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A Review of Multiple Criteria Analysis for Water Resource Planning and Management

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Abstract Multiple criteria analysis (MCA) is a framework for ranking or scoring the overall performance of decision options against multiple objectives. The approach has widespread and growing application in the field of water resource management. This paper reviews 113 published water management MCA studies from 34 countries. It finds that MCA is being heavily used for water policy evaluation, strategic planning and infrastructure selection. A wide range of MCA methods are being used with the fuzzy set analysis, paired comparison and outranking methods being most common. The paper also examines the motivations for adopting MCA in water management problems and considers future research directions.

Key words multiple criteria analysis · decision making · water resource planning

1 Introduction

Water resource management decisions are typically guided by multiple objectives measured in different units. Multiple criteria analysis (MCA) represents a body of techniques potentially capable of improving the transparency, auditability and analytic rigour of these decisions (Dunning et al. 2000; Romero and Rehman 1987). The MCA framework ranks or scores the performance of alternative decision options against multiple criteria which are typically measured in different units.

MCA emerged as a decision analysis technique in the 1960s and 1970s, partly resulting from the rapid growth of operations research in WW II. Some early applications of MCA were in military planning (see for example Eckenrode 1965). Today MCA is an established methodology with dozens of books, thousands of applications, dedicated scientific journals, software packages and university courses (Figueira et al. 2005a). It has received particular

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attention in water resource management, partly because water policy is seldom guided by a single objective.

Review papers have been published on the use of MCA in various fields of application. Pohekar and Ramachandran (2004) review over 90 published MCA studies in the field of energy planning. Hayashi (2000) examines the application of MCA to agriculture with reference to over 80 studies. Romero and Rehman (1987) review MCA use in 150 natural resource management applications. Out of fisheries, forestry, water and land resource applications Romero and Rehman (1987) find most applications of MCA occurred in water management. In the field of financial decision making Steuer and Na (2003) identify 265 MCA studies which they classify in terms of methodological approaches.

There have also been studies evaluating the many different techniques for ‘solving’ an MCA problem. An early study by Cohon and Marks (1975) evaluates MCA methods used for water resource management based on three criteria: computational efficiency; explicitness of trade offs, and the quantity of useful information supplied. Tecle (1992) takes a novel approach by using MCA itself to evaluate 15 MCA methods as applied to watershed management. Comparative studies of MCA methods to water management problems have been made by Gershon and Duckstein (1983), Ozelkan and Duckstein (1996), Eder et al. (1997). A general finding from these studies is that no single MCA technique is inherently better.

This paper reviews 113 published water resource management MCA studies from 34 countries. The review is limited to water management applications only and the papers are drawn only from peer reviewed scientific and professional journals. This is not an exhaustive study and further MCA applications no doubt exist, many of which would be in unpublished reports. The studies reviewed cover a wide range of water management issues and feature different MCA techniques. The aim is to understand the development and current status of how MCA is being used for water resource management.

2 Definition for MCA

The wide variety of multi-criteria methods in use for water management required an up-front definition to guide our review. There are a variety of terms used to refer to MCA. Some other names include multiple objective decision support (MODS), multi-attribute decision making (MADM) and multi-criteria decision analysis (MCDA). These approaches share the same fundamental theoretical underpinnings and are collectively referred to in this paper as MCA. MCA can be defined as a decision model which contains:

- A set of decision options which need to be ranked or scored by the decision maker;
- A set of criteria, typically measured in different units; and
- A set of performance measures, which are the raw scores for each decision option against each criterion.

The MCA model is represented by an evaluation matrix $\boldsymbol{X}$ of n decision options and m criteria. The raw performance score for decision option i with respect to criterion j is denoted by $x_{i,j}$. A minimum requirement for the MCA model is at least two criteria and two decision options ($n \geq 2$ and $m \geq 2$). The importance of each criterion is usually given in a one dimensional weights vector $\boldsymbol{W}$ containing m weights, where w_j denotes the weight assigned to the jth criterion. It is possible for $\boldsymbol{X}$ and $\boldsymbol{W}$ to contain a mix of qualitative (ordinal) and quantitative (cardinal) data.

