A decision-making framework for groundwater management in arid zones (with a case study in Namaqualand).

by

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Groundwater management, crystalline aquifers, multiple criteria decision analysis, value function methods, decision model

Abstract

A decision making framework for groundwater management in arid zones (with a case study in Namaqualand).

PhD thesis, Department of Earth Sciences, University of the Western Cape

The main aim of the work on which this thesis is based was to develop a framework for sustainable management of groundwater resources in arid zones with emphasis on Namaqualand in the north-western region of South Africa.

The first part of the thesis focuses on describing the groundwater resource base and legislative framework for groundwater management. Most aquifers in South Africa occur in fractured rock ranging in age from earliest Pre-Cambrian to Jurassic. Primary aquifers are mostly restricted to the coastal plains and river deposits. Characterisation of the fractured rock aquifers has been limited. Thus, an inadequate knowledge base exists in a number of hydrogeological domains to understand the attributes and dynamics of fractured rock aquifers. A serious shortcoming in our knowledge base is to understand the institutional arrangements necessary for proper resource management. This is particularly important in view of the National Water Act of 1998, where groundwater is subject to the same protection measures as surface water. These measures are sophisticated and require tools and technologies to be developed to support sustainable groundwater management and utilisation.

The technical, economic, social, legal, political and environmental issues affecting groundwater management of arid zones of South Africa were analysed. The objectives and appropriate measures to overcome the barriers for sustainable development were also presented. This was necessary to structure the decision problem and to generate and identify the decision alternatives. Thus decision alternatives have been formulated for the various elements of the objectives in order to achieve preferred scenarios.

The main part of the thesis was the development of a decision-making framework for groundwater management in the arid zones of Namaqualand. A multiple criteria decision analysis (MCDA) approach was adopted to assist in the formulation of the decision-making framework. In order to select the most

appropriate MCDA technique, some background was required on the theoretical aspects. A value function method was selected, which provides decision support by interval SMART/SWING. This method incorporates informational uncertainty through interval judgements. The decision problem supported the selection of this method because of the discrete alternatives and uncertainty associated with groundwater management. Further, the method provided an interactive technique to interrogate various decision alternatives based on prior knowledge of the decision-maker.

The software WINPRE was utilised in the value tree construction and analyses. A number of value trees and attributes were defined. These attributes were evaluated against the identified alternatives. This provided a systematic framework for the analytical understanding of the problem. As a result a number of preferred alternatives were elicited.

The analyses resulted in a model for groundwater management in arid zones. The ideal state for groundwater management was presented, but in practice this is difficult to implement, mainly because of human and financial resources. As a result a critical path was established based on the analyses done in this thesis. This was applied to the Namaqualand example. In this example the activities to support a Catchment Management Strategy was identified. This means that the decision-maker is able to focus on issues that are deemed important. More importantly, the method allows the decision-maker to develop the various consequences of the alternatives with stakeholders.

As a result of the decision model a number of strategies were proposed for sustainable groundwater management in arid zones with a case study in Namaqualand. A consequences table were developed which could be used for M&E purposes.

March 2004

Declaration

I declare that *A decision making framework for groundwater management in arid zones (with a case study in Namaqualand)* is my own work, that it has not been submitted for any degree or examination in any other university, and that all the sources I have used or quoted have been indicated and acknowledged by complete references.

Full name.. Date......................................

Signed...

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Table of Contents

Contents

List of Tables

List of Figures

List of Appendices

1 Introduction

1.1 Rationale for the study

In South Africa, groundwater is a national strategic resource, which assists in poverty alleviation and economic development. This is because:

- Approximately two-thirds of the rural population depend on groundwater for their domestic needs.
- Most of the livestock farms, which are crucial contributors to agricultural production at commercial and subsistence level, depend on groundwater.

The continued viable use of groundwater resources, especially in the context of the recently promulgated legislation, will require management systems that integrate groundwater into the broader water resource management framework. This is necessary in order to:

- Ensure at further productive use of groundwater helps to sustain rural livelihoods;
- Optimise the contribution of groundwater to urban water supply systems which take full account of the inter-linkages with surface water;
- Secure the equitable contribution of groundwater to economic development and poverty alleviation;
- Maintain aquifer system integrity (e.g. prevention of over-exploitation and salinisation);
- Protect groundwater resources from pollution and degradation;
- Sustain the proper functioning of ecosystems that depend on groundwater.

Approximately 90% of groundwater resources in South Africa are located in fractured-rock aquifer systems (Appendix B). In such aquifers, groundwater is contained in fractures (hard rocks), fissures and dissolution cavities (dolomite and limestone) and to some lesser extent, also in pores in weathered rock (Vegter, 1995). As a result the storativity and transmissivity compare poorly with primary aquifers where water storage can represent up to 30% of gross volume. Groundwater quality varies throughout South Africa with rainfall and residence time being an important factor in determining quality. The interaction between surface water and groundwater is currently poorly understood. There is recognition that knowledge of these linkages is crucial for proper management of the water resources of South Africa.

Understanding fractured-rock aquifer systems is therefore critical to sustain adequate water supplies to rural communities. In addition, the prevailing socio-economic and broader environmental situations and implications need to be understood in order to ensure that water service provision makes a meaningful contribution to sustainable rural livelihoods. At present, the poor continue to be the most vulnerable to changes in water resource availability and are the least able to adapt their livelihoods in order to cope with change (DFID, 2000).

Since 1994, South Africa has gone through an extensive review of water legislation. This has resulted in the promulgation and implementation of the Water Services Act (DWAF, 1997) and National Water Act (DWAF, 1998). A key focus of these acts is on the provision of adequate water to previously marginalised communities. The National Water Act also corrected an anomaly that considered groundwater as private water beyond the regulatory jurisdiction of the state. This lack of accountability for proper groundwater resource management and use commonly resulted in over-exploitation of groundwater resources (Lazarus, 1998).

The challenges that the implementation of the legislation pose to the hydrogeologist and groundwater resource manager are manifold and diverse (Table 1). Hydrogeologists are still struggling to apply the growing knowledge base effectively to the more efficient management of environmental resources and to improve public and political perceptions of groundwater (Foster, 2000). This is a consequence of there being many remaining knowledge gaps to be addressed, some of which are identified in Table 1. A major need is for the development and application of groundwater decision support systems which integrate current knowledge.

The need for the development and application of a decision support framework for effective groundwater management was clearly illustrated in a study focussing on a groundwater supply and strategy for sustainable delivery of water services in the arid regions of South Africa (Titus et al. 2002). The decision problem consisted of a number of coping strategies to develop a holistic approach to sustainable development of the groundwater resources of the region. In this situation, the decision-maker is often confronted with overwhelming issues. A set of approaches are required that synthesise this information in a coherent framework that allows the decision-maker to identify the critical pathways or activities in dealing with a complex decision problem. A multiple criteria decision analysis (MCDA) approach (Bogardi, 1994; Bender and Simonovic, 1995; Simonovic, 1996; de Jong et al. 1996) needs to form the basis for such a framework. MCDA is a collection of formal approaches which seek to take explicit account of multiple criteria in helping individuals or groups explore decisions that matter (Belton and Stewart, 2002). Decisions matter when the level of conflict between criteria, or of conflict between different stakeholders regarding what criteria are relevant and important, assumes such proportions that intuitive "gut feel" decision making is no longer satisfactory (Belton and Stewart, 2002). The complexity of the decision problems concerning sustainable groundwater management in arid areas provided the motivation for this research which is described in this thesis.

Table 1 Challenges for groundwater resources - identifying knowledge gaps (after Foster, 2000; Xu et al. 2000).

Issue	Challenge (knowledge gap)
Supply	Provision of water services to communities from resources that are located in traditionally low yielding hydrogeological domains.
Abstraction	The lack of public and political awareness of the consequences of excessive groundwater exploitation, and this absence of an adequate consensus for action The need (in many nations) to define groundwater abstraction rights and mobilise stakeholder participation The uncertainty of resource evaluation due to inadequate monitoring of aquifer response to abstraction and recharge
Management	Transformation of government organisations to enable them to facilitate the management process through strategic planning, legal provisions, groundwater databasing and aquifer monitoring. Translation of the principles of sustainable development and integrated water resource management (IWRM) to reality in order to ensure sustainable groundwater management Raising political and public awareness of the need for sustainable development **Development and application of groundwater resource decision support systems** Assignment and consolidation of groundwater use rights and introduction of realistic abstraction charges Stimulation of stakeholder participation through the formation of aquifer user associations Breaking the common resource-management paradigm that groundwater recharge is a fixed parameter with recognition that it varies markedly in a temporal sense with long-term climatic cycles and changes, with surface engineering works and with changes in

	irrigated agriculture and with urban water-service systems Recognition of the interaction and interdependence between groundwater and surface water resources, which often greatly favours their conjunctive use
Protection	Identifying land areas where aquifers are vulnerable to pollution as a result of insufficient intrinsic pollutant attenuation capacity, especially in the capture areas of major groundwater supply sources Controlling the subsurface contaminant load in such areas by exerting appropriate control over existing land-use practices and future land-use planning A more integrated approach to the management of groundwater and wastewater in urban areas
Hydrogeological Sciences	Tools for improved evaluation and prediction of groundwater interactions with the surface water environment Realistic valuation (as opposed to evaluation) of groundwater resources as a basis for more rational abstraction charging. Improved characterisation of groundwater recharge, flow and storage in relation to assessing the role of aquifers in conjunctive use or integrated management schemes and for drought preparedness Improved understanding of subsurface biochemical/biological processes determining the natural contaminant attenuation capacity of aquifers in their vadose and saturated zones Ecological role and function of groundwater (aquatic and terrestrial). Further development of natural and artificial tracer techniques to assess recharge rates and transit times of groundwater in aquifer systems, and thus their vulnerability to surface water contaminants

1.2 Research objectives

This study focuses on the development of a framework for sustainable management of groundwater resources in arid zones of Southern Africa, based largely on the application of knowledge gained through a case study in the Buffels River catchment in Namaqualand (Figure 1).

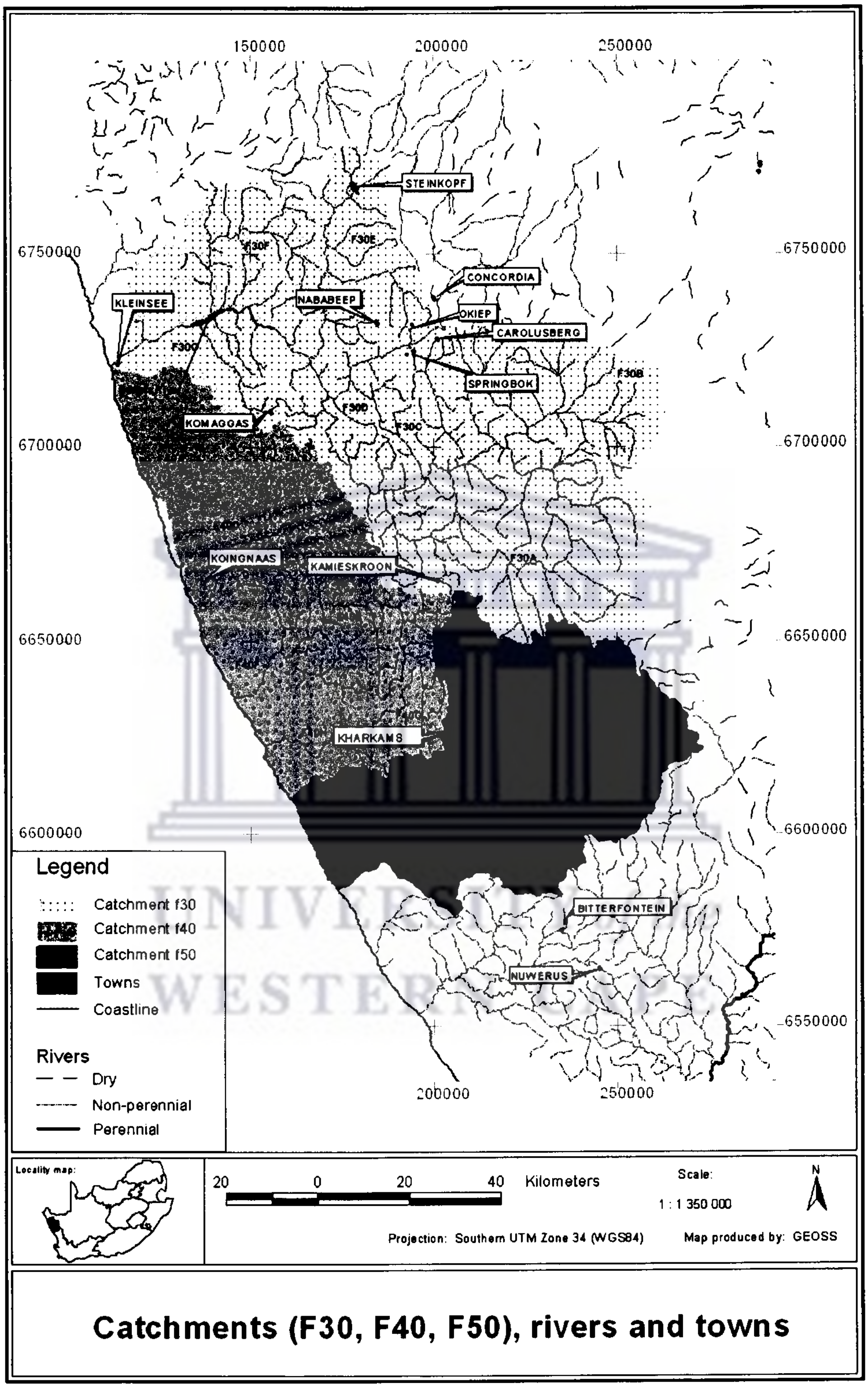

Figure 1 Locality of the study area in the northwestern parts of South Africa (Titus et al. 2002).

The specific objectives of this study were to:

(a) Identify the technical, economic, social, legal, political and environmental issues affecting groundwater management in arid zones of South Africa.

(b) Develop strategies (or objectives) to overcome the barriers to sustainable development of groundwater resources.

(c) Develop a decision-making framework for sustainable groundwater management in arid zones (with special emphasis on Namaqualand).

(d) Develop a monitoring and evaluation system to measure the success of sustainable groundwater supply projects.

The thesis intends to demonstrate that the adoption of MCDA is an effective tool to promote the sustainable development and effective use of groundwater resources in the arid region of Namaqualand. As a consequence the following research hypotheses are formulated:

- Application of a MCDA method is a basis for quantitative analysis of numerous alternative measures for enhancing sustainability of groundwater use in arid zones that represent viewpoints of conflicting groups with different values and management objectives.
- MCDA analysis assists in developing policy responses and strategies for groundwater management at community and catchment scale.
- Information technology tools such as MCDA should be used in a participatory manner to support groundwater management decision-making.

1.3 Research approach

The first part of the study consisted of identifying issues (technical, economic, social, legal, political and environmental) affecting groundwater management in South Africa. Special attention has had to be given to the legislative environment for water resource management because of the recent extensive review of water legislation which resulted in the promulgation of the Water Services Act (DWAF, 1997) and National Water Act (DWAF, 1998).

The second part of the study of the study was aimed at the development of a decision-making framework for groundwater management in arid zones. This consisted of problem formulation, based on an understanding of development needs, management objectives and decision criteria. Both social and technical data gathered through various field investigations were considered in order to generate this understanding (Adams, 1998; Bense et al. 1998; Stevens, 1999, Rydhagen, 1999; Flanagan, 2000; Mafanya, 2000; Davids, 2000; Williams, 2000; Fors, 2000; Clarke 2001 and Titus et al. 2002).

1.4 Contribution of the thesis

The main contribution of this thesis is the provision of a systematic framework for addressing multiple decision alternatives developed for groundwater management in arid zones. This is in view of the over-whelming amounts of information and competing needs that a decision-maker is confronted with in executing his/her duties. The implementation of a groundwater supply scheme is normally also done in an environment of limited financial resources. A critical path (or a best set of approaches) was established as a means towards achieving sustainable groundwater-based rural livelihoods. Further, a monitoring and evaluation (M&E) system was established based on a consequences table, which presents indicators for groundwater management. The above outcomes constitute a total framework for use by the groundwater resource manager when considering multiple issues (both social and technical) in the process of making sound decisions for better resource management.

Other, supplementary, contributions of the thesis include:

- The identification of key social and technical issues related to groundwater management in arid zones.
- Formulation of various decision alternatives and constraints within the context of groundwater management in arid zones.
- The application of an interval assessment MCDA approach to water resource management.
- The incorporation of community needs (obtained through various socio-economic studies) in the decision-making framework.

1.5 Structure of the thesis

Following on this introductory chapter, Chapter 2 presents the legislative framework for groundwater management in South Africa.

Chapter 3 provides the background information to the study. This chapter formulates the decision problem by identifying the key social and technical issues related to groundwater development. It focuses on structuring the problem with a view to the effective use of MCDA tools.

Chapter 4 presents an overview of MCDA methods. This includes a discussion on the decision aid process and the philosophical basis of MCDA. The different MCDA methods are then classified based on the attributes of the models as documented in the literature. Lastly a protocol is developed to select the appropriate MCDA approach for the resolution of the decision problem as formulated in Chapter 3.

In Chapter 5 the axiomatic conditions and theoretical foundations for Value Function methods by interval assessments are presented and described.

Chapter 6 constructs the value tree for sustainable groundwater resource management. This is based on the objectives, attributes and decision alternatives developed in Chapter 3. An interval assessment methodology is utilised as described in Chapter 5.

Chapter 7 consolidates the results of the preceding chapters into a decision making framework for groundwater management in arid zones.

In Chapter 8 a monitoring and evaluation system is presented based on a consequences table of the respective attributes.

Chapter 9 presents the conclusions and recommendations emanating from the study.

2 Legislative framework for groundwater management in South Africa

2.1 Introduction

South Africa water legislation considers groundwater as a national resource to be managed in a sustainable manner. The Water Services Act and National Water Act (DWAF, 1997; DWAF, 1998) provide the framework for delivery of water services while also providing a combination of legal obligations, rights, responsibilities and constraints for the sustainable development and management of water resources in South Africa.

The National Water Act provides the framework for the attainment of IWRM principles. The Act recognises the unity of the water cycle, and the interdependency of all its elements, both in terms of quantity and quality. There is further recognition that the protection of water resources falls within a broader framework of integrated environmental management. The requirements of the National Water Act represent a challenge to groundwater resource managers at an operational level. Before the Act was promulgated, landowners were entitled to unlimited use of groundwater resources (riparian doctrine).

The focus of groundwater management in South Africa, for the foreseeable future, will be on equitable allocation for economic development, maintaining resource integrity and meeting basic human needs. The challenge is to implement these principles in reality. Management strategies will be needed to address the unique characteristics and role of groundwater, while at the same time preserving the concept of a common resource.

2.2 Legislation prior to 1994

The water law in South Africa prior to 1994 was based on the development needs (domestic, agricultural and industrial) of white settlers. Roman law, Roman Dutch law and later English and American law shaped South African water law (Kavin, 2000). The result of this was the distinction made between public and private water (riparian principle). The riparian principle entitled landholders to unlimited use of private streams and groundwater resources found on their land. In 1912 the Irrigation and Conservation of Waters Act was introduced, which dealt mainly with irrigation. Priority use of water was given to agriculture. This legislation was repealed in 1956 through the introduction of the Water Act. This was necessary, due to the rapid growth of mining and industry. However, the Act entrenched the concept of private water and there was no obligation to share resources equitably. The lack of accountability for proper groundwater resource management and use commonly resulted in over-exploitation of groundwater resources (Lazarus, 1998). The Water Act 54 of 1956 made the following distinction between different categories of groundwater (Lazarus, 1998; Kavin. 2000):

- Subterranean water
- Public Surplus water
- Deemed Private water

Subterranean water was a special category of groundwater, the right-to-use and control of which was vested in the Minister. This was done through the declaration of a subterranean Government water control area and, as a result, different allocation rules applied. The currently proclaimed Subterranean Government Water Control Areas are listed in Table 2. Existing subterranean water control boards will continue in operation until they are restructured as water user associations (DWAF, 1998).

Provisions in the Water Act of 1956 (which still apply in most cases) limited the use of groundwater in subterranean water control areas, as a measure for groundwater management. Section 30(1) of the Water Act of 1956 implies a distinction between unused water and water that was allocated and used immediately prior to the declaration of a subterranean government water control area. The right to use and control water that was allocated and used immediately prior to the declaration of the control area is vested in the land owners to which the right was previously allocated (Lazarus, 1998; Kavin, 2000). The right-to-use and control subterranean water only vests in the Minister if the water was unallocated or unused immediately prior to the declaration of the area as subterranean government water control area (Lazarus, 1998; Kavin, 2000).

Table 2 Subterranean Government Water Control Areas (DWAF, 2003).

Name	Geology	Extraction $10^6 m^3$/year	Reasons for proclamation
Uitenhage	Chalk formation, Tertiary	6.78	The safeguarding of artesian sources against indiscriminate drilling.
Kroondal-Marikana	-	24	Request of farming community for safeguarding of groundwater extraction against excessive pumping by the platinum mines.
Bo-Molopo	Dolomite	68	Safeguarding of groundwater for urban supply
Baden	Table Mountain sandstone and Bokkeveld shale	< 1	Complaints of a few farmers
Nyl River Valley	River alluvium and adjacent hard rock	>7	Envisaged artificial recharge of alluvium in Nyl River and the protection of groundwater sources for urban water use.
Saldanha	Tertiary to recent unconsolidated sediments	< 1	Safeguarding of envisaged urban water supply
Crocodile River Valley	River alluvium and adjacent hard rock	50	To prevent over-exploitation and control river flow. Also to control releases from Vaalkop and Roodekoppiesdam effectively.
Strandfontein	Tertiary to recent unconsolidated sediments	0.175	Safeguarding of town supply
Lower Berg River Valley	Tertiary to recent unconsolidated sediments	< 2	Safeguarding of source for future large urban supply
Yzerfontein	Tertiary to recent unconsolidated sediments	0	Safeguarding of source for future large urban supply
Wadrif	Tertiary to recent unconsolidated sediments	0	Safeguarding of source for future large urban supply (Lamberts Bay)

A second category of groundwater potentially subject to regulation in terms of the 1956 statute was water which fell within the statutory definition of public water. Surface water (streams) qualified as public water; such water was further categorized as either normal flow or surplus water (Lazarus, 1998; Kavin, 2000). Since underground water could not qualify as normal flow since it did not visibly flow, it qualified as surplus water which was any public water other than normal flow (Lazarus, 1998; Kavin, 2000). As such, it effectively escaped any form of strict regulation, and in essence was no different from private water (next category).

The final category of groundwater was water that was pumped from underground such as water from boreholes. Provided this water was not derived from a public stream, the 1956 Act deemed this water to be private water (Lazarus, 1998; Kavin, 2000). It is this categorization of groundwater as 'deemed private water' that in the past created the greatest obstacles to water managers concerned with managing all water resources in the national interest (Lazarus, 1998; Kavin, 2000). The sole and exclusive use and enjoyment of private water vested in the owner of the land on which it is found (Lazarus, 1998; Kavin, 2000).

The lack of explicit recognition of the public nature of all groundwater in the Water Act of 1956 was an inexplicable anomaly, because most hydrologists in the world recognise the continuity of the hydrologic cycle. The National Water Act of 1998 rectified this anomaly by recognising groundwater as public water. This was previously also reflected in the following of the Water Law Principles (DWAF, 1997) which guided the process of water law reform:

- **Principle 2:** All water, wherever it occurs in the water cycle, is a common resource to all, the use of which shall be subject to national control. All water shall have a consistent status in law, irrespective of where it occurs.
- **Principle 4:** The location of water resource in relation to land shall not in itself confer preferential rights to usage. The riparian principle shall not apply.
- **Principle 5:** In a relatively arid country such as South Africa, it is necessary to recognise the unity of the water cycle and the interdependence of its elements, where evaporation, clouds and rainfall are linked to groundwater, rivers, lakes, wetlands and the sea, and where the basic hydrological unit is the catchment.
- **Principle 6:** The variable, uneven and unpredictable distribution of water in the water cycle should be acknowledged.

2.3 The National Water Act of 1998

The National Water Act introduces the following measures:

- Formal recognition of the unity of the hydrologic cycle;
- Provision for resource protection and sustainability (through resource directed measures and source directed controls);
- Confirmation of water as a national resource under national management;
- Obligations to meet rights of neighbouring states with regard to shared watercourses;
- Decentralisation of water management within a national framework;
- Limitation of rights into perpetuity;
- Requirement to allocate water specifically to achieve socially and economically optimal water use;
- Formal requirement for water conservation and demand management;
- Economic pricing of water.

The framework, within which groundwater resources will be allocated, is summarised in Figure 1. The **first step** is the establishment of a vision for the resource. At national level this is done through the National Water Resource Strategy (NWRS) and in consultation with the relevant stakeholders in each water management area (WMA). South Africa has been subdivided into 19 WMAs.

The **second step** is to implement Resource Directed Measures (RDM) to protect the capability of water resources (groundwater included) to support utilisation in the long term. RDM, which are being progressively developed, are provided for in the National Water Act (DWAF, 1998). The RDM consists of three core concepts (DWAF, 1999):

(a) **Classification.** Under a national protection-based classification system, water resources can be grouped into classes representing different levels of protection. The risk of unacceptable impact on the resource through utilisation, which can be accepted in each class, is inversely related to the level of protection required for that class. This provides a nationally consistent basis and context for deciding on an acceptable level of short-term risk, weighed against the requirements for long-term protection of a water resource. For water resources, which are especially important, sensitive, or of high value, little or no risk would be acceptable, and they would be assigned a high protection class. In other cases, where the need for short to medium term utilisation of a water resource may be more pressing: the resource would still be protected, but would be assigned a class which reflects a higher risk

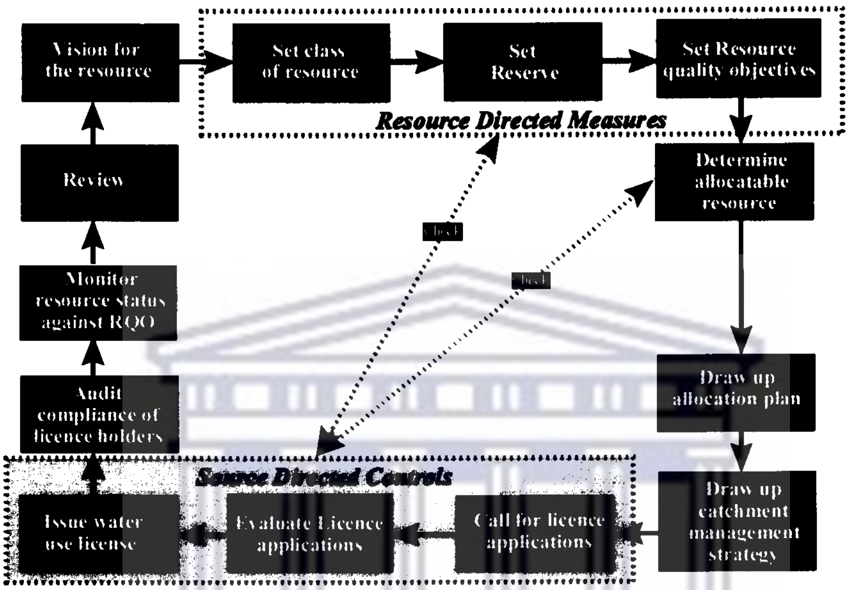

Figure 2 Legislative framework for groundwater management in South Africa (DWAF, 1999).

(b) **The Reserve.** This is defined by the Act as "the quantity and quality of water required:

- To satisfy basic human needs by securing a basic water supply for people who are or who will in the reasonably near future be relying upon, taking water from, or being supplied from the relevant water resource; and
- To protect aquatic ecosystems in order to secure ecologically sustainable development and use of water resources."

(c) **Resource Quality Objectives (RQOs).** The RQOs for a water resource are a numerical or descriptive statement of the resource quality conditions, which should be met in the receiving water resource, in order to ensure that the water resource is protected. RQOs are scientifically derived criteria, based on the best available scientific knowledge and understanding. They represent our best assessment of the resource quality, which is necessary to provide a desired level of protection to a water resource, with a particular degree of assurance or risk.

The **third step** is to determine the allocatable portion of the resource, once the RDM have been determined. The allocation plan must address issues such as facilitating social and economic development. The right to use of water is established in the National Water Act on condition that one or more of the following stipulations apply:

- Permissible under Schedule 1 (minimal or no impact)
- Permissible as a continuation of an existing lawful use
- Permissible in terms of a general authorisation (low risk of unacceptable impact)
- Authorised under a licence (high risk of unacceptable impact if not controlled)

General authorisations for groundwater have been given for South Africa (Table 3). In arid zones only Schedule 1 uses are permitted, while groundwater-stressed catchments have been excluded from general authorisations. The efficient and sustainable use of water resources is encouraged through the adoption of water conservation and demand management practices.

Table 3 General groundwater use authorisations in South Africa (Braune, 2000)

Zone 1	**General Authorization (m^3/ha/annum)**
1 (arid regions)	Only Schedule 1 use
2	≤ 60
3	≤ 300
4	≤ 750

The **fourth step** is to implement source directed controls to prevent or minimise impact on groundwater resources. This is done through regulatory controls and incentives. The Department of Water Affairs and Forestry proposes to effect its policy goals through, among other things:

- Establishing an understanding of the importance and vulnerability to pollution of the country's groundwater resources, and
- Establishing an understanding of the relationship between polluting activities (sources) and quality effects in the groundwater, i.e. understanding the origin of pollutants, the pathways

which these pollutants could follow into the environment and the ultimate fate of these pollutants.

The **final step** is the implementation of a monitoring and evaluation system to determine whether the policy goals are being implemented and having the desired outcomes.

2.4 Summary

The legislative framework for groundwater management has been established. Previously groundwater management was beyond the jurisdiction of the state. The National Water Act recognises the unity of the hydrological cycle, which means groundwater is subject to the same protection measures as surface water. These measures are sophisticated and require tools and technologies to be developed to support sustainable groundwater management and utilisation in South Africa, as also recognised in Table 1.

Achieving sustainable and optimised aquifer management is complex. Poor assessment of groundwater resources, inadequate analyses of the consequences of groundwater exploitation, or lack of technical understanding and inadequate institutional frameworks, may lead to management decisions that could cause irreversible loss of stored groundwater or quality of groundwater, or even the aquifer storage capacity. In managing the resource, decision makers need to consider multiple issues. The next chapter presents the decision problem for groundwater management in arid zones.

3 Decision Problem

3.1 Introduction

Crystalline metamorphic and igneous terrains are found extensively in the northern provinces of South Africa (Appendix B). The availability of significant groundwater resources is therefore crucial for sustainable rural livelihoods. Groundwater is, more often than not, the only viable water supply to local communities. The groundwater resources of the Namaqualand region are a prime example of resources derived from crystalline metamorphic and igneous basement aquifers, upon which rural communities are heavily dependent.

The development of a decision-making framework for addressing widely-ranging technical and socio-economic issues will greatly assist in promoting sustainable development and effective use of groundwater resources in the region. The decision-maker is often confronted and in some cases over-whelmed, with conflicting needs and supporting information when faced with having to decide on how best to use limited resources in implementing water services programmes. A set of approaches are required that synthesise this information in a coherent framework that allows the decision-maker to identify the critical pathways or activities in dealing with a complex decision problem. This chapter formulates the decision problem by identifying the key social and technical issues related to groundwater development in the region. It focuses on structuring the problem with a view to the effective use of MCDA tools (Chapter 5). Necessary steps are to:

- Understand the social and resource context and available decision tools
- Review the decision context
- Identify the objectives
- Generate and identify the decision alternatives

3.2 Background information

3.2.1 Social context

The study region has an area of 47 700 km^2 and a population of 60 000. Mining is the main contributor to the economy of the region. The poverty levels are high, as is unemployment (Younge, 2002). This is because the region has relied heavily on non-renewable resources that are now becoming exhausted (Odendaal, 2001).

The Namaqualand District Municipality consists of 14 small urban settlements, six communal areas, large areas of white-owned farm land and mining company property. The six communal areas are Richtersveld, Steinkopf, Leliefontein, Komaggas, Concordia and Pella. Livestock farming is the predominant agricultural activity in the communal areas, which have animal populations of 160 000 small stock, 3 000 cattle and 8 500 donkeys – more than twice the recommended carrying capacity (Hoffman et al. 2000).

The following land-use pressures have been identified as the top threats to biodiversity (Boonzaaier et al. 2002) and therefore to the flow of environmental goods and services on which society depends:

- Mining activities
- Overgrazing
- Harmful farming methods (pesticides, grazing methods, fertilizers)
- Ad hoc tourism development
- Unmanaged tourism activities
- Lack of awareness of conservation amongst local people
- Poaching (reptiles and succulents in particular)
- Lack of coherent planning for conservation and development

The Namakwa Water Board is responsible for water supply in the region. Surface water supply from the Orange River is restricted to the larger towns such as Springbok and Nababeep. This is largely due to the remoteness of the rural settlements. Consequently, groundwater is largely the only option available to these communities.

Currently communities in Namaqualand are also at risk because the way in which groundwater is managed is unsustainable, for the following reasons (Titus et al. 2002):

(a) the sustainable yield of current boreholes cannot meet the required demand;

(b) The natural quality of the groundwater does not conform to health guidelines;

(c) The region is prone to drought conditions (meteorological, hydrological and agricultural);

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... and by Toens et al (1991a, b, c, d, 1991). Most of the work was related ... ctive is given in Toens et al (1993) ... by Stevens (2002); Davids (2003); ... (2002) developed a groundwater ... pply in the region. The occurrence, flow, storage and water quality characteristics of aquifers in the Namaqualand region are described in Appendix B (Section B.2).

3.2.3 The groundwater resource management dilemma

There is wide recognition that a holistic, systematic approach relying on IWRM must replace the current fragmentation in managing water (World Water Council, 2000). The interaction and connection (including inter-dependencies) of three complex and rapidly changing systems provide the rationale for adoption of an IWRM approach. These are:

- The environmental system, of which water is a vital part and a constituent of all living things
- The hydrologic cycle, which governs the flow of water and regeneration of water resources; and
- The human socio-economic system of activities

The planning and management of water resources are closely associated with societal development and progress. However, this needs to take place within the context of sustainable development, which means approaching the planning process from a prolonged temporal and wider spatial perspective. This further increases the complexity of the decision-making process. Further, IWRM is a decision-making problem that involves competing decision makers representing private and public interests, hierarchical decision levels and decision problems which are influenced by physical and societal constraints (Bogardi, 1994).

The following definition of IWRM is used (GWP TAC, 2000):

> "IWRM is a process which promotes the co-ordinated development and management of water, land and related resources, in order to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems."

The recent recognition of groundwater as an integral component of the hydrological system requires its integration into the broader water resources management framework. Groundwater management is among the most important, least recognised and highly complex of natural resource challenges facing society (Foster, 2000). The challenges for groundwater resources are identified in Table 1. In arid- zone basement aquifers these groundwater management challenges are compounded for groundwater management and consist of the following (after Pietersen, 1999):

- Low rainfall and high evaporation rates affect recharge to basement aquifers resulting in the slow circulation of groundwater causing groundwater quality and quantity problems
- Recurrent droughts occur resulting in water-related stress (normally accompanied with over-exploitation) for both communities and the natural environment
- The poor natural water quality of basement aquifers associated with low rainfall areas has a health impact on the affected communities
- The lack of suitable institutional arrangements at the local level and at catchment scale hinders proper resource management
- Groundwater protection measures are frequently not in place to prevent resource degradation

Frequently in arid environments where rainfall is scarce groundwater may be the sole source of water supply. This means that effective groundwater management is crucial for sustainable groundwater use. Morris et al. (2003) present two contrasting perspectives on groundwater management:

(a) The first is a technical view that proposes a measured approach to management based on the reinforcement of existing institutions to tackle hydrogeological problems in a logical and progressive way.

(b) The second view proposes a more holistic approach to sustainability in which coping strategies as well as technical measures form part of the groundwater problem-solving process.

This first approach requires that there is sufficient awareness of the status of groundwater, both its quantity and quality, and an understanding of the aquifer characteristics. The legal framework with rights and obligations is also in place with sufficient awareness in governmental planning and society at large of the importance of groundwater. The above understanding is supported by a monitoring system in order to identify whether problems are occurring or are likely to occur (Morris et al. 2003). In practice, the first approach requirements are rarely met in full.

This thesis adopted the second approach towards sustainable management of groundwater resources. Alternative courses include not only technical measures, but focus also on socio-economic issues which need to be addressed to enable communities to better cope with marginal and variable resources e.g. community involvement, climatic variability and cost recovery as identified in Table 4. In this regard a MCDA approach was used to facilitate the interrogation of the various alternatives (Chapter 5 and 6).

3.2.4 The need for decision analysis tools

Arising from the complex issues identified in Sections 3.2.1, 3.2.2 and 3.2.3, is the need for decision tools that consider the social context and groundwater characteristics in the area in an integrated way. This is necessary in order to:

- Reduce poverty
- Develop sustainable rural livelihoods

Decision analysis (DA) encompasses a series of techniques for structuring complex decision problems and for exploiting this structuring to gain insight into best approaches to address the problems being considered. The two pillars upon which most of the modern DA rests are normative decision theory and psychological (descriptive) decision theory (Brachinger and Monney, 2002). Normative decision theory is based on theories of coherent or rational behaviour in decision making in which, certain principles of rationality are developed to which a rational decision maker has to adhere if he or she wants to reach the "best" decision. Psychological decision theory, empirically investigates how decision makers really make their decisions and, based on empirical findings, develops descriptive theories about real decision behaviour (Brachinger and Monney, 2002).

Figure 3 shows a flow chart of the different steps involved in the DA process (Pfeiffer, 1997). The process starts with the identification of the problem. The next step requires the identification of the objectives and alternatives. This is followed by the decomposition of the problem to understand its structure and to measure uncertainty and value. Decomposition is seen as the key to DA (Pfeiffer, 1997). According to Pfeiffer (1997), DA techniques are used to create models of the structure of the decision problem (alternatives or choices); they use probability to build models of the uncertainty and utility functions which describe how the decision makers value outcomes and trade off competing objectives (preferences). During the sensitivity analysis, aspects of the model are changed and the effect on the outcome is evaluated (Pfeiffer, 1997). DA will typically be a process going through several iterations before a satisfactory alternative is found (Pfeiffer, 1997).

