

EXECUTIVE SUMMARY

Overview

This report is the culmination of a number of years research at the University of Cape Town, on the role of *multiple criteria decision analysis (MCDA)* in water resources planning, particularly in the light of the requirements of the National Water Act, Act No. 36 of 1998.

MCDA is that branch of management science and decision analysis which deals with conflicting objectives in decision making in a structured and systematic manner. MCDA provides a rigorous theoretical foundation for a total decision support process incorporating the following key steps:

- Structuring of decision making goals in terms of explicitly defined hierarchies of criteria;
- Evaluation of alternative courses of action or strategies in terms of the extent to which they satisfy each of the identified criteria;
- Aggregation across criteria to generate a measure of the extent to which each course of action or strategy satisfies the overall goals (of management, of society, etc.) represented by the criteria.

Many different techniques within the broad MCDA field have been developed for the above steps. It is not the intention of this report to provide a comprehensive exposition of all of the field (but see, for example, Belton and Stewart (2002) for such an exposition). On the basis of practical experience in action research (see, for example, the case studies included in this document), we have found two approaches to be particularly useful in the context of water resources planning in South Africa. These two approaches are particular implementations of *value measurement* and *goal programming*, which we shall denote by VM-MCDA and GP-MCDA respectively.

The VM-MCDA approach evaluates alternatives in terms of simple scoring functions, initially with respect to each criterion individually, and then in an overall sense incorporating the relative importance of each criterion. VM-MCDA is a simple transparent process and is well suited to use in group workshop sessions and for subsequent analysis and consolidation of the conclusions from such workshops.

The GP-MCDA approach is based on specifying numerical target levels of achievement for each criterion, and in using mathematical programming techniques to search for alternatives which come closest to achieving these target levels. GP-MCDA is well suited to use by analysts in the background to generate potential strategies for closer consideration and evaluation by stakeholders.

Further details on each of the two approaches are given below.

This report is subdivided into two main Parts. Part I provides guidelines for the use of MCDA methods, and is organised to reflect the key stages of the water management cycle. The intention is to provide potential users of the approach with understanding of the underlying assumptions and methodologies, and the potential they offer for facilitating different stages of the management cycle. Part II describes a number of case studies in which these approaches were used.

Part I - Guidelines

1. Introduction

The first group of activities in the water management cycle is called the resource directed measures (Stage 1). Stage 2 (water resource planning and management strategies) includes activities aimed at supporting both water resource protection and water-use authorisation. Stage 3 (water-use authorisations) is the main means by which water-use (either abstraction or discharge) is controlled and therefore the resource protected. Stage 4 (monitoring) is not dealt with in these guidelines except for a brief mention in Chapter 5.

The **value measurement** (VM-MCDA) approaches described here are only those which use simple weighted addition of scores. In other words, for each alternative (course of action or strategy) a , an overall weighted value or score is defined by:

$$V(a) = w_1v_1(a) + w_2v_2(a) + \dots + w_nv_n(a) \quad (i.1)$$

This requires the evaluation (scoring) of alternatives on a number of separate criteria (partial values, v_i), and the estimation of weights w_i . Although some of the theoretical assumptions are often not met, the weighted summation is (a) reasonably robust to some violations (apart from over-linearisation of the partial values), and (b) the most simple and transparent VM-MCDA method to apply. The stages of a VM-MCDA process are:

- Problem structuring - where the problem is explored, scenarios or alternatives are defined, criteria for the evaluation of the alternatives are defined and organised into a hierarchical criteria- or value-tree,
- Evaluation - The alternatives are evaluated (scored) on the basis of each of the criteria separately,
- Aggregation - The separate evaluations are aggregated using equation (i.1) after defining weights,
- Analysis - The results are further analysed for sensitivity to weights and scores and to explore the implied trade-offs, and
- Feedback and refinement - Feedback is given to the participants and evaluations and weights may be refined

VM-MCDA is particularly useful in settings where a group of specialists (and other stakeholders) interactively evaluate consequences in a workshop setting.

