making challenges, some regulatory agencies and environmental managers have moved toward more integrative decision analytic processes, such as comparative risk assessment (CRA) or multi-criteria decision

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analysis (MCDA). These methods are designed to raise awareness of the trade-offs that must be made among competing project objectives, help compare alternatives that are dramatically different in their potential impacts or outcomes, and synthesize a wider variety of information (Fig. 1b).

Comparative risk analysis has been most commonly applied within the realm of policy analysis. Andrews et al. (2004), for example, distinguish between CRA use at macro and micro scales. At the macro scale, programmatic CRA has helped to characterize regional and national environmental priorities by comparing the multi-dimensional risks associated with policy alternatives. U.S. government agencies at various levels have logged significant experience with policy-oriented, macro-level CRA. International CRA applications are reviewed in Tal and Linkov (2004) and in Linkov and Ramadan (2004). At smaller scales, so-called micro-CRA studies have compared interrelated risks involving specific policy choices, such as chemical versus microbial disease risks in drinking water. In these micro-scale applications, the CRAs often have specific objectives within the broader goal of evaluating and comparing possible alternatives and their risks. Bridges et al. (2005) discuss micro-scale applications of CRA in more detail.

Central to CRA is the construction of a two-dimensional decision matrix that contains project alternatives' scores on various criteria. However, CRA lacks a structured method for combining performance on criteria to identify an optimal project alternative. MCDA methods and tools, on the other hand, do provide a systematic approach for integrating risk levels, uncertainty and valuation. MCDA helps decision-makers evaluate and choose among alternatives based on multiple criteria using systematic analysis that overcomes the limitations of unstructured individual or group decision-making. Although almost all decision analysis methodologies share similar steps of organization in the construction of the decision matrix (often the end result of the CRA process), there are many MCDA methodologies which each synthesize the matrix information and rank the alternatives by different means (Yoe, 2002). Yet, taken by themselves, few MCDA approaches are specifically designed to incorporate multiple stakeholder perspectives or competing value systems.

Fortunately, MCDA tools can be naturally linked with an adaptive management paradigm. Adaptive management explicitly acknowledges the uncertainty in managers' knowledge of a system. As a consequence of this uncertainty, adaptive management holds that no single best policy can be selected, but rather a set of alternatives should be dynamically tracked to gain information about the effects of different courses of action. Adaptive management concepts were introduced more than 20 years ago, but their implementation to date has been primarily limited to a few large-scale projects in long-term natural resource management, where uncertainty is so overwhelming that optimization is not possible. Even though managers of smaller projects are confronted with the same problems and often have to go through the frustrating experience of changing their management strategy when it fails, our review shows that the field of environmental management is far from accepting and using adaptive management approaches. Although adaptive management is recognized and even recommended by many state and government agencies, adaptive management applications vary widely in their implementation of the concept and there is no framework that robustly incorporates adaptive management in environmental practice.

In this paper, we review regulatory policies and case studies of MCDA applications and successful adaptive management implementation across a wide range of projects and application areas. Our review indicates a need to integrate adaptive management with a set of decision-making tools that will allow it to build on current optimization-based management approaches. We are thus proposing a solution in which we

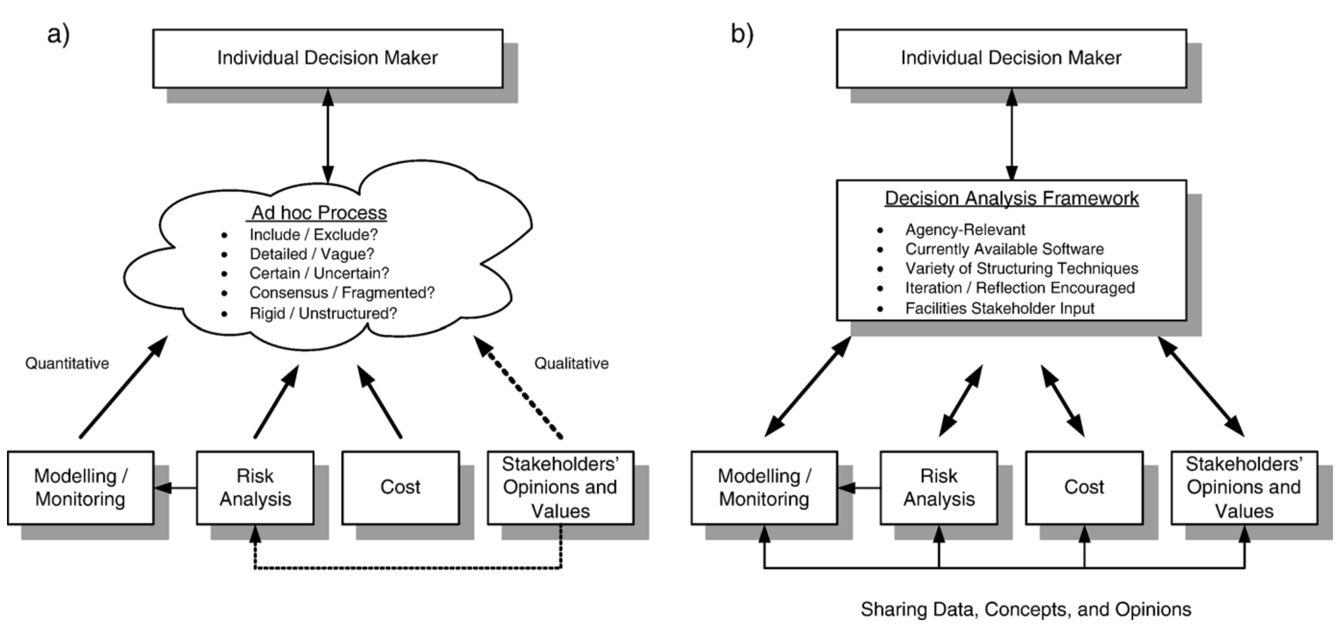


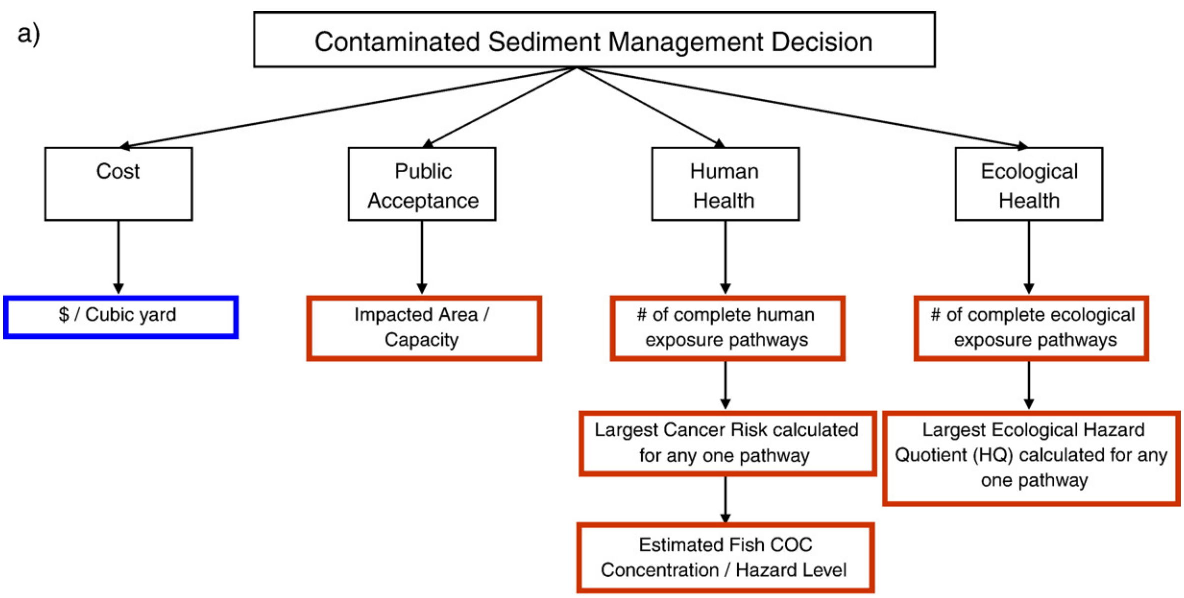
Fig. 1. Current (a) and evolving (b) decision-making processes for contaminated sediment management.

choose a strong adaptive management framework, for which there exist many support tools in the literature, and integrate it with multi-criteria decision analysis as a best method for dealing with uncertainty when selecting a management option. The two methods complement each other and form a comprehensive management framework.

