SCENARIO BASED MULTICRITERIA POLICY PLANNING FOR WATER MANAGEMENT IN SOUTH AFRICA

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EXECUTIVE SUMMARY

This project arose out of a recognition of an existing need within water resources management, and of a new technology that had the potential for addressing that need. The need was for a justifiable and credible means of achieving an equitable balance between the conflicting needs of the different interests of society, when developing new water schemes or allocating water between competing uses. This need was recognized some time back by the Department of Water Affairs in formulating its water management strategies. For example in the 1986 publication of the Department of Water Affairs entitled *Management of the Water Resources of the Republic of South Africa*, it is stated (page 6.4) that while "... economic merit is generally the dominant criterion against which development projects are assessed, particularly since this criterion is readily expressed in numerical terms ... the DWA's water management strategy recognizes that goals other than the production of goods and services are also important and strives to identify and to assign an appropriate significance to each goal". This same publication recognizes the particular problems identified in the 1970 Commission of Enquiry into Water Matters relating to the **intangible** benefits of projects such as "... the interest displayed by the public in recreation, the quality of the environment and the aesthetic possibilities presented by water resource development". It needs hardly to be added that since 1970, other equally intangible socio-political criteria have also come much to the fore. While this need has been recognized for more than 20 years, however, there remained little in the way of effective means for ensuring particularly that the intangible goals, not immediately expressible in numerical terms, do in fact receive their "appropriate significance".

It should perhaps be emphasized at this stage that although the research reported here was motivated initially by the needs of *water management*, the results would be generally applicable to a wide variety of *other resource management* problems, wherever there exists the need to take cognizance of conflicting and sometimes intangible interests of society. In fact, members of the project team working on this research have already been looking at the application of the results to pelagic fisheries' management in the Western Cape. For the purposes of this report, however, we will focus on water management issues only.

In parallel with the increasing recognition of the need identified in the opening paragraph, there was a development in the management science literature of an assemblage of techniques which are broadly classified as *Multiple Criteria Decision Making (MCDM)* tools. These tools are used to develop (usually computer-based) decision support systems, which can guide managers, policy planners, or other interested parties, towards the finding of a solution which achieves in some sense the maximum level of satisfaction of all conflicting goals and interests. They assist in identifying the key value judgments which have to be made, amongst the usually confusing mass of data which tends to be generated in the evaluation of any policy alternative; and provide means of comparing "apples and oranges" in a logically justifiable manner. A preliminary perusal of the literature regarding MCDM developments in the 1970s and 1980s revealed that much of the stimulus for this work came from water resource planning problems, particularly in the USA. On *prima facie* grounds, therefore, it seemed that the field of MCDM could and should be able to provide precisely the means needed for ensuring just consideration of all costs and benefits, direct, indirect and intangible, when assessing water resource policy decisions in the Republic of South Africa.

With this background, the research project was formulated with the following overall aims:

(1) To establish a formal and quantified hierarchical structure of water planning and management goals, representing a consensus of opinion amongst all major users of water, which can be used in assessing alternative water policies and plans;

(2) To investigate and to develop procedures whereby such goal structures can be integrated into formal Decision Support Systems (DSS), in which the outputs of various systems models can be evaluated in terms of their contributions to management goals;

(3) To demonstrate the relevance of the multi-criteria decision support system approach in water planning, by implementing and testing an operational DSS for at least one problem setting, as a "demonstration" project.

At an early stage of the project it was agreed with the Department of Water Affairs and Forestry, and the Water Research Commission (and approved by the Steering Committee), that the attention would be focussed on the particular problems being encountered in the Eastern Transvaal, and particularly the Sabie-Sand River system. It was hoped that this could serve also as the "demonstration" project.

It rapidly became clear that "a formal and quantified hierarchical structure of water planning and management goals" which would apply generally in all contexts was an unachievable aim. In its place was required an extension of the procedure envisaged in the second aim, to allow for the systematic identification of the relevant goal structure in each case. An implication was that the procedure itself should be adaptable for use no matter how the goal structure appeared in any one case.

The broad research methodology adopted was to formulate an initial prototype procedure for aim (2), and then to attempt its implementation for the Sabie-Sand catchment area. In this way problems with the decision support procedure could be identified quickly, and the procedure itself updated to rectify such problems. In the end, the analysis of the policy planning problems was based on realistic, but still somewhat hypothetical policy options for the region. This became necessary as complete and comprehensive policy proposals were not available: in fact, it became evident that any decision support procedure must include support for the process of generating a broad range of potential policies. What emerged from this research was a new procedure which we have termed *scenario-based policy planning*, which draws not only from the MCDM literature, but also from the modern concept of scenario analysis. The proposed procedure is fully described in Chapter 4 of the main report (and summarized in Figure 4.1 of the report), but in outline contains the following features:

(a) A process of identifying policy elements and thereby the ranges of policy scenarios which can feasibly be implemented;

(b) Use of experimental design procedures to generate a representative set of feasible policy scenarios (called the *background set*), typically 50-200 in number: consequences of each of these would be evaluated in sufficient detail to be able to specify each scenario comprehensively for the purpose of direct comparisons by representatives of different interests;

(c) Use of formal MCDM methods to make a further selection from the background set of ± 7 scenarios (called the *foreground set*) for direct value assessments;

(d) Comparisons of scenarios within and between interests, using computer assisted multicriteria decision support aids: initially attention is focussed on eliminating less generally acceptable scenarios, while later this attention shifts towards identifying possible consensus;

(e) Iterative repetitions of steps (c) and (d), continually refining the foreground set in the search for the most generally acceptable scenarios.

The proposed procedure makes extensive use of workshops, or *"decision conferences"* at which representatives of different interests explore their own value judgments and preferences, in the context of well-defined scenarios. These preferences are expressed by aligning the scenarios along a 0-100 scale (sometimes termed a "thermometer" scale). These scales are comparable between interests and criteria, irrespective of how tangible or intangible they may be, and thus serve to identify areas of serious disagreement or of possible compromise. Step (d) of the procedure includes formal decision support for this between-interest comparison as well. A number of these workshops were conducted as part of the research, in order to establish the usefulness of the approach.

Overall conclusions from the research can be summarized as follows:

(i) Conventional methods of multiple criteria decision making (MCDM) do not directly offer a means of systematically addressing the less tangible costs and benefits to society of water policy decisions. Multicriteria decision analysis techniques are nevertheless useful for eliciting value judgments concerning all societal interests, by a process of direct comparisons of 7 ± 2 comprehensively defined *policy scenarios*, expressed on a "thermometer" (i.e. 0-100) scale. The resulting measures are comparable across interests, and provide one of the few, if not only, justifiable means of comparing intangible costs and benefits with each other and with tangible costs and benefits. This conclusion is supported by experience with evaluating hypothetical policy scenarios for the Sabie-Sand River region.

(ii) Existing software support is available to implement the comparative measurements described in (i). The VISA package (Visual Interactive Sensitivity Analysis for multiple criteria decision aid), appears to be the most appropriate software to use at this stage. Workshops using this software can be constituted with little effort, to facilitate the process of rating policy scenarios on "thermometer" scales, both within relatively homogeneous interest groups (to assess their value preferences) and globally (to identify potentially acceptable consensus policies). It is recommended that this approach be taken into immediate use, whenever a relatively small number of policy alternatives need to be evaluated and compared.

(iii) In the longer run, the systematic and comprehensive *scenario based policy planning* procedure is recommended. Full software support for this procedure has yet to be developed, but the feasibility of individual steps has been demonstrated (although further research to refine certain of these steps is recommended).

As indicated earlier, the first of the original three aims turned out to be unrealistic, leading to an extension of the second aim. It is believed that this extended second aim, as stated, has been fully achieved. As a result of these extensions to aim (2), it was not possible to develop a comprehensive software support for implementing the recommended procedures however. Thus a fully operational Decision Support System was not available for testing on the "demonstration project" (aim (3)). Nevertheless, the basic concepts and procedures of the DSS have been tested in this context, as required by the third aim. This has, *inter alia*, demonstrated that the absence of the software does not hinder implementation of the general procedures, by means of sequences of workshops under the guidance of a facilitator familiar with the procedures and the commercial decision analysis software (VISA) currently available.

The state of the art of multicriteria decision analysis has been substantially extended by this work, in the sense that no previous literature has attempted any general framework which addresses the particular problems of application to resource planning. Such problems include the complexity of models for computing the consequences of specific policies, and the need to integrate subjective evaluations of the intangible issues with more objective data, when the range of possible policy options is very large.

Future research is still needed:

- to refine certain technical steps in the procedure itself, and to incorporate the procedure into a fully operational computerised DSS;

- to integrate the procedure with GIS or similar technologies for the most effective display of scenarios; and

- to test the procedures in real-life policy planning.

All of these research needs are included as objectives in a new project accepted by the Water Research Commission (for the period 1993-1995) under the title "The development of procedures for decision support in water resources management".

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LIST OF ACRONYMS AND TERMINOLOGY

The following acronyms appear throughout the report:

ACRU	Agricultural Catchments Research Unit, University of Natal (referring to the hydrological model constructed by this unit)
AHP	Analytic Hierarchy Process*
DSS	Decision Support System
ELECTRE	ELimination Et Choisis Translation REalité* (a French acronym which has been translated as "elimination and choice translating algorithm")
GDSS	Group Decision Support System
GIS	Geographic Information System
IMGP	Interactive Multiple Goal Programming*
MCDM	Multiple Criteria Decision Making (See notes on terminology below)
NGT	Nominal Group Technique
SMART	Simple Multi-Attribute Rating Technique*

Those marked by asterisk (*) are all different methods which have been proposed for MCDM problems, and are reviewed in Appendix A.

An attempt is made to avoid technical terms in the main report, but the following terminology occurs frequently:

ATTRIBUTE (or SYSTEM ATTRIBUTE): A measurable property of a system which can serve as a basis for comparing outcomes of different policy actions, and which can in principle be predicted (from systems models or expert judgment) for any proposed policy. Typical attributes relevant to water management include maximum and minimum streamflows in various rivers, investment costs, water availability per head of population, etc.

CRITERION: A basis for comparing different decision or policy options according to one point of view.

MULTIPLE CRITERIA DECISION MAKING (MCDM): A general term in the management science literature, referring to the collection of procedures and methods used for solving decision problems in which conflict between two or more criteria exists.

OBJECTIVE: A quantified representation of a criterion, usually expressed in the form of a desire to maximize or to minimize some system attribute.

POLICY ELEMENTS: Individual instruments or components of a water management policy which might be considered. Typical policy elements are construction of reservoirs, implementation of water or land usage restrictions, allocation of investment funds to competing projects, etc.

SCENARIO: A comprehensive description of a possible future state of any system: the term POLICY SCENARIO is used when this description includes both a statement of policy assumed to be implemented, and the consequences thereof.

No mathematical symbols are used in the main report. Mathematical symbols or terminology necessary for the discussion in any particular Appendix are defined in that Appendix.

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The Steering Committee responsible for this project consisted of the following persons:

Mr H Maaren	Water Research Commission (Chairman)
Mr P W Weideman	Water Research Commission (Secretary)
Mr J M Bosch	FORESTEK, CSIR (later replaced by Mr P Manders)
Mr A Conley	Department of Water Affairs and Forestry
Dr G C Green	Water Research Commission
Prof D C Midgley	
Prof P J T Roberts	Institute for Commercial Forestry Research, University of Natal
Dr D W van der Zel	Department of Water Affairs and Forestry
Mr P S van Heerden	Department of Agricultural Development
Prof W Zucchini	University of Cape Town

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1. INTRODUCTION

The research described in this report had a two-fold origin. On the one hand there was a recognition that the management of water resources in South Africa will have to satisfy, and be seen to satisfy in a fair and equitable manner, the needs and aspirations of increasingly divergent interests in society. This theme recurs in various forms throughout the 1986 publication of the Department of Water Affairs on the *Management of the Water Resources of South Africa* [10], in which, for example, the need is stressed for easily understood means of evaluation of intangible and indirect consequences of water policy, in a manner comparable with direct economic consequences (cf. Section 7.1 of [10]). On the other hand, the literature of the specialized branch of management science known as *multiple criteria decision making (MCDM)* revealed that water resource planning problems constituted a substantial proportion of applications considered. There seemed thus to be considerable scope for bringing modern MCDM techniques to bear on the management of water resources in South Africa. Some more recent literature has in fact tended to support this view. For example, Talcott (ref [23], in a special issue of the journal *OR/MS Today* devoted to environmental management) states that "the various techniques of decision analysis, especially those dealing with multiple decision criteria, data envelopment analysis and the analytic hierarchy process, provide a reasonable way to frame the choices to be made, and some help in making them". Ellis (ref[11]), in the same issue adds that "when environmental OR (*Operations Research*) projects have succeeded, in our experience, they have done so because they are multiobjective. Environmental problems *are* multiobjective ...".

The original objectives of the research were set out in the original proposal as follows:

(1) To establish a formal and quantified hierarchical structure of water planning and management goals, representing a consensus of opinion amongst all major users of water, which can be used in assessing alternative water policies and plans.

(2) To investigate and to develop procedures whereby such goal structures can be integrated into formal Decision Support Systems (DSS), in which the outputs of various systems models can be evaluated in terms of their contribution to management goals.

(3) To demonstrate the relevance of the multi-criteria decision support system approach in water planning, by implementing and testing an operational DSS for at least one problem setting as a "demonstration project".

With reference to the third aim above, it was recognized at the planning stages that research of this nature could not be done in abstract, and there needed to be some realistic, even if not entirely real, case study to serve as a practical focus for the work. In view of the wide range of research activities already under way in the Sabie-Sand River system, it was agreed that this could serve as such a focus. For this reason, the practical examples referred to in this report will frequently relate to this catchment area, but the principles are believed to be generally applicable. This use of a realistic case study did indeed turn out to be useful, although (as will become evident later) it did also introduce complications which hindered the full achievement of all the original objectives. In particular, it was not possible to design and develop a fully-fledged computerized DSS which can be used directly in the Sabie or other catchment areas. We will report on a general procedure that has been validated to some degree (but still requiring some refinement of detail), and the ultimate goal of developing a DSS implementing this procedure still appears to be realistic in the long-term, quite probably linked to a Geographic Information System.

In outline, the following phases of the research as it actually took place can be identified:

(i) Literature review and problem familiarization: A systematic literature search was conducted, details of which are described in Chapter 2 and in Appendix A. A disturbing feature was the recognition that many reported applications of MCDM to water resources planning were either on problems of a rather limited scale, or were not demonstrably implemented at all. This immediately gave warning that the research might have to be more fundamentally ground-breaking (and thus more extensive) than initially envisaged.

At the same time field trips were taken into the Sabie River region, to examine the problem setting at first hand, and to meet with some of the important actors. The annual meetings of the KNP Rivers Research Programme also provided valuable opportunity to gain understanding of the complexities of the situation.

(ii) Attempted implementation of standard MCDM methods: On the basis of discussions with various concerned groups, an attempt was made to implement the standard approaches described in the literature, within the context of the perceived problems of water resource development in the Sabie-Sand region. The problems encountered are described in detail in Chapter 3, but the important of these are the difficulties of identifying the ranges of policy options, and the fact that the hierarchy of criteria did not naturally decompose into clearly defined, operationally predictable system attributes (cf. Appendix A for some discussion of these terms). These problems did nevertheless contribute significant insights into both the limitations of conventional procedures and the requirements of any practically meaningful procedure in this context.

(iii) Development of alternative procedures: In consequence of (ii), alternative procedures needed to be developed. These can broadly be described as *MCDM scenario planning* procedures, and are described in the current context in Chapter 4.

(iv) Testing of the alternative procedures: The methods of testing the new proposed procedure had of necessity to be somewhat different to the testing originally envisaged for more-or-less conventional procedures, and are described in Chapter 6. A key requirement was to develop realistic planning scenarios for the Sabie-Sand River regions. It was soon evident that the development of complete scenarios lay beyond the scope (i.e. the resources) and purpose of present project, and the focus was limited to producing scenarios which were of sufficient realism so that different parties could meaningfully express preferences between them. Even this process took several months to complete.

Although it was recognized that any practical implementation of the proposed procedures would have to take place in a group workshop context, an attempt was made to carry out the experimental implementation for testing purposes by means of a mail survey, in order to achieve wide coverage with minimal expenditure of resources and time. This had, unfortunately, limited success, because of the incompleteness of the scenarios and the unfamiliarity of respondents with the procedure (see Chapter 6 for details). There was only time remaining for a relatively small number of actual workshop implementations, but these did give positive evidence in favour of the new procedure.

2. LITERATURE SURVEY

The main literature study was undertaken during the first year of this project, and the results of this study are appended as Appendix A to this report. Apart from the literature survey itself, Appendix A contains a technical overview of the field of MCDM and of the technical terms used therein, in order to facilitate interpretation of the survey itself. Sections A2-A5 of this Appendix are taken (apart from minor revisions) from an informal interim project report which was distributed in 1991. Subsequent to this survey, one of the authors was invited to prepare a comprehensive survey of MCDM methods in a more general context for the journal *Omega: The International Journal of Management Science* [22]). Reprints of this paper are available from the author on request. It will be evident from Appendix A that the field of MCDM is well-developed, with a number of quite divergent approaches being reported. Problems of water and other resource planning are frequently used to illustrate the different methodologies (although it is not always clear as to how real these applications are). In Appendix B, we have drawn together the most common of these approaches, and illustrated them by means of a hypothetical water resource planning problem, based broadly on the issues current in the Sabie-Sand River region (which is used elsewhere in this report as a case study for illustrative purposes). It is hoped that Appendix B will clarify the concepts in Appendix A, and demonstrate how the MCDM techniques can be used in practice. This should serve the dual purpose of (a) giving planners some guidelines as to how the methods might be applied as a first pass in generating potential policy recommendations, and (b) illustrating the implementation problems (discussed in Chapter 3) when applied more generally to policy analysis and evaluation.

Some specialized literature relevant to the specific proposals arising out of our research will be referenced at the appropriate points in Chapters 4-7 of this report. But apart from this, we are not aware of any major new developments over the past 18 months which need to be added to the survey of Appendix A. The main features and general conclusions of this survey are summarized in the following paragraphs.

2.1 The process of formally structuring management objectives hierarchically is well documented in the literature. This is seldom specific to water resources planning, but does refer to public policy issues in a more general context. Standard textbooks such as those of Keeney and Raiffa [16] and von Winterfeldt and Edwards [25] summarize this work well. The use of group techniques in this context, for example in "public value forums", are also well validated (cf. Keeney *et al.* [15]. The structuring of objectives itself is relatively qualitative in nature, although most writers do make some reference to assessment of quantitative importance weights on the objectives. Important empirical work which identifies the sensitivity of such weights to the structure of the objectives hierarchy, and to the precise method of elicitation is that of Weber *et al.* [26] and of Borcherding *et al.* [5]. The PAWN (Policy Analysis for the National Water Management of the Netherlands) study [13] conducted in the 1970s is perhaps the most germane to the current project, and includes a hierarchy of objectives which was used as a framework for systematically comparing different proposed policies on the basis of the outputs from a variety of systems models. (It is interesting to note that the criteria listed in Section 10.2 of [13] bear a remarkable similarity to that which we derived, and as described in Section 3.1 of this report, although our hierarchy was constructed before we had received the report on the PAWN study.) The PAWN study did not, however, attempt to construct formal quantitative measures of overall goal achievement, which was left to holistic judgment.

2.2 The extension of the qualitative structuring of objectives to quantitative measures of goal achievement is widely discussed in the literature, both in the context of water resources planning and in a wide variety of other policy planning issues. Unfortunately, a very large proportion of this work falls into one of two categories:

(a) Operational-level decisions (eg. release rules from dams), in which relatively well-defined tangible goals (cf. also Section 3.1) can be defined (in contrast to our interest in forming a basis for the treatment of the more intangible goals of society); or

(b) Hypothetical studies, seemingly unvalidated in any practical sense, often introduced mainly to serve as an example of the application of some specific new technique of Multi-Criteria Decision Making.

A few writers do seem to notice a role for MCDM methods, in which relatively tangible surrogate goals are used as a substitute for more indirect and intangible objectives, as a means of generating short-lists of alternatives (or *policy scenarios* as we will term them), but do not seem to develop this theme. This approach does, in fact, form part of the procedure which we are recommending in consequence of the research reported here.

2.3 In our view, the only truly comprehensive theory of value measurement that can be applied to the range of intangible issues relevant to water planning in South Africa, appears to be that of *multi-attribute value (utility) theory*. The role of so-called *decision conferencing* [14] in applying this theory in the public policy domain appears to be very important, although is seldom emphasized in the literature (perhaps because those with expertise in this area prefer to sell it as consultants, rather than to publish).

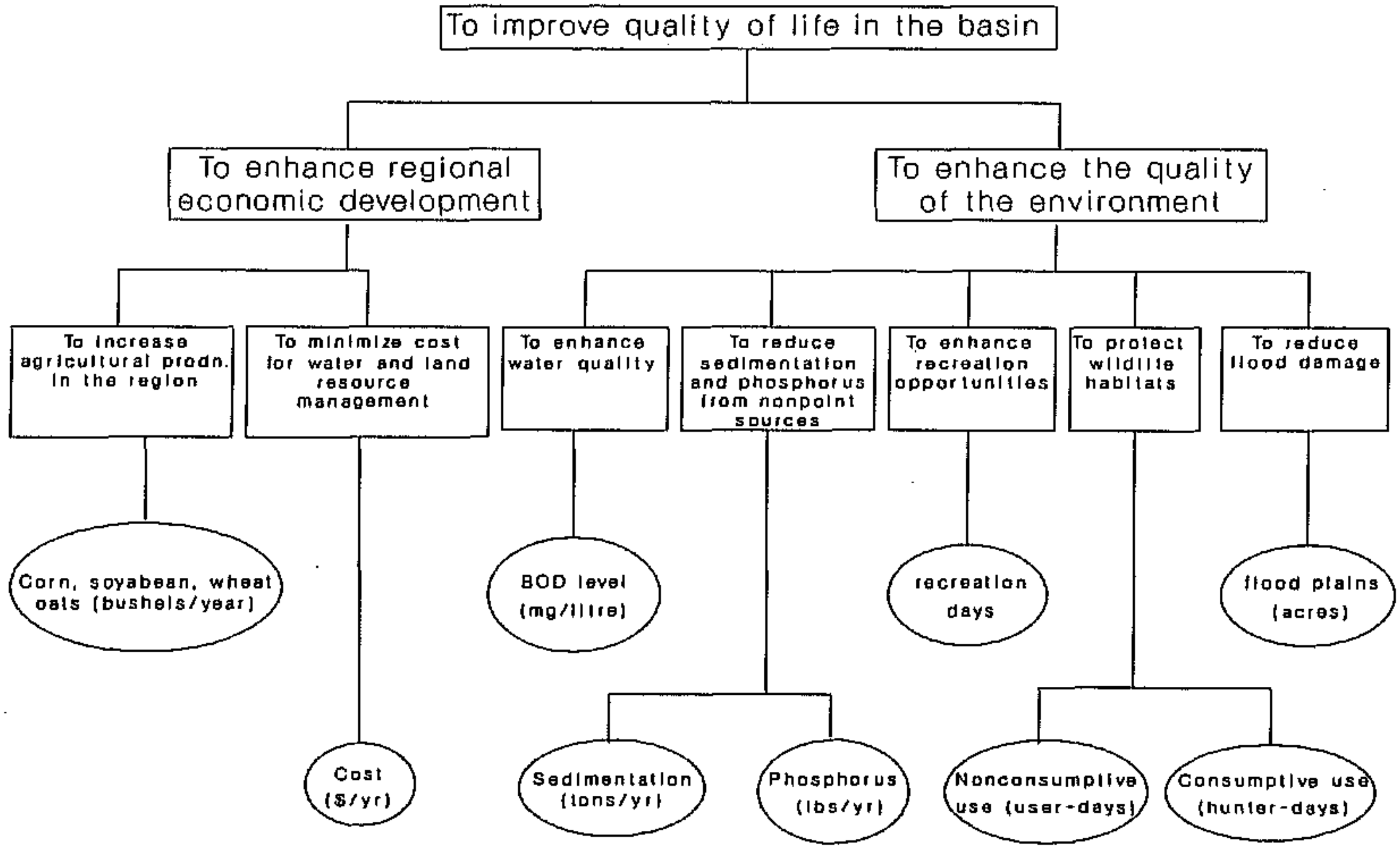
The bulk of the literature found initially could be classified as falling under 2.2 above, and the quantity of this literature certainly suggested that our answer lay there. In the next Chapters we report on the process of discovery which led us to conclude that this initial perception was false. In retrospect, we can see that all the elements of a solution were in the literature, but seemed not to be gathered together. In summary, the proposed procedures described in Chapter 4 involve scenario generation using *inter alia* many of the standard MCDM concepts, taken together with a decision conferencing approach based on multi-attribute value theory.

3. ATTEMPTED IMPLEMENTATION OF STANDARD MCDM APPROACHES, AND PROBLEMS EXPERIENCED

Appendix B illustrates how multiple criteria decision making (MCDM) can *in principle* be used in generating, evaluating and comparing alternative water resource planning policies. It is believed that a combination of approaches such as these can in fact be usefully employed in a first-pass screening of potential policy options, so that more detailed evaluations can be focussed on the more critical issues. The procedures do require value judgments to be made by users, but are also relatively robust to these judgments. In attempting to extend these MCDM techniques to facilitate the essentially political process of final policy selection, however, problems do arise, not least of which are that the methods are often not easily understood by non-specialists, and that they tend to work best on the more quantifiable objectives of society. In this Chapter, we discuss the difficulties which arise in extending the MCDM methods to policy evaluation in the public domain, when intangible and indirect goals should and do play a significant role.

3.1 Identification of System Attributes as Measures of Goal Achievement

As indicated in Appendix A, there exists a considerable body of literature regarding the process of decomposing a complex and imprecise general goal statement (e.g. to maximize welfare of all peoples in a region) into a hierarchy of increasingly precise sub-goals (such as maximize agricultural outputs). Of course, achievement of one sub-goal will in general conflict with the achievement of others, which is the essence of the study of MCDM. An example of this, in a water planning context, is given in Figure 3.1 which is taken from Chankong and Haimes [7]. Which of two proposed policies contributed most to "quality of life in the basin" would be highly arguable; to determine which of two policies contribute most to bushels per year of corn would probably be left to the judgment of the



<u>Source</u>: V. Chankong and Y.Y. Haimes, **Multiobjective Decision Making: Theory and Methodology** (North Holland, 1983), Figure 1.3

Figure 3.1: Illustration of an objectives hierarchy (taken from Chankong and Haimes [7] Figure 1.3)

relevant agricultural experts.

The common (and often unstated) assumption in MCDM is that a hierarchy such as that in Figure 3.1 can so be constructed that at the lowest level the objectives are expressed as maximizing or minimizing some well-defined *system attribute* (see Appendix A). This is well illustrated in Figure 3.1, where the attributes are productions of various crops, cost, three water quality measures, three measures of water utilization and the area protected from floods. In all cases, these attributes would be predictable in unambiguous terms (even if not with absolute precision) from appropriate systems models, for any proposed policy actions. Standard MCDM approaches are then directed towards finding a best compromise between these surrogate, but well quantified, objectives.

In terms of the original research objectives, the first step would be to develop a hierarchy such as that in Figure 3.1, but in general terms that could be applied (with suitable adaptation of specific details) to any water planning in South Africa. This might then serve as a guideline for planners, to ensure that all national interests receive the necessary attention in every case. By a combination of informal discussions, workshops, and the circulation of earlier drafts for comment, a broad level of consensus was reached that the hierarchy shown in Figure 3.2 covered most important criteria. It should be emphasized, however, that this should not be viewed as a complete and validated hierarchy of criteria, but rather as an aid which may be of value as a checklist in future planning,

The hierarchy of Figure 3.2 differs markedly from that of Figure 3.1, in that it does not lead to an unambiguous set of objectives, expressed in terms of maximization or minimization of system attributes. In principle, we would need to go one step further in order to achieve this. In some cases, this further step would be quite simple, particularly in the case of economic benefits. But the research project was motivated in the first instance by a search for methods of dealing with indirect and intangible criteria, and it is precisely here that it seemed not possible to achieve any consensus on further development of the hierarchy.

Two workshops were held with officials of the Department of Water Affairs and Forestry, representing various interests within the department, in order to establish at least a *prima facie* list of possible attributes which might be used as measures of goal achievement. The attributes identified in this way were consolidated into the following list, after circulation for comment:

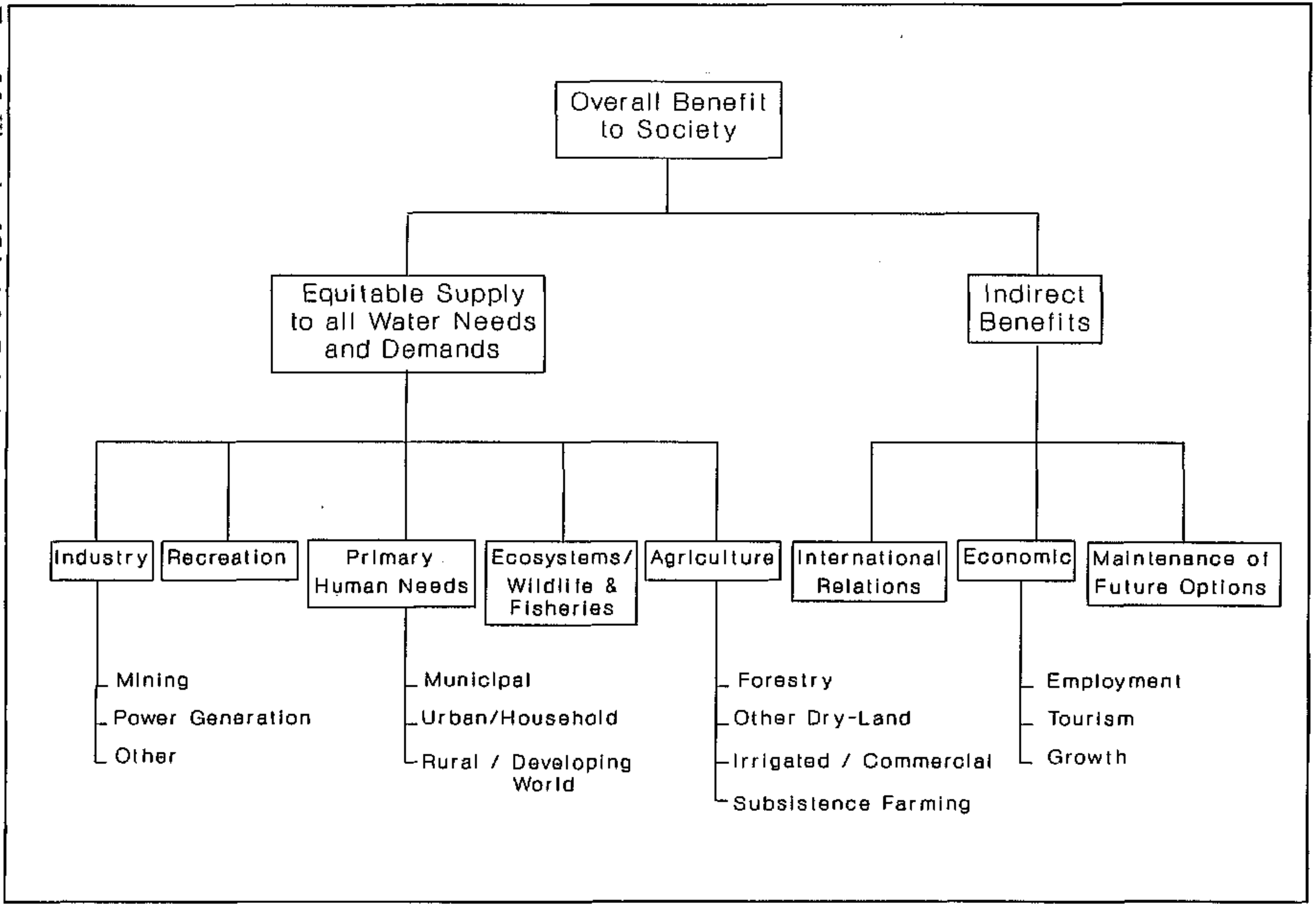


Figure 3.2: Hierarchy of Criteria for Evaluation of National Water Resource Policies on South Africa

(a) Capital costs

(b) Operating costs

(c) Direct economic benefits and disbenefits (tourism, forestry, irrigation for commercial agriculture, etc.)

(d) Flow regime at designated reference points in the basin (possibly described in terms of deviations from current conditions): Points to be considered are: expected total annual flow, expected minimum and maximum flows during year, and other percentiles of flow distribution.

(e) Water condition at designated reference points in the basin (also possibly described in terms of deviations from current conditions): Points to be considered are: quality (BOD, dissolved solids, suspended solids, etc.) and water temperature.

(f) Risk

Although these attributes are not fully defined operationally, and although many link to more than one interest in Figure 3.2, there did seem to be some potential for the setting of surrogate goal measures in these terms. In fact, the scenario definitions, forming part of the procedure to be outlined in Chapter 4, would normally be expressed largely in terms of these attributes. In practice, however, representatives of a number of the interest groups (e.g. ecosystem and rural human needs) were unwilling or unable to decompose their interests into sub-objectives of the form *minimize* or *maximize* measures drawn from (a)-(f) above. Subsequent workshops (cf. Section 6.3) gave evidence that they could react to specific scenarios postulated in such terms, classifying these as "good" or "bad" (an important point in justification of the scenario planning approach), but they seemed not to be able to commit themselves to a specific set of goal measures *a priori*.

Were it possible to identify surrogate goals, expressed in terms of system attributes, for all criteria in Figure 3.2, then software could have been developed to implement standard methods of MCDM in any specific context; and this software could have incorporated constraints on the effective weights attached to each goal, to ensure that in any specific case, due consideration is given to all interests, tangible or intangible. But this was not to be! Any procedure, therefore, needs to take into account the fact that for some criteria at least, assessment of goal achievement will have to be in holistic and subjective terms, and not in terms of system attribute measures. The challenge thus shifted towards procedures which could make use of such subjective judgments, in a manner which would ensure comparability between criteria, but which would be as free as possible from manipulation.

3.2 Identification of Policy or Decision Alternatives

The MCDM literature, as reviewed in Appendix A, has relatively little to say about the process of generating alternative courses of action, or policies. Although this is acknowledged to be an important and difficult task, the descriptions of most MCDM approaches start on the assumption that this task has already been completed, and that a well-defined set of alternative policies already exist. The methods of MCDM are thus directed towards the process of selecting a most satisfactory alternative from such a pre-defined set.

Since the set of alternatives will always be context-dependent, an early focus of the research was to examine the extent to which alternative policies, or *policy scenarios* (which we have found to be a convenient term, in recognition of the fact that all possible alternatives can never in practice be evaluated), can be identified. This was done using the Sabie-Sand river system as a case study. A "brainstorming" session, using a Nominal Group Technique [9], was conducted over two afternoons (with subsequent feedback to participants). The purpose of these workshops was to identify the policy instruments which are in principle relevant to the Sabie-Sand River Region (irrespective of whether or not the necessary legislative machinery for implementation exists at present or not), expressed in terms of a number of *policy elements* (i.e. those components or instruments of policy for which more-or-less independent ranges of action are possible in principle, even if not necessarily desirable). The elements identified as a result of these workshops are as follows:

(1) Restrictions on private storage
(2) Restrictions on rate of abstraction from public streams
(3) Afforestation permits
(4) Construction and operation of reservoirs and/or other irrigation schemes (including provision of standpipes of water for human consumption in rural communities)
(5) Interbasin transfers (into or out of the basin)
(6) Restrictions on other forms of land use
(7) Tariff and financing schemes
(8) Population and urbanization controls or incentives
(9) Creation of public participation forums
(10) Centralization/Decentralization of decision making
(11) Public education (both general and focussed on political leadership)
(12) Use of rain-enhancement schemes

Even if there existed only three or four options for each element, this could generate in excess of 10 million possible policies. Clearly, these cannot all be evaluated in detail, and some sub-set of these (*policy scenarios*) has to be selected for evaluation. Choice of this subset appears to be an important and critical phase of the analysis, and must receive explicit attention (as is done in the proposed procedures of Chapter 4). For the purposes of the research reported below, we focussed on the first four of the above policy elements, as a case study. Even with this restriction, an additional feature became evident, *viz.* the dynamic nature of the problem. Within relatively short periods (for example, the time between the two workshops referred to above), perceptions as to which options required serious attention varied quite dramatically. This made it difficult to tie down a fixed set of representative alternative policies to which standard MCDM procedures could be applied. Clearly, therefore, any useful decision support procedure (or computerised Decision Support System) has to be able to cope with this dynamic change, without requiring a completely fresh analysis from the start whenever the set of alternatives changes.

3.3 Predictability of the Consequences of Policy Actions

Suppose (contrary to the observations of Section 3.2) that an explicit and stable set of alternative policies has been established, and that (contrary to the observations of Section 3.1) that all criteria are representable in terms of a fixed and finite set of system attributes. Standard MCDM theory assumes that it is possible to assess in some way the values of each system attribute for each alternative policy, at least in a probabilistic sense. (For example, if winter flow level at a particular point in a river during a 50-year drought were such an attribute, at very least a probability distribution, or a confidence interval, for this level would have to be estimated for each alternative.) This assumes the existence of a reasonably well-calibrated and validated model, which in the case of water resources planning in Southern Africa may not always be true. In some cases, a number of different models may exist, espoused by different groups, not always generating similar results; in other cases, there may simply not exist any adequate model. This implies that human judgments have to be made as to which model to use, or what weight to attach to each model (since good planners will probably look at the predictions of many models in this case), and as to the consequences of alternative policies for those attributes for which no credible model exists. Provision needs to be made for the inputs of such judgment, as well for the monitoring of such judgment for internal consistency.

Although in our case the two suppositions at the start of this Section do not hold, the same problems of the validity and credibility of models still carry through even for the scenario planning procedure proposed in the next Section. Thus any procedure developed needs to be flexible in allowing users to express expert views regarding outcomes of policy scenarios in opposition to, or in place of, more formal mathematical models. What is required is that the rationale behind such judgmental inputs, as well as their internal consistency be recorded and monitored, and that their effect on the solutions obtained be carefully assessed by means of appropriate sensitivity studies.

3.4 Conclusions from Attempted Implementation of Standard MCDM Approaches

Three key conclusions could be reached from the phase of the research described in this Chapter, as follows:

3.4.1 Policy analysis can at any one stage only be directed at a very small subset of all possible policy options, i.e. what we have termed policy scenarios. The process is however dynamic, and the set of policy scenarios under consideration will continually be subject to revision and to refinement. Any decision support systems or procedures must facilitate both the identification of suitably rich subsets of policy scenarios, and the process of revising or refining the subset chosen for evaluation.

3.4.2 Although meaningful policy scenarios can be, and indeed have to be, defined in terms of quantitatively predictable system attributes, the ultimate assessment of these on the basis of indirect or less tangible benefits or costs must always remain a matter for holistic human judgment. The purpose of a decision support system or procedure is to ensure that the process of judgmental evaluation is (as far as is possible) consistent, coherent, comparable (across different interests), and seen to be just and fair.

3.4.3 Subjective value judgments on intangible issues in particular, are intrinsically linked to an assumed context. (A distance of 30km has some meaning in the absence of context; the beauty of a rose can only be related to that of other roses which we have seen or experienced.) It is therefore absolutely essential that any decision support system or procedure make the context of any value judgments completely and unambigously known to all persons involved.

In the following Chapter, we develop a decision support procedure derived from the above considerations. At this stage it is a *procedure* rather than a fully developed and computerised *decision support system (DSS)*, but we do indicate what computer software is available to facilitate parts of the procedure. A key issue in developing the procedure is that of *value measurement* (cf. 3.4.2 above), the principles of which are well set out in books such as von Winterfeldt and Edwards [25], and are referred to in Appendix A. The value measurement component of our proposed procedure rests heavily on the "SMART" (Simple Multiattribute Rating Technique) procedure, also described in [25]. This is a simple implementation of multiattribute utility theory, which is in turn a theory derived from a careful axiomatization of what constitutes coherent decision making practice. The theory is not without its critics, but little in the way of an alternative is available. Perhaps the closest alternative is the so-called Analytic Hierarchy Process (AHP), but for reasons discussed in Section A4 of Appendix A, and because the processes in AHP are considerably less transparent to users than with SMART, we conclude that the AHP is not appropriate in the water resource planning context.

4. SCENARIO BASED POLICY PLANNING

In the previous chapter we have motivated a decision support procedure based on the generation and analysis of small numbers of policy scenarios. In this chapter we define this procedure more specifically, although all technical details are confined to Appendix C. The concepts behind the procedure have evolved from the literature and from our experiences in a number of workshops. Many technical details as well as full computer implementation remain topics for future research.

The following quote from Bogetoft and Pruzan [4] broadly highlights the elements of the process which will be described:

> ..." *we suggest that the prescriptions summarized ... below should guide the planning process.*
>
> *1. Each participant should determine for himself which values, objectives and criteria he feels are relevant to the planning process and the decision to be made.*
>
> *2. The participants should openly discuss their objectives and then focus on the criteria which they choose to measure the quality of the group's proposed actions.*
>
> *3. As a means of structuring the discussion, it may be helpful to generate a matrix of evaluations of the different alternatives with respect to the different criteria.*
>
> *4. Based upon these discussions and analyses new alternatives should be identified (or created) and evaluated.*
>
> *5. Based upon such discussions and analyses, a "collective" choice should be arrived at.* "

4.1 Definition of scenario based policy planning.

Scenario based policy planning is an approach which is of particular use in problems of broad societal impact when:

i. It is not possible/ feasible to specify fully all policy options

ii. The stated goals of the problem are intangible (i.e. not directly measurable quantitatively)and may need to be approximated by a variety of surrogate goals.

iii. The relationships between the different interests or criteria on the one hand and the available policy actions on the other hand, are not clearly defined.

iv. Considerable time and effort need to be invested in determining the effects or outcomes of proposed policies.

The approach makes it possible for decision makers and other concerned parties to express value judgements by means of direct comparisons between specific alternative policy options, the consequences of which are specified as far as possible. Although the number of alternatives under comparison at any one time will be quite small, these can still be chosen so as to reflect the ranges of options available. To fully specify the effects of a single proposed policy is a large and lengthy project. In order that the process does not become bogged down by detail prematurely, effects of policy are described in less detail at the earlier stages of the process (i.e. before the set of policies has been reduced very far) than later on when the effects of a few policies are described in more depth.