The **goal programming** (GP-MCDA) approaches generally require that consequences of alternatives can be expressed in terms of quantitative attributes. Goals or aspiration levels are then set for each attribute. A variety of algorithms exist for finding the alternative that in some sense produces performance levels which are closest to goals

2. Stage 1: Resource Classification and Reserve Determination

The basic VM-MCDA approach is relevant as a process for integrating the various steps of Stage 1 and for obtaining an overall evaluation of different scenarios' effects on the resource. Equation (i.1) provides the basis for this stage. In this case the criteria to be measured are (a) subcomponents of the ecological components (geomorphology, riparian vegetation, fish, aquatic invertebrates and water quality), (b)

economic and (c) social components. For each resource unit the scenarios' scores (for each of these subcomponents or components) are aggregated to obtain an overall ecological (R_i), economic (E_i) and social (S_i) evaluation for the resource unit. These resource unit scores can be further aggregated to obtain overall ecological (R), economic (E) and social (S) evaluations for the whole river. An overall ranking of scenarios can be obtained by aggregating these three separate evaluations. At each aggregation stage, swing weights need to be defined. Thus, using VM-MCDA a simple weighted sum of scores is used at each aggregation step. The weighted sum could be augmented with other rules such as "maxmin" (maximise the minimum score). In the case of the ecological criteria, Ecological Categories (ECs) have been defined which correspond to "levels of achievement" on each criterion and a system for their integration to an "ecostatus" is being developed. For the economic and social criteria a standard set of criteria has not been developed. The problem structuring stages help to define criteria, scoring systems and weights and the augmentation of the weighted sum with other rules would also be considered.

3. Stage 2: Water resource planning and management strategies

STAGE 2 is concerned with water resource planning for the development of strategies for the achievement of resource quality objectives, and for the development of strategies for the future allocation of water (among other things). Currently, the two planning and strategic frameworks envisaged by the Department of Water Affairs and Forestry (DWAF), beyond the National Water Resource Strategy, are the Internal Strategic Perspectives (to be undertaken by DWAF) and Catchment Management Strategies (CMSs) (to be undertaken by Catchment Management Agencies (CMAs)). The Internal Strategic Perspectives outline DWAF's specific "strategic perspectives" regarding the protection, use, allocation, conservation etc. of the Water Management Area in question. Once a CMA is established for the Water Management Area it will take over many of these functions and develop a CMS. The CMS is an overall plan, campaign or process for managing the Water Management Area in order to achieve the objectives defined in the CMS, National Water Resource Strategy or elsewhere (DWAF 2001). The CMS could well adopt some or all of the objectives set by DWAF in the Internal Strategic Perspectives. As such the Internal Strategic Perspectives precedes the CMS, which may, in turn, build on the Internal Strategic Perspectives. Only two of the strategies contained in the CMS are dealt with here: the water resource protection strategy and the development of a water allocation plan (WAP).

The **water resource protection strategy** is a strategy designed to ensure that the Reserve and resource quality objectives established in Stage 1 are met. Therefore the effects of different strategies need to be measured in terms of the same components as were evaluated in Stage 1 (augmented or trimmed as relevant). The Scenario Based Policy Planning approach (an extended VM-MCDA approach, see Stewart et al. 1993, 1997 and 2001 and Joubert and Pollard 2000) is useful in this context. Scenarios are constructed which consist of different levels of primary attributes of the catchment (e.g. dam sizes, land-uses). Known relationships between the criteria and these attributes (value functions) can be used, or specialists give scores to the criteria based on their knowledge of the issue. In the examples, only one attribute is used, namely land-use. Scenarios of different combinations of land-uses can be compared to see their effects on the resource quality objectives. Additionally, strategies which affect the probability of a change in the attribute of concern or the magnitude of the affect on the criterion can be examined.