A great variety of MCA algorithms can be used to either rank or score the decision options. The MCA algorithms will define, by some means, one or both of these functions:

$$r_i = f_1(\boldsymbol{X}, \boldsymbol{W}) \tag{1}$$

$$u_i = f_2(\boldsymbol{X}, \boldsymbol{W}) \tag{2}$$

Here r_i is an ordinal number representing the rank position of decision option i and u_i is the overall performance score of option i. The solution of r_i and u_i occurs within a broader MCA decision making process. Numerous authors (RAC 1992; Howard 1991) have described the MCA process and it generally contains the following stages:

1. *Choose decision options.* Usually there is a finite set of decision options which are to be ranked or scored, which creates a 'discrete' choice problem. In some cases the aim is to identify an optimum quantity subject to constraints, which creates a 'continuous' choice problem.
2. *Choose evaluation criteria.* The criteria are used to measure the performance of decision options. They should be non-redundant and relevant to the decision maker's objectives (Keeney and Raiffa 1993). Redundant criteria are typically highly correlated and measure the same underlying factor.
3. *Obtain performance measures ($x_{i,j}$)for the evaluation matrix.* The values for $x_{i,j}$ may be either ordinal or cardinal, and can be sourced from expert judgements or other environmental and economic models.
4. *Transform into commensurate units.* An MCA problem will almost always contain criteria in different units. Transformation places them onto a commensurate scale, often 0 to 1, so they can be meaningfully combined in the overall utility function.
5. *Weight the criteria.* Criteria are rarely of equal importance to the decision maker and a variety of methods are available to assign weights at either cardinal or ordinal levels of measurement.
6. *Rank or score the options.* At this stage the weights are combined with the performance measures to attain an overall performance rank or score for each decision option. A wide range of ranking algorithms, which use ordinal and/or cardinal properties of the performance measures, can be used in this task.
7. *Perform sensitivity analysis.* Systematic variation of the weights, performance measures and ranking algorithms can reveal where the MCA model needs strengthening and the robustness of results given input assumptions.
8. *Make a decision.* The MCA model aims to inform, but not make, the final decision. There is typically a requirement for some level of human judgement to account for relevant issues that could not be adequately modelled in the MCA.

This process often involves several iterations, with earlier stages being revisited as the analysis unfolds.

3 Types of MCA Techniques

Since the 1960s a great many techniques have emerged to 'solve' an MCA problem. A detailed description of all the algorithms used is well beyond our scope. A recent review of some MCA methods is available in Figueira et al. (2005a). Some of the major MCA techniques encountered in this review are classified as follows:

1. *Multi-criteria value functions.* Two commonly applied value functions are weighted summation and weighted multiplication. The weighted summation model is often expressed as:

$$u_i = \sum_{j=1}^{m} v_{i,j} w_j \tag{3}$$

The weights (w_j) are non-negative and sum to 1, and $v_{i,j}$ is a transformed performance score for $x_{i,j}$ on a scale of 0 to 1 where 1 represents best performance. The overall performance score for each option is given by u_i. In weighted multiplication the summation operation is replaced with a multiplication operation. This makes criteria non-compensatory where a zero score (arising from $v_{i,j}w_j$) on any one criterion results in an overall zero performance score for the decision option regardless of how well it performs on other criteria.