The approach operates both at the individual (within interest group) and collective (within and between interest group) levels. Within each interest group the procedure helps concerned parties to formulate their preferences between policy alternatives, and to produce a rank ordering of preferred scenarios in a manner which is clearly conveyable to decision makers and to other interest groups. At the "between interest group level" the various interest groups are helped to find possible consensus positions. The full procedure is illustrated diagramatically in Figure 4.1; the steps are described in the following sections and illustrated where possible by reference to the Sabie River case study. It should be noted, however, that the scenario-based policy planning procedure can in principle be

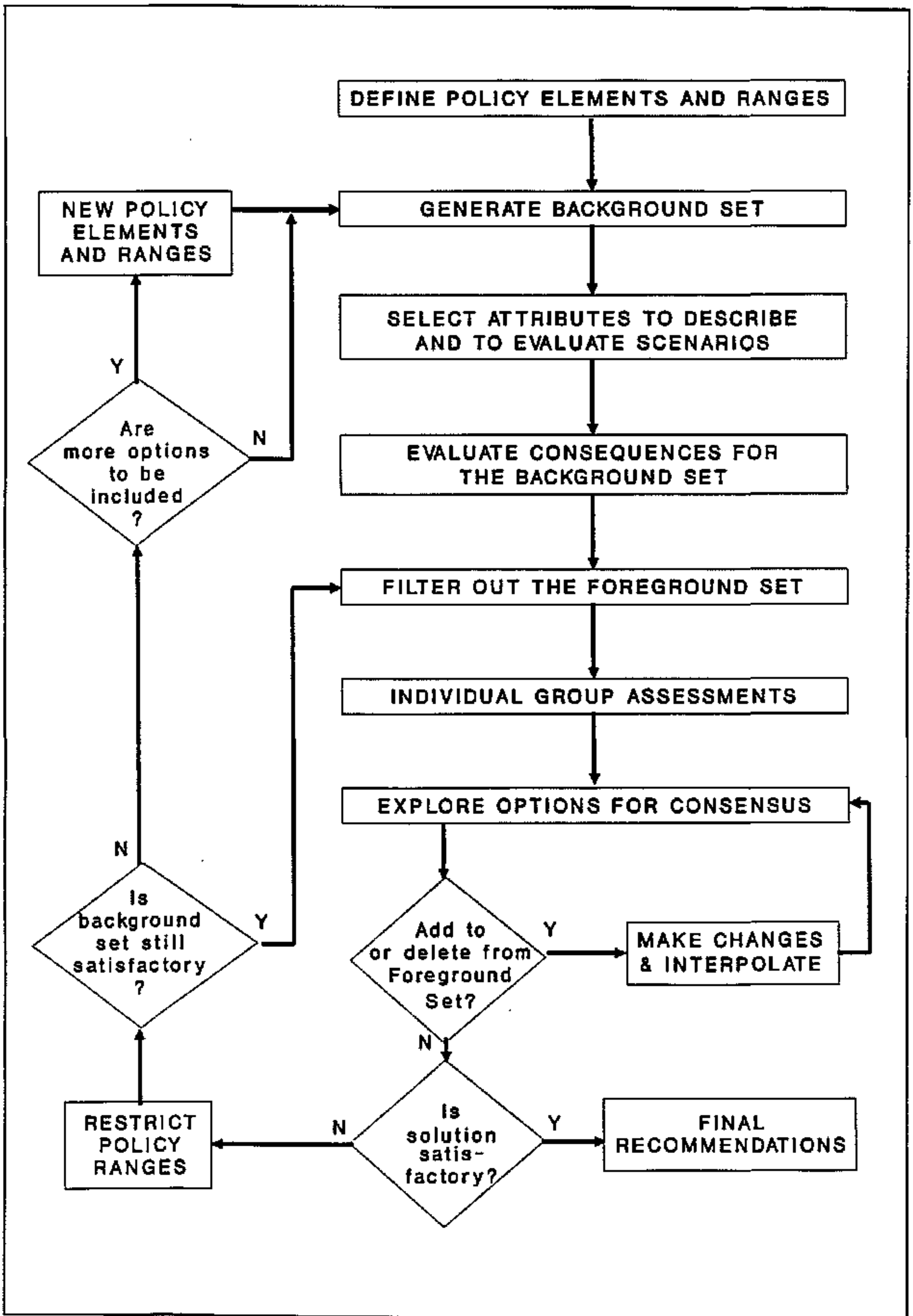


Figure 4.1: Scenario-Based Policy Planning

applied at scales other than that of river basin planning (although this is the context in which the procedures have been initially developed and tested). Similar procedures could be applied at a higher level, such as for the development of national water planning strategies. Within the constraints of any such strategy, the procedure can be applied at the catchment area level. At this level, policy analysis would still be at a relatively broad level (e.g. land use expressed in terms of percentage increase or decrease in overall levels of afforestation), and the procedure could again be applied to (for example) more detailed analyses of land use options within the bounds of the broad policy directives (thus considering types and quantities of timber to be planted in specific areas in order to achieve the desired percentage change in overall afforestation in a most desirable manner). In this way, the scenario-based policy planning procedure can be implemented hierarchically; after provisional consensus is reached at one level of aggregation, the effects of the implementation of this consensus could be investigated at a more disaggregated level, with any problems being fed back to the higher level analysis (which would require a further iteration at least to take into consideration the new information received).

4.1.1 Define Policy Elements and Ranges:

In order to determine in principle the full range of policy options which are available, all possible policy elements (i.e. instruments or components of policy) which can be made use of need to be identified. In addition, the ranges of freedom of action for each element need to be stated. At early stages, conscious effort is required to ensure comprehensive coverage of all conceivable options which is best achieved by means of brainstorming techniques involving relevant policy makers and interest groups. The nominal group technique (NGT) [9] is well suited for this purpose, and has been used in the Sabie River case study. The elements identified are described in section 3.2; the following subset of the policy elements and their ranges has been used for purposes of illustration and testing of the procedures:

i. Restrictions on storage, described in terms of maximum additional small storage permitted : Between 0 and 5 million cubic metres

ii. Restriction on abstraction rate for irrigation, described in terms of percentage below current levels : Between 0 and 60%

iii. Afforestation permitted, described in terms of percentage change from current levels : From a 2.5% reduction to a 5% increase

iv. Total volumetric capacity of the Injaka and New Forest dams : Either 0 (i.e. not built) or between 76 and 206 million cubic metres

v. Percentage of the rural population provided with standpipes for water supply: Between 40% and 85%

vi. Percentage of the rural population who have access to standpipes serving not more than three households : Between 10% and 40%

In practice each of these ranges would be split into a finite grid of values; for example the range of values for (i) might be split into increments of 0.5 or 1 million cubic metres.

4.1.2 Generate *Background Set.*

Once all policy elements, and a grid of values for each of these, have been identified, it becomes possible to generate all possible policies, i.e. all possible combinations of the different levels of the policy elements (within the chosen grid of values). We denote this set as the *Full Set* of policy scenarios (see Appendix C1 for definition). Note that some of the policies generated may be infeasible and as such need to be screened out. Even with relatively coarse grids of values, however, the size of the Full Set may be so large as to be impractical to work with. Thus it needs to be selectively reduced into manageable subsets that the decision maker or other interested parties can evaluate. For this purpose we define what we shall term the *Background Set* i.e. a pool of scenarios that is sufficiently rich so that all interested parties can find a reasonably satisfactory alternative, perhaps by interpolation between scenarios. The Background Set can contain scenarios with elements of policy at key selected levels only i.e. the set will contain scenarios with the "cornerstones" of policy elements only. Thus the set will be greatly reduced from the Full Set but will be of such a nature that through judicious interpolation, virtually any scenario can be found within it. Interpolation between the scenarios in such a set must be able to accomodate non-linearity and interaction between policy elements. One way to achieve this is to choose the Background Set in such a way that it is possible to fit a quadratic surface for each attribute as an approximation to the response for any combination of policy elements.

Appendix C2 describes how the principles of Experimental Design may be used to generate this set, although improved methods for this step are the subject of on-going research. Note that this step is essentially technical in nature, not involving value judgements, but needs to be handled with care to ensure the necessary richness of the resultant set.

We make use of the simple example described in Appendix B2 to illustrate how the background set may be generated. Note that the aim of the procedure is to choose a set that allows for response surface fitting to be able to interpolate quadratically between the elements of the set (for continuous variables) and to estimate main effects and interactions for discrete variables.

Four independent policy elements are identified in our simple example. Table C2 in Appendix C2 shows that in this case 25 scenarios will be required to form a background set of sufficient size to allow for reliable interpolation. These 25 scenarios are composed by generating different combinations of the levels of the policy elements shown below :

Policy element :	Level :				
	0	1	2	3	4
% change in Forestry	-3	-1	1	3	5
% cut in Irrigation	20	27.5	35	42.5	50
Dam Size (% of maximum)	60	70	80	90	100
% Rural population served	30	37.5	45	52.5	60

The actual Background Set size that was generated in the Sabie case study for purposes of testing the procedure was in fact smaller than this (as will be reported in chapter 6). This was mainly due to practical considerations and the fact that this whole "Scenario Based Policy Planning" algorithm was in fact evolving during the process of working through the Sabie case study. It is suspected that in practical real world problem settings the background set might contain 100 to 500 potential policy scenarios.

4.1.3. Select attributes to describe and evaluate scenarios.

In order for the decision makers and other interested parties to be able to evaluate different policy options, specific attributes or measures of comparison need to be defined. These attributes must somehow mirror underlying goals either explicitly or implicitly. In some instances an actual policy element, eg. degree of afforestation permitted, may be the attribute that specifically and directly measures degree of satisfaction for some criterion or interest (in this case the Forestry Industry). In other instances the issue of interest may be for example protection of plant diversity which is indirectly related to measures such as seasonal high or low flows at particular points in the river but cannot be expressed precisely and unambiguously in terms of these. Even in this latter case, the attributes chosen should include the "surrogate objectives" as defined in Appendix C3. These are attributes which are such that minimization or maximization of the measure could plausibly represent a desired goal of at least one interest group, and are used at earlier stages of the procedure (in the generation of the "foreground set" - see Section 4.1.5) to select out potentially good options for detailed comparisons. (For example, maximization of winter low flow levels might at least partially represent certain ecological goals, within the ranges of values likely to be experienced.)

Decision makers or other parties will subsequently have to evaluate scenarios subjectively using model-based predictions as aids, but relying largely on expert and informed opinion. The attributes selected for describing scenarios must be sufficient to facilitate informed evaluations by all main interest groups, but must also be chosen realistically in the light of the availability of credible predictive models. The scenario-based planning approach is an iterative one which allows for the fact that all parties involved will come to understand their own needs and the dynamics of the entire system better as the procedure unfolds. Thus the attributes which are defined at a first pass of the procedure may be somewhat macro level attributes determined by fairly coarse models of the system. At subsequent iterations of the procedure (see section 4.1.8) the interaction may reveal the importance of further attributes and more sophisticated models may be brought into play.

The selection of suitable attributes needs to be done at group brainstorming sessions (as with the selection of policy elements), but these need to be repeated at various times during the scenario-based planning procedure. In the initial exploratory workshops for the Sabie Catchment case study, the main attributes selected related to flow regimes, which for the purposes of our experimental studies appeared to be best summarised in terms of:

i. Mean total annual flows;
ii. Lower quartiles, medians and upper quartiles of summer and winter flows; and
iii. 10-year low and 10-year high flow levels;

at each of five selected sites in the Sabie-Sand river system.

4.1.4. Evaluate consequences for Background Set .

In this step the attributes, or performance measures, defined above need to be calculated for each of the scenarios in the Background Set, using the best available models. Although full model runs are only carried out for the background set, recall that this set is specifically designed to allow for rapid and interactive interpolation of attribute values for any other scenario of interest.
Bearing in mind that the process is designed to converge in that the set of scenarios under consideration is pruned at each iteration (see section 4.1.8), some detail may be left out at early stages if this requires overly detailed and expensive investigations.

4.1.5. Filter out *Foreground Set.*

The essential rationale behind scenario based planning is that the only way in which value judgements of intangible or indirect criteria can meaningfully be expressed is by direct comparision of specific scenarios. To this end a further selection of scenarios has to be made from the Background Set to obtain a few scenarios which may be presented to the decision makers and other interested groups for direct comparison. The initial selection of this *Foreground Set* will be explicitly from the scenarios forming the Background Set. In subsequent iterations scenarios comprising the Foreground Set may require interpolation between elements of the Background Set (cf. discussion section 4.1.4).

As participants will be required to compare all elements of the foreground set directly, this cannot contain more than about 7 to 9 scenarios. This assertion is based on Miller's finding

[19] that human cognitive skills can generally cope with at most 5 to 9 separate items (the "magic number 7 plus or minus 2") of information at any one time.

This step of selecting a foreground set is one in which standard multiple criteria decision making techniques can be effectively employed, due to the fact that the nature of the task is more clearly delineated. The procedure that is proposed for Foreground Set selection draws on a number of standard methodologies and is detailed in Appendix C3. It is one which aims to ensure a good spread of scenarios whilst also attempting to satisfy the known underlying goals of society. This procedure is somewhat technical in nature, and will be computerized in a future Decision Support System. An example of the selection of a foreground set, based on the 20 scenarios in the simple example of Appendix B2, is provided in Appendix C3.

The manner in which the Foreground Set scenarios are displayed is crucial to the success of the procedure. They need to be succinctly yet comprehensively portrayed in a manner which is meaningful to all interested parties. The use of Geographic Information Systems (GIS) appears to offer considerable display opportunity and this link will be the subject of continuing research (possibly in collaboration with the Crocodile Catchment System project of FORESTEK).

4.1.6. Individual Group Assessments.

This is the stage at which the value judgements of each interest group are developed (under the guidance of a facilitator) and recorded for comparison with those of other groups. A detailed description of the workshops run with each interest group is given in Appendix B3 and as such only a brief illustration of the procedure will be presented here. Each interest group is required to :

i. Identify the criteria which are relevant to their interests (and the attributes which can be used to assess achievement of these criteria). For example, during one of our experimental workshops (see Section 6.3), the Forestry group identified the following criteria of interest to their industry : Company profits/ shareholder interests; Regional /National interests; and Image/ responsibility to the community .

ii. Score each alternative policy scenario in the foreground set with respect to each criterion so identified. This is achieved by asking the group to first identify the best (score of 100) and worst (score of 0) alternatives for each criterion, and thereafter to fit the remaining alternatives in between these two, on a so-called "thermometer scale".For example, the Forestry group rated Scenario 2 as best and scenario 3 as worst on the criterion of Image. The remaining three scenarios were rated according to how they fared relative to these two as illustrated by the thermometer scale in Figure 4.2

iii. Weight the relative importance of the impact of each criterion from the point of view of this group's overall interests.

iv. Interactively experiment with changing these weights in order ultimately to provide an overall score for each policy scenario. This overall score is essentially a weighted sum of the scores assigned to each criterion. The effects of two different sets of weights is illustrated in Figure 4.3.

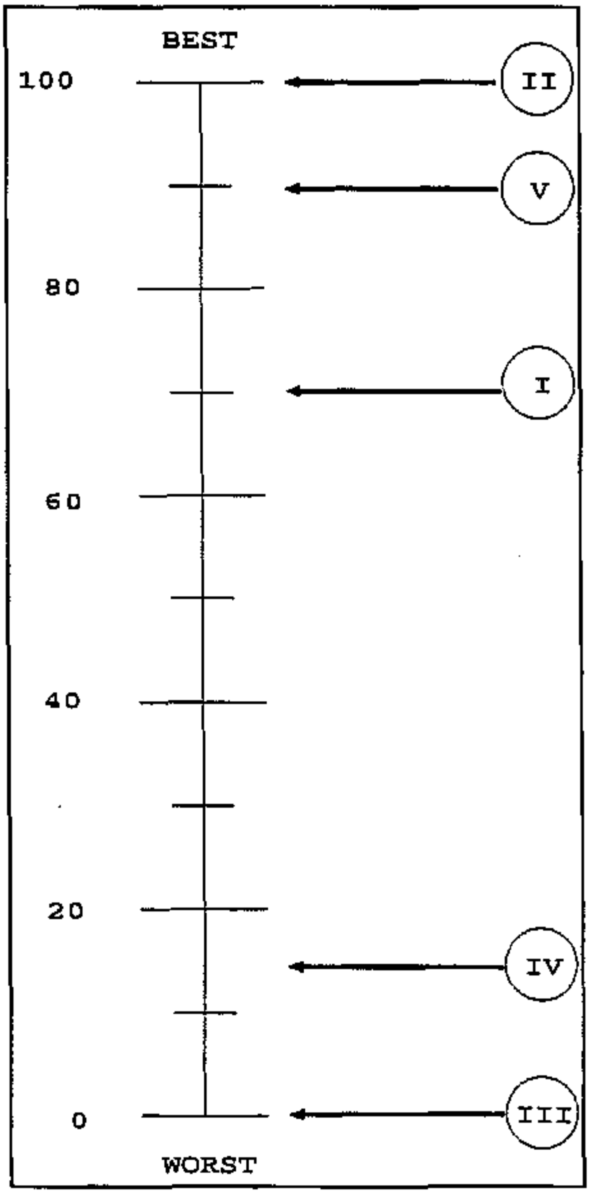


Figure 4.2: Thermometer scale indicating scenario scores for Forestry criterion "image"

4.1.7. Explore options for consensus :

Once scores from each scenario in the foreground set are obtained for each interest group, the next step is to identify those scenarios with the best potential for acceptance as a compromise or consensus position. This step could be carried out either in a group decision making forum, with representation from each interest group, or by planners seeking to generate proposals. For purposes of comparability the scores from each interest group are rescaled to lie between 0 (worst option for this interest) and 100 (best option). These are then used as the basis for discussion on consensus. Bui [6] describes the essence of the consensus seeking process : "In effect, when a decision maker first attempts to establish an order of preferences, his analysis often results in a ranking of the alternatives ... He would then logically choose the alternative that is ranked first in the vector of preferences. However, unless the chosen alternative obviously outranks its counterparts, there is no reason why the next ranked alternative could not be considered as a comparatively acceptable solution." Various methods of exploiting this "leeway" in the relative differences in the preference rankings assigned by the different interest groups have been explored and will briefly be illustrated here. The precise choice of technique and software to be used at this stage is still however the subject of further investigation.

The first step in the consensus seeking process is simply to display the scores assigned to each alternative by each interest group and to visually search for a good compromise solution. If no immediate consensus obviously emerges, the ELECTRE method may be a useful tool for assisting the search. It allows for direct comparison between scenarios which makes it compatible with the scenario based approach, and has the advantage of being relatively transparent to the user. An extension of this method by Vetschera [24] incorporates an interactive decision process to successively reduce the number of options being considered until at most one remains. This is achieved by means of manipulating the thresholds by which one option is deemed to outrank another (see Appendices A3.3 and B2.4 for details). Software which implements Vetschera's method has been obtained and appears to be suitable, although with some modifications to the presentation and user interface.

The Interactive Multiple Goal Programming (IMGP) method (see Appendices A3.2 and B2.2) also appears to be a useful means of seeking consensus across the interest groups.

By means of illustration of the above approaches, suppose the interest groups scored the foreground set scenarios as shown in Figure 4.4. Then the different approaches might proceed as indicated in the following paragraphs.

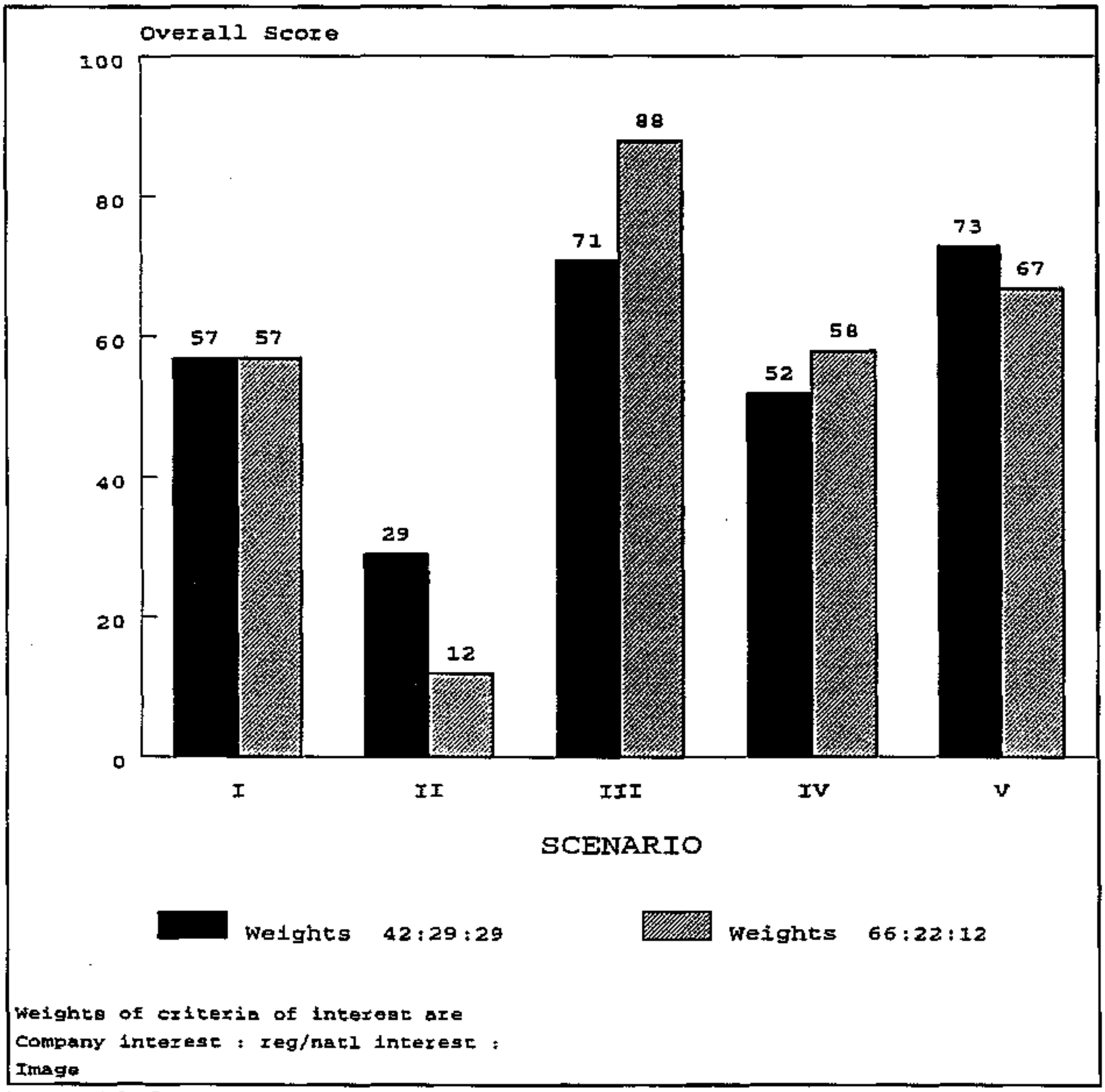


Figure 4.3: Overall scenario scores for two sets of weights

i. *Visual search :*

Scenario I is clearly unsuitable and can be disregarded.

Scenario II rates very poorly for Forestry but otherwise fares well.

Scenario III rates very poorly for Conservation and for Irrigators.

Scenario IV rates poorly for Irrigators but is ranked highly by all other interests.

Scenario V scores above 40 for all criteria and well on most.

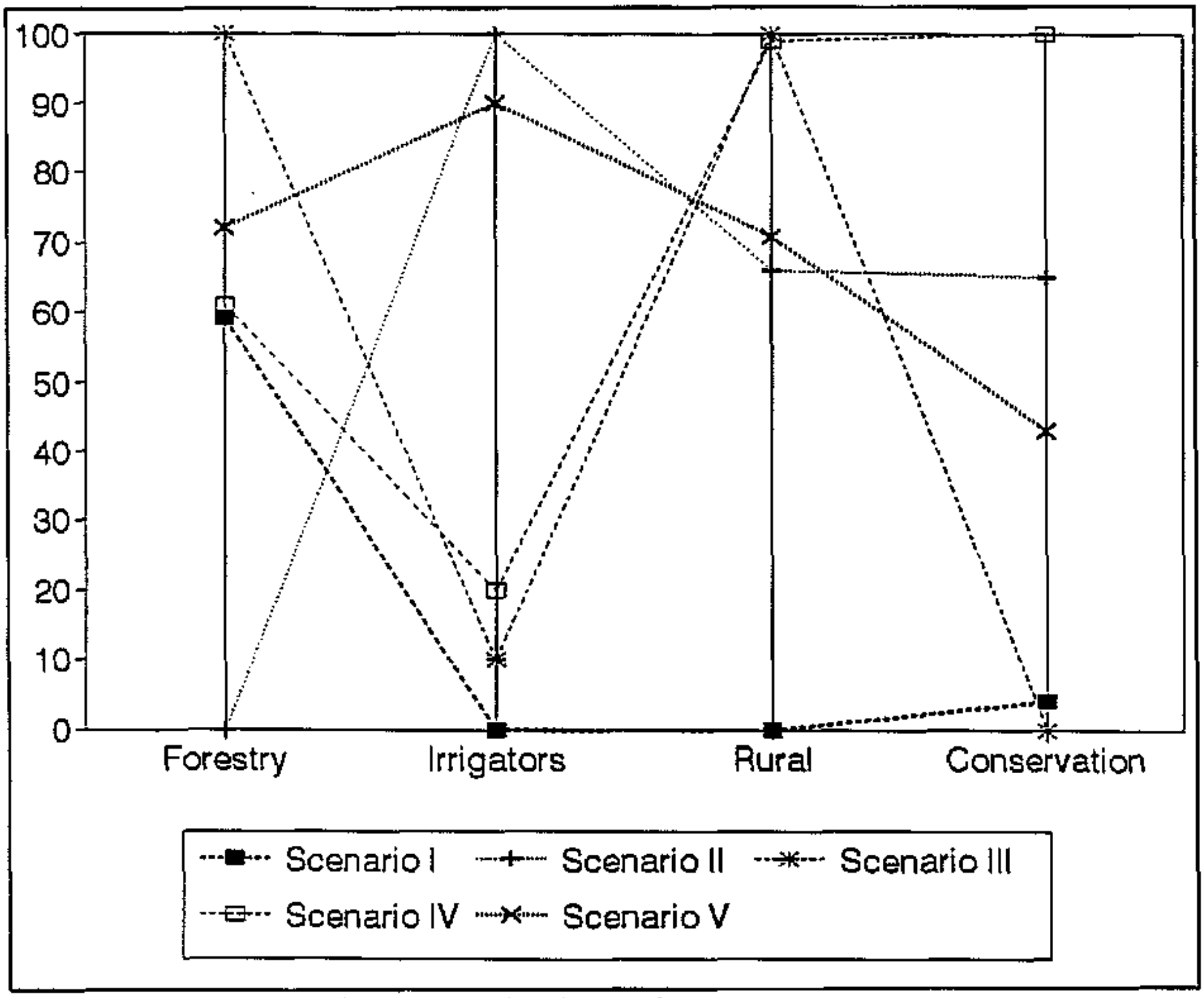


Figure 4.4: Scores assigned to scenarios by different interest groups

This tends to indicate that we should focus our efforts on scenarios IV and V and probe more closely the differences between these two.

ii. *Application of the IMGP procedure of Spronk [20]:*

A simple application of IMGP to the above table of scores yields the following sequence (where "solution" gives guaranteed lower bounds on scores for each attribute, and "potential" gives the best achievable scores for each attribute amongst alternatives not yet deleted). The initial position, where no alternatives have been deleted, is such that the lower bound, i.e. the "solution", for each interest group is 0 and the potential is 100. Then the position after deleting alternative I is as follows :

	Conservation	Forestry	Rural	Agriculture
Solution	0	0	66	10
Potential	100	100	100	100

Note that there has been no drop in potential by deleting I but there has been an improvement in some attributes of the solution. Deleting alternative III yields the following position :

Solution	43	0	66	20
Potential	100	72	99	100

which indicates that the solution for "Conservation" has improved while the potential for attributes "Forestry" and "Rural" has diminished. After deleting alternative II, the lower bound on the solution for attribute "Forestry" is greatly improved as follows:

Solution	43	61	71	20
Potential	100	72	99	90

This leaves us with a choice between scenarios IV and V.

iii. *Application of the ELECTRE method:*

This may proceed along the following lines. Assuming equal voting weights, the Concordance matrix becomes :

	Scenario				
	I	II	III	IV	V
I	-	1	1	0	0
II	3	-	2	1	2
III	3	2	-	2	2
IV	4	3	2	-	2
V	4	2	2	2	-

while the Discordance matrix is given by :

	Scenario				
	I	II	III	IV	V
I	-	100	100	99	90
II	59	-	100	61	72
III	4	90	-	100	80
IV	0	80	39	-	70
V	0	22	29	57	-

The sequence of interactions might then be as follows (see Appendix B2.4 for description of the methodology). (1) At a concordance threshold c^* of 4, and a discordance threshold d^* of 0, IV and V outrank I (with no further outrankings). (2) Reduction of c^* to 3 and an increase of d^* to 4 leads also to III outranking I. (3) Further reduction of c^* to 2 and an increase of d^* to 39 results in IV also outranking III, and V outranking II and III. (4) By retaining c^* of 2 and increasing d^* to 59, II also outranks I. At this stage only scenarios IV and V remain non-outranked.

All the above approaches indicated that scenarios IV and V were the most likely options to produce consensus and that we should focus our attention on further refining around these two. Note that in this case each approach yielded the same result which will not always be the case. Investigation has so far not revealed an obvious reason for employing one of these methods above another but the procedure is still being refined.

4.1.8 Further iteration of the planning process.

At this stage in the process the following outcomes may occur :

(i) Planners or the group forum are able to find a scenario within the Foreground Set which they are satisfied offers a satisfactory compromise solution. The process is then terminated and final recommendations are made.

(ii) Although some elements of the foreground set may be eliminated there may remain too high a level of conflict between the remaining scenarios for there to be satisfaction that a consensus has been reached. Participants are then offered the opportunity to select different scenarios for the foreground set. The group needs to decide why the scenarios remaining in the foreground set do not satisfy their needs and to select intermediate levels of the policy elements which appear to be more satisfactory. They may be guided in this process by using reference points i.e. selected levels of policy related to the outcome attributes as indicators of the effects of certain directions of policy. The group will then use this new foreground set to re-examine options for consensus. Because scenarios that are introduced into the foreground set at this stage will not have been evaluated by the separate interest groups, the group forum must infer individual interest ratings on these scenarios. All of these activities may occur in a single workshop session

(iii) A point may be reached when the foreground set has been altered so much from the original set of scenarios that individual interest groups need to re-assess them. Alternatively there may be a feeling within the group forum that more detailed information or information on other attributes is needed to advance the consensus seeking process. They may in this case need to refer back for further analysis i.e. re-iterate the process making use of the understanding gleaned so far by restricting the ranges of policy to be examined. For example they may realise that only levels 2 and 3 of changes to the levels of afforestation (i.e. 0% and 2.5%) need to be considered. They may then wish to continue the analysis, beginning with a freshly filtered Foreground Set for each interest group to consider.

In case (iii), however, there may also be a need to re-assess the effectiveness of the Background Set. If the present policy ranges have been restricted to such a degree (in this particular iteration alone or over a number of iterations of the process) that a large proportion of the Background Set is no longer valid then it would make sense to regenerate a new Background Set. This gives rise to two possibilities:

A. The restrictions placed on the ranges of policy to be examined further are such that the scenarios in the background set which still fall within these ranges are so few in number that this set is no longer effective for the purposes for which it was designed (see section 4.1.2) and a new background set is generated.

B. Alternatively, new policy elements or ranges of values beyond those originally proposed, may be introduced at this stage. This situation may arise when the planners or group forum realise that the process is not converging because a particular policy element has been omitted. Equally, the situation may be such that the process has converged to such a point that particular policy elements are fairly well determined and there now exists scope to focus in more detail on the remaining elements. An example of this may be where, perhaps after a few iterations, it has been decided that dams of a particular volumetric capacity will be built and that there will be no change in afforestation levels. One of the remaining levels of policy to be determined is that of rates of abstraction allowed and it may now be decided to expand the terms of this attribute to include the frequency of abstraction and the types of abstraction that will be allowed.

In both of the above cases, the procedure has essentially to restart with a new background set, but one which is more closely clustered around a consensus position.

4.2 Advantages of the policy based approach

4.2.1 By encouraging consideration of a rich variety of options, and by allowing the impacts on all interest groups to be expressed and compared in a commensurate manner, this approach, if used early enough in the planning process, can serve to prevent the polarization of views which makes later consensus-forming difficult.

4.2.2 Policy based scenario planning allows value judgements to be made in a clearly defined and unambiguous context. The method is easily communicable and does not present as a "black box" to decision makers, i.e. they can be taken through each of the steps of how the inputs which they provide finally produce an aggregate scoring.

4.2.3 Quantitative and qualitative attributes are placed on an equal footing in that they are treated in the same way by the methodology.

4.2.4 The approach is particularly conducive to incorporating modern scenario planning facilities such as GIS.

4.2.5 It can be used at an early stage in the planning process to get an indication of people's views without necessarily having all the required information on proposed scenarios and outcomes.

The same procedure can be repeated subsequently at increasing levels of refinement.

4.3 Disadvantages of the approach

4.3.1 The methodology is very dependent on the thoroughness with which the initial stages are undertaken. If sufficient effort is not invested in exploring all possible policy elements in setting up the policy elements and their associated ranges of values or options, then particular interest groups are likely later to become disillusioned with a process which does not even give consideration to alternatives which yield their preferred outcomes.

4.3.2 Similarly, the method will fail if the background set is not rich enough to accomodate all interests and if there is not a sufficient mechanism for exploring the background set so that a "good" (i.e. moving towards consensus) foreground set can be presented to the decision makers. In general then, the outcome is likely to be influenced by the choice of scenarios made at each step.

4.3.3 As with any other new approach, a substantial change in mode of thinking is required by both planners and representatives of interest groups. It is perhaps debatable whether this constitutes an "advantage" or a "disadvantage", but change is never easy, and does require extra flexibility on the part of planners and participants. In this case, the change of thinking comes about in that the method does not provide a means of reaching a "best" decision according to some strict set of constraints and goals. Rather it provides a means of sifting through and exploring a number of alternatives (a number that would be too vast to handle by some *ad hoc* unsystematic process). Also it assumes that the unwritten "constraints" or goals in the minds of the decision makers will actually shift as they go through the process.

4.3.4 Considerable time and effort is required to set up the policy scenarios and their consequences. A series of workshops needs to be organized in order to identify the relevant policy elements and system attributes, and thereafter studies need to be commissioned in order to establish the consequences of the scenarios in the "background set". These studies may entail both public scoping and the running of large systems models. Finally, the result of these studies need to be collated into a form suitable for presenting meaningful scenarios to particpants.

4.3.5 There is no externally verifiable means of validating the process or the "solution". One is reliant on people's sense of satisfaction with the efficacy of the process and its outcome.

5. AVAILABILITY OF SOFTWARE SUPPORT

5.1 The Ideal Group Decision Support System (GDSS)

Modern information technology should in principle be capable of supporting the full scenario-based planning procedure within a single DSS structure. This would incorporate multiple terminals so that different participants in a single workshop, or different interest groups, can develop their own preference structures in parallel, before coming together to assess potential compromises. The technological feasibility of this approach is well illustrated by the **Co-oP** system ("A Group Decision Support System for Cooperative Multiple Criteria Group Decision Making") described by Bui [6]. (This reference describes the system; we have not had a copy of the system itself for assessment, although such a copy has been promised by Professor Bui.)

Ideally, a system to support the procedure of Chapter 4 should contain the following features:

5.1.1 Individual and group support during the Nominal Group Technique stage, for the identification of policy elements, and of system attributes.

5.1.2 Generation of a background set of scenarios, and the issuing of requests for evaluations of these in terms of specified attributes. (These evaluations would take place off-line from the GDSS itself, and would typically involve the running of many, often quite large-scale models; nevertheless, it might be feasible for the "requests for evaluation" to be made automatically from one computer to another through a network.)

5.1.3 Generation of the foreground set of scenarios.

5.1.4 Systems for displaying scenarios generated in a manner which facilitates informed value judgments: This might well require some form of GIS or related technology.

5.1.5 Support for the decision analysis phase within a single interest group: This would include the defining of criteria of evaluation, the scoring of scenarios in terms of these criteria on a "thermometer scale", weight sensitivity for combining scores across criteria, and the selection of final scores for the scenarios.

5.1.6 Support for the consensus-forming stage, i.e. implementation of the ELECTRE or Interactive Multiple Goal Programming phases.

5.1.7 Overall management of the iterative process implied by Figure 4.1: This must include all the interactive options, such as eliminating or adding scenarios from or to the foreground set, and the background processing such as interpolation to ensure rapid responses to requests by users to examine other scenarios.

5.2 Currently Available Computer Packages

Since a number of the concepts included in the scenario-based planning procedure of Chapter 4 were developed as part of the current project, it is evident that no software could exist which would fully incorporate all of the features 5.1.1-5.1.7. In particular, the differentiation between the foreground and background sets seems to be a new approach. The **Co-oP** system referred to earlier [6] comes as close as anything we have yet been able to identify. **Co-oP** does not however really identify the concepts of attributes (as distinct from criteria of evaluation) or policy elements as needing support per feature 5.1.1 above. Also **Co-oP** does not use the foreground-background set philosophy, nor does it include any GIS-type links. It does, however, differentiate the within-interest and between-interest consensus-forming phases, and can thus be said to include features 5.1.5-5.1.7. It does not seem that the rest of the features can simply be added to **Co-oP**, however, which implies that a new GDSS will probably have to be designed and coded from scratch. The particular interest in **Co-oP** is its clear demonstration of the technological and hardware feasibility of implementing a GDSS with the desired features, and thus any new development should learn from the experiences of the developers of the **Co-oP** system (with whom we have made contact).

A number of packages have been developed which to a greater or lesser degree address feature 5.1.5. Perhaps the best known of these is **Expert Choice** [12], which implements the Analytic Hierarchy Process (AHP) for this purpose. Although in the hands of an expert facilitator AHP can produce quite valuable insights in scoring alternative scenarios on single criteria and globally, we have reservations concerning its general use, particularly in the context identified in this report. Some technical reasons for this conclusion are set out in Appendix A4. Other packages such as **Logical Decision** [18] are technically sound, but do assume that criteria of evaluation are exhaustively identified and linked to quantitative system attributes, which as we have seen does not apply in the water resource planning context.

Two packages stand out particularly as implementing feature 5.1.5 in the sense in which we interpret it: these are **VISA** (Visual Interactive Sensitivity Analysis) [3] and **HIVIEW** [2]. Both work on the basis of clearly defined decision or policy scenarios, allow definition of different criteria of evaluation not necessarily directly linked to quantitative attributes, and allow direct scoring of the alternatives in terms of these criteria on a 0-100 scale. **HIVIEW** in fact literally displays a "thermometer" scale on which the scores can be indicated (by using a mouse); for **VISA** this needs to be done off-line (e.g. on a flip chart or overhead projector). Both provide for the users to enter weights on the criteria, and then use computer graphics to demonstrate the sensitivity to the derived ordering of alternative scenarios to changes in these weights. This process is particularly well-implemented in **VISA**, in which the weights on each criterion and the resulting scores (obtained as a weighted sum of scores on each criterion) are displayed as bar graphs. Users simply change the heights of each bar representing weights, in order to see the effect on the overall scores. Illustrations of these VISA outputs are given by Figures 6.2, 6.4, 6.6 and 6.7. Various other forms of sensitivity analyses are also possible with VISA, but the reader is referred to the software documentation [3] for details.

We have found **VISA** to be a valuable tool for implementing the scenario-evaluation steps of the procedures in group workshop sessions, as described in Section 6.3. **VISA** is also of value for the consensus forming step, where the interactive modification of weight bars (as described in the previous paragraph) and the side-by-side display of multiple thermometer scales (as illustrated in Figures 6.1, 6.3 and 6.5) is particularly useful. One minor practical problem is that in moving from the within-interest phase to the between-interest (consensus-forming) phase, the scores have to be re-standardized off-line. (**VISA** in principle allows between-group considerations to be included as the top level of a hierarchy of interests and criteria, but the scores emanating from different interests are differently scaled, which makes the top-level comparison difficult in our context; according to one of the developers of **VISA**, Dr Valerie Belton of Strathclyde University in Glasgow, they could, however, easily provide us with a version which does the re-standardization automatically.)

At this stage (i.e. in the absence of a full GDSS as described in Section 5.1), **VISA** is strongly recommended for any implementation of the scenario-based planning procedures. It is easily used and understood. We are investigating the possibility of obtaining a licence to incorporate the key submodules of VISA into the GDSS to be developed over the next few years.

In Chapter 7, we shall also report on another software package **EQUITY** [1], which in effect implements the full procedure, but in the special context of dividing a single resource between competing users. This is too simplistic for the general water resource planning problem, but does appear to have relevance to the allocation of water from a fixed resource to competing users at times of drought. This is mentioned further in Chapter 7.

6. HYPOTHETICAL CASE STUDY: SABIE RIVER BASIN

At the outset of the project, the intention was to use the Sabie-Sand River system as a case study for testing the procedures as they were developed. This was motivated by two considerations, viz. that a comprehensive systems study of the region had at that stage just been completed [8], and that although there were many potential conflicts in the region, these appeared not to have reached a stage where trust between different actors had broken down totally. As the project progressed, the problems specific to this region assisted in providing focus for developing and evaluating procedures. The procedures themselves evolved rather more slowly than had initially been envisaged, and a full-scale application to the problems of this region, using the full procedure outlined in Chapter 4, was not possible. Nevertheless, most components of the procedure were tested in the context of realistic, but incomplete and partially hypothetical problems relating to the Sabie-Sand River system. The use of hypothetical case studies was inevitable at this stage of the research, as it was highly undesirable to apply an untested procedure directly in a real politicized and conflict-laden negotiation process. There were also not the resources available to implement the procedure in parallel with other approaches. Although inevitable, this use of hypothetical case studies does suffer from the disadvantage that participants were perhaps less motivated and less emotionally involved in the debate than they would be in a real situation, and it must be acknowledged that any conclusions reached need to be treated with some caution in light of a possible lack of full committment by participants. It is difficult even to speculate as to whether this effect will be to the advantage or disadvantage of the methods being tested.

In this Chapter we outline the methods and results of these tests, partly to demonstrate how the procedures of Chapter 4 evolved, and partly to provide justification for recommending these procedures.

6.1 Outline of Methods Adopted for the Study

Initial familiarization visits to the region included general discussions with representatives of the Department of Water Affairs and Forestry (which at that stage were still separate, with Foresty falling under Environment Affairs), the governments of Gazankulu and Lebowa, and the Kruger National Park. It was immediately evident that clearly defined goals and/or clearly defined alternative policies (or courses of action) were not available. The breakdown of broad national water planning interests (as given in Figure 3.2) evolved from these meetings, and were widely circulated for comment (which led to no significantly further additions or deletions).

Use was made of the Nominal Group Technique [9] in workshop settings, involving participants from the Department of Water Affairs and Forestry, and from the consultants responsible for the Sabie Systems study (Chunnett, Fourie and Partners [8]), aimed at establishing ranges of policy action which could be considered, and general societal goals by which such action might be assessed. The results have been summarized in Sections 3.1 and 3.2. Many of the goals identified in this way (see Section 3.1) were not however operationally well-defined (especially those of flow regime, water condition and risk - how does one measure the extent to which any proposed policy contributes to, or detracts from, achievement of these goals?). Systems models of varying complexity exist which would predict streamflows throughout the system at different times of the year for any specified policy. It might be expected that goals related to flow regimes and to risk might be expressible in terms of the probability distributions of streamflow (e.g. high and low flows, floods of specific return periods) and designated points in the river systems. Specific water condition measures (such as temperature and standard quality measures) at designated points may be less easily predictable. These will probably need to be derived from the streamflow predictions and it may be sufficient to use a finite number of these as surrogates for the water condition goal. With these expectations in mind, the intention was to circulate a questionnaire to representatives of relevant interests (as identified in Figure 3.2), on which they could assess the relative importances of each of these *attributes* (or surrogate measures), as indicators of goal achievement. Pilot studies (i.e. attempts to administer the questionnaire to a few persons already familiar with the project) quickly revealed that respondents would find the questions difficult to interpret, and even more difficult to answer in the relatively abstract setting proposed. (Typical questions would have been: assess on a 1-5 scale the importance of 50-year flood levels at a point X on the goal of ecosystem preservation in the Kruger National Park.) In retrospect, the futility of such questions is perhaps self-evident, but this was not obvious at the outset, as questions of this nature have been common in other MCDM applications.

By about midway through the project, the necessity for working in terms of clearly defined *planning scenarios* (as described in Chapter 4) became evident. The later workshops (of those mentioned in the previous paragraph) thus focussed on the policy elements (as listed in Section 3.2), and ranges of feasible values for each. It was agreed that, for the purposes of the pilot study aimed at testing of procedures, alternative hypothetical but realistic policies for the Sabie-Sand River region could be formulated in terms of the elements listed in Table 6.1, in which the allowable ranges are also shown.

Table 6.1: Policy elements used for the Sabie-Sand experimental case-study

Policy element	Minimum value	Maximum value
Afforestation permitted (% change from *status quo* of area under afforestation)	-2½%	+5%
Maximum additional small storage permitted (Million m^3)	0	5
Restriction on abstraction rates for irrigation (% reduction below current rates)	0	60%
Total volumetric capacity of Injaka + New Forest dams (Million m^3)	0 (if neither are built) OR 76	206
% of rural population given access to standpipes serving 1-3 households*	10%	40%
% of rural population given access to standpipes within 100m of dwelling*	30%	75%
% of rural population remaining reliant on natural streams or rivers*	15%	60%

* Naturally the last three components must always total 100% in any specific scenario

In order to test the scenario-based planning and decision analysis procedures (which were still in a process of development when testing had to commence), two approaches were envisaged. One was to develop a form of questionnaire which could be distributed to a wide variety of interested parties, and was designed to have each individual respond as he or she would in an actual group workshop. The thinking was that in this way we might achieve greater coverage of potentially interested parties within resource limitations (primarily time and research personnel, but also cost); and allow participants greater time for reflection. In the event, this approach did not yield very satisfactory results as a result of a very small response rate (even after considerable expenditure of effort in attempting to contact non-respondents repeatedly by mail and by telephone), but details of the approach and reasons for the non-responses are given in Section 6.2

The second approach was to conduct real-life workshops using the procedures, even though full supporting computer hard- and software were not available, and even though the number of workshops which could be run were limted both by resource constraints and by logistics (i.e. finding suitable dates and venues to suit all participants). Four such workshops were scheduled, one each for the following interest groups: environment, forestry, rural communities and irrigation boards. In the end the last two groups had to be combined into a single workshop. Details of these workshops and the results obtained are given in Section 6.3.