2. Comparative risk assessment application to New York/New Jersey Harbor

We have taken the New York/New Jersey Harbor as a case study to illustrate an environmental management problem that could benefit from combined MCDA/adaptive management application. A decision scenario for the harbor is presented in Fig. 2. The harbor faces contaminated sediment management issues — several million cubic meters of sediments must be dredged each year to maintain navigation channels for harbor access (Wakeman and Themelis, 2001). Due to long-term human use of the harbor area, significant contaminant concentrations have been recorded in certain areas. Additional challenges have been created by the restriction of ocean disposal to only clean sediments, as well as plans for deepening existing channels to allow increased access for larger vessels. For these reasons, decision-makers elected to systematically explore additional sediment management options and their associated costs and risks.

A comparative screening-level risk assessment (Driscoll et al., 2002) was developed for generalized areas within the



b)	Cost	Public Acceptability	Ecological Risk		Human Health Risk		
Alternatives	($/CY)	Impacted Area/Capacity (acres / MCY)	Ecological Exposure Pathways	Magnitude of Ecological HQ	Human Exposure Pathways	Magnitude of Maximum Cancer Risk	Estimated Fish COC / Risk Level
CAD	5-29	4400	23	680	18	2.8 E-5	28
Island CDF	25-35	980	38	2100	24	9.2 E-5	92
Near-shore CDF	15-25	6500	38	900	24	3.8 E-5	38
Upland CDF	20-25	6500	38	900	24	3.8 E-5	38
Landfill	29-70	0 *	0	0 *	21	3.2 E-4	0 *
No Action	0-5	0 *	41	5200	12	2.2 E-4	220
Cement-Lock	54-75	0	14	0.00002	25	2.0 E-5	0 *
Manufactured Soil	54-60	750	18	8.7	22	1.0 E-3	0 *

Fig. 2. (a) Example decision criteria for the New York/New Jersey Harbor. Blue box: NY/NJ Dredged Material Management Plan (USACE, 1999) and Expert Opinion; red boxes: Driscoll et al. (2002); (b) example decision matrix for the New York/New Jersey Harbor. An ∗ beside a criteria value denotes an estimated value of 0 where Driscoll et al. (2002) provided a rating of “not applicable”.

harbor. Eight sediment management alternatives (including no action) were identified for consideration and assessed according to their performance on the criteria of human health risk and ecological risk: Confined Aquatic Disposal (CAD) refers to placing the sediments within a pit or depression on the bottom of a water body and capping the contaminated sediments with clean sediment; a Confined Disposal Facility (CDF) is a diked area where dredged material is placed and stored; Landfill refers to placement at a landfill site; and Cement Lock and Manufactured Soil refer to treatment or processing techniques that are applied to prepare the material for storage or subsequent beneficial uses (Fig. 2). To evaluate human health risk, three criteria were selected: the number of complete human exposure pathways, the maximum cancer risk calculated from all the pathways, and fish chemical-of-concern (COC) concentration. To evaluate ecological risk, two similar criteria were selected: the number of complete exposure pathways and the maximum calculated hazard quotient from all the pathways. The estimated cost in dollars per cubic yard was used as a cost criterion. Cost estimates were derived from expert interviews as well as estimates from the Dredged Material Management Plan (DMMP) for the Port of New York and New Jersey (USACE, 1999). In the example developed here, the impacted area (i.e. the amount of land required to manage the contamination) divided by the overall project capacity, an additional measure of cost, was expected to be inversely correlated with public acceptance. Fig. 2b provides the quantitative estimates for these criteria to parameterize the decision matrix (for greater detail, see Kiker and Bridges, submitted for publication).

The result of CRA is usually a qualitative examination of the decision matrix. For example, the conclusions of Driscoll et al. (2002) include: "the extent of the impacted area... is substantially greater for the near-shore and upland CDFs than for the island CDF;" "risk from the island CDF is greater than other placement and treatment alternatives;" and "relative risk for exposure to the undiluted sediment of the no-action alternative exceeds the relative risk of all other alternatives." Even though these conclusions may be indeed useful, they do not provide integration across multiple criteria and multiple alternatives. The rest of this paper presents decision support tools for higher-level integration of criteria and alternatives.

3. MCDA methods and tools

In contrast to CRA, MCDA provides a more fully developed approach to environmental management (Table 1). Whereas a decision matrix marks the endpoint for CRA, it is only an intermediate product of MCDA. After matrix generation, different MCDA methods require different types of value information and follow various optimization algorithms. A detailed analysis of the theoretical foundations of these methods and their comparative strengths and weaknesses is presented in Belton and Stewart (2002). Some techniques rank options, some identify a single optimal alternative, some provide an incomplete ranking, and others differentiate between acceptable and unacceptable alternatives.

Table 2 summarizes a number of current, sophisticated MCDA methods. Multi-attribute utility theory (MAUT) and the analytical hierarchy process (AHP) are more complex methods that use optimization algorithms, whereas outranking eschews optimization in favor of a dominance approach. The optimization approaches employ numerical scores to quantify the merit of each option on a single scale. Scores are developed from the performance of alternatives with respect to individual criteria and 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, the MAUT method transforms diverse criteria, such as those shown

Table 1
Comparison of decision process elements for *ad hoc* decision-making, comparative risk assessment, and multi-criteria decision analysis

Elements of decision process	*Ad hoc* decision-making	Comparative risk assessment	Multi-criteria decision analysis
Define problems	Stakeholder input limited or non-existent. Therefore, stakeholder concerns may not be addressed by alternatives.	Stakeholder input collected after the problem is defined by decision-makers 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 decision-maker usually from pre-existing 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 sub-criteria are often defined.	Criteria and sub-criteria hierarchies are developed based on expert and stakeholder judgment.
Gather value judgments on relative importance of criteria	Non-quantitative criteria valuation weighted by decision-maker	Quantitative criteria weights are sometimes formulated by the decision-maker, but in a poorly justified manner.	Quantitative criteria weights are obtained from decision-makers 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 2
Comparison of critical elements, strengths and weaknesses of several advanced MCDA methods: MAUT, AHP, and outranking (after ODPM, 2004; Larichev and Olson, 2001)

Method	Important elements	Strengths	Weaknesses
Multi-attribute utility theory	Expression of overall performance of an alternative in a single, non-monetary number representing the utility of that alternative	Easier to compare alternatives whose overall scores are expressed as single numbers	Maximization of utility may not be important to decision-makers
	Criteria weights often obtained by directly surveying stakeholders	Choice of an alternative can be transparent if highest scoring alternative is chosen	Criteria weights obtained through less rigorous stakeholder surveys may not accurately reflect stakeholders' true preferences
		Theoretically sound — based on utilitarian philosophy	Rigorous stakeholder preference elicitations are expensive
		Many people prefer to express net utility in non-monetary terms	
Analytical hierarchy process	Criteria weights and scores are based on pairwise comparisons of criteria and alternatives, respectively	Surveying pairwise comparisons is easy to implement	The weights obtained from pairwise 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: "it outperforms the other on enough criteria of sufficient importance (as reflected by the sum of criteria weights)" and it "is not outperformed by the other in the sense of recording a significantly inferior performance on any one criterion"	Does not require the reduction of all criteria to a single unit	Does not always take into account whether over-performance on one criterion can make up for under-performance on another
	Allows options to be classified as "incomparable"	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	The algorithms used in outranking are often relatively complex and not well understood by decision-makers

in Fig. 2, into one common 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 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, AHP uses a quantitative comparison method that is based on pair-wise comparisons of decision criteria rather than utility or 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 decision-maker would 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 AHP 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. 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 under-performance 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 (Seager, 2004).

4. MCDA applications in environmental management

Our non-exhaustive review of recent literature (Table 3) shows that MCDA has been used to support decision-making in contaminated site management and related areas. In this section we summarize decision analysis applications published in English language journals over the last 10 years that were located through Internet and library database searches (for greater detail, see Linkov et al., 2004, 2003). 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.