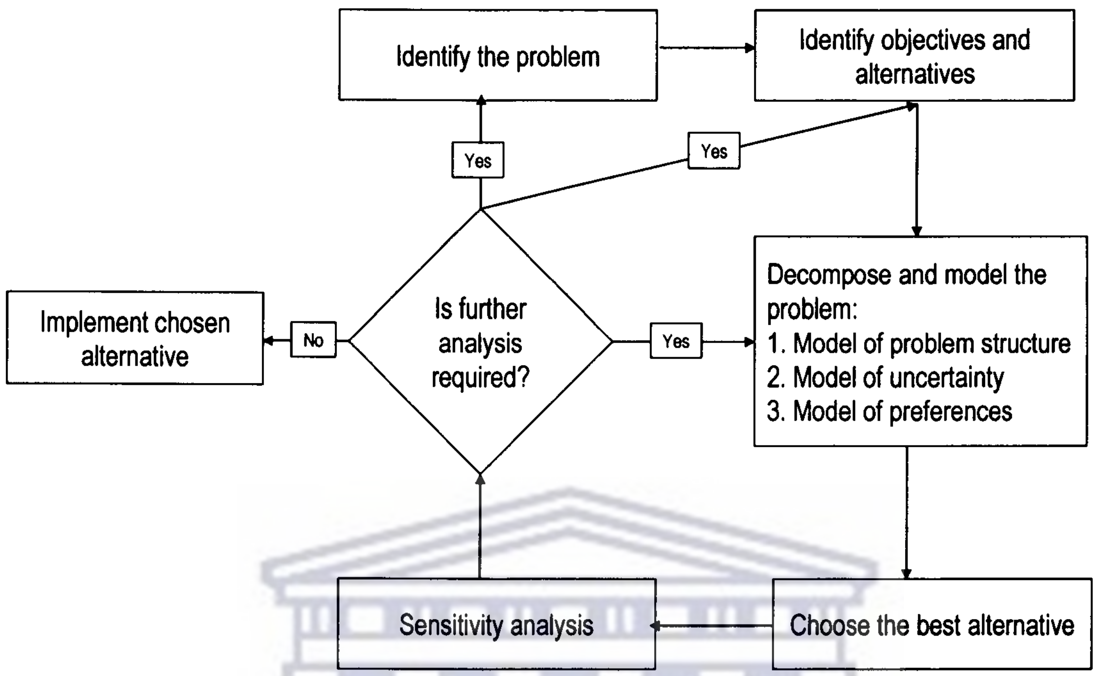

Figure 3 Flow chart of decision analysis process (from Pfeiffer, 1997).

There are two main problems dealt with in DA: uncertainty and multiple conflicting objectives (Brachinger and Monney, 2002). MCDA is a sub-discipline of DA and is further discussed in Chapter 4 and 5.

3.3 The decision context

The arid nature and groundwater characteristics of the region mean that communities are confronted with water quantity and quality issues. The people in the region face the following livelihood challenges (as they relate to water):

- A dependency paradigm, created through the adoption of inappropriate technologies (a scenario typical in developing communities);
- The burden placed on women to perform the daily chores and tasks in order to provide subsistence to households;

- Health risks (microbiological and chemical) associated with poor quality groundwater (natural and anthropogenic) and inadequate sanitation systems;
- Centralised decision-making which often does not take account of community dynamics and processes;
- The challenge to produce sufficient food in an environment of extreme climatic and water resource variability (mostly drought conditions);
- The degradation of the natural environment resulting in flood problems in periods of high rainfall;
- Policies that focus on basic needs rather than production (livelihood) requirements (supply approach rather than a demand driven approach);
- The low population densities, making reticulated water systems excessively costly.

The following definition is given for sustainable rural livelihoods (DFID, 2000) – A livelihood comprises the capabilities, assets (including both material and social resources) and activities required for a means of living. A livelihood is sustainable when it can cope with and recover from stresses and shocks and maintain or enhance its capabilities and assets both now and in the future, while not undermining the natural resource base.

Thus, in order to deliver sustainable groundwater services and thereby contributing to rural livelihoods in meaningful manner, the groundwater practitioner needs to address the following issues:

- Security of water supply and improved water facilities for productive use rather than for subsistence purposes only;
- Community involvement and ownership of productive water facilities and processes agreed upon, for sustainable use of the resource;
- The role of groundwater in maintaining the natural and economic resource base in the community;
- The sensitivity of the groundwater system to stresses (e.g. over-pumping) and variability over a range of spatial and temporal scales.

In the absence of surface water, the only water supply options to communities are groundwater, predominantly located in crystalline metamorphic and igneous rocks. To address the issues above will require an integrated decision making framework that incorporates technical and social considerations. MCDA is an appropriate approach for developing such a decision framework or model.

Developing an understanding of the issues involved in groundwater management in semi-arid terrains, has required detailed investigations. For this study, these took the form of:

- Field investigations to collect data in order to understand the physical conditions of the groundwater system. The Buffels River case study consisted of detailed investigations (hydrological, hydro(geological) and hydrochemical data collection, interpretation and analysis).
- Pilot studies and workshops in affected communities to consult and gain an understanding of issues related to water services. The methods used in the Buffels River case study example consisted of questionnaires and field data collected using participative techniques, semi-structured interviews and in-depth focus discussions among various communities in the region.
- Consultations with decision-makers, implementing agents and water resource managers at local, provincial and national level. This was done in the case study, through interviews and interactions at various forums

3.4 Identifying the objectives and associated measures

Results of various pilot studies, field investigations and stakeholder consultations have enabled Titus et al. (2002) to formulate a comprehensive set of objectives and associate measures (Table 4), which if applied successfully, would largely contribute to the achievement of sustainable livelihoods in poverty-stricken semi-arid areas such as Namaqualand. The process framework based on this list is illustrated in Figure 4.

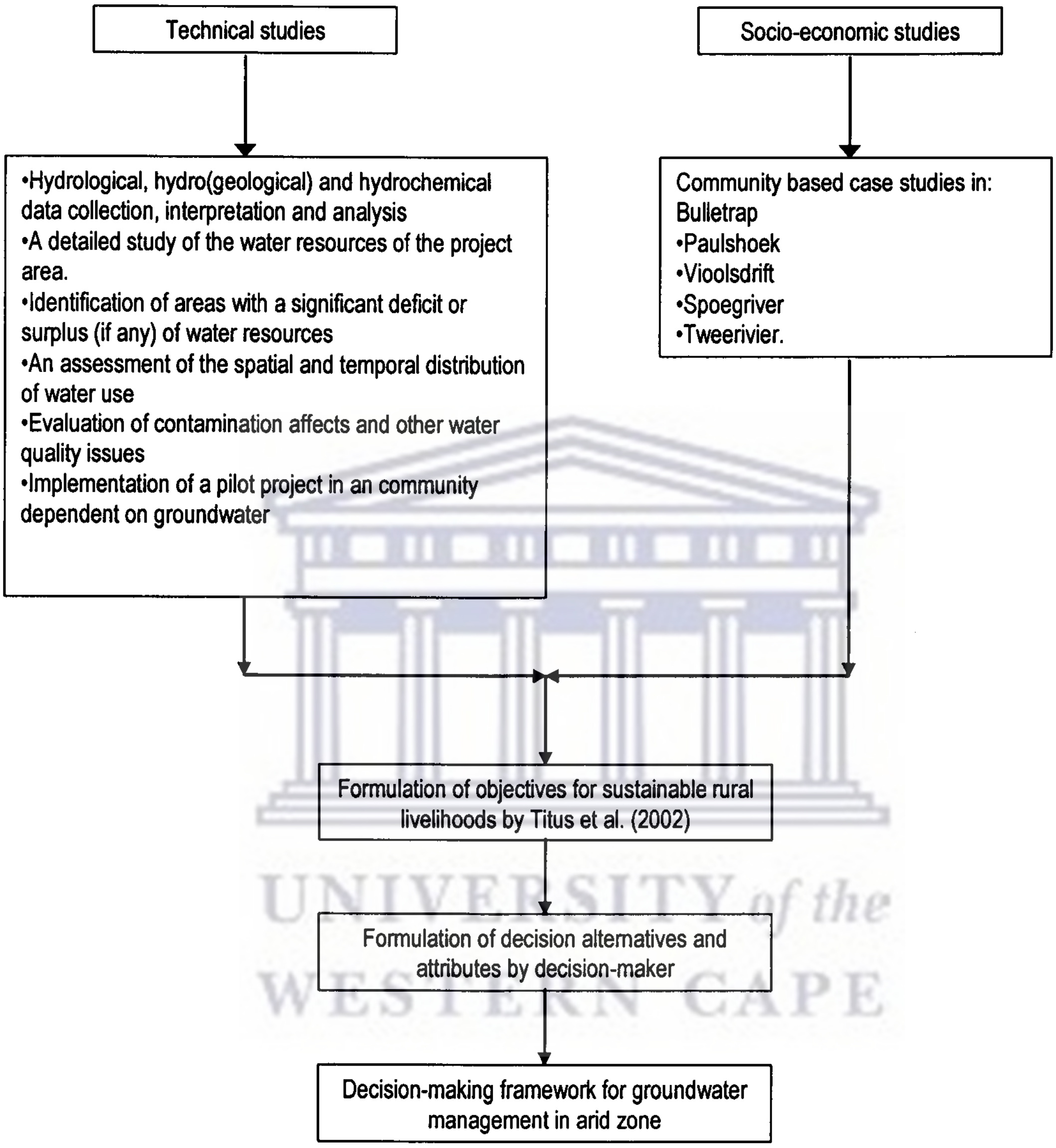

Figure 4 Process to identify objectives and related measures, alternatives and attributes in building a decision-making framework for groundwater management in the interest of sustainable livelihoods in arid zones.

Table 4 Objectives and associated measures for sustainable rural livelihoods (Titus et al. 2002).

Issues	Objectives and associated measures
Adverse climatic condition	Implement artificial recharge schemes to supplement poorly naturally recharged groundwater systems when surface water resources are in excess (see Murray, 2002). Continue conjunctive water use of groundwater and surface water resources Implement water harvesting by storing roof-runoff in rainfall tanks and the construction of structures to channel overland flow to reservoirs. Consider fog harvesting in coastal and mountainous regions. Implement water harvesting during exceptional rainfall events through retention walls in streams to enhance infiltration. Undertake proper maintenance of reservoir systems/pipelines to reduce leakage and evaporation. Closed tanks, instead of open dams, located in proximity of the boreholes may also reduce evaporation. Manage the resource properly through water level and water quality monitoring to characterise the response of the aquifer system with regard to adverse climatic conditions
Climatic variability and change	Predict drought conditions using most appropriate means Introduce predictive management options taking into account future water demand trends (i.e. population dynamics), resource availability and temporal variability in climatic conditions.
Aquifer system assessment	Develop a geological and geomorphological framework, that will contribute to an improved conceptual understanding of aquifer systems, with reference to: • The lithological and mineralogical make-up of the aquifer materials. The mineralogical composition of the various lithologies will affect the groundwater quality in terms of water-rock interaction reactions. • The tectonic and neo-tectonic development, which would have resulted in a structural imprint and affected the geomorphological landscape development. • The lithological and tectonic development, which may also assist with defining boundary conditions, at a regional scale, in terms of aquifer delineation and related aquifer classification approaches. • The geomorphological development, in relation to long-term climatic system changes, which would have resulted in specific soil characteristics and deep weathering profiles. Delineate and characterise the aquifer system at a regional level: • Distinguish and potentially rate different aquifer systems, in terms of both yield and quality of groundwater at a regional scale. • Characterise the physical nature and understand as well as predict the variability in hydraulic response of the aquifer system. • Characterise the transmissiveness and the available storage of the aquifer system based on the fractured nature of aquifers and the available drawdown that is associated with the

thickness of the regolith (i.e. weathered overburden), the depth to the most productive fracture zone(s) and the depth to the water table and/or piezometric level.

- Develop a regional groundwater flow model for a particular aquifer system with due reference to the tectonic and geomorphic development of the basement aquifer systems. The regional groundwater flow, for a particular aquifer system, must be based on the hydraulic gradients (as a function of elevation differences) and the average depth at which water could be sampled.
- Describe and distinguish between the various flow systems, for a particular aquifer system, at the relevant scale.
- Characterise the processes (i.e. water rock interaction, residence, evapotranspiration, etc.) that result in the generally poor groundwater quality and take cognisance of the factors (i.e. complex groundwater flow paths and flow systems, differential weathering processes, spatial variation in rainfall, etc.) that result in spatial and temporal variations in the groundwater chemistry for a specific aquifer system.
- Describe the seasonal and long-term climatic variability and the effects on both the quantity and quality of groundwater for a specific aquifer system.

Delineate and characterise the aquifer system at a local scale:

- Identify and rate different local aquifer systems in terms of both the yield and groundwater quality at an appropriate scale.
- Consult borehole logs (if available) to characterise the transmissiveness and the available storage of the aquifer system based on the fractured nature of aquifers and the available drawdown that is associated with the thickness of the regolith (i.e. weathered overburden), the depth to the most productive fracture zone(s) and the depth to the water table and/or piezometric level.
- Develop a local to intermediate groundwater flow model for a particular aquifer system with due reference to the prominent local relief. The local groundwater flow model, for a particular aquifer system, must be based on the hydraulic gradients (as a function of elevation differences) and the average depth at which water could be sampled.
- Describe and distinguish between the various flow systems, for a particular aquifer system, at a relevant scale.
- Identify the processes (i.e. water rock interaction, residence, evapotranspiration, etc.) that may result in the generally poor groundwater quality and take cognisance of the factors (i.e. complex groundwater flow paths and flow systems, differential weathering processes, spatial variation in rainfall, etc.) that result in spatial and vertical variations in the groundwater chemistry for a specific aquifer system
- Identify those regions, within the local to intermediate groundwater flow system that are subject to evapotranspiration and describe the effects on both the quantity and quality of groundwater for a specific aquifer system.

Select the most favourable target(s) for development (target selection should be based on a combination of favourable factors).

- Apply appropriate geophysical technologies and interpret results based on the conceptual

	understanding of the aquifer system • Conduct exploratory drilling and re-define knowledge and conceptual models of aquifer systems at this particular scale. • Undertake borehole development which must include the drilling of monitoring boreholes for the calculation of hydraulic parameters (i.e. storativity). The relative positioning (i.e. hydraulic connectivity and hydraulic system) and optimal number of boreholes and depth of boreholes are important factors. • Select the appropriate numerical method(s) for test pumping analyses based on the meeting of underlying conditions for the particular method(s) and on a conceptual understanding of the aquifer system. Data collection in the field must be as accurate and representative as possible • Determine the sustainable yield of the aquifer system with due consideration of all the above-mentioned factors. Select an appropriate approach for a particular region and utilise relevant techniques.
Protect the aquifer (and ecosystems) from impacts	Identify and protect environmental assets (e.g. perennial springs and artesian springs). Identify potential threats to these systems and protection/mitigation measures (e.g. maintaining water levels and volumes, reducing borehole development, etc.). Identify pollution threats to the aquifer systems (e.g. on-site sanitation; stock watering points, etc.). Apply measures to protect the aquifers from threats (i.e. use of techniques for delineating protection zones in fractured environments). Characterise the groundwater contribution to baseflow (i.e. local to intermediate groundwater flow system maintains the water levels in wells located in the alluvium of the Buffelsriver).
Manage the aquifer systems in a sustainable manner	Assess water demands/requirements for the region at community and regional scale • Demographic considerations e.g. population growth/decline, downscaling of mines, economic development initiatives • Water use – domestic, stock farming, agricultural purposes (present and future use) • Upgrade options (house connections, yard taps, water borne sewerage) • Mechanisms to control water demand (pricing) • Mechanisms for optimal water usage (water conservation) Assess the water resources system (see aquifer system assessment) Identify water resources management problems, constraints and uncertainties • Uncertainties ▪ Model and structural uncertainties (wrong conceptual models) ▪ Parameter uncertainty (recharge; hydraulic conductivities) ▪ Decision uncertainty (how to compare and weigh social objectives) ▪ Scale (long-term consequences of proposed water developments and the possibilities for reversing the consequences of past development decisions) • Constraints ▪ Resource yield (storage capacity) ▪ Funding ▪ Legislative requirements (e.g. reserve)

Develop and analyse alternative strategies and instruments of implementation

Prepare for implementation (legislation, organization, planning)

- Determination of the objective need for water supply, as well as the community's perception of such needs
- An appraisal of existing water supply facilities in relation to social and economic benefits
- Assessment of the institutional capacity to implement and manage water supply schemes, together with the need for institutional development
- Presentation of a range of technical options and the implications of each option (e.g. O&M, training and cost recovery)
- Identification of means of establishing community participation in the planning, design, implementation and O&M of such projects
- Willingness to pay for O&M and affordability of O&M
- Leadership

Implement the project

- Presentation of technical options and implications for the community
- Discussion with the community on the advantages and disadvantages of each option.
- Reaching agreement with the community on the selected option, time schedule and tasks and duties of all parties involved in the implementation
- Provide the outline and preliminary design of the actual design/maintenance programme, including the requirements for training and cost recovery based on agreements with the community.

Monitor (water availability, quality and demand)

- Quantity
  - Natural indicators
    - Resource dimensions
    - Recharge/discharge mechanisms and rate
    - Sustainable yield and availability
  - Policy and management indicators
    - Licensing/allocation
    - Monitoring – abstractions
    - Monitoring – water levels
    - Management issues
  - Management issues indicators
    - Artificial recharge
    - Over-exploitation of resources
- Quality
  - Natural indicators
    - Groundwater quality (fluoride and salinity)
  - Policy and management
    - Water use practices

	- Point pollution sources - Diffuse pollution sources • Groundwater dependant ecosystem ▪ Aquatic ecosystem preservation ▪ River base flows (in-stream needs) • Socio-economic impacts ▪ Competing uses ▪ Economic value of water ▪ Tariffs ▪ Awareness ▪ Community acceptance and satisfaction level ▪ Operation and maintenance requirements
Cost recovery	Select appropriate technology, which is affordable to operate and maintain. If the technology is not affordable e.g. desalination systems, cross-subsidisation is inevitable Involve the appropriate users of the water supply scheme (e.g. women) in selecting the technology and developing the cost recovery system Educate the community about the true cost of water, and source agreements at the beginning regarding the tariff system. Ensure at all times that the water supply system is operational so that communities can have confidence in services rendered. i.e. • Schemes for domestic water supply should ensure the availability of raw water for 90% of time • The flow rate from an outlet should not be less than accepted standards Obtain contributions from communities during the implementation phase (construction); communities need to contribute incrementally as targets are achieved.
O&M skills base	Develop skills (including gender and equity considerations) from an operation and maintenance perspective. The O&M of the system must be effective i.e. the system should not fail due to drought or technical reasons. Some women are often the stable influence in communities, with firm commitments to the family and health; actively promote their role, especially with regard to the development of the O&M system. Consider the desire for people to upgrade systems (or to cater for other requirements) in the planning, so that vandalism of the system is limited to the minimum Train key people so that the skills base is retained within the communities. Systems frequently fail because the operators migrate for better opportunities Conduct follow up monitoring after implementation for a three year period so that systems stay operational
Community participation and education	Ensure acceptance by implementers that communities are the owners of the water supply schemes Facilitate joint decision-making and development of trust among various partners. Target training needs at achieving (a) general community awareness of water, sanitation and health related issues (b) local government officials with regard to basic understanding of water and sanitation (c) water care technicians

3.5 Generating and identifying decision alternatives

Stewart et al (2001) found that in water resource management situations there were often no pre-defined management alternatives, and that an important part of the problem structuring stage was that of defining alternatives. Forming and considering various scenarios were a means of developing the alternatives. In creating scenarios for sustainable groundwater resource development, especially within a rural context, it is important not to develop unrealistically high expectations concerning desired outcomes. The livelihood challenges as they relate to water are:

- The provision of a basic quantity of water for domestic purposes, i.e. to meet normal household and health requirements;
- The contribution to economic development and poverty alleviation;
- The maintenance of aquifer system integrity (e.g. prevention of subsidence and salinisation);
- The protection of groundwater resources from pollution;
- The proper functioning of ecosystems that are dependent on groundwater

Meeting these challenges needs to be done within the context of relevant legislation and policy goals. The following scenarios are possible:

Unacceptable:

Scenario 1 represents chronic water shortages, wasteful consumption patterns and over-exploitation of resources (including resource degradation through polluting activities). As a result of inadequate water provision communities cannot meet their health and food requirements, leading to malnutrition. The general population is unaware of their rights and responsibilities with regard to service delivery leading to sustainability problems of water schemes. The environment is degraded resulting in ecological demise.

Acceptable:

Scenario 2 focuses on increased coverage of services rather than sustainability. The driving forces for implementation are not the customers but the providers. In this scenario water services needs are provided but with limited support mechanisms. This results in a disenfranchised community with resultant disempowerment, especially of the vulnerable parts of the communities. The resources are used in an unsustainable manner and maintenance of services is neglected. This results in breakdown of intended benefits from provision of services. Ecological demise will be followed by social demise.

Ideal:

Scenario 3 is the preferred outcome. Communities are empowered through local government support (i.e. political and financial will) and are able to implement the sophisticated legislative requirements intended by the National Water Act and Water Services Act. This results in sustainable resource use with intended benefits of providing clean and safe water. This will ensure improved quality of life for present and future generations.

The current situation in Namaqualand (Williams, 2000; Titus et al. 2002) closely resembles Scenario 2. The challenge is to develop mechanisms to achieve the objectives and implement the measures identified in Table 4 and accordingly to move from Scenario 2 to Scenario 3. Scenario 1 is not an option and will not be discussed further.

It is accepted that the objectives and associated measures in Table 4 are too numerous and cumbersome for practical, economic implementation. The challenge is to establish the critical path for key intervention measures serving the high level objectives of sustainable livelihoods and to support the implementation of such measures through a monitoring and evaluation system. As a starting point, the author of this thesis has rationalised and shortened the categorised list of intervention measures presented in Table 4 by consolidating overlapping measures and discarding those considered of lesser importance .The result is a similarly categorised list of potential activities (key measures) designed to promote the achievement of sustainable livelihoods. If, as is usually the case, resources (human and financial) are limited, it would be crucial to decide which of these activities (or combination of activities) should be selected and pursued in order to bring about the best possible result in terms of achieving sustainable rural livelihoods. For this reason, the possible activities may be considered as, and termed, decision alternatives. Ideally, the decision alternatives should be generated and tested in a workshop format prior to the commencement of the decision-making process. For the purpose of this thesis, however, the decision alternatives formulated by the author are as follows:

3.5.1 Cost recovery

- Involve communities in the selection of technology and developing the cost recovery system
- Facilitate technology selection and tariff setting at local government level.

3.5.2 Aquifer management

- Conduct water demand assessments; develop community participation and management systems;
- Undertake technical assessments of the aquifer systems and institute aquifer monitoring systems.

3.5.3 Aquifer protection

- Develop protection zones around identified environmental assets.
- Compile an inventory of contamination sources
- Determine groundwater contribution to base flow
- Develop borehole protection zones from contamination sources

3.5.4 Aquifer assessment

- Undertake a detailed geological and geomorphological review of region (including geodynamics and structural geology).
- Characterise aquifers at regional scale (regional groundwater flow model).
- Characterise aquifers at local scale (e.g. proper pump testing analysis).

3.5.5 Coping with climate variability and change

- Use outputs of a suitable predictive model available to inform decision makers about spatial and temporal climate variability and change.
- Undertake a water demand analysis to indicate trends and resource availability.

3.5.6 Adverse climatic conditions

- Implement water enhancement strategies such as artificial recharge, water harvesting and fog harvesting.
- Reduce water loss and leakage through measures such as maintenance of water distribution systems.
- Practise water level and water quality monitoring in order to characterise the response of the aquifer system with regard to adverse climatic conditions and to adapt water supply in accordance with such conditions.

3.5.7 Ensuring O&M skills base

- Ensure training and retention of necessary skills (including gender considerations) for the operation and maintenance of the water services system at community level,
- Facilitate operation and maintenance of water services by local authorities.

3.5.8 Facilitating community participation and education

- Ensure implementation of effective community participation and education on all water services schemes
- Ensure that training is targeted at local government level (e.g. water care operators)

3.6 Summary

This chapter established the context for developing an appropriate framework for the sustainable management of groundwater resources in the region, the objectives of which are to:

- Determine the sustainable yield of the aquifer systems and to develop policy and strategies for groundwater management at community and catchment scale
- Protect the aquifer from possible pollution risks such as improper location of pit latrines and indiscriminate disposal of waste
- Protect the communities from poor quality groundwater
- Establish mechanisms for communities to participate in a meaningful way – they need to be well informed as regards the functioning of their water resources systems and likely consequences of their decisions
- Develop appropriate monitoring and evaluation systems for resource sustainability as well as delivery and proper operation and maintenance of installed systems

Based on present conditions prevailing in the region, an exhaustive list of potentially beneficial groundwater-related management interventions has been drawn up. A selection of key interventions from the list should be effective in moving from the current situation to a preferred sustainable livelihoods-based development scenario. A MCDA approach will be used to throw more light on the interventions required. Theoretical considerations concerning the use of MCDA are presented in Chapters 4 and 5.

4 Multiple Criteria Decision Analysis

4.1 Introduction

In Chapter 1, it was established that a MCDA approach would be most appropriate for addressing the multiple management objectives within the context of a decision support framework for groundwater management in arid zones. The problem has been structured in Chapter 3 with a view to the effective use of MCDA tools. In order to select the most appropriate MCDA technique, some background is required on the theoretical aspects.

MCDA (also known as MCDM) is the general field of study which includes decision making in the presence of two or more conflicting objectives and/or decision analysis processes involving two or more attributes (Tecle and Duckstein, 1994). The general objective of MCDA is to assist a decision-maker or a group of decision-makers to choose the best alternative from a range of alternatives in an environment of conflicting and competing criteria. In recent years several methods have been proposed to deal with MCDA problems. These are (after Bruel et al. 2000):

- Distance-based methods, where one seeks to minimise a distance measure between an ideal or utopian point and the Pareto-optimum function.
- Multiple attribute utility theory, where the multiple points of view are aggregated in a unique function, which must be optimised.
- Outranking methods, among them ELECTRE and PROMETHEE: they aim to build an outranking relation which represents the decision-maker's preferences. Finally, they give a ranking of different actions, from the best to the worst.

Stewart (1992) suggests that the aim of any MCDA technique is to provide help and guidance to the decision maker in discovering his or her most desired solution to the problem. The typical decision-making process includes the following three general steps, carried out iteratively and not necessarily in a linear or sequential manner (Henig and Buchanan, 1999):

- **Component identification.** Identify alternatives and criteria.
- **Mappings.** Identify attributes. Associate the alternatives with the attributes.

- **Understand and expand.** Understand and confront the decision-maker's preferences. Expand the set of alternatives.

Steps in the decision-making process may be alternatively stated as (Larsson, 2000) as:

- Alternatives; which are the possible actions?
- Expectations; which are the possible consequences of each action, and how probable are they?
- Preferences; How valuable are the consequences?
- Decision rules; how is a choice made among alternatives?

In this chapter an overview of MCDA methods is presented. This includes a discussion of the philosophical basis of MCDA. Lastly a rationale is developed to guide the selection of an appropriate MCDA approach for the decision-making problem under consideration.

4.2 The philosophical basis for MCDA

The key philosophical departure point in defining MCDA as a formal approach to types of problem solving (or mass reduction), lies in attempting to represent decision making goals (which are more often than not imprecise) in terms of a number of individual (relatively precise, but generally conflicting) criteria (Stewart, 1992). The major advantage of the approach is that MCDA techniques allow for the explicit consideration of multiple objectives that are expressed in different units. There are however, immense complexities and uncertainties in solving MCDA problems as a result of (Despic and Simonovic, 1997):

- The criteria being quite often in conflict and competition
- Most of the criteria being non-commensurable
- Many potential users of water resources with different preferences
- Almost every single criterion containing abundant information and representing a very complex system by itself
- Evaluating qualitative criteria being difficult and at best performed only on the linguistic scale

The sequence of steps in solving a MCDA problem is given in figures Figure 5A and 5B.

The first step is to define the problem, with a clear understanding of problem objectives and criteria. A criterion is defined as any concern, interest or point of view according to which alternative courses of action can (more-or-less) unambiguously be rank ordered (Stewart et al. 2001).

Once the problem has been defined, appropriate pieces of information are collected to serve as inputs into the multi-criteria decision problem (Tecle and Duckstein, 1994). The data can be either objective or subjective in nature. This is step 2.

Step 3 includes generation and specification of the relevant criteria, establishment of the set of variables or feasible decision alternatives, definition of the problem constraints or restrictions, estimation of the attribute values to express the impact of the decision alternatives upon the individual criterion selected and identification of needed parameters (Tecle and Duckstein, 1994). According to Tecle and Duckstein (1994) the attribute values and parameter values are then used to construct carefully, a functional relationship that explicitly describes the structural relationships or quantitative structure between the inputs (decision alternatives or variables, constraints and parameters), states (intermediate variables describing the system), and outputs (values for the criteria as expressed through the problem objective functions).

Algebraic equations and evaluation matrices are formulated to represent the functional relationship between inputs, states and outputs. This is the fourth step.

The fifth step in the MCDA paradigm deals with solution technique construction or selection in order to solve the problem as formulated in Step 4 (Tecle and Duckstein, 1994). The solution methods in MCDA commonly used to solve multiple and conflicting objectives, are given in Section 4.4.

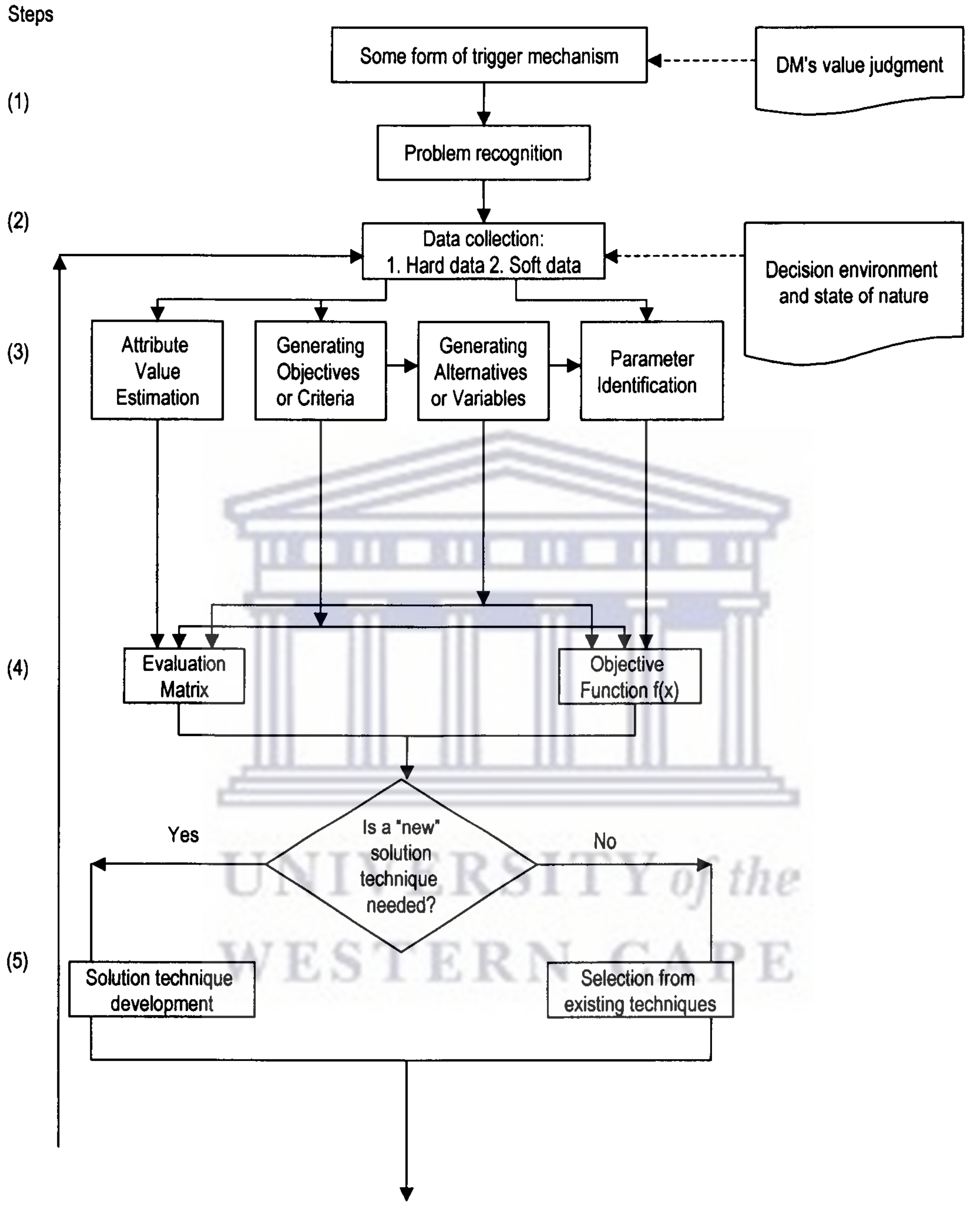

Figure 5A Paradigm of MCDA (Tecle and Duckstein, 1994).

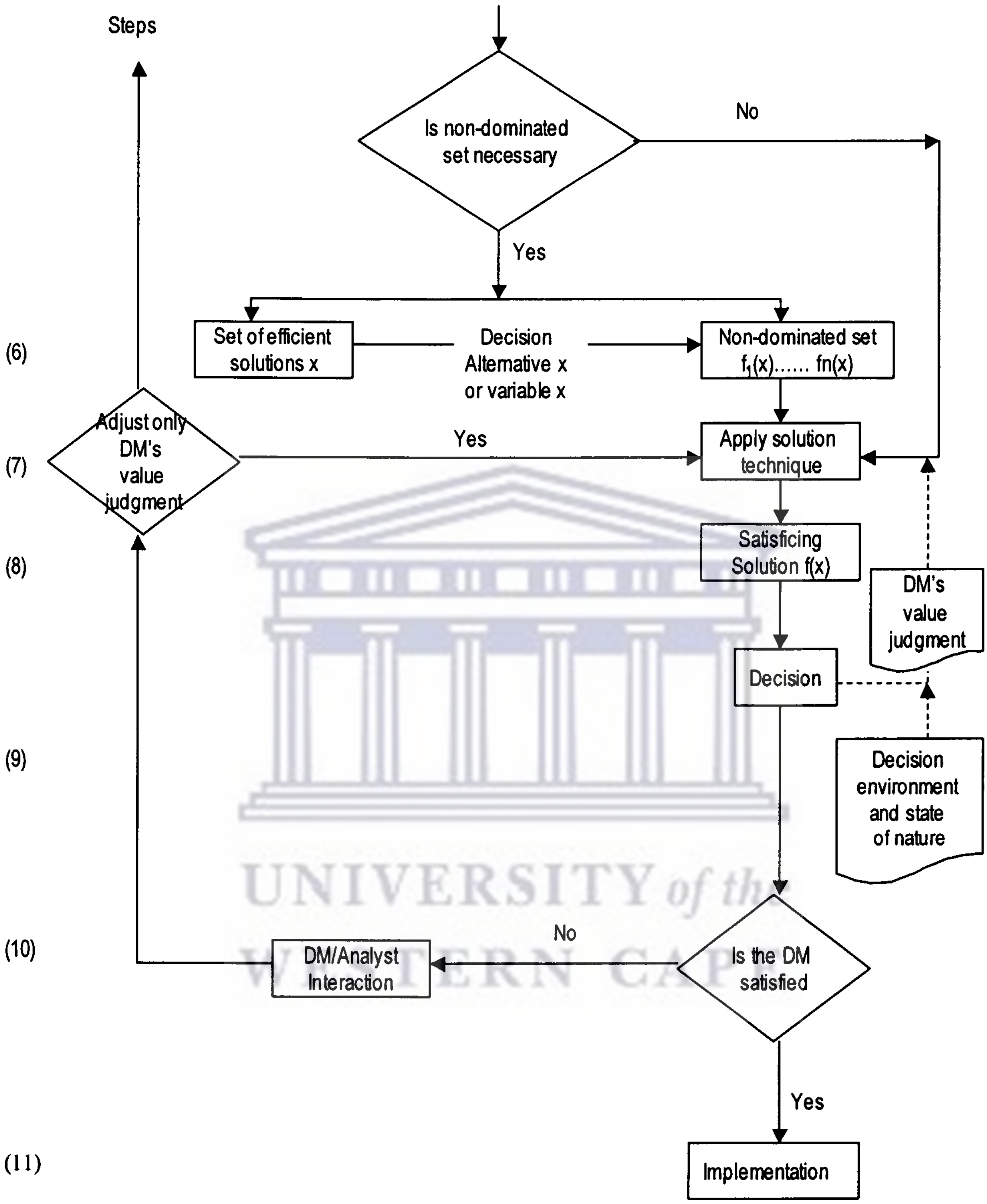

Figure 5B Paradigm of MCDA (Tecle and Duckstein, 1994).

The solution technique selected is then used to determine the set of efficient solutions and the non-dominated set of solutions to the problem (Step 6). This process involves the generation and the estimation phase, which consists of determining the efficient solution set in terms of the decision variables defined in Step 3 and mapping the set of efficient solutions obtained into the criterion or objective function space to determine the non-dominated set or set of satisfying solutions, respectively (Tecle and Duckstein, 1994).

The next steps, 7 and 8, are used to determine the optimal solution and to make the most appropriate decision. The evaluation and acceptance of the solution by the decision makers are Steps 9 and 10. Depending on the acceptability of the solution, it will then be implemented. This is Step 11.

4.3 Classification of MCDA methods

MCDA can be classified into two categories: multiple attribute decision problems (also known as Multi Attribute Decision Making) and multiple objective optimisation problems (also known as Multi Objective Decision Making). A multiple objective optimisation problem is normally described as a problem with a continuous solution space that can be optimised in a mathematical way by using objective functions and constraints (Gelderman and Rentz, 2000). The multiple attribute decision problems involve the selection of the "best" alternative course of action from a given number of alternatives described in terms of their attributes. There is only a discrete solution space. The set of decision alternatives has been predetermined (Traintaphyllou et al. 1998). Although MCDA problems could be very different in context, they share the following common features (Xu et al. 2001):

- Multiple attributes/criteria often form a hierarchy
- Conflict among criteria
- Incommensurable units
- Mixture of qualitative and quantitative attributes
- Mixture of deterministic and probabilistic attributes
- Uncertainty in subjective judgements
- Uncertainty due to lack of data or incomplete information

Stewart (1992) classifies MCDA methods according to the following approaches:

- Value or utility based approaches
- Goals and reference points
- Outranking concepts

4.3.1 Value or utility based approaches

Value or utility methods select or evaluate alternatives according to a value function (in the deterministic case) and a utility function (in the probabilistic case). It is assumed that all performance assessments as well as the factors describing the decision criteria's importance can be quantified (Girod et al. 2000). The importance factors are used for aggregating the restricted, numeric utility scores into an overall utility for each alternative (Girod et al. 2000). The decision-maker's preference towards risk is incorporated into a mathematical function, a utility function (Henig and Buchanan, 1999). Applications of these techniques to water resources are found in Shih and Ingram (1981); Reynolds and Peets (2001) and Thirumalalaivasan and Karmegan (2001).

These methods are further described in Chapter 5 and Appendix C and will not be detailed here.

4.3.2 Goals and reference points

In goal programming, the decision-maker specifies some goals to be achieved; if they are achieved the decision-maker is assumed to be satisfied; if not, the method seeks to get as "close as possible" to the goals. A number of methods may be categorized under goal programming and reference point methods (Offringa, 1996):

- Archimedean
- Pre-emptive
- Tchebycheff (Min-Max) method
- The Step Method (STEM)
- The interactive Multiple Goal Programming Method

- Wierbicki's reference point method
- Satisfying Tradeoff interactive reference point procedure
- The visual Interactive Goal Programming (VIG) method
- The STRANGE method
- The method of the displaced ideal
- The sequential Multiobjective Problem Solving Method (SEMOPS)

Compromise programming is a modification of the goal programming method. The concept of non-dominance is used to select the best compromise solution or alternative. A solution is said to be non-dominated if there exists no further feasible solution that will cause an improvement in a value of the objective function or criterion functions without making a value of any other objective function worse (Strager, 1995). This is known as the Pareto Principle: a state *A* is preferable to a state of the world *B* if at least one person is better off in *A* and nobody is worse off. A state is said to be Pareto optimal or Pareto efficient when there is no further state in which one individual can obtain higher satisfaction without at the same time lowering the satisfaction of at least one another individual (Strager, 1995). Another, variant is composite programming. This method employs a hierarchical normalised distance type of methodology (Woldt and Bogardi, 1992). Applications of these techniques to water resources problems are found in Woldt and Bogardi (1992); Strager (1995) and Tkach and Simonovic (1999).