The general procedure as described in Chapter 4 involves four steps which had to be completed prior to the questionnaire and workshop phases. These are:

(1) Selection of the "background" set of scenarios;

(2) Selection of appropriate attributes for describing consequencesof policy scenarios;

(3) Computation of consequences in terms of these attributes, for each scenario selected; and

(4) Selection of the "foreground" set of scenarios, between which participants (in the questionnaires or workshops) would have to express value judgments.

These steps started during the second half of 1991, before the full procedures as described in Chapter 4 had been developed. In fact the recommendations of Chapter 4 were to a substantial degree motivated by the experiences encountered in attempting these steps. The resulting scenarios were not merely hypothetical, but were also not truly ideal in terms of the criteria set out in Appendix C. Nevertheless, these scenarios appeared to be sufficiently realistic and balanced to be meaningful to participants, and thus still served as a good basis for the testing of the group decision support procedures (which are the key recommendations arising from this research).

The background set was initially designed (using rather more *ad hoc*, less systematic, experimental design procedures than those of Appendix C2) on the basis of the first four elements in Table 6.1. The attributes which had been identified related only to streamflow, which was thought not to be dependent upon the last three policy elements. Streamflow characteristics for each scenario were computed by Chunnett, Fourie and Partners, expressed in the form of runoff sequences for each month of the year, at five sites in the basin, for a simulated history of 64 years. The following summary statistics were used to represent the data at each site in a statistically meaningful and justifiable manner (given the length of the simulated sequences): mean total annual flow; upper and lower quartiles and median of the distribution of monthly runoffs over summer and winter; and mean 10-year low and high flows. The foreground set was selected by hand in accordance with the basic principles outlined in Appendix C3. Values for the last three policy elements were allocated in consultation with the Department of Water Affairs, to complete a realistic set of five scenarios for use in the questionnaires and workshops. These scenarios are fully described in Appendix E, Sections E2-E4.

6.2 The Questionnaire Approach

Appendix D contains the questionnaire designed for this approach. Repondents are asked in effect to perform two tasks, viz.

(1) (Parts B and C of the questionnaire) To identify attributes of importance to their interests, to give percentage scores (0=worst and 100=best) to different levels of performance on these attributes, and to weight the chosen attributes relative to each other: This process is not part of the scenario-based planning procedure ultimately recommended in Chapter 4, but is implicit in many multi-criteria decision analysis techniques (cf. Appendix A3.1). The intention was to have some assessment as to whether this process can reliably and adequately be employed in the water planning context. Provided that certain technical conditions hold (see Appendix A3.1), it is justifiable to calculate a score for any specific scenario by adding the value achieved for each attribute (estimated by interpolating between the relative scores given in Table 1 of the questionnaire) multiplied by the corresponding weight (given in the same Table). The ordering of the foreground set of scenarios implied by these scores can be compared with the holistic scoring provided by the same respondent (Table 3 of the questionnaire). Keeney *et al.* [15] had found that these two approaches yielded convergent results in a similar context (energy planning), but both were administered in a workshop

setting, and not by questionnaire. If there is a high degree of consistency between the two orderings, then not only does this tend to validate both procedures, but it opens up the possibility of by-passing the holistic ordering step every time the foreground set is altered (which might then speed up the search for acceptable policies).

(2) (Part D of the questionnaire) To provide a holistic ordering and scoring of the scenarios in the foreground set (essentially as required in procedures set out in Section 4.1.6): The assumption here was that each respondent represented a fairly well-defined interest, which turned out to be a somewhat unrealistic assumption. On the other hand, to provide for multiple perspectives on which global ordering had to be done in one questionnaire would have seriously complicated an already difficult set of questions.

The final page of the questionnaire allowed respondents to comment on the questionnaire itself and on the procedures.

Considerable effort was put into selecting people to whom the questionnaire should be sent. We did wish to approach only those with strong background knowledge of the Sabie-Sand Rivers region, and the water resource problems there. At the same time we wanted to cover as wide as possible a range of interests. In the end, only 20 questionnaires were sent out, but these covered the main forestry companies, homeland governments, irrigation boards, the Development Bank of SA, CSIR, The Rural Advice Centre, and nature conservation groups.

One of the reasons for limiting the distribution of the questionnaire, was that we were attempting a near-100% response rate, by continually re-contacting non-respondents by telephone and mail. In the end, however, only six responses were received. The primary reasons given for non-response were:

(a) That the tasks were too difficult: In retrospect, it does seem to be rather difficult to explain in writing what is required in tasks such as scoring on a thermometer scale (Section 4.1.6), although it seems relatively easy to demonstrate verbally (cf. Section 6.3). The first tasks on the questionnaire (Parts B and C) were perhaps unwise, as these were even more difficult to describe and to explain.

(b) That the scenarios were insufficiently well-defined for them to do the necessary assessments: This was of course the problem with using hypothetical scenarios, which were somewhat incomplete, and was echoed by some of the respondents as well. This clearly emphasizes the need, when implementing the scenario-based planning procedures, to ensure that scenarios are clearly defined for all parties concerned (perhaps by using, *inter alia*, Geographic Information System technologies). On the other hand, understanding does not come easily. No matter what procedure is followed, any process of synthesizing value judgments of different sectors of our communities must demand that those participating in debate, discussion forums and workshops do take effort to understand the real implications of alternatives on the table.

The six respondents were equally divided in their assessments of the tasks as "very difficult", "difficult" or "not too difficult". Three of the six were "confident" in their responses, while the other three were either "somewhat unsure" of or had "little or no confidence" in their responses.

The small number of responses preclude any far-reaching conclusions. Little or no significant correlation could be found between the holistic scores on the five scenarios (Table 3 of the questionnaire), and those derived from the sum of weighted values as described above (based on the responses in Tables 1 and 2 of the questionnaire, although Table 2, dealing with scoring different graphical displays of scenarios, was only used by one respondent). Which of the two sets of scores better represents the true long-term preferences of each interest represented cannot of course be determined from this result. In fact the most plausible conclusion is that neither represent the values of the respondents very well. The *prima facie* evidence is therefore that the use of questionnaires to elicit the value judgments and preferences of different interest groups for use in planning will not be satisfactory. There appears to be no alternative to the workshop, or public value forum, type of approach, as has been proposed in Chapter 4, at least for the first round of discussions and value assessments. Perhaps at later stages in the process (for example, for re-evaluation after the foreground set has been modified following the elimination of some policy scenarios), a questionnaire might replace the full workshop, but this would only be possible once all participants are familiar and happy with the key tasks (e.g. ordering scenarios along a "thermometer" scale). This possibility will need to be investigated, but at this stage we would recommend that all value assessments, and scoring of scenarios, be carried out in group workshop sessions, as recommended in Chapter 4.

6.3 The Workshop Approach

In order to test the validity of the group interaction procedures recommended, a series of workshops was planned at which the foreground set of 5 senarios as defined in Appendices E2-E4 would be evaluated by different groups, precisely as for a real planning exercise. Each workshop involved a particular interest group. The material in Appendices E2-E4 was sent to workshop participants some weeks prior to the workshops, so that they were reasonably familiar with these scenarios at the start. Each workshop was of a half-day duration; this is rather short, but we were restricted by the amount of time that important actors could make available for participation in what was a hypothetical exercise. The programme for each workshop was as follows (with approximate times for each point):

(1) *Introduction and review of aims. (15 minutes)*

(2) *Description and demonstration of the multi-criteria value assessment technique (30 minutes)*

Here some simple examples, based in part on Appendix B, were used to illustrate the steps which would be followed at the workshop.

(3) *Clarification and elaboration of the hypothetical scenarios. (15 minutes)*

It had emerged from the questionnaire approach that the scenarios in Appendix E contained ambiguities. This time was taken to identify these ambiguities, and to agree on the assumptions that would be made for purposes of the workshop.

(4) *Identification and weighting of sub-goals relevant to the group's interests. (30 minutes)*

The group was asked to discuss whether they had immediate total consensus (within their group) as to rank-ordering of the 5 scenarios directly. This never occurred! They were then asked to identify the various criteria or sub-goals (or even sub-sub-goals if necessary) which lay behind the lack of consensus. The aim was to establish criteria in such a way that unambiguous and agreed rank-orderings could be established for each criterion individually. Thereafter, they were asked to allocate a weight of 100 to the most important of these criteria, and correspondingly lesser weights to all others. For these workshops, the aim was only to identify a small number of such criteria, in order to test the procedures. In full-scale implementation, very much more than 30 minutes is needed for this step.

(5) *Scoring of scenarios by each sub-goal, and globally. (60 minutes)*

The group was asked to order the scenarios on a thermometer scale, for each of the sub-goals (criteria) identified in step 4. Thereafter the VISA software (see Chapter 5) was used to produce an initial global rank-ordering of the scenarios (according to the interests represented at the workshop), based on the scoring for each criterion, and the weights allocated to each criterion. VISA also allows the group to examine the sensitivity of the derived global ordering to various of the inputs, especially the criterion weights. Adjustments were accordingly made to these inputs, until consensus was reached that the global ordering produced by VISA was indeed a fair reflection of the interest represented.

(6) *Brief comparison with other interests, and evaluation of the consensus-forming capacity of the procedures. (30 minutes)*

The final global scores agreed to at the end of point 5 were then viewed as one criterion, and compared with the scores (actual or hypothetical, depending on the sequencing of the workshops) of other interest groups. VISA was used as in point 5, but now as a tool for identifying an overall most desirable policy from all points of view, by again examining the sensitivity of derived rank orders to weights on each global interest (in this case, conservation, forestry, rural communities and commercial agriculture).

(7) *Review*

Participants were asked to assess the ease of understanding of the procedures and the confidence they had in the results generated on a scale of 1 to 5. The questions were as follows:

How easy are the procedures to understand? (1=Easy; 5=Difficult)

Q1.: Use of "thermometer" scale for scores

Q2.: Use of weights on sub-criteria or interests

Q3.: Method of combining weights and scores

How satisfied or confident are you in the procedures as a method for exploring and expressing your needs? (1=Dissatisfied or Lack Confidence; 5=Satisfied and Confident)

Q4.: Confidence in the scores generated

Q5.: Confidence in the weights generated

Q6.: Satisfaction with the way in which the issues were clarified by the procedure

Q7.: Confidence in the manner in which views could be expressed

Q8.: Confidence that the procedure will lead to better balance between conflicting interests

Four workshops were originally scheduled, but as a result of last minute drop-outs of some of the participants, only three workshops ultimately took place, covering the interests of nature conservation, forestry industry, irrigation boards and rural communities (with the last two combined into a single workshop). Although these do by no means cover all interests relevant to the region, they do represent a broad cross-section on which the methodologies could be tested. The activities of each workshop are briefly summarized in the following paragraphs.

Group 1: Nature Conservation

An additional policy element which should be included is the release policy. Attributes should include measures giving information about states in the riparian zones; and the duration of low flow level events, or more generally, some measures of deviation from natural fluctuations in streamflows.

It was agreed to exclude tourism as a sub-goal of conservation, as this should preferably be included under economic benefits. Two possible decompositions into criteria were discussed. The first was a partition into *ecological requirements* and *biotic diversity requirements*;

roughly speaking these related to overall preservation of the environment particularly outside of game reserves, and to protection of species (a game reserve function). A second possible decomposition into sub-criteria, was simply to examine hydrological patterns at sites A (which can dry up without permanent damage) and E respectively, as these represent two broadly different considerations. This latter approach was adopted for purposes of the workshop. In scoring, participants placed considerable importance on the provision of supplies to rural communities, which was thought to be an important determinant of water quality. Ideally this should have been a separate sub-criterion within the conservation interests.

Figure 6.1 displays the scores given to each of the five scenarios on each of the two criteria. Figure 6.2 shows the final weights given to the criteria, and the effects on the implied ordering of the alternatives. (Both Figures 6.1 and 6.2 are copies of the final outputs of the VISA software, as seen by the participants at the conclusion of the workshop).

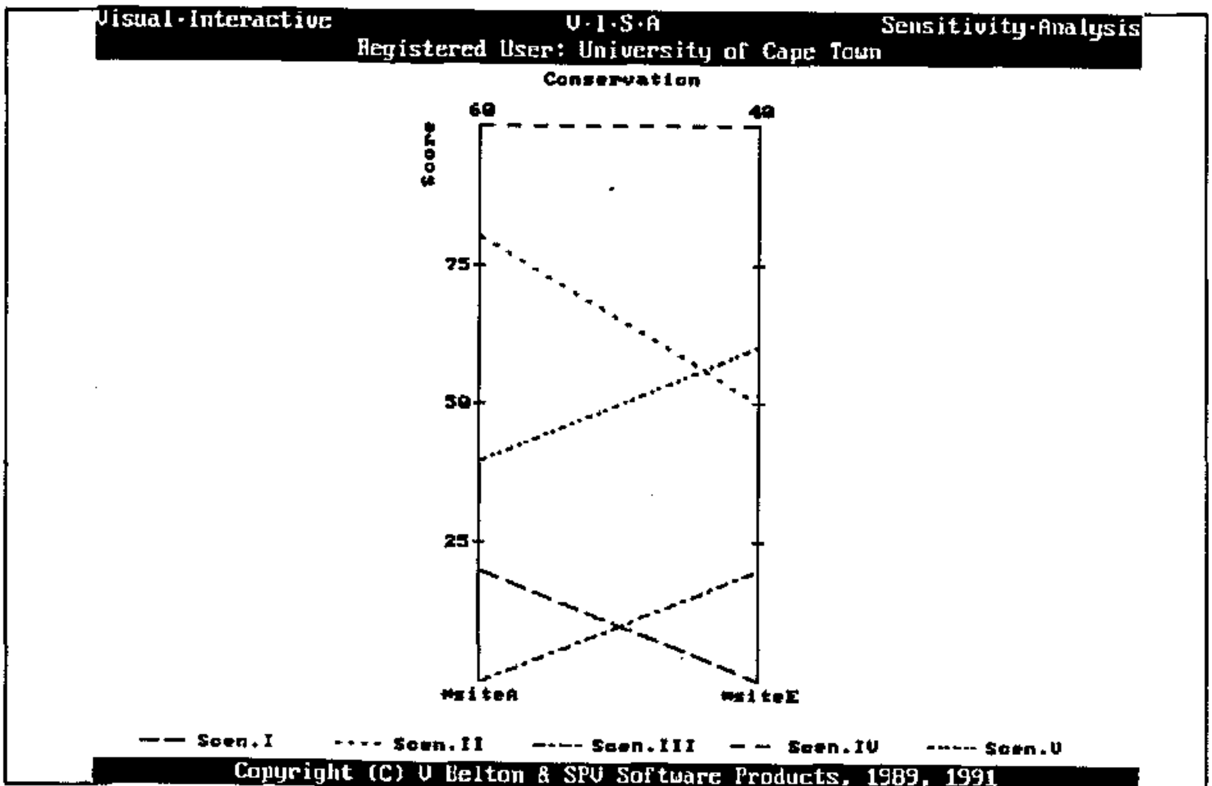


Figure 6.1: Scoring of scenarios by the nature conservation workshop

Group 2: Forestry Industry

An additional **policy element** which needs to be included relates to <u>where</u> additional or reduced afforestation is to occur.

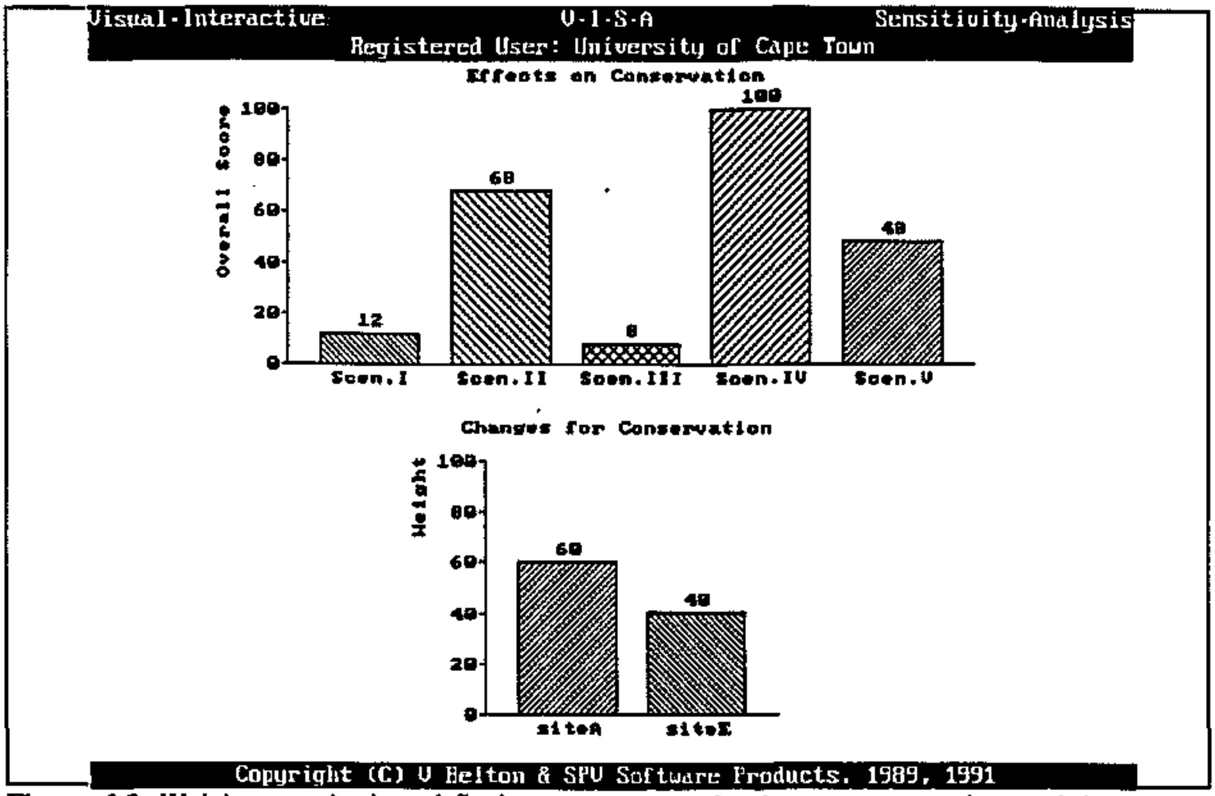


Figure 6.2: Weights on criteria and final scores on scenarios (nature conservation workshop)

Major concern was expressed in this workshop that the added value, or economic multiplier effects, of forestry need to be made explicit, presumably as additional attributes. Without these, it was felt that the true importance of forestry (not just for the industry, but for the wider community) would be under-rated. This concern is conjectured to be the primary reason for the two negative reponses to one of the review questions from participants at this workshop (see "Discussion"), viz. that two of the participants in forestry workshop gave a rating of 2 (on a 1-5 scale) for "confidence in the manner in which views could be expressed".

Three sub-goals were identified: (1) company profits, or shareholder interests (over the long term); (2) regional/national interests (incl. job creation); and (3) image/ responsibility to the community.

The VISA outputs showing scores on each criterion, the weights on the criteria, and the final global scoring are displayed as Figures 6.3 and 6.4.

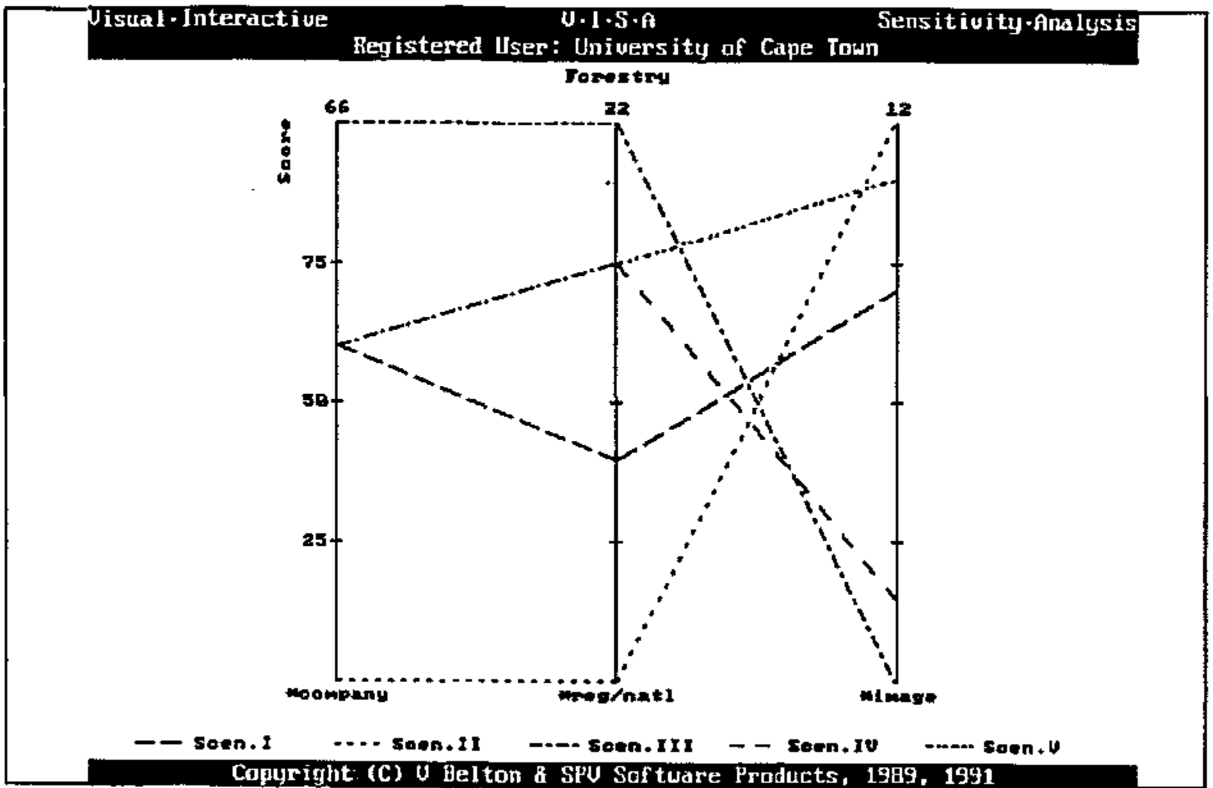


Figure 6.3: Scoring of scenarios by the forestry industry workshop

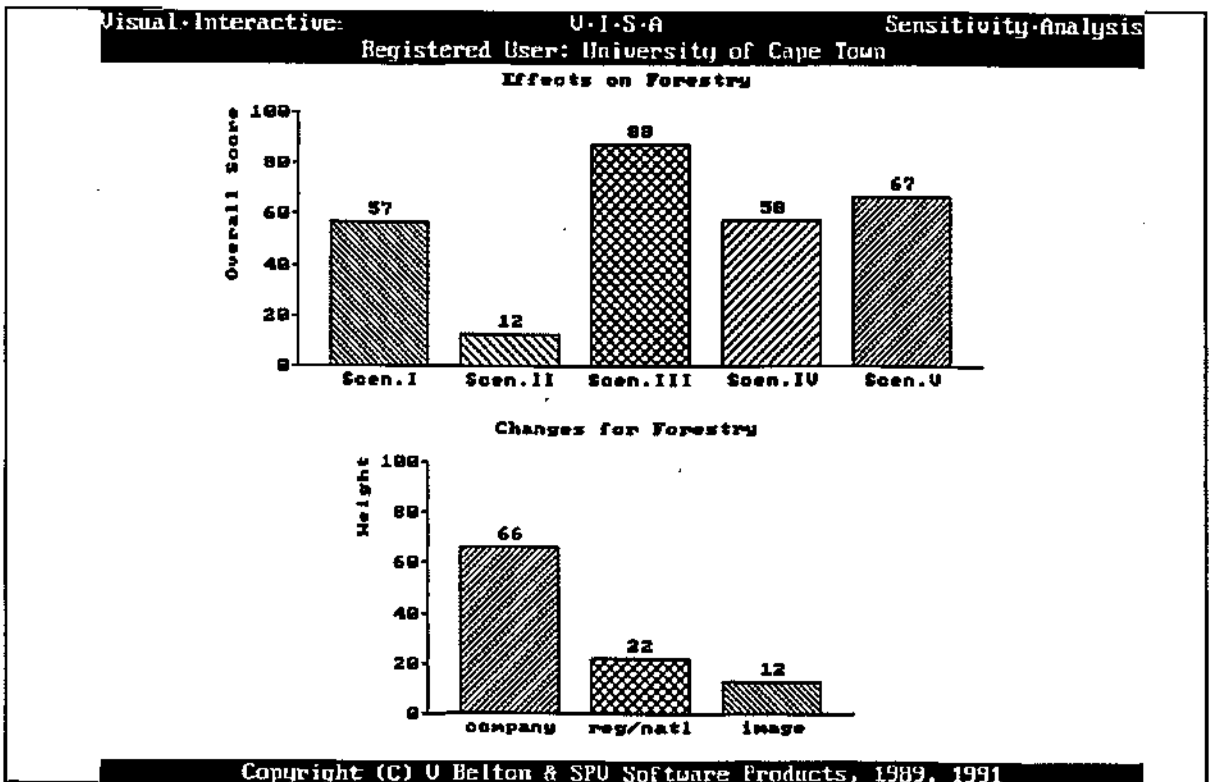


Figure 6.4: Weights on criteria and final scores on scenarios (forestry industry workshop)

Group 3: Rural Communities and Irrigation Boards

The original intention was to run these groups, representing respectively the developing (subsistence farming) and formal commercial agricultural sectors, separately. As a result of the non-appearance of a number of expected particpants, and the late arrival of another, the groups were however combined. This turned out to be fortuitous, as it provided a test of the procedures in a group involving widely differing and potentially conflicting interests.

Policy elements for scenarios should include more details on types of restriction (Do they apply for the whole year, or only at certain times? Are they based on annual consumptions, or on maximum rates of abstraction?), and the area to be irrigated from the dam. Further discussion suggested that combinations of reticulation, roof tanks and boreholes might also need to be considered.

The **irrigation** interests were ultimately represented purely as viability of commercial farming, which was not decomposed into any further sub-criteria. Nevertheless, during discussions, there was a recognition by irrigators that satisfaction of the basic needs of rural communities was also in their own interests, in order to avoid having large dissatisfied communities on their doorsteps. **Rural community** interests were (1) small farm agriculture, (2) availability of employment in commercial farming (with these two at similar levels of importance), and (3) health/ availability of clean water. It was difficult to assess impacts on (1) from the scenarios. The scoring of scenarios by (2) would be equivalent to the irrigation interests. It was agreed therefore that scenarios would be scored in this workshop on the basis of two criteria, viz. viability of commercial farming and health/availability of clean water.

The VISA outputs showing scores on each criterion, the weights on the criteria, and the final global scoring are displayed as Figures 6.5 and 6.6. In retrospect, the weights in Figure 6.5 would seem to represent more the irrigation interest than the rural communities themselves, who would possibly place somewhat greater than 50% weight on the availability of clean water. For this reason, we show in Figure 6.7 a somewhat modified pair of weights, indicating a perhaps more realistic evaluation from rural interests alone. Unfortunately, there was not time at the workshop to explore this in full.

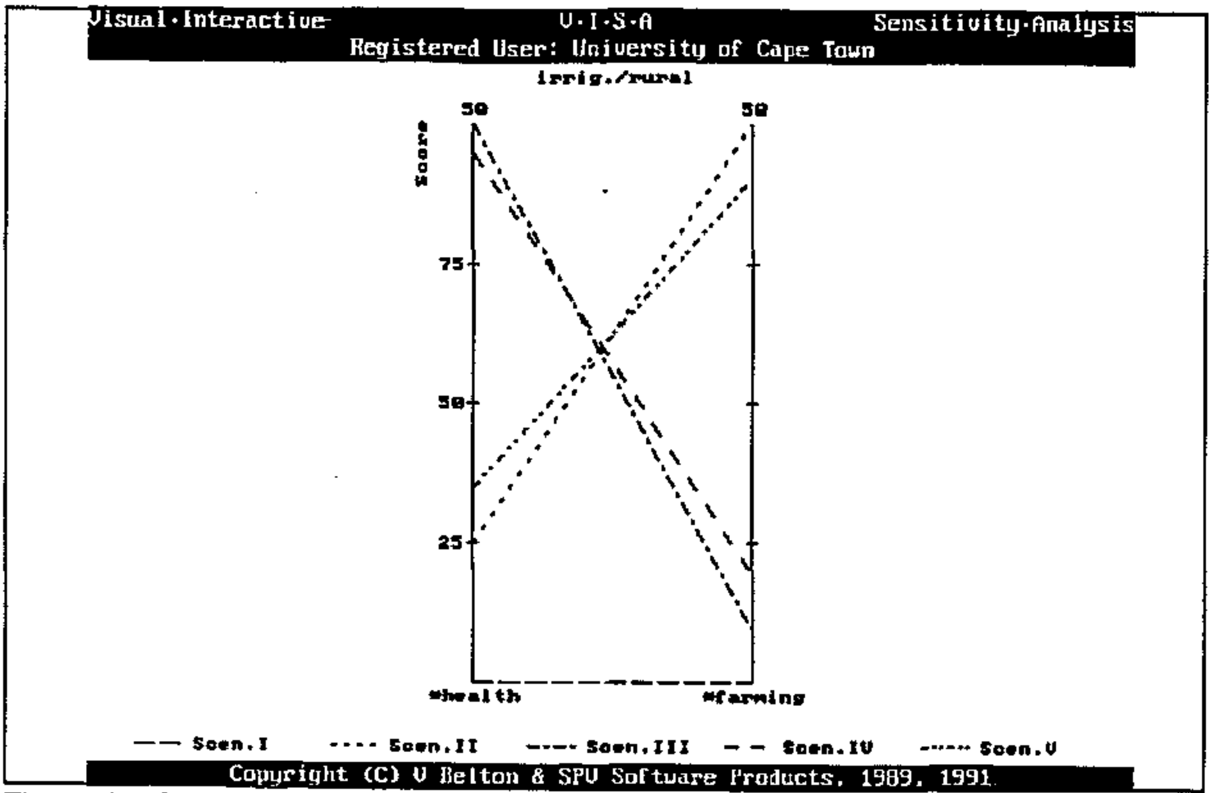


Figure 6.5: Scoring of scenarios by the rural/irrigation workshop

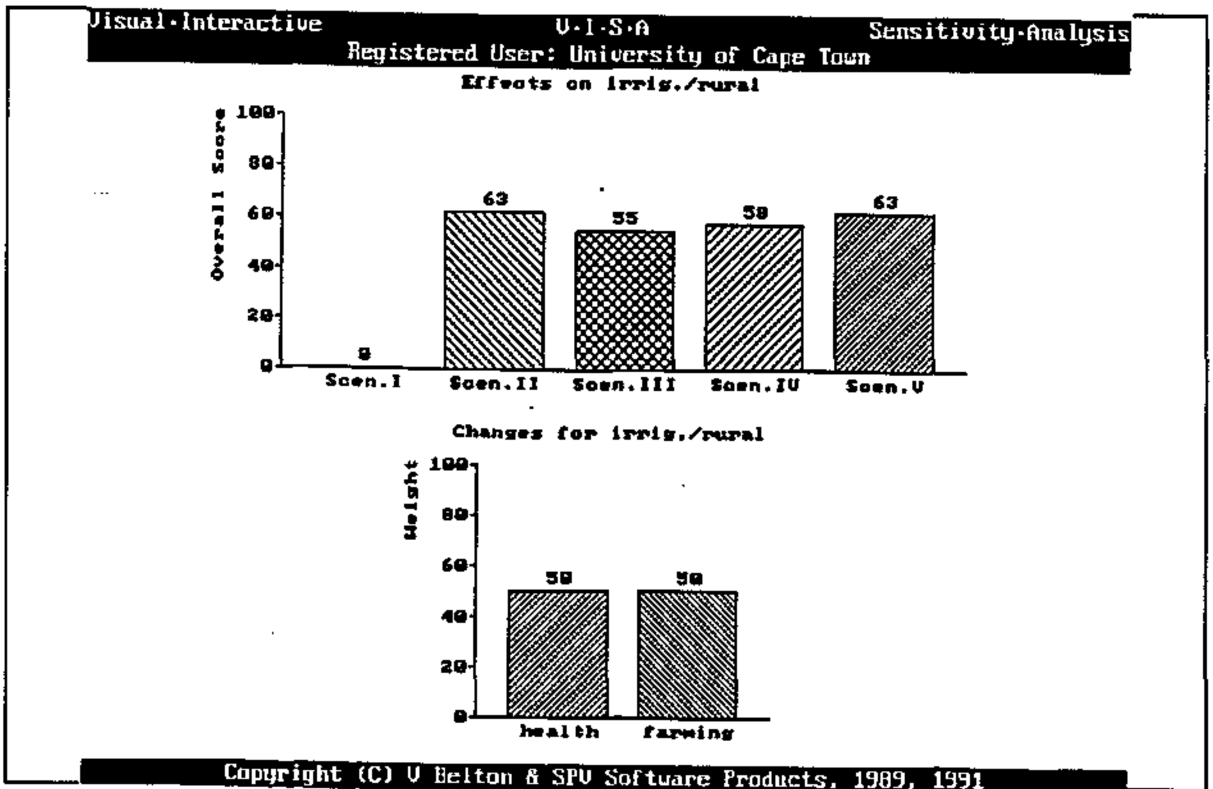


Figure 6.6: Weights on criteria and final scores on scenarios (rural/ irrigation workshop)

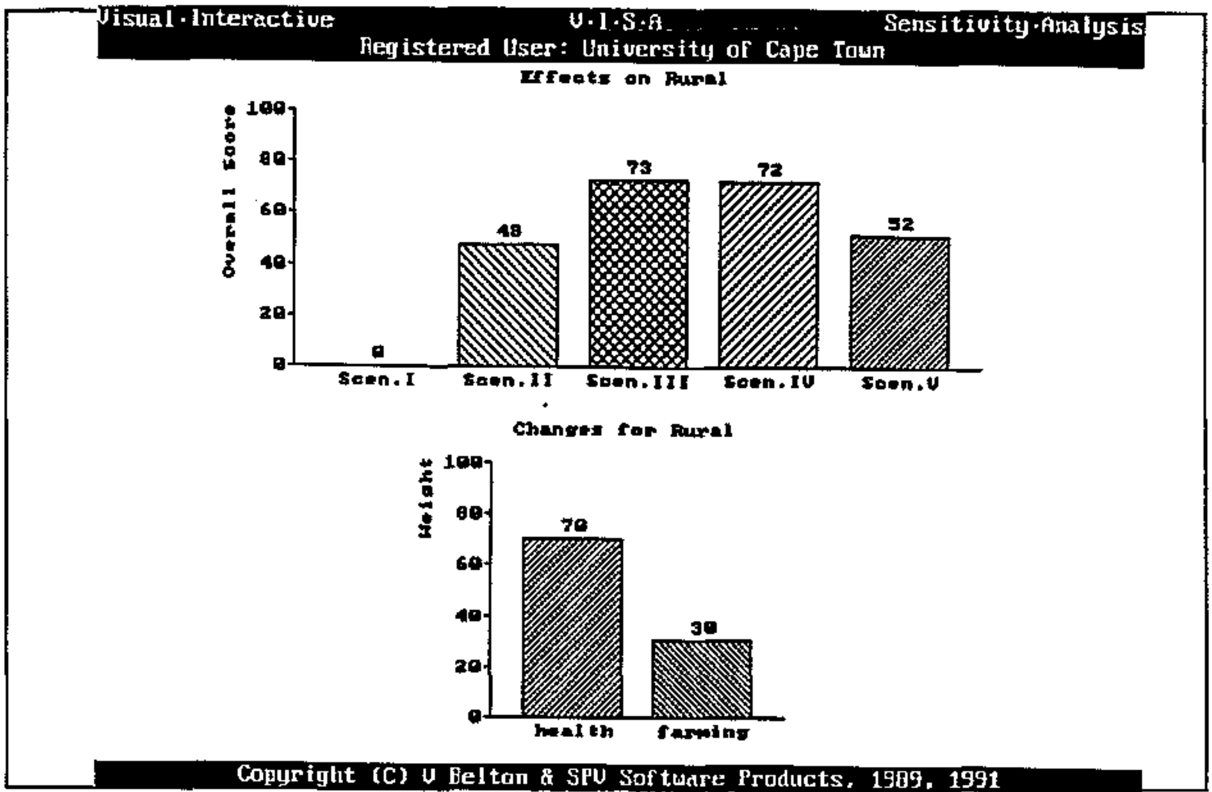


Figure 6.7: Modified weights on criteria and final scores on scenarios, conjectured to be appropriate to rural interests

Table 6.2: Response frequencies to questions regarding ease of understanding of procedures

	Easy				Difficult
SCORES:	1	2	3	4	5
Use of "thermometer" scale for scores	7	3	1	-	-
Use of weights on sub-criteria or interests	3	7	1	-	-
Method of combining weights and scores	-	8	3	-	-

Discussion of response to review questions

Responses by workshop participants to the review questions are summarized in Tables 6.2 and 6.3, as well as graphically in Figures 6.8 and 6.9. There is clearly no problem as regards ease of use or understanding, although there is a gradation with thermometer scale scores being easiest, followed by weights and by the combining of weights and scores. This is perhaps not surprising, and some

Table 6.3: Response frequencies to questions regarding confidence in procedures

	Dissatisfied or Lack Confidence				Satisfied and Confident
SCORES:	1	2	3	4	5
Confidence in the scores generated	-	-	2	8	1
Confidence in the weights generated	-	-	3	7	1
Satisfaction with the way in which the issues were clarified by the procedure	-	1	2	5	3
Confidence in the manner in which my/our views could be expressed	-	2	-	3	6
Confidence that the procedure will lead to better balance between conflicting interests	-	-	-	8	3

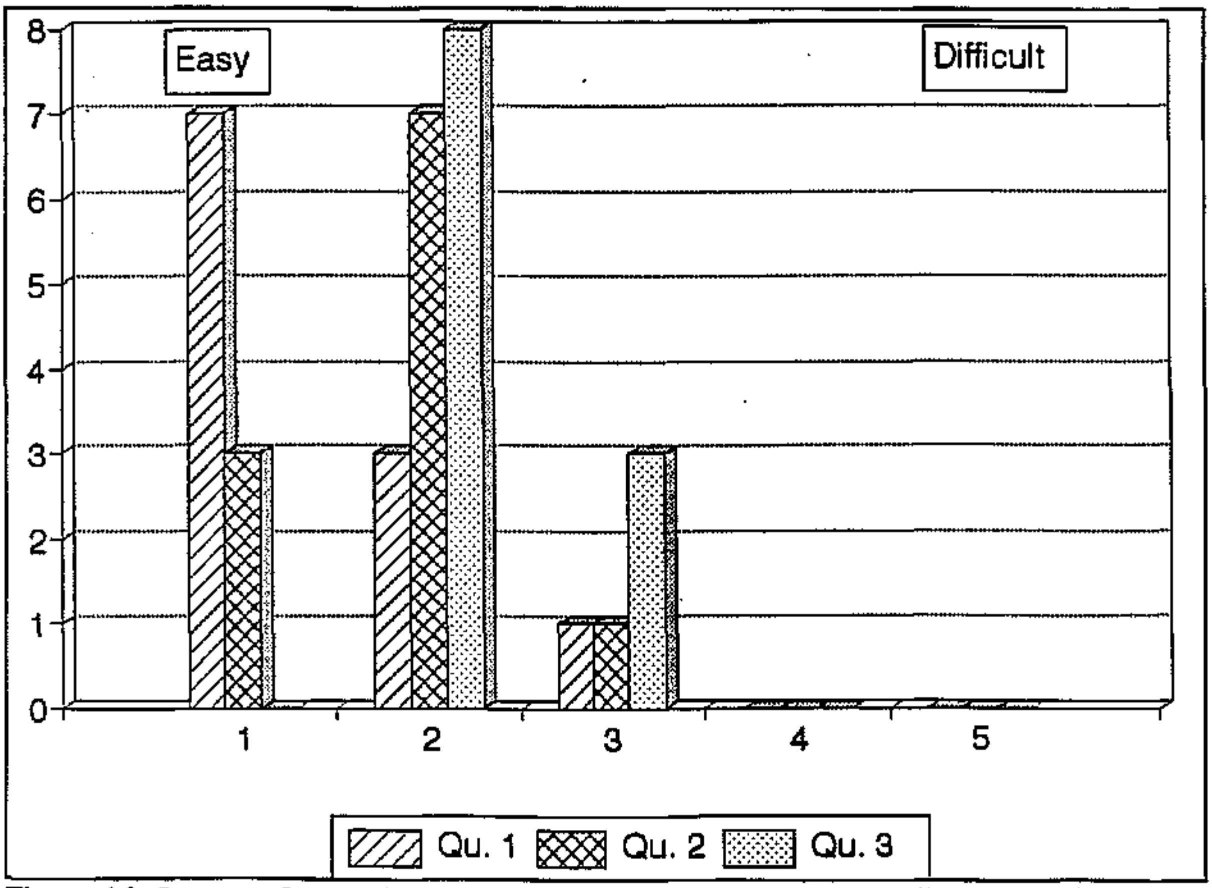


Figure 6.8: Response frequencies to questions regarding ease of understanding of procedures

further educational effort should overcome any residual problems.

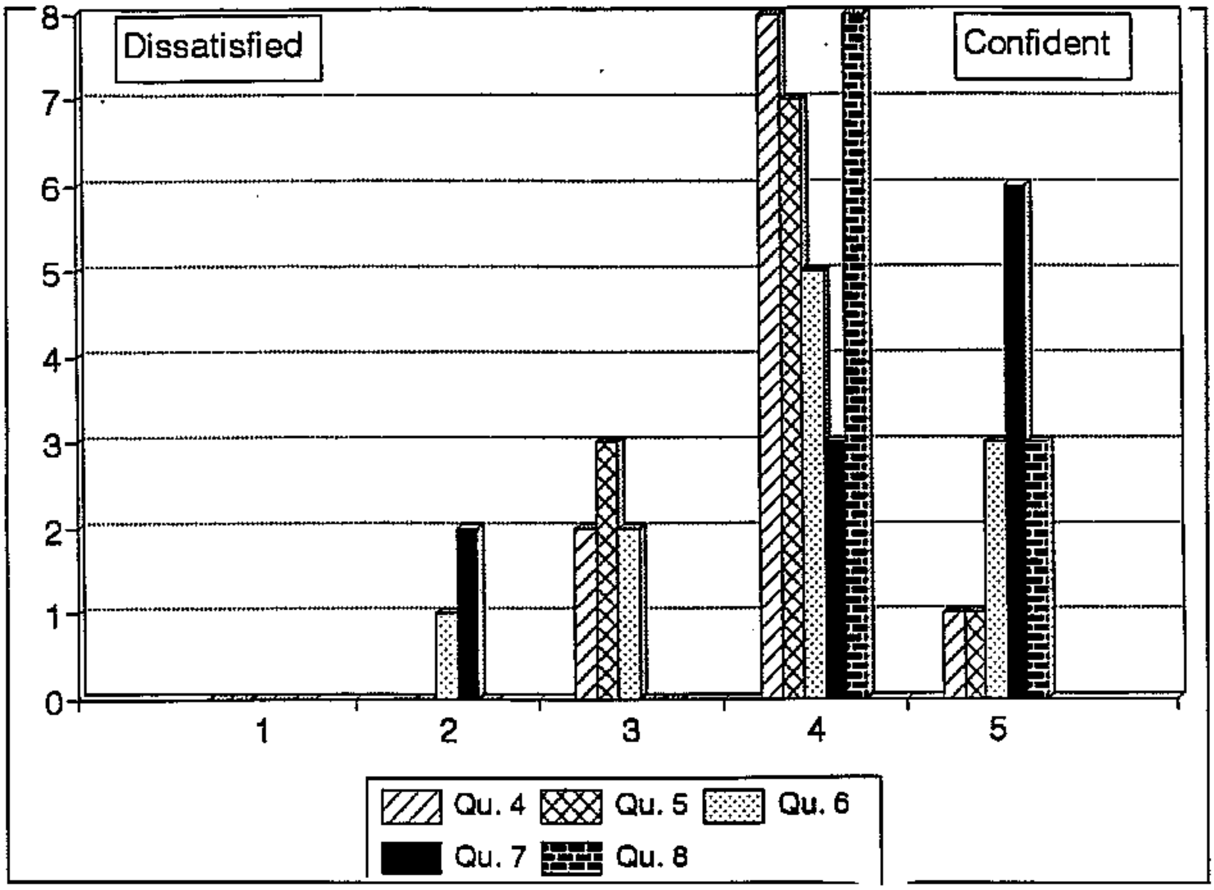


Figure 6.9: Response frequencies to questions regarding confidence in the procedures

We have commented on the two "forestry" responses in which a score of 2 (lacking confidence) for the question on "confidence in the mannner in which views could be expressed", and have conjectured a reason. Apart from this, the respondents clearly have a high level of satisfaction with the procedures adopted. The least satisfactory (but still not disturbing in any way) response is with regard to "satisfaction with the way in which the issues were clarified by the procedure". This may well be due to the fact that the hypothetical scenarios were not adequately specified (a point which came out very clearly during discussions). The need for having well-defined scenarios has, however, been emphasized at other points in this report.