4.1. Remediation of contaminated sediments and aquatic ecosystems

MCDA has been applied to the remediation of sediments and aquatic systems. MAUT, for example, has been used in radioactive site management (Arvai and Gregory, 2003; Gallego et al., 2004; Ríos-Insua et al., 2002) and has also been utilized in the Superfund cleanup process (Grelk, 1997; Grelk et al., 1998; Parnell et al., 2001). Wakeman (2003) uses the simple multi-attribute rating technique (SMART) to analyze alternatives for dredging contaminated sediments at a Superfund site in Montana. Pavlou and Stansbury (1998) apply a formal analysis of the trade-off between environmental risk reduction and cost to contaminated sediment disposal, and Stansbury et al. (1999) later augment the use of risk–cost trade-off analysis with fuzzy set theory and composite programming. Rogers et al. (2004) employ an outranking method to incorporate stakeholder values into the process of selecting one of a group of novel technological alternatives for sediment management. 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.

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 aquatic ecosystems. Doley et al. (2001) use models and cost-effectiveness analysis to find an optimal way to reduce nitrogen discharge into the Potomac River. Wladis et al. (1999) evaluate alternative emission control scenarios for NO_x, SO_2, and NH_3, considering how these pollutants affect groundwater. Kholghi (2001) and Ganoulis (2003) apply MCDA to decide how to manage wastewater 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. Outranking has also been used to prioritize wastewater projects (Al-Rashdan et al., 1999) and to find an optimal wastewater treatment system (Van Moeffaert, 2002).

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. MAUT-based methods have been applied to compare current and alternative water control plans in the Missouri River (Prato, 2003), while Ni, Borthwick, and Qin use AHP to determine the optimal length and location for a coastline reclamation project (Ni et al., 2002; Qin et al., 2002). Other MCDA methods, including distance techniques such compromise programming and game theory, have also been used (Mimi and Sawalhi, 2003). Analyses of water bodies in the United States (Bella et al., 1996), Europe (Özelkan and Duckstein, 1996), and South Africa (Joubert et al., 1997) have examined water uses such as consumption, recreation, conservation, and power generation, while a number of other analyses (Gregory and Failing, 2002; Hämäläinen et al., 2001; Marttunen and Hämäläinen, 1995; Gregory and Wellman, 2001; McDaniels, 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.

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. In two papers (Mardle et al., 2004; Soma, 2003), AHP analysis involving stakeholder opinion is also applied to fishery management. 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 identify the optimal allocation of funds for research into fish stocks.

Table 3
MCDA applications for contaminated site 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	Ríos-Insua et al., 2002; Gallego et al., 2004
	MAUT	Remediation of mixed-waste subsurface disposal site	DOE	Grelk, 1997; Grelk et al., 1998; Parnell et al., 2001
	Outranking (PROMETHEE)	Selecting novel technological alternatives for sediment management	Dartmouth College and the 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 et al., 2000; Accorsi et al., 1999a,b
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	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, 2002
	Outranking (PROMETHEE)	Prioritization of wastewater projects in Jordan	Staffordshire University, UK	Al-Rashdan et al., 1999
	Elicitation of criteria from stakeholders	Determining the effects of a proposed 30% reduction in nitrogen loading to the Neuse Estuary in North Carolina	University of North Carolina	Borsuk et al., 2001
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 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
	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 and MAUT/SMART	Environmental impact assessment of 2 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
	Mental modeling	Watershed management	USEPA	Whitaker and Focht, 2001; Focht et al., 1999
Prioritization of sites/areas for industrial/military activity	AHP + GIS	Land condition assessment for allocation of military training areas	US Army Engineering Research and Development Center	Mendoza et al., 2002
	AHP + GIS	Selection of boundaries for national Park	International Institute for Geoinformation Science and Earth Observation, the Netherlands	Sharifi et al., 2002
	PROMETHEE	Waste management activities in Canada	Natural Sciences and Engineering Research Council of Canada	Vaillancourt and Waaub, 2002
	ELECTRE + GIS	Land management: develop a land suitability map for housing in Switzerland	Swiss National Foundation for Research (FNRS)	Joerin and Musy, 2000
	MAUT + GIS	Selection of park boundaries	DOE	Keisler and Sundell, 1997
Natural resource planning	AHP	Natural park management	USDA Forest Services	Schmoldt et al., 1994; Peterson et al., 1994; Schmoldt et al., 2001
	MAUT	Management of spruce budworm in Canadian forests	National Science and Engineering Research Council of Canada	Levy et al., 2000
	MAUT	Improvement of habitat suitability measurements	Finnish Forest Research Instyitute	Store and Kangas, 2001
	AHP	Environmental vulnerability assessment for Mid-Atlantic Region	US EPA/DOE	Tran et al., 2002
Stakeholder involvement	MAUT	Risk attitudes by farmers in Spain	EU; Spanish Government	Gomez-Limon et al., in press
	MAUT	Air-Quality Valuation in Korea	Korea University	Kwak et al., 2001
	PROMETHEE	Sustaining exploitation of Renewable Energy Sources	National Technical University of Athens	Georgopoulou et al., 1998
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 in for the Buccoo Reef Marine Park in Tobago	UK 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

5. Adaptive management and environmental decision-making

The MCDA methods and tools discussed above can be used to support environmental decisions in traditional management schemes, but we see their strength when coupled with adaptive management. In traditional management (Fig. 3a), goals are set and different management strategies are considered. One management strategy is selected as the optimal one, and once it is implemented, its performance may not be monitored closely. At some point, the strategy will likely be evaluated, and if it is perceived to have failed a different one will be installed in its place. The goals themselves are not often reconsidered, and in this framework any change in the management strategy or admission of uncertainty about the system being managed is prone to be interpreted as failure.

Adaptive management stands in contrast to existing environmental management methods. Adaptive management acknowledges that uncertainty is inherent in any natural system, and it seeks to minimize this uncertainty by learning about the system being managed. Its basic process is straightforward: when managing any system, one chooses a management action, monitors the effects of the action, and adjusts the action based on the monitoring results. There are two types of adaptive management: passive (Fig. 3b) and active (Fig. 3c). Both processes begin with setting goals, modeling the system, and selecting and implementing a management strategy. Passive adaptive management involves implementing one management strategy at a time, whereas in active adaptive management multiple experimental alternatives are examined in contrast to a control to isolate factors which affect the system. The managed ecosystem is then monitored to collect as much information as possible about the effects of the management strategy on the system. Ideally, the results of the monitoring affect model estimation and parameter values, and the management strategy is evaluated and adjusted as a result. During the adaptive management process, in contrast to traditional management, change is welcome, learning is emphasized, and even goals and objectives for the project may be revisited and revised.

The recent publication *Adaptive Management for Water Resources Project Planning* (NRC, 2004) provides a comprehensive framework for the entire adaptive management process. In our review, we use the six elements of adaptive management laid out by the National Research Council (NRC, of the United States National Academy of Sciences) to summarize multiple studies where elements of adaptive management were applied. This section introduces these elements and presents a few important studies that could help with understanding the framework we propose later in this paper. Papers are drawn from a wide range of application areas, from fisheries to wildlife management to forest, terrestrial, and aquatic ecosystems. Readers are encouraged to consult the accompanying tables (where papers are laid out by application area — see Table 4 for government applications, Table 5 for applications in the literature, and Table 6 for review papers) as well as our full review (Satterstrom et al., 2006) for more details. Although the majority of examples are drawn from North American literature, the adaptive management approach is applicable in all locations.