4.3.3 Outranking methods

Outranking methods attempt pairwise or global comparisons among alternatives (Tkach and Simonovic, 1999). In determining whether alternative **A** can be said to be at least as good as alternative **B**, taking all criteria into account, two issues are taken into consideration (Stewart et al, 1992):

- Which criteria are concordant with the assertion
- Which criteria are strongly discordant with the assertion to the extent they could "veto" any consensus

Examples of outranking techniques are Elimination ET Choix la Realité (ELECTRE) and Preference Ranking Organisation Method of Enrichment Evaluation (PROMETHEE). Applications of these techniques are found in Raju and Kamur (1999) and Bruel et al. (2000).

These methods are frequently used in combination. Examples relating to water resources are found in Duckstein and Goicoechea (1994); Bender and Simonovic (1995); Simonovic (2001) and Ganoulis (2001).

4.4 MCDA technique selection: factors to be considered

The selection of the appropriate MCDA technique is crucial to the decision-making process. This is related to the way in which preferences, expressed by the weights and scales, are incorporated into various techniques (Nachtnebel, 1994). This might be caused by (Nachtnebel, 1994):

- different ways of introducing preferences
- different sequence in introducing preferences
- different number of parameters describing preferences
- improper definition of the problem
- neglecting relevant decision settings
- application of inappropriate MCDA methods

Nachtnebel (1994) proposes five groups of criteria to consider in selecting the various techniques:

(e) mathematical programming versus decision analysis
(f) quantitative versus qualitative criteria
(g) time when preferences are introduced
(h) interactive or non-interactive methods
(i) way of comparing alternatives

MCDA methods differ however, in the way the idea of multiple criteria is considered, the application and computation of weights, the mathematical algorithm utilised, the model to describe the system of preferences of the individual facing decision-making, the level of uncertainty embedded in the data set and the ability for stakeholders to participate in the process (De Montis et al. 200). The MCDA technique selected will typically need to (De Montis et al. 2000):

- Deal with complex situations (criteria), consider different scales and aspects (geographical scales, micro-macro-link), social/technical issues and type of data (uncertainties)

- Involve more than one decision-maker (stakeholder participation, actors, communication, and transparency) and
- Inform stakeholders in order to increase their knowledge and change their opinion and behaviour (problem structuring, tool for learning, transparency)

De Montis et al. (2000) found a utility (or value function) approach, when evaluating a number of MCDA techniques, to be the best choice considering the above considerations. The following criteria were outlined as a checklist in selecting an MCDA technique (Strager, 1995):

- How accurately does a method represent the decision-maker's value structure?
- How many objectives and alternatives can be included?
- Are sensitivity analyses easily made?
- Can the values of several decision-makers be considered?
- Does the decision-maker comprehend the purpose, assumptions, and wording of the method?
- In choosing weights or other parameters, do procedures elicit responses that are accurate and stable reflections of the decision maker's values?
- Do decision makers have confidence in the results?

4.5 MCDA technique selection for application in the decision framework for sustainable groundwater development/management

A multiple attribute decision method (or a value based approach or value measurement theory) was chosen (Section 4.4). To be consistent with respect to terminology these methods will be called value function methods. Value function methods are one of the more widely applied MCDA methods and has benefited from the longstanding interests of psychologists, engineers, management scientists which has brought a continuing awareness of behavioural and social issues as well as the underlying theory (Belton and Stewart, 2002). The technique has the following advantages in view of the author:

- The method are able to deal with the complex issues as identified in Table 4, which lists the objectives and associated measures for sustainable rural livelihoods in Namaqualand.

- Typical decision making scenarios need the involvement of multiple stakeholders and requires the process to be facilitative and transparent. Value function methods can assist in the problem formulation phase and informing stakeholders about the decision processes.

The major characteristics of groundwater management decision-making are the existence of considerable uncertainty, the potential for irreversible outcomes, the involvement of multiple decision makers and the likelihood of having conflicting objectives (after (Hajkowicz et al. 2000). In Chapter 3, the decision problem was shown to consist of (after Hajkowicz et al. 2000):

- A finite number of alternative plans or options
- A set of criteria by which the alternatives are to be judged

Value function methods as discussed in Section 4.3.1 provide a technique to rank or choose among alternatives in such a manner that the satisfaction derived from the choice is as large as possible. The value function method selected provides decision support by interval SMART/SWING. The theory is discussed in Chapter 5. Interval judgements are a way of handling preferential and informational uncertainty in MCDA (Mustajoki et al. 2001). Informational uncertainty is a feature of groundwater management. Computer support is through the Workbench for Interactive Preference Programming (WINPRE) software for interval SMART/SWING, PAIRS and preference methods developed by Mustajoki et al. (2001). Extensive theoretical and software development for these methods were done at the Systems Analysis Laboratory, Helsinki, University of Technology (Mustajoki and Hämäläinen, 1999; Pöyhonen and Hämäläinen, 2001; Hämäläinen et al. 2001). The technique of decision support by interval SMART/SWING has been applied to water resource management issues (Hämäläinen et al. 1999; Hämäläinen et al. 2000; Hämäläinen and Mäntysaari, 2001).

4.6 Summary

This chapter presented an overview of MCDA methods. The methods include value or utility based approaches; methods based on goals and reference points and methods based on outranking concepts. A value function method was selected, which provides decision support by interval SMART/SWING methods. The decision problem favours the selection of this method, because of the discrete alternatives and uncertainty associated with groundwater management. This value function method incorporates informational uncertainty through interval judgements.

In the next chapter the theory of the selected value function method is described. A general description of value function methods is given in Appendix C.

5 Value Function Methods (Interval Assessments)

5.1 Introduction

This chapter presents the axiomatic conditions and theoretical foundations for value function methods using interval assessments. A general description of value function methods is given in Appendix C. Section 3.4.1 presented a short introduction to value function methods. Published case studies of the application of value function methods to water resource management problems are referred to in Appendix C (Reynolds and Peets, 2001; Hämäläinen et al. 1999; Hämäläinen et al. 2000; Hämäläinen and Mäntysaari, 2000; Mustajoki et al. 2002).

Value function methods assume that an individual can choose among the alternatives available to him/her in such a manner that the satisfaction derived from this choice is as large as possible (Duckstein and Goicoechea, 1994). In brief, value function methods involve a process of scoring options, initially against the most basic criteria among which there is little conflict or ambiguity, and then gradually aggregating these scores across more-and-more divergent concerns and interests (Stewart et al. 2001).

Value function methods share the following characteristics (after Jackson, 1999):

- **Alternatives**: Value function methods involve screening (classifying), prioritising, selecting, and or ranking a finite number of alternatives.
- **Multiple attributes**: Value function methods have multiple attributes that a decision maker must define according to each problem's unique conditions. Although there is no specific set of characteristics a decision attribute should have, there is general agreement that decision attributes should be:
    - *Complete and exhaustive* – All important performance attributes deemed relevant to the final decision should be included in the decision-making process.
    - *Contain mutually exclusive items* – Listed attributes should be independent entities so that appropriate tradeoffs may be assessed. Also this helps prevent double counting of an attribute's worth.

- *Be restricted to performance attributes of the highest degree of importance* – Listed attributes should focus on high priority issues, thus providing a sound basis for deriving lower level decision criteria.

- **Incommensurable units**: Each attribute may have different units of measurement.
- **Attribute weights**: Value measurement methods require information regarding the relative importance of the selected decision attributes, which is usually denoted as a set of weights. Attribute weights can be assigned by a decision-maker directly or indirectly.
- **Decision matrix**: Value function problems can be concisely expressed in a matrix format.

5.2 Axiomatic and mathematical foundations of value function methods

The intention of a value based approach is to construct a means of associating a real number with each alternative in order to produce a preference order on the alternatives consistent with the decision-maker's value judgement (Belton and Stewart, 2002). The preferences that are to be constructed must be consistent with a set of axioms. These are (Belton and Stewart, 2002):

- **Preferences are complete**: For any pair of alternatives, either one is strictly preferred to the other or there is indifference between them (either $a > b$ or $b > a$ or $a \sim b$).
- **Preferences and indifferences are transitive:** For any three alternatives, say *a*, *b* and *c*, if $a > b$ and $b > c$, then $a > c$, and similarly for indifference.

Value function methods comprise two mathematical steps (Gelderman and Rentz, 2000):

(a) The aggregation of the judgments with regard to each criterion and alternative, and

(b) The ranking of the alternatives according to the aggregation rules.

In order to build the aggregate function different aggregation procedures are available. In a number of applications, the alternatives are evaluated additively (after Wakker et al. 2000):

$$V(v_1, v_2, \ldots\ldots v_p) = \sum_{i=1}^{p} w_i v_i$$

Equation 1

Where $V(v_1,v_2,....,v_p)$ is the overall value of the alternative, v_i is the partial value function associated with criteria i, and w_i is a weight factor to settle the exchange rates between the various attributes.

Another typical aggregation procedure is of the multiplicative form, which relates the global to the partial values according to the following expression (Belton and Stewart, 2003):

$$1 + kV(v_1, v_2, \ldots\ldots, v_p) = \prod_{i=1}^{p} [1 + kw_i v_i] \qquad \text{Equation 2}$$

The role of the multiplicative model is in applying expectation operators when directly and explicitly using probability models and subjective expected utility to order stochastic outcomes (Stewart, 2003).

For the additive form to be able to model the decision-makers strengths of preference consistently, a strong assumption is needed, termed additive difference independence. This means that the 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 of the other criteria (Stewart et al. 1992). 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 $k \rightarrow 0$), 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 (Stewart et al. 1993).

Once an initial model structure and a set of alternatives for evaluation have been identified, then the next step is to elicit the information required by the model (Belton and Stewart, 2002). There are two types of information, sometimes referred to as intra-criterion information and inter-criterion information or alternatively as scores and weights (Belton and Stewart, 2002). Figure 6 decomposes the various value function method approaches. These approaches are extensively discussed in Belton and Stewart (2002) and summarised in Appendix C.

The value function method selected for this study provides decision support by interval SMART/SWING (Section 4.5). The theory will be discussed later in this chapter. Interval judgements are a way of handling preferential and informational uncertainty in MCDA (Mustajoki et al. 2001). Informational uncertainty is a feature of water resource management.

Value Function Methods

- Intra-criterion information
  - Value function
    - Direct assessment methods
    - Indirect assessment methods
  - Construction of a qualitative scale
  - Direct rating of the alternatives
- Inter-criterion information
  - Attribute weighting methods
    - Direct
    - SWING weight method
    - SMART
    - SMARTER
    - TRADEOFF
  - Use of ordinal and imprecise information
    - Ordinal statements
    - Classification of outcomes
    - Interval assessment

Figure 6 Value function method approaches (after Belton and Stewart, 2002).

5.3 Interval judgements

Dealing with uncertainties related to data and preferential judgments is an essential part of any realistic decision making situation (Lindstedt et al. 2002). In those situations it is possible to use imprecise value statements such as intervals when judging objective weights and attributes performance levels (Dietrich and Hämäläinen, 2003). Imprecise statements can also be expressed as ordinal statements or classification of outcomes into semantic categories (Belton and Stewart, 2002).

Interval analysis was initially developed to bound computational error and it is a deterministic way of representing uncertainty in values by replacing a number with a range of values (Tung, 2001). The decision maker can capture the subjective uncertainty in preferences and thus avoid the often cumbersome elicitation of exact ratio estimates (Salo and Hämäläinen, 1995). The theory and methodology of preference programming through approximate ratio comparisons using interval judgements is given in Salo and Hämäläinen (1995). This is described in the section to follow.

5.3.1 Theory

In this method interval judgements are developed which allow the decision maker to enter ambiguous preference statements by indicating the relative importance of factors as intervals of values on a ratio scale (Salo and Hämäläinen, 1995). The decision maker can capture the subjective uncertainty in the preferences, thus avoiding cumbersome elicitation of exact ratio estimates. After each new statement the interval judgements are synthesised into dominance relations on the alternatives by solving a series of linear programming problems (Salo and Hämäläinen, 1995). This leads to an interactive process of preference programming which provides more detailed results as the decision maker gradually enters a more specific preference description (Salo and Hämäläinen, 1995).

Interval judgements are linear constraints on the local priorities. According to Salo and Hämäläinen (1995) a local priority vector w = ($w_1,\ldots, w_n$) is consistent with the interval judgements I_{ij} = [l_{ij}, u_{ij}] only if it satisfies the constraints

$$l_{ij} w_j \le w_j \le u_{ij} w_{ij}$$ Equation 3

The feasible region is the set of those local priorities which satisfy all such constraints (Salo and Hämäläinen, 1995). The feasible region can be written as:

$$S = Q^n \cap \{w | l_{ij} w_j \le w_i \le w_j\}$$ Equation 4

Where

$$Q^n = \left\{ (w_1,\ldots,w_n) \middle| w_i \ge 0, \quad \sum_{i=1}^{n} w_i = 1 \right\}$$ Equation 5

and l_{ij}, u_{ij} correspond to those interval bounds that the DM has specified.

Figure 7 shows the feasible region $S \in Q^3$ based on the judgements I_{12} = [1, 2], I_{13} = [1, 3] (Salo and Hämäläinen, 1995).

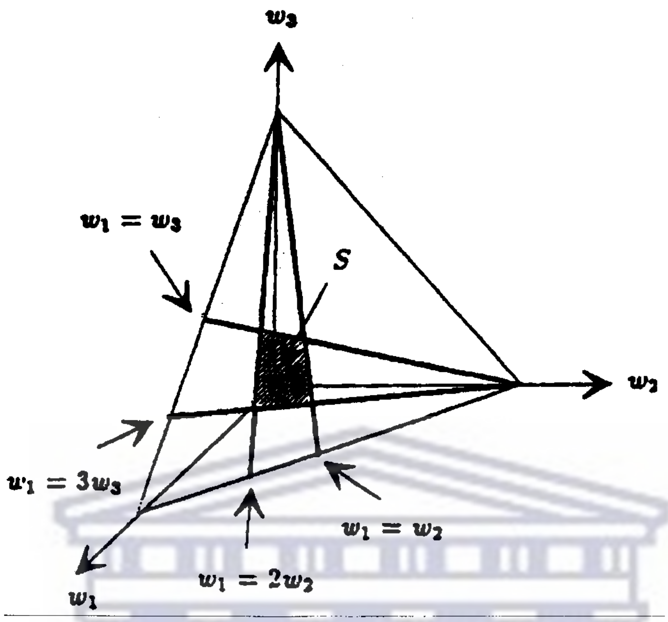

Figure 7 A feasible region (Salo and Hämäläinen, 1995).

Each combination of local priorities from the feasible regions gives a unique weight to each alternative (Salo and Hämäläinen, 1995). As the local priorities vary over the feasible region, every alternative receives an interval of weights. More specifically, if *V(x)*, the weight interval of alternative *x*, lies above that of alternative *y*, then any feasible combination of local priorities assigns to *x* a weight greater than that of *y* (Salo and Hämäläinen, 1995). In such a situation *x* is said to dominate *y* according to the absolute dominance criterion, which is defined by (Salo and Hämäläinen, 1995):

$$x \succ_A y \Leftrightarrow \min_{r \in V(x)} r > \max_{s \in V(y)} s \qquad \text{Equation 6}$$

Tight bounds for the weights of the alternatives can be found by solving optimisation problems in which the alternative weights are maximised/minimised subject to the DM statements (Salo and Hämäläinen, 1995). By taking advantage of the principle of hierarchical composition, which guarantees that the weights of upper level criteria are independent of the judgements on the lower levels, these problems can be decomposed into a series of linear programming problems over the feasible regions (Salo and Hämäläinen, 1995).

This decomposition is presented as follows (Salo and Hämäläinen, 1995):

> *The hierarchy $H = C \cup A$ consists of a set of criteria C and the set of alternatives A. For any criterion $x \in C$ the set x^-, which cannot be empty, contains those elements of H which are structured directly under x. Conversely, for any x the set x^+ consists of the criteria $y \in C$ such that x is structured directly under y. The hierarchy H can be partitioned into levels $L_1, L_2, \ldots, L_h$ such that L_h is the set of alternatives, L_1 consists of the topmost criterion b, and for criterion x $\in L_i$ the criteria in x^+ belong to L_{i-1}.If x is an alternative then x^+ is the set of criteria y for which $y^- \subset A$. For such an x, the set x^+ contains the criteria in L_{h-1}, but it can also contain criteria on the higher levels of the hierarchy.*

5.3.2 Interval SMART/SWING

Mustajoki et al. (2003) studied the use of intervals in SMART and SWING weighting ratio estimation methods. The DM in SWING gives one hundred points to the most important range of attribute in changing from its lowest level to highest level. A fewer points is given to the other attribute ranges to denote their relative importance compared to the most important attribute change. The attributes weights are elicited by normalising the sum of the points to one (Mustajoki et al. 2003). In SMART, the DM gives ten points to the least important attribute (Mustajoki et al. 2003). Then, he/she gives more points to the other attributes to address their relative importance (Mustajoki et al. 2003). SMART and SWING are algebraic methods, i.e. the weights are derived from a set of minimum number (n-1) of linearly independent judgements on preference relations with some simple system of equations (Mustajoki et al. 2003).

The next generalisation of SMART and SWING is to allow the DM to reply with intervals to the ratio questions (Mustajoki et al. 2003). This is known as interval SMART/SWING. The reference attribute is given a fixed number of points, but the points for the other attributes are given as intervals (Mustajoki et al. 2003). The constraints for the attributes weight ratios are derived from the extreme ratios of the points given to the reference attribute and the other attributes (Mustajoki et al. 2003), i.e.

$$\frac{ref}{\max_A} \leq \frac{w_{ref}}{w_A} \leq \frac{ref}{\min_A}$$ Equation 7

where *ref* represents the points given to the reference attribute and max_A (min_A) the maximum (minimum) number of points given to any non-reference attribute *A* (Mustajoki *et al*, 2003). For example, if the reference attribute is given 100 points and attribute *A* an interval of 50-300 points, the constraints for the weight ratio are $100/300 = 1/3 \leq w_{ref}/w_A \leq 2 = 100/50$ (Mustajoki et al. 2003).

5.4 Summary

Value function methods by interval assessments were discussed in this chapter. This method (decision support by interval SMART/SWING) which will be used in the subsequent chapters is generalised in three ways (Mustajoki et al. 2001):

(a) The reference attribute is allowed to be any attribute, not just the most or least important one

(b) The decision maker can reply with intervals to the weight ratio questions to account for judgemental uncertainty

(c) The reference attribute can also be given as an interval to describe, e.g. the ambiguity of the attribute.

This method provides an interactive technique for the decision maker to interrogate various decision alternatives. It accommodates informational uncertainty, a characteristic of water resource management issues. In the next chapter an analysis of the decision problem through the selected technique is applied.

6 Value Tree Construction and Analyses

6.1 Introduction

The aim of the structuring and hierarchical modelling of the objectives is to create a systematic framework for developing an analytic understanding of a problem and a basis for quantitative analysis (Dietrich and Hämäläinen, 2002). This chapter develops the value trees for sustainable groundwater resource management. The value tree is based on the objectives and decision alternatives identified in Chapter 3. Attributes are specified and used to measure the extent to which objectives are achieved in different decision alternatives. After the value trees are constructed they need to satisfy the following conditions (Dietrich and Hämäläinen, 2002):

(a) Completeness

- All relevant objectives should be included in the hierarchy
- The set of attributes completely defines the degree to which the overall objective is met

(b) Operationality

- Attributes should be meaningful and assessable

(c) Decomposability

- Attributes should be judgementally independent i.e. it should be possible to analyse one attribute at a time

(d) Non-redundancy (independence)

- The set of the attributes should be non-redundant (or sufficiently independent) to avoid double counting of the consequences

(e) Minimum set

- The set of attributes should be minimal.

6.2 Value function analysis

The problem is structured visually with WINPRE. The selection of WINPRE is discussed in Section 4.5. Value function analysis derives an overall value score for each of the alternatives. The purpose of the value function elicitation is to model and describe the importance and desirability of achieving different performance levels of each of the given attributes (Dietrich and Hämäläinen, 2002) which are considered in order to arrive at a suitable alternative. When assessing a value function, two main phases can be identified (Dietrich and Hämäläinen, 2002):

- Choosing the range
- Value elicitation

Weight elicitation is done through interval SMART/SWING (Chapter 5). The following procedure is used (Dietrich and Hämäläinen, 2002):

(a) Choose one of the attributes as reference
(b) With respect to the reference attribute, compare the other attributes
(c) Assign 1.0 points to the best attribute
(d) Use preference ratios to calculate the values for the other attributes

The task is to develop a decision-making framework, considering the importance and interrelationship of the various attributes with respect to the decision alternatives (Section 4.6). The software WINPRE is used for the analysis.

6.3 Consequences and evaluations of decision alternatives

6.3.1 Cost recovery

6.3.1.1 Current situation (Scenario 2)

In Namaqualand cost recovery is related to the sophistication of the level of technology. Most communities are supplied from boreholes equipped with diesel-operated pumps. In many instances, studies conducted by Williams (2000) found that these boreholes were frequently not functional. The reasons for this were (Titus et al. 2002):

- The high ratio of people to boreholes – in some cases, more than 300 people per borehole
- The misuse of pumps
- The drop in groundwater levels during dry periods
- The poor rate of payment for services
- Many of the pumps are located in remote and scattered places, which in turn complicates access; maintenance thus takes place on a irregular basis
- Maintenance and cost differ from place to place depending on the availability of spare parts and technicians. Community participation is poor and those residents who are dissatisfied with water regulations often damage water systems and ignore rules formulated by their leaders.

As seen from above, the breakdown of systems is attributed to technical, social-economic and institutional factors. In some communities the systems employ technologies e.g. desalination which are too sophisticated for community management. The communities are thus dependent on outside assistance, which involves additional costs and results in poor ownership of these systems. The following approaches have been proposed to promote sustainability of systems:

- The selection of pumping systems, which are low yielding to minimise excessive drawdown.
- Cross-subsidisation for technologies such as desalination, which are not affordable.

Willingness to pay for water services is largely dependent on affordability and the level of service and proper functioning of the systems. The main source of income in the communal reserves of Namaqualand is stockfarming, subsistence agriculture, pension payments and welfare. The unemployment rate in the communal reserves is a source of major concern.

The successful management of water and sanitation services depends on the ability of communities to contribute financially to the operation and maintenance (O&M) of these systems. Unwillingness to contribute financially occurs widely within the communal areas of Namaqualand (Williams, 2000). The communities are caught in the classical catch 22 situation: people do not want pay for poor services but the service is poor because of limited cost recovery. Furthermore, cost recovery is low in relation to the economic value of the services provided, also resulting in poor maintenance of the services. This results in free-loading i.e. some households contribute and others not. Community members have been unwilling to pay the water committee or a designated person, preferring to make a payment at an office.

These and other realities need to be taken into account, when designing the tariff structures for water services. For example the current water use of communities is frequently below the free basic water use level. This means cross-subsidisation is inevitable.

6.3.1.2 Decision alternatives

The various decision alternatives for the objective cost recovery are given in Section 3.5.6. These are repeated for ease of reference:

- Involve communities in the selection of technology and developing the cost recovery system (C.Inv.)
- Facilitate technology selection and tariff setting at local government level (L.Govt)

The attributes for effective cost recovery (CR) were chosen as:

- High proportion of people (expressed as a percentage) who pay against those who do not pay to recover operation and maintenance costs (Payment).

- Technical competency of community based technical operators to conduct daily operation and maintenance of projects and to make basic repairs (Cain et al. 2000). This is expressed as the % of assurance of supply (Assur.)
- Adequate tariff structure for recouping recurrent costs, expressed as a percentage of monthly recurrent costs recovered (Tariff)

6.3.1.3 Evaluation

The problem is structured visually (Figure 8). Figure 9 presents the interval SMART/SWING weighting window of WINPRE. The process to identify the attributes, alternatives and attributes in building a decision-making framework for groundwater is given in Figure 4. In this window the relative importance of the three attributes identified in section 6.3.1.2 are compared. The value intervals are reflected in Figure 10 and Figure 11.

The reference attribute chosen was 'Assur.'. This is directly linked to the sophistication of the technology and thus the ability to ensure a continued water supply. The attributes of 'Payment and 'Tariff' are dependent on a sustained water supply otherwise no payments can be collected and setting tariffs becomes redundant. Implementation of inappropriate technology leads to:

- Poor cost recovery
- Lack of ownership of the water supply scheme
- Dependence of communities on outside agencies (dependency paradigm)
- Weak institutions
- Poor operation and maintenance

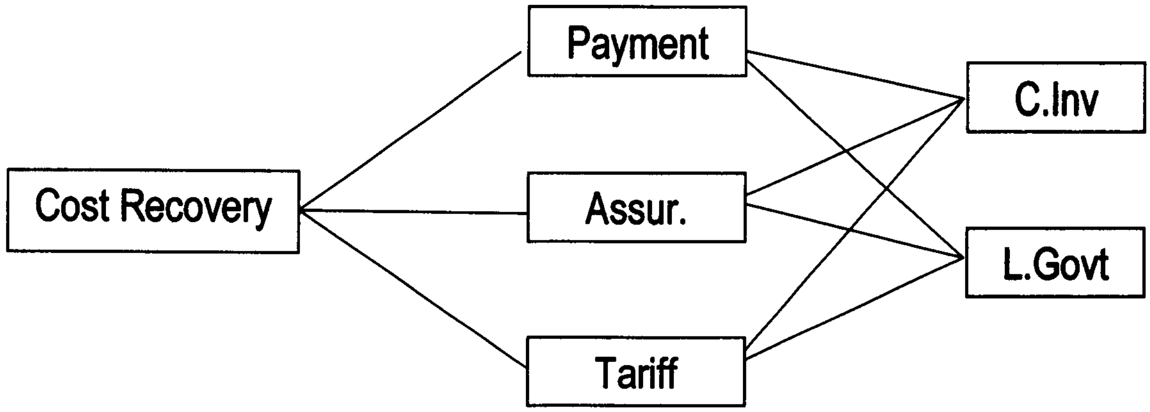

Figure 8 Value tree for cost recovery.

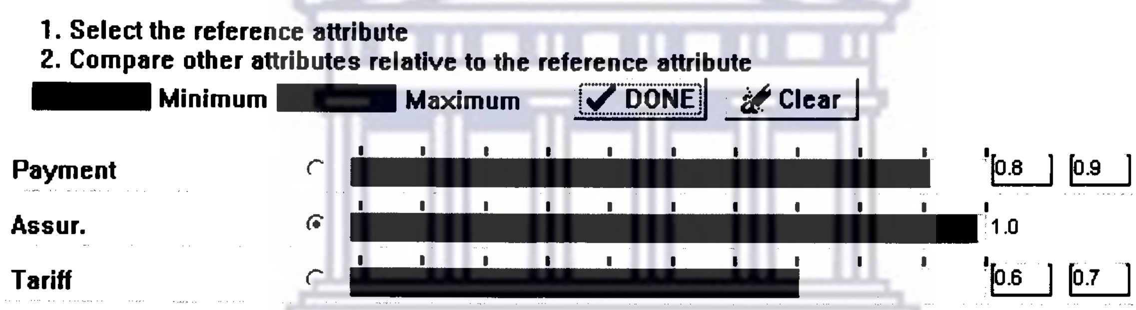

Figure 9 Interval SMART/SWING weighting in the decision-making procedure (comparison of payment, assurance of supply and tariff structure).

The value intervals (or constraints) for the attribute 'Payment' are given in Figure 10. Despite local authority involvement, poor cost recovery is evident throughout a number of communities in Namaqualand. The level of proportion of people who pay against those who do not pay to recover operation and maintenance costs can range from 40% to 70%. Where there is significant community involvement this ranges from 70% to 100%.

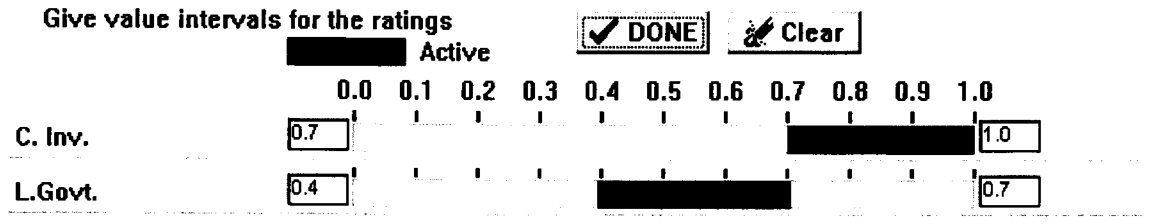

Figure 10 Local score intervals for the attribute payment ('Payment').

The value intervals (or constraints) for the attribute 'Assur.' are given in Figure 11. In this case the intervals for community involvement are given as between 90% and 100%. Where there is significant involvement and leadership of communities in the decision-making process, there is greater acceptance and better functioning of water supply systems (Williams, 2000). This leads to a greater possibility for assurance of water supply. In the case of local government, the great distances between government centres and communities prevent effective involvement, and consequently this result in breakdown of services. The interval chosen in this case ranges from 40% to 90% of assurance of supply.

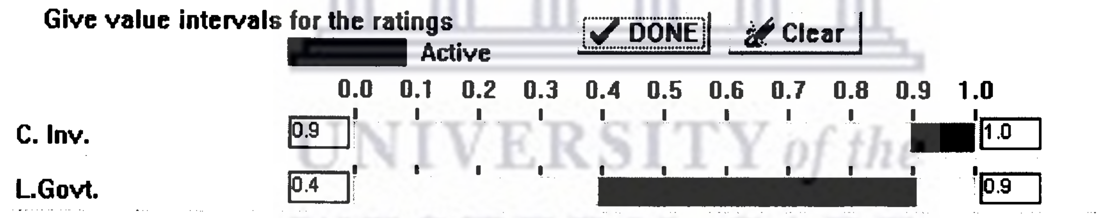

Figure 11 Local score intervals for the attribute assurance of supply ('Assur.').

The value intervals (or constraints) for the attribute 'Tariff' are given in Figure 12. The cost of water influences water demand. If water is too expensive, then affordability becomes an issue and communities resort to unsafe sources of drinking water. If on the other hand, water is not properly valued, wastage and improper use will result. In the case of local government involvement, frequently as a result of improper consultation, the wrong tariff structures are put into place, resulting in affordability issues. In this case the interval range is given as 30% to 70%. Through proper community involvement procedures, tariff setting takes into account various issues such as affordability and economic considerations. The interval range in this case is chosen between 70% and 100%.

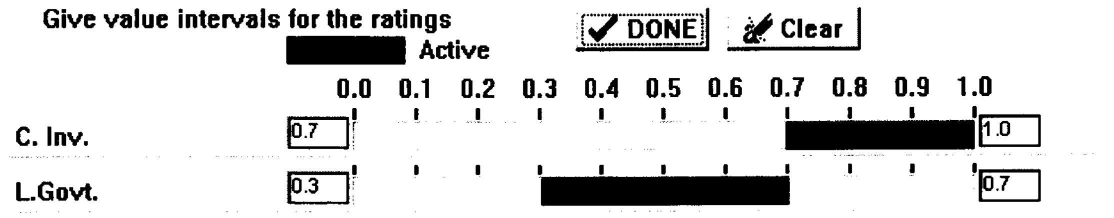

Figure 12 Local score intervals for the attribute tariffs ('Tariff').

The combination of the above relationships gives the overall value intervals and the possible dominance relations shown in Figure 13. The definition of dominance pertains to one alternative having a higher value (per the value function) for all values over the interval ranges (Stewart, 2003). In this case there is no dominated alternative, which would indicate that both local government and community involvement are crucial to the implementation of water services.

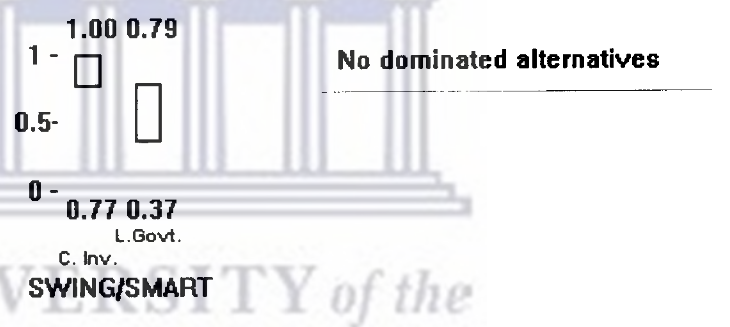

Figure 13 Overall value intervals and dominance relations (in this case no dominant relations).

Sustainable systems are based on affordable, appropriate technology which continues to provide a high level of benefit after completion of the project. In particular, the community must be aware of the proper use of the systems and must be able to afford the related operation and maintenance costs. Technologies which provide an acceptable level of service, and can be operated and maintained at local level, and importantly match the social and cultural circumstances of the communities, are more suitable.

As a consequence of the above analysis, neither of the alternatives, 'C.Inv." and 'L.Govt', have relative dominance over the other. This demonstrates that the both are crucial for implementing sustainable groundwater supply schemes. In the decision-making framework these aspects cannot be omitted or ignored.

6.3.2 Aquifer management

6.3.2.1 Current situation (Scenario 2)

The medium to long-term sustainability of the groundwater resources, particularly for domestic water supply, is a function of the groundwater quantity or yield, and groundwater quality associated with these fractured crystalline aquifers (Titus et al. 2002). Management of the aquifer systems has two broad objectives (Titus et al. 2002):

- To contribute to water security
    - Provide communities with adequate water, in terms of quantity and quality, to meet the functional requirements of promoting health and supply of food;
    - Develop community awareness of their rights and responsibilities with regard to services, so that they are involved in decisions about the selection of water sources, appropriate technology, cost recovery mechanisms and management arrangements;
    - Devise capacity building and training programmes to empower communities and develop necessary capabilities such as project management and operation and maintenance skills;
    - Provide employment for local communities through further skills development
- Measures to ensure resource sustainability are to:
    - Determine the sustainable yield and develop policy and strategies for groundwater management at community and catchment scale;
    - Protect the aquifer from possible pollution risks such as those associated with improper location of pit latrines and indiscriminate disposal of waste;
    - Protect the communities from poor quality groundwater;
    - Establish mechanisms for communities to participate in a meaningful way – they need to be well informed about the functioning of their water resources systems and the likely consequences of their decisions;
    - Protect the integrity of the system (the aquatic and aquifer environment);

- Develop appropriate systems to monitor and evaluate resource sustainability as well as delivery and proper operation and maintenance of installed systems

6.3.2.1.1 *Groundwater quality and quantity*

The groundwater in Namaqualand, because of the nature of the geology, is of poor quality. Quality is a function of the residence time which influences the water-rock interaction, which in turn results in varying groundwater chemistry (Titus et al. 2002). The groundwater in Namaqualand has a dominant NaCl character, which is the result of the influence of salt dissolution and leaching as well as the weathering of hydrous minerals, especially biotite, on the activities of Na^+ and Cl^- ions in solution.

Appendix D compares the groundwater chemistry with water quality guidelines at selected towns. This assessment does not take into account microbiological factors, which can significantly affect the use of water for drinking and stock watering purposes. Appendix E contains the guidelines for domestic use. A number of borehole water samples in Namaqualand have been found to have fluoride concentrations above the maximum recommended concentration of 1.5 mg/l. Values in excess of 5 mg/l and as high as 10 mg/l are not uncommon. This could pose a health risk for long-term users of this water for drinking, since dental and skeletal fluorosis can arise from long-term exposure to high fluoride concentrations. Toens et al. (1998) found high values of uranium and arsenic in groundwater in the region. Over large areas 500 µg/l or even 100 µg/l of arsenic concentrations have been encountered (Toens et al. 1998). Similar elevated levels of uranium exist in the region. Sami et al. (2003) conducted a study to predict elevated arsenic and uranium occurrences in South Africa and clearly showed that the Namaqualand region has high risk areas.

Monitoring abstraction rates is important, as information on abstraction rates needs to be evaluated against recharge rates and sustainable resource utilisation. Abstraction must not exceed the rate of replenishment. However, in some cases sustainable yield calculations are ignored by borehole operators. This result in mining of the aquifer and localised depletion of groundwater takes place.

6.3.2.1.2 *Management systems*

Legislation provides the framework for the setting up of institutions and establishes the levels of service to be provided. At a national level, DWAF is responsible for water resource management. One of the National Water Act's main objectives is to progressively decentralise and devolve the responsibility and authority for water resource management to appropriate regional and local institutions in order, among other things, to enable water users and other stakeholders to participate more effectively in the management of water resources (DWAF, 2002). The institutional framework for water management consists of (DWAF, 2002):

- The Minister of Water Affairs and Forestry
- The Department of Water Affairs and Forestry
- Water Management Institutions and Responsible Authorities
- Water Management Areas
- Catchment Management Agencies (CMAs)
- Water User Associations (WUA)
- Advisory Committees
- Forums
- Institutions for Infrastructure Development and Management
- Institutions for International Management
- Water Tribunal

Local communities cannot participate in all the relevant institutions, but notable opportunities exist in three of these structures, namely CMAs, WUAs and Forums. There is no provision in the National Water Act or Water Resource Strategy for creating forums specifically for water resource management purposes. As is the case in Namaqualand, the rural communities support a range of different institutions such as churches, sports organisations and committees (Titus et al. 2002). Most of the communities on the communal reserves have an organisation called the "Plaaslike Ontwikkelingsforum" (Local Development Forum) that operates in the community and is responsible for community welfare and development projects. The Forums have various subcommittees responsible for different tasks, including water. These Forums have an important task to provide local knowledge, expertise and information and monitor water management at community level. The proper functioning of these local Forums presents challenges and is dependent on proper representation and consultation among different stakeholders.

WUAs are co-operative associations of individual users who wish to undertake water related activities at a local level for their mutual benefit (DWAF, 2002). They operate in terms of a formal constitution as set out in the guidelines prepared by DWAF (DWAF, 2002). They are expected to be financially self supporting from water use charges determined and made in terms of the pricing strategy, and payable by members (DWAF, 2002). The establishment of WUAs is in its formative stages. The proper establishment of WUAs is critical for proper resource management.

The proposed CMA which will have responsibility for the Namaqualand region will cover the largest water management area (namely the Lower Orange) in South Africa and will not be able to address local needs. A CMA manages water resources, and co-ordinates the water related activities of water users and other water management areas within the water management area (DWAF, 2002). The initial functions include the important responsibility for the agency to develop a catchment management strategy (DWAF, 2002).

Stakeholder participation in the above structures will be crucial for sustainable development of groundwater resources in the region. The involvement of communities in the collection of relevant information and the empowerment of communities in the decision-making process is needed prior to the implementation of water and sanitation schemes. It is important to recognise that no community is homogeneous, and frequently structures are controlled by the "privileged" sectors of the community. Also the needs of different sectors of the community may differ and cause conflict; for example, some members may need water for agricultural purposes in addition to their basic need. Discussions with stakeholders in the region showed that the following improvements would increase the effectiveness of public participation with regard to aquifer management (Titus et al. 2002):

- There needs to be a greater understanding about the roles and responsibilities of the different groups, particularly between rural communities and consultants. This will improve accountability and transparency in aquifer management and help the end-users to understand their responsibilities better. This includes the responsibility to pay for services received.