At the conclusion of each workshop, a period of discussion was encouraged, to elicit the overall impressions of participants to the use of the procedures. Their generally favourable expressions are evident from the responses to the review questions, but other points which arose are worth recording here:

(1) Scenarios need to be much more detailed and complete, which limits the potential for using hypothetical scenarios for future testing.

(2) A half-day is much too short. A minimum of one day, and possibly two days, is needed.

(3) People want documentation on how the method works. (This will be prepared in the near future.)

(4) Selection of criteria with which to assess scenarios is critical. Although such criteria must be finalised with the participants, some preliminary work on this by the facilitators is necessary.

6.4 Conclusions from the Case Study

The following overall conclusions can be drawn:

6.4.1 The use of Nominal Group Techniques for identifying policy elements and system attributes for describing scenarios is well-established and effective in generating the necessary information.

6.4.2 An important determinant of the success of the scenario-based policy planning and decision analysis procedure is the effort put into compiling and representing policy scenarios. It must be emphasised, however, that such effort is essential, no matter what procedures are followed, if interest groups and the wider community are to be adequately informed about the results of expert technical evaluations.

6.4.3 People from a wide variety of backgrounds are capable and confident in comparing small numbers of scenarios on the basis of various criteria, using the "thermometer scale".

6.4.4 Confidence in these procedures extends even to the process of finding compromise solutions, i.e. participants in workshops were convinced of the need to give way from their own ideal positions, when confronted with the effects on others (as demonstrated on the relevant "thermometer scales").

6.4.5 It is essential (at least for the first full cycle illustrated in Figure 4.1) that the assessment and comparison procedures be done face-to-face in workshops, public value forums or "decision conferences". These workshops should not be too large (not more than 6-10 persons at a time, initially representing relatively homogeneous interests), and should not be rushed. Our experience supports the recommendations elsewhere (e.g. [14]) that a two-day session is required.

7. APPLICATION OF PROCEDURES TO RESOURCE ALLOCATION PROBLEMS

The major thrust of this report has been the application of decision analysis procedures to problems of relatively long-term water policy planning and development. This is the context in which very divergent value judgments come most dramatically into play, and was identified as the most important issue to be addressed in this research.

Some thought, however, will make it clear that in fact the general procedures outlined in Chapter 4 are applicable to a much wider class of problem settings: in fact to any in which there are a large number of possible actions, affecting different interest groups in different ways, and in which a substantial degree of conflict and/or lack of trust exists or may arise. One particular situation of this form is the allocation of water from existing facilities to competing users, especially at a time of shortage. The *policy elements* then relate simply to the amounts provided to each user, and to the total amount available (since this itself is to some extent a policy variable, based on the level of risk and exploitation of other sources which can be afforded). The interest groups equate with users. The **EQUITY** software [1] provides a useful and simple way of implementing the procedures in this context. A unique feature is that **EQUITY** requires the specification of general societal criteria of evaluation. Supplies to each user are then to be evaluated (by the user group) in terms of their contributions to each of these criteria (on a "thermometer scale"). Weights of different contributions are assessed both between these societal criteria (e.g. environment *versus* economy), and between user groups for each societal criterion (e.g. is the 0-100 scale of economic benefits achieved by forestry greater than or less than the 0-100 scale of economic benefits achieved by power generation?) **EQUITY** allows users to explore the Pareto optimal frontier, i.e. ranges of policies which achieve maximum benefits for (say) a given risk level, for various levels of this risk.

At this stage, we have not evaluated this approach experimentally, but it appears to hold promise, and further evaluation thereof is included as one of the aims of the follow-up Water Research Commission project. Details of the approach, expressed in terms of a simple example, are given in Appendix B4.

8. CONCLUSIONS AND RECOMMENDATIONS

In effect, the main conclusions and recommendations of this research are contained within the proposed scenario-based planning procedure (Chapter 4), and the conclusions from the case study (Section 6.4). These can, however, be summarized in the following:

8.1 Conventional methods of multiple criteria decision making (MCDM) do not directly offer a means of systematically addressing the less tangible costs and benefits to society of water policy decisions. Multicriteria decision analysis techniques are nevertheless useful for eliciting value judgments concerning all societal interests, by a process of direct comparisons of 7 ± 2 comprehensively defined *policy scenarios*, expressed on a "thermometer" (i.e. 0-100) scale. The resulting measures are comparable across interests, and provide one of the few, if not only, justifiable means of comparing intangible costs and benefits with each other and with tangible costs and benefits. This conclusion is supported by experience with evaluating hypothetical policy scenarios for the Sabie-Sand River region.

8.2 Existing software support is available to implement the comparative measurements described in 8.1. The VISA package (Visual Interactive Sensitivity Analysis for multiple criteria decision aid), appears to be the most appropriate software to use at this stage. Workshops using this software can be constituted with little effort, to facilitate the process of rating policy scenarios on "thermometer" scales, both within relatively homogeneous interest groups (to assess their value preferences) and globally (to identify potentially acceptable consensus policies). It is recommended that this approach be taken into immediate use, whenever a relatively small number of policy alternatives need to be evaluated and compared.

8.3 In the longer run, a systematic and comprehensive *scenario based policy planning* procedure is described (Chapter 4 of the report, and particularly Figure 4.1) and recommended. Full software support for this procedure has yet to be developed, but the feasibility of individual steps has been demonstrated (although further research to refine certain of these steps is recommended). The recommended procedure includes the following key steps:

(a) A process of identifying policy elements and thereby the ranges of policy scenarios which can feasibly be implemented;

(b) Use of experimental design procedures to generate a representative set of feasible policy scenarios (called the *background set*), typically 50-200 in number: consequences of each of these would be evaluated in sufficient detail to be able to specify each scenario comprehensively for the purpose of direct comparisons as described in 8.1;

(c) Use of formal MCDM methods to make a further selection from the background set of ± 7 scenarios (called the *foreground set*) for direct value assessments;

(d) Comparisons of scenarios within and between interests, using the thermometer scales and other multicriteria decision support aids: initially attention would be focussed on eliminating less generally acceptable scenarios, while later this attention would shift towards identifying possible consensus;

(e) Iterative repetitions of steps (c) and (d), continually refining the foreground set in the search for the most generally acceptable scenarios.

8.4 Although the broad structure of the scenario-based policy planning procedure has been identified, further research is still needed:

- to refine certain technical steps in the procedure itself, and to incorporate the procedure into a fully operational computerised DSS;

- to integrate the procedure with GIS or similar technologies for the most effective display of scenarios; and

- to test the procedures in real-life policy planning.

All of these research needs are included as objectives in a new project accepted by the Water Research Commission (for the period 1993-1995) under the title "The development of procedures for decision support in water resources management".

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APPENDIX A

LITERATURE REVIEW AND SURVEY OF MULTIPLE CRITERIA DECISION MAKING (MCDM) PRINCIPLES

A1. INTRODUCTION AND SUMMARY

The primary purpose of this Appendix (which is a minor revision of an interim report circulated to members of the steering committee for the overall project in 1991) is to provide a technical overview of the literature relevant to decision analysis in water resource planning, with particular reference to problems of group decision making and the treatment of indirect and intangible societal goals. Since much of the literature makes use of the methods and terminology of the branch of operations research/management science called *Multiple Criteria Decision Making (MCDM)*, we provide first a general overview of this field in Sections A2-A4 (where Section A4 relates specifically to the strengths and weaknesses of the AHP technique, which is perhaps the best-known MCDM method in the RSA). This overview is to some extent a summary of a more general survey published by one of the authors (Stewart, 1992). The main literature review then follows as Section A5. Simple illustrations of the use of the more important of these MCDM methods in the context of water resources planning is given in Appendix B.

A2. THE MULTIPLE CRITERIA DECISION MAKING (MCDM) APPROACH TO PLANNING AND DECISION MAKING PROBLEMS

In order to discuss the role of MCDM and other Decision Analytic tools, we need first to have clarity on the definitions of terms as we shall use them. Unfortunately, there is not unanimity in the literature on these terms; and furthermore, some common usage is restrictive when we come to consider national resource planning problems (as we shall see below). We thus will use the terminology as defined below:

Decision or Policy Scenario: A description of one possible plan of action (an "**alternative**") for the future. At tactical planning levels this might be a relatively simple decision alternative (such as the location of a reservoir), but we will generally be dealing with broad policy issues, in which case the policy scenario would be complex, and possibly imprecisely defined as regards operational details.

Outcome scenario: A description of the consequences of implementing a particular policy or decision (scenario); it may of course not be possible to predict the outcome scenario corresponding to a given policy scenario with certainty, in which case a number of possible outcome scenarios need to be described, perhaps with probabilities associated. The combination of a policy scenario and an associated outcome scenario may simply be termed a **scenario**.

Attributes: The features or properties used to describe a scenario, for the purposes of identifying the most desirable policy. The scale of measurement used to define an attribute may be **cardinal** (a direct numerical measure, which may however be on a subjective scale), **ordinal** (a rank ordering of outcomes according to a particular feature) or **nominal** (a classification of outcomes into unordered classes, such as for example colour). The intention in the choice of attributes is to provide "a basis for evaluating whether goals have been met" (Chankong *et al*, 1985). For this reason it is common to associate attributes on a one-to-one basis with goals or objectives (Keeney and Raiffa, 1976), but as we shall see below, this can be a restrictive view, particularly when different goals relate to different interest groups.

Where appropriate, we shall represent a scenario purely as a vector of attributes designated $(z_1,z_2,\ldots,z_n)$, where n is the number of attributes, and where the attributes refer to those properties of policy or outcome scenarios which directly affect achievement of one or more societal goals.

Criterion: The dictionary definition of criterion is a principle or standard by which things (in our case, alternative policies) can be judged or compared. It is difficult to find a precise technical definition for criterion in the MCDM literature. The implication is usually that "criterion" is synonymous with attributes or goals or objectives (cf. definitions below); in fact, Chankong *et al* (1985) see criterion as a composite word to incorporate goal or objective. Perhaps most useful is the definition given by Bouyssou (in Chapter I of Bana e Costa, 1990), that a criterion is a tool allowing comparison of alternatives according to a particular significance axis or point of view.

For this review, we will use **criterion** to signify a principle used in comparing alternatives according to one point of view. This leaves open the question as to what **performance measure** would be associated with the criterion, in order actually to perform the comparisons. (Thus a criterion may be "aesthetic beauty"; but selection of a suitable measure of how much aesthetic damage results from an electricity pylon may be problematical!) Often there may be a well-defined attribute that plays this role; ideally, one would wish to have a marginal utility measure (see below) to represent real value judgements on the level of performance achieved according to the criterion.

Criteria need to be selected with some care. It must be ensured that all important "points of view" are covered, and yet that the number of criteria be kept small. The criteria should be unambiguously interpretable to those whom it affects. The criteria should be value independent in the sense that comparisons of alternative outcomes in terms of one criterion should be meaningful without concern about other criteria. (This does not, of course, preclude the possibility of statistical dependence, viz. that good performance on one criterion may only be possible at the expense of poorer performance on another criterion; but it should still be possible to give meaning to the concept of "good" in terms of one criterion, without knowing the levels of performance achieved for the other criteria.)

Where appropriate, we shall associate a vector of utility values $(u_1,u_2,\ldots,u_p)$ with each alternative, to represent its worth in terms of each interest or criterion, where u_i is the marginal utility relevant to criterion i, and p is the number of criteria.

(Single criterion, marginal or individual) Utility: A measure of the relative degree to which alternatives satisfy the aspirations or desires represented by a specific criterion ("point of view"), which we shall denote by u_i for criterion i. Ultimately this must be a subjective measure of performance, although in some circumstances it may be derived from a **utility function** which relates utility to one or more attributes, i.e. $u_i=u_i(z_1,z_2,\ldots)$.

Objective or Goal: An operational definition of a particular criterion, expressed either as a direction of increasing preference ("objective"), or as a desired level of achievement ("goal"), in terms of the appropriate attribute or performance measure.

Non-dominated (efficient, or Pareto optimal) solutions: If we have two alternatives, such that the first is at least as good as the second on <u>every</u> criterion, and is strictly better on some (i.e.

their outcome scenarios are not identical), then we say that the first dominates the second. Alternatives which are not dominated by any other are termed non-dominated, or efficient, or Pareto optimal. If the set of criteria are complete in representing all possible concerns, then we can generally disregard any alternatives which are dominated by others. In practice, the set of criteria are seldom strictly complete, and a solution which is only slightly dominated by the best solution could possibly, in some cases, remain a good contender; nevertheless, for ease of analysis, many MCDM methods ignore dominated solutions.

The conventional MCDM approach assumes in effect a single decision-maker, or at very least a group decision-making context in which group members have more-or-less homogeneous interests. In this case, it is natural to have a one-to-one link between criteria and attributes (with the latter serving as performance measures). Any attribute not related to a criterion is irrelevant; while any criterion related to more than one attribute indicates either a redundant attribute, or a representation of more than one point of view (requiring a refinement of the criterion). Even where the criterion is highly judgemental (aesthetic appeal, for example), a nominal scale (5 or 7 point, say) can be used as the relevant attribute. At this point, it is possible in principle to relate each utility to its corresponding attribute, in the form of a marginal utility function $u_i=u_i(z_i)$. If marginal utilities are explicitly required for further analysis, then it is usual to estimate the form of the function $u_i(.)$ *a priori* (cf. Keeney and Raiffa, 1976, or von Winterfeldt and Edwards, 1986); there is then no need to ascertain utility values for each outcome scenario separately, as these can be determined from attribute values (the latter generally obtained from appropriate systems models).

A number of MCDM procedures are summarized in the following Sections, but all attempt by one or other means to translate the separate evaluations of alternatives by the different criteria, into a single preference ordering. In "multiattribute utility theory" (MAUT), also termed "multiattribute value theory" (MAVT), and the "analytic hierarchy process" (AHP) approaches, a global utility or value function is established, as a function of $u_1,u_2,\ldots,u_p$, and is used as a global super-criterion. In goal and reference point approaches, interactive methods are used to vary goals (defined in terms either of attributes directly, or of single-criterion utilities) in a systematic manner, until a single winner emerges, as the only scenario satisfying all goals.

Game theory addresses the more complex situation, in which each criterion can be associated with a particular person, or interest group (which may be called an "player"). The primary interest in game theory relates to synthesizing the individual utilities $u_1,u_2,\ldots,u_p$ into a global utility or social benefit function. In this sense the intention is much like that of MAUT or AHP, although the assumptions are different. Little explicit discussion is devoted in game theory to the process whereby the individual utilities are obtained. Evidently, however, the utility corresponding to each actor may itself be a synthesized multi-criteria utility (i.e. a multi-attribute utility), viewed from that player's perspective. The same attributes might however be relevant to more than one criterion (= player), and may influence different criteria in different ways. In general therefore, we would have a very complex situation in which $u_i = u_i(z_1, z_2, \ldots, z_n)$, which requires more careful treatment than in standard MCDM approaches.

At first sight, it would appear that regional and national water planning problems contain features both of the standard MCDM problem (eg. criteria such as GNP growth), and of the game theory problem (eg. interests of forestry and of downstream users). This will probably lead to a complicated relationship between criteria, and the attributes used to define scenarios; these complications appear to have received little attention in the literature up to now.

A3. OVERVIEW OF GENERAL MCDM APPROACHES

A number of reviews of the MCDM literature have appeared, for example Goicoechea *et al.* (1982), Changkong *et al* (1985), Steuer (1986), Zionts and Lotfi (1989), Bana e Costa (1990) and Stewart (1992). Furthermore, literature specific to the relevant water resource planning problems are reviewed in the Section A5 of this report. The purpose of this Section is not to repeat these reviews, but rather to create a general framework within which the rest of the literature review can be read.

A3.1 Utility and Value Functions

These approaches seek to assess first the marginal utilities $u_1, u_2, \ldots, u_p$, and then to combine these into a global utility function $U(u_1, u_2, \ldots, u_p)$, of some assumed form, representing overall strengths of preference of the decision maker between outcomes. Typical forms which are assumed are the additive form:

$$U(u_1,u_2,\ldots,u_p) = \sum_{i=1}^{p} w_i u_i \qquad (1)$$

or the multiplicative form, which relates the global to the marginal utilities according to the following expression:

$$1+kU(u_1,u_2,\ldots,u_p)=\prod_{i=1}^{p}[1+kw_iu_i] \qquad (2)$$

For the additive form to be able to model the decision maker's strengths of preference consistently, a strong assumption is needed, termed additive difference independence; this means that preferences between risky outcomes depend only on the marginal distributions for each performance measure, or alternatively that absolute strengths of preference between two outcomes differing only on one criterion do not depend on the levels of achievement on the other criteria. This is a stronger assumption than that required for the multiplicative form (which contains the additive case as the special case achieved in the limit as $k \to 0$), which is preferential or weak difference independence, requiring only that relative strengths of preference between scenarios differing on one criterion only, are independent of levels of achievement on the other criteria.

Classical multi-attribute value (or utility) theory assesses both the marginal and global utility functions by requiring the decision makers to evaluate sequences of hypothetical scenarios to find points of indifference. The process is tedious, and involves choices which may be far removed from reality, but requires no further behavioural assumptions, such as the scales of preference on which decision makers express strengths of preference.

Von Winterfeldt and Edwards (1986) suggest a variation which they term SMART (Simple Multi-Attribute Rating Technique), which follows the basic multi-attribute utility model, but assesses the utilities by direct questions regarding relative strengths of preference between scenarios, which is less tedious than the indifference approaches. A similar approach is adopted in the V•I•S•A method discussed by Belton and Vickers (1990).

The Analytic Hierarchy Approach (AHP) of Saaty (1980), assumes only the additive form. Marginal utilities are assessed by evaluations of strengths of preference between every pair of possible outcomes, for each criterion separately. This has the advantage of focussing attention on to real outcomes only, but is limited in applicability to relatively small numbers of alternative outcomes. The lack of basis for many of the assumptions in AHP, the response scales and the methods of estimation have been criticised by a number of authors, as discussed in Section A4.

Some interactive decision support systems for MCDM do not attempt to assess the utility functions *a priori*; they assume only some general (and often approximate form), and present to the decision maker a sequence of restricted choices (i.e. between 2 or 3 possible outcome scenarios only). The choices made by the decision maker in this setting are used to draw further inferences about the shapes of the utility functions, which in turn guide the selection of further potential solutions. Examples of such approaches are found in Korhonen, Wallenius and Zionts (1984) and in Steuer (1986), Section 13.4. These approaches suffer from the disadvantage that the rationale for the final choice made is not clearly recorded, which is a serious shortcoming in problems involving a significant political component.

A3.2 Goal Programming and Reference Point Approaches

Goal programming is perhaps the earliest of the formal MCDM methods. Generally, a reference point approach starts by having the decision maker specify achievement levels for each criterion, in terms of the relevant performance measures. These levels are typically of one of three types:

(a) Goals or aspiration levels, i.e. performance levels which would fully satisfy the goals or aspirations of the decision makers, and such that there is little or no additional benefit in going beyond these; while the goals should individually be realistic, they would not generally be simultaneously achievable, so that these levels represent an ideal towards which the decision maker is striving.

(b) Veto or exclusion levels, i.e. performance levels which if violated for even just one criterion would render the entire scenario totally unacceptable.

(c) Reference levels, i.e. a realistic expectation from the decision maker as to what would be acceptable compromises between the conflicting demands of the different criteria.

Let the performance levels specified for the criteria be represented by $(g_1,g_2,\ldots,g_p)$; and suppose that any scenario is represented by a corresponding set of performance measures $(z_1,z_2,\ldots,z_p)$, where each z_j may either be an appropriate attribute measuring performance for criterion j, or the corresponding marginal utility.

Goal programming searches for the scenario that minimizes a measure of underachievement of the goals, typically a function such as:

$$\sum_{i=1}^{p} w_i.\min(0, g_i - z_i)$$

or sometimes a function of the form:

$$\mathrm{Max}_{i=1}^{p}[w_i.\min(0, g_i - z_i)]$$

The idea is that once a solution is found, the decision maker would review his or her goals, and that the process would be repeated, until no further progress is made.

A similar approach can be adopted for exclusion levels, i.e. by maximizing a measure of over-achievement, but this is rarely done. For interactive decision support, the reference point approach introduced by Wierzbicki (1980) seems more suitable: this in fact seeks both to minimize underachievements and to maximize overachievements, but with the greatest weight being placed on the largest underachievements, and can thus be used together with any of the three types of specified performance levels indicated above (but most effectively with the last of these)

A3.3 Outranking Approaches

The outranking approaches are popular in Europe, and particularly in France, where they were developed by Roy and co-workers at the University of Paris Dauphine (cf. Bana e Costa, 1990, Chapter II). These approaches seek to represent the evidence for and against the assertion that one policy or decision alternative is at least as good as another, or "outranks" it. The basic form of outranking approach is the ELECTRE method (or more correctly methods, as there exist a number of variations of ELECTRE).

Evidence in favour of the assertion that one alternative is at least as good as another (or "concordance") is summarized in terms of a form of voting scheme between criteria, i.e. each criterion is awarded a voting weight, which is allocated to the alternative that is judged to be best according to this criterion (with votes shared in the case of a tie). Evidence against the same assertion (or "discordance") is summarized by a form of veto accorded to any criterion for which the first alternative is worse than the second by more than a prescribed margin.

One method of applying ELECTRE (ELECTRE Is) is simply to declare that one alternative outranks another if the concordance is above some threshold, and there is no discordant veto (for veto margins prescribed *a priori*). A more complicated form of ELECTRE (ELECTRE III) is to define a "credibility" index in such an assertion, which may lie between 0 (no evidence of outranking) and 1 (definite outranking).

A3.4 Game Theory

Multi-person game theory assumes in effect that each criterion is associated with a particular "player" (a person or a group), and that marginal utilities u_i can be associated with each policy scenario. If there is uncertainty regarding the outcome scenario corresponding to a policy scenario, then it is required that u_i be the expectation of the marginal utilities taken across all possible outcome scenarios.

Game theory aims at identifying solutions to the decision problem which are the most acceptable compromise between the players. The basic game theory solution is the Nash Solution, which is derived from a few simple axioms and the assumption that all players have equal status. The Nash solution is to select the policy scenario which maximizes the product of the marginal utilities $\prod_{i=1}^{p} u_i$. Kalai (1977) demonstrated that relaxation of the assumption of equal status leads to the modified rule maximizing:

$$\prod_{i=1}^{p} u_i^{\alpha_i}$$

where the α_i are importance weights which sum to one.

There is great similarity in the solutions generated by the game theory and MAUT (multiplicative form) models when the outcomes are known with certainty for each policy scenario. Where there is uncertainty, however, an important difference emerges. Game theory takes the product of the individual expectations for each criterion; while MAUT takes the expectation of the total product. The consequence of the game theory approach is that the solutions depend only on what are termed marginal probabilities for each criterion. This is best understood by means of a simple example. Suppose that outcomes can simply be classifed as "good" or "bad" for each of two criteria. Consider the four outcome scenarios which are possible within this classification, viz.:

A = {"good" ; "good"}   (i.e. "good" on both criteria)
B = {"good" ; "bad"}
C = {"bad" ; "good"}
D = {"bad" ; "bad"}

Now consider two policy scenarios, with the first generating outcomes A and D with equal probabilities; and the second generating B and C with equal probabilities. The game theory solution declares these two policy scenarios as being equally desirable, as each gives a 50:50 chance of a "good" or "bad" outcome for each criterion. And yet, in national policy planning, the two policies may very well not be preferentially equivalent. If the criteria represent two interest groups, then the option leading to A or D may be preferred, as the result is always equitable (*ex post*) to both parties. On the other hand, if the criteria represent different types of economic benefit, then the option leading to B or C may be preferred, as we never lose out completely. The MAUT model thus appears to be the more versatile for policy planning problems.

A4. MULTI-ATTRIBUTE UTILITY (VALUE) THEORY (MAUT or MAVT) AND THE ANALYTIC HIERARCHY PROCESS (AHP)

As indicated in Section A3.1, value based methods start by associating marginal utilities with each scenario, separately for each criterion. These marginal utilities are subsequently aggregated into a single global utility for each outcome. In fact, it is common practice to develop the set of criteria hierarchically, with broad imprecise criteria (eg. maximizing welfare) being broken down into increasingly detailed but more precise criteria (eg. maximizing disposable income per family). In this case, criteria are not aggregated in a single step; criteria at the lowest level of the hierarchy and which share the same predecessor criterion at the next level are aggregated into a single measure of performance for this criterion. This is then repeated at the next level, until the global utility is derived. These are technical details however, which do not affect the discussion below.

MAUT assesses the marginal utilities either by comparing trade-offs against some common currency, or by comparing hypothetical gambles involving different levels of performance, or by direct judgemental assessments of the relative importances of different sizes of increment in performance. AHP assesses the marginal utilities by asking for relative strengths of preference (expressed on a nominal 9-point scale) between each pair of possible policy scenarios (assuming in effect that the corresponding outcome scenarios are known with certainty). Both do assume that such preference statements concerning the impacts on a single criterion can sensibly be made by the decision maker, without reference to performance levels associated with other criteria, but the literature on AHP does not emphasize the existence of this assumption.

We have noted in equations (1) and (2) of Section A3.1 that different forms of aggregation function can be assumed, depending on the form of preferential independence assumptions which can be made. AHP assumes the additive form (1) with no specific justification. Now it is true that (1) is often assumed in MAUT even when the assumptions are not entirely verifiable, but then care is taken to ensure that the definition of the marginal utilities is such that equal increments in u_i correspond to equal strengths of preference, in other words such that preferences are measured on an **interval scale**, as implied by an additive form. AHP, on the other hand, assesses preferences on a **ratio scale**, which is not in general consistent with the additive aggregation in (1). Lootsma (1990) deals with this criticism in more detail.

The weight parameters in (1) or (2) as assessed in MAUT have a simple and natural interpretation as the worth of the "swing" from worst to best on one attribute relative to similar "swings" on the other attributes. In AHP, especially because the marginal utilities u_i are scaled to sum to one, which confounds the "swing" worths between the weights and the marginal utilities, the weights have a less easily understood meaning (cf. Belton, 1986). It is this problematical interpretation of the weights which lies at the heart of the "rank-reversal" phenomenon, mentioned in criticism (3) below.

The appeal of AHP lies in its considerable simplicity relative to most MAUT applications, although in practice its application is limited to cases which can be described in terms of a relatively small number of scenarios (less than about 7, say, because of the large numbers of pairwise comparisons needed). There have, however, been a number of criticisms of AHP which have appeared in the literature, and in our view not well answered by the proponents of AHP. Some of the more important of these criticisms are those of Belton and Gear (1983), Schoner and Wedley (1989), Islei and Lockett (1988), Lootsma (1990) and Dyer (1990). We shall here only attempt to summarize these criticisms briefly.

(1) Validity of the additive model: We have commented on this point above. The additive model implies that if two attributes are of equal importance, then equal increments in u_i represent equal worths, and there is no natural zero to the utility scale. In AHP, however, ratios of the u_i are assessed, assuming some implicit natural zero point. The justification for using the additive model is thus not at all clear, and in fact must be considered questionable.

(2) The meaning of the importance weights: This we have dicussed above.

(3) Normalization of marginal utilities: The estimated marginal utilities are normalized in AHP so that their sum (over all decision scenarios) is one, on the apparent basis that this also represents a slicing of an importance "cake" between the different alternatives. It has been demonstrated however that the relative ranking of an alternative is affected by the presence or absence of other alternatives, particularly if they have similar outcomes, a phenomenon termed "rank reversal". Since the specification of the list of decision scenarios under consideration is part of the analysis, and can be quite arbitrary, this makes the rank orderings generated by AHP correspondingly arbitrary (cf. Dyer, 1990). Although in written responses to both Belton and Gear (1983), and to Dyer (1990), Saaty has defended this property of AHP, many analysts find it disturbing.

In more recent work, Saaty (1990) has suggested the use of an "absolute measurement" mode of analysis for avoiding the rank reversal property. Instead of comparing alternative scenarios directly in terms of each criterion, one defines and compares a set of absolute "ratings, intensities or grades of the criteria". This does, however, presuppose the existence of some objectively meaningful scale such that a "rating, intensity or grade" can be attributed to any specific scenario. This is likely to be difficult precisely for those more intangible criteria for which we are seeking a method of value measurement, and must therefore limit the applicability of AHP in this context when used in this mode.

(4) Validity of the assumed ratio scale: Comparisons between outcomes in terms of one criterion, and between criteria for determining weights are expressed on a nominal scale, which is interpreted in AHP as the ratio of marginal utilities or weights. No real justification for this assumption has been offered apart from some anecdotal evidence.

(5) The "eigenvector" estimation procedure: AHP estimates both the marginal utilities and the

importance weights from matrices of pairwise comparisons, by evaluating the eigenvectors of the these matrices corresponding to their largest eigenvalues (mathematical properties which need not be described here). These would be the correct values if all comparisons were completely consistent with the assumption that these comparisons represent ratios of utilities or weights. If the comparison matrices do not exhibit such consistency, then there is no evident reason why the eigenvector remains a good estimate. In fact both Lootsma (1990) and Islei and Lockett (1988) give arguments against this approach.

It is evident, therefore, that although AHP is a useful simple tool, which can generate valuable insights into the structure of a decision problem, great circumspection is necessary before it is used as a resource allocation system in politically sensitive situations. At least one reason for the early acceptance of AHP as a decision analytic tool, was the ready availability of convenient software for implementing the procedure. Other software systems have however subsequently become available (see main report, Section 5) and thus AHP no longer has any particular advantage in this respect.

A5. REVIEW OF LITERATURE SPECIFIC TO THE APPLICATION OF MCDM TO DECISION SUPPORT IN WATER AND OTHER RESOURCES MANAGEMENT

In this review, literature is classified according to the type of problem addressed. Four categories are identified as follows:

(i) Qualitative or Quantitative Goal Assessment

(ii) Operational to Medium Term Planning of Water Resources

(iii) Long Term Planning of Water Resources

(iv) MCDM in Other Resource Planning Problems

(v) Group Decision Support and Models for Conflict Resolution

Section A5.1 reviews articles in category (i), dealing primarily with identifying, structuring, expressing or measuring goals. The section is subdivided as follows:

(a) Generating and Structuring Goals

(b) Measurement of Goal Achievement

1. Intangible Goals
2. Non-commensurate Goals

Operational level decisions (category (ii)) on the whole are concerned with numerical solutions rather than choice of a strategic alternative. Furthermore, the set of possible alternative strategies in operational level decisions, although large, can generally be expressed implicitly in mathematical terms (eg. as all vectors of some given size which satisfy stated constraints), and can thus in effect still be evaluated exhaustively. This is different to long-term planning decisions where at any one stage, only a relatively small number of distinct alternatives can be evaluated. A problem as large as that of long term planning of an entire river system cannot realistically be dealt with in the same amount of detail as that required for a subsection of it, such as a particular operational strategy. Literature under category (ii) is thus not directly relevant to our current strategic planning interests, but is included here briefly for the sake of completion.

A5.1 Qualitative or Quantitative Goal Assessment

This category is subdivided into two sections. The first deals with eliciting and structuring goals, the second with measurement of these goals.

A5.1.1 Generating and Structuring Goals

Keeney and Raiffa (1976), and Von Winterfeldt (1980) show that it is possible even in complex problems, to structure management objectives hierarchically. At the top level of the hierarchy is a general statement of the overall objectives (e.g. maximise benefit to a community). In general the broad objective at the top level of the hierarchy is too vague to be of practical use in decision making. The objectives are progressively better defined at lower levels of the hierarchy, until at the lowest level they become very specific (e.g. to increase the employment rate). These lowest level objectives need to be 'operationally meaningful' in the sense that a scenario can be more or less unambiguously judged according to this attribute. We note that the identification of specific objectives in this way is a necessary pre-requisite to further MCDM analysis.

One of the problems associated with structuring the goals in this fashion is noted by Weber *et al* (1988), who conclude that the way in which the global objective is decomposed affects perceptions of the importance of these. Evidence supporting this is given by the results of a study in which subjects assigned more weight to the attributes in the more detailed parts of the hierarchy of objectives. Some similar experience is reported by Borcherding *et al.* (1991), who look specifically at the effect of the method of eliciting judgmental weights on this and other issues.

In the classical approach to MCDM, it is generally assumed that there is one decision maker (DM). When there is more than one DM, the process of choosing and structuring objectives involves a group of individuals. Clearly, this is a more complex process than for a single DM, as group members may have differing interests, opinions and goals. The role of group processes in goal assessment is thus an important issue which has been addressed by a number of authors. We summarise some of the broad themes of this work in the following paragraphs.

Key articles in the area of group identification of objectives are Keeney *et al* (1987) and Keeney (1988) which deal specifically with the construction of a hierarchy of objectives. Keeney *et al* (1987) address the problem of constructing a single hierarchy of objectives for a group of individuals. The differing objectives of group members are taken into account by developing a methodology for constructing a combined hierarchy of objectives from the hierarchies of objectives obtained from each individual. The context of their study is the development of a hierarchy of objectives to aid in the evaluation of long term energy policies in West Germany. The aim is that the hierarchy of objectives should depict the concerns of German society regarding choice of an energy system. To this end, various political and social organisations are consulted about their values, and individual hierarchies of objectives are constructed for each. The authors construct a combined hierarchy of objectives from these individual hierarchies as follows. The main objectives from the individual hierarchies are listed. The list is reduced by aggregating similar objectives and identifying subobjectives. Thereafter, subobjectives from the next level of each of the individual hierarchies are placed under the relevant major objectives. The number of such subobjectives is reduced in the same way as the number of main objectives are reduced. This process is repeated for all the levels of the hierarchies. Finally a check is made that all objectives have been included in the single hierarchy.

Keeney (1988) makes use of group discussions to identify objectives. In this way, different interests can be represented in the structuring of objectives. Each individual is asked to list his or her ownr objectives. The process of constructing the combined hierarchy of objectives Keeney *et al* (1987) is applied in the context of evaluating alternatives in the management of spent nuclear fuel. Three hierarchies were constructed from panels composed of 10-15 individuals. The panels represented the technical, government and public interest viewpoints.

When there is substantial conflict, such as for example the conflict between groups for the use of a limited resources, there may be major difficulties with the structuring of goals in a group setting. Literature concerning techniques that deal with conflict resolution are reviewed in Section A5.5.

A5.1.2. Measurement of Goal Achievement

There are two main issues concerning the area of goal measurement arising from the literature. The first is how to express attainment of any specific goal. Some goals are easy to measure in unambiguous and tangible terms, for example minimisation of operating costs. Goals expressed in economic terms generally fall into this category. Other goals, such as maintenance of environmental quality, are difficult to calibrate, and are best described as less tangible, or even intangible.

The second issue relates to the comparison of criteria or goals which are not directly commensurate. Goals may be expressed in different units (eg level of pollution and unemployment rate); but even goals expressed in apparently similar units may not be commensurate, for example the fixed and operating costs of an project. Linked to this is the topic of tradeoff values, which can be described as the rates of exchange between criteria.

The above two issues are not distinct in that our aim ultimately is to achieve some justifiable means of measuring both tangible and intangible goals in such a way that they are commensurate in some sense, so that levels of attainment of different goals can be related.

1. Intangible Goals

Lootsma *et al* (1986) use magnitude scaling to asssess intangible goals. This article is discussed in more detail in Section A5.4.

One important intangible aspect of goal assessment is that of incorporating risk and uncertainty into the analysis. Risk minimisation is frequently a somewhat intangible concept, even when referring to otherwise quite tangible measures. A closely related issue is that of imprecision in the DM's judgement on goal achievement or importance for an otherwise tangible goal.

Goicoechea *et al* (1979) in the context of land allocation in Arizona, address the issue of incorporating risk into the tradeoffs between the objectives, in a method known as PROTRADE. In this approach, the DM is required to express trade-offs not only between desired levels of each attribute, but also between these levels and probabilities of achieving them. These inputs are used to estimate an approximate utility function. The inputs required from the DM seem rather difficult to interpret, and the method does not appear to have found wide application.

Haimes (1984) reviews methodologies that incorporate risk and uncertainty in a MCDM framework. The sources of risk and uncertainties include those emanating from the data base, the models being used, and the real and perceived importance of the consequences of the alternatives.

2. Non-commensurate Goals

A common approach to the problem of objectives expressed in non-commensurate units is to express all the objectives in economic terms. This approach is applied in the fields of Resource Economics and Cost Benefit analysis, which attempt to assess the monetary values of intangibles. In areas such as water resource planning where some criteria at least are highly politically charged, this approach becomes most problematical. While it is possible to assess *a posteriori* what <u>effective</u> values have been placed by society on, for example, human life or maintenance of biodiversity on ecosystems, there is no basis for extrapolating these to new situations. Decision makers, furthermore, become very wary of being associated with explict monetary valuations in these situations (eg. Sugden *et al*, 1978).

One application of such an economic benefit approach is the case study from New Mexico discussed by Ward (1987), who demonstrates a method of associating economic values with each competing water use, even where these do not have direct economic benefits. In New Mexico, an economic value of water for various uses is important for determining the legal basis for allocating water. The author estimates the economic benefit of providing additional water to be used for recreation in the basin.

Multi-attribute utility theory (Keeney and Raiffa, 1976, or von Winterfeldt and Edwards, 1986) is an alternative approach which looks at acceptable trade-offs between different goals directly, rather than to follow the emotionally contentious route of using money terms. The result is a value, or "utility" measure, which is a commensurate medium of exchange between goals.

Flug and Montgomery (1988) discuss the comparison of competing water demands when objectives are expressed in different units or are otherwise noncommensurate. They model the effect of different river flows on the benefits derived from recreational use of the river, with application to a river in West Virginia, USA. Utility functions are constructed for each of three recreational uses chosen for the analysis. These are then combined additively to form a joint utility function, using two sets of weights. (Refer to Section A3.1 for a discussion of the conditions under which this assumption may be justifiable.) Decision scenarios are compared using these estimated utilities.

Mehrez and Sinuany-Stern (1983) also use an additive utility function to determine tradeoffs between the objectives in the evaluation of alternative water projects in Israel. A total utility for each combination of projects was estimated. Four attributes were used to evaluate the alternatives. They do not describe exactly how these utilities are arrived at or whether the assumption needed to apply the additive form consistently, applies.

A5.2 Operational to Medium Term Planning of Water Resources

Shamir (1983) reviews methodologies used in planning and managing water resources, and briefly discusses a number of case studies. These include the selection of a water resources plan for a region in Israel (STEM method); a water supply plan for an area in Holland (linear programming); real time operation of a river basin in Washington (linear programming); and water and land use management in Canada (linear programming).

Generating techniques are techniques that create a non-dominated set of solutions without requiring the DM to state preferences regarding the goals, often used in the context of linear programming. This can, of course, do no more than to produce a shortlist of efficient possibilities, from which a final judgemental choice has to be made. Generating techniques have been applied by many authors in the context of operational to medium term planning, some of which applications are reviewed in the following paragraphs.

Peralta and Killian (1987) address the problem of choosing a strategy for the management of groundwater. For the goals of minimising the annual cost of water supply and maximising the total annual volume of groundwater withdrawn, a set of non-dominated solutions is generated. An alternative is then chosen interactively from this solution set, using tradeoff functions (i.e. the amount of one attribute that must be sacrificed in order to attain a specified improvement in another).

Steuer and Wood (1986) apply multiple objective mixed integer programming to a prototype river basin water quality planning problem, in which water users along the river (agriculture, recreation and industry) specify water quality requirements. There are eight goals - six concerning water quality and two of cost minimisation. The paper emphasizes technical details of the algorithms rather than the particular application, however.

Sakawa (1986) applies fuzzy set theory in this context. Fuzzy set theory is a branch of mathematics that is concerned with treating imprecision in human logical reasoning (in this case the DM's specification of his goals), but it should be noted that there are criticisms of the axiomatic foundations of the theory, particularly as regards whether the measures used to model imprecision are empirically meaningful (cf. French 1984, 1989). Interactive computer graphics are used by Sakawa in generating and examining Pareto optimal solutions at each iteration. The method is applied to a storm drainage system problem, involving five goals, all expresed in economic terms. The fuzzy goal values are determined by a hypothetical DM. They demonstrate the feasibility of the method, but note that it should be revised in the light of real world problems.

In the context of determining operating rules for water resources management, Jamieson (1986) recommends the "satisficing" approach. In this approach, which is really a form of goal programming, goals are said to be satisfactorily attained if their levels of achievement are within acceptable boundaries. An example of the approach is described, which, at the time of writing, was being developed for the Thames basin in the United Kingdom.

A5.3 Long Term Planning of Water Resources

Cohon and Marks (1975) describe, classify and evaluate various MCDM techniques for water resource planning. Techniques are classified into generating techniques, techniques which rely on prior articulation of preferences, and techniques which rely on progressive articulation of preferences. Many other authors have subsequently referred to the classification scheme introduced in this paper. Three criteria for evaluating MCDM techniques are suggested - computational efficiency, explicitness of tradeoffs among the objectives and the amount of information generated for decision making. MCDM techniques are evaluated according to each of these criteria. According to these criteria, ELECTRE, goal programming and the prior articulation of utility functions were found to be inappropriate for large water resource planning problems. They criticise MAUT on the grounds that the decision makers have no knowledge of the influence of the utility functions on the final outcome. This criticism is however outdated, as more recent approaches (eg Belton and Vickers, 1990) apply MAUT in an interactive setting.

A criticism more frequently levelled at MAUT (Duckstein *et al*, 1982) is that it is too time consuming. It does require a lot of interaction with the DMs. However, in cases of public importance, MAUT provides a useful record as to how the decision was reached. When there are many conflicting groups, there is often a need to to show that justice is being done.

Duckstein and Opricovic (1980) examine the choice of water resources plans for the Central Tisza River Basin in Hungary. There are five planning alternatives, which are described in terms of 12 attributes. They apply compromise programming (Zeleny, 1973), in which a solution 'close' to the ideal (but infeasible) solution is found. The ranking of alternatives provided by this method are compared to those obtained on the same case study by David and Duckstein (1976) who apply ELECTRE, and Keeney and Wood (1976) who apply MAUT. The authors note that in the case study, the compromise solution provided insight into why there are differences in results obtained using ELECTRE and MAUT. This insight rests on how the 'closeness' to the ideal solution is defined.

Duckstein, Gershon and McAniff (1982) also compare ELECTRE, compromise programming and MAUT. The case considered is that of river basin planning in Santa Cruz, Arizona where diverse user groups (urban, agricultural, Indian and mining) compete for water. The basin is also characterised by rapid population growth. Five goals are identified, viz. increasing water supplies, flood protection, environmental, utilisation of resources and recreation. These goals are decomposed into 13 attributes. Twenty five planning alternatives are identified, including actions such as building dams and reclaiming wastewater. Alternatives for the basin are evaluated with respect to the attributes by water resources experts. Whereas Duckstein and Opricovic (1980) compare the techniques only with respect to the final choice of alternative, these authors also discuss and apply other characteristics of the techniques, for example the ease of computation. In general, the techniques give similar rankings and are found to be fairly robust. They claim that only ELECTRE can be used directly on qualitative data, as the other two methods require qualitative data to be quantified (but in fact this step of MAUT is nothing other than a means of scoring different qualitative outcomes, which it thus, by definition, handles quite comfortably). MAUT is criticised because it is time intensive - in terms of computation and interaction with the DM. They conclude that compromise programming is the most appropriate technique to apply to the problem at hand.

Gershon and Duckstein (1983) compare four approaches to river basin planning : ELECTRE, compromise programming, game theory and MAUT. They too consider the above case of the Santa Cruz river basin. The techniques yield similar results. Sensitivity analyses are performed and the methods found to be robust. Differences in results are thought to be linked to the way in which discordance is used.

The variant of ELECTRE applied in the above two papers is described by Gershon, Duckstein and McAniff (1982), using the same case study. They combine two approaches to ELECTRE, known as ELECTRE I and II. ELECTRE I is used to reduce the number of alternatives, and ELECTRE II is then applied to rank the remaining alternatives.

Datta and Peralta (1986) discuss procedures for evaluating alternative strategies for managing water for agricultural use in America. They deal with the case where there are only two objectives. These are to minimise the cost of water supply and to maximise the amount of water pumped from an aquifier. Both the objectives are readily quantifiable. Alternatives were generated using the ϵ-constraint method. The group of decision makers is presented with a set of Pareto optimal solutions, and select a single strategy from these. The Surrogate Worth Tradeoff (SWT) method, in which decision makers classify various available tradeoffs according to degree of desirability or acceptability, is applied interactively, using interactive computer graphics, in order to facilitate group decision making. The impact of a selected strategy on the decision variables, and the impact of changes in these on the objective function can be displayed. The application of SWT in a non-interactive setting is also described.