The **development of a WAP** requires the examination of the effects of different WAPs on the criteria of concern (again these would be based on those established in Stage 1). VM-MCDA can be used in a

similar way to that for the water resource protection strategy where scenarios are simply constructed from different percentage allocations to different sectors. GP-MCDA can also be used, for example, to minimise deviations from goals for each of the criteria.

4. Stage 3: Water-use authorisation

Evaluating individual licence applications requires that a consistent set of indices is established so that each application is evaluated in similar way to previous and future applications. These indices would need to be nationally consistent but geared towards each Water Management Area by adjusting, for example, the weights (issues irrelevant to a particular Water Management Area might be given a zero weight). Once again these indices should be those established in Stages 1 and 2. In other words the effects of granting (or not) an individual licence should be measured in terms of its effects on the same criteria which were used to evaluate Reserve scenarios and water resource protection strategies. The individual licence should also be compared with the WAP to see if it consistent with that. It might be necessary to establish additional measures, particularly where, for example, effects on the individual applicant are relevant, and where criteria based on Section 27 of the National Water Act have not yet been included in previous stages. Once the set of indices has been established, the same VM-MCDA procedures as used in previous stages can be used based on equation (i.1) Compulsory licensing would apply the same criteria, but is easier to accomplish as all water-uses are evaluated simultaneously. GP-MCDA could also be used in the compulsory licensing context.

5. Synthesis: An integrated process

Given the alignment of data needs and indices needed in the different stages of the water management cycle, the system of equations established for Stage 1 (Chapter 2) can be applied to all stages. The following briefly describes this, using only the ecological variables as an example, where the symbol r (in various forms) stands for the ecological resource. Regardless of whether the scenarios or alternatives being compared are Reserve flow scenarios, water resource protection strategy scenarios, allocations for a WAP, individual licences etc. the following might apply:

1. Within each resource unit (RU) i , the subcomponents j of the ecological elements are given scores r_{ij} :
 - (a) For different Reserve scenarios in Stage 1,
 - (b) As a result of applying different hypothetical water resource protection strategies or of changing attribute levels (e.g. land-use) during the Stage 2 development of water resource protection strategies,
 - (c) As a result of applying different hypothetical WAPs to the RU,
 - (d) In evaluating different individual licence applications,
 - (e) In evaluating different hypothetical compulsory licence scenarios, or
 - (f) When updating monitoring information.
2. Within a RU, these subcomponents r_{ij} are aggregated, as in formulae (i.1) to obtain an evaluation of the (in this case ecological, R_i) impacts on the RU:

Ecological impact on RU1 = $R_1 = \alpha_{r1}r_{11} + \alpha_{r2}r_{12} + \dots + \alpha_{rn}r_{1n}$, where the α_{rj} are the weights of the ecological resource (r) subcomponent (j) (for example, α_{ej} would be economic weights)

3. For the river, the RU scores are aggregated to obtain an overall ecological evaluation of the river (R):

$R = \beta_{R1}R_1 + \beta_{R2}R_2 + \dots + \beta_{Rm}R_m$, where the β_{Ri} are the weights for each RU (i) for the ecological resource R. Different weights might apply for RUs from the point of view social or economic factors, see Sections 2.5 and 2.6).

4. For the river, the R scores are aggregated with the economic (E) and social (S) scores obtained in a similar way (by going through 1 to 3) to obtain an overall score for the scenario a:

$V(a) = \mu_1R + \mu_2E + \mu_3S$ where the μ_1 to μ_3 are the weights given to the ecological, economic and social criteria groupings, respectively.

Using this coherent system means that evaluations in different stages are compatible. Without comparable evaluations between the different stages, decisions made during different stages might actually work against each other. For example, if new ecological measures are defined for the development of a water resource protection strategy, there will be no obvious way of knowing whether the Reserve and other resource quality objectives will actually be achieved.