- Communities need to see the results of their contributions and level of participation. Some communities might perceive that they suffer from participation fatigue, especially if there is little to show for it.
- The two-way flow of information needs to start as soon as possible. Stakeholders need to start articulating their priorities and water resource managers need to start communicating their constraints.
- Existing community structures should be used and improved rather than putting energy into starting new forums.
- Vertical links have been established between users and suppliers but not among users. There needs to be more communication among users and consensus building regarding the future of the catchment. The development of a vision for the future should precede a detailed road map. Once stakeholders agree to work towards a scenario that benefits them, they should also understand the benefits of paying for services received.

The available funding, to a large degree, influences the establishment of functioning institutions and proper assessment of the available groundwater resources. A requirement of legislation is RDM (Chapter 3). The key steps required for a reserve determination are as follows (Xu et al. 2003):

- Conceptualise the aquifer system as part of the catchment
- Indicate which sections of stream are receiving groundwater fed base flow
- Conduct flow simulation for groundwater and surface water interaction
- Undertake water balance studies
- Carry out on-going model calibration as more monitoring data become available.

6.3.2.2 Decision alternatives

The various decision alternatives for the objective aquifer management are given in Section 3.5.2. These are repeated for ease of reference:

- Conduct water demand assessments; develop community participation and management systems (CommM);
- Undertake technical assessments of the aquifer systems and institute aquifer monitoring

systems (TechnM)

The attributes for desirable aquifer management (AM) were chosen as:

- Proactive monitoring takes place of drinking water quality with respect (a) substances which are general indicators of water quality (b) substances which are commonly present at concentrations which may lead to health problems (c) substances which occur less frequently at concentrations of real concern to health and (d) substances which may commonly be present at concentrations of aesthetic or economic concern in domestic water sources (Qual)
- Licensing of all water uses (Licens)
- Legislative requirements met, i.e. RDM and SDC set. Institutions (CMAs, WSP, WSA) in place (Legisl)
- Funds for capital and recurrent costs available (Funds)
- Technical data on existing water services incorporating detailed data on water sources, infrastructure etc available (EWS)
- Water supplied for productive use and economic development (ED)
- Macro-scale demographic information (growth, trends and dynamics) and community based studies available (Demogr)
- Community-based demand-side planning takes place (DM)

6.3.2.3 Evaluation

The problem is structured visually (Figure 14). Figure 15 presents the interval SMART/SWING weighting window of WINPRE. In this window comparison is made between the attributes drinking water quality; licensing of all water uses; legislative requirements; available funds for capital and recurrent costs; technical data incorporating detailed data on water sources, infrastructure etc; water supply for productive use; macro-scale demographic information (growth, trends and dynamics) and community-based demand side planning. In this case the reference attribute was chosen as drinking water quality. Access to clean water together with improved hygiene practices has a significant impact on human health in rural areas. The value intervals are reflected in Figure 16, Figure 17, Figure 18, Figure 19, Figure 20, Figure 21, Figure 22 and Figure 23.

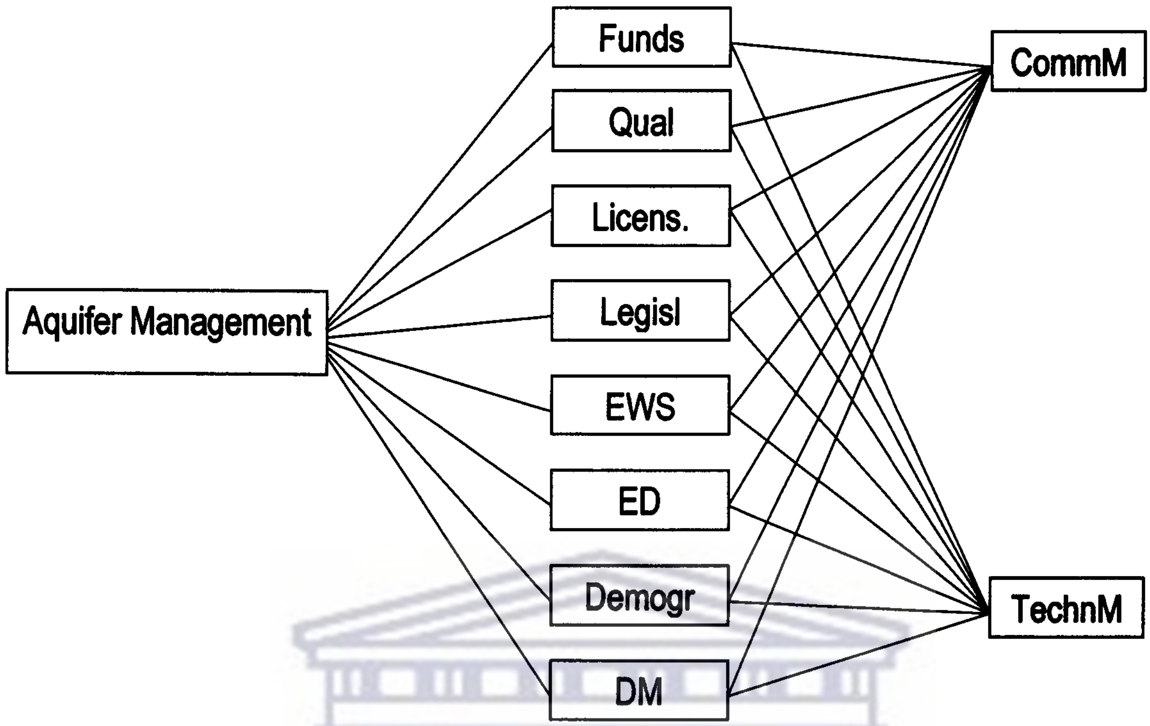

Figure 14 Value tree for aquifer management.

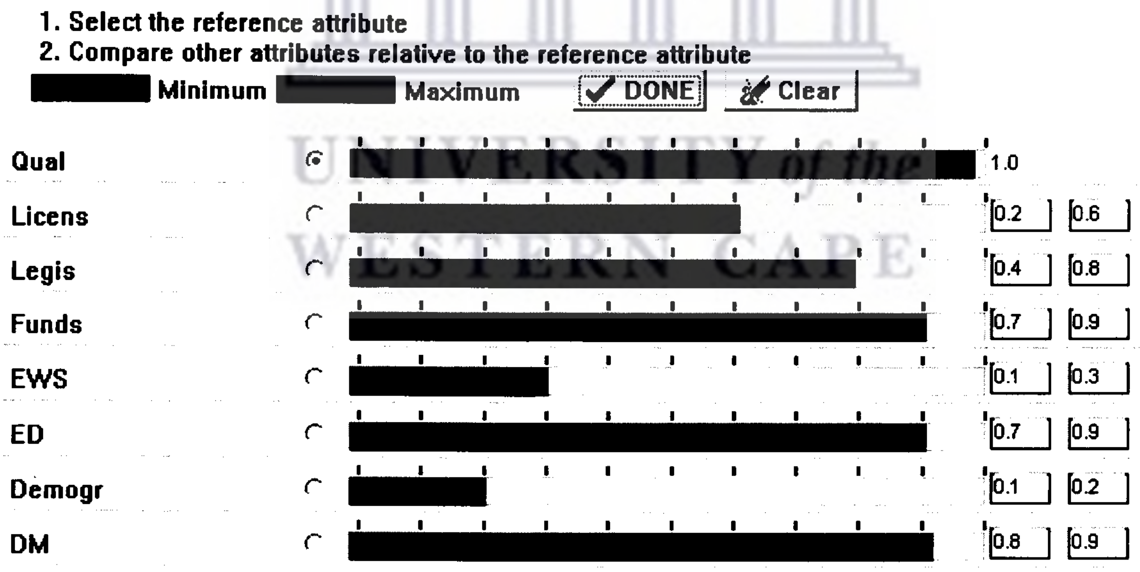

Figure 15 Interval SMART/SWING weighting in the decision-making procedure (comparison of attributes).

The value intervals (or constraints) for the attribute 'Qual' are given in Figure 16. Proper protection of the water resource from polluting activities will only happen if there is significant community management of the system. In arid zones, the natural quality of groundwater is poor with high trace constituents, such as fluoride. The system is also prone to microbial contamination as a result of improper protection measures.

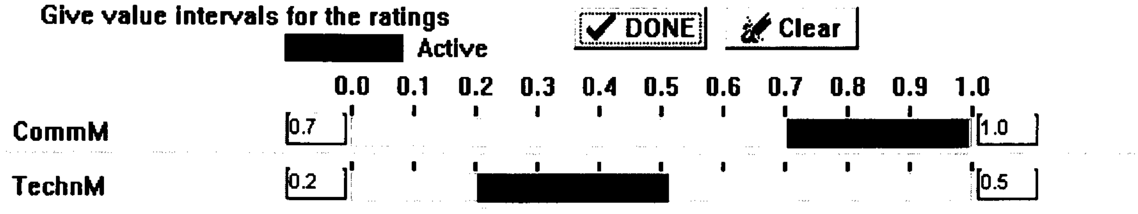

Figure 16 Local score intervals for the attribute drinking water quality ('Qual').

The value intervals (or constraints) for the attribute 'Licens' are given in Figure 17. Transparent water allocation mechanisms are necessary to ensure proper allocation and thus the meeting of water demand adequately in space and time.

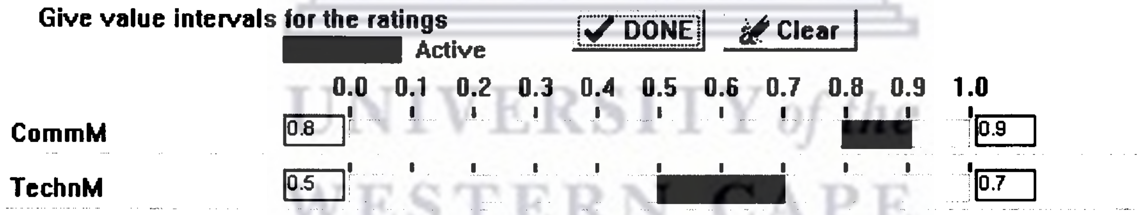

Figure 17 Local score intervals for the attribute license ('Licens').

The value intervals (or constraints) for the attribute 'Legisl' are given in Figure 18. Legislation provides the framework for the setting up of, and establishes the level of, service to be provided. If a technical management approach is adopted, legislation will be implemented, more as a top-down approach resulting in improper consultation, and institutions will be weak. Following a community management approach may result in a bottom-up approach; properly functioning institutions will exist, supported by a sophisticated legislative framework.

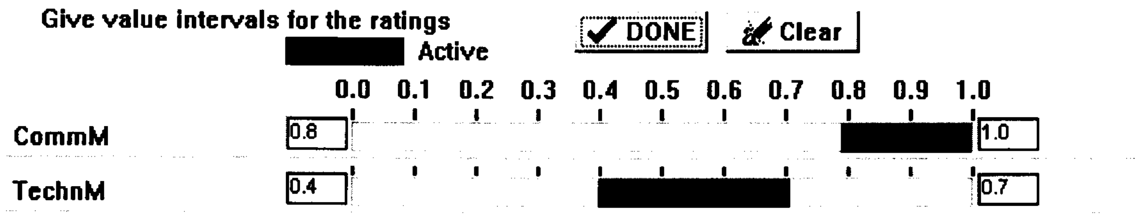

Figure 18 Local score intervals for the attribute legislation ('Lisenc').

The value intervals (or constraints) for the attribute 'Funds' are given in Figure 19. The available funding to a large degree influences the establishment and functioning of institutions and proper assessment of available groundwater resources. Adequate funding is required to meet the needs of the people suffering from a lack of resources. In most cases funding is controlled by technical parties as opposed to community management.

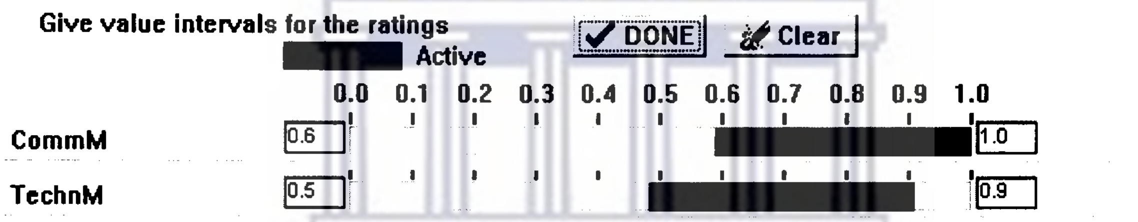

Figure 19 Local score intervals for the attribute funds ('Funds').

The value intervals (or constraints) for the attribute 'EWS' are given in Figure 20. The existing water services include aspects such as the level of service and which can determine water demand. Current focus of policy is on meeting the needs of un-serviced communities.

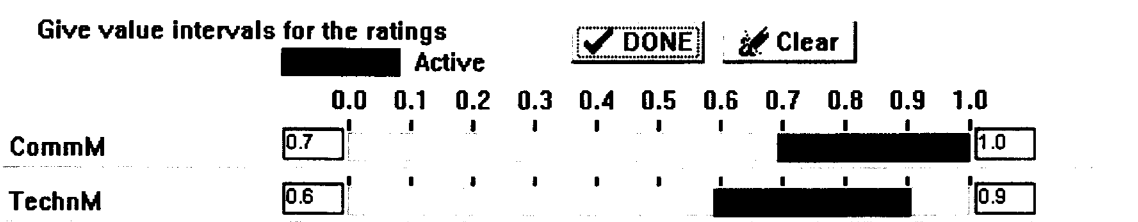

Figure 20 Local score intervals for the attribute existing water services ('EWS').

The value intervals (or constraints) for the attribute 'ED' are given in Figure 21. The level of economic development will influence level of services. This will be done in accordance with macro-economic policies in the affected region/country.

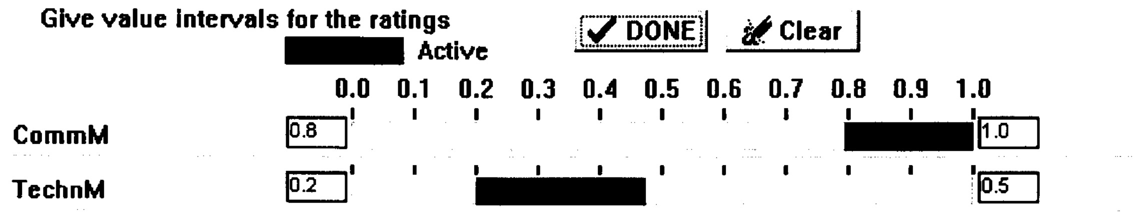

Figure 21 Local score intervals for the attribute economic development ('ED').

The value intervals (or constraints) for the attribute 'Demogr' are given in

Figure 22. Knowledge of population size, growth and dynamics are crucial for proper planning in terms of meeting water demand. Normally macro-scale demographic information is being collected and verified, giving information on population growth, trends and dynamics. However, in addition to macro-scale information, community based studies are being done to obtain community-scale demographic information.

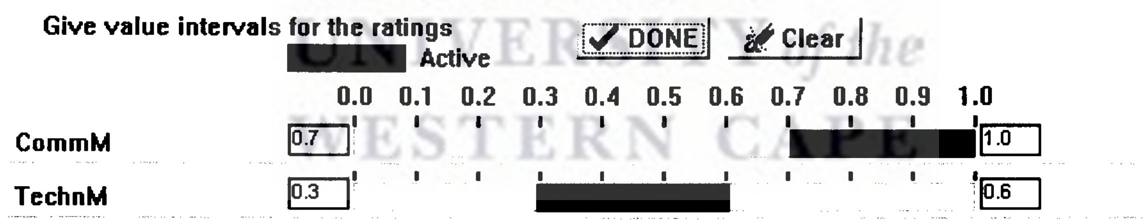

Figure 22 Local score intervals for the attribute demography ('Demogr').

The value intervals (or constraints) for the attribute 'DM' are given in Figure 23. Extreme climatic conditions such as drought pose many challenges for water demand in arid zones. There is competing demand for scarce water resources such as domestic use, livestock watering and for agricultural purposes. Proper demand planning means that communities' water requirements are being met in an adequate manner.

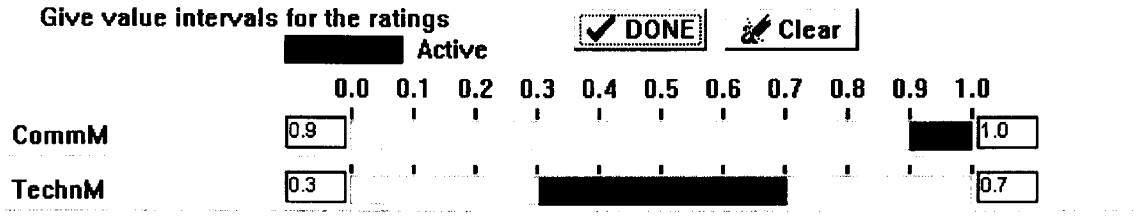

Figure 23 Local score intervals for the attribute water demand ('DM').

The combination of the above relationships results in the overall value intervals and the dominance relations shown in Figure 24. It is clear from the analyses that the alternative, focussing on conducting water demand assessments; develop community participation and management systems is the dominant alternative from the analyses.

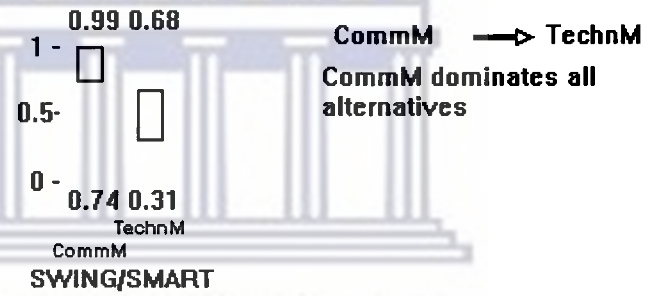

Figure 24 Overall value intervals and dominance relations.

6.3.3 Aquifer protection

6.3.3.1 Current situation (Scenario 2)

Pro-active protection of groundwater resources in Namaqualand is non-existent. The delineation of protection zones is not in place. Van Tonder et al. (2001) developed a methodology for borehole protection areas in fractured rock aquifers. The protection zones are divided into the following classes (Van Tonder et al. 2002):

- Protection zone I (Fencing): The fence around a borehole must be at least 5 m from the borehole. For a borehole that is supplying water to less than 20 persons, a well-constructed sanitary seal is sufficient. Quality monitoring is important.
- Protection zone II (Microbial pollution): A second protection zone around the borehole is suggested. This zone protects drinking water from microbial contamination.
- Protection zone III (Hazardous elements): If persistent hazardous non-degradable elements are present, the whole catchment area of a borehole must be protected.

In the case of community water supplies, a Protection zone II should suffice. In the case of the delineation of Protection zone II, the areal extent of the fracture is very important (Van Tonder et al. 2002). Once bacteria or an element reaches the fracture, its movement will be very rapid towards the abstraction borehole. Van Tonder et al. (2002) introduced methods to estimate fracture extent and travel times. These protection zones need to be determined for all water supply boreholes in Namaqualand.

6.3.3.2 Decision alternatives

The various decision alternatives for aquifer protection are given in Section 3.5.3. These are repeated for ease of reference:

- Develop protection zones around identified environmental assets (ProZone).
- Compile an inventory of contamination sources (ContInv).
- Determine groundwater contribution to baseflow (BaseFl).
- Develop borehole protection zones from contamination sources(BPZone)

The attributes for desirable aquifer protection (AP) were chosen as:

- Source Directed Controls in place for groundwater resources (SDC)
- Groundwater resources classified (Class.)
- Basic human needs reserve established (BHN)
- Ecological reserve established (Reserve)
- Resource Quality Objectives set (RQOs)

6.3.3.3 *Evaluation*

The problem is structured visually (Figure 25). Figure 26 presents the interval SMART/SWING weighting window of WINPRE. In this window comparison is made between the attributes source directed controls, classification of groundwater resources, basic human needs, ecological reserve set and RQOs. In this case the reference attribute was chosen as basic human needs. The setting of a basic human needs reserve is a requirement under the National Water Act. This is frequently, the only reserve that can be set for groundwater in arid zones. The value intervals are reflected in Figure 27, Figure 28, Figure 29, Figure 30 and Figure 31.

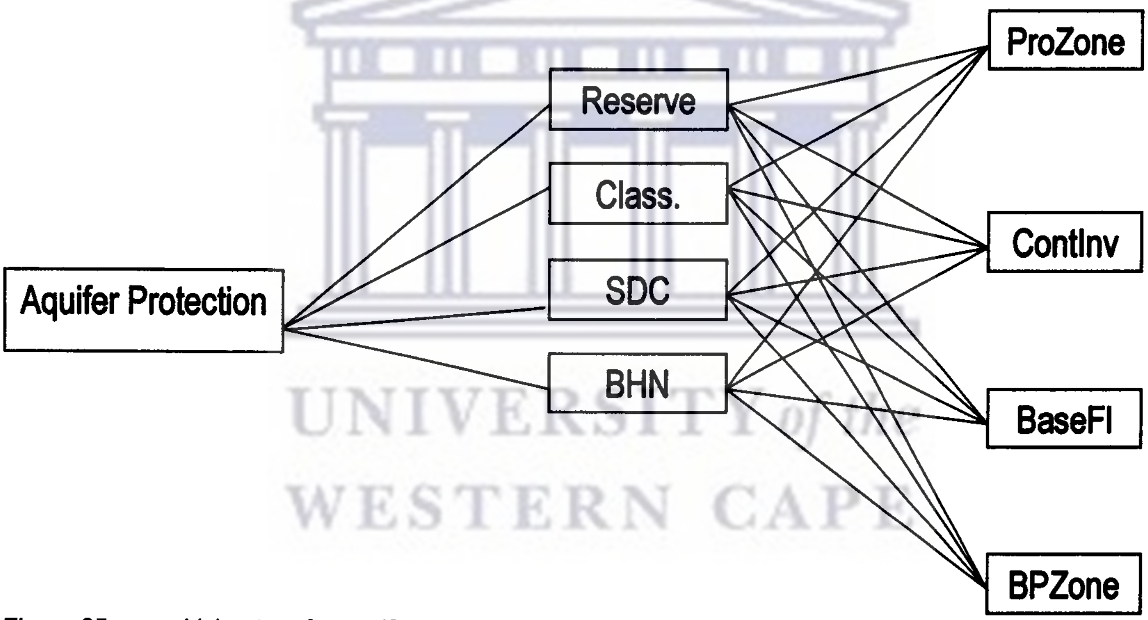

Figure 25 Value tree for aquifer protection.

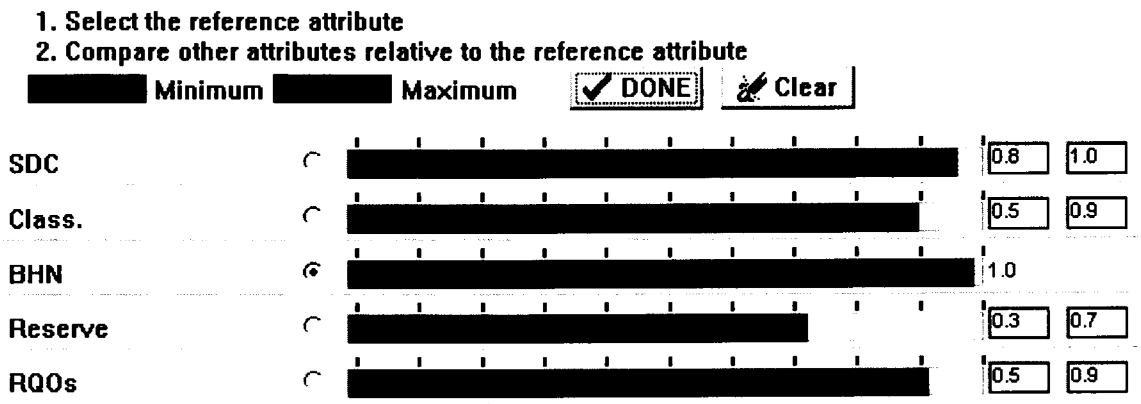

Figure 26 Interval SMART/SWING weighting in the decision-making procedure (comparison of attributes).

The value intervals (or constraints) for the attribute 'SDC' are given in Figure 27. Source directed controls are measures to protect the aquifer from land-use impacts. This relates to necessary protection measures such as protection zones or the prevention of certain land-use activities.

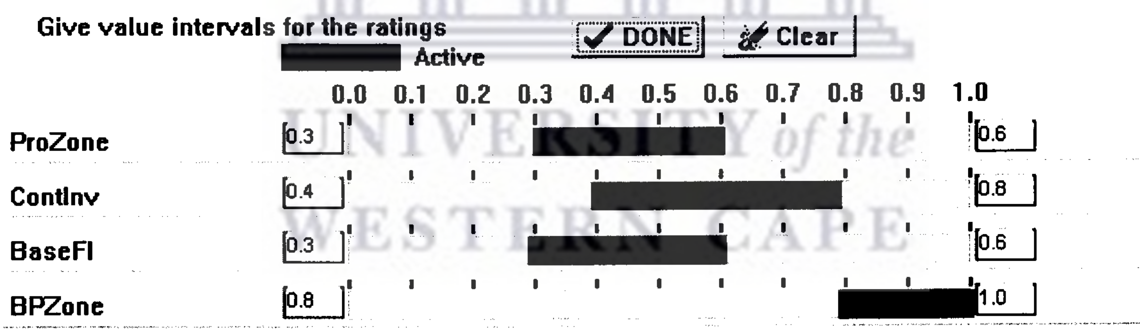

Figure 27 Local score intervals for the attribute source directed controls ('SDC').

The value intervals (or constraints) for the attribute 'Class.' are given in Figure 28. The classification of water resources is a measure which links to the required level of protection of groundwater resources (Chapter 2).

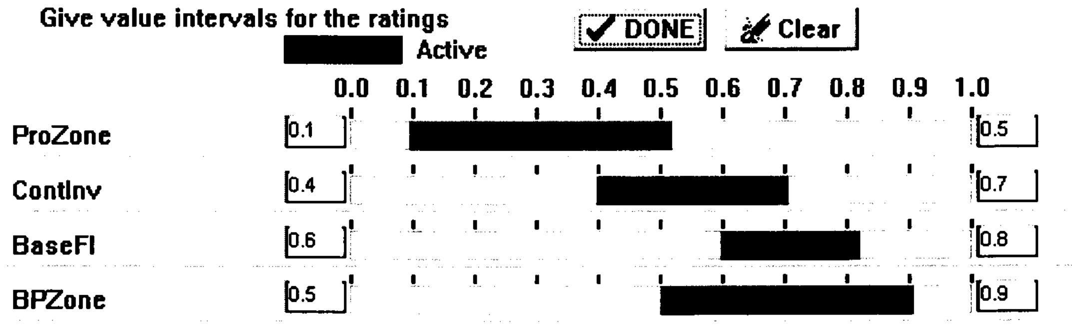

Figure 28 Local score intervals for the attribute classification ('Class.').

The value intervals (or constraints) for the attribute 'BHN' are given in Figure 29. The provision of water for basic human needs is a requirement of the National Water Act (Chapter 2).

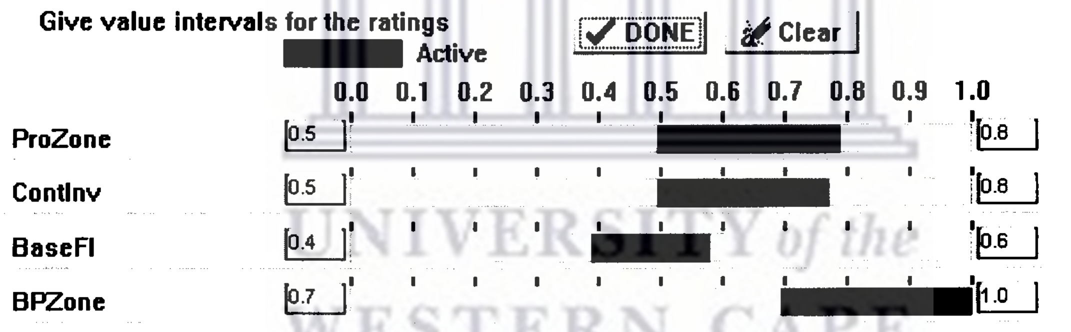

Figure 29 Local score intervals for the attribute basic human needs ('BHN').

The value intervals (or constraints) for the attribute 'Reserve' are given in Figure 30. The setting of the ecological reserve is a requirement of the National Water Act (Chapter 2).

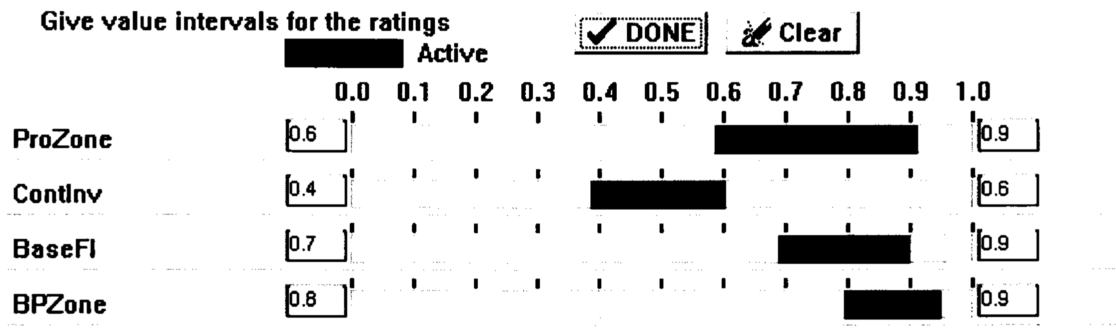

Figure 30 Local score intervals for the attribute ecological reserve ('Reserve').

The value intervals (or constraints) for the attribute 'RQOs' are given in Figure 31. RQOs are a requirement under the National Water Act (Chapter 2).

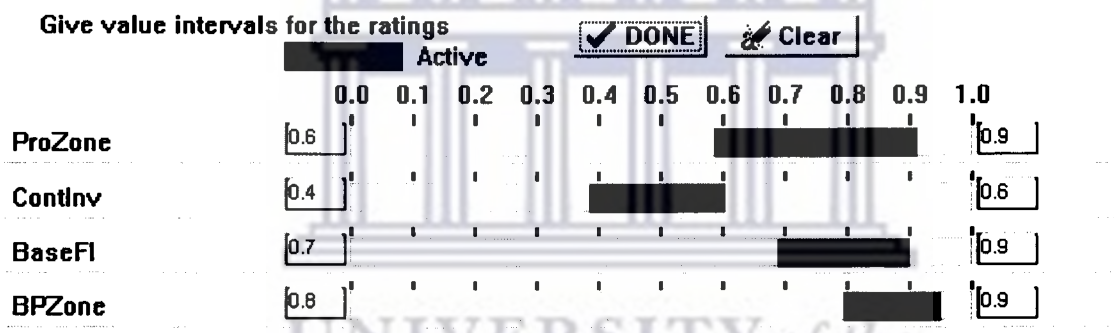

Figure 31 Local score intervals for the attribute 'RQOs'.

The combination of the above relationships results in the overall value intervals and the dominance relations shown in Figure 32. It is clear from the analyses that the alternative, focussing on developing borehole protection zones from contamination sources, is the dominant alternative.

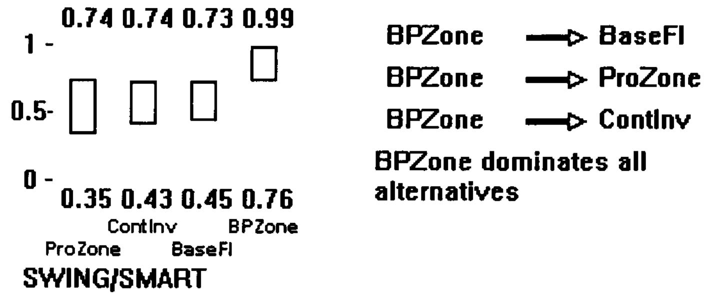

Figure 32 Overall value intervals and dominance relations.

6.3.4 Aquifer assessment

6.3.4.1 Current situation (Scenario 2)

Understanding the occurrence attributes and dynamics of the aquifer system is crucial to proper resource assessment. Without this understanding, there will not be proper quantification of the resource and by implication, either under- or over-utilisation, which will impact on social and economic development within communities.

Stevens (2002) evaluated 28 pump test data sets (Table 5). The data were collected from DWAF, Toens and Partners and Hippo and A&B pumps (Stevens, 2002). The pump test data were interpreted using well known analytical methods, mostly the Theis and Cooper-Jacob method. These methods were developed for porous media and are only valid for radial flow. The following flow types can occur during pump tests in fractured reservoirs (Van Tonder et al. 2002):

- Linear flow
- Radial flow
- Spherical flow

Table 5 represents transmissivity (T) and storativity (S) values as extracted from the various reports. The T values for some of the areas are unrealistically high for this type of aquifer (Stevens, 2002).

Table 5 T and S- values extracted from reports (from Hassan, 2002).

Town	Borehole number	Transmissivity (m^3/day)	Storativity
Tweerivier	LF 90/201	9.5	5×10^{-4}
Steinkopf	SK 103	1505; 260	2.1×10^{-7}
Steinkopf	SK 93/106	2	
Steinkopf	SK 93/107	29.5	
Steinkopf	SK 93/108	38.8	
Steinkopf	SK 91/102	4720	

Stevens (2002) interpreted pump test data using techniques developed for fractured rock aquifers (Table 6). The T values are much lower and realistic for this type of environment (Hassan, 2002).

Table 6 T and S- values calculated using AQUATEST (from Hassan, 2002).

Town	Borehole number	Transmissivity (m^3/day)	Storativity
Kommagas	KG 93/114	0.28	2.66×10^{-3}
Kommagas	KG 93/113	14.61	6.07×10^{-4}
Kommagas	KG 93/111	0.10	1.27×10^{-3}
Kommagas	KG 93/107	0.68	1.00×10^{-2}
Klipfontein	LF 98/312	0.08	9.54×10^{-2}
Spoegrivier	G 45805	0.38	1.00×10^{-4}
Garies	G45779	1.43	1.67×10^{-4}

Reinterpretation of existing data provides a framework for reassessing aquifer parameters in order to adapt pumping strategies.

A geological review is necessary to identify potential target features. This includes (Sami et al. 2002):

- Geological characterisation
  - Lithology
  - Faults and dykes
  - Identification of domains

- Geodynamics (identification of extensional structures)
    - Tectonic and deformational history
    - Strain analysis
    - Effect of existing structures
    - Expected deformation vs. observe structures
    - Structural analysis
    - Consideration of geochronology on lithology
    - Mapping of faults and joints
    - Structural analysis

Groundwater flow and storage in the basement aquifers of Namaqualand is complex, as result of the widely varying orientation of the fracture system. This has been described in Section 2.2.

6.3.4.2 Decision alternatives

The various decision alternatives for aquifer assessment are given in Section 3.5.4. These are repeated for ease of reference:

- Undertake a detailed geological and geomorphological review of region (including geodynamics and structural geology) (Geology).
- Characterise aquifers at regional scale (regional groundwater flow model) (Flow).
- Characterise aquifers at local scale (e.g. proper pump testing analysis) (Local).

The attributes for proper aquifer assessment (AA) were chosen as:

- Regional groundwater flow model with time series information (hydraulic head distribution) developed (WL).
- Application of analytical methods for fractured rock aquifer parameter estimation (with proper understanding of underlying assumptions) and analyses of water level fluctuations during long term abstractions (RY)
- Regional flow systems established, in terms of (a) occurrence and type of aquifers (b) boundaries of aquifers (c) areal distribution of groundwater recharge (including type and

amount of recharge (d) expected groundwater heads and (e) flow directions and general chemical composition (FS)

- Geological understanding developed i.e. through geological review, geodynamics and structural analysis of aquifers (Geol).

6.3.4.3 Evaluation

The problem is structured visually (Figure 33). Figure 34 presents the interval SMART/SWING weighting window of WINPRE. In this window comparison is made between the attributes water levels, resource yield, flow systems and geology. In this case the reference attribute was chosen as flow system. Developing a correct conceptual model of the groundwater flow system will greatly enhance sustainable development of the resource. A systems approach to groundwater assessment is required, which results in a complete understanding of the aquifer framework, including constraints. The value intervals are reflected in Figure 35, Figure 36, Figure 37 and Figure 38.

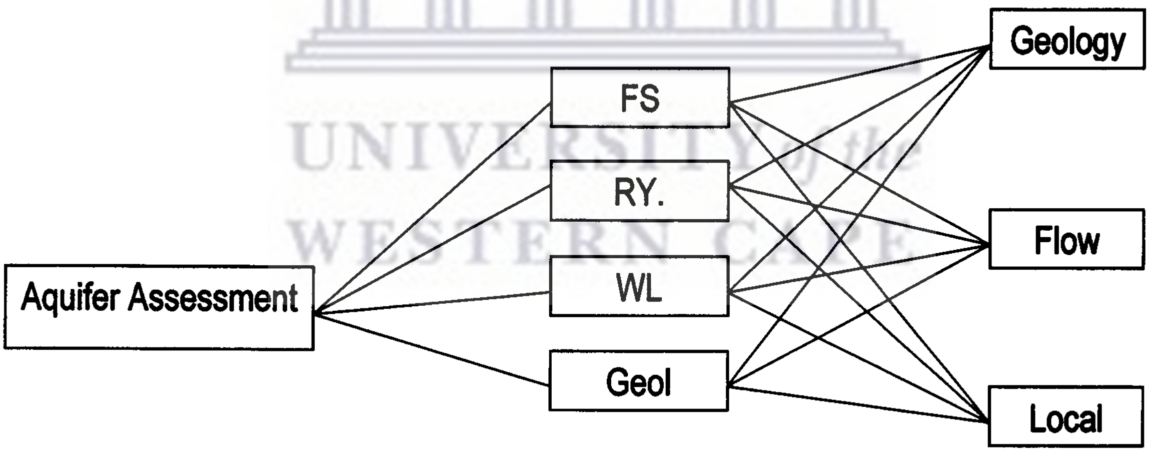

Figure 33 Value tree for aquifer assessment.

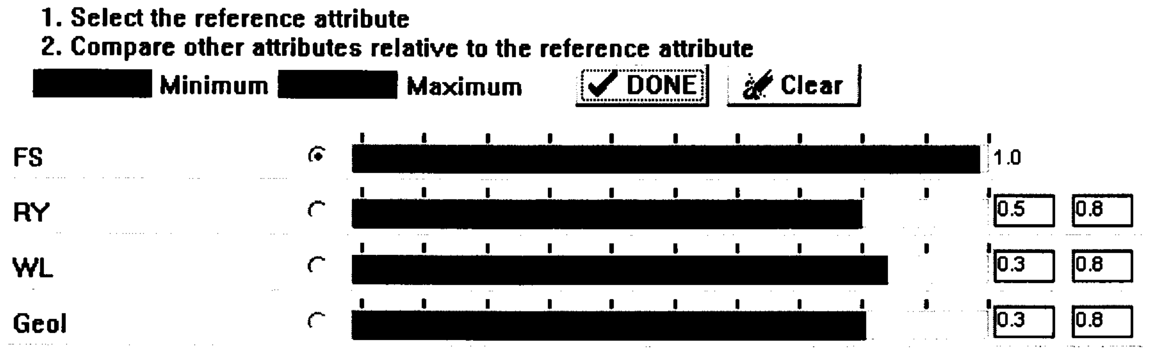

Figure 34 Interval SMART/SWING weighting in the decision-making procedure (comparison of attributes).

The value intervals (or constraints) for the attribute 'FS' are given in Figure 35. A systematic understanding of the regional groundwater flow system contributes to sustainable utilisation of the resource.