Interactive computer use in analysing alternatives is discussed by Kunreuther and Miller (1985), in the context of flood hazards. They believe that the role of the interactive model is to aid communication with the parties involved and conclude that such systems provide insights into the advantages and disadvantages of different alternatives and into potential conflicts. French *et al* (1980) claim that the use of interactive computer graphics is valuable as a communication tool, especially in the communication of results to non-technical users, and improves data management substantially. Fedra and Loucks (1985) also discuss the use of interactive computer technology in water resources and environmental planning.

The use of Geographic Information Systems (GIS) with MCDM in river basin management is discussed by Goulter and Forrest (1987). They argue that GIS is an important component of the decision support system, and discuss the advantages of using GIS, giving a short review of GIS applications in water resources planning. There does seem to be relatively little in the literature on the integration of MCDM concepts into GIS for planning, however.

Jamieson (1986) mentions mixed integer programming as one of the ways of identifying an alternatives when faced with a large choice of options in long term planning. This facilitates the 'yes or no' type decisions that are made, such as, whether or not to build a particular reservoir. The technique is used as a basis to choose a national water resources plan with a 30 year horizen for England and Wales in 1973, in which the goal is to minimise cost.

Haimes *et al* (1979) consider planning in the Maumee river basin in America, using the SWT method. The goal of improving the overall quality of life is broken down into the goals of enhancing national economic development and enhancing environmental quality. The basin is subdivided into five areas. Four planning alternatives are considered. Tradeoff values expressed in dollars are generated, using the ϵ-constraint method, for six attributes: BOD load, reduction in erosion, reduction in phosphorus, recreation, wildlife habitat and flood plain acquisition.

Walker (1986) addresses the case in which a choice is to be made from amongst a large number of alternative policies. Systematic screening strategies to exclude some of these alternatives from further analysis are described. These screening strategies are applied to a case study to choose a water management alternative in the Netherlands. The author concludes that the screening is simple and inexpensive, and reduces the time and cost required to evaluate a larger number of alternatives.

The "Policy Analysis of Water Management for the Netherlands" (PAWN) study (Goeller *et al*, 1983) was established by the Dutch Government, and contributed to the formulation of a new Dutch national policy on water management. Agriculture, industry, nature preserves and companies that supply drinking water all compete for groundwater. In dry years, users such as agriculture, power plants and shipping compete for surface water, and there is also competition between different regions. Water problems in the Netherlands are aggravated by its dense population, and the fact that the major source of water is the polluted Rhine River. As much of the country is below sea level, salinity is a major problem. The four types of water management problems in the Netherlands are shortage, salinity, quality (pollutants other than salt, and other environmental quality issues) and flood. Alternative scenarios are composed of a combination of technical (changes to water distribution infrastructure), managerial (rules by which infrastructure is operated), pricing (charges on water use) and regulation (administrative or legal restrictions on water use) strategies. The chief objective of PAWN was to suggest alternative scenarios that address the water problems, to assess the effects of these policies, and to present these effects in a form in which the DMs can choose between alternative scenarios. Alternatives were identified by evaluating many possible alternatives in terms of a few major attributes in the early stages. In the final stages, the best alternatives were evaluated in terms of the full set of criteria. The attributes by which alternatives were evaluated were agriculture, shipping, thermal pollution, water quality, national impacts and other environmental concerns. The effects of the alternatives were determined with the aid of mathematical models. Results were presented to the DMs by means of scorecards, on which the criteria for each alternative were presented. DMs could then weight these criteria in order to select an alternative.

PAWN did not recommend a particular alternative, but provided an assessment of the alternatives in terms of the criteria, without further decision support other than the scorecards. The PAWN study started in 1976, which was before the recent advances in MCDM techniques and interactive decision support. Its main focus was on identifying alternatives, and assessing the impact of these in terms of the criteria.

A5.4 MCDM in Other Resource Planning Problems.

Romero and Rehman (1987) provide a comprehensive review of the use of MCDM techniques in the planning and management of fisheries, agriculture, forestry and water resources. Generating techniques, goal programming, ELECTRE, utility theory, mixed integer programming and compromise programming are among the techniques mentioned.

Mendoza *et al* (1986) demonstrate the amenability of the type of decisions taken in agroforestry to analysis by MCDM techniques, and describe how agroforestry planning problems can be formulated as a MCDM problem. They also classify MCDM techniques in the context of agroforestry. Mendoza *et al* (1987) apply MCDM techniques to a hypothetical agroforestry system. Two objectives are taken into account, both of which are assumed to be easily measured. Seventy eight alternative strategies are considered. They describe the application of the various MCDM approaches to the hypothetical problem. They favour interactive methods on the basis of the DM's active involvement.

A key article in the area is that of Lootsma *et al* (1986) who consider a budget allocation problem in the context of energy research and development in the Netherlands. The Energy Research Council (which consists of representatives from diverse organisations) makes recommendations on budget allocation to the government. The article presents findings from a pilot study amongst nine of the Council members. The authors address the problem of goal measurement, particularly the impossibility of assessing the socio-economic benefits of the alternatives. They make use of scaling techniques to assess preference weights and socio-economic benefits. Scaling techniques originated in the social sciences, and are used to place quantitative measures on value judgements. A hierarchy of objectives for assessing the social impacts of energy research and development was constructed. Preference weights which should reflect the Council's view of their relative importance, are assigned to the criteria. The authors note that sensitivity of the solution to the weights and social impacts must be examined, especially when these are not agreed to by all members. They recommend an interactive system to show the effects of changes to the weights. They found that the decision model was useful for highlighting points of agreement and disagreement in order to reach a compromise and to ensure that important aspects of the problem are not overlooked.

Glover and Martinson (1987) apply a generating technique approach in the context of land use planning in which the broad objective is stated to be the maximisation of "net social benefit". This goal was not decomposed further. A Geographic Information System was used for the data base. The formulation of the problem is unusual in that it is essentially linear programming, but interactive because the weights and constraints can be modified on inspection of the solution.

Hallefjord *et al* (1986) use linear programming to aid planning decisions made by the Swedish Forest Service. They emphasize that the aim in applying MCDM to long term planning problems is to explore solutions and generate alternative strategies, for management to gain insight into the problem, rather than to "find the optimum".

Goal Programming is used by Sandiford (1986) in a fishery resource allocation context in Scotland. The problem is to reduce the catching capacity in the fishery. The goals are biological (the weights of fish species that is allowed to be taken), economic and distributional (which is measured by the number of jobs provided). Thus the goals are readily quantified. An adaptation of goal programming in which the weights in the objective function are not specified *a priori* is used. Ridgley (1984) also describes the application of goal programming in water and land-use planning.

The technique of *"Modelling to generate alternatives"* (MGA) produces alternative solutions which are very different from previously generated solutions but which are still "satisfactory" with respect to the objectives. The emphasis is on useful or practical, rather than optimal solutions. The philosophy of this approach is that in a complex problem, there are issues that cannot be adequately modelled because they are qualitative in nature, unknown, or unrevealed by the DM (Brill, 1982). It is therefore important to examine other solutions, including dominated ones. Arguments in favour of MGA contend that individuals may want to consider a solution which is technically dominated with respect to the modelled objectives, but which may have other (unmodelled) benefits.

Mendoza (1988) uses Hop, Skip and Jump (HSJ), also an MGA technique, to generate management strategies for timber and wildlife management. HSJ (Brill *et al*, 1982) uses formal optimisation methods to generate alternative solutions. Management are considered to have only three goals - timber volume harvested, the number of species in the area and the number of porcupines (an ecological objective). It is taken for granted that the effect of alternative strategies on the goals is easily measured.

Campbell and Mendoza (1988) discuss two MGA techniques which can be applied to forest planning; HSJ (described above) and the efficient random generation technique (ERG) (Chang *et al*, 1982). They consider a problem with five objectives. ERG differs from HSJ in that it maximises randomly generated objective functions in order to generate different solutions. The authors conclude that the two approaches give similar results.

MCDM approaches are applied to the management of fisheries by Stewart and Brent (1988), who develop a decision support system to aid decisions in setting annual fishing quotas. Five broad goals are identified, which are decomposed into 13 attributes. The intention is that various interactive MCDM methods can be used to select alternatives. Stewart (1988) describes the use of STEM, ISGP and IMGP in this fisheries problem, and finds IMGP to be on balance the most reliable and useful in facilitating consensus between different interest groups. Sandiford (1986) (described above) also deals with MCDM in a fisheries context.

A5.5 Group Decision Support and Models for Conflict Resolution

Keeney *et al* (1990) deal with the use of MAUT in group processes. The context of the problem is evaluation of alternative long term energy policies in West Germany, for which four alternative scenarios were postulated. Use was made of public value forums, which are meetings of members of the public, or interest groups, involving between five and 25 participants each. The authors describe a public value forum (involving members of the public) held to assess the feasibility of applying MAUT with utilities provided by laypeople, and reconciling and combining these utilities with those obtained from experts. A hierarchy of objectives was constructed prior to the forum, as described by Keeney *et al* (1987), and is discussed in Section A5.1(a). The scenarios were evaluated by each participant using MAUT, and by intuitive evaluation. Participants attempted to reconcile any differences between the two evaluations, which resulted in most participants changing their initial rank ordering of the alternatives. The authors concluded that such a forum is a feasible and useful procedure for involving the community in the evaluation of alternative scenarios.

A possible disadvantage of the application of utility functions in practical situations is that the construction of utility functions is generally found to be time intensive. In response to this disadvantage, and in the context of selection of a project to provide fresh water to a city in the USA, Anandalingam and Olsson (1989) propose a methodology to simplify the process of obtaining utility functions by reducing the number of alternatives under consideration This is accomplished by means of screening strategies, which eliminate alternatives that are dominated, technically infeasible or have unacceptable risks.

The bulk of the literature on conflict resolution deals with two-way conflict, for example, Raiffa (1982). In this book, the process of negotiation is seen from a quantitative (decision and game theory) view point, but with much practical experience of real conflict resolution. However this is mainly two way conflict resolution, for example labour-union conflict. Amongst the issues of a multi party nature, there is a short chapter (chapter 21) on environmental conflict resolution which deals largely with payments that may be made between parties in order to achieve concensus. Although this may well be of some interest, it is not the direct thrust of the our current research.

French (undated technical report) describes how multi-attribute value theory can be applied in a group setting by means of what he terms "decision conferencing". Decision Makers meet together for a substantial period (typically two days), under the guidance of a facilitator and a decision analyst. The facilitator and the decision analyst are skilled in the processs of group discussion and of value theory repectively, but "seldom ... have any expertise in the context of the issues at hand". Their role is to assist the DMs in structuring the decisions facing the group, but the structure and value judgements come from the group. Considerable use is made of interactive computer software for developing hierarchies of objectives, for assessing weights and utilities, and for examining the sensitivity of outputs from the process to the subjective inputs provided.

A general framework for group decision support systems, with particular reference to the use of MCDM methods, is provided by Bui (1987) in the system called *Co-oP*. He clearly identifies three important phases in the group decision making process as follows (Bui, p42): (i) generalized and unified decision support for individual decision making, (ii) communication support, and (iii) negotiation support for assisting the individual in negotiating with other decision makers of the group. This book and the associated software emphasise the role of modern computational technology in facilitating all three of the above phases. Each individual interfaces with a personal decision support system which facilitates the process of formulating his/her own preference rankings on a set of decision alternatives (by a procedure based mainly on ELECTRE and AHP, but with the alternative of using multiattribute value theory in place of AHP). Thereafter, the value judgments can be communicated between the individuals and/or to a facilitator. A heuristic process termed the *Negotiable Alternative Identifier* is used to identify a shortlist of alternatives which have a high level of desirability for all participants. Although of interest in the structure it provides for the design of group decision support systems using a high level of technology, Co-oP does seem to be aimed primarily at cases in which group members have a substantial degree of conformity of purpose (eg. the management team of a company in the process of making a senior appointment), and may thus be of lesser relevance to resource management problems with high levels of conflict and antagonism.

Phillips (1988) discusses features that a group decision support system should incorporate. Among these are that it is able to help structure the thinking of the group, that it is able to deal with group dynamics, that its method of operation is understandable to participants and that it is flexible. A case study (in a marketing context) that makes use of decision conferencing is described. A hierarchy of objectives is constructed by the group with the aid of the facilitator.

Vetschera (1990) surveys recent developments in group DSSs for individual and group use. Typically, group decision making involves both individual and group stages. The obtaining of a group opinion is classified in two ways, either the whole group participates in forming a new opinion, or individual opinions, which were previously obtained, are aggregated. Aggregation techniques are often based on MCDM methodology, which can also be used to determine compromises between group members. DSS techniques are classified according to the type of support provided at the individual and group stage. He expresses the view that there are no systems that provide interactive guidance (i.e. providing a structure for the decision process without determining the outcome) at the individual stage and for facilitation at the group stage (although this is precisely what Bui, 1987, claims for his Co-oP system).

Kersten (1988) looks at an interactive procedure for use in group decision making problems. He notes that the traditional utility based approach to decision making may not be of much use as the utility functions are not stationary, necessitating a decision procedure in which these, as well as goals and preferences can be changed. He discusses the case where scenarios (or proposals, in the case of negotiation), are formulated by individual DMs, and the aim of the group process is to obtain consensus on pre-defined alternatives.

Kersten and Mallory (1990) discuss the formulation of decision making problems where a rule-based system is used to represent the DM's understanding of the problem.

Khorramshahgol *et al* (1984) propose that the Delphi method be used to structure objectives prior to goal programming. The Delphi method is a procedure to obtain consensus from a group that makes use of written responses. The Delphi consists of a series of questionnaires, the first of which invites participants to respond to a broad issue, usually in the form of open ended questions. Subsequent questionnaires are structured around responses to the previous questionnaire. In the final questionnaire, participants assign priorities to issues of importance, by voting. By the use of questionnaires, anonymity is retained, thus encouraging expression of ideas. It also avoids the problem experienced in face-to-face meetings in which a few influential members can dominate the process. A fuller description of Delphi is given by Delbecq *et al* (1975). Khorramshahgol and Steiner (1988) apply the proposal of

Khorramshahgol *et al* (1984) in the context of allocating funds to competing projects. Specifically, the problem relates to selection between rural roads projects in the U.S. The group participating in the Delphi consisted of 12 road engineers considered to have knowledge of the problem. Khorramshahgol *et al* find that by taking into account the opinions of several experts in this way, the outcome becomes widely acceptable, and less subjective than if only one expert is involved. Disadvantages of the method were found to be the large amount of time taken by the Delphi method, and the assumption that the DMs could specify the desired levels of each goal exactly.

Deason and White (1984) perform a systematic comparison of different types of group processes applicable to the specification of the hierarchy of objectives. Types of procedures of relevance to the problem in the context of funding water resources development projects on Indian reservations in the U.S. that have appeared in the literature are identified. They use the nominal group technique (cf Delbecq *et al*, 1975) to generate the set of objectives. The group consisted of 22 water resource experts from the Bureau of Indian Affairs of the U.S. Department of the Interior. A list of 34 objectives was generated. By voting, the participants ordered the objectives in terms of their perceived importance, so structuring these objectives into a hierarchy.

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APPENDIX B

ILLUSTRATIONS OF THE USE OF MULTIPLE CRITERIA DECISION MAKING METHODS IN WATER RESOURCES PLANNING

B1. INTRODUCTION

This Appendix illustrates the use of the different methods of **multiple criteria decision making (MCDM)** suggested in the literature, as reviewed in Appendix A, and some variations of these which have emerged as part of the current research, in the context of simplified and hypothetical water planning problems. It is hoped that this will serve not only to clarify the methods themselves, but also to motivate the need for the proposed variations (as described in Section 4 of the main report). The hypothetical nature of the examples must be stressed at the outset. We have, in order to focus discussion, hypothesized possible value judgments that might have been expressed by different groups such as "forestry" or the "Kruger National Park", but ***these do not in any way reflect actual value judgments of these groups***, and are to serve for illustration only.

To simplify discussion, we will concentrate on the problem of selecting a single alternative from a list of potential regional development plans, but will also briefly examine the problem of allocating water between competing uses. It is useful to look first at the processes which precede such a selection. The first step is to generate the list of alternative policies or plans. Typically, this process requires the identification of all major dimensions, or components, of policy. In an area such as the Sabie-Sand River system, these policy components may include reduction or increase in afforestation, location and sizing of dams, restrictions on irrigation for agriculture, and the extent to which rural communities are provided with standpipes for water. Feasible ranges of policy for each of these components need to be assessed, after which many policy scenarios can be created consisting of specific choices for each component. For purposes of illustration, we shall consider a simplified situation for a region such as the Sabie, in which only the following policy components are relevant:

(a) Change in afforestation, relative to *status quo*, permitted or enforced, with a feasible range of options from -3% (i.e. a 3% reduction) to +5%;

(b) Percentage reduction in current levels of irrigation for agriculture in the area, with permissible values between 20% and 50% of current use;

(c) The sizing of the dam to be constructed at a pre-determined site, expressed as a percentage of the optimal size from engineering/economic considerations, which may range between 60% and 100%;

(d) Percentage of the rural population to be provided with standpipes within 100m of their dwellings, with values ranging between 30% and 60%.

Many (although probably not all) possible combinations of feasible values for these four components can be considered as feasible alternative policy scenarios. Again for purposes of illustration, let us suppose that preliminary feasibility studies have generated the 20 policy scenarios defined in the Table B1 (see end of this Appendix), where columns 2-5 of the Table specify the choices for each component corresponding to each scenario.

A second step required prior to the selection process, is to identify the criteria according to which the selection is to be made. This is often done hierarchically, starting with a general statement of overall goal (such as maximizing the well-being of all peoples in the region), and decomposing this into more specific goals (relating to environmental, economic and health goals, for example), or even sub-goals (eg. dividing health goals into even more specific issues such as infant mortality, incidence of TB, etc.). Once these criteria are established, the standard MCDM procedure is to identify those *attributes* of the scenario which best indicate degree of achievement of each goal or sub-goal. The identification of criteria, and of associated attributes requires considerable analysis and consultation with all interested parties (by means of workshops, interviews, questionnaires, etc.). For the purposes of the next Section (which is to illustrate the conventional methods of multicriteria analysis) let us assume that the major criteria are (i) investment costs (in dams and other infrastructure), (ii) economic benefits from forestry and the formal agricultural sector, (iii) provision of clean and convenient water to rural communities, and (iv) environmental conservation; and that the following attributes, together with the policy components (a)-(d) above are sufficient to assess the degree of satisfaction of the related goals:

(1) Total investment costs in millions of Rand;

(2) Percentage change (from status quo conditions) in total annual flow;

(3) Percentage change (from status quo conditions) in the minimum flow during the year;

(4) Percentage change (from status quo conditions) in the peak flow during the year.

Illustrative values for these attributes are given for the 20 scenarios in the Table B1, in columns 6-9.

The data in Table B1 will be used to illustrate the various MCDM approaches, and their strengths and weaknesses, in Sections B2 and B3. In Section B4, we will briefly discuss the application of MCDM methods in the context of a different category of problem, namely that of the allocation of scarce water resources to competing users.

B2. CONVENTIONAL MCDM APPROACHES

B2.1 The Conventional Multiple Objective Representation

The conventional approach often adopted in the literature for problems such as the policy selection problem discussed in the Introduction, starts with the assumption that the criteria can be reduced to specific *objectives* expressed in terms of the attributes. Each objective is further assumed to be defined in either a strictly maximizing or a strictly minimizing sense. For "maximizing" objectives it is assumed that "all other things being equal" more will always be preferred to less (i.e. in the hypothetical case in which increases in this objective can be achieved without affecting any other objective), and the reverse for minimizing objectives. This defines a *multiple objective optimization* problem. In the illustrative example of Table B1, the objectives may be something like the following:

Maximize the change in forestry (in the positive direction) [the economic benefit from forestry criterion];

Minimize the cut in irrigation;

Maximize the proportion of the rural population served by standpipes;

Minimize investment costs;

Maximize annual flow (i.e. maximize change from status quo, in the positive direction);

Maximize minimum flow levels (i.e. maximize change from status quo, in the positive direction).

In the case of peak flows, the objective might be quite complicated, as very high peak flows imply disastrous floods, but some ecological process require that the peak flows not be too low. This demonstrates an important problem which can arise in implementing conventional MCDM procedures in this context, but for the purposes of Section 2 we will illustrate the conventional methods in the context of the six objectives stated above.

B2.2 Goal Programming and Related Techniques

Goal Programming requires that certain desired performance levels (goals) be specified by the decision maker for each objective. An example of a set of goals may be the following:

Change in forestry $\geq$ 0%
Cut in irrigation $\leq$ 35%
Proportion rural population served by standpipes $\geq$ 30%
Investment cost $\leq$ R600m
Change in annual flow $\geq$ -10% (i.e. not more than a 10% drop in total annual flow)
Change in low flow $\geq$ +10%

It is easy to verify that there is only one policy scenario in Table B1 which satisfies all of these goals, viz. scenario number 9. This, in a sense, then completely "solves" the decision problem. In general, however, there may either be many alternatives satisfying a set of goals, or (perhaps more commonly) none. In such cases, the approach of goal programming is to seek an alternative which "best" satisfies the goals in some or other sense. One of the problems of applying goal programming is that different decision makers may approach the specification of goals in different ways. For some, a goal may mean a point towards which to strive, but which is expected to be unattainable (and there is thus no expectation of finding an alternative satisfying all goals). For others, a goal is an absolute, non-negotiable bottom line; a policy scenario not meeting all goals is simply unacceptable, and the expectation is to do much better. A third group may look on goals as a realistic expectation of what can be achieved (or nearly so, if not precisely). The difficulty is that the concept of "best satisfying" a goal needs to be interpreted differently in each of these three cases - a point not always clearly made in the literature.

As an example of the case in which goals are somewhat unattainable (the case which is in effect assumed in standard goal programming), let us suppose that the goals above were changed to the following:

Change in forestry $\geq$ 2%
Cut in irrigation $\leq$ 30%
Proportion rural population served by standpipes $\geq$ 50%
Investment cost $\leq$ R575m
Change in annual flow $\geq$ 0
Change in low flow $\geq$ +25%

Now there is no solution satisfying all goals. The standard approach is to define a measure of underachievement on each goal for each alternative, which is zero if the goal is satisfied, and is the difference between the actual and goal levels otherwise. Thus for policy scenario no. 1, the underachievements are: 5% on forestry; 0 on irrigation cuts; 20% on rural population served; and 0 on the remaining criteria. These underachievements need to be scaled so as to be commensurate in some way; the easiest way to do this is to fix some degree of underachievement on one criterion, and then to specify sizes of underachievements on the other criteria which are judged to be of equal importance (a value judgement, of course). Suppose that these degrees of underachievement which are of equal importance were determined as follows: 2% for forestry; 15% for irrigation cuts; 10% for rural population served; R80m on cost; 30% on annual flow and 25% on low flows. The scaled underachievements for scenario no.1 are then: 2.5 (=5%/2%) for forestry, 2 (=20%/10%) for rural population served, and zero for all others. This calculation is repeated for all scenarios. The scenario then selected is that which has the smallest value for either the sum of scaled underachievements, e.g. 4.5 for scenario 1, or the maximum scaled underachievement, taken across all criteria, e.g. 2.5 for scenario 1. These two approaches are called respectively "Archimedean" and "Tchebycheff" Goal Programming. In this case, scenario no. 10 comes out best on both scores, with scaled underachievements of 1, 0.333, 0, 0.625, 0.033 and 0 for a sum of 1.992 and a maximum of 1.

B2.3 Multi-Attribute Value Function Techniques

A more direct approach is to attempt to find a simple scoring function, so that we can associate with each scenario an overall value score. A common, but potentially dangerous or misleading, approach is simply to add up the values achieved on each criterion (counting the minimizing criteria in a negative direction), weighted in some or other way. The first problem is the difference in scales between different criteria, although this is easily overcome by standardizing values on each criterion to some consistent scale (eg. 0-100), or by dividing through by differences on those criteria which have equal importance, as done for the goal programming underachievements above. The major practical problems, however, are (a) that often the concept of importance weight is not unambiguously defined or understood by different participants; and (b) that rather extreme solutions tend to be generated (i.e. very good on some criteria but very poor on others). The second problem arises because the weighted sum cannot allow for changing (usually decreasing) marginal returns on increases in any criterion (i.e. the more that is achieved on a particular criterion, the less the value of any further increases). As an example of this problem, let us suppose that the values for each criterion in Table B1 were divided through by the same differences of equal importance as used for the goal programming above, to give comparably scaled values. The scenario which comes out with the highest sum of scaled values is scenario no. 1, which is best amongst the 20 on cuts in irrigation, cost and annual flow change (and nearly best on the change in low flow), while being worst of all for forestry and for rural population served. This occurs in spite of the fact that forestry has in effect a very high weighting, since the range of scaled values from best to worst (i.e. -3%/2%=-1.5 to 5%/2%=+2.5) is wider than for all except the low flow criterion (which has a slightly wider range from -1.2 to +3.2). Thus scenario 1 hardly seems to qualify as a good compromise solution.

It is nevertheless possible to retain the simplicity of an additive scoring approach, while overcoming the problems mentioned above, by formal use of a *multi-attribute value function* (sometimes termed a *utility function*). This requires two steps, i.e. the assessment of a *marginal value function* (as described below) for each criterion taken in turn, and then the assessment of importance weights.

The assessment of the marginal value function is best described by means of example, but does require the use of some mathematical notation. Let us consider the change in forestry criterion, which we shall represent by the symbol z_F. The marginal value function is a function of z_F, which we shall represent as $v_F(z_F)$. Recalling that our assumed objective for forestry is in the "maximizing" sense, we note that the best and worst outcomes are +5% and -3% respectively. We start by standardizing $v_F(z_F)$ so that $v_F(-3)=0$ and $v_F(5)=1$ (say). At this stage we need to bring in the value judgments of the relevant decision maker(s). We are looking for a particular value for z_F, a "*mid-value*" point, such that the value perceived to be gained in moving from -3% to z_F ("all other things being equal") is just equivalent to moving from z_F to +5%. The way in which we would assess this would be by means of a sequence of questions which might proceed something like the following:

Question	Answer
Which would be of more value or importance: to avoid a decrease in forestry to 3% below the status quo level, or to gain an increase in forestry to +5%?	To avoid the decrease. [*NOTE that this implies that the mid-value z_F level is less than 0.*]
Suppose that the a decision had been made to reduce forestry by 1½%: which would now be of more value: to avoid a further decrease to 3%, or to improve from the 1½% cut to a 5% increase?	The increase from -1½% to +5% is of greater value.
Suppose that a decision had been made to reduce forestry by ¾%: which would now be of more value: to avoid a further decrease to 3%, or to improve from the ¾% cut to a 5% increase?	These would be of about equal value.

Perhaps a few more iterations than the above might be necessary in practice, but in principle the search for the mid-value can be answered in this way, and for this value z_F we have that $v_F(-0.75)=0.5$. Now we can repeat the process (a) between -3% and -0.75%, to obtain a point with value 0.25; and (b) between -0.75% and +5%, to obtain a point with value 0.75. One could in fact go on indefinitely, but this is often sufficient. A smooth curve can be drawn in to interpolate values of $v_F(z_F)$ for other z_F. A useful functional form for smoothing in such curves is often of the following form:

$$v_F(z_F)=a-be^{-z_F/R_F}$$

for some suitable value for the parameter R_F (sometimes called the "risk tolerance", as it is related to the amounts that a "rational gambler" would be prepared to wager, if his values were in fact represented by such a function). The parameters a and b are arbitrary in theory, but are conventionally chosen to ensure that $v_F(z_F^{min})=0$ and $v_F(z_F^{max})=1$, where z_F^{min} and z_F^{max} are respectively the worst and best values for z_F. In our example, $z_F^{min}=-3$ and $z_F^{max}=5$, and a value of $R_F=3.955$ gives $v_F(-0.75)=0.5$ when $a=1.152$ and $b=0.540$ (which is required to ensure the standardization to the 0-1 interval).

It is then necessary to assess importance weights for each criterion. In this case, these weights should represent the relative importances of the "swing" from best to worst on each criterion. Thus in assessing for example, the relative weights for the change in forestry and cuts in irrigation, we would need to ask what the relative impact or importance is of a swing from a 3% cut to a 5% increase in forestry, relative to the swing from a 20% to a 50% cut in irrigation. The usual procedure is to identify the criterion having greatest (or least) impact, and to associate a nominal *weight* of say 100 (or 1). The weights of all other criteria are then assessed relative to this most (or least) important criterion. Thus for example the swing on low flows (from -30% to +80%) might be deemed to have the greatest impact, and given a weight of 100. The -3% to +5% swing in forestry might then be assessed as having about 90% of the importance of the swing on low flows and would thus be given a weight of 90.

Although the calculations are tedious to report here in full, we have applied the above approach, using parameter values (for the exponential value function) and importance weights as follows for each of the criteria:

Criterion	Risk Tolerance Parameter (R)	Importance Weight
Change in forestry	3.955	90
Cut in irrigation	15	45
Rural population served	10	70
Cost	175	70
Change in annual flows	35	60
Change in low flows	30	100

Using the above figures, if we calculate the weighted sum of the marginal value functions for each scenario, it turns out that no. 10 comes out with the highest total value (or "utility"), closely followed by scenarios 12, 8 and 11. We have seen earlier that scenario 10 is a very balanced alternative.

The utility function approach can be quite time-consuming to apply, but a point often made in its favour is that the discipline of going through the exercise of assessing the value functions and the weights creates considerable insight. This insight can be far more important than the mechanical ordering of the alternatives by the value function. This approach is closely related to that which we shall be discussing under the heading of "direct value assessment" in Section B3. There is also a close link with AHP (the "Analytic Hierarchy Process"), perhaps better known through the "Expert Choice" software; as indicated in Appendix A, however, our conclusion is that AHP can yield quite misleading results in inexpert hands, partly because of its severely "black-box" nature, and partly as a result of certain theoretical shortcomings (cf. Appendix A).

B2.4 The Outranking Approach

This approach, rather favoured in Europe, is best suited for comparing a relatively small number of policy scenarios (say not more than about 10). For illustration here, let us consider only the five scenarios marked by the letters A-E in Table B1. The outranking approach consists of two steps: a voting step and a veto step. Each criterion is given a weighted number of votes. For illustration, we shall use the same weights as in the utility function approach above (although, strictly speaking, the weights have rather different meanings in the two contexts). For each pair of scenarios, we calculate the proportion of the votes which favour each. Thus in comparing scenarios A and B, we note that A is better than B on the criteria of cut in irrigation (weight=45), cost (weight=70), change in annual flow (weight=60) and in low flow (weight=100), giving a total weight favouring A over B of 275; B is thus better than A on the remaining criteria having a total weight of 160. The total weight of votes is 435, giving proportions favouring A and B respectively of 275/435=0.632 and 160/435=0.368. These proportions are referred to as the *concordances* of A and B with respect to each other. A complete matrix of concordances can then be set up as follows:

SCENARIO	A	B	C	D	E
A	-	.632	.517	.580	.632
B	.368	-	.385	.529	.580
C	.483	.615	-	.529	.580
D	.420	.471	.471	-	.506
E	.368	.420	.420	.494	-

The concordances give a weight of preference in favour of one scenario over another. It may nevertheless happen that although one scenario is better than others on most criteria, its performance on the remaining criteria may be so bad that it still cannot be said to be preferred. In order to monitor this situation, a second matrix is created, the *discordance* matrix, in which each scenario is compared against every other scenario in terms of the largest adverse difference taken across all (scaled to make them comparable). Consider for example scenario A compared against scenario B. The only adverse criteria for scenario A are change in forestry (for a difference of 3%) and rural population served (a difference of 10%). If these are scaled (for purposes of illustration) by the differences of equal value used in the goal programming solution, then the scaled differences are 3/2=1.5 and 10/10=1; the "discordance" for A against B is thus 1.5. On the other hand, the discordance for B as compared against A will be the largest scaled difference on the other four criteria, i.e. the maximum of {30/15=2; 50/80=0.625; 30/30=1; and 15/25=0.6} which is 2. The following table sets up all the discordances (using the equal-value differences from the goal programming example).

SCENARIO	A	B	C	D	E
A	-	1.5	2	4	4
B	2	-	1	2.5	2.5
C	2.5	1.875	-	2.5	2.5
D	3.2	2.6	3.2	-	2
E	3.125	2.5	2	2.5	-

The interpretation of these matrices is that one alternative "*outranks*" another if its concordance with respect to the other is sufficiently high (i.e. $\geq c^*$ say) and the discordance is sufficiently small (i.e. $\leq d^*$ say). In effect, A outranks B if the evidence is not inconsistent with the assertion that A is as good as, or better than, B. If the thresholds c^* and d^* are too severe then we will have no scenarios outranking any other, while if they are relaxed too far all scenarios will outrank each other. A simple procedure, therefore, is to start with the most extreme values (i.e. c^* as the largest entry in the concordance matrix, which is 0.632 in our example, and d^* as the smallest entry in the discordance matrix, which is 1 in our example), and to relax these systematically. In our example, for $c^*=0.615$ (the second largest value) and $d^*=1.875$ (the third smallest value) we have that A and C outrank B. We need to move down two more levels on the concordances to $c^*=0.529$, and two more levels on discordances to $d^*=2.5$ to obtain in addition that B and C both outrank D and E. This is probably as far as we need to go, as this gives us a great deal of insight into the problem, in particular that the attention of decision makers needs to be focussed on to the choice between A and C. The results of the outranking analysis can also usefully be displayed in graphical form, as shown in Figure B1.

The outranking approach does not claim to offer an absolute procedure for rank-ordering decision alternatives. But it can help in pruning out less desirable options, and in understanding the relationships between alternatives.

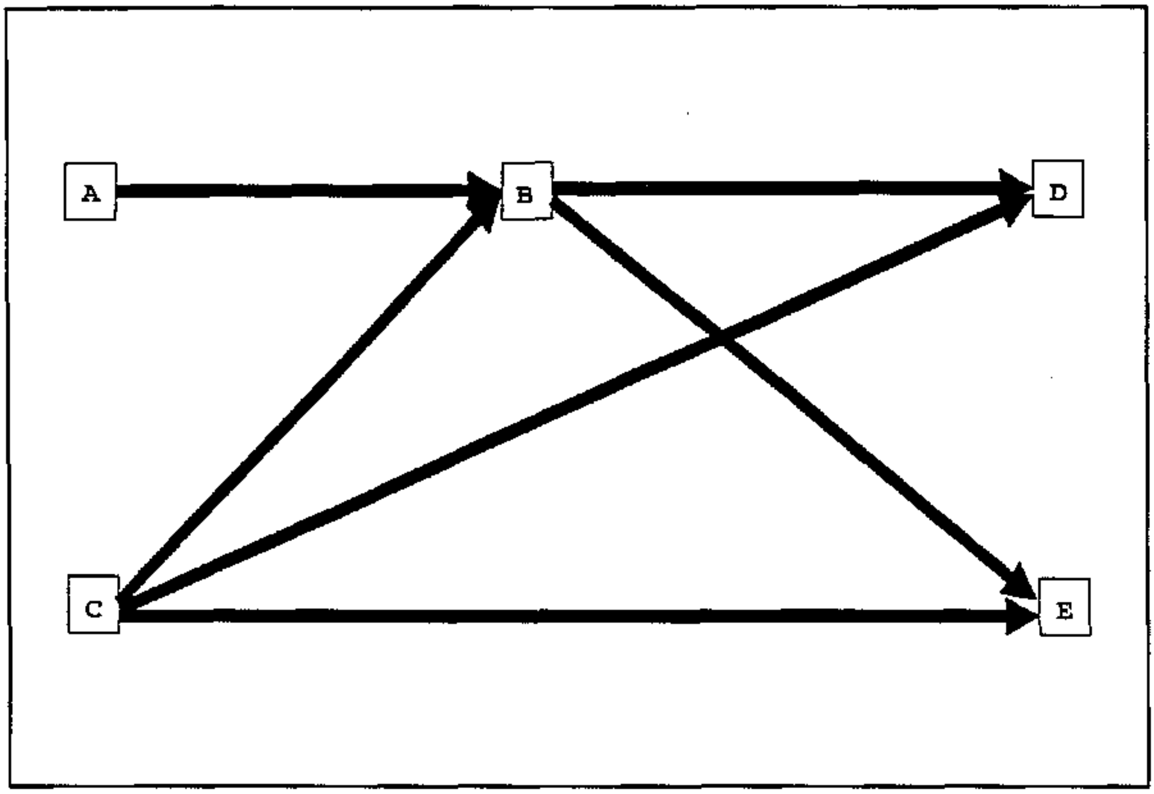


Figure B1: "Outranking" relations between scenarios

B3. DIRECT VALUE ASSESSMENT BY INTEREST GROUPS

B3.1 Reasons for Using Direct Value Assessment

The methods described in Section B2 work well, and give useful insights, *provided that* it is possible to represent all interests in terms of unambiguous directions of preference for a number of attributes (which are themselves in principle predictable, by models and/or by expert judgment, for any policy scenario under consideration). In practice, less tangible interests may not easily be expressed in such terms, and in any case different interests may have diametrically opposing needs for the same attribute. (For example, a certain frequency of flooding may be highly desirable from an environmental point of view, but equally undesirable for agriculture.) It may then become impossible to use the conventional MCDM methods in the manner described previously. Many of the principles do nevertheless apply. Instead of a hierarchy of objectives based on system attributes, however, we need to develop a hierarachy of more general *criteria* or *interests*. In order to apply the principles, it is necessary to have a method of valuing each scenario according to each criterion/interest (direct, indirect or intangible) in a comparable manner. Once this is done, the methods of Section B2.3 in particular (but also Sections B2.2 and B2.4) are directly applicable once more. It is the process of assessing such values which is the topic of the following Sections.

B3.2 Evaluation by Individual Interest Groups

Let us start by considering a single interest group, such as forestry or rural communities. What defines a "single interest" is somewhat judgmental, but it should in most cases be possible to reach some reasonable consensus as to what constitutes a more-or-less homogeneous interest group. Each such interest group defines a criterion by which scenarios need to be evaluated. Members of this group, by discussion of the scenarios, described in terms of as many attributes as can reasonably be predicted, are first asked simply to rank order policy scenarios according to their global preferences. This task becomes increasingly difficult as the number of policy scenarios increases, and it is generally accepted that not more than about 7 ("plus or minus 2") alternative scenarios can be assessed at a time in this way. On the other hand it is also necessary not to have too few scenarios, as it is then difficult to ensure that the set of alternatives under consideration is sufficiently rich to provide a reasonable range of choices for all interests. In practice, therefore, we would aim for about 6-8 well-selected scenarios to be rank-ordered by each interest group. For purposes of illustration here, however, we will suppose that only the five scenarios labelled by the letters A-E in Table B1 are to be assessed. In practice, also, the scenarios will have to be described in much greater detail than that illustrated in Table B1, and it is likely that the use of GIS for this purpose will become increasingly important as interest groups with little or no technical background are drawn into assessments of this nature.

As an illustration of the rank ordering, suppose that the forestry industry interests are primarily concerned with the permitted percentage change in forestry; this implies that A will rank last, D and E more-or-less equally best, with B and C also more-or-less equal and somewhere in the middle. This does not necessarily imply that B and C, or D and E, are totally equivalent. For example, the feeling may be that a larger dam may lead to less future pressure on the forestry industry, and the overall ranking from best to worst might then be E-D-C-B-A.

While it may be relatively easy for the forestry interest group to achieve consensus on such a rank ordering, this may not be true for other interests. To continue the example, suppose that the Kruger National Park found that rank-ordering from their perspective was not at all self-evident or uncontroversial. This inevitably suggests the existence of sub-criteria (or sub-interests). These need to be identified explicitly in the group session. For example, it may be found that the impacts of the scenarios on the Kruger National Park are substantially different from the points of view of tourism, protection of certain large mammalian species, and protection of riverine ecosytems. Once these sub-interests are identified, the rank ordering of scenarios is carried out for each of these separately. Of course, it may turn out that one or more of these sub-criteria need to be decomposed further into sub-sub criteria, etc., before unambiguous rank orders can be specified.

Now suppose that for some criterion (or sub- or sub-sub-criterion) we have reached the position where an agreed and unambiguous rank order exists. The next step is to position these along a so-called "thermometer" scale, i.e. placing the lowest ranking option at the 0 point and the best option at the 100 point. The other alternative scenarios are then placed along this axis in such a way that the intervals between scenario positions, or "scores", represent the relative gains which are perceived to be obtainable from moving from one scenario to the next best one. This is illustrated in Figure B2 which is a hypothetical representation of how the forestry interests might have rated the five scenarios (in the order previously given). In this figure we note how scenarios D and E are viewed as very similar in value, and similarly for B and C. We see also that according to the scale shown, the gain in avoiding any reduction in forestry (an interval of 60 on the scale, from scenario A to scenario B) is of a much greater magnitude than gains through increases in forestry. Note that this evaluation may contain strong elements of subjective judgment, which may incorporate many indirect or intangible issues aside from the purely economic.

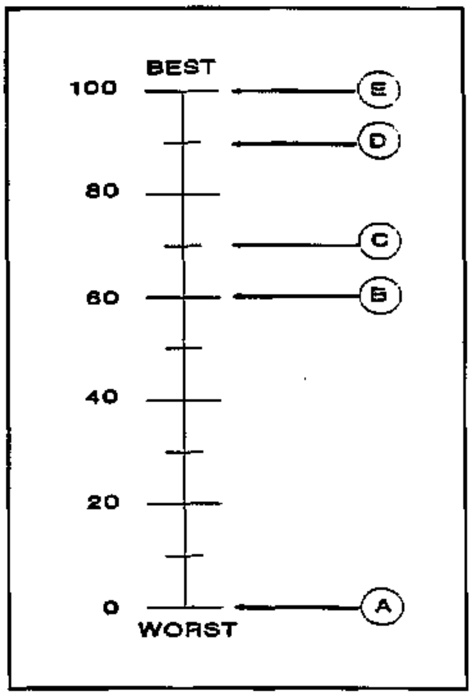


Figure B2: Hypothetical evaluation of a set of preferences on a thermometer scale

Where interests (such as those of the Kruger National Park) need to be sub-divided into a number of sub-criteria, there would be a scale of scores as in Figure B2 for each of these (i.e. for tourism, for mammalian species conservation and for riverine ecosystem conservation in the case of the Kruger National Park). These have to be combined to give an overall score. When individual scoring is carried out on the thermometer scale, there are good theoretical grounds for combining the scores by means of a weighted average, where the weights represent the relative importances to each of the interests, of a swing from the best to the worst *in the range of options given*. The Table below illustrates how sets of "thermometer-scale" scores for the three sub-criteria hypothesized for the Kruger National Park, are synthesized into single rank order. For example, for scenario B, the weighted average is 0.4x80+0.23x100+0.37x70=81 (to the nearest integer). The final column simply re-scales the weighted average scores in the preceeding column to the full 0-100 scale once more. The weights used above are not, it must be emphasized, some abstract generalization (such as: "preservation of ecosystems is more important than tourism"), but rather an expression of a belief that in terms of the range of opportunities represented by scenarios A-E, the impact on (say) tourism is greater than the impact on riverine ecosystems (or *vice versa*).