2. *Outranking approaches.* The methods of PROMETHEE[1] (Brans et al. 1986) and ELECTRE[2] (Roy 1968; Figueira et al. 2005b) are two commonly applied outranking approaches. They involve identifying every pair of decision options i and i' giving $n^2 - n$ pairs in total. Outranking approaches apply some type of utility function, which contains criteria weights, to determine the amount option i outperforms i'. There have been considerable variations made to the ELECTRE and PROMETHEE methods over time.
3. *Distance to ideal point methods.* These approaches identify ideal and anti-ideal values for the criteria. They then identify the decision options that are closest to the ideal and furthest from the anti-ideal. Where no ideal or anti-ideal is easily defined the minimum and maximum criterion values may be used. Two common techniques of this type are compromise programming (Zeleny 1973; Abrishamchi et al. 2005) and TOPSIS[3] (Lai et al. 1994).
4. *Pairwise comparisons.* One of the most widely applied pairwise comparison techniques is the Analytic Hierarchy Process (AHP; Saaty 1987). The Analytic Network Process (ANP; Saaty 2005) and MACBETH[4] (Bana e Costa et al. 2005) are other MCA methods involving pairwise comparisons. These approaches involve comparing criteria and alternatives in every unique pair giving $n(n-1)/2$ comparisons. The comparisons can be made to attain criteria weights and decision option performance scores. Various scaling systems can be used. In the AHP, for example, decision makers are asked to express preference for one criteria/option over another in each pair on a nine point scale.
5. *Fuzzy set analysis.* Fuzzy set theory was first used by Zadeh (1965) in the development of decision support models. It was later applied in MCA applications (Buckley 1984;

[1] PROMTHEE stands for Preference Ranking Organization MeTHod for Enrichment Evaluations.

[2] ELECTRE stands for ELimination Et Choix Traduisant la Realité; Elimination and Choice Expressing the Reality.

[3] TOPSIS stands for Technique for Order-Preference by Similarity to Ideal Solution.

[4] MACBETH stands for Measuring Attractiveness by a Categorical Based Evaluation TecHnique.

Leberling 1981). Fuzzy set theory is based on a gradual transition from one class to another. Items can have partial membership in multiple sets. This can be particularly powerful in handling uncertainty inherent in MCA problems. Fuzzy approaches may apply concepts from the other MCA methods.

6. *Tailored methods.* The ability to create new MCA methods based on adaptations of existing ones, or development of new algorithms is practically limitless. For example, Hyde et al. (2004) adapt weighted summation to create a "reliability based approach" to MCA involving the use of rank correlation coefficients.

The papers reviewed in this study employed 61 unique MCA techniques. Of these 19 were considered 'conventional' methods which often have computer software, widely published methodology and considerable prior application. The remaining MCA techniques were considered 'tailored' methods. In tailored methods the researchers have made considerable adaptation to conventional methods or developed new methodology.

The majority of studies applied more than one MCA method, usually to test the sensitivity of the result. This means the total number of method applications, including conventional and tailored methods, exceeds the total number of studies reviewed. Table I shows that the most commonly applied methods were fuzzy set analysis, compromise programming (CP), the analytic hierarchy process (AHP), ELECTRE and PROMETHEE.

Several researchers have conducted comparative studies of MCA in water resource management (Gershon and Duckstein 1983; Ozelkan and Duckstein 1996; Eder et al. 1997). These comparative studies involve the application of numerous MCA techniques to a single problem, then the resultant ranking or scoring of decision options is compared. These studies often show different MCA methods are in close agreement and there is no clear methodological advantage to any single technique. Having found similar results in forestry management Howard (1991) concludes that the most important aspect of MCA is the selection of criteria and decision options. These early stages of MCA can be referred to as 'structuring' the decision problem. Despite an abundance of algorithms to solve an MCA problem once it has been structured, there are few methods to help analysts and decision makers choose criteria and decision options in the first place.

Table I Water resource applications of conventional MCA methods

MCA method category	MCA methods	Number of applications
Fuzzy set analysis	Fuzzy set analysis	22
Distance to ideal point	Compromise programming (CP)	17
Pairwise comparisons	Analytic Hierarchy Process (AHP)	15
Outranking methods	ELECTRE I, II, III, IV and TRI	15
Outranking methods	PROMETHEE I, II, V	12
Multi-criteria value function	Multi attribute utility theory (MAUT)	8
Distance to ideal point and outranking methods	Multicriterion Q Analysis (MCQA I, II and III)	3
Distance to ideal point	EXPROM	3
Pairwise comparisons	MACBETH	1
Weighted summation / multiplication	Weighted summation	1
Distance to ideal point	TOPSIS	1
Total		98

4 Types of MCA Applications

In this study eight types of MCA application in water resource management were identified:

1. *Catchment management.* This involves applications of MCA to problems of whole catchment management, which are often concerned with land use and land management patterns. An example of this application can be drawn from Chang et al. (1997) where MCA methods are employed to evaluate land management strategies within a catchment in Tweng–Wen reservoir watershed in Taiwan. Land use within the catchment is guided by economic and environmental objectives.
2. *Ground water management.* These studies use MCA specifically for the management of groundwater, often to determine the best ways of remediation of contaminated groundwater supplies. It is illustrated by Almasri and Kaluarachchi (2005) who use MCA to evaluate options for managing nitrate contamination of groundwater in the Sumas–Blaine aquifer in Washington State, US.
3. *Infrastructure selection.* These studies are concerned with choosing major water infrastructure supply options for a city or region. Most involve urban water supply. An example comes from Eder et al. (1997) who use MCA techniques to evaluate 12 water supply infrastructure options for the Austrian part of the Danube River. The options involve major infrastructure such as hydroelectric power schemes.
4. *Project appraisal.* These studies use MCA to rank or score a set of water management projects which often involve some form of water condition restoration activity. For example, Al-Rashdan et al. (1999) use MCA to prioritise a set of projects aimed to improve the environmental quality of the Jordan River.
5. *Water allocation.* These applications involve decisions about how much of a limited water resource is allocated to competing uses. An example comes from Agrell et al. (1998) who use MCA to inform water release decisions from the Shellmouth Reservoir in south-west Manitoba, Canada. Water release aims to deliver on multiple social, economic and environmental uses.
6. *Water policy and supply planning.* This involves the evaluation of policy options (e.g., levies, legislation, awareness raising) and longer term strategic planning for a region's water supply. An example comes from Joubert et al. (2003) where MCA is used to evaluate water demand and supply management policies in Cape Town, South Africa.
7. *Water quality management.* These papers involved an application of MCA primarily involving the evaluation of options aimed specifically at improving water quality (as opposed to supply). They often involve human and ecosystem health objectives. An example comes from Lee and Chang (2005) where MCA is used to develop a water quality management plan for the Tou–Chen River Basin in northern Taiwan.
8. *Marine protected area management.*[5] This involves the use of MCA to manage nearshore marine environments. One such study by Fernandes et al. (1999) uses MCA to evaluate coral reef management options in the Caribbean.

An additional category was termed 'method papers.' These papers explored MCA methods for water management on a theoretical level. Some papers involved elements of

[5] Marine protected area management is arguably a borderline case of 'water resource' management. In this study it has been included because coastal terrestrial freshwater resources form part of the nearshore marine ecosystem. For example, the Great Barrier Reef in Australia is impacted by water quality of coastal catchments in Northern Queensland (Haynes 2001).

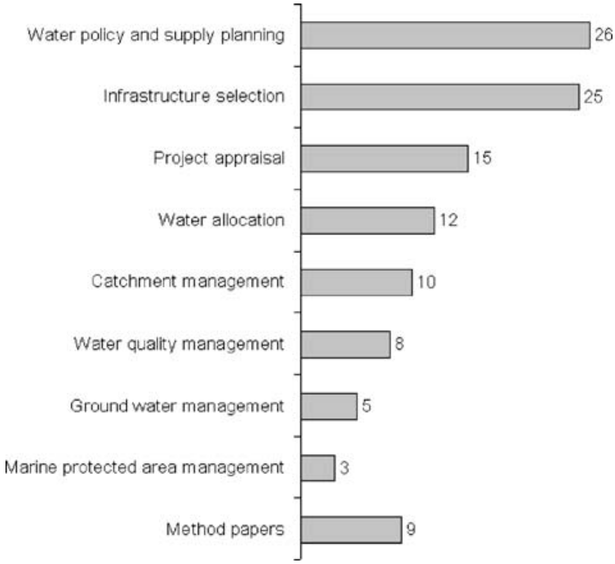

Figure 1 Different types of water MCA application.

two or more categories. In each case an attempt was made to place the application into its dominant category. The number of papers per category is given in Figure 1.