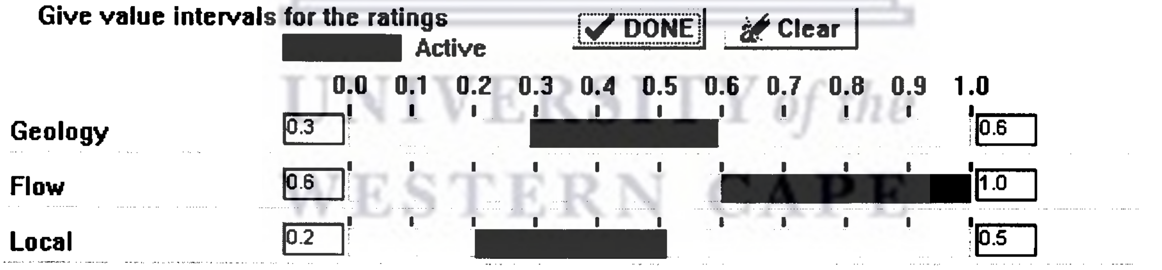

Figure 35 Local score intervals for the attribute flow systems ('FS').

The value intervals (or constraints) for the attribute 'RY' are given in Figure 36 Aquifer parameters such as storage and transmissivity are crucial in determining sustainable abstraction rates. The sustainable yield of the resource to a large extent determines the level of service. Setting of these parameters is difficult in fractured rock domains due to the heterogeneity of the system. Adequate information is needed to determine the correct conceptual model and the use of the correct methods to determine aquifer parameters.

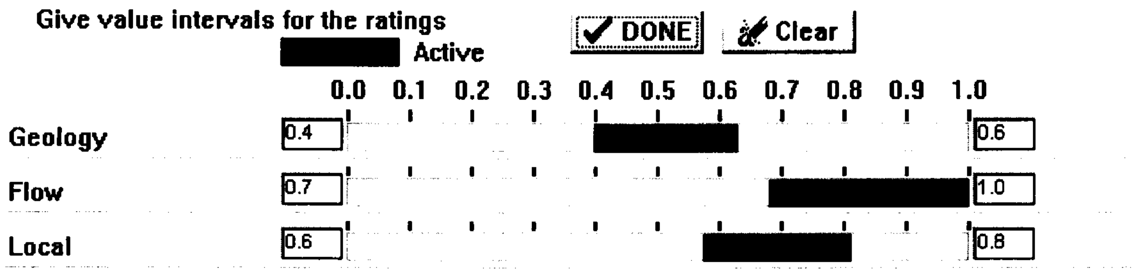

Figure 36 Local score intervals for the attribute resource yield ('RY').

The value intervals (or constraints) for the attribute 'WL' are given in Figure 37. Knowledge of water levels is important to understand systems characteristics such as groundwater flow. Water levels provide an indication of recharge and long term yield of the aquifer. Monitoring networks are required to obtain a systems perspective of the groundwater potential.

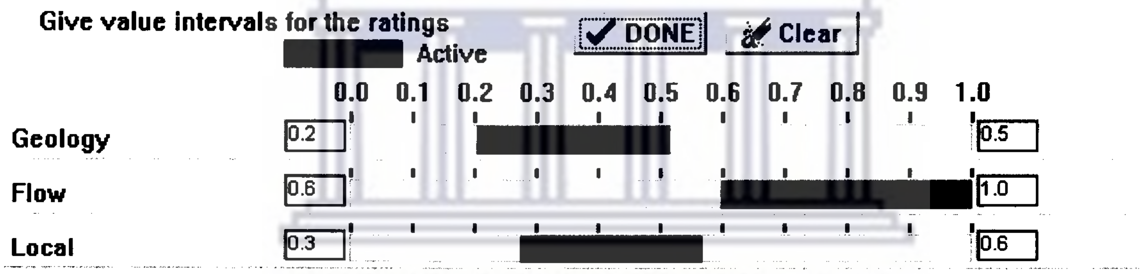

Figure 37 Local score intervals for the attribute water levels ('WL').

The value intervals (or constraints) for the attribute 'Geol' are given in Figure 38. The geological system provides the reference framework for the characteristics of the groundwater system. It is important to understand the structural geology and geodynamics of the system.

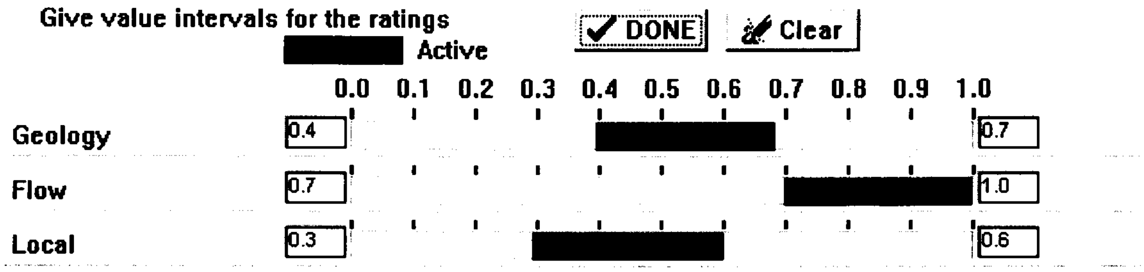

Figure 38 Local score intervals for the attribute geology ('Geol').

The combination of the above relationships results in the overall value intervals and the dominance relations shown in Figure 39. It is clear from the analyses that the alternative, focussing on characterising aquifers at regional scale (regional groundwater flow model), is the dominant alternative.

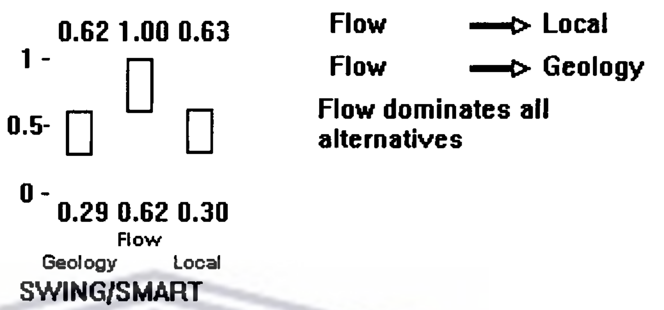

Figure 39 Overall value intervals and dominance relations.

6.3.5 Climate variability and change

6.3.5.1 Current situation (Scenario 2)

Climatic conditions and variability associated with arid zones pose significant water management problems. Such conditions largely influence natural recharge to the aquifer system and vulnerable communities usually have difficulty in responding to climatic extremes.

Drought is a common feature in the region and Namaqualand and livelihoods are affected by various forms of droughts, i.e. meteorological, hydrological, and agricultural.

Annual meteorological droughts have been defined broadly as occurring when annual rainfall is below 70% of the average, becoming more severe when two or more consecutive years each experience 70% or less of the average rainfall (Orpen, 1997). According to this definition, severe meteorological drought conditions have been experienced in Namaqualand several times since the 1950s (1964, 1969-70 and 1978-1979).

The two forms of drought that affect the sustainable livelihood of communities in arid zones include hydrological and agricultural drought. Hydrological drought refers to the lack of recharge into aquifers, and runoff into natural man-made reservoirs (Seeley, 1999). A common association in arid zones is that recharge is dependent on the intensity of the rainfall event. According to Lloyd (1999), no recharge (in terms of resources) occurs in hyper-arid areas (rainfall < 50 mm/annum). Only indirect recharge occurs in arid areas (rainfall 50 - 200 mm/annum), and indirect recharge dominates over direct recharge in most semiarid areas (rainfall of, say 200 – 400 mm/annum). Direct recharge occurs when water enters the saturated zone of the aquifer directly from precipitation infiltrating through the unsaturated zone. With indirect recharge, water enters the saturated zone indirectly through some form of runoff infiltration (Lloyd, 1999). However, determining recharge in arid regions is problematic, due to the following:

- Infrequency, irregularity and intensity of rainfall events
- Unsaturated zone thickness
- Geological complexities
- Low recharge rates
- Difficulty in determining water balance parameters

Agricultural drought negatively influences agricultural functioning. This is however, a relative concept, because, where water is used mainly for livestock watering, drought impacts are likely to be substantially different in arid and humid areas (Calow et al. 1999). The unpredictability of the rainfall in Namaqualand makes the region marginal for agriculture. Crop failure due to drought is common.

Since droughts are frequent, minimising their impact should form part of regular planning. The fluctuations in water availability between wet and dry years need to be understood.

Water conservation and water demand management (WC/DM) relate to the efficient and effective use of water and the minimisation of loss or waste of water (DWAF, 2002). Communities in Namaqualand use water sparingly because of limited resources. However, in a situation of "abundance" of water, wastage can occur. This relates also to not taking ownership of the operation and maintenance of distribution systems. Strategic objectives for WC/DM should include (DWAF, 2002):

- Implementation of efficient distribution management measures
- Ensuring adequate information to support decision making

- Promoting the efficient use of water to consumers and customers
- Adopting integrated planning principles
- Ensuring the implementation of WC/DM best practices in new developments
- Contributing to catchment management strategies
- Ensuring adequate institutional and financial capacity for WC/DM

6.3.5.2 Decision alternatives

The various decision alternatives for climate variability and change are given in Section 3.5.5. These are repeated for ease of reference:

- Use outputs of a suitable, available predictive model to inform decision makers about spatial and temporal climate variability and change (PredMo).
- Undertake a water demand analysis to indicate trends and resource availability (WDA).

The attributes for successful coping with climate variability and change (CVC) were chosen as:

- Drought prediction practised (DP)
- Demand-side planning practised (DM)

6.3.5.3 Evaluation

The problem is structured visually (Figure 40). Figure 41 presents the interval SMART/SWING weighting window of WINPRE. In this window comparison is made between the attributes drought prediction and demand side planning. In this case the reference attribute was chosen as demand side planning. The demand for water needs to be managed with appropriate measures and tools. These measures include education. The value intervals are reflected in Figure 42 and Figure 43.

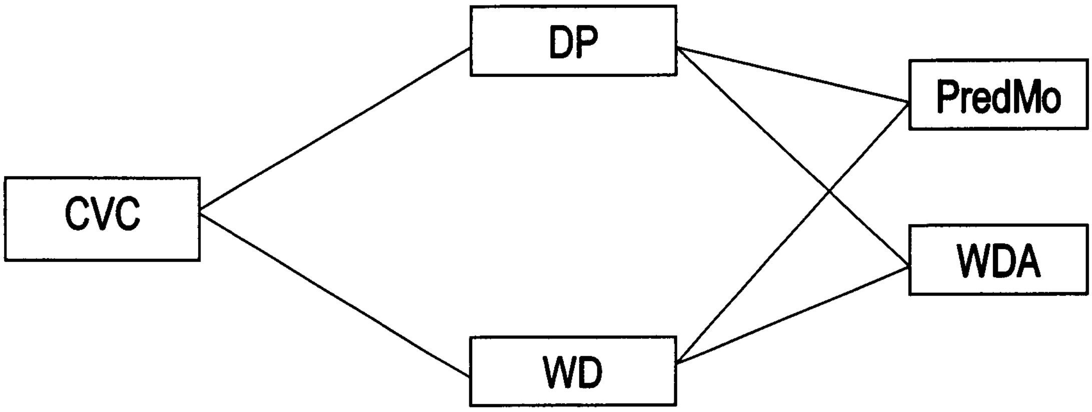

Figure 40 Value tree for climate variability and change.

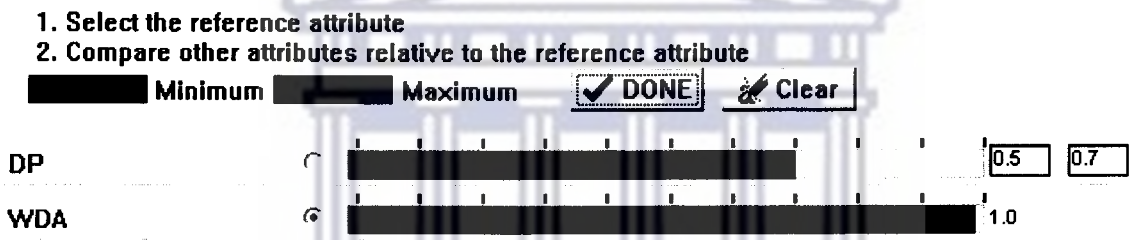

Figure 41 Interval SMART/SWING weighting in the decision-making procedure (comparison of attributes).

The value intervals (or constraints) for the attribute 'DP' are given in Figure 42. Developing drought prediction capabilities will assist in resource planning and development of coping strategies to assist in addressing rural livelihood issues.

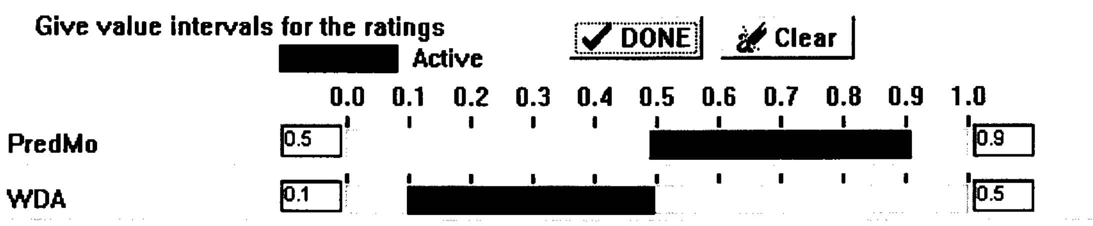

Figure 42 Local score intervals for the attribute drought prediction ('DP').

The value intervals (or constraints) for the attribute 'WD' are given in Figure 43. Water demand management practices needs to be implemented in communities in order to have efficient and effective use of water resources. These are effective measures for communities to cope with climate change and variability.

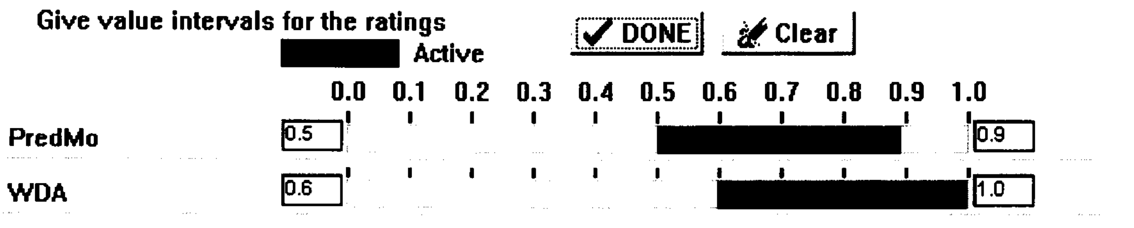

Figure 43 Local score intervals for the attribute water demand analysis ('WD').

The combination of the above relationships results in the overall value intervals and the dominance relations shown in Figure 44. In this case there is no dominated alternative, with would indicate that both using an available predictive model to inform decision makers about spatial and temporal climate variability and change and water demand analysis to indicate trends and resource availability alternatives are crucial for sustainable resource development.

Figure 44 Overall value intervals and dominance relations (in this case no dominant relations).

6.3.6 Adverse climatic conditions

6.3.6.1 Current situation (Scenario 2)

Murray and Tredoux (2002) have demonstrated the usefulness of artificial recharge of groundwater. One of the pilot areas was Karkams in Namaqualand. The village of Karkams has a mean annual rainfall of 250 mm, a population of 1690, and depends solely on groundwater (Murray, 2002). Two controlled injection tests were conducted using sand-filtered water from the adjacent ephemeral river (Murray and Tredoux, 2002). Approximately 1300 m^3 to 7800 m^3 of water can be injected depending on the rainfall and river flow (Murray and Tredoux, 2002). This amounts to 0.4 to 2.2 times the borehole's sustainable yield (Murray and Tredoux, 2002). An additional benefit of introducing this fresh water to the aquifer is that it improves the groundwater quality (Murray and Tredoux, 2002).

Artificial recharge is an appropriate technology, depending on the hydrogeological conditions, that can augment community's water supply. This technology or water conservation is not applied on a large scale in Namaqualand.

6.3.6.2 Decision alternatives

The various decision alternatives for dealing with adverse climatic conditions are given in Section 3.5.6. These are repeated for ease of reference:

- Implement water enhancement strategies such as artificial recharge, water harvesting and fog harvesting (WES).
- Reduce water loss and leakage through measures such as maintenance of water distribution systems (Wloss).
- Practise water level and water quality monitoring in order to characterise the response of the aquifer system with regard to adverse climatic conditions and to adapt water supply in accordance with such conditions (WMon)

The attributes for successfully dealing with adverse climatic conditions (ACC) were chosen as:

- Regional groundwater flow model with time series information developed (hydraulic head distribution) (WL).
- Licensed abstraction rates for all water uses (Licens)
- Water conservation i.e. optimal and productive use of water resources practised (WC).
- Operational artificial recharge schemes in place (AR).

6.3.6.3 Evaluation

The problem is structured visually (Figure 45). Figure 46 presents the interval SMART/SWING weighting window of WINPRE. In this window comparison is made between the attributes regional groundwater flow model, abstraction rates, water conservation and artificial recharge. In this case the reference attribute was chosen as artificial recharge. As a result of adverse climatic conditions in arid zones, technologies such as artificial recharge will be crucial to enhance water supplies. The value intervals are reflected in Figure 47, Figure 48, Figure 49 and Figure 50.

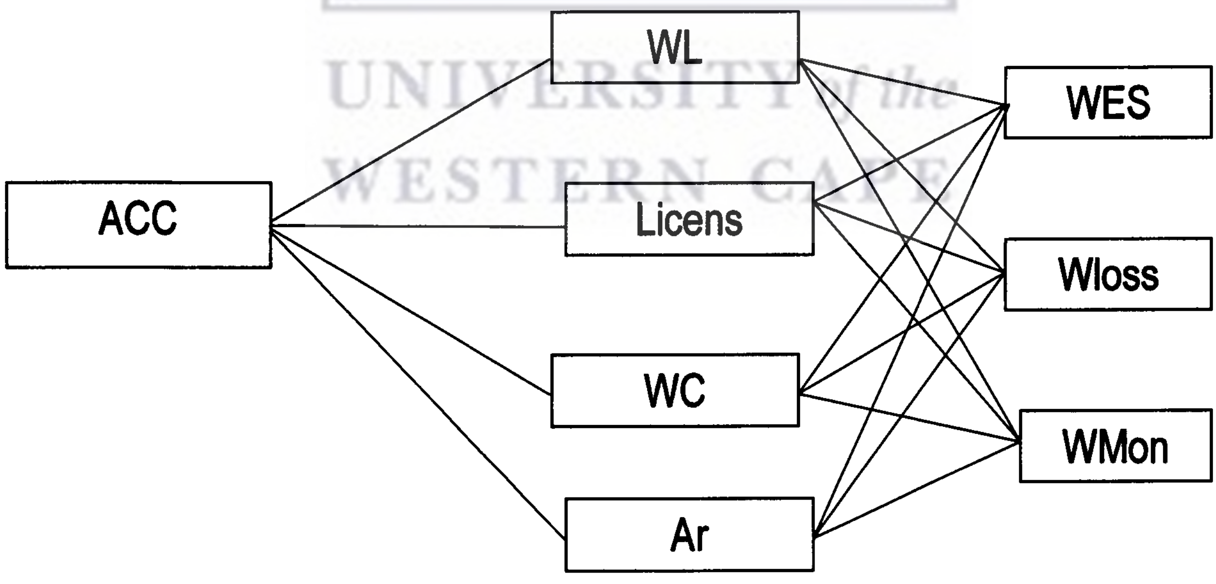

Figure 45 Value tree for adverse climatic conditions.

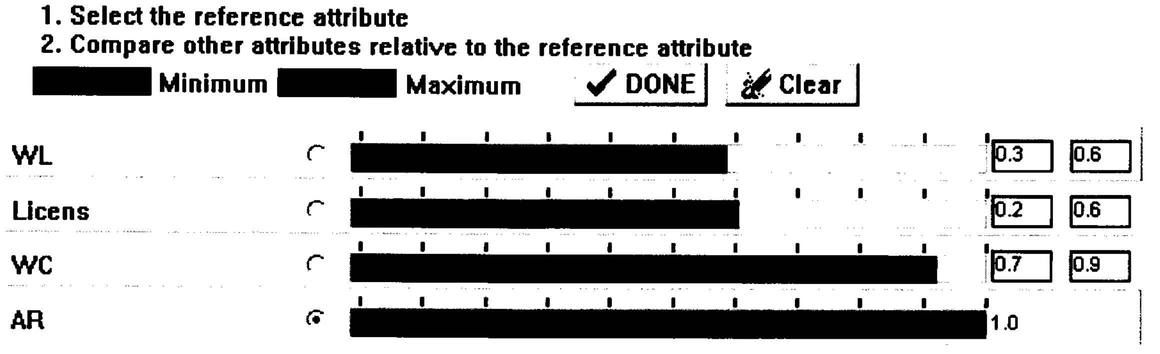

Figure 46 Interval SMART/SWING weighting in the decision-making procedure (comparison of attributes).

The value intervals (or constraints) for the attribute 'WL' are given in Figure 47. Understanding the flow regime is crucial to manage water resources and developing the appropriate mechanisms for protection of water resources.

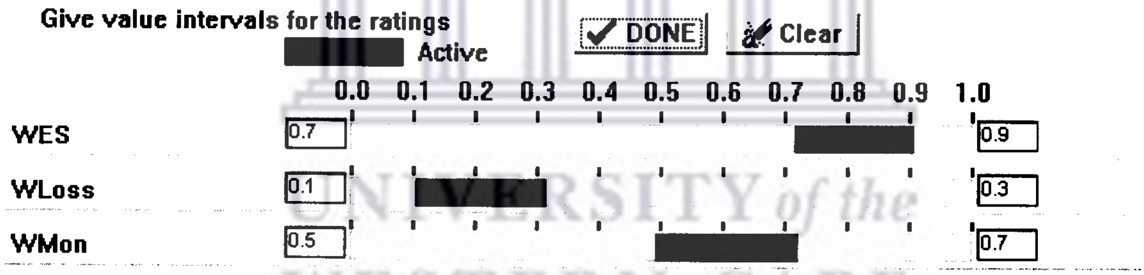

Figure 47 Local score intervals for the attribute water level ('WL').

The value intervals (or constraints) for the attribute 'Licens' are given in. The amount of abstraction is crucial to understand the water use patterns.

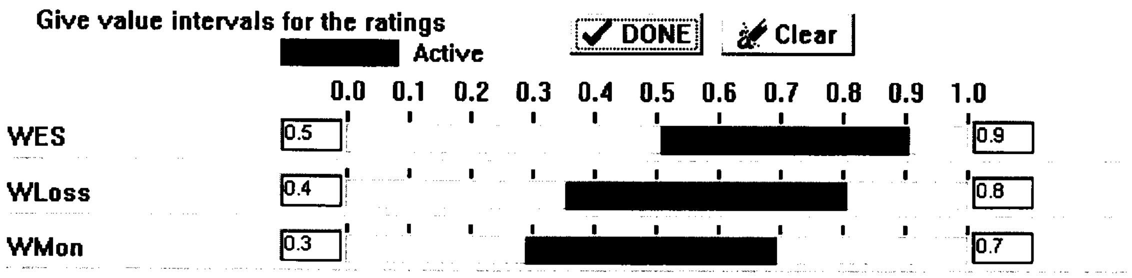

Figure 48 Local score intervals for the attribute abstraction ('Licens').

The value intervals (or constraints) for the attribute water conservation ('WC') are given in Figure 49. Communities in arid regions, because of scarce water resources, frequently use water in a sparing manner. However, when more water than normally required or inappropriate technologies are made available, wastage occurs. The optimal and productive use of water is required, which should lead to improved health in affected communities.

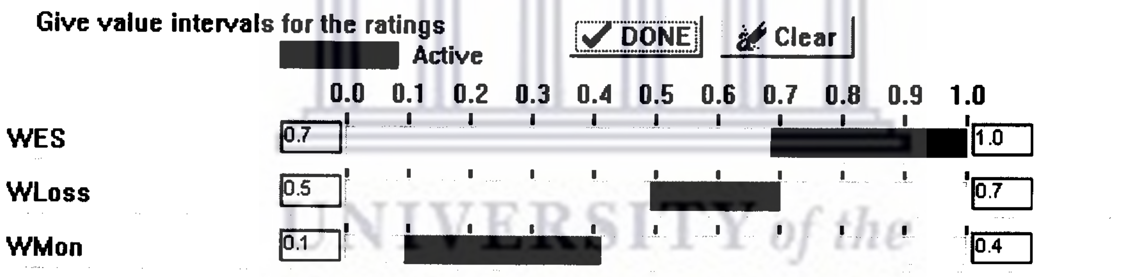

Figure 49 Local score intervals for the attribute water conservation ('WC').

The value intervals (or constraints) for the attribute 'AR' are given in

Figure 50. In this case the value of artificial recharge is understood and the technology implemented, resulting in sustainable resources.

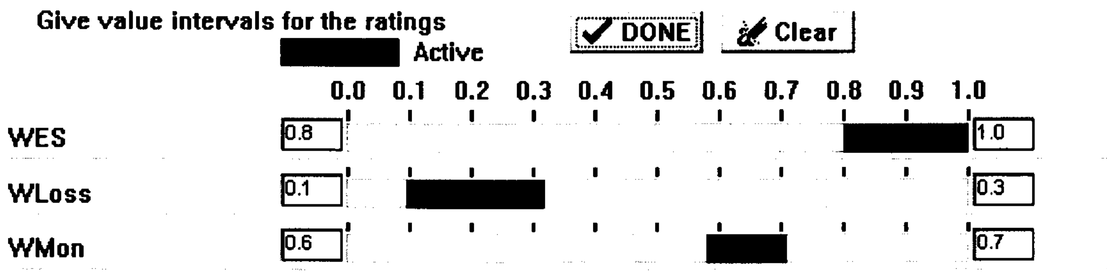

Figure 50 Local score intervals for the attribute artificial recharge ('AR').

The combination of the above relationships results in the overall value intervals and the dominance relations shown in

Figure 51. It is clear from the analyses that the alternative, focussing on implementing water enhancement strategies such as artificial recharge, water harvesting and fog harvesting, is the dominant alternative.

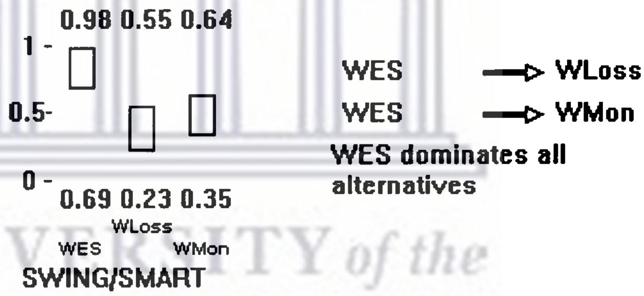

Figure 51 Overall value intervals and dominance relations.

6.3.7 O&M skills base

6.3.7.1 Current situation (Scenario 2)

The Namaqualand area is vast and sparsely populated, with a poorly developed infrastructure. Communities located on the communal reserves of Namaqualand (Leliefontein, Rietpoort, Richtersveld normally have off-site standpipes. The locations of the standpipes generally comply with water services standards. The main water-service related issues are quantity and quality of the water and maintenance of infrastructure (due to the sophistication of the technologies).

The bucket system is the most generally used sanitation system, although pit latrines and the veld and used on a smaller scale. Some communities do not have sanitation and waste removal services, and consequently residents are responsible for the removal and disposal of their own domestic and human waste.

Operation and maintenance of systems is the core issue which has resulted in the failure of systems in the past. The maintenance problems are related to over-sophistication (e.g. desalination systems) and the problem of centralisation. Local government responsible for maintenance is located in Springbok. Local community members have not in general been trained to maintain the supply systems. This needs to be rectified, if communities are to take ownership of the watering points and systems.

6.3.7.2 Decision alternatives

The various decision alternatives for building an adequate O&M skills base are given in Section 3.5.7. These are repeated for ease of reference:

- Ensure training and retention of necessary skills (including gender considerations) for the operation and maintenance the water services system at community level (Train),
- Facilitate operation and maintenance of water services by local authorities (LAuth).

The attributes for an adequate O&M skills base were chosen as:

- Adequate proportion of people (expressed as a percentage) who pay against those who do not pay to recover operation and maintenance costs (Payment).
- Appropriateness of technology acceptance (Appropr.)
- Funds available to cover recurrent costs (Funds)
- Tariff structure adequate to recoup recurrent costs (Tariff).

6.3.7.3 Evaluation

The problem is structured visually (Figure 52).

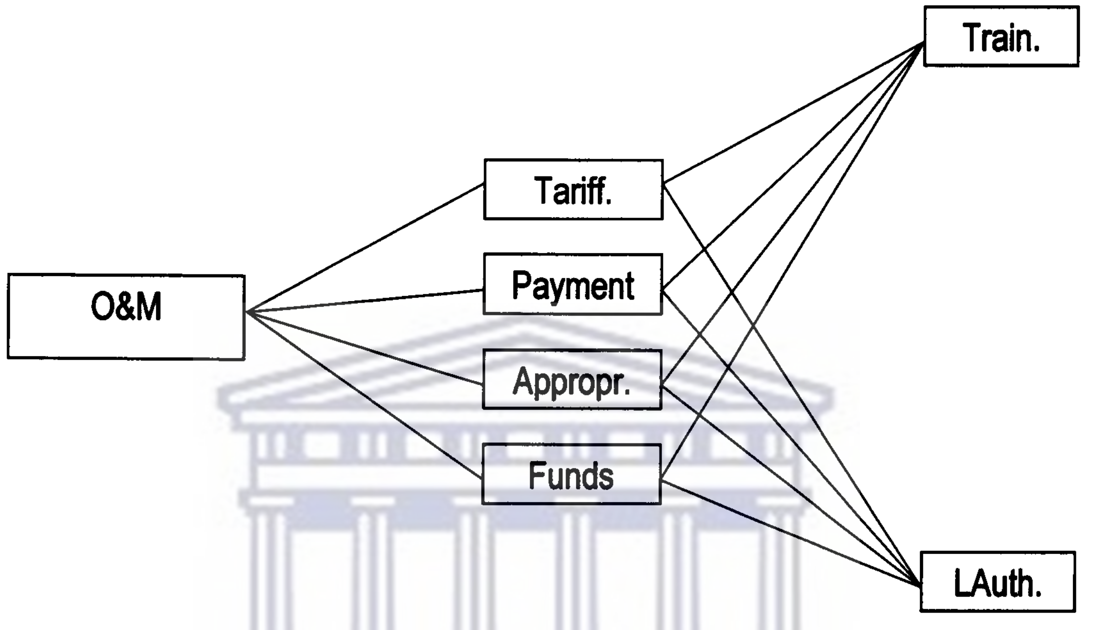

Figure 52 Value tree for O&M.

Figure 53 presents the interval SMART/SWING weighting window of WINPRE. In this window comparison is made between the attributes proportion of people (expressed as a percentage) who pay against those who do not pay to recover operation and maintenance costs; appropriateness of technology, available funds for recurrent costs and tariff structure to recoup recurrent costs. In this case the reference attribute was chosen as appropriateness of technology. The value intervals are reflected in Figure 54, Figure 55, Figure 56 and Figure 57.

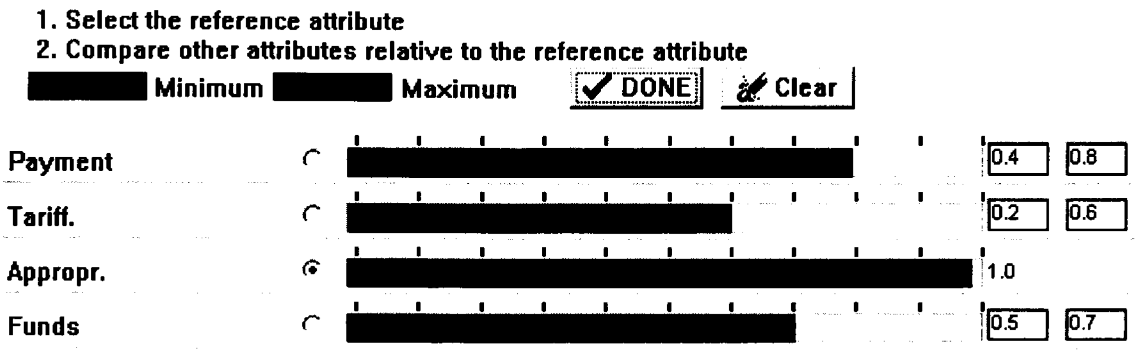

Figure 53 Interval SMART/SWING weighting in the decision-making procedure (comparison of attributes).

The value intervals (or constraints) for the attribute 'Payment' are given in Figure 54. Recouping recurrent costs are crucial for O&M.

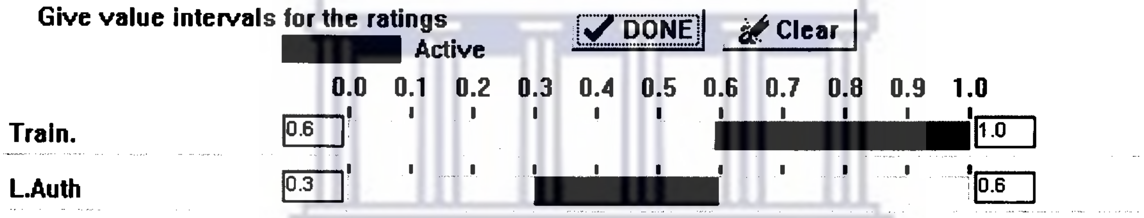

Figure 54 Local score intervals for the attribute water payment ('Payment').

The value intervals (or constraints) for the attribute 'Tariff' are given in Figure 55. The setting of appropriate tariffs influences payment and thus resources available for O&M.

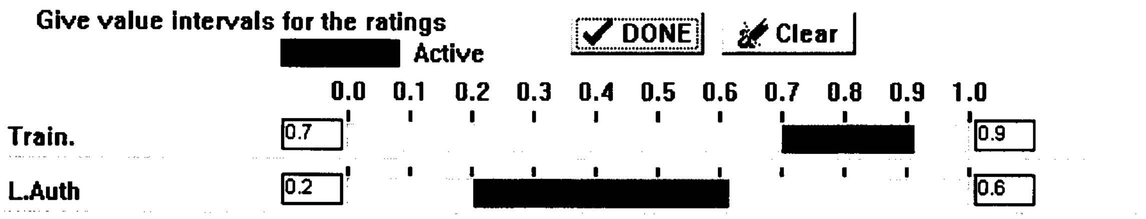

Figure 55 Local score intervals for the attribute tariff ('Tariff').

The value intervals (or constraints) for the attribute 'Appropr' of technology are given in Figure 56.

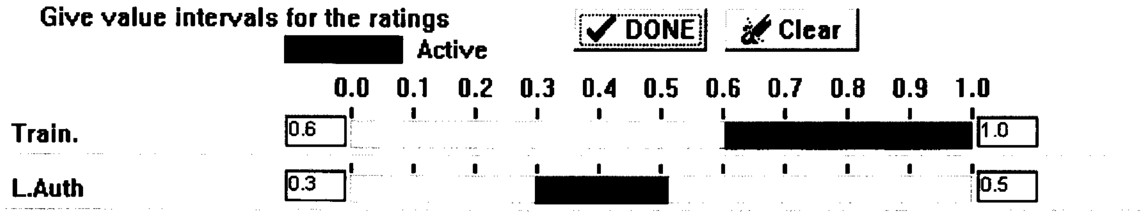

Figure 56 Local score intervals for the attribute appropriateness of technology ('Appropr').

The value intervals (or constraints) for the attribute 'Funds' are given in Figure 57. The funds available for recurrent costs are critical for continued functioning of water systems.

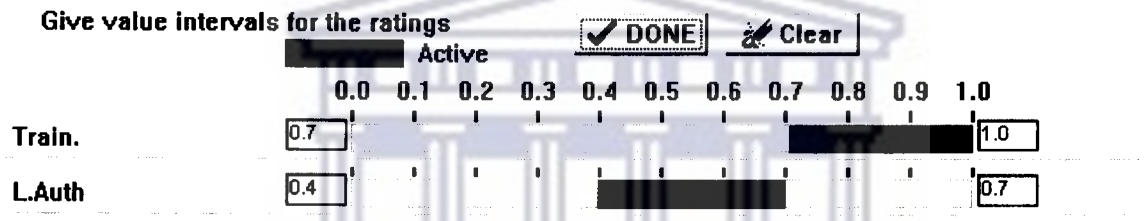

Figure 57 Local score intervals for the attribute funds 'Funds'.

The combination of the above relationships results in the overall value intervals and the dominance relations shown in Figure 58. It is clear from the analyses that the alternative, focussing on training and retention of necessary skills (including gender considerations) to operate and maintain the water services system, is the dominant alternative.

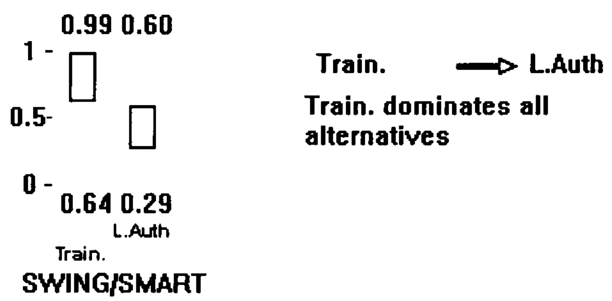

Figure 58 Overall value intervals and dominance relations.

6.3.8 Community participation and education

6.3.8.1 Current situation (Scenario 2)

Community participation and management are crucial to delivery of sustainable water services. The communities' level of awareness will relate closely to the level of participation in development and maintenance of water services.

It is critical that water services are needs driven. The prescription of technologies for communities by consultants is unacceptable. Communities should preferably be presented with a number of optional solutions. This will lead to discussion with communities on the advantages and disadvantages of each option. Agreement is reached by consensus, taking into account local conditions and resources. Thus the aim should be to develop community awareness of their rights and responsibilities with regard to services, so that they can be involved in decisions about selection of water source, appropriate technology, cost recovery mechanisms and management arrangement.

In a case study conducted by Williams (2000) in Paulshoek, some residents felt that a lot of money was being used to improve their water supply system, but they as community did not have a say in the type of systems being installed. As a result, the water system was frequently not operational due to poor maintenance of the technology, vandalism and almost no payment for services. According to the water bailiff, community members did not respect his authority and open and close taps as it pleases them (Williams, 2000). It is noteworthy that expensive modern systems were installed to meet the needs of the community (Titus et al. 2002). Proper consultation and acceptance of the technology would have alleviated these problems. A dependency has been created on outside parties through the technology not being suited to local conditions.

Women are largely responsible for meeting the water service needs of their households. Frequently this responsibility is not reflected in the decision-making structures. Women should be at the centre of any capacity building strategy. In a case study in the Peddie district of the Eastern Cape, Monyai (2003) identified the following factors affecting women's participation in project implementation:

- The planning cycle of the project was done without an input from the women. Decisions about their involvement in terms of participating in and benefiting from the project were complete and finalised before they were informed about the project.
- The times at which community meetings were held did not take into consideration domestic responsibilities and other cultural engagements of women.
- There was a lack of proper information concerning opportunities for employment created by the project. The processes governing recruitment for employment raised dissatisfaction among the majority of women.
- The problem of timidity of women resulting from a lack of self-confidence and fear of expressing themselves in public was not taken into account. Women were expected to take part in public meetings without any processes of preparing them to be able to assert themselves in public gatherings.

In Namaqualand the cultural constraints are not as prevalent as these in the Eastern Cape case study. Nevertheless, the lack of participation also hinders sustainable development of water resources.