Scenario	Scores (and weights) for each criterion			Weighted average score	Re-standardised score
	Tourism (0.40)	Mammals (0.23)	Rivers (0.37)		
A	50	100	100	80	88
B	80	100	70	81	89
C	100	90	70	87	100
D	0	0	85	31	0
E	60	40	0	33	4

Even with the quite precise definition of the meaning of weights in this context, their assessment remains fairly imprecise. Fortunately, sofware exists which enables one quite easily to evaluate the sensitivity of the final rankings to choice of weights. Figure B3 is a sample output from one software package (VISA, see main report Section 5), on which the

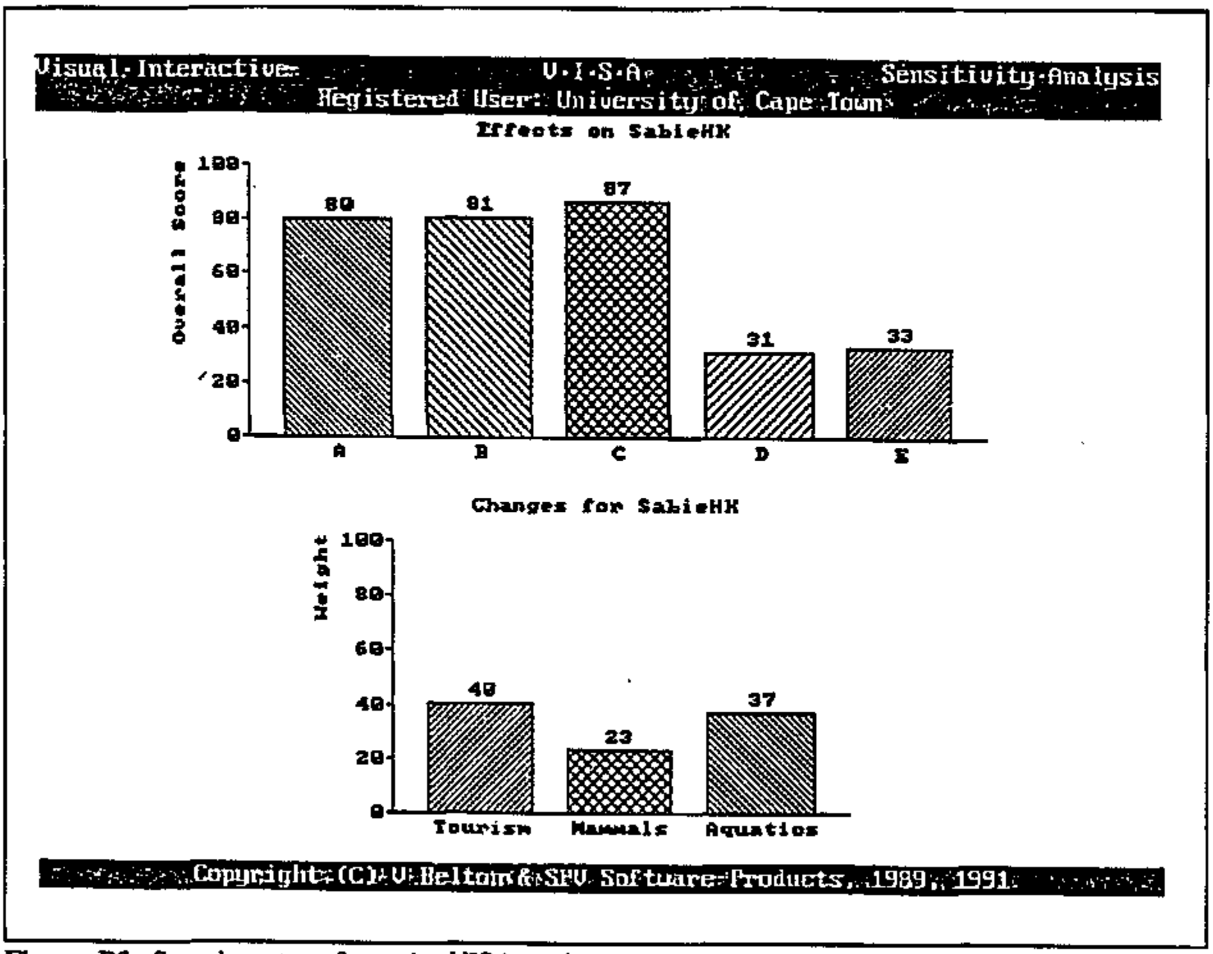


Figure B3: Sample output from the VISA package

weights and final scores for the above example are shown as bar graphs. In using VISA, one can directly experiment with increasing or decreasing the heights of the bars corresponding to the weights, to see the effect on the final rankings. In this case, the results turn out to be relatively insensitive to the weights: the only real difference is that the preference order C>B>A reverses when the weight on tourism drops below about 0.3 (or 30 in the figure), with corresponding increases in the other two weights (so that they still sum to one). The general pattern, in which A, B and C are very similar in value, and much preferred over D and E, remains. VISA in fact allows for a wide range of sensitivity studies which we are unable to discuss in detail here.

B3.3 Consensus-Seeking between Groups

The rationale behind the procedures described in the previous two Sections, is that different interests, with benefits which are not equally quantifiable or tangible, can be compared on a

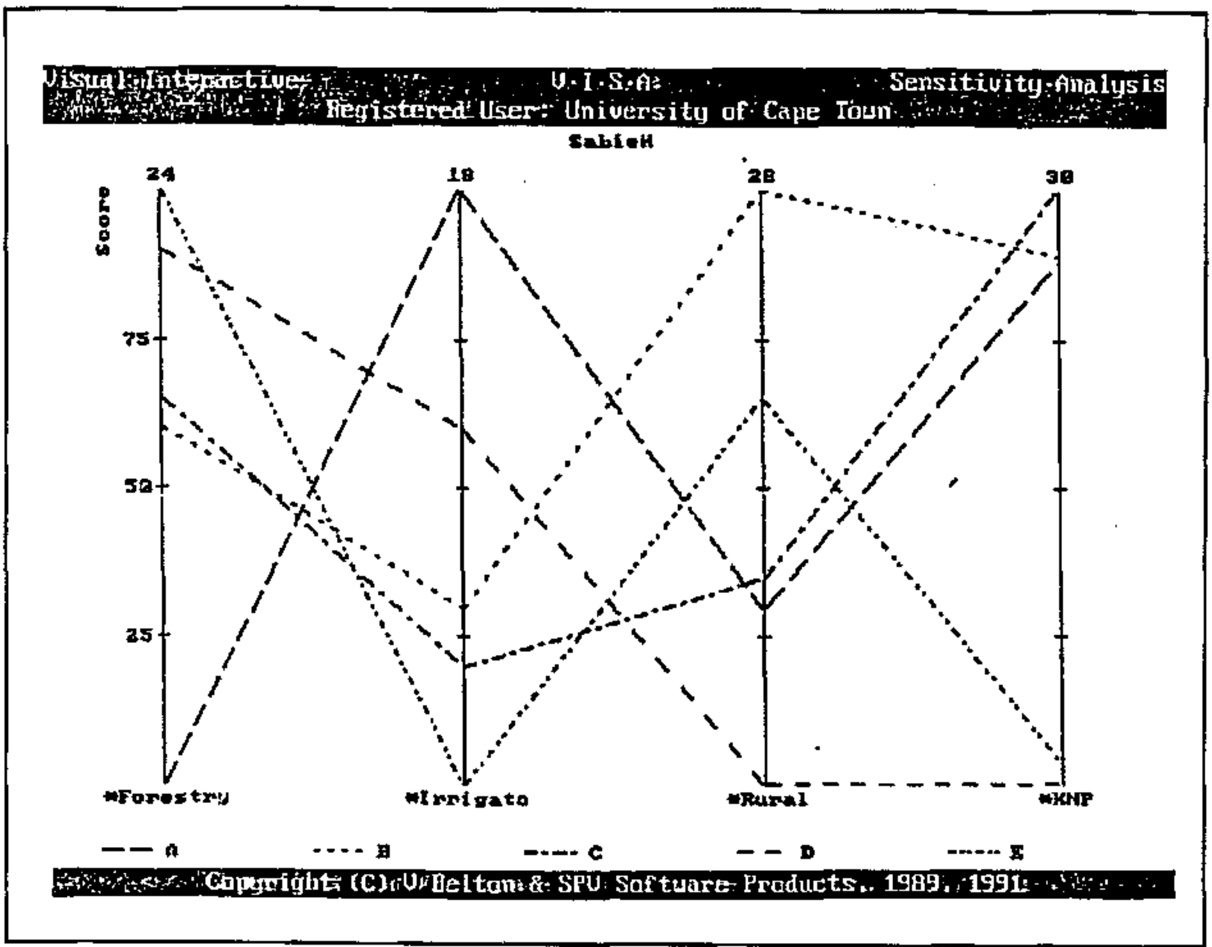


Figure B4: Multiple thermometer scales for four different interests

standardized basis. It remains still to discuss the process of comparison, which would lead to the identification of possible compromise or consensus positions. Certainly the thermometer scales for each interest, if placed side by side provide very clear and concise information to all parties, regarding the impacts of proposed policies on each. This is illustrated in Figure B4 (taken from the VISA package), for the five scenarios we have been discussing, for the forestry and Kruger National Park interests (as we have hypothesized them above), as well as for hypothesized scorings for irrigators and rural communities. The lines representing each alternative scenario join together the points on the thermometer scales for each interest. It is, for example, evident that scenario B is perhaps more widely acceptable than any of the others, in that it is never rated less than 30 on the scale for any interest, and is in fact 60 or over for all but one interest group. This argument can be viewed as a form of goal programming (Section 2.2). Another possibility would be to allocate weights to each interest, and to compute again a weighted average score. On technical grounds this is justified by the properties of a thermometer scale, although this might be politically sensitive. Certainly, one must emphasize that the weights do not represent the intrinsic importance of each interest group, but are meant to indicate the strength of the impact on each of these groups, when choices only from within the five scenarios currently under consideration are to be made. (For example, perhaps the irrigators themselves may accept that they are not strongly influenced by whatever decision is made, in which case their scorings here would receive a relatively low weight.) If equal weights are given to each interest, then B does score higher than any other, and this result is only changed by quite extreme variations (increases in weights of forestry to 0.55, or of irrigators to 0.38, or of Kruger National Park to 0.69; or a decrease in the weight on rural community interests to 0.04). This would at least give grounds for proposing B as the candidate for further evaluation.

Some aspects of the approach are still subject to further research. In particular, other methods for identifying possible compromises (other than the *ad hoc* suggestions in the last paragraph), and for introducing and deleting new scenario proposals quickly and efficiently, are still being sought.

B4. APPLICATION TO WATER ALLOCATION PROBLEMS

In all of the above examples, we have examined choice between a number of discrete planning scenarios. The concepts are nevertheless in principle extendable to other decision processes, although the precise mechanism of implementation is still the subject of research. In this final Section, we will briefly outline how the procedures may apply in a water allocation setting. We are here adopting an approach proposed by researchers at the London School of Economics, and incorporated into their software entitled EQUITY (see main report Section 5)

Let us suppose that we have 100 *units* of water to be allocated between agriculture (i.e. irrigation), industry, maintenance of downstream flow for ecological purposes, and forestry. The forestry "allocation" would probably be indirect in this case, in the sense that the policy might rather determine levels of afforestation, but the consequences in terms of reduced runoff for allocation to other users can still be viewed as an allocation to forestry. For each of these users, a number of possible stratagems can be applied. For illustration here, suppose that for irrigation, industry and downstream flow we consider four possibilities, *viz.* severe cuts in allocation, mild cuts, maintenance of status quo or increased allocation; while for forestry the options are reduction, status quo or increase. Suppose further that the water usage (in the "units" used above) corresponding to each level for each user has been determined to be as in the following Table:

	Severe Cuts	Mild Cuts or Reductions	Status Quo	Increased Allocation
Agriculture	5	20	40	50
Industry	30	50	60	70
Downstream Flow	10	20	30	40
Forestry		20	30	40

Note that to maintain all users at the *status quo* level requires 160 units, which is well above the 100 assumed to be available.

We have in fact 4x4x4x3=192 different scenarios which can in principle be considered. Fortunately, in this case, all 192 need never be assessed simultaneously, since the interests of any one group are dependent only upon which of the 3 or 4 choices relevant to themselves are made.

For overall decision making at this operational level, we would need to be explicit about what overall criteria are at issue. For purposes of illustration, suppose that the decision makers are fundamentally concerned about three criteria: economic benefit, environmental impact, and quality of life. Each of the four user groups can be considered in turn. For example, the impacts of the 4 options for industry on each of the criteria can be assessed on a thermometer scale, precisely as described in Section 3.2. Of course, not all criteria need necessarily be impacted by the allocation made to industry, in which case there would be no need for the assessment. For example, there may be no <u>direct</u> environmental impact resulting from the allocation to industry: the greater allocations to industry will, of course, in practice imply less to downstream flow, but this impact is captured when considering the allocation to downstream flow. Once all the thermometer scale assessments are complete, two levels of weight assessment are required. Firstly, a comparison is made between the relative impacts of the swing from minimum to maximum allocation for each user, from the point of view of a single criterion. A weight of 100 is allocated to the most important of these impacts, and weights for the other impacts are assessed relative to this. This is repeated for each criterion in turn, to obtain what are termed the "*within criterion*" weights. If the allocations for a particular user have no impact on a particular criterion, then the corresponding within-criterion weight is zero. Secondly, the overall importance of each criterion in this context needs to be assessed. In this case the largest impacts (across all users) for each criterion are compared directly. Once again, the criterion for which the largest impact is adjudged the most important (amongst all criteria) is given a weight of 100, and the others are then rated accordingly. These are termed the "*across criterion*" weights.

To aid in fixing the above ideas, Table B2 (at the end of the Appendix) displays hypothetical assessments which might have been made in the above example. The thermometer scale scores should by now be familiar. As regards economic impacts, the effects of the swing from minimum to maximum allocation to industry is adjudged to be more important than the corresponding swings for the other users. In comparison, the swings from minimum to maximum allocation to agriculture and to forestry respectively, are adjudged to represent about 33% and 65% of the economic benefit of the corresponding swing for industry. This then gives the within criterion weights for economic benefit. Similar interpretations apply for the other two criteria. The across criterion weights shown in the second row of Table B2, indicate that the impact on economic benefits of the industry allocations (with a "within-criterion" weight of 100) are adjudged to be of equal importance to the impact on environmental benefits of the downstream flow allocations (with a "within-criterion" weight of 100). On the other hand, the impacts of the downstream flow allocations on quality of life (also having a "within-criterion" weight of 100) are adjudged to be only about 70% as important as the other two. It is worth re-emphasizing that none of these weights are seen in abstract: they represent adjudged importances of the impacts of very specific ranges of action.

The same example (per Table B2) can also serve to illustrate how these inputs are used to assess the value of different allocation decisions. There are in total seven impacts to be considered (i.e. all cases in Table B2 with non-zero within-criterion weights). The importance of the minimum-to-maximum swing in any particular case is given by the product of the relevant within-criterion and across-criterion weights. These serve as direct measures of the benefits to each criterion, obtained from a maximum allocation to each user, and are given in Table B3 (at the end of the Appendix), together with a re-standardization of these benefit measures to sum to 1000 (a strategy adopted in the EQUITY software to facilitate interpretation). With this basis, we are able to assess a measure of total benefit for any proposed allocation, by multiplying the measure of potential benefit for each of the 7 impacts in Table B3, by the "thermometer-scale" scores corresponding to the proposed allocation (viewed as percentages). Thus, if a proposed package contains mild cuts in downstream flow, the benefits accruing will be 20% of 240 (=48 for environmental benefits) plus 70% of 168 (=117 for quality of life) giving a total of 165. Similar calculations can be done for each user, and the benefits accumulated into a grand total. Thus, for example, we could calculate a total benefit measure for the following proposed package thus: Agriculture - Severe cuts (Benefit = 0); Industry - Mild cuts (Benefit = 144+20 = 164); Downstream flow - Mild cuts (Benefit = 165, as above); and Forestry - Reduction (Benefit = 0). This gives a total of 329 out of a possible 1000. The water usage for this plan is 5+50+20+20=95 units, i.e. close to the maximum available. In principle, the above calculation can be carried out for all combinations of allocations which result in usage not exceeding 100 units. The EQUITY software can be used to generate the diagram in Figure B5, in which "P" represents the above proposal (benefit of 359/1000, or about 36%), and "B" and "C" two alternatives which give either similar benefits for less water usage, denoted as "COST" (C), or greater benefits for the same water usage (B). The plan indicated as B differs from P by reducing the allocation to industry (to severe cuts), and by increasing allocations to downstream flow and forestry (to status quo). This gives a benefit of 472/1000 (47%) for the same water usage. In fact, the EQUITY software can be asked to search for the allocation yielding maximum benefit for a fixed constraint on usage, which it interprets somewhat flexibly. For example, in this example, the solution generated by EQUITY for a constraint of 100 units on water availability gives an increased allocation to downstream flow, while being otherwise the same as the "B" option above. This results in a usage of 105 units, but a benefit of 57%. Given the imprecise nature of constraints, and the artificially discrete nature of the options under consideration, this proposal might well be a very good one to examine (with, if necessary, something like 5% further cuts on all users to meet the 100 unit constraint precisely).

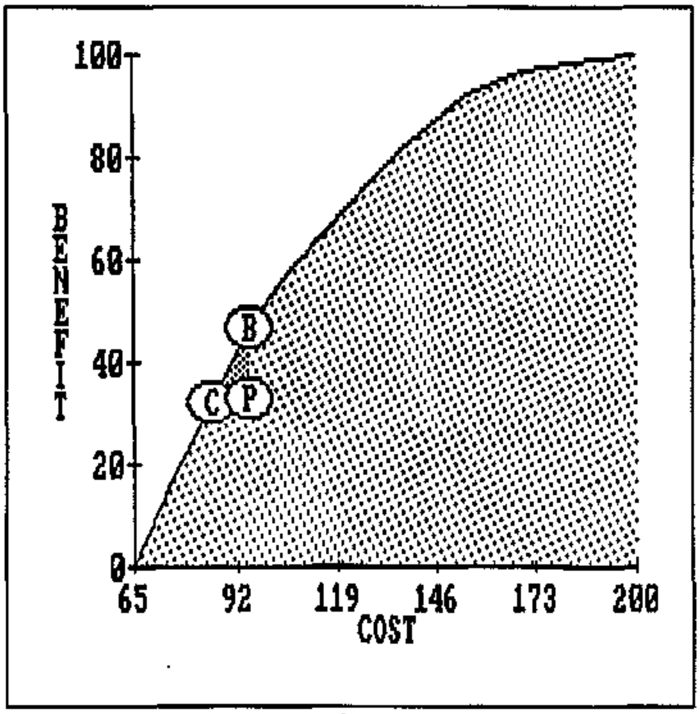


Figure B5: Sample output from EQUITY software

The full use of procedures such as that given by the EQUITY software in the water planning context still requires further research, but does appear to hold considerable promise.

TABLE B1: SIMPLIFIED AND HYPOTHETICAL POLICY SCENARIOS FOR A REGION SUCH AS THE SABIE

Policy Scenario	% Change in Forestry	% Cut in Irrigation	Dam Size (% of Max.)	% Rural Populn. Served	Cost (Rm)	% Change Annual Flow	% Change Low Flows	% Change Peak Flows
1 (A)	-3	20	60	30	450	20	50	-5
2	-3	35	80	40	575	17	65	-13
3	-3	50	60	40	500	15	65	-5
4	-3	50	100	50	650	15	80	-20
5	-1.5	20	60	30	450	7	35	-8
6	-1.5	35	80	40	575	5	50	-15
7	-1.5	50	60	40	500	2	50	-8
8	-1.5	50	100	50	650	2	65	-23
9	0	20	60	30	450	-5	20	-10
10	0	35	80	50	625	-1	35	-14
11 (B)	0	50	60	40	500	-10	35	-10
12 (C)	0	50	100	50	650	-10	50	-25
13	+2.5	20	60	30	450	-26	-5	-14
14	+2.5	35	80	50	625	-22	10	-18
15	+2.5	50	60	40	500	-31	10	-14
16	+2.5	50	100	60	700	-24	25	-26
17 (D)	+5	20	60	40	500	-40	-30	-15
18	+5	35	80	50	625	-43	-15	-23
19	+5	50	60	30	450	-58	-15	-22
20 (E)	+5	50	100	60	700	-45	0	-30

TABLE B2: Hypothetical Scores and Weights for the Water Allocation Example

Criterion:		Economic	Environmental	Quality of Life
Across Criterion Weights:		100	100	70
Agriculture:				
Scores:	Severe cuts	0	-	-
	Mild cuts	60	-	-
	Status quo	88	-	-
	Increase	100	-	-
Within Criterion Weights:		33	0	0
Industry:				
Scores:	Severe cuts	0	-	0
	Mild cuts	60	-	60
	Status quo	74	-	90
	Increase	100	-	100
Within Criterion Weights:		100	0	20
Downstream Flow:				
Scores:	Severe cuts	-	0	0
	Mild cuts	-	20	70
	Status quo	-	69	88
	Increase	-	100	100
Within Criterion Weights		0	100	100
Forestry:				
Scores:	Reduction	0	-	0
	Status quo	75	-	50
	Increase	100	-	100
Within Criterion Weights		65	0	50

TABLE B3: Measures of benefit for each impact

Impacts (User x Criterion):		Product of weights	Standardized benefit
Agriculture	Economic	3300	79
Industry	Economic	10000	240
Industry	Quality of Life	1400	33
Downstream flow	Environmental	10000	240
Downstream flow	Quality of Life	7000	168
Forestry	Economic	6500	156
Forestry	Quality of Life	3500	84

APPENDIX C

TECHNICAL DEFINITIONS AND DESCRIPTIONS OF THE SCENARIO PLANNING PROCEDURES

C1. INTRODUCTION

This Appendix parallels Section 4 of the main text, and specifies the procedures recommended in more precise mathematical or algorithmic detail. The procedures are also illustrated by reference to the simple example defined in Appendix B.

For the purposes of this Appendix, we adopt the following mathematical nomenclature:

x_i **The level chosen for the *i*-th policy element, on a standardized scale on which the minimum value is 0 and the maximum value 1.** As far as possible, policy elements should be defined so that the ranges of values that can be taken on for one element is not unduly affected by levels chosen for other elements. For example, definitions such as x_1=the proportion of rural communities served by household standpipes and x_2=the proportion of rural communities with access to communal (but not household) standpipes, would not be a good definition, since $x_2=0.6$ (say) implies that $x_1<0.4$. A better definition may be to set x_1=the proportion of the rural community without access to any standpipes, and x_2=the proportion of those with standpipes who have these available at their households. Pairs of values (x_1,x_2) can define the same scenarios with either definition, but in the latter case, values over the entire range from 0 to 1 can meaningfully be chosen for each of x_1 and x_2, independently of the value chosen for the other.

Note that in some cases, x_i may only be able to take on the values 0 or 1, and not any fractional values; for example, one element may refer to whether or not a particular dam is built, in which case $x_i=0$ means no dam, and $x_i=1$ means that it is constructed.

m **The number of distinct policy elements which are defined.**

y_j **The value for the j-th attribute defining some consequence of a chosen scenario.** Each y_j will be a function of one or more of the x_i's, which we shall express in the form: $y_j=f_j(x_1,\ldots,x_m)$.

n **The number of attributes which are defined.**

z_k **The k-th surrogate planning objective** (as defined in Section C3; cf. also Section B2.1). These will generally be selected policy elements x_i or attributes y_j, or simple functions of these.

p **The number of surrogate planning objectives defined.**

For the simple example of Appendix B, we had $m=4$, with standardised policy elements defined by:

x_1 = *[(% Change in forestry) + 3]/8*
x_2 = *[(% Cut in irrigation) - 20]/30*
x_3 = *[(Dam Size percenatge) - 60]/40*
x_4 = *[(% Population served by standpipes)-30]/30*

There were $n=4$ consequence attributes, being cost and percentage changes in annual, low and peak flows. In Section B2.1, there are $p=6$ objectives defined, the first three of which are x_1, x_2 and x_4 respectively, while the remaining three are y_1, y_2 and y_3.

In principle any combination of values for $(x_1,\ldots,x_m)$ defines a scenario (recalling that some x_i may be limited to 0 or 1 only), although some may be infeasible for a variety of reasons. In practice, even for the continuous policy elements (i.e. not constrained to be 0 or 1), one would only consider values on some finite grid of values (e.g. x_i increasing from 0 to 1 in steps of 0.05, or 0.01). Even with this practical restriction to a finite grid of values, there will remain a very large number of possible combinations of values for the x_i, i.e. scenarios. We shall term the collection of all possible scenarios generated in this way for a given grid of values as the **full set of scenarios**. In principle, the aim is to select a most satisfactory scenario from this set. Note that even for the simple example of Appendix B, and a grid of values with a spacing of 0.05, there are 21 possible values for each x_i, allowing for a total of $21^4 = 194481$ possible scenarios. It would, of course be impossible to evaluate each of these in full. In fact, it would usually not even be practicable to evaluate the y_j's for each scenario, as the functions $f_j()$ will generally be quite complex, requiring intensive computer processing (e.g. the running of models such as the ACRU run-off model) and/or human judgment. The first step in our proposed procedure is thus to select out a **background set** of typical scenarios which will characterize the full set. This step is discussed in the next Section.

C2. GENERATION OF THE BACKGROUND SET OF SCENARIOS

The intention is that all attributes will be evaluated (by any necessary combination of computer modelling and expert judgment) for each scenario in the background set, to form complete policy scenarios. This becomes the basic set of alternatives to which MCDM methods will be applied, in order to find generally satisfactory policies. During the process of search for a most satisfactory policy, planners or other interested parties may well wish to consider other scenarios, defined by combinations of policy elements not represented in the backgound set. At this stage, there may not be time to commission a complete evaluation of all attributes, and it would then be necessary to interpolate between scenarios in the background set to at least approximate the relevant attribute values. A minimal requirement here would be some form of quadratic interpolation, which might be expected to give reasonable approximations to the $f_j()$ functions, provided that attribute values vary reasonably smoothly with changing values of the x_i. These observations lead us to conclude that the backgound set should be chosen to satisfy at least the following properties:

(a) The scenarios in the background set must be sufficently widely spread amongst the full set of all possible scenarios, so that any scenario likely to be favoured by any interest group, or by consensus between a number of such groups, will be closely approximated either by a scenario in the background set, or by some weighted combination of these.

(b) There must be sufficient scenarios in the background set to permit the estimation of a quadratic approximation to any function $f_j()$, preferably with some redundancy to allow for localized interpolation only.

The selection of the background set is effectively a problem of experimental design (in statistical terminology), i.e. how do we select a number of *points* at which to make observations, so that we can *estimate* the effects of all factors (in our case policy elements) on a response of interest (in our case, an attribute value). The problem of experimental design for response surface fitting is well known in statistics. The ideal design is often claimed to be a full factorial design (all combinations of 0s and 1s for each x_i) plus a centre point (all $x_i = ½$) where possible (i.e. for continuous x_i). The number of scenarios in the full factorial design is 2^m, which grows very rapidly with the number of policy elements m. For larger m the full factorial design becomes impracticable. Although various fractional factorial designs have been proposed in the literature, we suggest a particular version below which is specifically aimed at maximizing the spread of scenarios which are to be considered (cf. property (a) above). Before giving the full definition of our proposed partial factorial design, we need first to give further consideration to the "centre point". As literally implemented, a standard design would give a background set with many rather extreme scenarios (all x_i at either maximum or minimum values), and only one intermediate set of values. This seems to conflict with desirable property (a) above, and we thus propose an "extended centre point", which is in fact a collection of scenarios, with x_i values between ¼ and ¾. This additional richness in the centre will also provide for the desired redundancy (property (b)) for quadratic approximation purposes.

The proposed design for the background set is thus defined as follows:

PARTIAL FACTORIAL DESIGN SET

For $m \leq 4$, use the complete 2^m factorial design (see example below).

For $m > 4$, the following design, consisting of $2+m+m^2$ points (scenarios) is proposed:

One point defined by $x_i=0$ for all elements i

m points, in each of which $x_j=1$ for a particular element j, and $x_i=0$ for all $i \neq j$

$m(m-1)/2$ points, in each of which $x_j=x_k=1$ for a particular pair of elements j and k, and $x_i=0$ for all $i \neq j,k$

$m(m-1)/2$ points, in each of which $x_j=x_k=0$ for a particular pair of elements j and k, and $x_i=1$ for all $i \neq j,k$

m points, in each of which $x_j=0$ for a particular element j, and $x_i=1$ for all $i \neq j$

One point defined by $x_i=1$ for all elements i

In statistical terms, this design does allow for the estimation of all main effects (of each element, or "factor" in conventional statistical terminology, on any attribute of interest), as well as all first-order interaction effects. Note also that if in fact no more than four elements influence a particular attribute, then the appropriate full 2^4 factorial design is embedded in the above design.

EXTENDED CENTRE POINT SET (For continuous policy elements only)

The following $1+2m$ points are proposed:

One point defined by $x_i=½$ for all elements i

m points, in each of which $x_j=¼$ for a particular element j, and $x_i=½$ for all $i \neq j$

m points, in each of which $x_j=¾$ for a particular element j, and $x_i=½$ for all $i \neq j$

As an example of the above, consider the case in which $m=4$, with all elements being continuously variable. The proposed background set then consists of the $2^4+1+8=25$ scenarios listed in Table C1.

The above example applies to the case of the simple example of Appendix B, although this procedure was not used in developing the set of alternatives given in Table B1. The standardized values, as given in Table C1, are easily converted back into the natural units for each element. For example, the first element was percentage change in afforestation, with the standardized value defined by: $x_1 = [(\%\ Change\ in\ forestry) + 3]/8$. It is easily confirmed that $x_1=0$ corresponds to -3%; $x_1=¼$ to -1%; $x_1=½$ to +1%; $x_1=¾$ to +3%; and $x_1=1$ to +5%.

It is also useful to compute the numbers of elements in the background set for various values of m, and to compare these with the minimum number necessary for estimation of a quadratic approximation to $f_j()$. A quadratic approximation can be expressed in the form:

Table C1: Background set design for $m=4$, expressed in standardized form

x_1	x_2	x_3	x_4
0	0	0	0
1	0	0	0
0	1	0	0
0	0	1	0
0	0	0	1
1	1	0	0
1	0	1	0
1	0	0	1
0	1	1	0
0	1	0	1
0	0	1	1
1	1	1	0
1	1	0	1
1	0	1	1
0	1	1	1
1	1	1	1
½	½	½	½
¼	½	½	½
½	¼	½	½
½	½	¼	½
½	½	½	¼
¾	½	½	½
½	¾	½	½
½	½	¾	½
½	½	½	¾

$$f_j(x_1,\ldots,x_m) = a + \sum_i b_i x_i + \sum_i \sum_{j \le i} c_{ij} x_i x_j$$

which contains $1+m+m(m+1)/2$ parameters. Attribute values for at least this number of scenarios are necessary for the fitting of a quadratic approximation therefore. The following table gives the number of scenarios in the background set according to the proposed design, and the minimum number needed for quadratic interpolation, for various values of *m*:

TABLE C2: Numbers of scenarios needed for different numbers of policy elements

m	Number of scenarios in the backgound set	Minimum number of scenarios for quadratic interpolation
2	9	6
3	15	10
4	25	15
5	43	21
6	57	28
8	88	45
10	133	66
15	273	136
20	463	231

For practical planning purposes, it is probably advisable not to include too many policy elements at any one time, possibly not more than 10-12. Thus we would typically expect to have around 100-200 scenarios in the background set, for which full evaluation studies will have to be done.

C3. SELECTION OF A FOREGROUND SET OF SCENARIOS

As described in the main report, value judgments from interested parties can only effectively be expressed in terms of comparisons between a relatively small number of scenarios. The work of Miller [C2] suggests that about 7 would be an ideal number of scenarios for this purpose. (Less would limit the range of options represented in this set, while more would cause judgmental problems.) We will term this set of scenarios as the *foreground set*.

Choice of scenarios to constitute the foreground set is an important step in the process. Ideally, these should be chosen to contain realistically close-to-best expectations for all important interest groups, as well as some potentially good compromise solutions. Although we have elsewhere in this report commented on the limitations of formal *multiple criteria decision making (MCDM)* methods in identifying a final policy which best satisfies all interests, these same MCDM methods can be extremely valuable in selecting the foreground set. What is required is firstly to define a number of surrogate planning objectives based on the available attribute values. These surrogate objectives should be chosen so as to represent the types of aspirations which can be expected to be found amongst the interest groups, very much as described in Section B2.1 of Appendix B. Care should be taken that these objectives are reasonably complete in the sense of including the important considerations of each significant interest group, and these should therefore be identified in the same group "brainstorming" sessions, as those in which policy elements and attributes are identified (cf. Section 4.1.1). In fact, it would normally be appropriate to include each surrogate objective as an "attribute" (unless, of course, it is defined directly by one of the x_i). Let us denote the surrogate obectives by $z_1,z_2,\ldots,z_p$. For purposes of discussion we will assume that the aim is to maximize each z_k as far as is possible, and that each z_k is standardized to a maximum value of 1 and a minimum value of 0.

Once the surrogate objectives have been defined, MCDM methods are clearly appropriate for purposes of identifying a sub-set of alternative scenarios which satisfy our aims with the foreground set. In fact this selection is essentially similar to the process of *filtering* defined by Steuer [C3], where he, too, aimed at selecting a small number of alternatives to be presented to "decision makers" for evaluation. The Steuer approach consists of the following steps:

(1) Generate random sets of weights $w_1,w_2,\ldots,w_p$ (which sum to 1), and for each set generated find the alternative (or scenario in our terms) which maximizes $\sum_{k=1}^{p} w_k z_k$. Maintain a list of all alternatives which are generated in this way.

(2) "Filter" the list generated in step (1) to select out the required number of alternatives in such a way that the "distances" (in a Euclidean sense) between the chosen alternatives are

maximally different.

Although appealingly simple, the above scheme was developed by Steuer for the case in which the full set of alternatives (he did not have our intermediate step of a background set) was of a linear programming structure, and in which all objectives are linear functions of the variables representing the policy elements. One of the advantages of the linear programming structure, is that maximization of linear sums of the z_k can be shown to generate all Pareto optimal alternatives (see Section A2 for definition). This result does not unfortunately carry over to more general problems, implying that some more sophisticated criterion is needed. Such a criterion is provided by the *scalarizing function* of Wierzbicki [C4], which can be expressed in terms of the *minimization* of the following:

$$\operatorname*{Max}_{k=1}^{p} w_k(z_k^* - z_k) + \epsilon \sum_{k=1}^{p} w_k(z_k^* - z_k)$$

where z_k^* is some "reference level" for objective k. In our case an appropriate reference level may be the "ideal point" defined by $z_k^*=1$ for all k (at least for the initial iteration of the scenario-based planning procedure - see final comments in this Section).

Steuer's filtering step derives from the fact that he works with the full and continuous set of alternatives, and this step in effect plays the role of our background set determination (i.e. to get a good spread of values). In view of the care taken in our procedure to select the background set for a good and even spread of scenarios, step (1) of Steuer's procedure (but using the Wierzbicki scalarizing function) tends eventually to generate all elements of the background set. The design of the background set also ensures that these scenarios are nearly equidistant from each other, and the result is that Steuer's step (2) makes a more-or-less arbitrary choice, which is hardly satisfactory. Nevertheless, the Steuer random weight generation idea does have merit even in our context. Although all elements of the background set may evantually be chosen, some are chosen much more frequently in step (1) than others: our basic proposal therefore is simply to select the foreground set as the 7 scenarios in the background set which are most frequently generated in step (1) of Steuer's algorithm (using the scalarizing function criterion). These are the alternatives which appear to be "most likely" to be viewed as well-balanced between the generally conflicting objectives.

It is useful here to examine a simple example of the procedure, as applied to the scenarios in Table B1 (viewed as the background set), with the seven objectives as defined in Appendix B. For reference, the following Table lists each objective, the best and worst values for each (within the background set defined by Table B1), and the direction of preference for each (i.e. minimizing or maximizing):

Surrogate objective	Best value	Worst value	Direction
Change in afforestation	+5%	-3%	Maximizing
Cut in irrigation	20%	50%	Minimizing
Percentage of population served by standpipes	60%	30%	Maximizing
Investment costs	R450m	R700m	Minimizing
Change in annual flow	+20%	-58%	Maximizing
Change in minimum flow	+80%	-30%	Maximizing

The entries in Table B1 are standardized by subtracting out the "worst" value in the above Table, and dividing by (Best value - Worst value). For example, for scenario 11 in Table B1, which has 0% change in afforestation, $z_1=(0-(-3))/(5-(-3))=0.375$; while for investment costs of R500m, $z_4=(500-700)/(450-700)=0.8$. The standardized surrogate objective function values (z_k) can be computed for all 6 objectives, which are given in the Table below. In the same Table we give a hypothetical set of weights (w_k) on the objectives (summing to unity) for purposes of illustration, and the product term $w_k(1-z_k)$.

Standardized values for Scenario 11						
Standardized value	0.375	0	0.3333	0.8	0.6154	0.5909
Illustrative weights	0.15	0.11	0.23	0.19	0.26	0.06
$w_k(1-z_k)$	0.0938	0.1100	0.1533	0.0380	0.1000	0.0245

For the purposes of setting up the scalarizing function, note that the maximum value in the last row is 0.1533, while the sum of values in the last row is 0.5196. The value of the scalarizing function for scenario 11 is thus given by $0.1533+0.5196\epsilon$. Scalarizing function values can be calculated in this way for each scenario, and for any given set of weights; the scenario yielding the lowest value is viewed as optimal for these weights, and would then be selected in step (1) of the procedure.

The number of times (out of 1000 randomly generated sets of weights) that each scenario was selected in step (1), using the scalarizing function with $\epsilon=0.1$, was recorded as follows:

Scenario:	1	2	3	4	5	6	7	8	9	10
Frequency:	74	61	44	20	31	18	11	4	106	213
Scenario:	11	12	13	14	15	16	17	18	19	20
Frequency:	26	9	59	107	24	39	108	39	1	6

The foreground set would thus for this example have been scenarios 1, 2, 9, 10, 13, 14 and 17.

One possible problem that might have been anticipated with the proposal as defined and illustrated above, is that the more extreme scenarios may be less likely to be generated, which might conflict with our goal of maintaining a widely representative range of options. We examined this in the context of the above example, by generating weights not uniformly randomly, but with much greater emphasis on extreme weights (i.e. with the weight for one objective very high relative to the others). A series of studies were conducted in which, in the random generation of weights, only 1/7-th of the set of weights were generated in the random sense implied by our proposed procedure; in all other cases, one objective was selected to receive an average of N times the weighting on any other objective. But even with $N=10$, the foreground set turned out to consist of scenarios 1, 2, 4, 9, 13, 16 and 17, which still contains 5 of the original 7 in the foreground set. As an additional investigation, we also examined the effects of changing the value of ϵ over a wide range. The rationale behind this is that minimization of linear functions tends to generate much more extreme values than minimization of the maximum-function. In fact we found that for values of ϵ between 0 and 0.25 there was no change in the foreground set generated. The evidence at this stage is thus that the potential for this problem appears *prima facie* to be quite small, and that the procedure for generating the foreground set is relatively robust to specific parameter choices. Clearly, this does require additional research, and as a protection to ensure a reasonable spread of scenarios in the foreground set, we recommend that ϵ be kept at moderately large values (e.g. 0.1 or 0.2).

Up to now, we have considered only the initial generation of the foreground set, i.e. in the first iteration of the overall scenario-based planning procedure as illustrated in Figure 4.1 of the main text. In subsequent iterations, it may be necessary to generate new foreground sets in such a way as to reflect the consensus views arrived at (by planners, or in consensus-forming groups as the case may be). One procedure that has been found to work is based loosely on ideas of Korhonen, Wallenius and Zionts [C1]. Suppose that the consensus reached is that certain scenarios in the foreground set should definitely be retained for further consideration; while certain other scenarios in the foreground set should definitely be discarded from further consideration. (This classification need not be exhaustive; certain scenarios may not be classifiable under either heading.) Now as each set of weights is generated according to our proposed procedure, it is possible to check whether these weights would lead to one or more of the discarded scenarios being ranked more highly (according to the scalarizing function) than any of the scenarios classified as retained for further consideration. If so, then these weights cannot truly represent the group's values, even in a surrogate sense, and should not be permitted. The procedure as above can still otherwise be applied, but based only on sets of weights which are permitted according to this test. It is very likely that certain scenarios will never be selected on this basis, implying that they can for the moment be disregarded, reducing the effective size of the background set. As a test of this proposal, it was applied to the same example above for two particular cases:

> Case 1: Scenarios 1, 9, 10 and 14 retained; scenario 2 discarded: In this case, virtually no sets of permitted weights led to any of scenarios 1-7 being selected. The resulting foreground set was modified to 9, 10, 13, 14, 15, 17 and 18.
>
> Case 2: Scenarios 1, 9, 10 and 14 retained; scenario 17 discarded: In this case, virtually no sets of permitted weights led to any of scenarios 13-20 being selected. The resulting foreground set was modified to 1, 2, 3, 5, 9, 10 and 11.

An extension of this general idea is to use the above procedure initially, not to generate a foreground set, but to eliminate (for the current iteration of the procedure) scenarios which are hardly or not at all selected using permitted weights. These can then be replaced by generating a large number of random convex combinations of the remaining scenarios, and filtering out (in the sense of Steuer [C3]) a sufficient number of maximally distinct new scenarios to return the background set to its original size. (Attribute values for these would have to be obtained by interpolation as previously described.) Thereafter, the initial foreground set generation procedure can then be re-applied. The advantage of this extension seems on *prima facie* grounds to be that the overall scenario-planning will become increasingly focussed around smaller ranges of options as the process continues, leading to some sense of convergence. Full details of this extension and its advantages do still require further investigation, however.

An alternative, and potentially attractive procedure for the same purpose is not to screen out nonpermitted weights in the above way, but rather to change the reference points z_k^* in some way. This has in fact been suggested by Wierzbicki (in a personal communication). At this stage, we have not however been able to suggest an adequately justifiable procedure for using the retention or rejection of specified scenarios to arrive at new reference points. This, too, must be a matter for further research, and at this stage we can only recommend the procedure described in the previous paragraph.

REFERENCES CITED IN APPENDIX C

[C1] P. KORHONEN, J. WALLENIUS and S. ZIONTS, "Solving the discrete multiple criteria problem using convex cones", **Management Science**, Vol 30, pp 1336-1345, (1984)

[C2] G.A. MILLER, "The magical number seven, plus or minus two: some limits on our capacity for processing information" **The psychological Review**, Vol 63, pp 81-97, (1956)

[C3] R.E. STEUER, "**Multiple Criteria Optimization: Theory, Computation, and Application**", Publ. John Wiley & Sons, New York, (1986)

[C4] A.Z. WIERZBICKI, "The use of reference objectives in multiobjective optimization", **Multiple Criteria Decision Making Theory and Application**, Publ. Springer-Verlag (Lecture Notes in Economics and Mathematical Systems, 177), Berlin, (1980)

APPENDIX D

QUESTIONNAIRE DESIGNED FOR POSSIBLE TESTING OF THE DECISION ANALYSIS PROCEDURES

The following pages replicate the questionnaire (see Section 6.2 of the main report for discussion) precisely as distributed to participants. The aim of the questionnaire was to assess whether interested parties could respond to the types of questions envisaged in the proposed group decision analysis procedures.

Note that references in the questionnaire to Appendices 1-4 refer to Appendices E1-E4 in this report.

UNIVERSITY OF CAPE TOWN

DEPARTMENT OF STATISTICAL SCIENCES

<u>QUESTIONNAIRE REGARDING RELATIVE IMPORTANCE OF DIFFERENT COMPONENTS AND CONSEQUENCES OF RIVER BASIN DEVELOPMENT POLICIES FOR VARIOUS INTEREST AND USER GROUPS</u>

(EXPLORATORY CASE STUDY: SABIE RIVER BASIN)

PART A: IDENTIFICATION OF INTEREST REPRESENTED

Please indicate (by checking the appropriate box below) which of the following user groups or interests are closest to your particular concerns, responsibilities or expertise at this time (which are hereafter referred to as the "interests you represent"):

Forestry		Agriculture (Formal Sector)	
Tourism		Other Economic (Excl. Forestry, Agriculture and tourism)	
Local or Regional Government		Rural Communities (Incl. Subsistence Farming)	
Environmental Conservation (Excl. Game Parks)		Game Parks / Reserves	
International Relations		Other (Please specify):	

PART B: ASSESSMENT OF IMPORTANT ATTRIBUTES

Appendix 1 lists a number of quantitative **<u>attributes</u>** which could describe a development policy and its consequences for the Sabie River Basin. Some of these attributes refer to flow conditions at three points in the basin, indicated on the map attached to the Appendices as sites A,C and E respectively. Four possible options (or outcomes) are listed for each attribute, under the headings OPTION 1, OPTION 2, etc. Consider the importance of each attribute in terms of the overall impact (on the interests you represent) of changes in this attribute <u>over the ranges shown</u>. On this basis, select the most important attributes from Appendix 1 (up to a maximum of ten), and enter the corresponding codes (i.e. 1.1, 1.2, ..., 3.3.9) into the first column of Table 1. Note that provision is made for specifying further attributes, not listed in Appendix 1, but which you deem to be of importance.

Now, in the second column of Table 1, allocate an importance score to each attribute which you have listed in this Table as follows:

(a) Allocate a score of 100 to the most important attribute.

(b) Allocate a score between 0 and 100 to the least important attribute in the list, in such a way that the score indicates the importance of this attribute <u>relative</u> to the most important attribute, expressed in percentage terms.

(c) Then allocate intermediate scores to all other attributes in the same way.

Finally, for each attribute which you have listed, and in the remaining columns of Table 1 (which correspond to the OPTIONs for each attribute), enter a score of 100 for the most desirable OPTION, and a 0 for the least desirable. For the remaining two OPTIONs enter intermediate scores (i.e. between 0 and 100), in such a way that differences between columns represent the relative gains in moving from one OPTION to the next most desirable. (NOTE that these scores are <u>intended to be a subjective evaluation of value to the interest which you represent</u>.)