5.1. Management objectives which are regularly revisited and accordingly revised

The first key element of adaptive management is a regular review of a project's objectives. Stakeholders must agree on what the basic objectives are, and the project's objectives should be reviewed when new information becomes available. Interestingly,

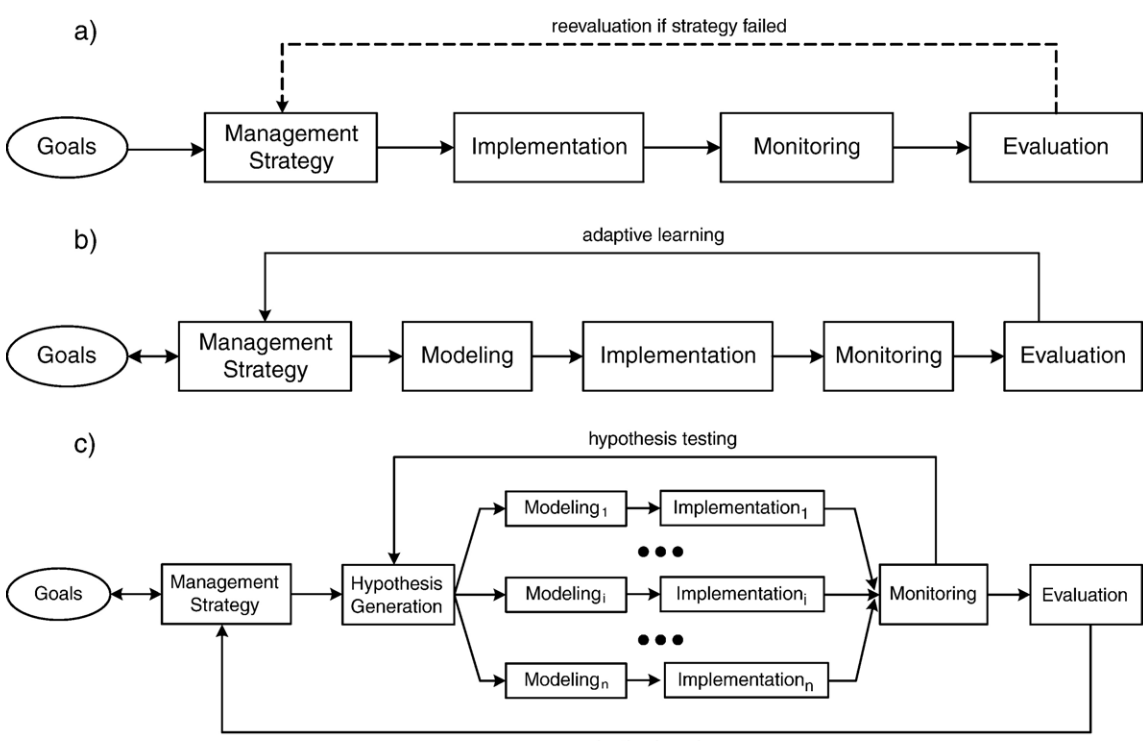


Fig. 3. (a) Traditional management; (b) passive adaptive management; (c) active adaptive management.

few adaptive management papers discuss the updating and revision of objectives as new information is acquired. Many, in fact, take it for granted that their objectives are static goals. The NRC explicitly incorporates this step in its framework for the remediation of contaminated Navy sites (NRC, 2003).

5.2. A model of the system(s) being managed

Modeling tools are integral to many adaptive management processes. They provide a basis for understanding why change occurs in the environment being managed and can also be used to predict the possible effects of different strategies (such as Bearlin et al., 2002, who uses a stochastic population model for trout cod while choosing an adaptive management strategy for their reintroduction). Quantitative mathematical models are preferred, but because adaptive managers often deal with substantially uncertain situations, conceptual models are still useful (for example, Thom, 1997, 2000). Our review indicates that modeling is one of the more widely used components of the adaptive management process. Nevertheless, models often address ecological processes only; integrated models that explicitly incorporate decision alternatives as well as costs and social considerations are still rare.

5.3. A range of management choices

An active adaptive management process includes the generation of a range of management choices. Implementing multiple strategies simultaneously, along with a control, is conceptually similar to a scientific experiment, albeit with less straightforward results. Although our review shows that examples of passive adaptive management centered around a single policy dominate the literature, there are a few good examples of the active method. In an important early paper, Walters and Hilborn (1978) discuss adaptive management in the context of the optimization of harvesting policies for exploited wild populations. More recently, Allison et al. (2004) model and evaluate multiple options as they come to a conclusion about logging road deactivation in order to manage landslide risk and ecological health.

5.4. Monitoring and evaluation of outcomes

Once a manager has generated and implemented a range of options, monitoring and evaluation are required to determine which option performs the best. This is by far the most heavily emphasized aspect of adaptive management. Many monitoring frameworks have been developed, covering either specific types of areas such as multinational large marine ecosystems (LMEs) (Duda and Sherman, 2002) or protected areas in general (Parrish et al., 2003), and ranging from simple data collection to sophisticated statistical methods (Sit and Taylor, 1998).

5.5. A mechanism(s) for incorporating learning into future decisions

Because the central idea of adaptive management is to reduce uncertainty about the system being managed, learning is an important goal for any project. Kiker et al. (2001) emphasize that current knowledge is insufficient for Everglades restoration, and they advance adaptive management as a way to promote holistic understanding useful to decision-makers and political representatives. Many other authors also espouse learning as an objective: for example, McDaniels and Gregory (2004) recommend that learning be a goal of the management decision process.

5.6. A collaborative structure for stakeholder participation and learning

An important element of adaptive management is the inclusion of stakeholders. All affected parties, including the public, industry, scientists, and government agencies, need to feel represented and need to gain information through the process. Many case studies have shown that stakeholder involvement is essential to adaptive management (Gunderson, 1999; Gilmour et al., 1999; Shindler and Aldred Cheek, 1999). Active adaptive management could easily be seen as environmental experimentation, and it is therefore important for decision-makers to keep stakeholders – especially the public – informed not only of its goals, but also of the problems it faces and its methods for addressing them. When management fails to incorporate stakeholders into decisions, distrust and political tension result.

6. Emergence of adaptive management in regulatory agencies

Regulatory agencies in the United States and around the world recommend adaptive management, but agencies often implement or emphasize only specific elements of the process. The EPA, for instance, has implemented adaptive management in many projects. Among the most notable are the Mississippi River Basin project, which utilizes models and monitoring quite heavily as it attempts to reduce the uncertainties surrounding the biochemical mechanisms of hypoxia (EPA, 1999a, 2001b), and the Lake Superior Lakewide Management Plan (EPA, 2002), which calls for a less structured periodic refining of management strategies based on new information and public input. These EPA examples show the range of possible variability between adaptive management projects — whereas the Mississippi River Basin project emphasizes the modeling and monitoring aspects of adaptive management but lacks stakeholder involvement, the Lake Superior project does exactly the opposite, soliciting public input but not emphasizing modeling or monitoring.

The National Oceanic and Atmospheric Administration (NOAA) uses adaptive management, especially in its coastal management and coastal habitat restoration activities (NOAA, 2004c). The adaptive management process implemented in these cases is passive, involving iterations of a five-step cycle: plan, act, monitor, evaluate, and adjust (NOAA, 2004a). NOAA emphasizes the monitoring and evaluation elements of adaptive management. Sutinen (2000) developed a monitoring and assessment framework for the agency, but the degree to which its projects include other aspects, such as modeling or