PART II - Case studies

6. Thukela project: MCDA analyses of Steps 2 and 3 of STAGE 1

We were involved in the end stages of the Thukela Reserve project (run by IWR Source to Sea¹) on an observer basis. Information from the project was analysed and this contributed to the development of the guidelines for Stage 1. In the first analysis, the contribution of the ecological components to the overall ecostatus was assessed using ordinary least squares regression and linear programming. The regression indicated that aquatic invertebrates and riparian vegetation contributed the most to the ecostatus score. The linear programming analysis, where the scores associated with different ECs and ecostatuses were constrained in various ways, showed that the specialists had tended to use a non-linear scale (with bigger “gaps” between lower categories D to F than between higher categories A to C) for the ecosystem components. However, the non-linearity was less evident in the combined ecostatus scores. In the second analysis, the sensitivity of results (the overall status of the river under different scenarios) to two different scoring systems and two different weights sets was assessed. The overall river status was not sensitive to these assumptions. Although the weighted sum of resource unit scores provided a useful overall evaluation of the scenarios, additional information was also required: a particular scenario may have performed better than another (and therefore be “preferred”), but it may have “overperformed” in that it had achieved a category above the recommended EC.

7. DRIFT and DRIFTSOLVER

DRIFT (developed by Southern Waters²) makes use of a VM-MCDA approach in that the effects of different reductions (or augmentation) of flow in various flow classes (dry and wet season low flows and eight classes of high flows) are scored against various ecological subcomponents (of geomorphology, riparian vegetation, fish, aquatic invertebrates, water quality). These scores can be summed using a weighted summation to obtain an overall score for a particular flow regime (selection of reductions for each of the ten flow classes). DRIFTSOLVER (developed in conjunction with Southern Waters) uses a

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² Southern Waters Ecological Research & Consulting (Pty)Ltd, PO Box 13280, Mowbray, 7705, Cape Town Tel: +27-21-4653135.

binary integer goal program to optimally (ecologically) distribute flow between the different reduction levels of the ten flow classes by trading off these scores against the quantity of water required for each flow reduction level.

8. Evaluation of water supply augmentation and demand management options for the City of Cape Town

A number of water supply augmentation and demand management options had been identified for the City of Cape Town which is facing water shortages in the near future. Working in collaboration with Palmer Development Group³, value functions were established for a number of criteria under five broad categories (yield, technology, public and institutional buy-in, social, environmental). The alternatives could be given an overall rating based on the weighted summation of their scores, and grouped into (a) groups with similar characteristics, (b) groups which could be immediately implemented, those which required more study, etc. A year later, three additional supply options could relatively easily be added to the evaluation and the ratings updated.

9. The Usutu-Mhlathuze GIS-based DSS

A geographical information system based decision support system (DSS) was developed for the Usutu-Mhlathuze by W-MAC⁴ and we contributed to the MCDA aspects of its development. The DSS linked a hydrological model (at that time, to ACRU a physical based agrohydrological model⁵), which could calculate the water-use of various land-uses, with economic and employment information for each grid square. VM-MCDA scores were calculated for each land-use in each grid square. From a particular set of weights for the three criteria (water-use, gross margin and employment), the DSS determined the best land-use for each grid square and produced ArcView® maps of the resulting land-use. It also produced maps of the resulting VM-MCDA scores and of the difference between the original land-use's and the scenario's VM-MCDA scores. This DSS was intended to be able to assist in the assessment of licence applications, by indicating the effects of land-use or water-use scenarios on the catchment or WMA.

10. A genetic algorithm approach to multiobjective land use planning

A paper, to be published in *Computers and Operations Research*, 2004, Vol 31(14):2293-2313, is attached as Chapter 10 of this report. The paper describes work that was done in collaboration with the Free University of Amsterdam. The work described is, in a sense, the next level of sophistication to the sort of work described in Chapter 9, because explicitly spatial criteria (e.g. connectedness, fragmentedness) are also considered.

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