TABLE 1:

Attribute Code	Importance Score	Relative Scores for each OPTION			
		OPTION 1	OPTION 2	OPTION 3	OPTION 4
Additional attributes (give description and importance score):					

PART C: ASSESSMENT OF IMPORTANT GRAPHICAL ATTRIBUTES

Appendix 2 describes five hypothetical planning scenarios for the Sabie River Basin in terms of the attributes defined in Appendix 1. In addition to these descriptions, aspects of the estimated hydrological consequences of each scenario are presented graphically in Appendix 3. Graphs 1-15 give the minimum, lower quartile, median, upper quartile and maximum monthly flows (for each month of the year) over a 64 year period, for each site; each graph shows the relevant figures for all five scenarios. Graphs 16-24 illustrate the distributions of winter and summer flows (average monthly totals over three-month periods in each case), and of total annual flows, for each of the three sites. These are shown as "box-and-whisker" plots placed side-by-side for each of the five scenarios. The central "box" in each case shows the interquartile range of the distribution, with the median shown by the central line through the "box". The lower "whisker" stretches down to the minimum (over the 64 years); the long upper "whisker" tapers off into a series of dots (starting from a point 1½ times the distance from median to upper quartile above the "box"), to emphasize the long-tailed nature of these distributions, but also terminates at the 64-year maximum.

Please check in the relevant box below, the value of the graphs, relative to the numerical information contained in Appendix 1, in helping you to assess the impacts of the five scenarios on the interests which you represent.

The graphs are much more valuable for assessing impacts	The graphs are somewhat more valuable for assessing impacts	The graphs and the numerical information are of equal value	The graphs are somewhat less valuable for assessing impacts	The graphs are much less valuable for assessing impacts

If in your case these graphs contain little information of value (i.e. if you have checked the right-hand box above), then skip immediately to PART D of the questionnaire. But otherwise continue as follows:

(a) Enter the identifying numbers for the most important of these graphs (up to a maximum of 10) into the first column of Table 2.

(b) Enter importance scores for each of the graphs selected per (a) into the second column of Table 2, as done for the numerical attributes in PART B.

(c) For each graph selected in this way, rate the five scenarios against each other in terms of the conditions described by this graph alone. Give scores of 100 and 0 to the best and worst cases respectively, and intermediate scores for the other three scenarios, precisely as done when comparing attribute OPTIONS in PART B. Enter these scores into the last five columns of Table 2.

TABLE 2:

Graph No.	Importance score	Relative Scores for Each Scenario:				
		I	II	III	IV	V

PART D: HOLISTIC EVALUATION OF FIVE SCENARIOS

Look carefully again at the five hypothetical scenarios described in Appendices 2 and 3. In Table 3, enter a global score of 100 to the scenario which is the most desirable of the five from the point of view of the interests which you represent, and a global score of 0 to the least desirable. Allocate intermediate scores to the other three scenarios in such a way that the differences in scores represent the relative gains or losses perceived in changing from one scenario to another.

TABLE 3:

Scenario	Global Score
I	
II	
III	
IV	
V	

Finally, check the relevant boxes below, to indicate the <u>ease</u> with which you felt you could carry out this last task, and the <u>confidence</u> which you have in the scores allocated.

TABLE 4:

EASE OF TASK		CONFIDENCE IN SCORES	
Very difficult		Highly confident	
Difficult		Confident	
Not too difficult		Somewhat unsure	
Relatively straightforward		Little or no confidence	

<u>PART E:</u> ANY OTHER COMMENTS YOU WISH TO ADD

APPENDIX E

APPENDICES TO THE QUESTIONNAIRE OF APPENDIX D, INCORPORATING DEFINITIONS OF THE FOREGROUND SET OF SCENARIOS USED IN THE WORKSHOPS

This Appendix was originally prepared as an accompaniment to the questionnaire of Appendix D. The foreground set of five scenarios used for both the questionnaire and the workshops is fully defined in the Tables and Figures constituting Appendices E2-E4.

APPENDIX E1: LIST OF ATTRIBUTES USED TO DESCRIBE PLANNING SCENARIOS, AND RANGES OF VALUES OR OUTCOMES FOR EACH

E1.1 Attributes determined directly by policy formulation

CODE	ATTRIBUTE	Possible values:			
		OPTION 1	OPTION 2	OPTION 3	OPTION 4
1.1	Afforestation permitted (%age change from current)	-2½%	0	+2½%	5%
1.2	Maximum additional small storage permitted (10^6m^3)	0	1	3	5
1.3	Restriction on abstraction rate for irrigation (% below current levels)	0	20%	40%	60%
1.4	Total volumetric capacity of Injaka + New Forest Dams (10^6m^3)	0	76	136	206
1.5	Surface area flooded by Injaka + New Forest Dams (ha)	0	720	1060	1440

E1.2 Socio-economic attributes

CODE	ATTRIBUTE	Possible values:			
		OPTION 1	OPTION 2	OPTION 3	OPTION 4
2.1	Total Capital Costs for Dams and Infrastructure (10^6 Rand)	200	425	650	875
2.2	Percentage of rural population with access to standpipes serving not more than 3 households	10%	20%	30%	40%
2.3	Percentage of rural population served by public standpipes within ±100m of dwelling.	30%	45%	60%	75%
2.4	Percentage of rural population which are reliant on natural streams or rivers for water.	15%	30%	45%	60%

E1.3 Attributes describing river flow characteristics

E1.3.1 Flow characteristics at site A (see Appendix E4)

CODE	ATTRIBUTE	Possible values:			
		OPTION 1	OPTION 2	OPTION 3	OPTION 4
3.1.1	Mean total annual flow (10^6 m^3)	130	215	300	380
3.1.2	Lower quartile of summer flows (10^6 m^3 per month)	4	6	8	10
3.1.3	Median summer flow (10^6 m^3 per month)	14	21	28	35
3.1.4	Upper quartile of summer flows (10^6 m^3 per month)	40	65	90	115

CODE	ATTRIBUTE	Possible values:			
		OPTION 1	OPTION 2	OPTION 3	OPTION 4
3.1.5	Lower quartile of winter flows (10^6 m^3 per month)	0.15	0.22	0.27	0.34
3.1.6	Median winter flow (10^6 m^3 per month)	0.35	0.50	0.65	0.80
3.1.7	Upper quartile of winter flows (10^6 m^3 per month)	0.9	1.4	1.8	2.2
3.1.8	10-year low flow level (10^6 m^3 per month)	0	0.03	0.06	0.09
3.1.9	10-year high flow level (10^6 m^3 per month)	175	300	425	550

E1.3.2 Flow characteristics at site C (see Appendix E4)

CODE	ATTRIBUTE	Possible values:			
		OPTION 1	OPTION 2	OPTION 3	OPTION 4
3.2.1	Mean total annual flow (10^6 m^3)	400	800	1200	1600
3.2.2	Lower quartile of summer flows (10^6 m^3 per month)	20	40	60	80
3.2.3	Median summer flow (10^6 m^3 per month)	35	70	105	130
3.2.4	Upper quartile of summer flows (10^6 m^3 per month)	90	175	260	350
3.2.5	Lower quartile of winter flows (10^6 m^3 per month)	10	20	30	41
3.2.6	Median winter flow (10^6 m^3 per month)	12	24	36	48
3.2.7	Upper quartile of winter flows (10^6 m^3 per month)	14	28	42	56
3.2.8	10-year low flow level (10^6 m^3 per month)	7	15	23	31

CODE	ATTRIBUTE	Possible values:			
		OPTION 1	OPTION 2	OPTION 3	OPTION 4
3.2.9	10-year high flow level (10^6 m^3 per month)	275	550	825	1100

E1.3.3 Flow characteristics at site E (see Appendix E4)

CODE	ATTRIBUTE	Possible values:			
		OPTION 1	OPTION 2	OPTION 3	OPTION 4
3.3.1	Mean total annual flow (10^6 m^3)	200	700	1200	1700
3.3.2	Lower quartile of summer flows (10^6 m^3 per month)	12	35	57	80
3.3.3	Median summer flow (10^6 m^3 per month)	15	55	95	135
3.3.4	Upper quartile of summer flows (10^6 m^3 per month)	50	150	250	350
3.3.5	Lower quartile of winter flows (10^6 m^3 per month)	6	17	29	40
3.3.6	Median winter flow (10^6 m^3 per month)	7	20	34	47
3.3.7	Upper quartile of winter flows (10^6 m^3 per month)	8	24	39	55
3.3.8	10-year low flow level (10^6 m^3 per month)	5	13	22	30
3.3.9	10-year high flow level (10^6 m^3 per month)	150	500	850	1200

APPENDIX E2: DEFINITION OF FIVE HYPOTHETICAL PLANNING SCENARIOS (The "Foreground Set")

E2.1 General Scenario Definition

ATTRIBUTE	SCENARIO				
	I	II	III	IV	V
Afforestation (% change)	0	-2%	+5%	0	0
Additional small storage ($10^6 dm^3$)	0	3	5	5	1
Abstraction restriction (% below current)	0	20%	60%	60%	0
Total Dam Cap. ($10^6 dm^3$)	0	136	206	206	76
Area flooded (ha)	0	1060	1440	1440	720
Capital costs (10^6 Rand)	210	650	820	780	530
%age of rural population with access to standpipes serving 1-3 households	10%	20%	30%	20%	10%
%age of rural population served by public standpipes within $\pm$100m	30%	40%	45%	60%	50%
%age of rural population reliant on natural streams or rivers	60%	40%	25%	20%	40%

E2.2 Hydrological Summaries for Site A

ATTRIBUTE	SCENARIO				
	I	II	III	IV	V
Mean total annual flow (10^6 m^3)	134	261	285	292	376
Lower quartile: summer flows (10^6 m^3 per month)	4	7	7	8	10
Median summer flow (10^6 m^3 per month)	14	24	24	25	35

ATTRIBUTE	SCENARIO				
	I	II	III	IV	V
Upper quartile: summer flows (10^6 m^3 per month)	40	74	72	75	112
Lower quartile: winter flows (10^6 m^3 per month)	0.16	0.21	0.25	0.27	0.33
Median winter flow (10^6 m^3 per month)	0.34	0.50	0.64	0.64	0.76
Upper quartile: winter flows (10^6 m^3 per month)	0.91	1.47	1.86	1.80	2.24
10-year low flow level (10^6 m^3 per month)	0.05	0.05	0.01	0.07	0.08
10-year high flow level (10^6 m^3 per month)	176	367	400	404	523

E2.3 Hydrological Summaries for Site C

ATTRIBUTE	SCENARIO				
	I	II	III	IV	V
Mean total annual flow (10^6 m^3)	404	1026	1521	1548	1160
Lower quartile: summer flows (10^6 m^3 per month)	22	53	76	80	61
Median summer flow (10^6 m^3 per month)	36	87	118	124	98
Upper quartile: summer flows (10^6 m^3 per month)	89	224	322	320	259
Lower quartile: winter flows (10^6 m^3 per month)	10	26	41	41	27
Median winter flow (10^6 m^3 per month)	12	30	48	48	33
Upper quartile: winter flows (10^6 m^3 per month)	14	35	55	55	38

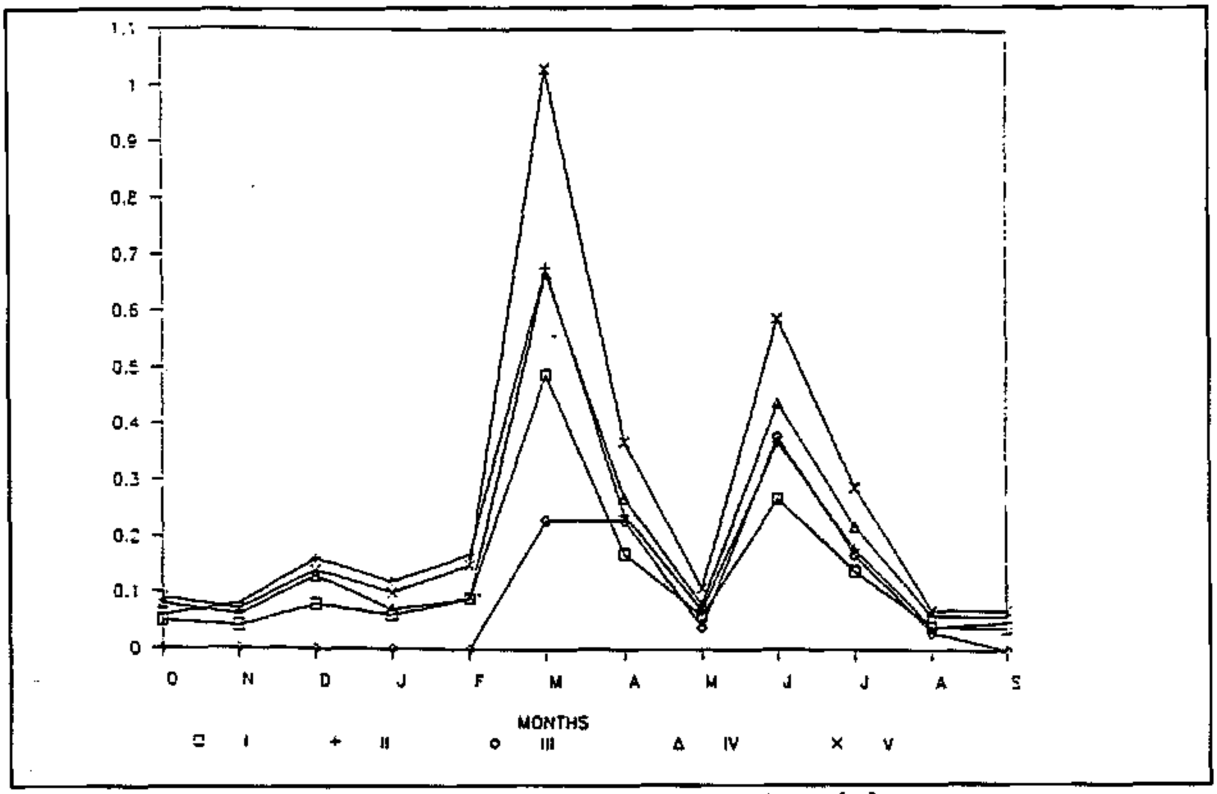
ATTRIBUTE	SCENARIO				
	I	II	III	IV	V
10-year low flow level (10^6 m^3 per month)	7	19	31	31	20
10-year high flow level (10^6 m^3 per month)	282	728	1059	1069	840

E2.4 Hydrological Summaries for Site E

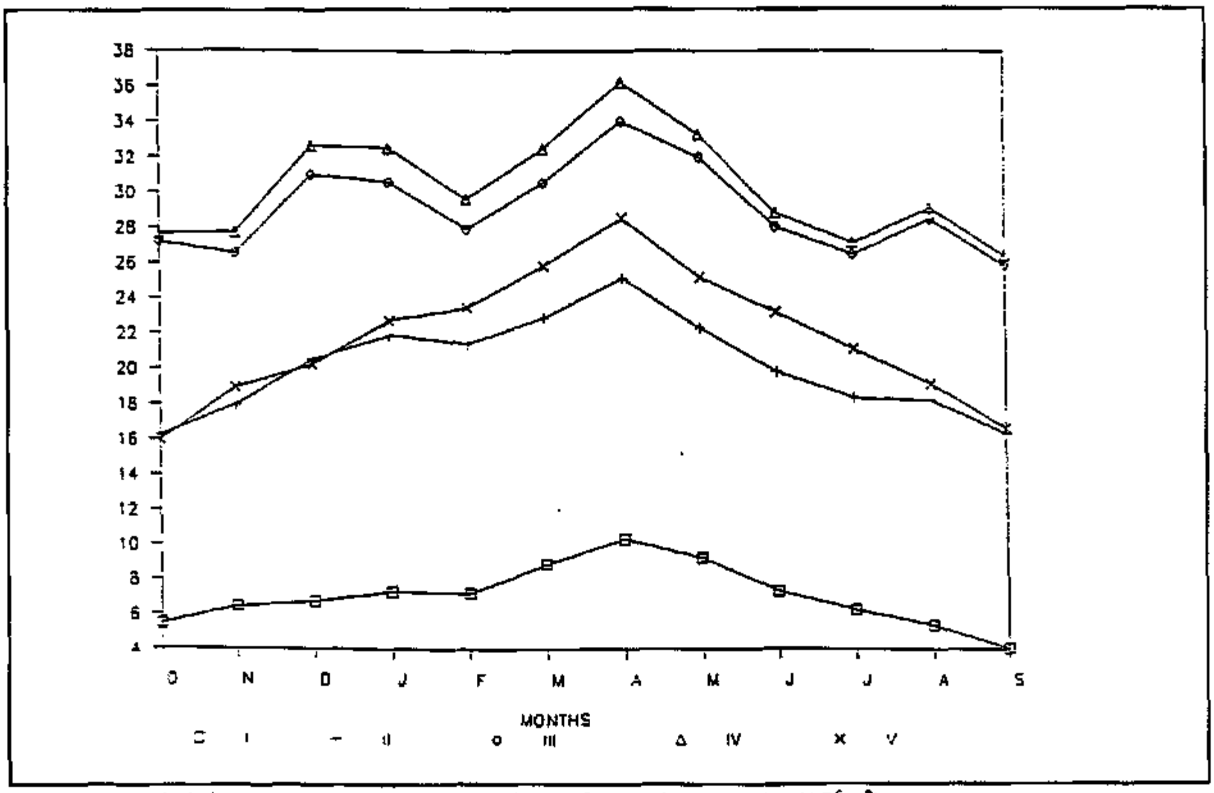
ATTRIBUTE	SCENARIO				
	I	II	III	IV	V
Mean total annual flow (10^6 m^3)	448	1026	1525	1553	1204
Lower quartile: summer flows (10^6 m^3 per month)	21	53	75	79	60
Median summer flow (10^6 m^3 per month)	41	87	119	126	100
Upper quartile: summer flows (10^6 m^3 per month)	97	224	313	322	270
Lower quartile: winter flows (10^6 m^3 per month)	8	26	40	40	26
Median winter flow (10^6 m^3 per month)	10	30	46	47	31
Upper quartile: winter flows (10^6 m^3 per month)	13	35	55	55	37
10-year low flow level (10^6 m^3 per month)	5	19	30	30	18
10-year high flow level (10^6 m^3 per month)	412	728	1086	1093	943

APPENDIX E3: GRAPHICAL REPRESENTATIONS OF CONSEQUENCES FOR THE FIVE SCENARIOS OF APPENDIX E2

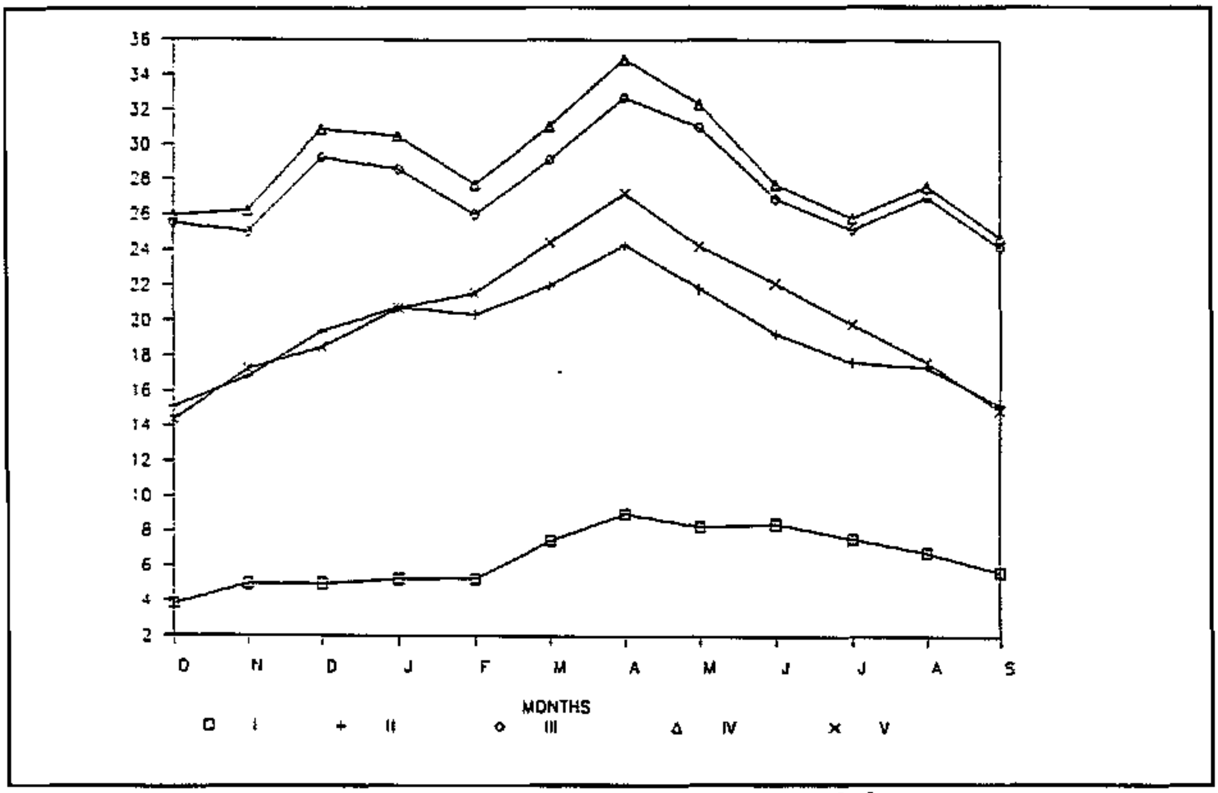
Pages E9-E21 contain the graphical information provided with the questionnaire. Graphs 1-15 give the minimum, lower quartile, median, upper quartile and maximum monthly flows (for each month of the year) over a 64 year period, for each site (i.e. sites A, C and E, as indicated on the map in Appendix E4); each graph shows the relevant figures for all five scenarios. Graphs 16-24 illustrate the distributions of winter and summer flows (average monthly totals over three-month periods in each case), and of total annual flows, for each of the three sites. These are shown as "box-and-whisker" plots placed side-by-side for each of the five scenarios. The central "box" in each case shows the interquartile range of the distribution, with the median shown by the central line through the "box". The lower "whisker" stretches down to the minimum (over the 64 years); the long upper "whisker" tapers off into a series of dots (starting from a point 1½ times the distance from median to upper quartile above the "box"), to emphasize the long-tailed nature of these distributions, but also terminates at the 64-year maximum.



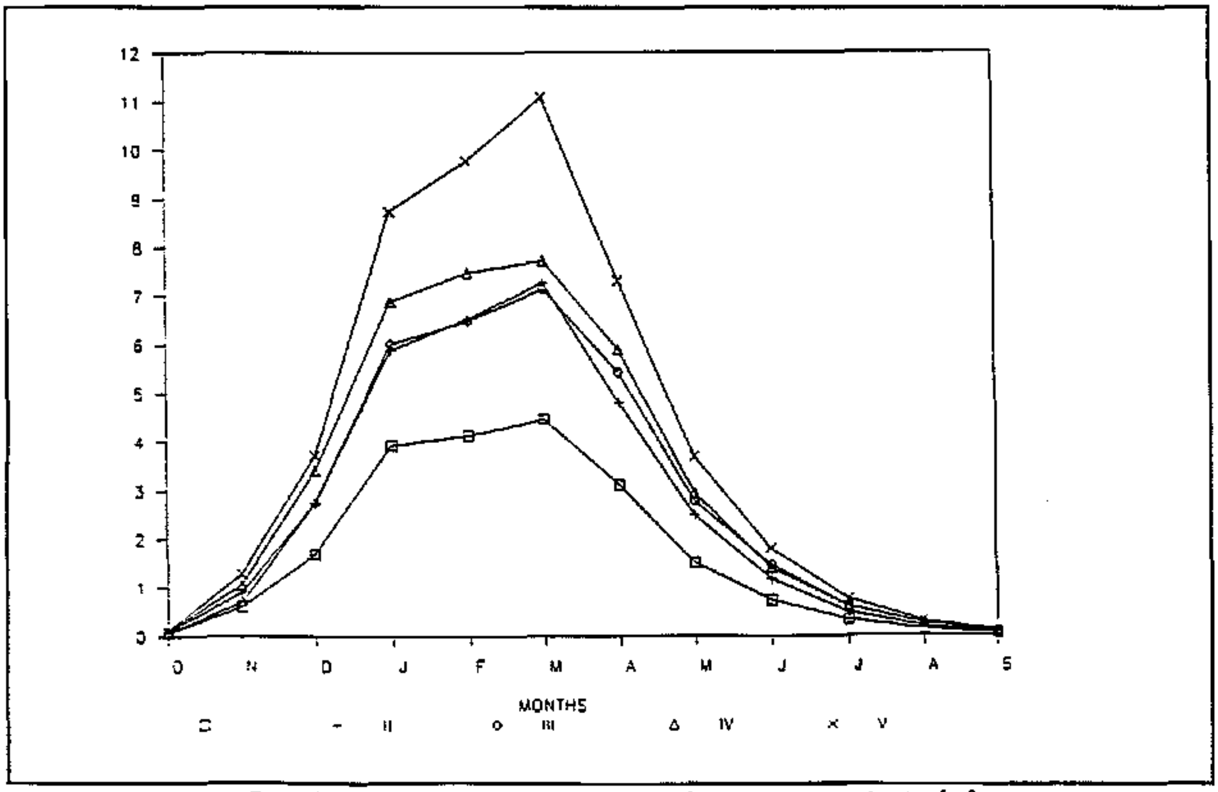
GRAPH 1: Minimum monthly flows at site A for each scenario ($10^6 m^3$)



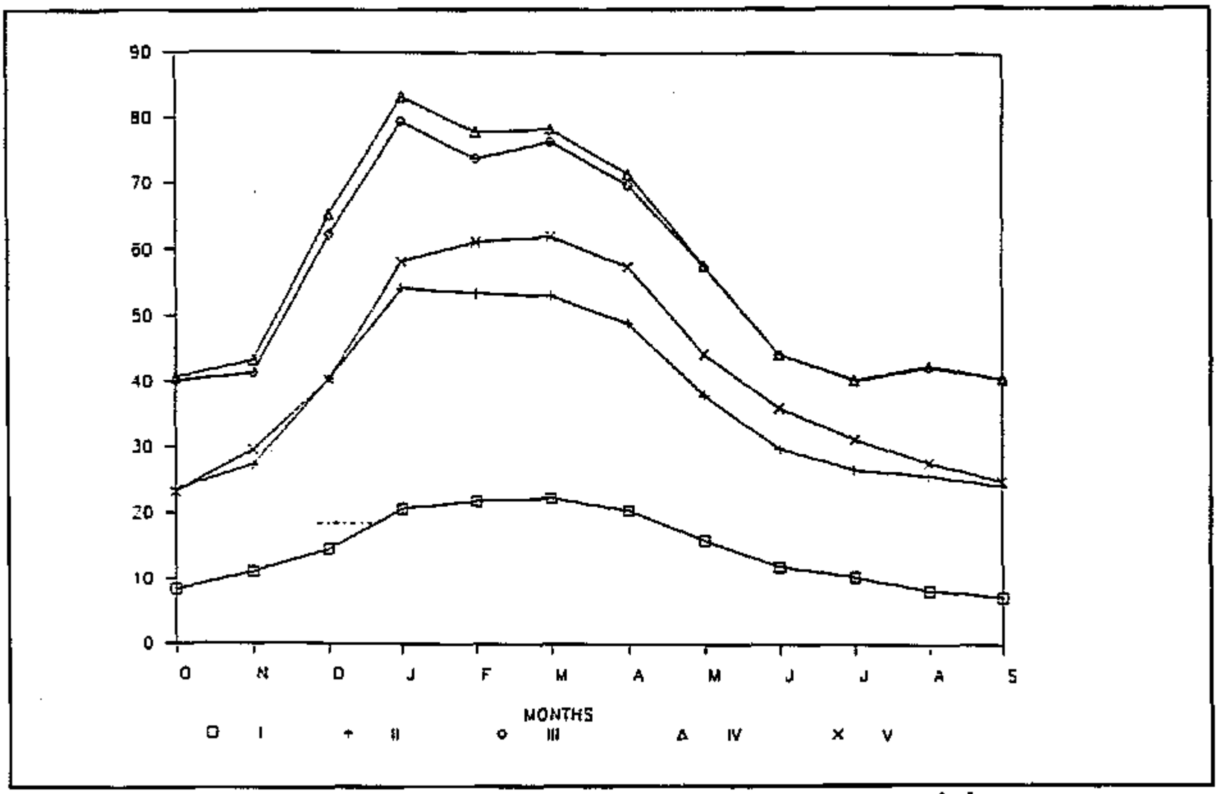
GRAPH 2: Minimum monthly flows at site C for each scenario ($10^6 m^3$)



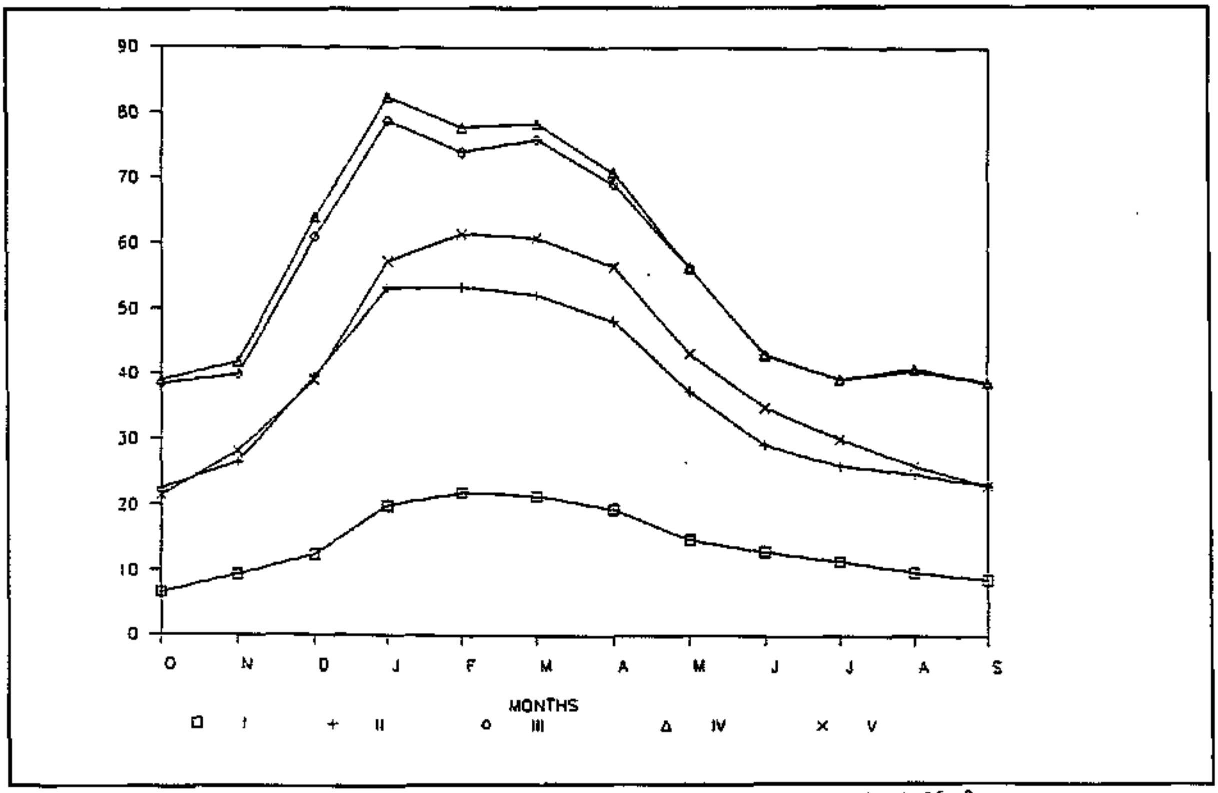
GRAPH 3: Minimum monthly flows at site E for each scenario (10^6m^3)



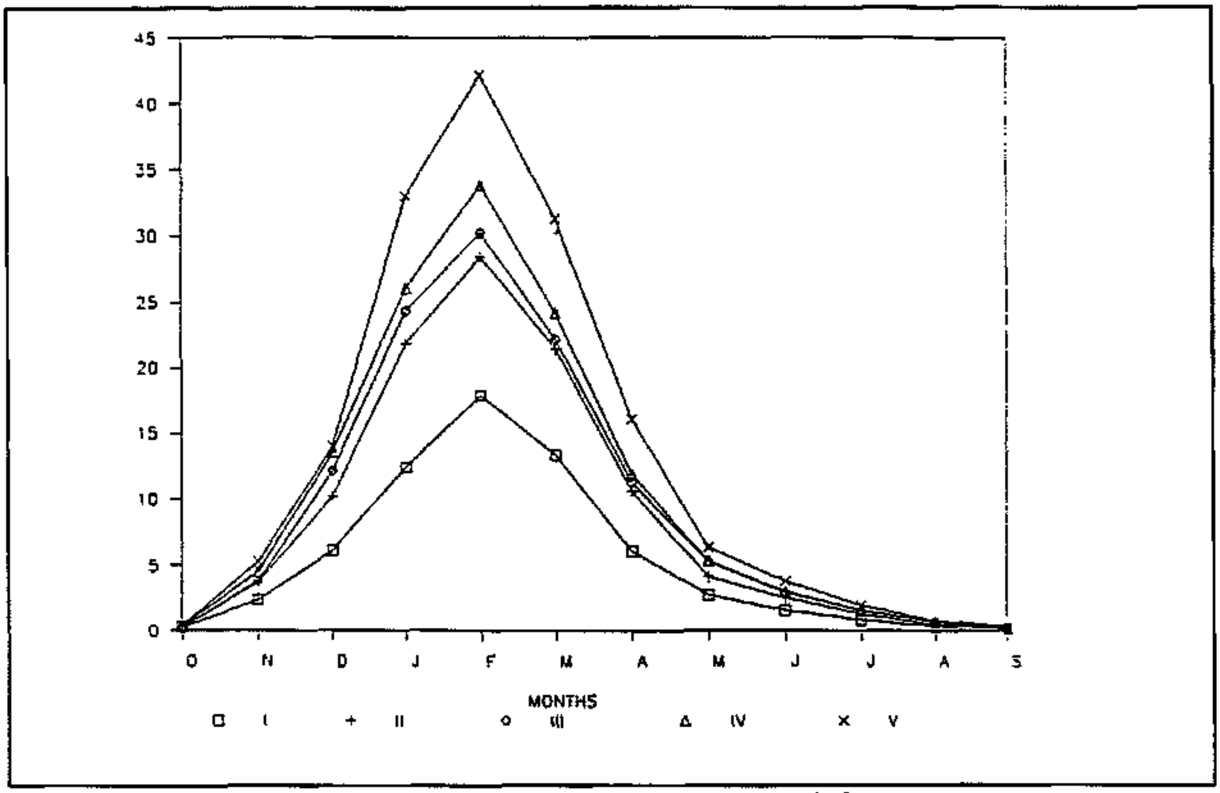
GRAPH 4: Lower Quartiles of monthly flow at site A for each scenario (10^6m^3)



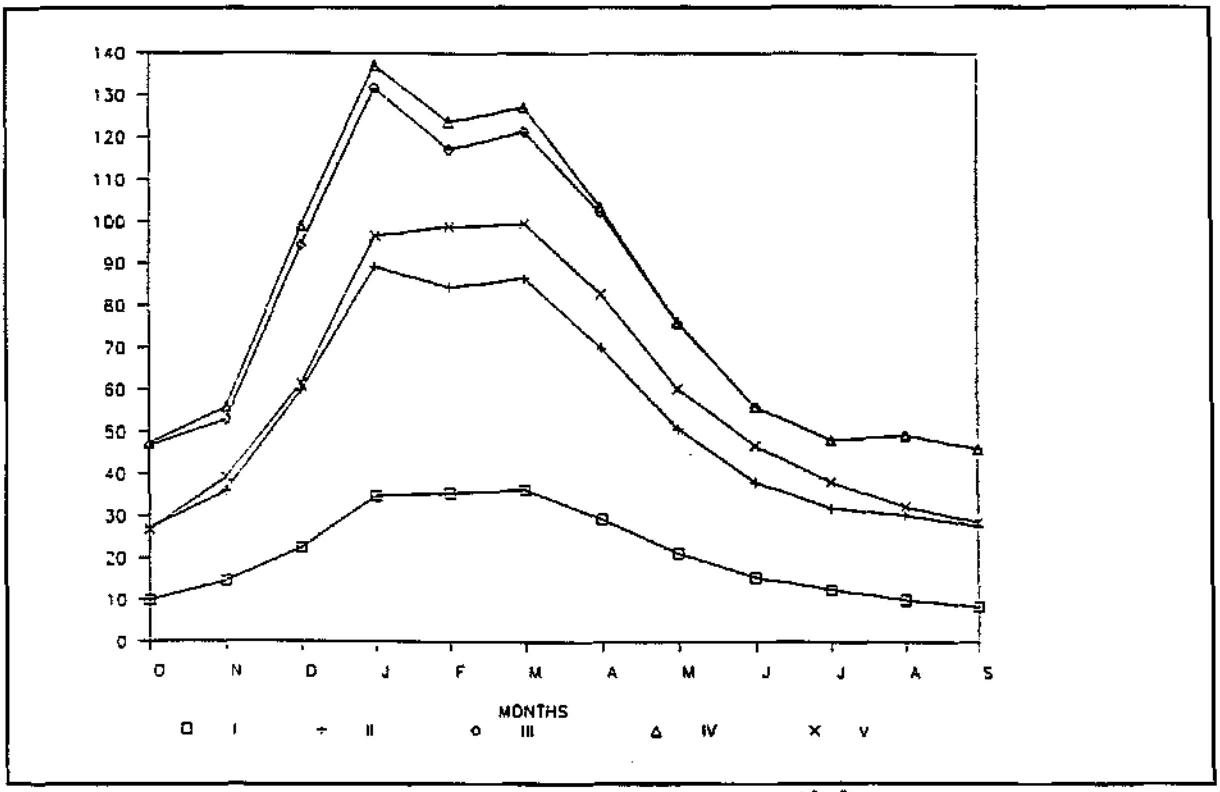
GRAPH 5: Lower Quartiles of monthly flow at site C for each scenario (10^6m^3)



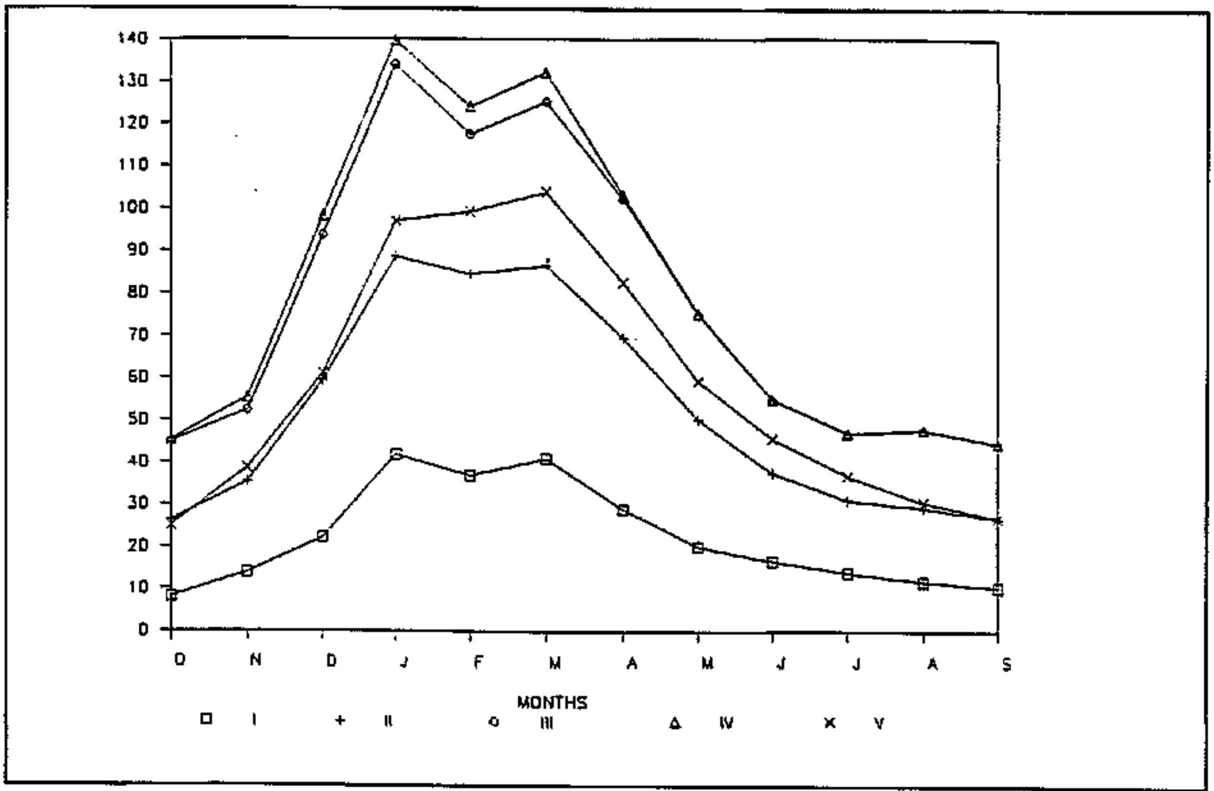
GRAPH 6: Lower Quartiles of monthly flow at site E for each scenario (10^6m^3)



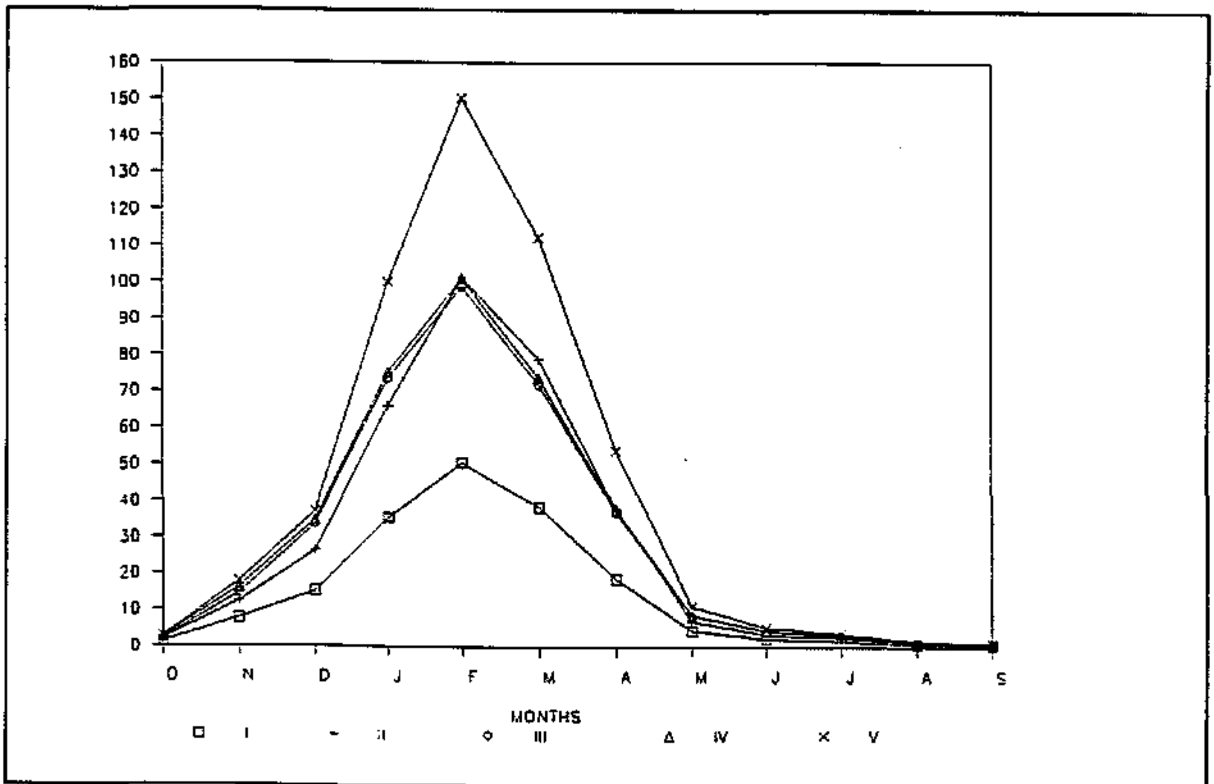
GRAPH 7: Median monthly flows at site A for each scenario (10^6m^3)