Table 4
Government application and guidance documents

Agency	Topic	Methods/tools	Application area	Elements of AM 1	2	3	4	5	6	Citation(s)
Environmental Protection Agency	Total maximum daily loads (TMDLs) for pollutants in the environment	Follow-up monitoring and evaluation	TMDLs for sediments, pathogens				■	▪		EPA, 1999b, 2001a
	Watershed management guide for tribes	Implementation monitoring, validation monitoring, effectiveness monitoring	Watershed management				■	▪		EPA, 2000
	Management of contaminated or hazardous sites, including brownfields	Sustainable development, monitoring framework	Hazardous site management	▪			■		▪	EPA, 1999a
	Integrated assessment of hypoxia in the northern Gulf of Mexico	Models to interpret change in hydrologic and ecological systems	Coastal and marine ecosystems		■		■	▪		EPA, 1999a, 2001b
	Lake Superior Lakewide Management Plan (LaMP), 2000	Extensive stakeholder involvement in LaMPs	Lake management	▪				■	■	EPA, 2002
	The "Triad" methodology for hazardous site management, applied specifically to brownfields	Systematic project planning, dynamic work plan strategies, and real-time measurement in service of a pre-fabricated decision support matrix	Hazardous site management		■	▪	■	■	▪	EPA, 2003
Department of the Interior	DOI's departmental manual	Adaptive management required of all bureau heads	NEPA compliance				▪			DOI, 2004
	Southeastern adaptive management group, better integration between research and management	Ecological and statistical theory, analytical and decision-support tools, and institutional arrangements	Adaptive management group				■		■	SEAMG, 2004
	The Bureau of Land Management's land use authorizations for oil and gas programs	Emphasis on monitoring	Land use				▪			BLM, 2003
	Restoration and enhancement of 42 miles of fish habitat in California while simultaneously supporting hydroelectricity generation	Detailed monitoring	Watershed management	▪	▪		■	▪	■	USBR, 2001
	Management of mercury contamination of Sacramento River Watershed	Offsets, modeling, monitoring	TMDLs, watershed management		■	▪	■		■	USGS, 2004
National Marine Fisheries Service	Socioeconomic and governance-related human dimensions of managing large marine ecosystems	Interaction matrices	Coastal and marine ecosystems				■		■	Sutinen, 2000
	Coastal restoration and management guidance; case study in Rhode Island marsh restoration	Well-formulated objectives and detailed monitoring, system-development matrix	Coastal and marine ecosystems		▪		■	▪	■	NOAA, 2004a,b,c
Department of Energy	Land use planning and process framework	Learning through monitoring	Land use				■	▪		DOE, 1996
	Modernizing NEPA implementation	Learning through monitoring	NEPA				■	▪		DOE, 2003
	Adaptive management of salmon and hydroelectricity in the Columbia River basin	Models and computing power	Hydropower		■	▪	■	■	■	DOE, 2002
	Adaptive management of hydroelectricity in general	Expedited hydropower license issuance under the condition that adaptive management be used at the site	Hydropower				▪			FERC, 2000
Department of Agriculture	Monitoring	Implementation monitoring, baseline monitoring, validation monitoring, effectiveness monitoring	Natural resource conservation				■			USDA, 2003
USDA Forest Service	Use of new decision-making techniques in adaptively managing the Bent Creek Experimental Forest in Asheville, NC	Multi-criteria decision analysis — analytical hierarchy process	Forest and terrestrial ecosystems			■	■	■		Rauscher et al., 2000
California Coastal Commission	Performance evaluation for wetland mitigation projects	Passive adaptive management, well-defined monitoring program	Coastal and marine ecosystems			▪	▪			CCC, 1995
United States Navy	Application of adaptive management to the environmental cleanup of Navy facilities	Various analytical tools for evaluating remedy effectiveness and need for change	Remediation	■	■	■	■	■	■	NRC, 2003

United States Army Corps of Engineers	Use of ecological models and adaptive management in restoration of coastal ecosystems	System-development matrix	Coastal and marine ecosystems	▪	■	▪	■		▪	Thom, 1997, 2000
	Decision-making framework for United States Army Corps of Engineers ecosystem restoration projects	Model-building; alternative restoration designs as “bet-hedging” strategy; multi-attribute decision analysis	General adaptive management		■	■	▪	▪		Pastorok et al., 1997
	Guidance for monitoring within adaptive management framework for the United States Army Corps of Engineers	Framework for monitoring in adaptive management	General adaptive management				■	■		USACE, 2003a,b
Fisheries and Oceans Canada	Socioeconomic framework for ecosystem-based fisheries management	Institutional analysis and development framework	Fisheries			▪	■			Rudd, 2004
Health Canada	Adaptive management of emissions trading as part of mitigation measures for greenhouse gases	Stakeholder involvement and learning	Climate change management						■	CCHO, 2000
	Adaptive management in the guise of a health and air quality risk management framework	Stakeholder involvement at every step	Air quality risk assessment			▪	▪		▪	Health Canada, 2003
Environment Canada	The ecosystem approach to natural resource management	Acknowledging uncertainty, learning about system	Biodiversity conservation					▪		Environment Canada, 2004a
	Environmental assessment best practice guide for wildlife at risk In Canada	Precautionary principle	Wildlife management			▪	▪	▪		Environment Canada, 2004b
	Canadian national wildlife disease strategy	Adaptive risk assessment and problem response framework	Wildlife management				■	▪	■	Environment Canada, 2004c
British Columbia Forest Service	Framework and mechanics for adaptive management of forest ecosystems	Framework for running adaptive management workshops; solutions to common barriers	Forest and terrestrial ecosystems	■	▪	■	■	■	■	Nyberg, 1999
	Examples of case studies in which the BCFS is applying adaptive management in the field	Management experiments to learn more about managed system	Forest and terrestrial ecosystems			■	■			BCFS, 2000
British Columbia Ministry of Forests	Reasons to implement adaptive management, problems with adaptive management, and tools for adaptive management of forests in British Columbia	Workshops, decision analysis, project design teams	Forest and terrestrial ecosystems	■	■	■	■	■	■	Taylor et al., 1997
British Columbia Ministry of Sustainable Resource Management	Land and resource management plan for the North Coast of British Columbia	Usage of up-to-date information and implementation of adaptive management	Forest and terrestrial ecosystems			▪	■	■		BCMSRM, 2004
World Wildlife Federation	Problems with the European Union Common Fisheries Policy and suggestions for fixing them	Ecosystem-based management and the precautionary principle	Fisheries						■	WWF, 2001a
	Adaptive management and example applications in conservation	Adaptive management definition and framework	General Adaptive Management		■	■	■	■	■	WWF, 2001b

Six Adaptive Management Criteria:
1. Management objectives that are regularly revisited and accordingly revised.
2. A model(s) of the system being managed.
3. A range of management choices.
4. Monitoring and evaluation of outcomes.
5. A mechanism(s) for incorporating learning into future decisions.
6. A collaborative structure for stakeholder participation and learning.

Meaning of symbols:
■ = discussed in detail/demonstrated/performed in paper or case study reviewed by paper.
▪ = mentioned or recommended but not explicitly carried out.

Table 5
Adaptive management application papers

Application area	Topic	Methods/tools	Funding agencies	Elements of AM 1	2	3	4	5	6	Citation
Fisheries	Importance of learning in the risk management process with a case study involving water use for fisheries and hydroelectric power in Canada	Treating learning as an objective in collaborative stakeholder groups	University of British Columbia; Decision Research			▪	▪	■	■	McDaniels and Gregory, 2004
	Cooperation between small-scale users and management agencies in salmon management in British Columbia	Data sharing, building institutional capacity	Simon Fraser University					▪	■	Pinkerton, 1999
	Prevention of shocks to developing fishery populations through adaptive management	Adequate monitoring of biological and economic fishery data	University of Washington; South Pacific Commission, New Caledonia			■	■	■		Hilborn and Sibert, 1988
	Simulation of adaptive management strategies for the reintroduction of trout cod	Stochastic population model, simulated monitoring uncertainty	Cooperative Research Center for Freshwater Ecology	▪	■	■	■	▪	▪	Bearlin et al., 2002
	Simulating active vs. passive adaptive fisheries management in the Philippines	Ecological modeling software	Bedford Institute of Oceanography, Canada		■	■	■			Bundy, 2004
	The Decision Analysis and Adaptive Management (DAAM) Project and the Lake Erie walleye and yellow perch fisheries	Decision analysis to rank management alternatives and quantify uncertainty; adaptive management to reduce uncertainty	University of Guelph, Ontario		■	■	■	■	■	Nudds et al., 2003
Coastal and marine ecosystems	Wetland and finfish restoration	Restoration success index, passive adaptive management with thresholds for enacting pre-planned corrective measures	Public Service Electric and Gas Company			■	■			Weinstein et al., 1997
	Restoration of salt hay farm wetlands on the Delaware River Estuary	Evaluation of alternative channel construction techniques	American Society of Civil Engineers			■	▪	▪		Weishar and Teal, 1998
	Management of economic, environmental, social, and political aspects of large marine ecosystems	Five-module assessment and management methodology	Coastal and marine ecosystems				■		■	Duda and Sherman, 2002
Forest and terrestrial ecosystems	Modeling and selection of management plan for forest in west-central Alberta, Canada	Computer simulation of forest management scenarios	Alberta Health and Wellness; Millar Western Forest Products; Environment Canada; West Fraser Mills; Alberta Environment		■	■	■	■	▪	van Damme et al., 2003
	Decision-making related to forest road deactivation in unstable terrain	Risk analysis	Forest Renewal British Columbia		■	■	■			Allison et al., 2004
	The need to consider pathogens, pests, and diseases in the adaptive management of forests	Computer modeling of pathogen distribution	National Research Foundation; Human Resource and Industrial Program; South African Forestry Industry		■					van Staden et al., 2004
	New system of environmental evaluation and its application in the Southern Appalachians	Novel environmental valuation system	National Science Foundation; Environmental Protection Agency		■	■	■	▪	■	Norton and Steinemann, 2001
	Management of oaks and pines in the Wisconsin Necedah National Wildlife Refuge	Adaptive management framework	University of Wisconsin; Necedah National Wildlife Refuge	▪	■	■	■	▪	■	Haney and Power, 1996
	Evaluation of management of Costa Rican and Nicaraguan forests	Focus on the need for adaptive management	CATIE/FINIDA Research Fund; Center for International Forestry Research			▪	▪	▪		McGinley and Finegan, 2003
	Ecosystem model-building for management of Southern bottomland hardwood forests	Delphi method of surveying experts	USDA Forest Service; Alabama Agricultural Experiment Station		■					Bliss et al., 1997
Florida Everglades	Adaptive management as a way to obtain the knowledge necessary for Everglades restoration	Ecological learning	University of Florida				▪	■	■	Kiker et al., 2001
	Adaptive management in the Central and Southern Florida Project Comprehensive Review Study, a plan for restoration of the Florida Everglades	Review	University of California at Berkeley School of Law		■	■	■	■		Voss, 2000