The majority of applications are in water policy evaluation, water supply planning and infrastructure selection. These decisions often have deep and long-lasting impacts on numerous stakeholders. They involve a requirement to handle multiple objectives for which MCA is potentially well suited. Relatively few applications have occurred in marine protected area management (Fernandes et al. 1999). These decisions typically involve multiple objectives and applications within this field may grow.

5 Other Trends in Water MCA Studies

The 113 water MCA studies reviewed in this paper were drawn from 34 countries (Table II). Thirteen studies were methodological and/or were not associated with any country in particular. Of the remaining 90 studies the majority were from the USA, India, Jordan, Spain, Taiwan and China. A total of 21 studies were from European countries. There were also 13 MCA studies from the Middle East Region where water resources are scarce, highly valued and subject to conflicting stakeholder needs (Mimi and Sawalhi 2003).

Table II Water MCAs by country

Country	Number of water MCA studies
USA	11
India	10
Jordan	10
Spain	5
Taiwan	5
China	4
Other (28 countries)	45

The earliest MCA study in this review was published in 1973 (Figure 2). After an initial surge of interest the annual publication rate then declined with no studies recorded for the 3-year period 1985–1987. In the late 1980s and 1990s the annual publication rate grew sharply with 2005 producing 14 studies, the most in any 1 year.

An explanation for the growth in annual publications since 1991 could be the adoption of 'sustainability' as an overriding water management objective in the early 1990s. Sustainability requires multiple objectives in natural resource planning and received worldwide attention in 1992 at the Rio Summit and with the publication 'Our Common Future' (WCED 1987). Government policy worldwide soon adopted sustainability principles.

A mix of continuous and discrete MCA models were used in the MCA studies reviewed in this paper. A continuous model solves a multi-criteria problem to determine an optimum quantity and has an infinite number of solutions. A discrete MCA model has a finite set of alternative options. Of the 113 studies 81 were discrete models, 22 were continuous and the remaining 10 were unable to be classified as either. The unclassified studies were methodological papers.

The 81 discrete MCAs had an evaluation matrix containing a fixed number of decision options and criteria. The mean number of criteria was 10.75 with a standard deviation of 7.33, a minimum of 2 and a maximum of 37. The mean number of decision options was 14.01 with a standard deviation of 16.3, a minimum of 2 and a maximum of 73. Those papers with a large number of criteria typically classified them with an objectives hierarchy. An 'objectives hierarchy' states the highest order objective first. This is then divided into a set of sub-objectives which are linked to criteria at the 'fingertips' of the hierarchy. The hierarchy makes the weighting task more manageable for decision makers when there are many criteria.

The evaluation matrices were not presented in all studies, therefore it was not possible to determine whether they contained quantitative (cardinal) data, qualitative (ordinal) data or a mix of both. It was possible to make determinations for 69 studies. Of these 21 were quantitative, 9 were qualitative and 39 were mixed.

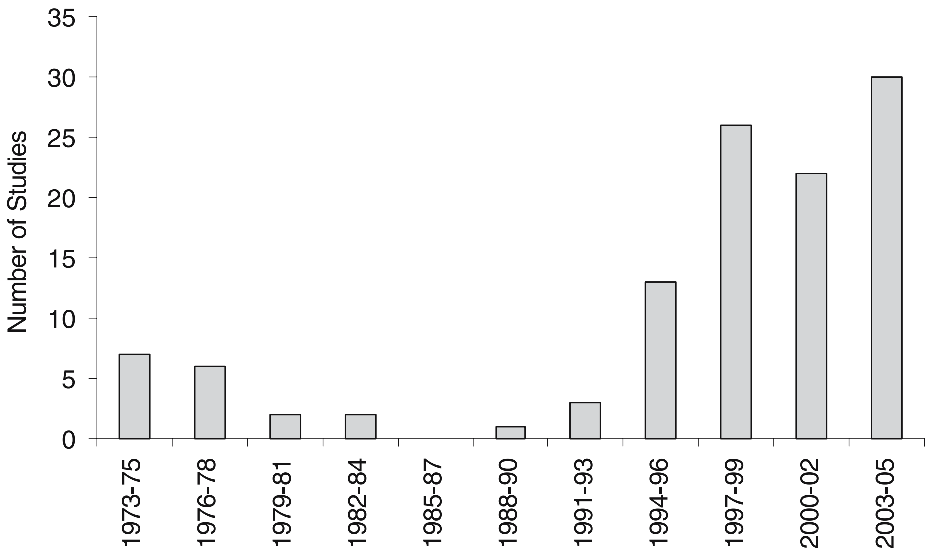

Figure 2 Water management MCA studies (identified in this paper) published since 1973.