The roles and responsibilities of the different actors are frequently not clearly stated. This often causes misunderstandings which may result in poor resource management. Agreements regarding the operation and maintenance procedures for the selected service levels should be concluded and should also specify cost recovery mechanisms. The institutional arrangements for water services and management as described in relevant legislation means that the appropriate legal entities can be constituted to conclude the necessary agreements.

The Water Services Act requires that Water Service Authorities (WSAs) prepare a Water Services Development Plan (WSDP). A WSDP is a plan to progressively ensure efficient, affordable, economical and sustainable access to water services (DWAF, 2001). It is a sectoral plan which deals with socio-economic, technical, financial, institutional and environmental issues as they pertain to water services (DWAF, 2001). Section 13 of the Water Services Act states that every draft WSDP must contain details (DWAF, 2001):

(a) of the physical attributes of the area to which it applies;

(b) of the size and distribution of the population within that area;

(c) of a time frame for the plan, including the implementation programme for the following five years;

(d) of existing water services

(e) of existing industrial water use within the area of jurisdiction of the relevant water authority

(f) of existing industrial effluent disposed of within the area of jurisdiction of the relevant water services authority

(g) of the number and location of persons within the area who are not being provided with a basic water supply and basic sanitation;

(h) regarding the future provision of water services and water for industrial use and the future disposal of industrial effluent, including-

  i. the water services providers which will provide those water services;
  ii. the contracts and proposed contracts with those water service providers;
  iii. the proposed infrastructure necessary;
  iv. the water sources to be used and the quantity of water to be obtained from and discharged into each source;
  v. the estimated capital and operating costs of those water services and the financial arrangements for funding those water services, including the tariff structures
  vi. any water services institution that will assist the water services authority;
  vii. the operation, maintenance, repair and replacement of existing and future infrastructure

(i) of the number and location of persons to whom water services cannot be provided within the next five years, setting out

  i. the reasons therefore, and
  ii. the time frame within which it may reasonably be expected that a basic water supply and basic sanitation will be provided to those persons; and

(j) of existing and proposed water conservation, recycling and environmental protection measures.

A WSDP has been prepared for the Namaqualand District Council which encompasses most of the study area (BVI, 2000). The report presents an inventory of the level of water and sanitation services, water and sanitation infrastructure but does not describe the water sources in the required detail. The community consultation processes consisted of:

- Obtaining information from officials in Namaqualand District Council
- Obtaining information from the Northern Cape (first order strategy and census '96 information)

- A workshop with interested and affected parties
- Distributing information by means of pamphlets

Effective communication and democratic practices are vital for sustainable resource management. This means that the decision making structures must be democratically elected. Moreover, the relationship between communities and their elected structures must be on a sound footing. These aspects were illustrated by two case studies amongst rural communities in Namaqualand (Titus et al. 2002).

In the one community, although the water committee was democratically elected, there has been a lack of full and sincere communication regarding project affairs between designated leaders and the community (Titus et al. 2002). The committee has not always regarded regular and healthy interaction with the community as necessary, which most probably indicates that they have not fully understood how pivotal effective communication is to the sustainability of the project (Titus et al. 2002). Leaders can also only rely on the support of communities if there is visible progress on the project (Titus et al. 2002). Despite the good relationship that existed initially, the water committee has lost the trust of community members, because they have not been able to satisfactorily respond to the critique of residents (Titus et al. 2002). Residents started to hold back payments as soon as problems arose (Titus et al. 2002).

By contrast, another rural community had dynamic leadership. This resulted in the project being implemented in a reasonable manner. This highlights the fact that lack of community solidarity negatively affects the sustainability of a water project.

6.3.8.2 Decision alternatives

The various decision alternatives for overcoming deficient community participation and education are given in Section 3.5.8. These are repeated for ease of reference:

- Ensure implementation of effective community participation and education on all water services schemes (CPE)
- Ensure that training is targeted at local government level (e.g. water care operators) (WCare)

The attributes for acceptable community participation and education (CPart.) were chosen as:

- A community driven WSDP plan (WSDP).
- Contractual agreements between Water Service Authorities, Water Service Providers and customers (Contracts).
- Decisions on community matters taken collectively in community meetings, using participatory processes. This type of decision-making encourages individual opinions to be heard, debated and consensus to be reached (Decisions).

6.3.8.3 Evaluation

The problem is structured visually (Figure 59). Figure 60 presents the interval SMART/SWING weighting window of WINPRE. In this window comparison is made between the attributes Community driven WSDP plan; contractual agreements between Water Service Authorities, Water Service Providers and customers; Decisions on community matters are taken collectively in community meetings, using participatory processes. This type of decision-making encourages individual opinions to be heard, debated and consensus to be reached. In this case the reference attribute was chosen as community driven WSDP plan. The value intervals are reflected in Figure 61, Figure 62 and Figure 63.

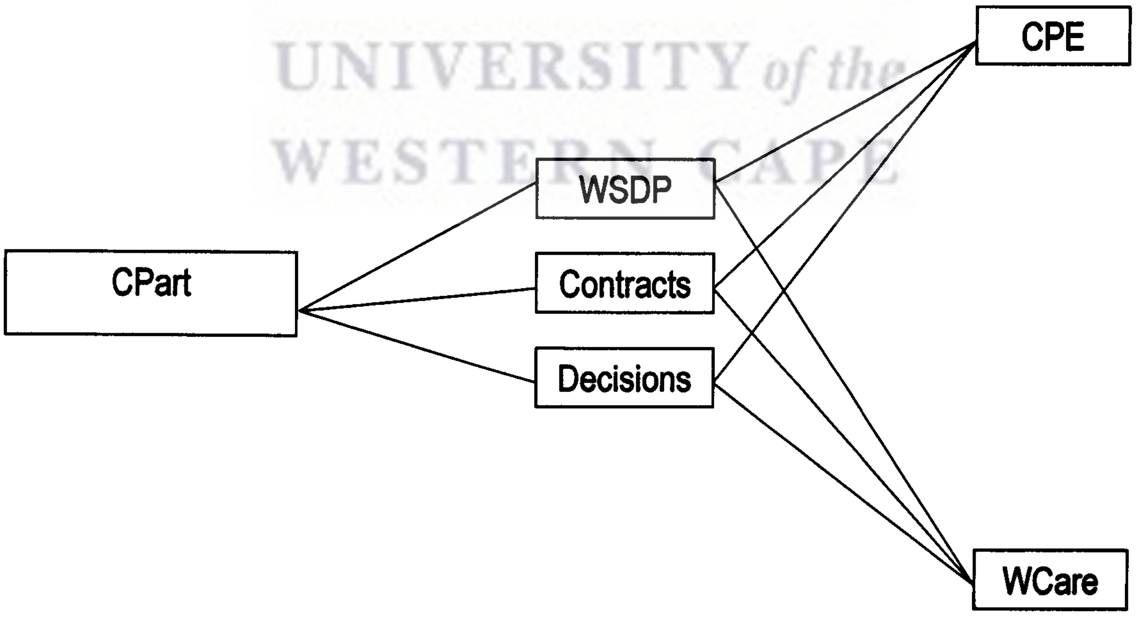

Figure 59 Value tree for overcoming deficient community participation and education.

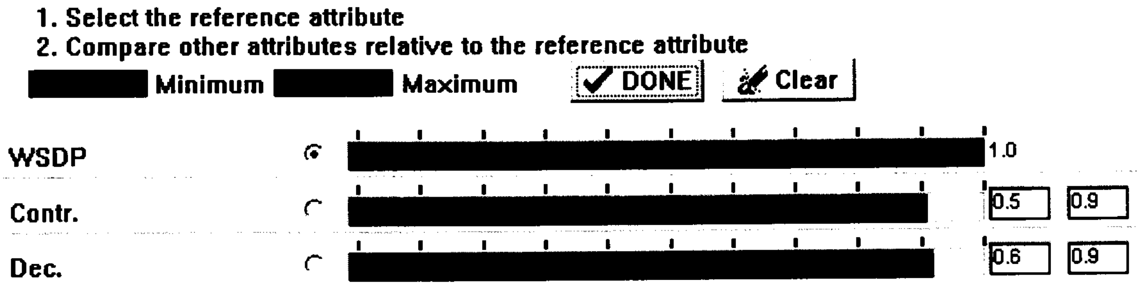

Figure 60 Interval SMART/SWING weighting in the decision-making procedure (comparison of attributes).

The value intervals (or constraints) for the attribute 'WSD' are given in Figure 61. Community driven WSDP plans will result in a plan that is accepted by all the stakeholders.

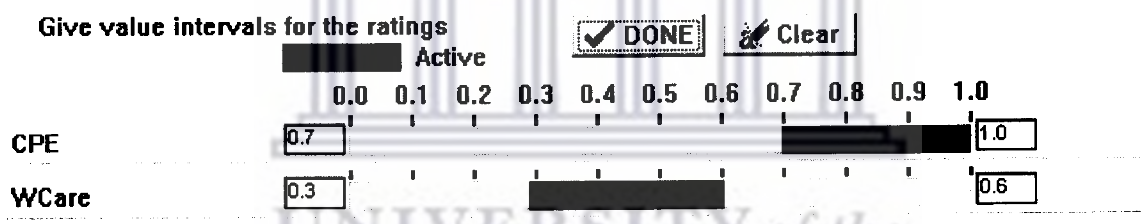

Figure 61 Local score intervals for the attribute WSDP ('WSDP').

The value intervals (or constraints) for the attribute 'Contracts' are given in Figure 62. Determining the roles and responsibilities of the different role-players or stakeholders is an important aspect for ensuring sustainability of water supply schemes. Roles and responsibilities need to be formalised in an agreement so that the different actors understand their responsibilities and accountabilities in terms of both implementation and operation and maintenance.

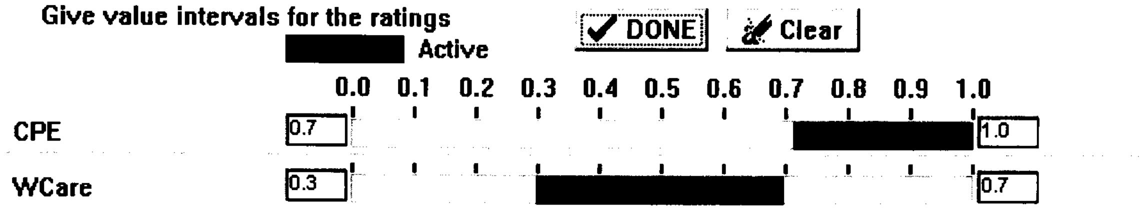

Figure 62 Local score intervals for the attribute contractual obligations ('Contracts').

The value intervals (or constraints) for the attribute 'Decisions' are given in Figure 63. Developing the capacity of communities through appropriate awareness programmes, such as for water and sanitation issues, assists in the decision-making process. This means communities are aware about the options and are able to assist in the decision-making process. Democratic leadership is crucial to facilitating the decision-making process and thereby ensuring effective participation of the relevant sectors within the community.

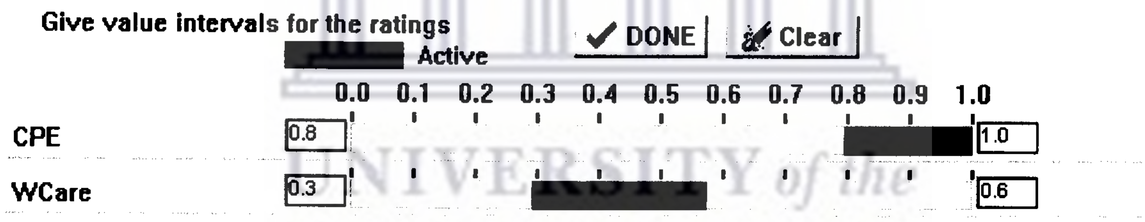

Figure 63 Local score intervals for the attribute decisions ('Decisions').

The combination of the above relationships results in the overall value intervals and the dominance relations shown in Figure 64. It is clear from the analyses that the alternative, ensuring implementation of effective community participation and education on all water service schemes, is the dominant alternative.

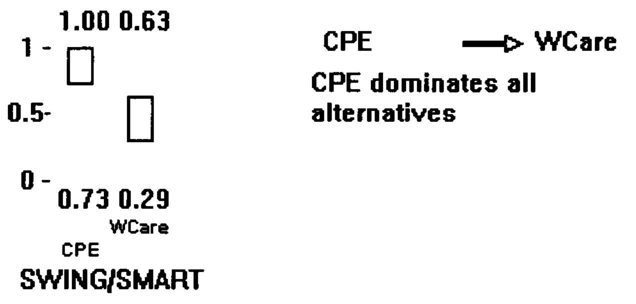

Figure 64 Overall value intervals and dominance relations.

6.4 Conclusion

A number of value trees and attributes pertaining to alternative decisions (courses of action) have been defined in this chapter. These attributes were weighted and used to obtain insight into the relative desirability of the alternatives identified in Chapter 3. This provided a systematic framework for the analytical understanding of the problem.

An interval assessment value function method was used to interrogate the decision problems. Utilising this interval meant that uncertainty of the various values could be recognised and accounted for. This provides the decision-maker with a measure of comfort in addressing such uncertain issues. In two cases, there was no dominant alternative. However, this was acceptable as the issues were equally important in the opinion of the decision-maker.

As a result of this chapter a number of preferred alternatives were elicited i.e.

- Cost recovery
  - Involve communities in the selection of technology and developing the cost recovery system.
  - Facilitate technology selection and tariff setting at local government level.
- Aquifer management
  - Conduct water demand assessments; develop community participation and management systems;
- Aquifer protection

- Develop borehole protection zones from contamination sources
- Aquifer assessment
    - Characterise aquifers at regional scale.
- Climate variability and change
    - Use outputs of a suitable predictive model available to inform decision-makers about spatial and temporal variability and change.
    - Undertake a water demand analysis to indicate trends and resource availability
- Adverse climatic conditions
    - Implement water enhancement strategies such as artificial recharge, water harvesting and fog harvesting.
- O&M skills base
    - Ensure training and retention of necessary skills (including gender considerations) for the operation and maintenance the water services system at community level,
- Community participation and education
    - Ensure implementation of effective community participation and education on all water services schemes.

As a result of the application of a MCDA technique, a number of critical alternative courses of action have been developed which otherwise would not have been elicited in a scientific manner. The strength of MCDA is that it can be used by individual or multiple decision-makers. In this case, the technique was utilised by a single decision-maker. However, the meaningful application of MCDA cannot be separated from prior knowledge of the subject matter. MCDA structures the decision-maker's knowledge in a 'systematic' manner which can be interrogated by third parties. The outcomes of the process are not counter-intuitive as the results are not surprise outcomes. The wisdom is that a 'common-sense' approach would not have delivered the same outcomes in terms of identifying various alternatives and evaluating the alternatives with respect to each other. The benefits of this approach have proved to be:

- A scientific defensible method.
- Addressing issues in a systematic and understandable manner.
- Applying and interrogating current knowledge in a systematic framework
- Incorporating uncertainty in the decision-making process.
- The potential to involve a number of stakeholders in the decision-making process.

- The identification of the critical issues and pathways in dealing with groundwater management in arid zones.

The decision alternatives could have been extended to consideration of importance across (as opposed to within) the various decision alternatives i.e. to be more mutually exclusive. The decision process could have been extended to consider the following scenarios (alternatives) for example, utilising attributes such as costs, technical feasibility etc.:

- The feasibility of importing water from the Orange River catchment to supply local communities; and
- The feasibility of developing local groundwater resources to supply communities with the necessary water services

The decision process could also have been extended to utilise more than one decision maker (such as a panel of decision-makers).

In the next chapter the various alternatives are summarised into a decision-making framework in the context of IWRM. This will provide a framework for sustainable management of groundwater resources in the region.

7 Application of Decision Model

7.1 Introduction

The aim of this chapter is to summarise the analyses of the alternatives in the previous chapters into a decision-making framework for groundwater management in arid zones. This will provide a framework for sustainable management of groundwater resources in the region. The fundamental requirements for an acceptable decision model are practical rather than scientific or mathematical.

In order to deliver sustainable groundwater services and thereby contribute to rural livelihoods in Namaqualand in a meaningful manner, the groundwater practitioner needs to address the following issues (Titus et al. 2002):

- Security of water supply and improved facilities for productive use rather than only for subsistence purposes
- Community involvement in and ownership of productive water facilities and the processes agreed upon, for sustainable use of the resource
- The role of groundwater in maintaining the natural and economic resource base in the community
- The sensitivity of the groundwater systems to stresses (for example, over-pumping), and variability over spatial and temporal scales

In order to allow the above issues to be addressed effectively, the following investigations and strategies need to be put in place to (Titus et al. 2002):

- Determine the sustainable yield of the aquifer systems and to develop policy and strategies for groundwater management at community and catchment scale
- Protect the aquifer from possible pollution risks such as the improper location of pit latrines and indiscriminate disposal of waste
- Protect the communities from poor quality groundwater

- Establish mechanisms for communities to participate in a meaningful way – they need to be well informed about the functioning of their water resources systems and the likely consequences of their decisions
- Develop appropriate monitoring and evaluation systems for regular assessment of resource sustainability as well as for ensuring delivery and proper operation and maintenance of installed systems

7.2 Ideal state

The 19 steps below represent an idealised proposed approach and methodology for groundwater resource development and management in arid zones. This approach was developed based on extensive experience in the groundwater services sector by the author of this thesis. Application of this sequential framework assumes sufficient human and financial resources are readily available, which is hardly the case. This is summarised in Figure 65.

(a) Consider a range of water services technologies that have been tried and tested under local conditions i.e. such technologies when used by community-based technical operators, have a history of assuring water supply 90-100% of time.

(b) Assess the current technical (water sources, infrastructure, etc.) and institutional arrangements for water services.

(c) Present a range of technical options to improve water services and implications for O&M, community management, training and cost recovery to local communities for consideration.

(d) Discuss with the communities the implications of each option.

(e) Involve appropriate users of the water supply scheme (especially women) in selecting the technology and developing the cost recovery system.

(f) Reach agreements with the communities (as customers), Water Services Authorities and Water Services Providers on the selected technical options and cost recovery system.

- In the case of rural water supply schemes give preference to community based water services providers.
- Once all the technical and institutional requirements have been determined, formalise agreements in the form of contracts.

(g) Facilitate a community driven water services development plan (WSDP), with close involvement of local authorities.

(h) Facilitate democratic decision-making through participatory processes, thereby encouraging individual opinions to be heard, debated and consensus to be reached.

(i) Re-assess existing pump test data by applying analytical methods for fractured rock aquifers (with proper understanding of underlying assumptions) and perform analyses of water level fluctuations during long term abstraction in order to obtain information on resource yield.

(j) Implement legislative framework in terms of licensing of all water uses (considering general authorisations) and institutional arrangements (CMAs, WSP and WSA).

(k) Assess funding commitments required for capital and re-current costs in terms of the project plan and infrastructure design, which accommodates water services for different uses and is based on both local and regional demographic trends.

(l) Develop tariff structures in consultation with relevant stakeholders to recoup current costs taking the 'free basic' water policy into consideration.

(m) Implement a proactive monitoring system for drinking water quality which considers (i) substances which are general indicators of water quality (ii) substances which are commonly present at concentrations which may lead to health problems and (iii) substances which may commonly be present at concentrations of aesthetic or economic concern in domestic water sources.

(n) Undertake a geological review, including among others a structural and geodynamic analysis.

(o) Develop a regional groundwater flow model with time series information (hydraulic head distribution). This should include (i) occurrence and type of aquifers (ii) boundaries of aquifers (iii) areal distribution of groundwater recharge (including type and amount of recharge) (iv) expected groundwater heads and (v) flow directions and general chemical composition.

(p) Delineate protection zones.

(q) Operationalise artificial recharge schemes and water harvesting systems to enhance security of water supplies to communities.

(r) Implement water conservation and demand management strategies to ensure optimal and productive use of water.

(s) Develop predictive and monitoring systems for drought.

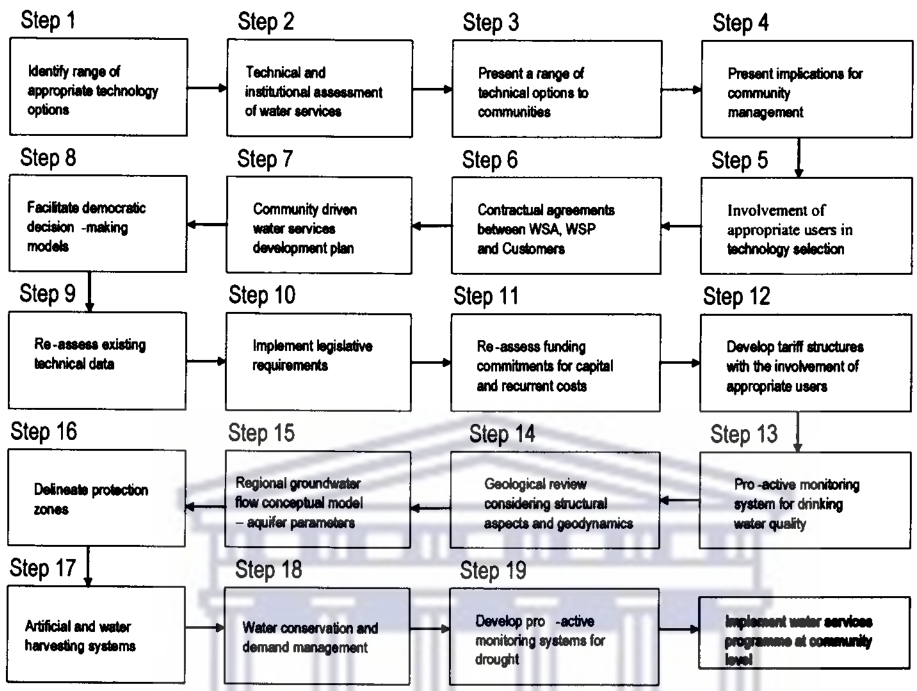

Figure 65 Sequential steps for developing a water services strategy based on rural groundwater supply.

7.3 Decision model

In Chapter 6 the objectives and alternatives identified in Chapter 3 were put into a value tree framework with the intention of assigning priorities in relation to the achievement of sustainable rural livelihoods. The importance and interrelationships of the various attributes in terms of achieving the most desirable scenario were analysed. As a result the most valued alternative courses of action were identified in Chapter 6, considering those objectives and associated measures considered by the author to be most important for sustainable rural livelihoods pertaining to the decision problem i.e.

- Cost recovery
- Aquifer management

- Aquifer protection
- Aquifer assessment
- Climate variability and change
- Adverse climatic conditions
- O&M skills base
- Community participation and education

Figure 66 establishes the critical path for issues to be addressed for groundwater management. The critical path focuses on the most crucial steps in the development of rural groundwater supply strategy and relates closely to the above objectives, measures and the corresponding alternatives identified in Chapter 6. Through application of MCDA the most important alternative course of actions were identified. These which need to be addressed and applied in order to move more closely to the 'ideal state', are the following:

- Involvement of appropriate users in technology selection
    - Involve communities in the selection of technology and developing the cost recovery system.
    - Ensure implementation of effective community participation and education on all water services schemes
- Facilitate democratic decision-making models
    - Ensure implementation of effective community participation and education on all water services schemes
- Develop tariff structures with the involvement of appropriate users
    - Involve communities in the selection of technology and developing the cost recovery system.
    - Facilitate technology selection and tariff setting at local government level.
- Regional groundwater flow conceptual model – aquifer parameters
    - Characterise aquifers at regional scale.
- Delineate protection zones
    - Develop borehole protection zones from contamination sources
- Artificial and water harvesting systems
    - Implement water enhancement strategies such as artificial recharge, water harvesting and fog harvesting

- Water conservation and demand management
    - Undertake a water demand analysis to indicate trends and resource availability
- Develop pro-active monitoring systems for drought
    - Use outputs of a suitable predictive model available to inform decision-makers about spatial and temporal variability and change.

The decision model provides a more scientific foundation from which the critical path should be further rolled out and followed in practice, i.e. in order to identify and address the critical concerns of water resource managers. The process is not overly-complicated and does not absolve the decision-maker from the necessary planning, judgement and management responsibilities.

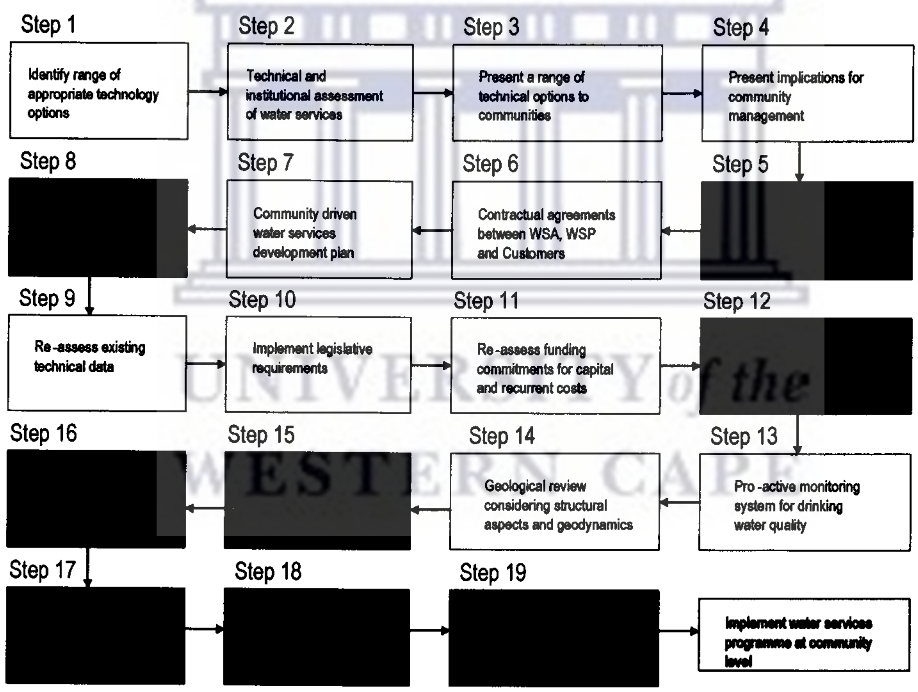

Figure 66 Decision model for groundwater resource management in arid zones.

7.4 Example of the use of the decision support model (Catchment Strategy for the Buffels River Catchment, Namaqualand)

The National Water Act requires that Catchment Management Agencies formulate a strategy to guide IWRM in their areas. To demonstrate the usefulness of MCDA, the Buffels River Catchment in Namaqualand was chosen (Figure 1). Most of the rural communities in the catchment are solely dependant on groundwater. The aquifer attributes and dynamics are discussed in Appendix B.

The formulation of a strategy for catchment management should happen early in the process and provide overall goals and guidance on how to achieve these goals (Titus et al. 2002). The Buffels River forms part of a larger water management area which to date has not been established (Titus et al. 2002). The catchment management strategy (CMS) must not be in conflict with the National Water Resources Strategy (NWRS) and will provide the framework for water resource management.

7.4.1 Involvement of appropriate users in technology selection

The importance of sophistication of the technology and the interrelationship to operation and maintenance is discussed and the current status provided in Section 6.3.1.1. Table 7 provides the various activities and actions for the objective to involve appropriate users in technology selection.

Table 7 Groundwater management strategy (technology selection).

Objective	Future direction
Involvement of appropriate users in technology selection.	• Present a range of technical options to communities, which are affordable to operate and maintain. If the technology is not affordable, as is the case of desalination, cross-subsidisation is inevitable e.g. through the use of the equitable share. • Facilitate the involvement of women and children's participation in selecting the technology and developing the cost recovery system. • Use a participative technique for communities to choose the most appropriate system with a clear understanding of their roles and responsibilities.

7.4.2 Facilitate democratic decision-making models

The current status regarding community participation and education is discussed in 6.3.8.1. Table 8 lists the activities needed to engage active community participation in water supply schemes.

Table 8 Groundwater management strategy (community participation and education)

Objective	Future direction
Facilitate democratic decision models	• Acceptance by implementers that communities are the owners of water supply schemes. • Development of joint decision-making and trust should be developed among the various partners. • Identification of means of establishing community participation in the planning, design, implementation and O&M of water services. • Fostering sound of leadership in the community.

7.4.3 Develop appropriate tariff structures

The current status regarding community participation and education is discussed in 6.3.1.1. Table 9 lists the activities necessary to develop appropriate tariff structures.

Table 9 Groundwater management strategy (tariff structures).

Objective	Future direction
Develop tariff structures with the involvement of appropriate users	• Provision of the outline and preliminary design of the actual design/maintenance programme, including the requirements for training and cost recovery. • Education of the community about the true cost of water, and early sourcing of regarding the tariff system.

7.4.4 Regional groundwater conceptual flow model – aquifer parameters

The current status regarding aquifer management is discussed in 6.3.2.1. Table 10 lists the activities needed to develop a regional-scale groundwater flow model. Table 11 considers favourable target selection.

Table 10 Groundwater management strategy (aquifer management – regional scale).

Objective	Future direction
Develop a regional conceptual groundwater flow model	• Distinguish and potentially rate different aquifer systems, in terms of both yield and quality of groundwater at a regional scale. • Characterise the physical nature and understand as well as predict the variability in hydraulic response of the aquifer system • Characterise the transmissiveness and the available storage of the aquifer system based on the fractured nature of aquifers and the available drawdown that is associated with the thickness of the regolith (i.e. weathered overburden), the depth to the most productive fracture zone(s) and the depth to the water table and/or piezometric level • Develop a regional groundwater flow model for a particular aquifer system with due reference to the tectonic and geomorphic development for the basement aquifer systems. The regional groundwater flow, for a particular aquifer system, must be based on the hydraulic gradients (as a function of elevation differences) and the average depth at which water could be sampled • Describe and distinguish between the various flow systems, for a particular aquifer system, at the relevant scale • Characterise the processes (i.e. water rock interaction, residence, evapotranspiration, etc.) that result in the generally poor groundwater quality and take cognisense of the factors (i.e. complex groundwater flow paths and flow systems, differential weathering processes, spatial variation in rainfall, etc.) that result in spatial and temporal variations in the groundwater chemistry for a specific aquifer system • Describe the seasonal and long-term climatic variability and the effects on both the quantity and quality of groundwater for a specific aquifer system.

Table 11 Groundwater management strategy (aquifer management – local scale).

Objective	Future direction
Select the most favourable target(s) for development (target selection should be based on a combination of favourable factors).	• Apply appropriate geophysical technologies and interpret results based on the conceptual understanding of the aquifer system • Conduct exploratory drilling and re-define knowledge and conceptual models on aquifer systems at this particular scale • Undertake borehole development which must include the drilling of monitoring boreholes for the calculation of hydraulic parameters (i.e. storativity). The relative positioning (i.e. hydraulic connectivity and hydraulic system) and optimal number of boreholes and depth and of boreholes are important factors. • Select the appropriate numerical method(s) for test pumping analyses based on the meeting of underlying conditions for the particular method(s) and on a conceptual understanding of the aquifer system. Data collection in the field must be as accurate and representative as possible • Determine the sustainable yield of the aquifer system with due consideration of all the above-mentioned factors. Select an appropriate approach for a particular region and utilise relevant techniques

7.4.5 Delineate protection zones

The current status regarding protection zones is discussed in 6.3.3.1. Table 12 lists the activities needed to protect the aquifer from pollution.

Table 12 Groundwater management strategy (aquifer protection).

Objective	Future direction
Delineate protection zones	• Application of measures to protect the aquifers from threats (i.e. use of techniques for delineating protection zones in fractured environments)

7.4.6 Artificial recharge and water harvesting systems

The current status regarding protection zones is discussed in 6.3.6.1. Table 13 lists the activities needed for artificial and water harvesting systems. These techniques also apply for water conservation and demand management.

Table 13 Groundwater management strategy (artificial recharge and water harvesting systems).

Objective	Future direction
Artificial recharge and water harvesting systems	• Implement artificial recharge schemes to supplement poorly naturally recharged groundwater systems when surface water resources are in excess • Continue conjunctive water use of groundwater and surface water resources • Implement water harvesting in rainfall tanks and the construction of structures to channel overland flow to reservoirs. • Consider fog harvesting in coastal and mountainous regions. • Implement water harvesting during exceptional rainfall events through retention walls in streams to enhance infiltration

7.4.7 Drought prediction

The current status regarding protection zones is discussed in 6.3.5.1. Table 14 lists the activities needed for drought prediction.

Table 14 Groundwater management strategy (artificial recharge and water harvesting systems).

Objective	Future direction
Drought prediction	• Predict drought conditions using most appropriate means.

7.5 Conclusion

In this chapter an idealised strategy for realisation of the ideal state for groundwater resource management was presented. The activities required in terms of this strategy have been based on experience gained through interaction with communities and stakeholders in Namaqualand regarding water services, and through field studies on occurrence and use of groundwater resources. However, implementation of the entire sequence is severely constrained by lack of human and financial resources. Adopting an approach based on local knowledge, supported by a MCDA approach, has enabled a more affordable, implementable critical path to be established for groundwater management in arid zones. This means that the decision-maker is able to focus on issues that are identified as most important. MCDA support should in future be extended by involving stakeholders in the MCDA processes, thus ensuring that the importance of issues identified are fully acknowledged by stakeholders. It is recognised that this process needs to be iterative rather than once off.

As a result of the decision model a number of strategies are proposed for sustainable groundwater management in the Buffels River catchment. These strategies formed part of larger set of potential strategies developed during the problem formulation stage and were narrowed down during the identification of the critical path of issues to be addressed.

In the next chapter an integrated monitoring and evaluation systems is proposed based on the criteria and an evaluation of the consequences.

8 Monitoring and Evaluation

8.1 Introduction

Developing integrated monitoring and evaluation systems to assess the effectiveness of the sustainable implementation of water supply schemes are an important component of the project cycle. Decision-making requires a quantitative assessment of the consequences of any action in the system (Rauch, 1998). It is therefore necessary to develop indicators and methods of analysis to ascertain whether the following criteria are being met (Robins et al. 2000):

- The water resource is capable of sustaining adequate quantity and quality to satisfy current and future demand.
- The water resource is monitored and managed and exploited in a sustainable and equitable manner.
- The community is involved with planning and implementation of the water supply.
- There is adequate provision for operation and maintenance at community level, including financing and monitoring of water point status.
- There is adequate provision for institution building at all levels necessary for the maintenance of the water supply system.

8.2 Consequences of the scenarios

The consequences of the different alternatives (scenarios) with respect to the desirable attributes are summarised in a consequences table based on the content of preceding chapters.

Table 15 presents indicators for groundwater management in arid zones for the attributes identified as the most important during the study. Adopting these criteria and managing the system accordingly, will result in the following questions being answered (Robins et al. 2002):

(a) Can the resource meet needs - now and in the future (quantity and quality)?

(b) Has an operation and maintenance plan been developed and agreed, detailing roles, responsibilities and training requirements?

(c) Have cost recovery mechanisms been established?

(d) Have the necessary institutional arrangements been established?

(e) What is the impact of the project on the environment?

(f) What are the current water usage/practices?

(g) Has the community been educated about the groundwater system (yield & quality aspects)?

(h) To what extent are the institutions functioning (addressing issues representative of the various sectors in the community)?

(i) Is cost recovery taking place? What are the factors influencing cost recovery?

(j) What is the progress on establishing the hardware requirements?

(k) Is training progressing as planned?

(l) Are there monitoring systems at local and catchment scale (water levels and water quality)?

m) Are systems and institutional arrangements functional?

Table 15 Consequences table for a decision-making framework for groundwater management in arid zones, based on the scenarios identified in chapter 3.

Attributes	Scenario 2	Scenario 3
Cost recovery[1]	40 - 70	70 – 100
Appropriateness of Technology [2]	70 - 90	90 – 100
Awareness to assist in the decision-making process[3]	Consultant driven WSDP plan	Community driven WSDP plan
Agreement on roles and responsibilities	Contract between WSA and WSP but no contract with community (customers)	Contractual agreements between WSA, WSP and customers
Democratic leadership	Decisions on community matters taken in a non consultative manner	Decisions on community matters are taken collectively in community meetings, using participatory processes. This type of decision-making encourages individual opinions to be heard,

[1] Proportion of people (expressed as a percentage) who pay against those who do not pay to recover operation and maintenance costs (Motaung, 2001)

[2] Community based technical operators are technically competent to conduct daily operation and maintenance of projects and to make basic repairs (Cain *et al*, 2000). This is expressed as the % of assurance of supply.

[3] Community based water service providers (WSP) are operational. This is generally the most suitable option for rural water supply schemes (Cain *et al*, 2000). The community developed the water services development plan (WSDP) through their elected government officials in local government authority.

		debated and consensus to be reached[4]
Drinking water quality	Monitoring for substances which are general indicators of water quality[5] (e.g. electrical conductivity, faecal coliforms, pH, turbidity and residual chlorine)	Proactive monitoring of[5]: Substances which are general indicators of water quality (b) Substances which are commonly present at concentrations which may lead to health problems (c) Substances which occur less frequently at concentrations of real concern to health (d) Substances which may commonly be present at concentrations of aesthetic or economic concern in domestic water sources
Water levels	Conceptual model of groundwater flow	Regional groundwater flow model with time series information (hydraulic head distribution)
Abstraction rates	General authorisations (Table 1.3)	Licensing of all water uses
Legislative requirements	Poor consultation in developing institutions	(a) RDM measures set (b) SDC implemented (c) Institutions (CMAs, WSP, WSA)
Available funding	Available funding for capital costs	Available funds for capital and recurrent costs
Resource yield	Application of conventional analytic methods	Application of analytical methods for fractured rock aquifers (with proper understanding of underlying assumptions) and analyses of water level fluctuations during long term abstractions
Cost of water	Tariff structure inadequate to recoup recurrent costs	Tariff structure adequate to recoup recurrent costs
Allocation of water	General authorisations	Licensing of all water uses
Existing water services	Limited technical data	Technical data incorporating detailed data on water sources, infrastructure etc
Economic development	Water supply limited to domestic use	Water supply for productive use
Demography	Macro-scale demographic information (growth, trends and dynamics)	Macro-scale information Community based studies
Source Directed Controls	Protection measures but inadequate monitoring	Groundwater protection zones
Resource Directed Measures	Measures set but poor consultation results in non-compliance	(a) Classification of water sources (b) Basic human needs reserve set (c) Ecological reserve set

[4] Motaung, N (2001)
[5] DWAF, DOH and WRC (1998)

		(d) RQOs set
Flow systems	Local flow systems	Regional flow systems (a) Occurrence and type of aquifers (b) Boundaries of aquifers (c) areal distribution of groundwater recharge (including type and amount of recharge) (d) Expected groundwater heads (e) Flow directions and general chemical composition
Water quantity	Scheme failure	(a) Productive water use requirements (b) Resource Yield
Water quality	Limited measures	Drinking water quality
Aquifer protection	Limited protection measures	Delineation of protection zones
Geology	Limited understanding of groundwater system	(a) Geological Review[6] (b) Geodynamics (c) Structural analysis
Drought prediction	Limited monitoring	Predictive and monitoring systems
Demand management	Supply-side planning	Demand-side planning
Water conservation	Water wastage	Optimal and productive use of water
Conjunctive use	Planning	Operational schemes
Water harvesting	Pilot studies	Appropriate systems
Artificial recharge	Pilot studies	Operational schemes

8.3 Conclusion

A consequences table has been developed for the various scenarios. It provides indicators that can assist the groundwater resource manager with assessing the sustainability of the project/programme and with further strategy development and implementation.

[6] Sami *et al*, (2002)

9 Summary, Conclusions and Recommendations

9.1 Summary

The main aim of the work described in this thesis was to develop a framework for sustainable management of groundwater resources in arid zones.