	Use of risk assessment and adaptive management in the Everglades and South Florida ecosystems and the Central and Southern Florida Project Comprehensive Review Study	Risk-based conceptual model	University of Miami; United States Geological Society; South Florida Water Management District; Harwell Gentile and Associates	■	▪	▪			Gentile et al., 2001
Rivers, other freshwater areas, and estuaries	Implementation of local watershed council management practices through adaptive management	Community-based conservation	Science to Achieve Results Graduate Fellowship, United States Environmental Protection Agency	▪	■	▪	▪	■	Habron, 2003
	Assessment of information needed for environmental flow allocation, Lachlan River, New South Wales, Australia	Assessment of information needs for adaptive management	Macquarie University; Land and Water Resources Research and Development Corporation Project MQU6					■	Hillman and Brierly, 2002
	Gaps that hinder groundwater resource management in New Zealand	Case study	New Zealand Ministry of the Environment	■		■	■		Lowry et al., 2003
	Application of the Plan for Analyzing and Testing Hypotheses (PATH) to the management of Snake River basin salmon stocks	Interagency collaboration, development of common data sets, reduction of uncertainty	Bonneville Power Administration	■	■	▪	■	■	Marmorek and Peters, 2001
Wildlife management	Applying adaptive management to regulating waterfowl harvest	Passive and active adaptation algorithms	United States Fish and Wildlife Service; United States Geological Survey	■		■			Johnson and Williams, 1999
	Adaptive management of the species kokako to determine the effects of pests on population density	Variation of pest populations, monitoring of experimental and control areas, statistical analyses	Department of Conservation, New Zealand; Foundation for Research, Science, and Technology, New Zealand		■	■	▪		Innes et al., 1999
	Conservation of biodiversity during natural gas exploration in Peru	Adaptive management with comprehensive monitoring	Smithsonian Institution; Shell International Limited	■	▪	■	■	■	Dallmeier et al., 2002
	Integration of adaptive management strategies into habitat conservation plans	Incentives for adaptive management in HCPs	Washington Department of Natural Resources; Washington Department of Fish and Wildlife	■	■	■	■		Wilhere, 2002
	Framework for conservation of biodiversity using adaptive management to develop knowledge and skills	Various protection and management, law and policy, education and awareness, and incentive-changing strategies	Foundations of Success; Wildlife Conservation Society	▪	▪	■	■		Salafsky et al., 2002
Remediation	Modeling of rehabilitation of Cooum River, Chennai, India	Conceptual model building through workshops	Madras–Waterloo University Linkage Program; CUC-AIT	■	■	■		■	Bunch and Dudycha, 2004
	Restoration of damaged wetlands at San Diego Bay	Focus on mitigation compliance	San Diego State University		▪	▪	▪		Zedler, 1997
General adaptive management	Models of optimization for harvesting policies for exploited populations	Theoretical adaptive optimization techniques	National Research Council, Canada; Environment Canada; International Institute for Applied Systems Analysis	■	▪	■	■		Walters and Hilborn, 1978
	Gaps in the science base needed for ecological management, including gaps in adaptive management	Incentivizing cooperation	USDA Forest Service; Natural Resources Conservation Service; OMB; EPA; NOAA; US Army Corps of Engineers; US Department of Interior; Office of Science and Technology Policy	▪		▪		■	Szaro et al., 1998
	Principles of public involvement in adaptive management	Six propositions for integrating citizens into adaptive management	People and Natural Resources Program of the Pacific Northwest Research Station, USDA Forest Service					■	Shindler and Aldred Cheek, 1999
	Case studies of adaptive management related to land use, water quality, and recreational access	Software for policy option analysis	Macquarie University; Wyong Shire Council; University of Sydney	■	■	▪		■	Gilmour et al., 1999
	Framework for adaptive ecological management and lessons learned from prior adaptive management attempts	Adaptive management framework from Nyberg, 1999	Society for Ecological Restoration International	▪	■	■	■	■	Murray and Marmorek, 2003

Table 6
Adaptive management review papers

Application area	Topic	Methods/tools	Funding agencies	Elements of AM						Citation
				1	2	3	4	5	6	
Fisheries	Use of adaptive management to reduce uncertainty in fishery management and experiences with the Atlantic Canada groundfishery	Review of case studies	Natural Sciences and Engineering Research Council of Canada	▪			▪	▪	■	Charles, 1998
	Discussion of gap between experimental marine ecology and fishery management; adaptive management as tool to bridge gap	Review	Presidential Chair in Science (Chile); Pew Charitable Fund Fellowship	▪			▪	▪	▪	Castilla, 2000
Coastal and marine ecosystems	Formal integration of adaptive management in coastal restoration through the Coastal Wetlands Planning, Protection, and Restoration Act (CWPPRA)	Reviews CWPPRA	Louisiana Department of Natural Resources				■	■	■	Steyer and Llewellyn, 2000
Forest and terrestrial ecosystems	Relationship between forests, agroforestry, biodiversity and using adaptive management to balance the three	Six key elements to biodiversity preservation in forests	The World Conservation Union						■	McNeeley, 2004
	Decision support systems for federal forests in the United States	Decision support system software	USDA Forest Service			■	■	▪		Rauscher, 1999
Florida Everglades	Uncertainty and the need for flexibility in adaptive Florida Everglades management	Stakeholder flexibility	John D. and Catherine T. MacArthur Foundation; Sustainable Everglades Initiative						■	Gunderson, 1999
Rivers, other freshwater areas, and estuaries	Gaps in knowledge about salinity management for freshwater biota	Review	Murray–Darling Basin Commission; National Action Plan Non-regional Foundation Funding		■					James et al., 2003
	Evaluation of estuary management through the National Estuary Program	National Estuary Program's Management Conference process	NOAA					■	■	Imperial et al., 1993
	Problems with implementing adaptive management in riparian ecosystems	Review/synthesis discusses challenges in each area	Natural Sciences and Engineering Research Council, Canada		■	■	■		▪	Walters, 1997
	Adaptive co-management for freshwater resource management	Involving multiple groups as decision-makers with co-management	FORMAS, the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning.					▪	■	Folke, 2003
Wildlife management	Integration of wildlife management and research through adaptive management	Hypothetico-deductive science, learning as an objective	North Carolina State University; Colorado Division of Wildlife; National Biological Service; Utah State University; United States Forest Service; University of Guelph; Missouri Department of Conservation		▪	■	▪	▪		Lancia et al., 1996
	Use of adaptive management in managing human–carnivore interaction	Behavior modification; isolation of humans from carnivores	Conservation International; Wildlife Conservation Society			■			▪	Treves and Karanth, 2003
General adaptive management	Review of twenty-seven methodologies for assessment of management of protected areas	Collection of quantitative data from monitoring and qualitative data from scoring by managers and stakeholders	WWF/IUCN Forest Innovations Project				■			Hockings, 2003
	Framework for assessing the effectiveness of management of protected areas	"Measures of Success" framework developed by The Nature Conservancy and its partners	The Nature Conservancy				■			Parrish et al., 2003
	Adaptive management as a decision-making approach for resource management agencies	Experiments utilizing similar small ecosystems	United States Geological Survey	▪	■	■	■	▪	■	Johnson, 1999

revisitation of objectives, can be limited. NOAA has used adaptive management in projects such as shore restoration in the Pacific Northwest, the restoration of native plant species in a Rhode Island marsh, and also in larger projects such as the Louisiana coastal wetlands, where there is again an emphasis on learning through monitoring (NOAA, 2004b).