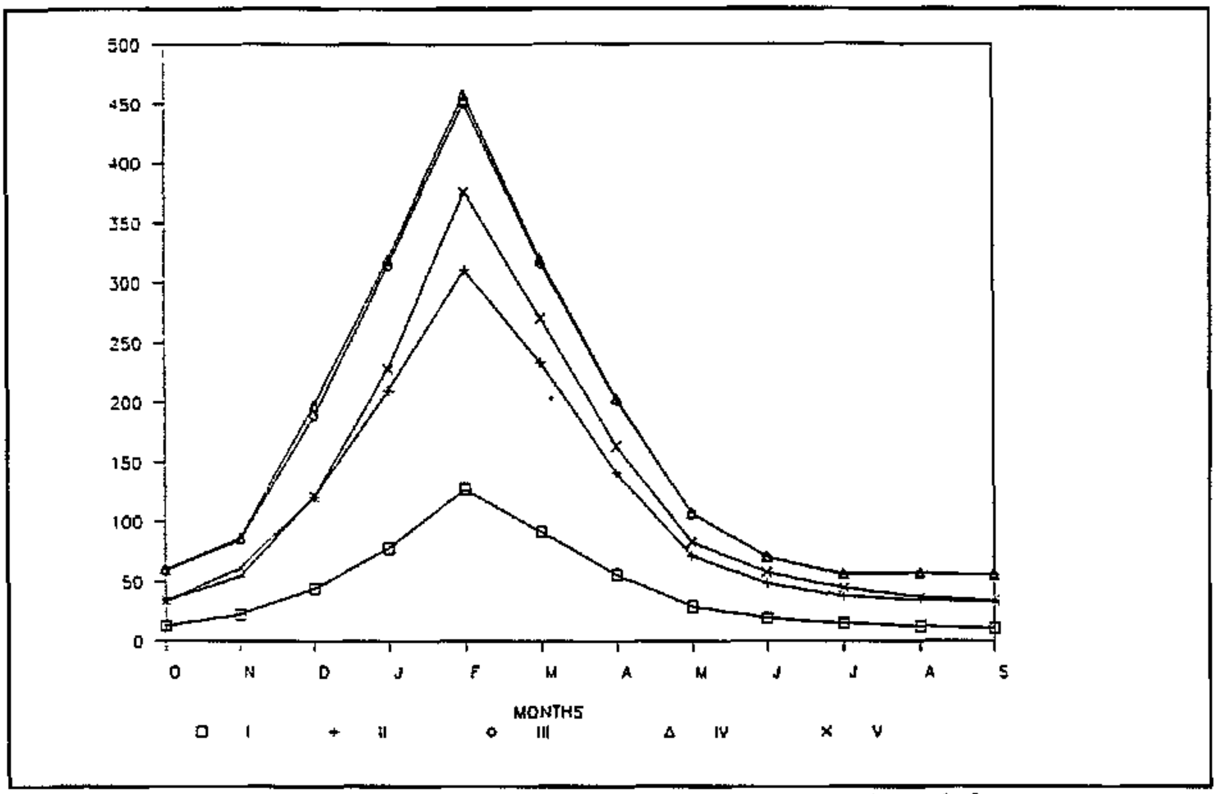
GRAPH 8: Median monthly flows at site C for each scenario (10^6m^3)



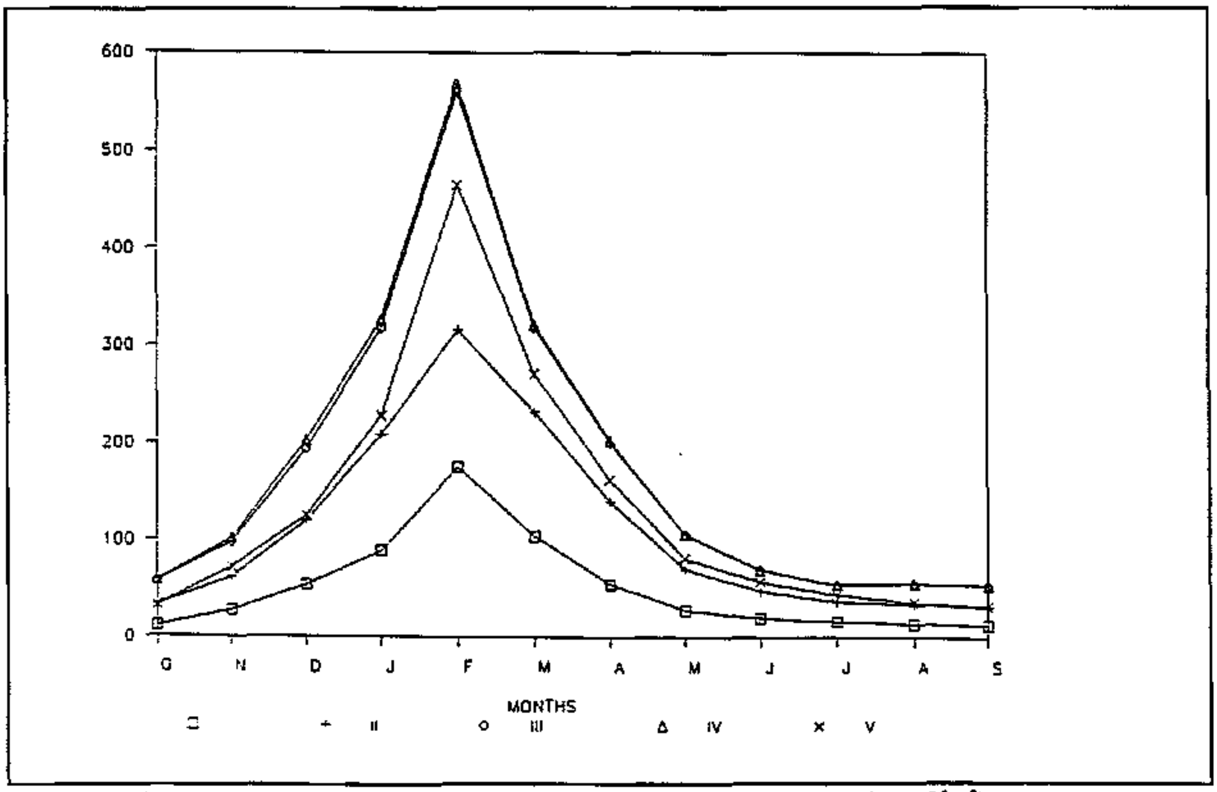
GRAPH 9: Median monthly flows at site E for each scenario (10^6m^3)



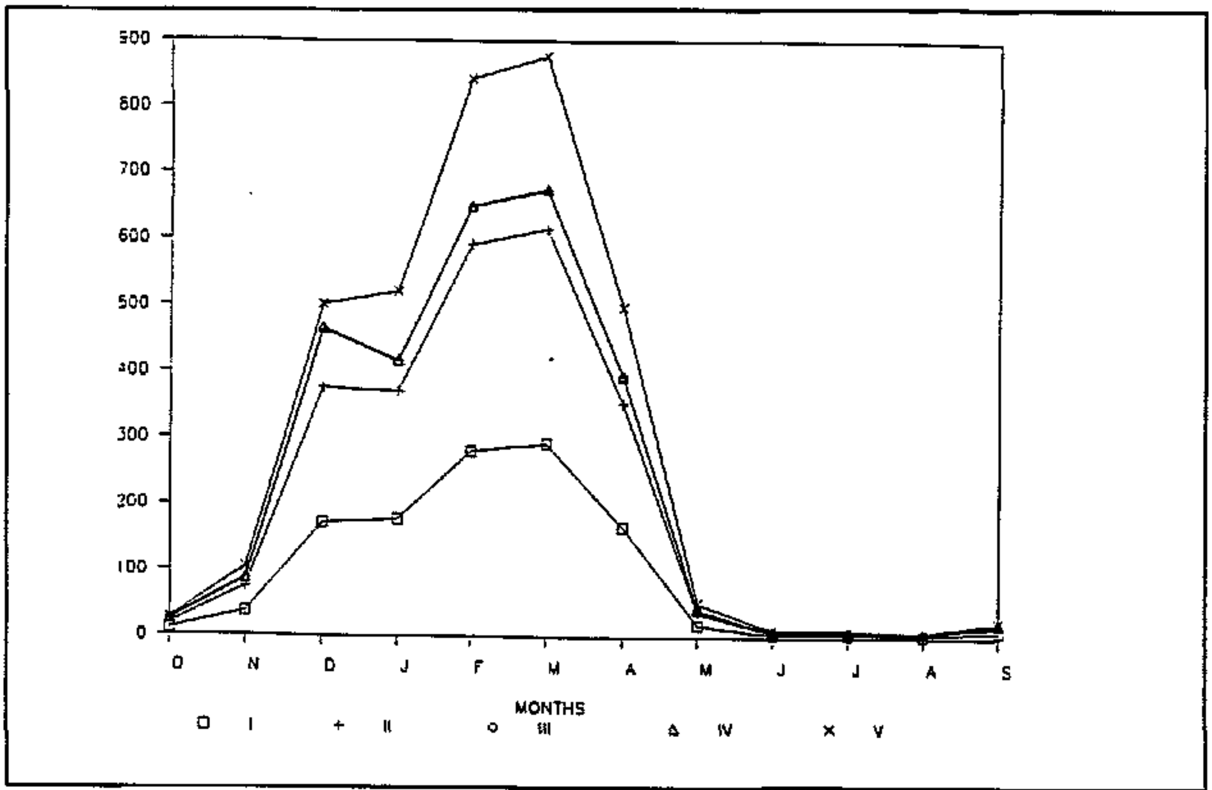
GRAPH 10: Upper quartiles of monthly flow at site A for each scenario (10^6m^3)



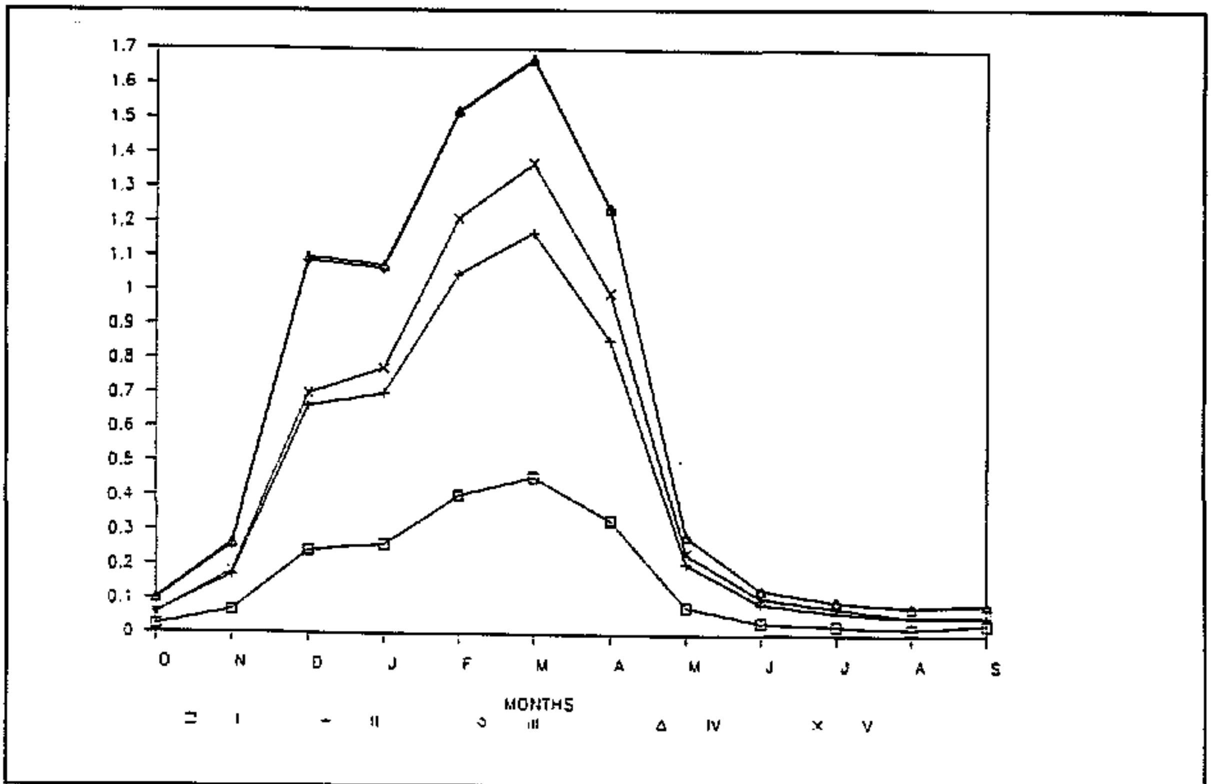
GRAPH 11: Upper quartiles of monthly flow at site C for each scenario (10^6m^3)



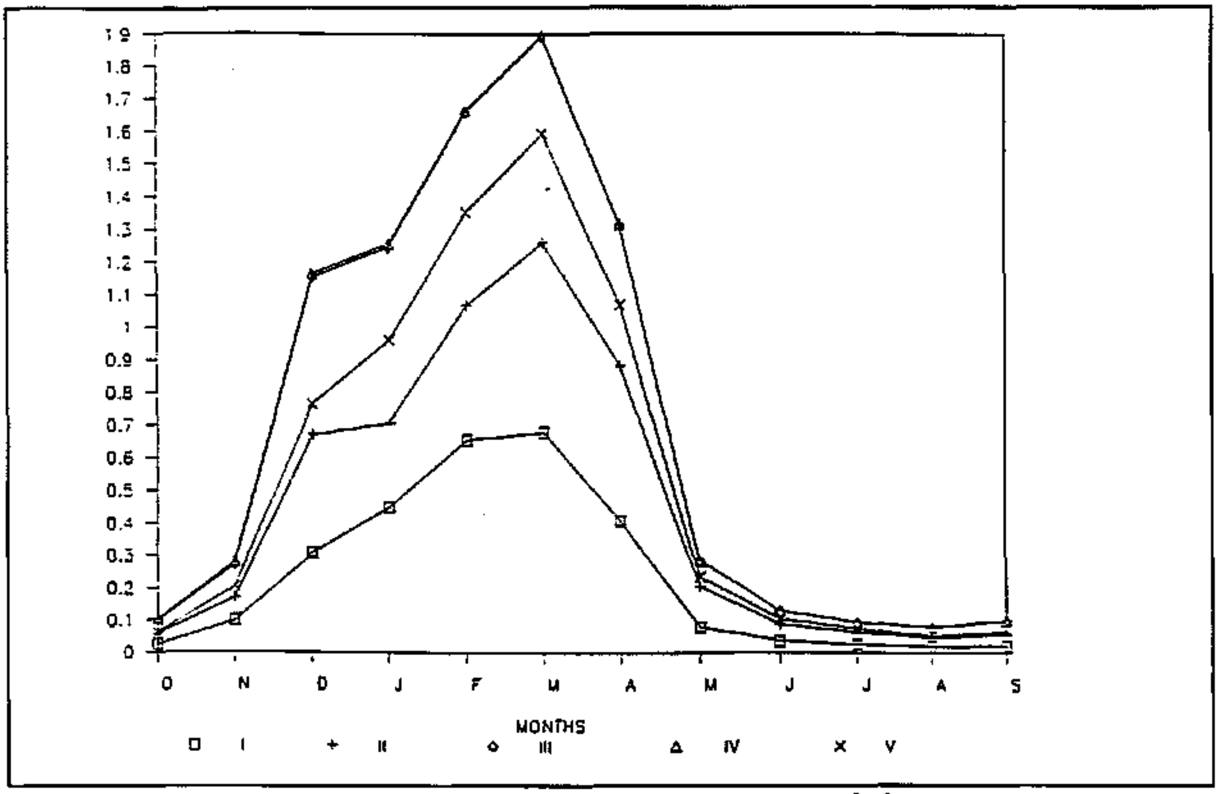
GRAPH 12: Upper quartiles of monthly flow at site E for each scenario (10^6m^3)



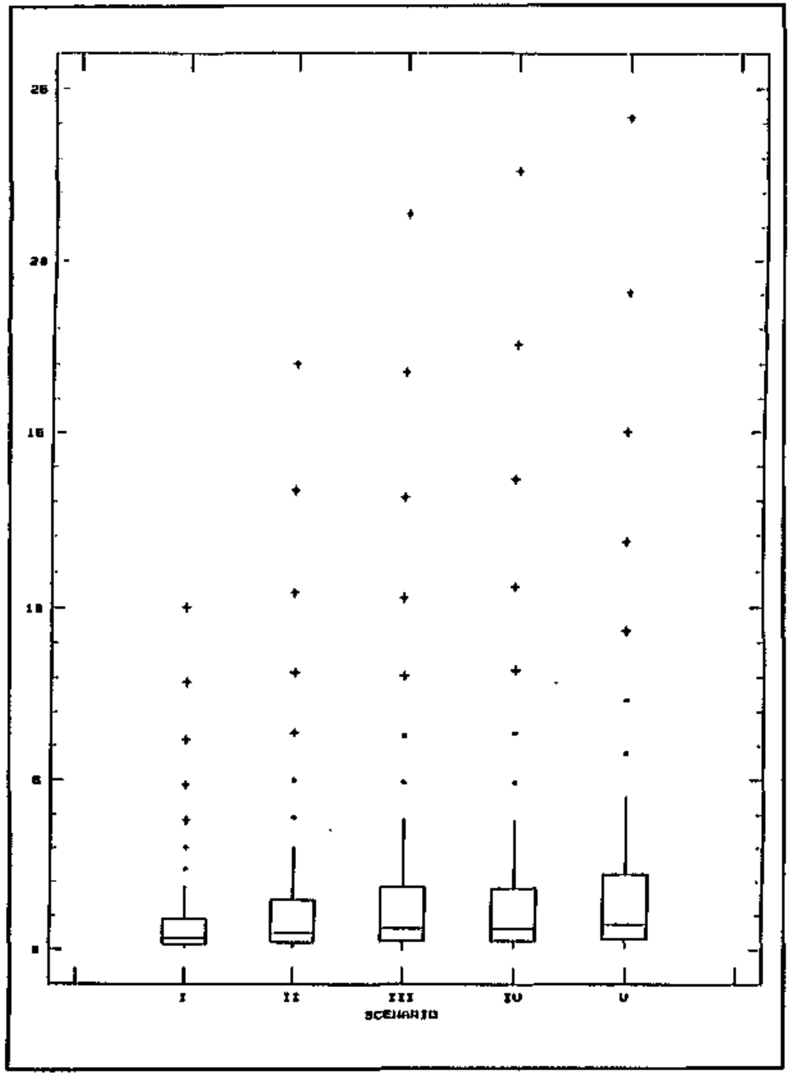
GRAPH 13: Maximum monthly flows at site A for each scenario ($10^6 m^3$)



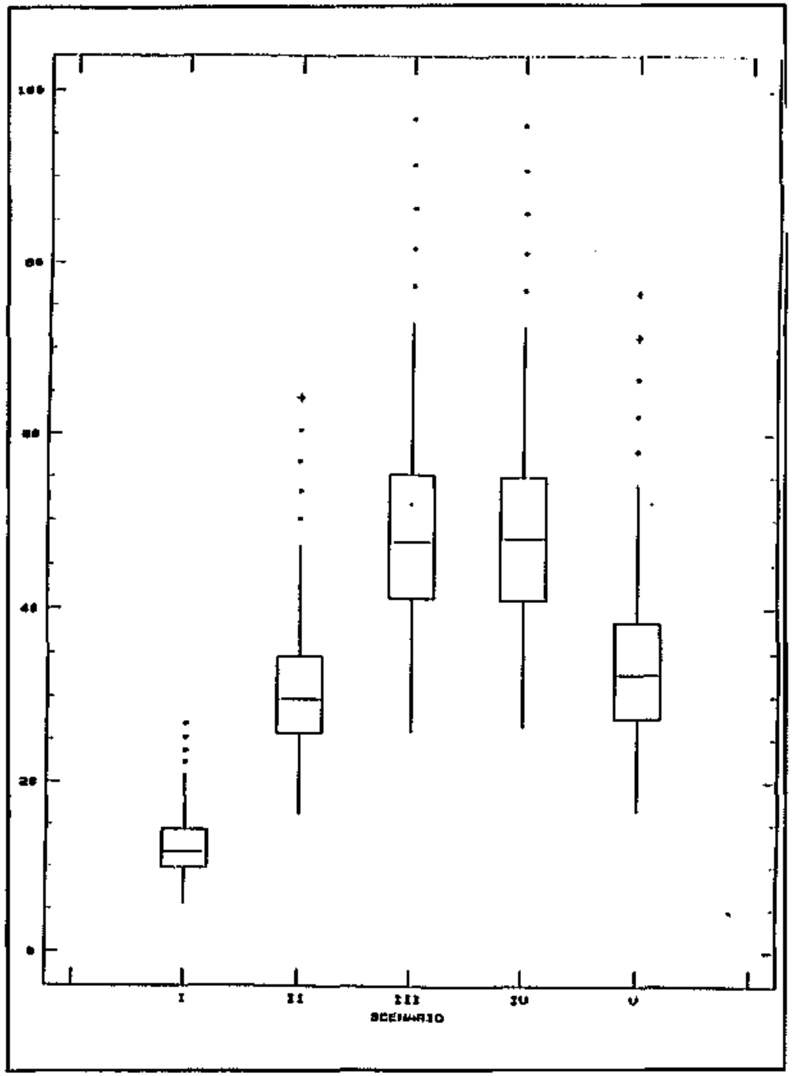
GRAPH 14: Maximum monthly flows at site C for each scenario ($10^9 m^3$)



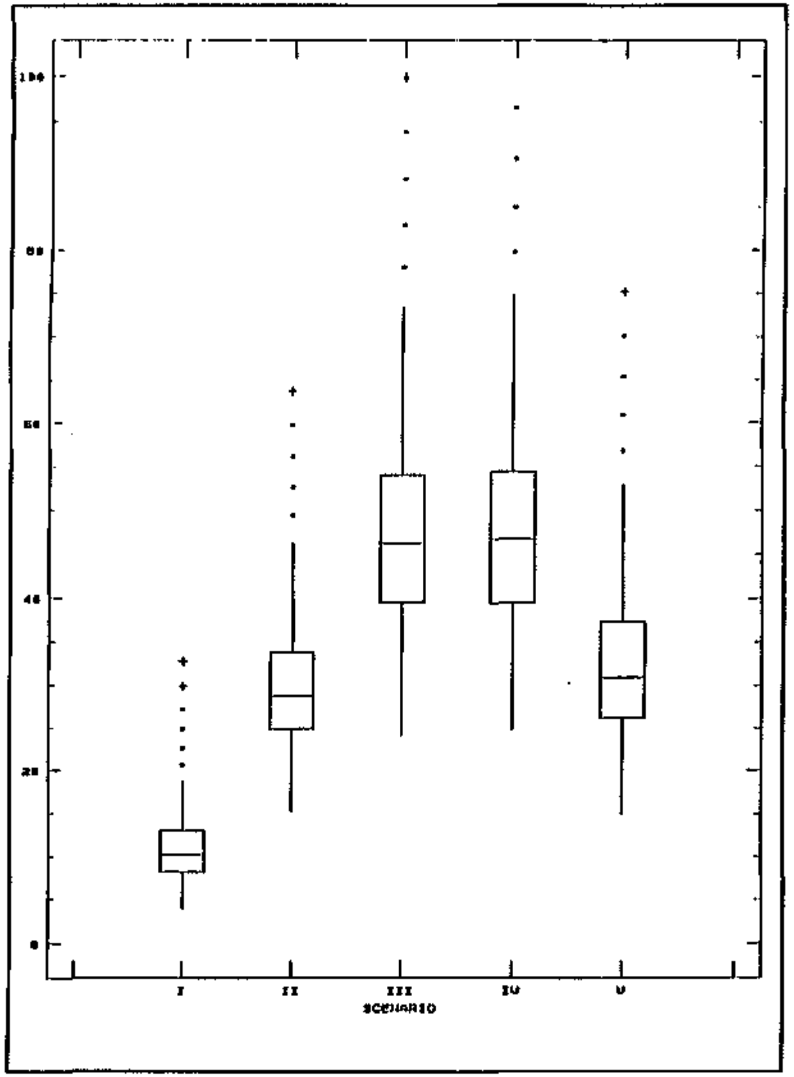
GRAPH 15: Maximum monthly flows at site E for each scenario ($10^9 m^3$)



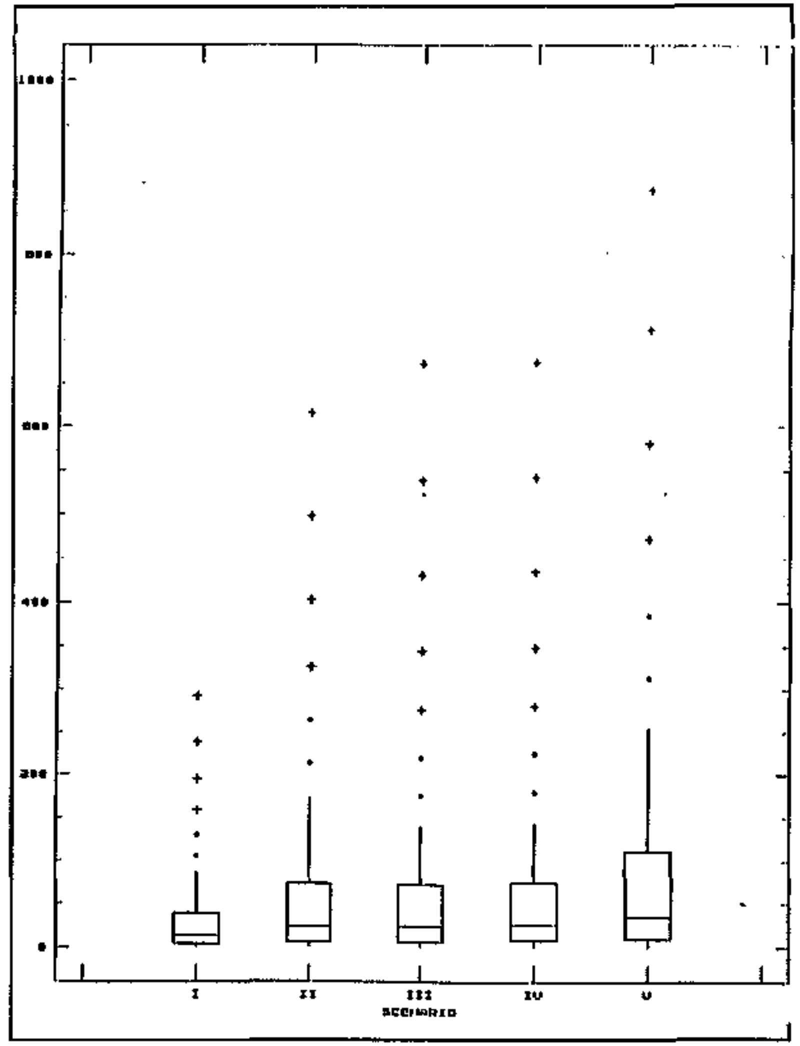
GRAPH 16: Box-and-whisker plot of winter flow distribution at site A ($10^6 m^3$ per month)



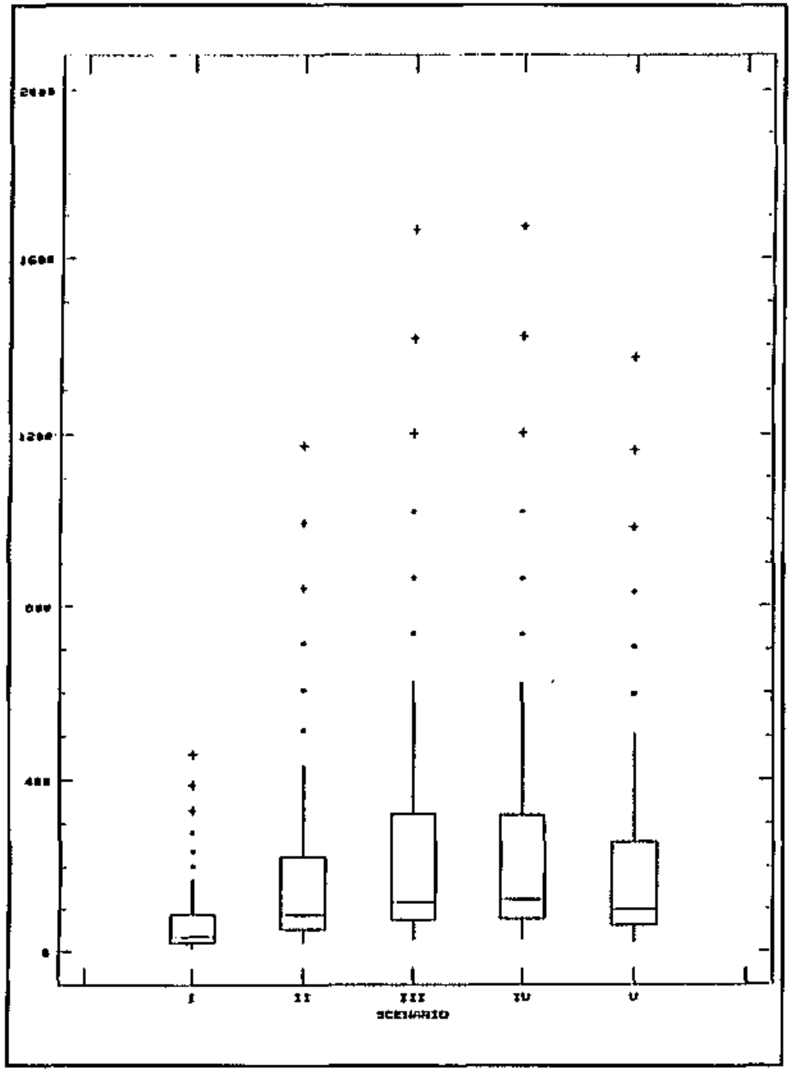
GRAPH 17: Box-and-whisker plot of winter flow distribution at site C ($10^6 m^3$ per month)



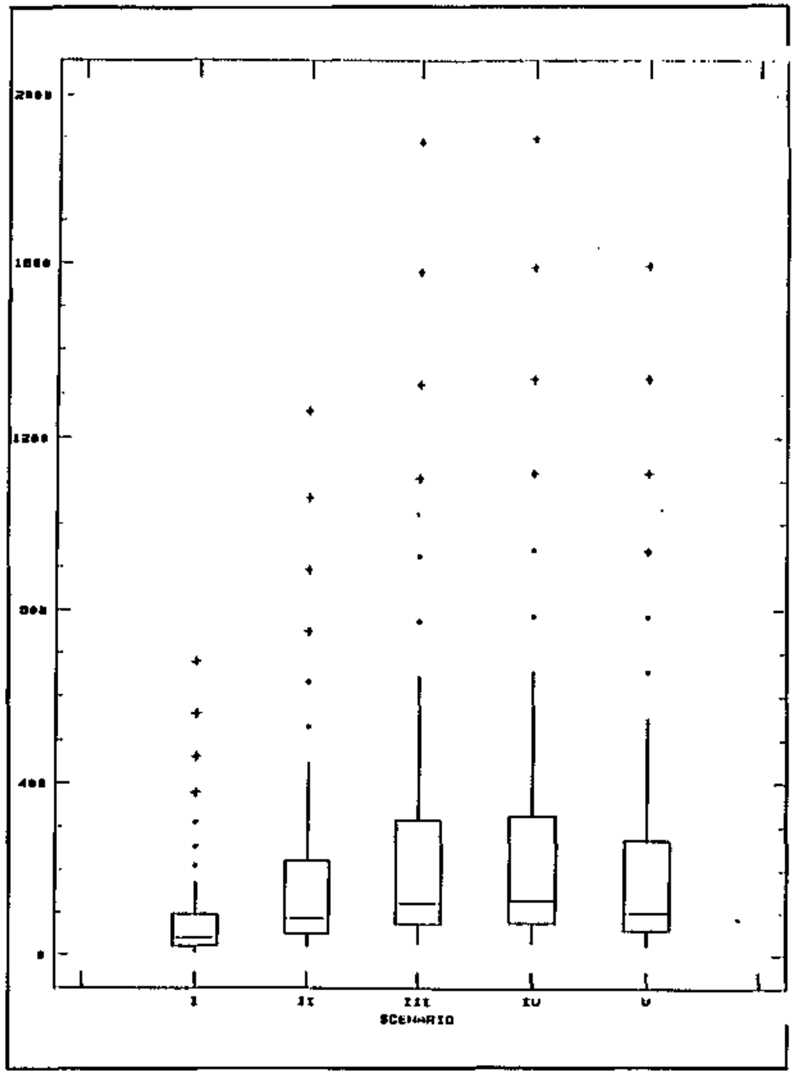
GRAPH 18: Box-and-whisker plot of winter flow distribution at site E (10^6m^3 per month)



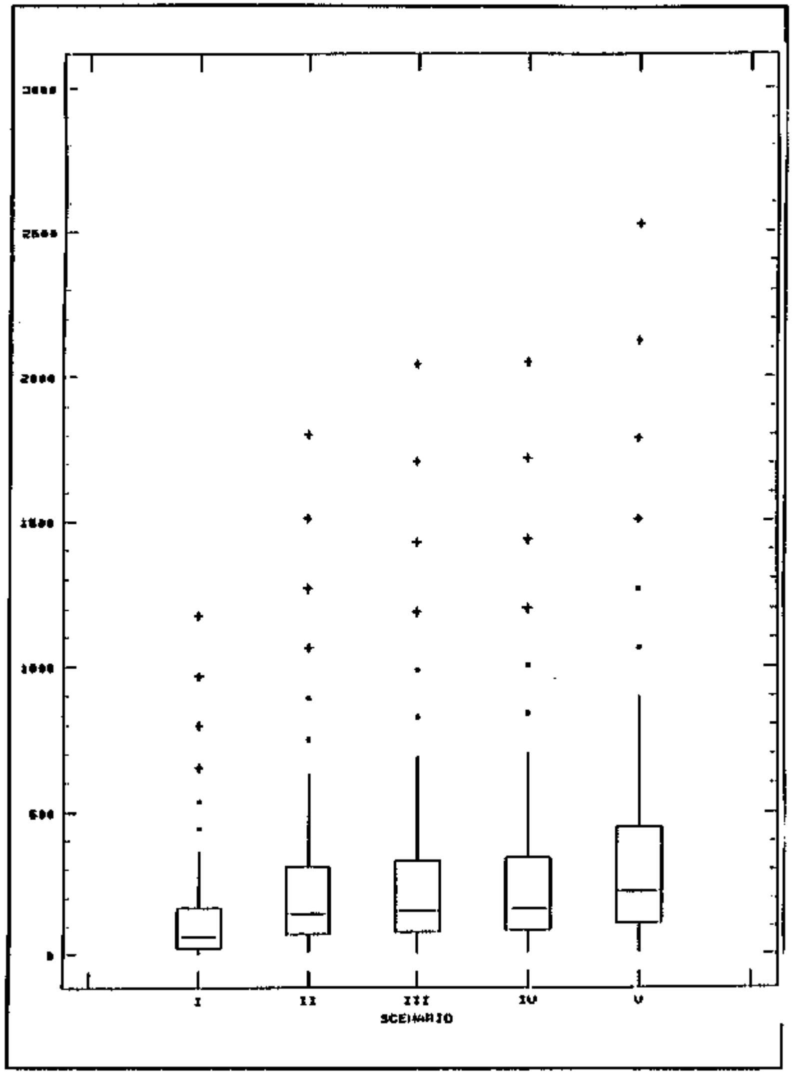
GRAPH 19: Box-and-whisker plot of summer flow distribution at site A (10^6m^3 per month)



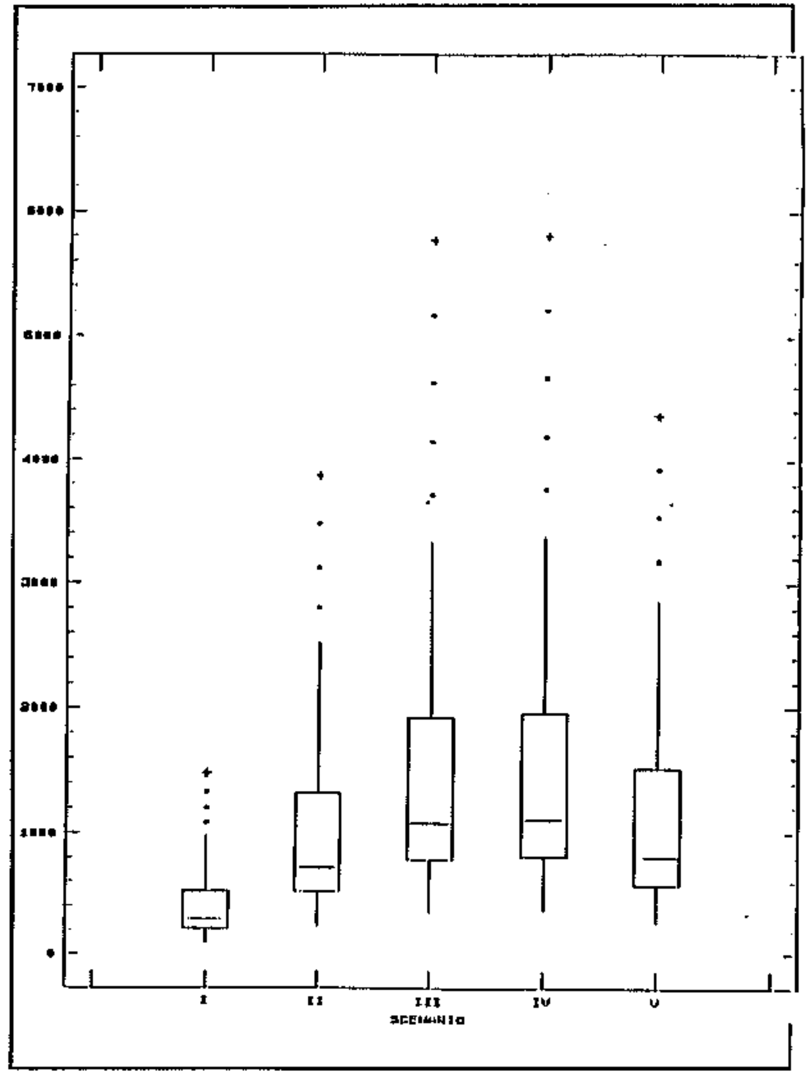
GRAPH 20: Box-and-whisker plot of summer flow distribution at site C ($10^6 m^3$ per month)



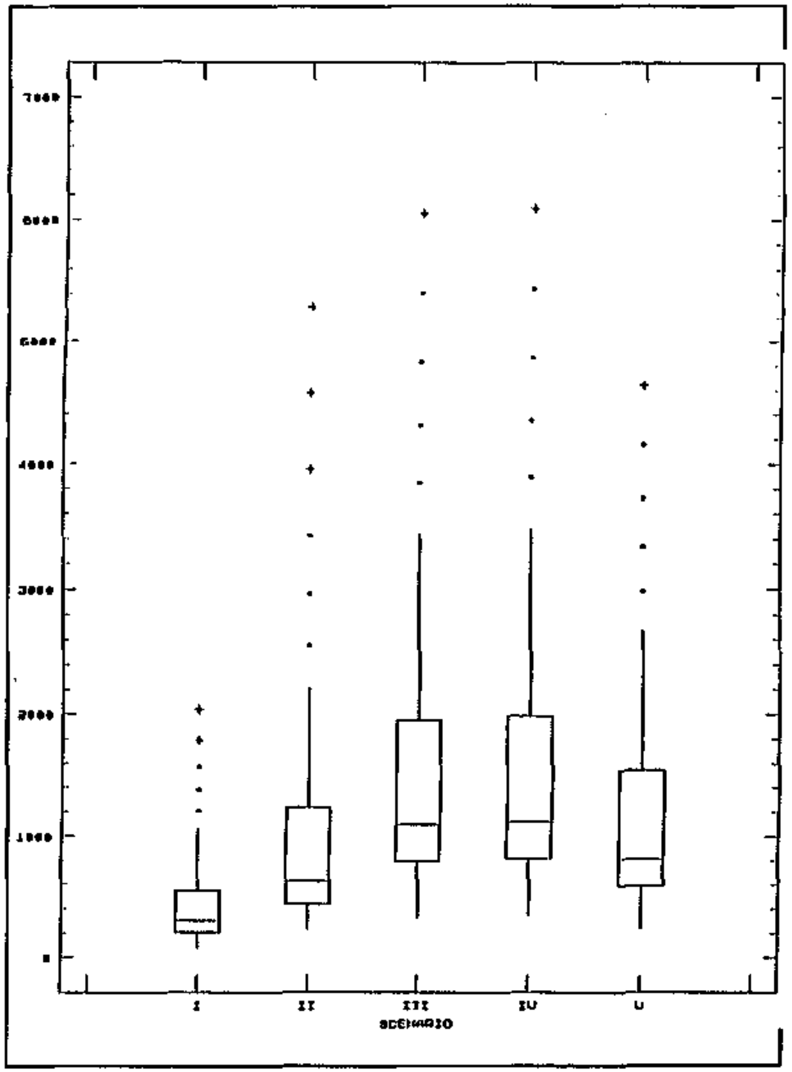
GRAPH 21: Box-and-whisker plot of winter flow distribution at site E ($10^6 m^3$ per month)



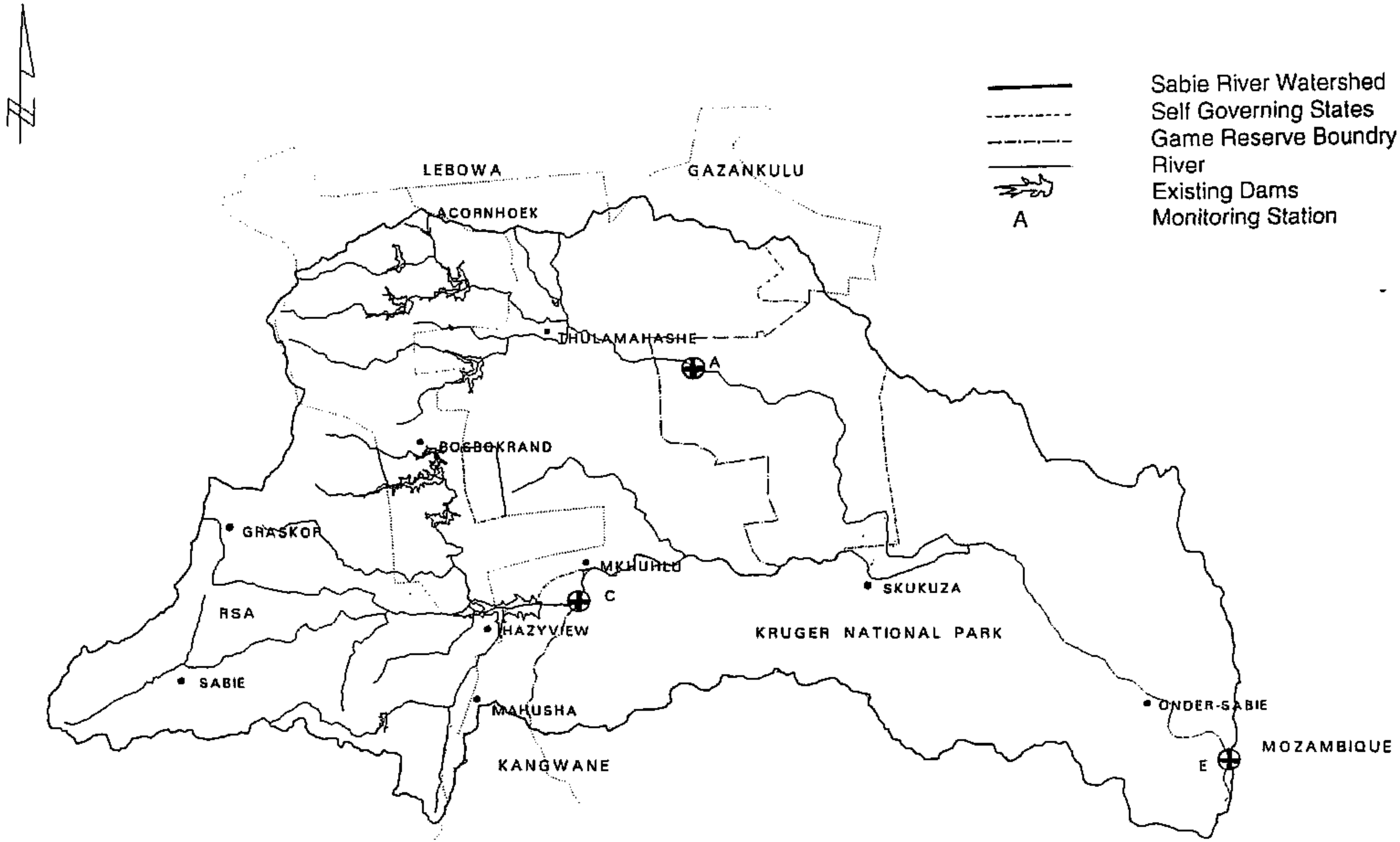
GRAPH 22: Box-and-whisker plot of total annual flow distribution at site A ($10^6 m^3$)



GRAPH 23: Box-and-whisker plot of total annual flow distribution at site C ($10^6 m^3$)



GRAPH 24: Box-and-whisker plot of total annual flow distribution at site E ($10^6 m^3$)



APPENDIX E4: MAP OF THE SABIE RIVER BASIN SHOWING SITES FOR WHICH STREAMFLOW STATISTICS ARE DEFINED FOR THE HYPOTHETICAL EXAMPLES