The first part of the thesis focuses on describing the groundwater resource base (Appendix B) and legislative framework for groundwater management (Chapter 2). Most aquifers in South Africa occur in fractured rock, ranging in age from earliest Pre-Cambrian to Jurassic. Primary aquifers are mostly restricted to the coastal plains and river deposits. Characterisation of the fractured rock aquifers has been limited. Thus, in a number of hydrogeological domains an inadequate knowledge base restricts understanding of the attributes and dynamics of fractured rock aquifers. A further serious shortcoming in our knowledge base is the understanding of the institutional arrangements necessary for proper resource management. This is particularly important in view of the National Water Act, which considers groundwater as a national resource. Groundwater is subject to the same protection measures as surface water. These measures are sophisticated and require tools and technologies to be developed to support sustainable groundwater management and utilisation.

In Chapter 3 the technical, economic, social, legal, political and environmental issues affecting groundwater management of arid zones of South Africa are identified. The objectives to overcome the barriers for sustainable development were also presented in this chapter. These are summarised in Table 4. It was necessary to compile a comprehensive list of options in order to structure the decision problem and to generate and identify the decision alternatives. The decision alternatives have been formulated with regard to the various optional measures which could be taken.

The main part of the study was the development of a decision-making framework for groundwater management in the arid zones of Namaqualand. A choice was made to adopt a MCDA approach. In order to select the most appropriate MCDA technique, some background was required on the theoretical aspects. This is presented in Chapters 4 and 5. Appendix C provides the general theoretical background for value function methods. A value function method was selected, which provides decision support by interval SMART/SWING. This method accommodates informational uncertainty through interval judgements. This method is particularly suited to the decision problem because of the discrete alternatives and uncertainty associated with groundwater management. Further, the method provides an interactive technique for the decision maker to interrogate various decision alternatives.

The software WINPRE was utilised in the value tree construction and analyses. A number of value trees and attributes were defined and are described in Chapter 6. The alternatives identified in Chapter 3 were evaluated against these attributes or criteria. This provided a systematic framework for the analytical understanding of the problem. As a result of this evaluation, a number of preferred alternatives were elicited i.e.

- Cost recovery
  - Involve communities in the selection of technology and developing the cost recovery system.
  - Facilitate technology selection and tariff setting at local government level.
- Aquifer management
  - Conduct water demand assessments; develop community participation and management systems;
- Aquifer protection
  - Develop borehole protection zones from contamination sources
- Aquifer assessment
  - Characterise aquifers at regional scale.
- Climate variability and change
  - Use outputs of a suitable predictive model available to inform decision-makers about spatial and temporal variability and change.
  - Undertake a water demand analysis to indicate trends and resource availability
- Adverse climatic conditions
  - Implement water enhancement strategies such as artificial recharge, water harvesting and fog harvesting.
- O&M skills base
  - Ensure training and retention of necessary skills (including gender considerations) for the operation and maintenance the water services system at community level,
- Community participation and education
  - Ensure implementation of effective community participation and education on all water

services schemes.

The analyses resulted in a value based model for groundwater management in arid zones (Chapter 7). While the ideal state of groundwater management is presented, in practice it is difficult to implement, mainly because of human and financial resource constraints. To assist in overcoming this difficulty, a critical path was established based on the analyses done in Chapter 6. As an example, the critical path was applied to identify necessary activities to support a CMS. The methodology enables the decision-maker to focus on issues that are deemed important. More importantly, the method allows the decision-maker to explore the various consequences of the alternatives with stakeholders.

As a result of the decision model a number of strategies have been proposed for sustainable groundwater management in arid zones. A consequences table which could be used for M&E purposes has been developed and is presented in Chapter 8.

9.2 Conclusion

As a result of the application of a MCDA technique, a number of potentially effective critical alternative courses of action have been revealed in a scientific manner which otherwise would not have been arrived at. The strength of MCDA is that it can be used by individual or multiple decision-makers. In this case, the technique was utilised by a single decision-maker. However, the meaningful application of MCDA cannot be separated from prior knowledge of the subject matter. MCDA structures the decision-maker's knowledge in a systematic manner which allows interrogation by third parties. The outcomes of the process are not counter-intuitive as there are not surprise outcomes. Nevertheless, a "common sense" approach would not have delivered the same outcomes in terms of identifying various alternatives and evaluating the alternatives with respect to one another. The benefits of this approach have proved to be:

- It resulted in a scientific defensible method
- Issues have been addressed in a systematic and understandable manner
- Current knowledge has been interrogated and applied in a systematic framework
- Uncertainty has been accommodated in the decision-making process
- The potential to involve a number of stakeholders in the decision-making process exists

- Critical issues and pathways in dealing with groundwater management problems have been identified

The decision alternatives could be extended to consideration of importance across (as opposed to within) the various decision alternatives i.e. to be more mutually exclusive. The decision process could also be extended to consider the feasibility of alternative scenarios, utilising attributes such as costs, technical feasibility etc, such as importing water from the Orange River catchment to supply local communities, versus developing local groundwater resources.

Application of the MCDA method has nevertheless allowed for the quantitative analysis of numerous alternatives that represent conflicting issues and management objectives.

In this thesis an idealised strategy for realisation of the desired state for groundwater resource management was presented. The potential activities to be accommodated in the strategy were based on experience gained through interaction with communities and stakeholders in Namaqualand regarding water services, and through field studies on the occurrence and use of groundwater resources. However, implementation of all possible activities would be severely constrained by lack of human and financial resources. Adopting an approach based on local knowledge, supported by a MCDA approach, has enabled a more affordable, implementable critical path to be established for groundwater management in arid zones. This means that the decision-maker is able to focus on issues that are identified as most important. MCDA support should in future be extended to involving stakeholders in the MCDA processes, thus ensuring that the importance of issues identified are fully acknowledged by stakeholders. It is recognised that this process needs to be iterative rather than once off.

As a result of the decision model a number of strategies have been proposed for sustainable groundwater management in the Buffels River catchment. These strategies form part of larger set of potential strategies developed during the problem formulation stage and narrowed down during the identification of the critical path of issues to be addressed. The strategies were aligned closely to the legislative requirements of the National Water Act. Thus, MCDA was utilised to develop policy responses and strategies for groundwater management at community and catchment scale, based on the National Water Act.

The application of MCDA has been demonstrated to be an innovative planning and information technology tool to assist the decision-making process towards sustainable groundwater resource management. The application of the tool in a participatory environment requires further refinement and adaptation.

In summary, the main contribution of this thesis is the systematic framework, in the presence of multiple decision alternatives, that has been developed for groundwater management in arid zones. A critical path (or a best set of approaches) has been established to achieve sustainable groundwater-based rural livelihoods. Further, a monitoring and evaluation (M&E) system is proposed based on a consequences table, which also presents indicators for groundwater management. The above outcomes constitute a framework which enables the groundwater resource manager to consider multiple issues (both social and technical) in making sound decisions for better resource management.

Other, supplementary, contributions of the thesis include:

- The identification of key social and technical issues related to groundwater management in arid zones.
- Formulation of various decision alternatives and constraints within the context of groundwater management in arid zones.
- The application of an interval assessment of MCDA approach to water resource management.
- The incorporation of community needs (obtained through various socio-economic studies) in the decision-making framework.

9.3 Recommendations

The following are among the more important recommendations for the application of MCDA methods in water resource management:

- MCDA is a tool and should be viewed as such by water resource managers. This means that methodology should be used circumspectly by decision-makers with the necessary experience base. A "black box" approach should be cautioned against.

- A catalogue of case studies preferably involving multiple stakeholders in a workshop environment needs to be developed to demonstrate the practical application of the technique. This would include identification of shortcomings.

The next steps for the application of MCDA techniques to groundwater resource management problems in arid zones are:

- To create awareness amongst water resource managers about the potential value and role of MCDA in supporting sustainable groundwater management. This is best done through demonstration studies and popular papers on the practical application of the technique.
- To use MCDA to support the development of catchment management strategies as required by the NWA
- To test and validate the framework as developed by the study in other but similar environments.

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Appendix A Glossary of terms and acronyms

Alternatives	Choices, action plans or strategies.
Attributes (Belton and Stewart, 2002)	A quantitative measure of performance associated with a particular criterion according to which an alternative is to be evaluated.
Criteria (Belton and Stewart, 1992)	A particular perspective according to which decision alternatives may be compared, usually representing a particular interest or point of view.
CMA	Catchment management agency
DA	Decision analysis
Dominance (Stewart, 2003)	Alternative having a higher value than another alternative (per the value function) for all values over the interval ranges
DWAF	Department of Water Affairs and Forestry
Fractured rock aquifers	Aquifers, the attributes, groundwater occurrence and flow dynamics which are controlled by fractures (cracks, fissures, joints and faults) or a fracture network
IWRM	Integrated Water Resource Management
IWRM defined (GWP TAC, 2000)	IWRM is a process which promotes the co-ordinated development and management of water, land and related resources, in order to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.
Livelihood (DFID, 2000)	A livelihood comprises the capabilities, assets (including both material and social resources) and activities required for a means of living. A livelihood is sustainable when it can cope with and recover from stresses and shocks and maintain or enhance its capabilities and assets both now and in the future, while not undermining the natural resource base.
MCDA	Multiple Criteria Decision Analysis
M&E	Monitoring and Evaluation
NWRS	National Water Resource Strategy
Objectives (Tecle and Duckstein, 1994)	The directions of state of change desired by the decision-maker(s).
O&M	Operation and maintenance
Residence time	The time that groundwater is in contact with the host rock, which provides opportunity for various chemical reactions to take place.

RDM	Resource Directed Measures
Riparian doctrine	The owner of the land is entitled to "reasonable" use of the groundwater resources.
RQOs	Resource Quality Objectives
Storativity (Fetter, 1994)	The storativity, usually expressed as *S*, is the volume of water that a permeable unit will absorb or expel from storage per unit surface area per unit change in head. It is a dimensionless quantity.
Transmissivity (Fetter, 1994)	This is a measure of the amount of water that can be transmitted horizontally through a unit width by the full saturated thickness of the aquifer under a hydraulic gradient of 1.
WINPRE	Workbench for Interactive Preference Programming
WMA	Water management area
WSA	Water services authority
WSDP	Water services development plan
WUA	Water user associations

Appendix B A review of groundwater resources of South Africa

B.1 Introduction

Most South African aquifers occur in fractured rock ranging in age from earliest Pre-Cambrian to Jurassic. Aquifers consisting of recent to Tertiary formations are restricted to coastal dune belts and unconsolidated deposits associated with rivers and Aeolian sands. Vegter (1995) delineated South Africa into 64 groundwater regions based on:

- Type of opening – primary or secondary
- Lithostratigraphy
- Physiography, and
- Climate

This resulted in the groundwater regions map (Figure B.1). Further refinement culminated in a series of hydrogeological maps of South Africa, which depict (Vegter, 2000):

- Borehole prospects;
- Saturated interstices;
- Depth of groundwater level;
- Mean annual groundwater recharge;
- Groundwater component of river flow;
- Groundwater quality;
- Hydrochemical types (in the form of an explanatory brochure)

This work was followed by a monograph on the hydrogeology of groundwater regions (Vegter, 2000). Currently, a series of reports dealing with each groundwater region is in preparation, with only 5 out of 64 regions having been completed.

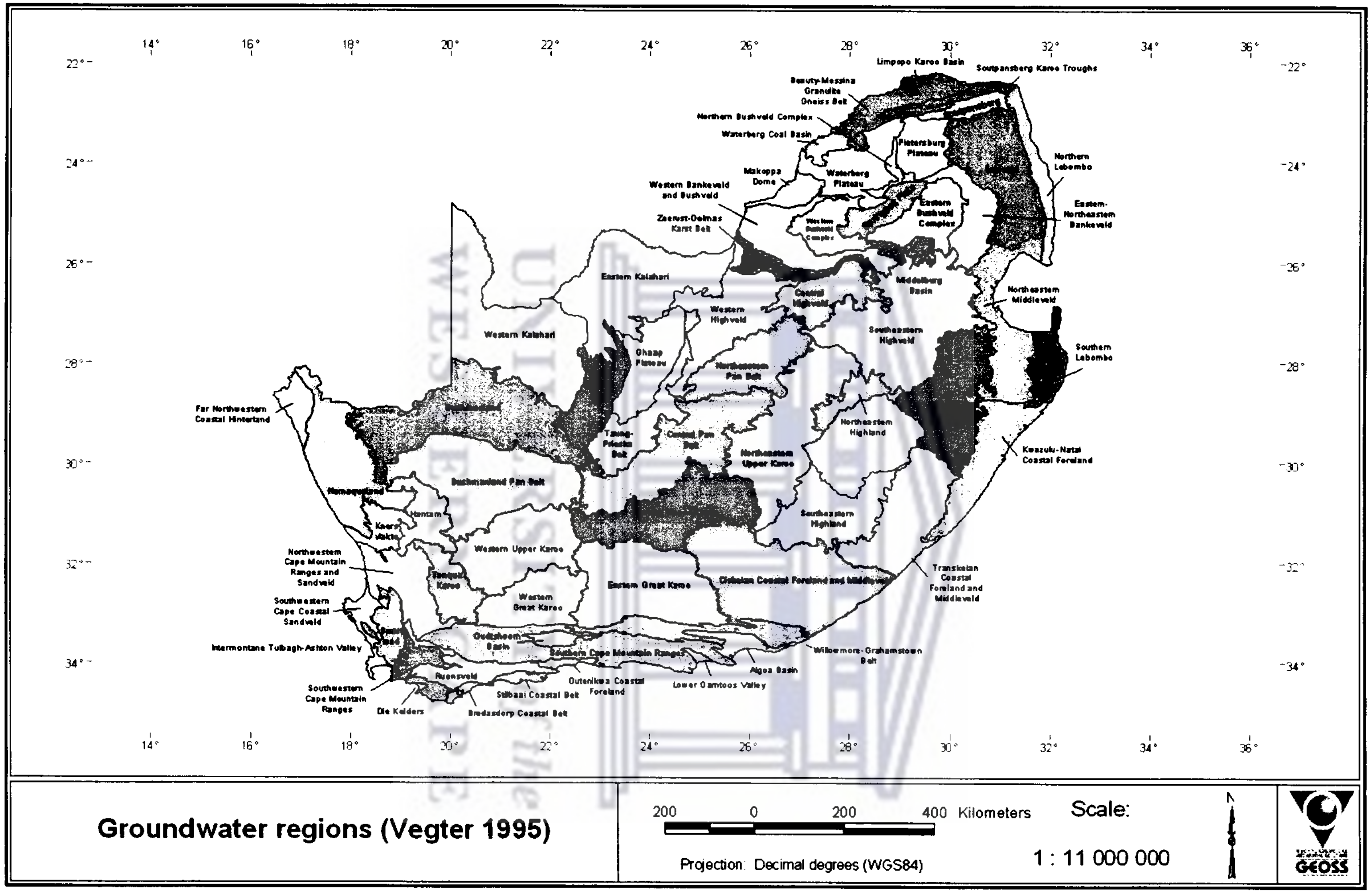

Figure B.1 Groundwater regions map of South Africa (Vegter, 1995).

In this Appendix, an overview of the different hydrogeological domains is presented. In order to facilitate discussion in this chapter, the following broad domains have been identified (Vegter, 2000):

- Crystalline metamorphic and igneous regions
- Intrusive rock regions
- Extrusive rock regions
- Sedimentary rock regions
- Composite regions
- Quaternary and Tertiary deposits

A discussion of the above-mentioned fractured rock aquifer domains follows below. The Quaternary and Tertiary deposits included in the above list for the sake of completeness are, however excluded from the discussion because the focus of this study is on hard rock domains and the challenges associated with groundwater management in such domains.

B.2 Crystalline metamorphic and igneous

B.2.1 Occurrence and attributes

In sub-Saharan Africa, crystalline metamorphic and igneous rocks occupy 40% of the land area and 220 million people live in rural areas underlain by such rocks (MacDonald et al. 2002). The occurrence of groundwater depends on the existence in the rock formation of a thick weathered zone (the upper-most 10 – 30 m) or the occurrence of deeper fracture zones (MacDonald et al. 2002) Lloyd (1999) concludes the following about igneous and metamorphic basement rocks:

(a) They are poor aquifer materials
(b) Their primary aquifer characteristics are negligible
(c) Lithology is not notably significant in influencing aquifer characteristics
(d) Fracturing is the most important aspect of aquifer potential but is inconsistent both spatially and in depth
(e) Weathering does not appear to generally enhance fractured hard rock aquifer potential

(f) They should be assessed in conjunction with any juxtaposed potential aquifer material

There are a number of important constraints to current development of basement aquifers, which include (Wright, 1992):

(a) The frequent high failure of boreholes, commonly in the range 10-40%, with the higher rates in drier regions or where the weathered overburden is thin;

(b) Shallow occurrence and fissure permeability of the bedrock aquifer component which makes for susceptibility to contamination by surface pollutants;

(c) The low storage of basement aquifers that may deplete significantly during sustained drought periods. Recharge is also sensitive to certain land use changes, notably those associated with desertification.

In South Africa, the following groundwater regions are characterised by crystalline igneous and metamorphic basement rocks (Figure B.1):

- Region 1 - Makoppa dome
- Region 3 - Limpopo granulite gneiss belt
- Region 7 - Pietersberg Plateau
- Region 19 - Lowveld
- Region 26 - Bushmanland
- Region 27 - Namaqualand

Knowledge concerning the crystalline metamorphic and igneous domains has been supplemented by two recent research reports (Titus et al. 2002; Sami et al, 2002). Also geohydrological reports of Groundwater Regions 1, 3, 7, 19 and 26 have been completed (Vegter 2001a, 2001b, 2003a and 2003b).

Titus et al. (2002) assumed a micro-fissured storage and transmission system for basement aquifers of Namaqualand. The micro-fissures store most of the water, which gets transmitted by the large fractures. This fractures and fissures serve as hydraulic conductors.

Most basement aquifers have a weathered overburden (regolith). Titus et al. (2002) found the following distinctive features of basement aquifers in Namaqualand:

- Weathering is present to depths of 54 m to 60 m below the ground level
- Differential weathering of rock types occurs together with localised weathering in fracture systems, especially joint systems. Fracture systems (e.g. joint systems, fault zones and fracturing associated with vein quartz) seem to be conduits for preferred flow, especially for the granitic/gneissic rocks.
- Single groundwater strikes are common

Sami et al. (2002) investigated the Limpopo Mobile Belt found in Groundwater Region 3. This region was found generally to be a poor aquifer. This is largely due to the low recharge and the extreme heterogeneity in targets. High yielding features are normally associated with regional fault zones. As a result, regional groundwater abstraction schemes from identified structures are preferable.

The Barberton Greenstone Belt, consisting of granites and meta-basalts, is located in Groundwater Region 19. The granites contain widespread quartz veining, which often fill the fractures; hence the granitic plutons are poor geological terrains for groundwater exploration (Sami et al. 2002). The meta-basalts are the best targets for groundwater exploration, especially when fractured by faults and dykes (Sami et al. 2002).

B.2.2 Flow and storage

Crystalline metamorphic and igneous aquifers have limited storage capacity and groundwater is generally rapidly depleted. Economic quantities of groundwater are associated with the weathered overburden. The most productive zone for groundwater is considered to be the lowest zone of the weathered profile and the top of the fractured bedrock. Viable yields are found where the weathering profile extends below the piezometric surface. The average yields are generally considered to be less than 1 l/s.

Titus et al. (2002) recognised shallow circulating and deeper, slower circulating groundwater systems in the Namaqualand Groundwater Region.

The shallow flow system (also known as the active system) occurs within the regolith. The deeper and slower flow system (also known as the passive system) occurs within the lowest zone of the regolith and the top of the bedrock. The shallow circulating and relatively young (i.e. active) groundwater flow systems occur particularly in the higher-lying, higher-rainfall regions which are characterised by dynamic, active recharge with rapid through-flow rates (Titus et al. 2002). Perennial springs are expressions of such shallow flow systems. The deeper circulating groundwater probably experiences insignificant recharge under present climatic conditions (Titus et al. 2002).

The aquifers of the Limpopo Mobile Belt are predominantly structurally controlled and significant water movement is restricted to major fracture and fault zones, primarily related to Karoo geodynamics (Sami et al. 2002). Major characteristics are as follows:

- Lineaments are primarily orientated in an ENE-WSW direction and are associated with normal faults related to block faulting. These fractures are the most favourable hydrogeological targets in the region and yields of up to 50 l/s can be obtained from these regional structures.
- A significant weathered zone aquifer exists, with yields of up to 4 l/s. Test pumping recovery suggests that this aquifer is extensive in nature. Deep seated fractures are only an aquifer when they are part of a regional fault structure.
- Target identification requires differentiating between lithological and tectonic contacts.
- Regional scale dip-dip normal faults are the most important water-bearing features with the most important of these being rejuvenated shear systems.

Sami et al. (2002) came to the following conclusions about groundwater occurrence and attributes in the Barberton Greenstone Belts:

- The best geological features for groundwater exploration in the Barberton Greenstone Belt are the NNE tending dip faults. E-W strike-slip faults have also been shown to be water bearing and are associated with formation of deep open cavities that enhance the permeability of the greenstones.

- Lineaments that have a NW-SE strike direction are more likely to compressional and therefore closed. The E-W striking lineaments are more likely to be strike-slip faults and are also the hydrogeological targets if there is no shear zone associated with the lineament.
- Dykes and sills do not seem to be important groundwater exploration targets as indicated by low yielding boreholes sunk through the dyke contacts thought to have been fractured.

B.2.3 Quality

Crystalline rock aquifers, because of the long residence time of groundwater, normally have poor groundwater quality. In the case of the Namaqualand Region, the groundwater chemistry seems to be dependant on the position of the sampling point within either shallow, fast circulating (i.e. active) or deeper, slower circulating (i.e. sluggish) flow systems (Titus et al. 2002). The shallow circulating and relatively young (i.e. active) predominantly interflow systems and the deeper and slower circulating (i.e. non-active/sluggish), relatively older groundwater systems were characterized by relatively weak and strong mineralisation, respectively (Titus et al. 2002). The distinctive characteristics of the two systems seem to be residence times. The groundwater systems in the Namaqualand Groundwater Region represent a continuous hydrochemical evolution sequence (Titus et al. 2002). Such a continuum indicates that stacked, multiple, local to intermediate flow systems that differ in terms of residence time (i.e. flow path length) and the factors influencing the groundwater salinity may dominate (Titus et al. 2002).

The dominant Na-Cl hydrochemical facies of the groundwater is a result of the influence of salt dissolution and leaching, as well as the weathering of hydrous minerals, especially biotite (Titus et al. 2002).

In the Limpopo Mobile Belt Groundwater Region, nitrate levels were found to vary from 88 to 428 mg/l NO_3. Elevated nitrate levels are a regional problem and can be attributed to (Sami et al. 2002):

- Low density cover of thornveld with little ground cover, hence nitrogen fixation in vegetation is inhibited
- Low organic content limits substantial nitrate accumulation in the soil, hence leaching of nitrates is facilitated

- Low rainfall limits plant cover and results in episodic plant die-offs, thus plant cover fluctuates. Large summer rainfall subsequently leaches nitrates released by plant die-off
- High temperature ensures rapid biological nitrification
- Low carbon to nitrogen ratios result in nitrogen being freely available for nitrifying bacteria as well as low clay content in the quaternary cover
- Absence of surface runoff
- Variations in recharge result in variations in nitrate by dilution

B.3 Intrusive rock regions

B.3.1 Occurrence and attributes

In South Africa, the following groundwater regions are characterised by intrusive rocks (Figure B.1):

- Region 14 - Western Bushveld Complex
- Region 15 - Eastern Bushveld Complex
- Region 16 - Northern Bushveld Complex

Two recent research reports have contributed to knowledge concerning these groundwater regions (McCaffrey and Willis, 2001 and Botha et al. 2001).

McCaffrey and Willis (2001) studied the distribution of fluoride-rich groundwater in the Eastern and Mogwase Regions of the Limpopo and Northwest Provinces of South Africa, which falls mostly within Groundwater Region 14.

Botha et al. (2001) conducted studies on the Lebowa Granite Suite of the Bushveld Igneous Complex (Groundwater Region 15). Three major aquifer types were identified:

- Fractured aquifers associated with major structures
- Fractured aquifers associated with dykes
- Weathered aquifers resulting from weathering of major structures.

B.3.2 Flow and storage

McCaffrey and Willis (2001) found for the Bushveld area that groundwater is generally confined to the upper 150 m and is hosted in shallow weathering zones, fractures and faults.

Botha et al. (2001) proved that the previous held perception that drilling deeper than 30 m is a waste of effort due to the closure of fractures and faults is incorrect. A regional approach to groundwater exploration utilising geophysics methods, resulted in groundwater strikes as deep as 98 m.

B.3.3 Quality

In the Mogwase Region, much of the area is underlain by groundwater having a fluoride concentration above the maximum permissible drinking water concentration. McCaffrey and Willis (2001) furthermore developed a comprehensive database of the concentrations of fluoride and other common anions and cations, together with data on pH, temperature, EC and alkalinity for this region. The source and mobility of fluoride in the hydro-geochemical environment of the study area was established, and also the spatial relations between fluoride-enriched groundwater and fluoride sources in rocks, mineralised areas and soils.

B.4 Extrusive rock regions

In South Africa, the following groundwater regions are characterised by extrusive rocks (Figure B.1):

- Region 18 - Western Highveld
- Region 5 - Soutpansberg Hinterland
- Region 13 - Springbok Flats
- Region 20 - Northern Lebombo
- Region 40 - Southern Highland

Knowledge concerning the domain is limited because of lack of research in the extrusive rock regions.

B.5 Sedimentary rock regions

B.5.1 Regions composed of Vaalian Strata

B.5.1.1 Occurrence and attributes

In South Africa, the following groundwater regions are characterised by Vaalian Strata (Figure B.1):

- Region 9 - Western Bankeveld and Marico Bushveld
- Region 10 - Soutpansberg Hinterland
- Region 13 - Karst Belt
- Region 12 - Eastern Bankeveld
- Region 24 - Ghaap Plateau

These regions are mostly dominated by dolomite formations. A number of research reports applicable to these groundwater regions have been produced recently (Janse van Rensburg et al. 1987; Bredenkamp et al., 1995; Bredenkamp, 2000 and Bredenkamp, 2002). The report by Bredenkamp (2002) is a synthesis of the results of several studies in the dolomite aquifers.

The report by Bredenkamp (2002) focuses mostly on Groundwater Region 9 (Figure B.2). The dolomite aquifers cover an area of about 5000 km^2, with storage estimated at 5000 million m^3 (Bredenkamp, 2002). It is estimated that available groundwater resources are 300 million m^3.

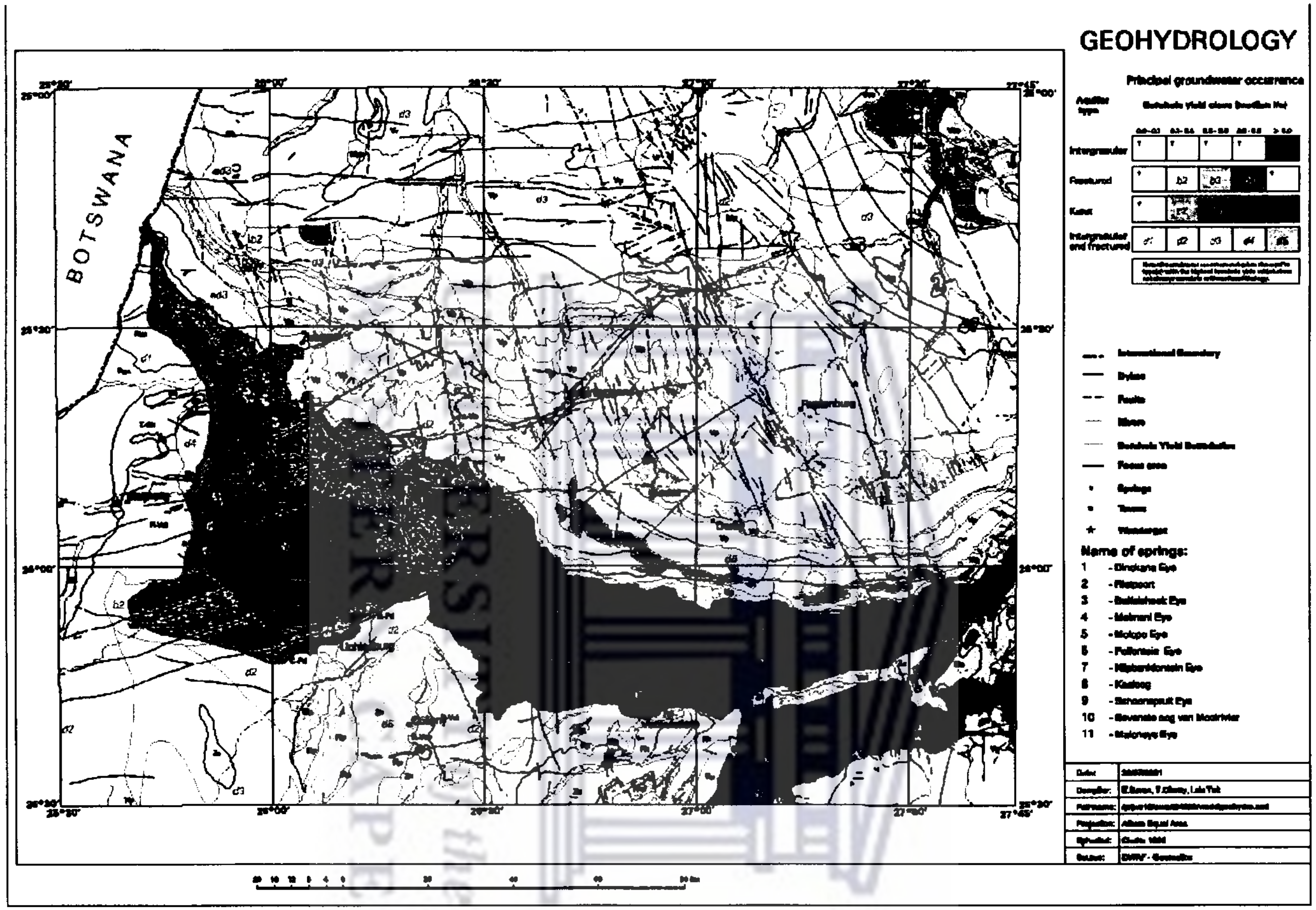

Figure B.2 Geohydrology of the dolomite aquifers in Northwest Province (Stephens and Bredenkamp (2002).

B.5.1.2 Flow and storage

Groundwater level monitoring points were established in the course of hydrogeological studies carried out in the region (Bredenkamp, 2002). The units are (Bredenkamp, 2002):

(a) Ventersdorp groundwater unit feeding the Schoonspruit eye which is the main water supply of Ventersdorp and of irrigation lower down.

(b) Grootpan unit where irrigation from groundwater has significantly expanded over the last 8-10 years, increasing concerns that it will deplete the groundwater resources of the area

(c) Extended Grootfontein unit supplies Mafikeng with water from a pumping scheme at the Grootfontein eye and overflow from the Molopo eye. At the same time large abstractions for irrigation occur in this compartment.

(d) Zeerust groundwater unit, from which water is supplied from the Rietpoort and Doornfontein pumping schemes to the town of Zeerust; and from Dinikana eyes and a few boreholes to settlements at Dinokana-Lehurutse.

(e) Lichtenburg-Itsoteng unit which supplies Lichtenburg with water, originally from springs but presently only from boreholes drilled in the dolomite.

B.5.1.3 Quality

Since these aquifers are in part overlain by areas of intensive land use and urbanisation, they are potentially susceptible to water quality deterioration. However, groundwater contamination by substances such as oil, fertilizer nitrate and other sources of pollution does not seem to be serious in the dolomite areas (Bredenkamp, 2002). This is probably due to the large volumes of water stored underground in relation to very localised infiltration of contaminants (Bredenkamp. 2002).

The groundwater quality of dolomite aquifers in the Northwest Province seems to be generally good (Bredenkamp, 2002). Table B.1 is a comparison of the water chemistry of different springs in the region. These results indicate that, generally, the springs have not been seriously polluted.

Table B.1 Comparison of the chemistry of different springs in relation to the characteristics of the recharge areas (after Bredenkamp, 2002).

	TDS mg/l	HCO3 mg/l	Cl mg/l	Sulphate mg/l	Comment
Dinokan Upper	351	207	4.9	6.6	Pristine spring – low TDS and Cl indicating higher recharge
Molopo	326	199	4.8	5.3	No contamination
Vergenoegd	399	244	4.9	6.6	Natural spring – no contamination
Skilpadfontein	442	272	5	6.5	Natural spring – no contamination

The Gauteng Dolomite Aquifer covers a large area in the highest populated province in South Africa (Van Wyk, 2002). The aquifer consists of a $CaMgHCO_3$ rich limestone overlying older sedimentary successions of which one of them is gold bearing Witwatersrand Super Group (Van Wyk, 2002). The total thickness of the dolomite is of the order of 250 to 1000m (Van Wyk, 2002). The system is highly compartmentalised due to presence of near-vertical intrusive dyke rock, which plays a major role in the groundwater flow regime, causing several large springs, which drain the dolomite compartments (Van Wyk, 2002).

Gold mining has had a major impact on the groundwater system, both in terms of quantity and quality (Van Wyk, 2002). Long-term, continuous dewatering of the deeply mined areas, which lie beneath the dolomite compartments, has caused dewatering (Van Wyk, 2002). .The western limb of the Gauteng Dolomite Aquifer, representing the West Rand and Far West Rand Dolomite groundwater systems has been dewatered since the late 1960's (Van Wyk, 2002). Dewatering has produced enormous problems with ground stabilisation, bulk treatment and dumping of water pumped from the mines (Van Wyk, 2002).

Mining is now approaching the stage where underground sections and shafts become redundant and sections of older mines no longer require dewatering (Van Wyk, 2002). Since the mid-ninety's water levels have been rising (Van Wyk, 2002). Rewatering of the redundant mined areas and ultimately filling of a dewatered compartment will cause decanting of recharged groundwater (Van Wyk, 2002). The two main issues arising from rewatering are (Van Wyk, 2002):

(a) how long it will take to fully recover (period before decanting) and

(b) what water quality could be expected when springs start flowing and shafts start to decant

One of the major factors contributing to water degradation is the reaction of water with sulphide minerals, producing acid rock drainage (Scott, 1995). This form the greatest threat to groundwater after closure of the mines (Hodgson et al. 2001).

B.5.2 Regions composed of Vaalian – Mokolian Strata

In South Africa, the following groundwater region are characterised by Vaalian - Mokolian Strata (Figure B.1):

- Region 25 - West Griqualand

Knowledge concerning the domain is limited because of lack of research in the Vaalian – Mokolian rock regions.

B.5.3 Regions composed of Mokolian Strata

In South Africa, the following groundwater regions are characterised by Mokolian Strata (Figure B.1):

- Region 6 - Waterberg Plateau
- Region 8 - Soutpansberg
- Region 11 - Middelsburg Basin

Knowledge concerning the domain is limited because of lack of research in the Mokolian rock regions.

B.5.4 Regions composed of Namibian Strata

In South Africa, the following groundwater regions consist of Namibian Strata (Figure B.1):

- Region 55 - Richtersveld

- Region 56 - Knersvlakte
- Region 57 - Swartland
- Region 58 - Outenikwa Coastal Foreland

Knowledge concerning the domain is limited because of lack of research in the Namibian rock regions.

B.5.5 Regions composed of Ordo-Devonian Strata

B.5.5.1 Occurrence and attributes

In South Africa, the following groundwater regions are characterised by Ordo-Devonian Strata (Figure B.1):

- Region 48 - Northwestern Cape Ranges
- Region 49 - Southwestern Cape Ranges
- Region 50 - Southern Cape Ranges
- Region 52 - Grountrivier-Klein Winterhoek-Suurberg-Kaprivier Ranges
- Region 53 - Ruensveld

Recent research reports have contributed to knowledge concerning these groundwater regions (Lomberg et al. 1997; Weaver, 1999 and Kotze, 2002). In addition, a handbook on Table Mountain Group aquifers, which encompasses most of the above Groundwater Regions, has been published (Pietersen and Parsons, 2002).

The dominantly arenitic Table Mountain Group (TMG) is well exposed within the Cape Fold Belt, which straddles the west and south coasts of South Africa (de Beer, 2002). Figure B.3 gives the distribution of TMG. The TMG formations have been exposed through two major tectonic events, the Cape Oregeny and the fragmentation of southwestern Gondwana during the Mesozoic (de Beer, 2002).

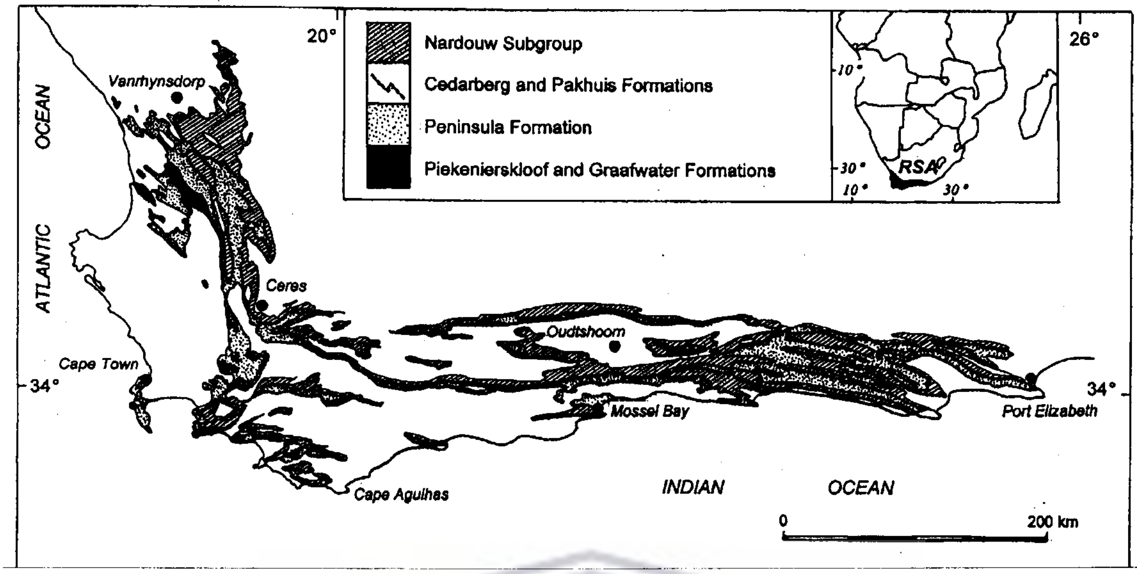

Figure B.3 Distribution of the TMG (de Beer, 2002).

Due a combination of favourable factors, such as structure and climate, the TMG forms one of the major fractured rock aquifers in South Africa. The TMG Aquifer System is sub-divided into five main characteristic hydrogeological domains, namely (Woodford et al. 2002):

(a) Western Area,
(b) Central Area, i.e. Agter Witzenberg-Ceres-Hex – Koo Valleys and Villiersdorp
(c) Coastal Belt, i.e. from Kleinmond to Mossel Bay
(d) Klein Karoo
(e) Eastern Cape, Plettenberg Bay to Port Elizabeth.

From a hydrogeological point of view, the TMG rocks represent a multi-porous medium that essentially consists of two major components, namely (Woodford, 2002):

(a) Fractures and
(b) Inter-fracture blocks or rock matrix.

TMG rocks are generally considered to form dual-porosity, fractured rock aquifer systems, where it is difficult to simultaneously quantify the groundwater flow within fractures and the rock matrix (Woodford, 2002).