Adaptive management is also working its way into other US agencies and departments. Although the Department of Energy's NEPA Task Force report "Modernizing NEPA Implementation" (DOE, 2003) finds that the department could employ adaptive management to a much greater extent, the DOE already uses it in managing the environmental effects of hydroelectricity production. One example is the adaptive management plan for balancing salmon conservation with electricity production in the Columbia River basin of Washington state (DOE, 1998), which emphasizes the use and continual refinement of advanced mathematical models. More generally, the Federal Energy Regulatory Commission (FERC) may choose to expedite license issuance for power plant construction under the condition that adaptive management be used at the site (FERC, 2000).

Varying elements of adaptive management have been implemented in Canada as well. Fisheries and Oceans Canada has advanced a socioeconomic framework for ecosystem-based fisheries management (Rudd, 2004), and Environment Canada has recommended adaptive management in general to compensate for humans' lack of complete understanding of complex ecosystems (Environment Canada, 2004a). It is on the provincial level, though, where we see the greatest use of adaptive management. British Columbia has thorough guides to adaptive management published locally (Nyberg, 1999; Taylor et al., 1997), and the British Columbia Forest Service is currently implementing many pilot adaptive management projects, including adaptive management of livestock grazing, riverbanks and streambanks, forest recreation sites, and grizzly bear habitat, among others (BCFS, 2000).

Many international agencies and organizations also call for the use of adaptive management in environmental policy. In the European Union, the Commission of the European Communities and the World Wildlife Federation both recognize adaptive management as a potential solution for managing overharvested fisheries stocks (CEC, 2001; WWF, 2001a). The Biodiversity Support Program has published a general guide to adaptive management that explicitly relates adaptive management to the scientific method and emphasizes learning and reducing uncertainty (WWF, 2001b). Additionally, the RAND Corporation (Lempert et al., 2003) recommends computer modeling and adaptive management in general as a way to help conduct long-term policy analysis.

7. Integration of adaptive management with multi-criteria decision analysis

As we have stated in our review, unlike traditional management schemes designed to find and follow the optimal remedial strategy, adaptive management acknowledges our inability to predict system evolution in response to changing physical environments and social pressures. Our review indicates that the concept of adaptive management is well respected in academia, and many government agencies have recommended it for application. Yet even though many papers acknowledge that effective environmental decision-making requires considering the environmental, ecological, technological, economic, and socio-political factors relevant to evaluating and selecting a management alternative, these factors are rarely considered in concert and decisions are often driven by just one aspect of the problem. The quantitative tools and methods for implementing adaptive management strategies are not systematized, and no framework is available for integration and organization of the people, processes, and tools required to make structured and defensible environmental management decisions.

We believe that a combination of adaptive management and MCDA will provide a powerful framework for a wide range of environmental management problems. It will allow both structured, clear decisions to be made and also the adjustment of those decisions based on their performance. The MCDA framework proposed in Linkov et al. (2004) and in many other papers incorporates feedback loops between each step of the process that leads to the selection of an alternative. Adoption of adaptive management views will allow an iterative application of the MCDA framework and, once an alternative is chosen, adding a feedback loop will allow the re-ranking of alternatives as well as goals and criteria weightings.

A general decision framework (Fig. 4) is intended to provide a road map to the environmental decision-making process. 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 in Fig. 4 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 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. Policy- and decision-makers spend most of their effort defining the problem's context and the overall constraints on the decision. In addition, they may be responsible for the final decision and subsequent policy implementation. Stakeholders may help define the problem, but they contribute the most in 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 the best of their abilities, to provide the technical input necessary for the decision process.

The decision-making process is in the center of the figure. While it is reasonable to expect that the process may vary in

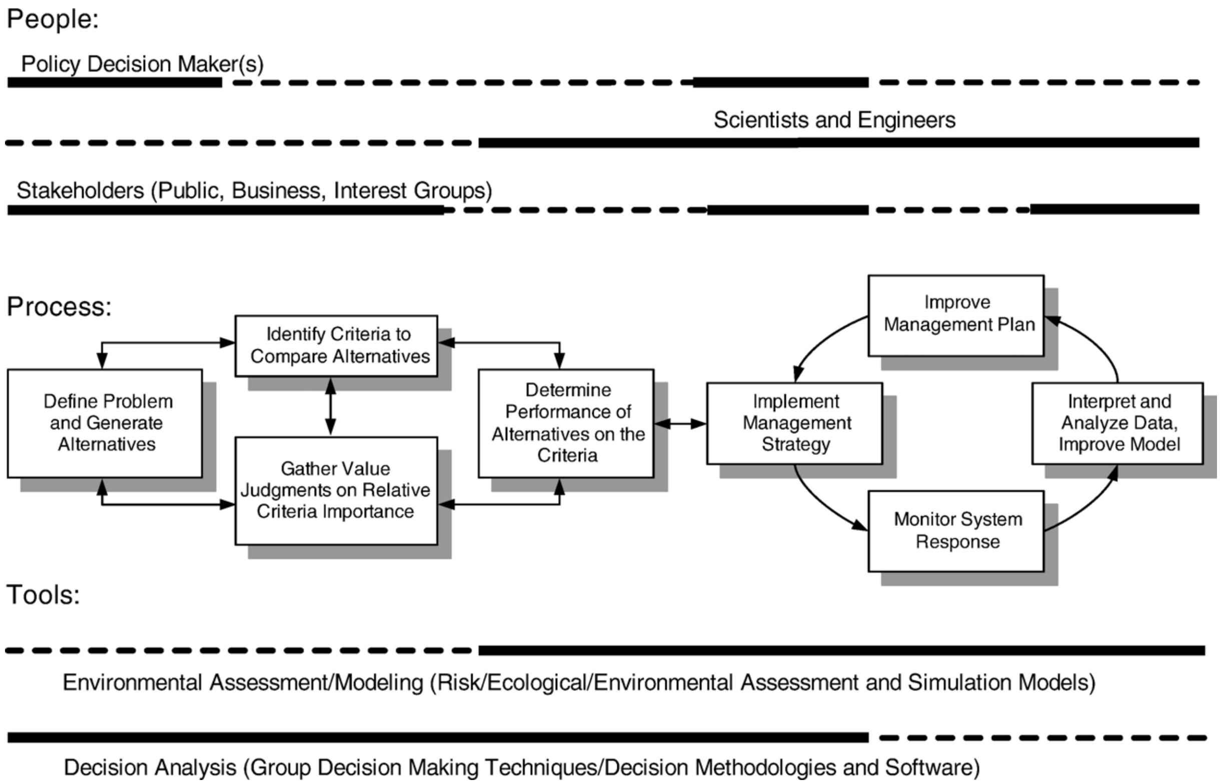


Fig. 4. Adaptive decision framework. Solid lines represent direct involvement for people or utilization of tools; dashed lines represent less direct involvement or utilization.

specific details among regulatory programs and project types, emphasis should be given to designing an adaptive management 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 Fig. 4 follows two basic activities: 1) generating management alternatives, success criteria, and value judgments and 2) ranking the alternatives by applying 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, or general societal acceptance) followed by a more detailed ranking of the remaining options by decision analytical techniques (AHP, MAUT, or outranking) that utilize the various criteria levels generated by environmental tools, monitoring, or stake-holder surveys.