An assessment was made of the issues covered by criteria in a subset of MCA studies that gave detailed criteria descriptions (Table III). The issues most commonly covered included: the cost of options (including calculations of net present value); the economic impacts (e.g., job creation and economic growth impacts); technical feasibility and; water quantity and supply. The distribution of benefits, i.e., fairness and equity concerns, and political feasibility also featured in several studies. Less common were human health considerations, energy and security of supply. The majority of studies used a broad range of social, economic and environmental criteria.

6 Reasons for Using MCA in Water Management

The water management MCA studies reviewed in this paper provide insights to why MCA is adopted. This section briefly explores some of the main reasons researchers adopted MCA over alternative decision making frameworks.

In many studies MCA was found to provide transparency and accountability to decision procedures which may otherwise have unclear motives and rationale (Brown et al. 2001; Joubert et al. 1997). Transparency in MCA is achieved by explicitly stating and weighting decision criteria. The reasons for choice are made explicit and past decisions can easily be audited. For example, Dunning et al. (2000) argue that MCA's 'logical' and 'well documented' approach makes it suitable to support decisions under Section 316(b) of the US Clean Water Act, which deals with the selection of remediation technologies for mitigating point source water pollution.

It is interesting to consider that whilst transparency is typically seen as a strength of MCA it may be a deterrent for some. Sometimes decision makers, either overtly or covertly, do not want to be too transparent. Dunning et al. (2000; p13) suggest MCA may not be adopted for US water quality legislation because it is too 'explicit:'

> Although we believe that the adoption of MUA multiattribute utility analysis would enhance the rule-making process for Section 316(b) of the US Clean Water Act, MUA is likely to be rejected by parties that believe their interests would be better served in the absence of an explicit approach that balances the interests of all parties or if consensus was not reached.

Conflict resolution is a common reason for adopting MCA. It becomes an issue when multiple perspectives are applied to a single water management decision (Cai et al. 2004; Yin et al. 1999; Chuntian and Chau 2002; Mustajoki et al. 2004). A striking example comes from Mimi and Sawalhi's (2003) use of multi-criteria techniques to inform the allocation of Jordan River water amongst Palestine, Israel, Syria, Lebanon and Jordan:

> "The negotiators need a decision tool based upon objective criteria or standards to reach equitable entitlements to shared water resources by all parties. This paper introduces a multi-criteria decision tool as a possible approach to the problem of allocating the waters of the Jordan River between all riparian parties." (p447)

The ability of MCA to help in conflict resolution partly results from its transparency. All parties are required to explicitly state their preferences through a structured process. It is then possible to identify areas of agreement and disagreement, thereby managing conflict. MCA can be used to identify shared solution space from multiple perspectives (Cai et al. 2004).

Table III Issues covered by evaluation criteria in selected water management MCA studies

	Tiwari et al. (1999)	Abrishamchi et al. (2005)	Tzionas et al. (2004)	Yin et al. (1999)	Srdjevic et al. (2004)	Mimi and Sawalhi (2003)	Karnib (2004)	Raju and Kumar (1999)	Eder et al. (1997)	Cai et al. (2004)	Joubert et al. (2003)
Cost of option (and net present value)	√	√	√	√		√	√	√	√	√	√
Economic (e.g., growth, employment, income, productivity)	√			√		√	√	√	√	√	√
Technical feasibility	√	√	√	√	√	√			√		√
Biodiversity and wildlife protection			√	√			√		√	√	√
Water quality enhancement		√	√						√	√	√
Water quantity & supply	√		√		√	√	√		√		√
Fairness & equity	√	√		√		√	√				√
Security and reliability of water supply					√						√
Political and legal feasibility		√		√		√			√		√
Energy supply	√						√		√		
Human health		√									√