As shown in Fig. 4, the tools used within group decision-making and scientific research are essential elements of the overall decision process. As with the involvement of different groups of people, tool applicability 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 the decision process, decision analysis tools can respond efficiently to reprocess and iterate with the new inputs. The framework depicted in Fig. 4 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 tools and scientific and engineering tools allows each to have a unique and valuable role in the decision process without attempting to apply either type of tool beyond its intended scope.

As with most other decision processes reviewed, it is assumed that the framework in Fig. 4 is iterative at each phase and can be cycled through many times in the course of complex decision-making. A first-pass effort may efficiently point out challenges that may occur, key stakeholders to be included, or modeling 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 that would benefit the overall decision process.

8. Application of MCDA/adaptive management framework to New York/New Jersey Harbor

The New York/New Jersey Harbor case study is a good example application of the combined multi-criteria decision analysis and adaptive management framework. The comparative risk assessment presented above covered the first three steps of the process identified in Fig. 4 (that is, problem formulation and alternative generation, criteria identification,

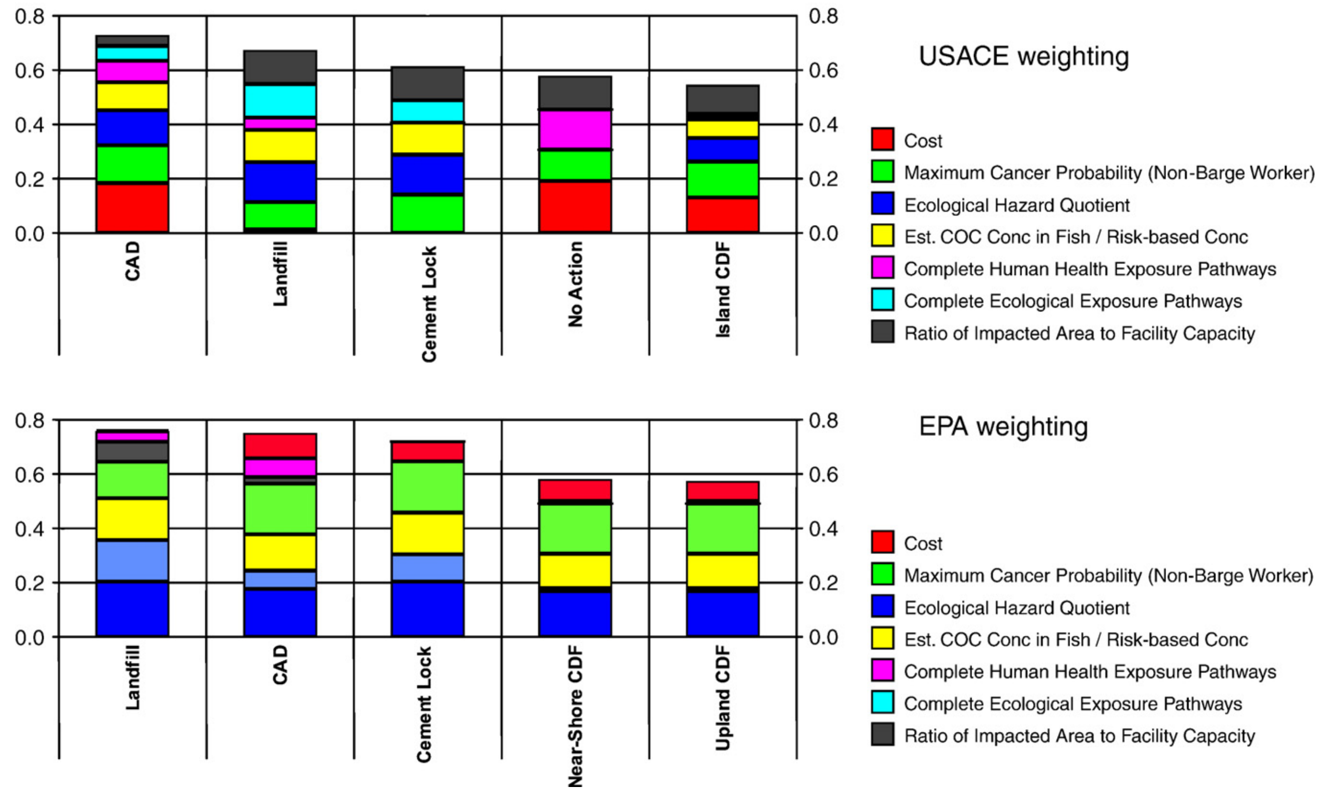


Fig. 5. Comparison of sediment management alternative scores when criteria weightings or related information change.

and evaluating performance of alternatives on the criteria). As we noted earlier, the fourth step (gathering value judgments on the relative importance of each criterion) is addressed only qualitatively within a CRA framework.

Kiker and Bridges (submitted for publication) present an example MCDA assessment of this NY/NJ case. Criterium Decision Plus software (InfoHarvest, 2004) was used to implement a SMART/MAUT approach to quantitatively incorporate stakeholder value judgments on criteria along with technical measures for specific criteria weighting. Value judgments on the importance of the seven decision criteria were elicited from a group of individuals experienced in the area of dredged material assessment and management in the US EPA, US Army Corps of Engineers and Academia using a "swing" weighting technique (discussed in more detail in Kiker and Bridges, submitted for publication). Fig. 5a shows an example ranking of five alternatives from Kiker and Bridges (submitted for publication) from one set of surveyed weights. The contained aquatic disposal (CAD) alternative is the most preferable because of its comparatively low cost and human health and ecological risks. A landfill is ranked second due to its relatively good risk reduction and public acceptability. Kiker and Bridges (submitted for publication) present more discussion on the results and their sensitivity to changing weights and value judgments.

In this framework, adaptive management considerations which call for a change in management strategy do not require expensive reevaluation of the whole decision model. For example, the cost of CAD operation may increase with time, and the relative safety of the CAD cell may become lower when it is getting close to its capacity. In this situation, revised cost and risk data can be easily incorporated into the decision model and tested for potential change in overall ranking given a variety of decision-relevant scenarios. These various conditions could relate to uncertainties in monitored data, stakeholder weights or values, or various "what-if" style scenarios. Fig. 5b shows a different criteria weighting scheme that results from the same decision model, but with different cost and risk data. The second scheme shows a different rank ordering of the management strategies, this time with a landfill topping the list. This example shows that under some criteria weights, monitoring values, and stakeholder valuations, rankings may change. In Fig. 5b, while the exact ranking changes, the upper three alternatives remain unchanged. This additional information may allow decision-makers and stakeholders to plan adaptively towards several generally-favored alternatives while discarding others that do not have consistently higher rankings over a variety of conditions. Thus, the MCDA structure, encompassing risk-based and other decision-relevant criteria, could efficiently assist the decision-makers as they construct adaptive strategies for monitoring and managing the contaminated sediments in the Harbor.

9. Discussion/conclusion

We are not the first to propose an integration of decision analysis methods with adaptive management. For example, Rauscher et al. (2000) propose a combination of the analytical hierarchy process and adaptive management. Pastorok et al. (1997) develop a decision-making framework combined with monitoring and adaptive management. Additionally, Nudds et al. (2003) with the University of Guelph Decision Analysis and Adaptive Management Project are applying a combination of methods to the management of yellow perch and walleye in Lake Erie. Their system emphasizes decision analysis, placing adaptive management in its service as a method to reduce the uncertainty present in decision calculations. Our proposed method, on the other hand, uses adaptive management as an overall planning and procedural framework, and we recommend decision analysis to help make structured, logical decisions concerning management options. We believe that our method will prove most fruitful, and we believe that our current review provides the most rigorous and justifiable foundation to date for successful application of the combined concept for environmental management of a wide range of projects. Using adaptive management and multi-criteria decision analysis gives structure to the decision-making process and allows the manager to learn about the system being managed and modify the management strategy based on new knowledge. Such a framework could be of great assistance to managers, saving them both time and resources as it helps them to understand the trade-offs involved between different management alternatives and to make justified, informed decisions.

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