Multi-stakeholder engagement and community participation were also seen as reasons for adopting MCA in water management decisions (Greiner et al. 2005; Fernandes et al. 1999; Nayak and Panda 2001). Brown et al. (2001) used MCA to engage stakeholders and build consensus based approaches to the management of a marine protected area. They found that (p432):

> The inclusion of stakeholder views and values within a rigorous framework can, potentially, provide rich information for regulators seeking to manage marine park resources in partnership with other stakeholders." ... "We believe that participatory approaches are complementary, not oppositional, to decision support tools such as MCA."

Another common reason for adopting MCA for water management is that MCA uses formal axioms of decision theory to inform choice. This helps ensure the analysis is logical and robust. Schultz (2001) argues that basing the US Environmental Protection Agency's Index of Watershed Indicators (IWI) on multiattribute utility theory would improve internal consistency and rigour. The adoption of formal rules for decision making can assist with auditability. An auditor can use an MCA model to recreate the decision problem at the time choices were made. Auditability is another reason for adopting an MCA approach.

Bana e Costa et al. (2004), Joubert et al. (1997) and Prato (1999) argue for the adoption of MCA to supplement benefit cost analysis (BCA). The two main limitations of BCA identified by these authors are: (a) a requirement for all outcomes to be expressed in monetary units and; (b) difficulties with achieving a fair distribution of resources amongst stakeholders. Water management decisions typically have important non-financial factors (e.g., health, biodiversity) and multiple stakeholder interests. The MCA framework ensures a robust analysis whilst permitting non-financial and distributional issues to be incorporated. This is prompting analysts to explore and apply MCA. However, Joubert et al. (1997) note that MCA and BCA are complementary methods each with different roles in decision analysis. It is not a question of 'Which one is best?' but rather 'Which tool is best suited to a particular problem?'

7 Future Research Needs

As MCA's application in water resource management approaches maturity the research needs are shifting. Algorithms for 'solving' an MCA problem, which produce a ranking or scoring of decision options, are in oversupply as hundreds have been developed since the 1960s. Efforts in water resource MCA research are now shifting toward these main challenges :

- Improving decision maker interaction with MCA models, including better methods for preference elicitation. This has been tackled in a recent study by Mustajoki et al. (2004) which uses decision support software called Web-HIPRE to elicit stakeholder preferences over the internet.
- Developing better means for incorporating multiple decision maker input to a single decision and resolving conflicts. Recent work by Cai et al. (2004) proposes a Tchebycheff algorithm (Steuer 1986) which involves constructing broadly acceptable scenarios which are progressively filtered down to compromise solutions.

- Improved ways for initial structuring of the MCA model, which involves selection of criteria and decision options. Mingers and Rosenhead (2004) describe several problem structuring methods (PSMs) which could potentially be applied in the early stages of MCA.
- Better ways for handling risk and uncertainty in MCA models including means for incorporating decision maker risk preferences. In recent work Hyde et al. (2004) propose a reliability based approach to MCA involving Monte Carlo simulation and rank correlation coefficients.

These research needs can be summarised as a requirement to more meaningfully embed MCA within real water management decisions. In other words, the algorithms for MCA are probably good enough, we now need to get them applied. This will require a deeper understanding of individual, group and organisation decision procedures in water resource management.

8 Conclusion

Application of MCA in water resource management is widespread and growing. This non-exhaustive review identified 113 studies published since 1973. It was found that the annual publication rate has been steadily growing since the late 1980s. The majority of applications are in water policy, supply planning and the evaluation of major infrastructure.

Water management is typically a multi-objective problem which makes MCA a well-suited decision support tool. The outcomes are often intangible and are measured in a variety of units. MCA has been found to assist with conflict resolution, stakeholder participation and community engagement. It has also been shown to improve the auditability, transparency and analytic rigour of water management decisions.

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