B.5.5.2 Flow and storage

Rosewarne (2002) gives an estimate of 0.001 for bulk storativity of the Peninsula and Nardouw formations of the Table Mountain Group. A rough dimensional analysis of the TMG gives a rock volume of 47 000 billion m^3 (Rosewarne, 2002). It is estimated that tens of billions of cubic metres of groundwater are stored in the TMG aquifers (Rosewarne, 2002). Weaver (2002) estimates an annual sustainable yield of 2600 million m^3. The current annual consumption of water by Cape Town is 500 million m^3 (Weaver, 2002).

The main groundwater intersections in the TMG aquifer are commonly at depths of > 100m below ground surface and geothermal evidence from hot springs indicates groundwater circulation to depths of up to 2000 m (Rosewarne, 2002). Some of the reasons for deep groundwater circulation are put forward as follows (Rosewarne, 2002):

- The TMG consists mainly of a thick sequence of fairly uniform, brittle quartzitic sandstone which would tend to fracture readily under stress.
- These rocks have been involved in a continental scale orogeny which led to the formation of the Cape Fold Belt, providing ample levels of stress to produce widespread and deep fracturing.
- The associated groundwater is usually acidic and low in dissolved solids, lessening the likelihood of blocking of fractures by deposition of minerals.
- TMG sandstones are predominantly composed of silica and so weathering products are less likely to lead to blocking of fractures.

B.5.5.3 Quality

Groundwater is considered to be of good quality in TMG aquifers i.e. of very low salinity. The TMG groundwater consists mainly of a low salinity, Na-Cl type which is very soft (Smart and Tredoux, 2002). It is generally acidic, poorly buffered due to the low calcium and bicarbonate, and therefore, very corrosive (Smart and Tredoux, 2002).

B.5.6 Carbo-Triassic

B.5.6.1 Occurrence and attributes

The main Karoo Basin encompasses an area of approximately 630 000 km^2 (Woodford et al. 2002). The following Groundwater Regions comprises Karoo aquifers or Carbo-Triassic Strata (Figure B.1):

- Region 2 - Waterberg Coal Basin
- Region 4 - Karoo Basin
- Region 28 - Eastern Highveld
- Region 30 - Northeastern Pan Belt
- Region 31 - Central Pan Belt
- Region 32 - Northern High Belt
- Region 33 - Southern Highland
- Region 34 - Northeastern Upper Karoo
- Region 35 - Bushmanland Pan Belt
- Region 36 - Hantam
- Region 37 - Tanqua Karoo
- Region 38 - Western Upper Karoo
- Region 39 - Eastern Upper Karoo
- Region 41 - Western Great Karoo
- Region 42 - Eastern Great Karoo
- Region 43 - Ciskeian Coastal Foreland and Middleveld
- Region 44 - Transheian Coastal Foreland and Middleveld
- Region 45 - Northwestern Middleveld

Numerous related research projects focussing on these groundwater regions (Kirchner et al. 1991; Botha et al. 1998; Chevallier et al. 2001; Sami et al, 2002 and Woodford and Chevallier, 2002) have been produced. These include a handbook on Karoo aquifers, which encompasses most of the above Groundwater Regions (Woodford and Chevallier, 2002).

A major characteristic of the Karoo Supergroup, which consists mainly of sandstone, mudstone, shale and siltstone, is the low permeability (Woodford et al. 2002). Figure B.4 is a schematic showing areal distribution of lithostratigraphic units in the Main Karoo Basin.

The Dwyka diamictite and shale have very low hydraulic conductivies, and virtually no primary voids (Woodford et al. 2002). Water is confined to within narrow discontinuities like jointing and fracturing. The Dwyka Group is not considered an ideal unit for large-scale development of groundwater. Sami et al. (2002) confirmed this viewpoint. The Ecca Group consists mainly of shales, with thicknesses varying from 1 500 m in the south to 600 m in the north (Woodford et al. 2002). Significant tracts of land are irrigated from groundwater found in the Ecca shales. This is surprising because this formation is considered dense. Aquifers in the Beaufort Group are multi-layered and multi-porous with variable thickness (Woodford et al. 2002). The characteristics and depositional history of the Molteno Formation would indicate better groundwater potential. The sediment bodies are more persistent than those of the Beaufort Group (Woodford et al. 2002). The Elliot Formation consists mostly of red mudstone (Woodford et al. 2002). This Formation thus presents more of an aquitard than an aquifer (Woodford et al. 2002). The Clarens Formation consists almost entirely of well-sorted, medium- fine-grained sandstones, deposited as thick consistent layers (Woodford et al. 2002). Although the Formation has a relatively high and uniform porosity (average 8.5%), it is poorly fractured and has a very low permeability (Woodford et al. 2002). The formation may therefore be able to store large volumes of water, but is unable to release it quickly (Woodford et al. 2002).

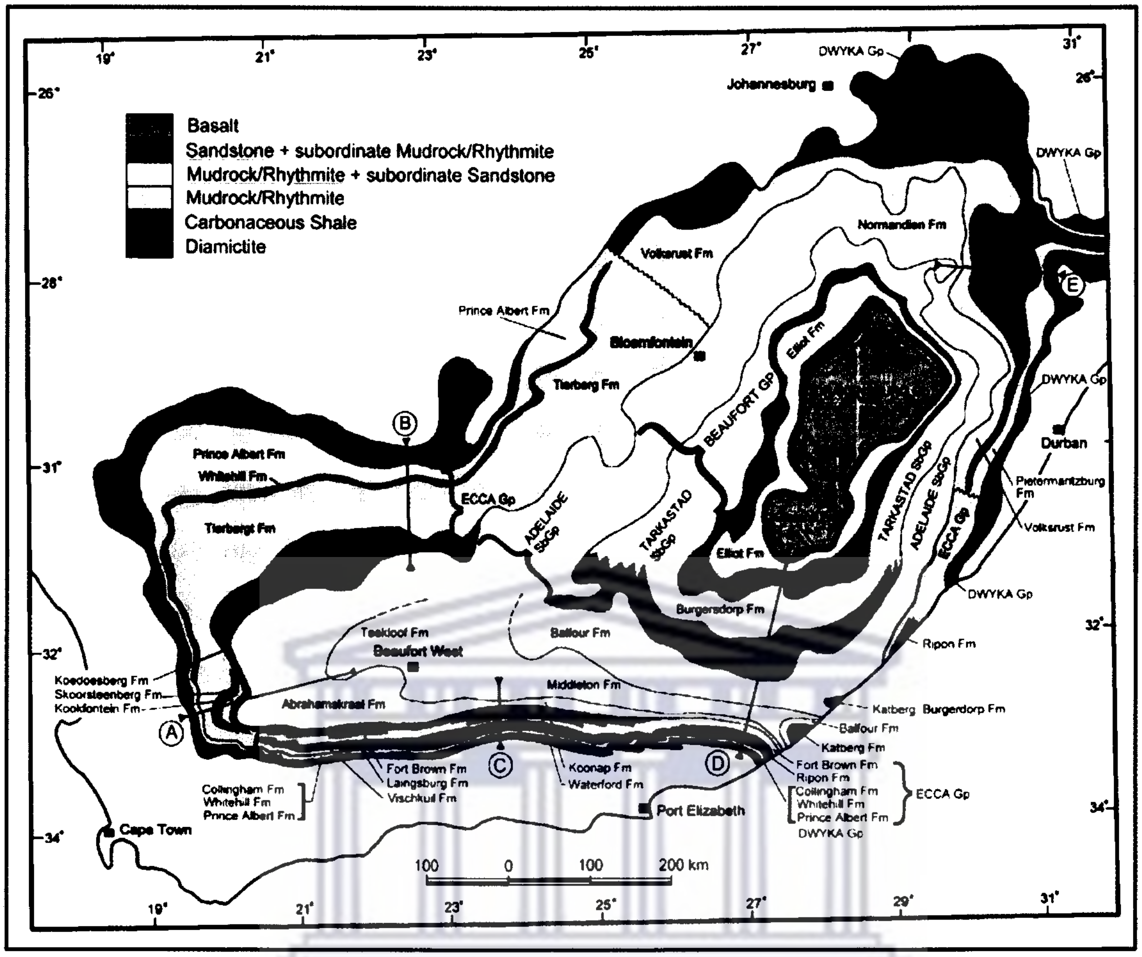

Figure B.4 Schematic areal distribution of lithostratigraphic units in the Main Karoo Basin (from Woodford et al. 2002)

Dolerite intrusives are prevalent throughout the Karoo Basin. The country rock is often fractured during and after dyke emplacement (Woodford et al. 2002). These discontinuities represent zones of relatively higher permeability which act as conduits for groundwater flow within the aquifer (Woodford et al. 2002). Most successful boreholes show some relationship with the dolerite intrusives.

B.5.6.2 Flow and storage

The aperture and areal extent of water-yielding fractures in Karoo Formations are limited, and therefore unable to store large quantities of water (Botha et al. 2002). The rock matrix is considered as the main storage units for water in Karoo aquifers (Woodford et al. 2002). Major flow in Karoo aquifers occurs from the rock matrix to the fracture, which supplies the borehole with water (Woodford et al, 2002). A highly permeable fracture quickly dewaters when pumped unless recharged through its surfaces (Woodford et al. 2002). The recharge rate depends on the rate at which the water can leak from the surrounding rock matrix to the fracture (Woodford et al. 2002). The immediate yield of a borehole is not limited by the amount of water stored in Karoo aquifers but more so by the finite rate at which water leaks from the matrix to the fracture (Woodford et al. 2002).

B.5.6.3 Quality

Karoo Formations display variable water quality properties (Woodford et al. 2002). Lateral changes in climatic patterns seems to be the main factor controlling the diversity of the mineralization and water types occurring in Karoo rocks (Woodford et al. 2002). Further variability is caused by recharge, evaporation, topography, soil type and thickness, vegetation cover and human activities (Woodford et al. 2002). The following solute processes have effects on groundwater quality in the Karoo aquifers (Woodford et al, 2002):

- Physical weathering
- Weathering of dolerite
- Weathering of sedimentary rocks
- Role of carbon dioxide
- Ion exchange and sorption
- Evapotranspiration
- Redox controlled reactions

Most of the Karoo Basin has total dissolved solids (TDS) in the range of 450 – 1000 mg/l (Woodford et al. 2002). This is shown in Figure B.5. High concentrations are limited to the westernmost and southernmost edges of the Basin (Woodford et al. 2002). The relatively well-defined picture of TDS may be skewed by the fact that fresh water related to the dolerite structures is sampled most often (Woodford et al. 2002). The groundwater quality in the sedimentary sequence is regarded as poorer due to longer residence time (Woodford et al. 2002).

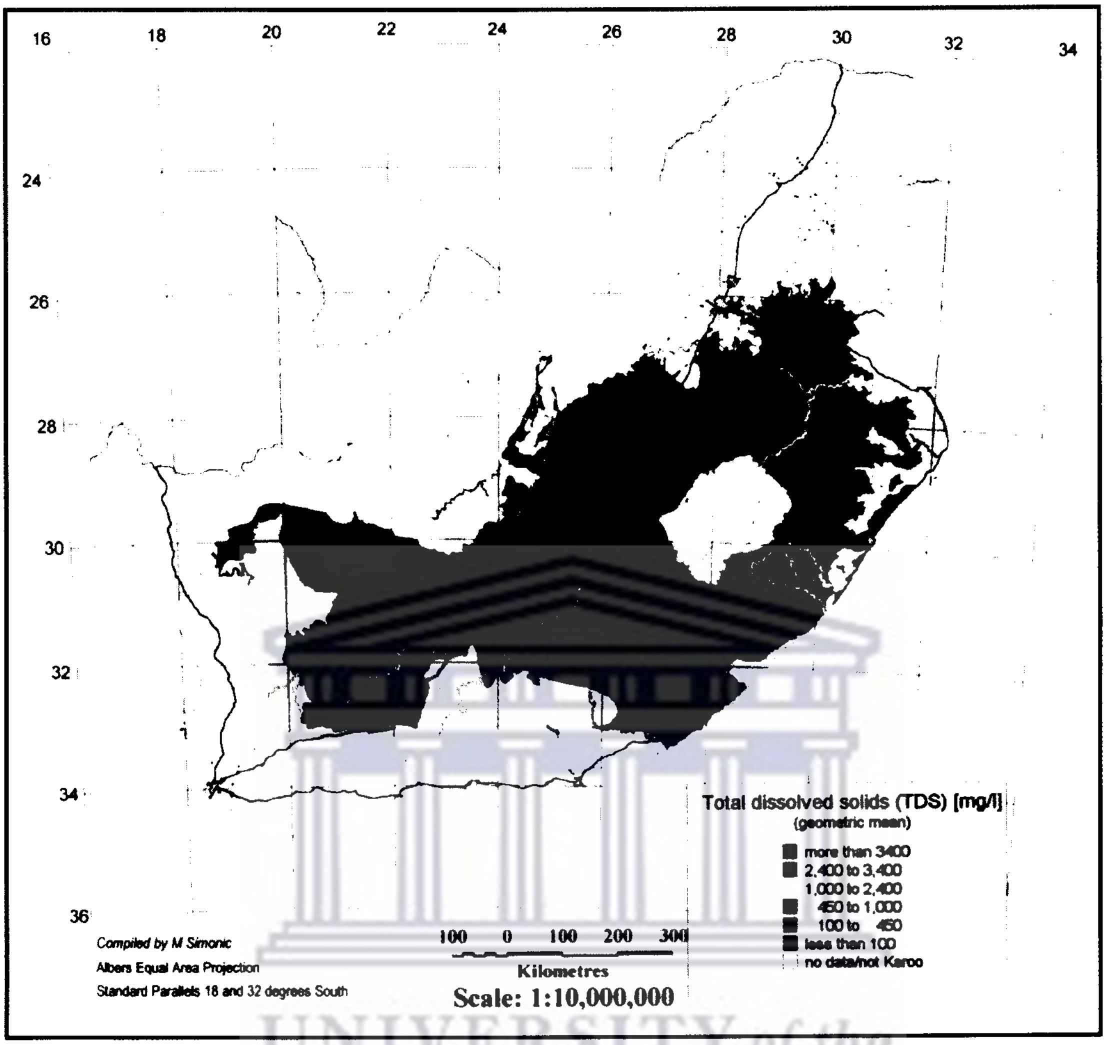

Figure B.5 Ranges of TDS expressed as a geometric means over representative lithological units (Woodford et al. 2002).

B.6 Composite regions

Regions have been classified as composite where (Vegter, 2000):

- No major rock type is dominant
- Several major lithostratigraphic units are involved
- More extensive primary aquifers than alluvial deposits are present

The following Ground Regions are considered to be composite regions (Figure B.1):

- Groundwater Region 23 (Western Kalahari)
- Region 29 - Dry Harts-Vaal-Orange Lowland
- Region 40 - Southern Highland
- Region 46 - Northeastern Middleveld
- Region 47 - Kwazulu Natal Coastal Foreland
- Region 51 - Oudtshoorn Basin
- Region 54 - Intermontane Tulbagh-Ashton Valley
- Region 59 - Southwestern Coastal Sandveld
- Region 63 - Lower Gamtoos Valley
- Region 64 - Algoa Basin

Sami et al. (2002) established that the rocks of the Natal Metamorphic Province in Groundwater Region 47 are characterised by negligible primary porosity and groundwater movement is primarily within hard rock aquifers and controlled by zones of deep weathering, faulting, fracturing and jointing.

B.7 Conclusion

The aquifers in South Africa are predominantly found in fractured rock domains. Characterisation of these resources has been limited. The dominant occurrence of groundwater in fractured rocks implies that these aquifer systems are more difficult to manage and to protect.

Most of the research has been focussed on the main Karoo Basin (B.5.6). This is to a large degree understandable because of the Karoo Basin being the largest aquifer system in areal extent in South Africa. The aquifers support the domestic and agricultural needs of a number of small towns and rural communities. The dolomite aquifers have also been studied in some detail. The key challenge for the dolomite aquifer system relates to the management of the resource which is threatened by various land use impacts and the protection of aquifer integrity. This will require an integrated aquifer management arrangement. The rest of the hydrogeological domains have been investigated in lesser detail.

There are many uncertainties and barriers to overcome in our current understanding of fractured rock aquifers in South Africa, ranging from the occurrence, attributes and dynamics of the system to the institutional arrangements necessary for sustainable management of the resource. Consequently, proper allocation of groundwater resources in South Africa will require integrated planning, namely (adapted from Xu et al. 2000):

- Development of scientific measures to assess fractured rock aquifers (recharge, flow and storage)
- Development of verifiable objectives for groundwater management (e.g. equity principles) and the translation of the principles of sustainable development and IWRM.
- Identification of groundwater management problems, constraints and uncertainties.
- Understanding the role of groundwater in the broader water resource management framework (i.e. understanding groundwater and surface water linkages).
- Understanding the environmental role of groundwater in sustaining dependent ecosystems and impact of abstraction on the environment.

A sound understanding of above-mentioned issues and of the applicable legislative framework is required for proper resource management.

Appendix C Value Function Methods

C.1 Introduction

This Appendix presents the background information to value function methods of decision-making in the face of multiple attributes. A short introduction has been given in sections 4.3.1 and chapter 5. Figure 6 summarises the various value function method approaches. Value function methods assume that the alternatives available to the decision-maker are fully identified; and that the consequences are fully known and can be described in terms of any of the relevant performance values (Offringa, 1996). MCDA approaches which have stochastic outcomes are known as utility function methods. Utility function methods can be viewed as extension of value function methods relating to the use of probabilities and expectations to deal with uncertainty (Belton and Stewart, 2002). According to Belton and Stewart (2002) the simple additive value functions, linked to sensitivity analysis, in most instances provide essentially the same results and insights.

There are two types of information, sometimes referred to as intra-criterion information and inter-criterion information or alternatively as scores and weights (Belton and Stewart, 2002).

C.2 Scoring process (intra-criterion information)

Scoring is the process of assessing the value derived by the decision-maker from the performance of alternatives against the relevant criteria (Belton and Stewart, 2002) which is the same as assessing the partial value functions $v_i(v_1,v_2,...,v_p)$ in Equation 1 (Belton and Stewart, 2002). If criteria are structured as a value tree then the alternatives must be scored against each of the bottom-level criteria (Belton and Stewart, 2002). These values need to be assessed on an interval scale of measurement, i.e. a scale in which the difference between points is the important factor (Belton and Stewart, 2002). The minimum and maximum points can be defined in a number of ways, but it is useful to distinguish between a local scale and global scale as described below (Belton and Stewart, 2002):

- A local scale is defined by the set of alternatives under consideration. The alternative which does best on a particular criterion is assigned a score of 100 and the one which does least well is assigned a score of 0. All the other alternatives will receive intermediate scores which reflect their performance relative to these two end points.

- A global scale is defined by reference to the wider set of possibilities. The end points may be defined by the ideal and the worst conceivable performance on the particular criterion, or by the best and worst performance which could realistically occur.

Once the reference points of the scale have been determined consideration must be given to how other scores are to be assessed (Belton and Stewart, 2002): This can be done in the following ways (Belton and Stewart, 2002):

- **Definition of a partial value function**. This relates to performance in terms of a measurable attribute reflecting the criterion of interests.
- **Construction of a qualitative scale**. In this case, the performance of alternatives can be assessed by reference to descriptive pointers, or word models (to which appropriate values are assigned).
- **Direct rating of the alternatives**. In this case, no attempt is made to define a scale which characterises performance independently of the alternatives being evaluated. The decision maker simply specifies a number, or identifies the position on a visual analogue scale, which reflects the value of an alternative in relation to the specified reference points.

C.2.1 Value function

Within the value measurement approach, the first component of preference modelling (measuring the relative importance of achieving different performance levels for each identified criterion) is achieved by constructing partial value functions, say $v_i(a)$ for each criterion (Belton and Stewart, 2002). A fundamental property of the partial value function must be that alternative *a* is preferred to *b* in terms of criterion *i* if and only if $v_i(a) > v_i(b)$; similarly indifference between *a* and *b* in terms of this criterion exists if and only if $v_i(a) = v_i(b)$ (Belton and Stewart, 2002).

The first step in defining a value function is to identify a measurable attribute scale which is closely related to the decision maker's values (Belton and Stewart, 2002). Such a function can be assessed directly or by using indirect questioning (Belton and Stewart, 2002).

C.2.1.1 Direct assessment methods

Direct assessment of a value function entails (Belton and Stewart, 2002):

- The value function is monotonically increasing against the natural scale – i.e. the highest value of the attribute is most preferred, the lowest value least preferred.
- The value function is monotonically decreasing against the natural scale – i.e. the lowest value of the attribute is most preferred, the highest least preferred.
- The value function is non-monotonic – i.e. an intermediate point on the scale defines the most preferred or least preferred point.

A value function translate a measure of achievement against the criterion concerned into a value score on the 0 - 100 scale. For example, if one criterion corresponds to the proportion of people (expressed as a percentage) who pay against those who do not pay to recover operation and maintenance cost for water supply schemes and the minimum likely level is judged to be 40% and the maximum is 100%, then a simple graph allows conversion from the natural scale of measurement to the 0 – 100 required for the MCDA. This is shown in Figure C.1.

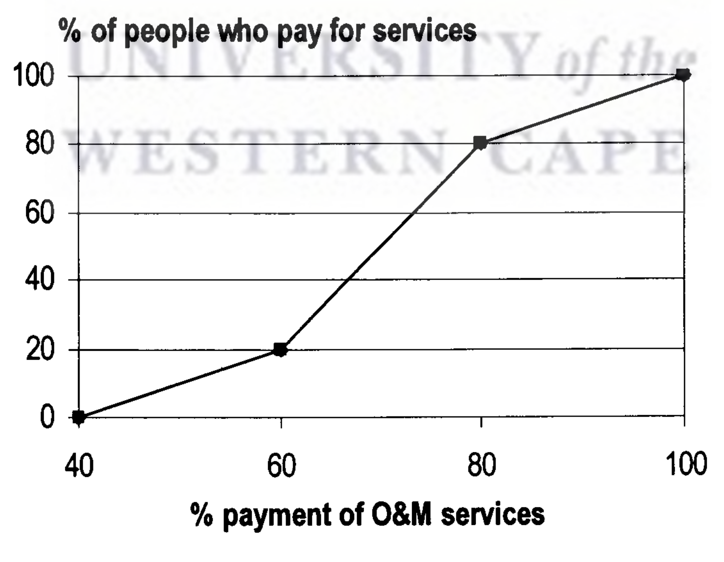

Figure C.1 An example to demonstrate use of a value function that is monotonically increasing.

For any option, its score on the criterion proportion of people (expressed as a percentage) who pay against those who do not pay to recover operation and maintenance cost is assessed by simply reading off the vertical axis, the score corresponding to the % of people who pay for water services, as measured on the horizontal axis. Thus an option where 70% of people pay for services, say, scores 50.

Where higher measurements on the scale of natural units corresponds to worse, rather than better performance, the slope of the function mapping achievement level on the 0 – 100 score is simply reversed.

The value functions used in many MCDA applications can for practical purposes be assumed to be linear. In some occasions it may desirable to use a non-linear function. For example, fluoride is needed in trace quantities during tooth formation to harden the tooth enamel. However above a certain level, chronic intake of high fluoride levels can damage the skeleton, causing a hardening of the bones and making them brittle. This is illustrated in Figure C.2. In this case, the judgement is that, once the levels reaches about 1.0 mg/L there is an increasing health impact.

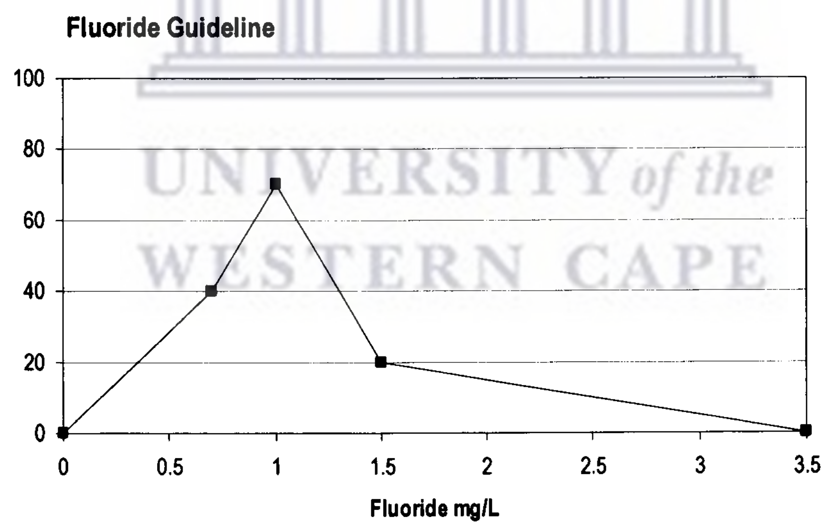

Figure C.2 An example to demonstrate use of a value function that is non-monotonic.

A non-monotonic value function is often an indication that the proposed measure actually reflects two conflicting values (Belton and Stewart, 2002).

C.2.1.2 Indirect assessment method

These methods assume that the value function is monotonically increasing or decreasing over the range of attribute measurements (Belton and Stewart, 2002). Two methods of assessment are widely used, namely the bisection and the difference methods (Belton and Stewart, 2002).

In the bisection method (also known as internal halving or halving the interval) the decision maker is presented with two objects and asked to define the attribute level that is halfway between the objects in respect of the relative strengths of the preferences (Dietrich and Hämäläinen, 2003). The decision step for this process of internal halving is first to choose the midpoint (equation C.1) and then to analyze the three probabilities that might arise (FIST, 2001).

$$x_M = \frac{(x_L + x_R)}{2} \qquad \text{Equation C.1}$$

This is illustrated in terms of the following steps to establish the root of the equation $f(x) = 0$.

(a) If $f(x_L)$ and $f(x_M)$ have opposite signs, a zero lies in $[x_L, x_M]$

(b) If $f(x_M)$ and $f(x_R)$ have opposite signs, a zero lies in $[x_R, x_M]$

(c) If $f(x_M) = 0$, then x_M is a root of the equation $f(x) = 0$. Continue bisecting the interval and repeat the process until the root is known to the desired accuracy.

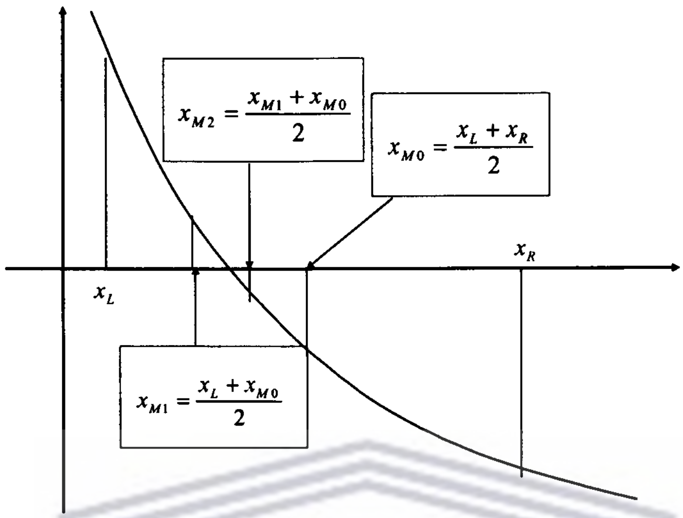

Figure C.3 The Bisection method (FIST, 2001).

The application of the bisection method is illustrated by considering the assessment of the criteria *Available Funding*, which was assessed by available funds per capita. The available policy information would indicate, depending on the type of scheme and the level of service planned, that this could range from R500 per capita to R2000 per capita. The value increases, that is, availability of funding is better satisfied, as the per capita allocation per person increases. In using the bisection approach the decision maker is asked to identify the point on the attribute scale which is halfway, in value terms, between the two end points (Belton and Stewart, 2002). To help the decision maker identify the midpoint value it may be helpful to begin by considering the midpoint on the objective scale and posing the following question: *is the increase from to R500 to R1250 a greater or lesser increase in value than an increase from R1250 to R2000?* Suppose the decision maker responds that the increase from R1250 to R2000 represents a greater increase in value, the analyst might then ask how an increase from R1250 to R1625 compares with an increase from R1625 to R2000, continuing until the midpoint is identified. Suppose this is found to be R1700 per capita. The next step would be to find the midpoints between R500 and R1700 per capita and between R1700 and R2000 per capita - suppose these are found to be R1000 and R1800 respectively. It is generally accepted that 5 points (the 2 endpoints and 3 "midpoints') give sufficient information to enable the analyst to sketch in the value function, as illustrated in Figure C.4 (Belton and Stewart, 2002).

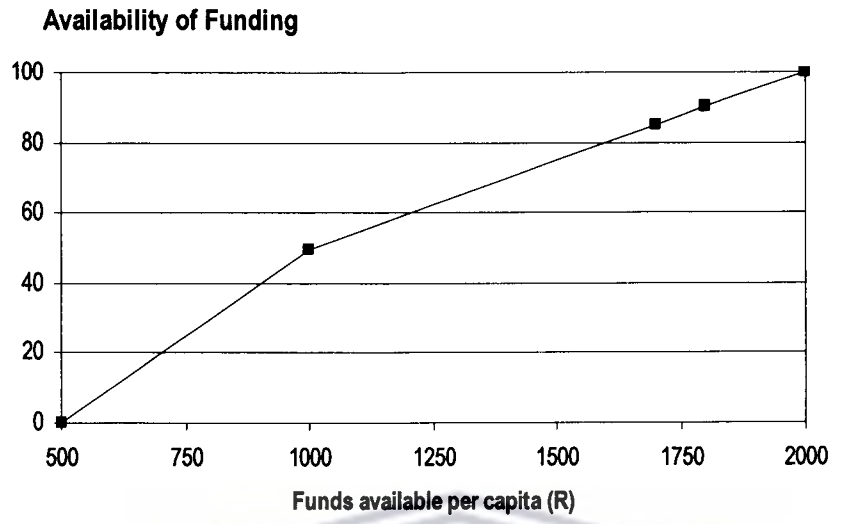

Figure C.4 Value function for availability of funds.

The difference method requires the decision maker to consider increments on the objectively measured scale and to relate these to differences in value (Belton and Stewart, 2002). Using the same example as above, the attribute scale is divided into, say, 4 equal intervals, as shown in Table C.1. The minimum allocation of resources per capita is R500 and the maximum per capita is R2000. Since preference is for more financial resources, an increase in the available funding per capita results in an increase in value. The decision maker is asked to rank order the specified difference according to increase in associated value (Belton and Stewart, 2002). The ranking gives an idea of the shape of the value function (Belton and Stewart, 2002). In this example, the increase in value is greatest for lower numbers of flights, suggesting a concave, increasing value function (Belton and Stewart, 2002). The curve could be sketched directly on the basis of this information, or may be further refined by asking the decision maker to assess the relative magnitude of value increases (Belton and Stewart, 2002).

Table C.1 Intervals on available funding per capita

Increase in available funding		Increase in value	
From	To		
R500	R875	1	= Greatest increase in value
R875	R1250	2	
R1250	R1625	3	
R1625	R2000	4	

C.2.1.3 Constructed measurement scale

In some instances a simple natural scale may not exist and it becomes necessary to construct an appropriate measurement scale (Belton and Stewart, 2002). For example, in delineating protection zones around boreholes in fractured rock aquifers from possible pollution from pit latrines, the decision maker need to take into account the various factors such as:

(a) The maximum expected NO_3 as N.

(b) The extent of the vertical or horizontal fracture.

(c) The estimation of the travel time from the surface to the water level and the position of the water strike.

One of the main concerns is the travel time and the risk of microbial pollution is assigned by using the guidelines as illustrated in Table C.2. A further concern would be the nitrate values (Table C.3).

Table C.2 Travel times and the risk of microbial pollution assigned to each (van Wyk et al. 2001).

Parameter	**No risk**	**Low risk**	**High risk**	**Very high risk**
Travel time (days)	>100	30-100	3-30	<3

Table C.3 Nitrate value intervals and the risk (to infants) associated with each interval (van Wyk et al, 2002).

Parameter	No risk	Low risk	High risk	Very high risk
N (mg/L)	<5	5-10	10-20	<20

Value functions can be constructed in relation to these risk factors, namely contaminant load and travel time. The risk of pollution to a borehole can then be assessed, which means a water supply borehole can be selected. This is illustrated in Table C.4.

Table C.4 Ratings of different proposed boreholes for water supply purposes (from van Wyk et al. 2002).

	NO3 mg/L	Areal extent of fracture	Travel time	Rating
Borehole 1	0	169	80	85
Borehole 2	4.8	50	1	100
Borehole 3	2	69	0.3	138

C.2.2 Constructing a qualitative value scale

Often it is not possible to find a measurable attribute which captures a criterion (Belton and Stewart, 2002). In such circumstances it is necessary to construct an appropriate qualitative scale (Belton and Stewart, 2002). An example is the classification of water resources into different categories (Table C.5). Qualitative scales should have the following characteristics (Belton and Stewart, 2002):

- **Operational**: allow the decision makers to rate alternatives not used in the definition of the scale.
- **Reliable**: two independent ratings of an alternative should lead to the same score.
- **Value relevant**: relates to the decision maker's objective
- **Justifiable**: an independent observer could be convinced that the scale is reasonable.

Table C.5 A broad classification of water resources (DWAF, 1998).

Class	Definition
A	Unmodified or approximate natural conditions.
B	Largely natural conditions with only a few localised modifications; no negative effects apparent
C	Moderately modified; moderate changes are apparent
D	Largely modified; a widespread loss of natural functioning
E	Seriously modified; the losses of natural functioning are extensive
F	Critically modified; modifications have reached a critical level and the region has been modified completely with almost complete loss of natural functioning.

C.2.3 Direct rating of alternatives

Direct rating can be viewed as the construction of a value scale, but defining only the end points of the scale (Belton and Stewart, 2002).If using a local scale, the alternative which performs best of those under consideration is given the highest score, usually 100 or 10, and the alternative which performs least well is given a score of 0 (Belton and Stewart, 2002). All other alternatives are positioned directly on the scale to reflect their performance relative to the two reference points (Belton and Stewart, 2002).

C.3 Direct rating of alternatives by pairwise comparisons

A systematic pairwise comparison approach is one of the cornerstones of the Analytic Hierarchy Process (AHP) (Belton and Stewart, 2002). AHP is based on decomposing a complex MCDA problem into a system of hierarchies (Triantaphyllou et al. 1998). AHP shows the relationship of goals, objectives (criteria) and alternatives. Uncertainties and other influencing factors can also be included (Forman and Selly, 2001). The three basic principles of AHP are (Forman and Selly, 2001):

(a) The **reciprocal axiom** requires that if $P_C(E_A, E_B)$ is a paired comparison of elements *A* and *B* with respect to their parent *C*, representing how many times more the element *A* possess a property than does *B*, the $P_C(E_B, E_A) = 1/P_C(E_A, E_B)$. For example if *A* is 5 times larger than *B*, then *B* is one fifth as large as *A*.

(b) The **homogeneity axiom** states that the elements being compared should not differ by too much, else there will tend to be larger errors in judgement.

(c) The third axiom states that **judgement** about, or the priorities of, the elements in a hierarchy do not depend on lower level elements.

A fourth axiom was introduced which says that participants in the AHP who are able to rationalise their comparisons should do so adequately in order to influence the outcome of the process.

The AHP deals with the structure of an *MxN* matrix (*M* = the number of alternatives and *N* = the number of criteria). The matrix is constructed using the relative importance of the alternatives in terms of each criterion (Triantaphyllou and Mann, 1989). The vector $(a_{i1}, a_{i2}, \ldots a_{iN})$ for each *i* is the principal eigenvector of an *NXN* reciprocal matrix which is determined by pairwise comparisons of the impact of the M alternatives on the j^{th} criterion (Triantaphyllou and Mann, 1989).

According to AHP the best alternative (in the maximum case) is indicated by the following relationship (Triantaphyllou and Mann, 1989):

$$A^{*}_{AHP} = \max_{i} \sum_{j=1}^{N} a_{ij} w_j \quad \text{for } i = 1,2,3,\ldots M \qquad \text{Equation C.2}$$

C.4 Eliciting weights (inter-criterion information)

In any evaluation not all criteria carry the same weight, thus it is desirable to incorporate an assessment of the relative importance of criteria (Belton and Stewart, 2002). The weight assigned to a criterion is essentially a scaling factor which relates scores on that criterion to scores on all other criteria (Belton and Stewart, 2002). Thus, if criterion A has a weight which is twice that of criterion B, this should be interpreted that the decision maker rates 10 value points on criterion A the same as 20 value points on criterion B and would require such scores in order to be willing to trade one for the other (Belton and Stewart, 2002).

Weighting methods can be either holistic or decomposed (Alaja, 1998). In holistic weighting, the alternatives are compared and the weights for the attributes are calculated from the scores given to the alternatives (Alaja, 1998). In a decomposed weighting method only the attributes of the various criteria are compared (Alaja, 1998). The weights for the attributes can be elicited either hierarchically or non-hierarchically (Alaja, 1998). In hierarchical weighting the weights are obtained separately for attributes belonging to different branches or sub branches of the value tree (Alaja, 1998). Final weights for the lowest level elements of the value tree are then obtained through multiplication (Alaja, 1998). In non-hierarchical weighting all the lowest level elements are compared simultaneously (Alaja, 1998).

C.4.1 Attribute weighting methods

Attribute weights reflect the ranges of attributes pertaining to the different criteria. Most attribute weighting methods do not make use of the value rating of consequences i.e. attribute weights do not depend on the shape of the value function (Pöyhönen and Hämäläinen, 2001). Thus, in most experimental studies and also in practical applications the value functions are often assumed to be linear (Pöyhönen and Hämäläinen, 2001).

C.4.1.1 Direct (or Direct Point Allocation)

Direct weighting is a simple procedure in which the decision maker is asked to allocate points to the attributes directly (Alaja, 1998; Pöyhönen and Hämäläinen, 2001). The attribute weights are then calculated by dividing these points by their sum (Alaja, 1998). The decision maker is asked, for example, to divide 100 points among the attributes (Pöyhönen and Hämäläinen, 2001).

C.4.1.2 The SWING weight method

SWING is a ratio estimation method where the decision-maker first chooses the most important of the attributes and assigns 100 points to it (HUT, 2002). Then the decision-maker evaluates the other attributes compared to the most important one, by assigning points (at most 100) to them (HUT, 2002). The weights are dependent on the scales being used for scoring as well as the intrinsic importance of the criteria (Belton and Stewart, 2002).

Let x_i^* be the best and x_i^0 the worst outcome of the attribute X_i, i Є (1,....,n). Furthermore let $a_0 = (x_1^0, x_2^0,....,x_n^0)$ be the worst possible alternative (Dietrich and Hämäläinen, 2002). In the SWING method the decision maker is asked to consider the alternative a^0 and choose one attribute, say x_i, to be shifted to the highest level x_i^* (Dietrich and Hämäläinen, 2002). Thus,

$$v(a_0) = 0 \qquad \text{Equation C.3}$$

$$a_i = (x_1^0, x_2^0, ..., x_{i-1}^0, x_i^0, x_{i+1}^0, ..., x_n^0 \qquad \text{Equation C.4}$$

$$v(a_i) = w_i v_i(x_i^*) = w_i = 100 \qquad \text{Equation C.5}$$

Where *v* is the value function that assigns a number *v(a)* to each alternative and $w_i v_i$ is the weighted normalised value (score).

,

The attribute x_i is then given 100 points (Dietrich and Hämäläinen, 2002). Next, the decision maker is asked to choose another attribute to be shifted to the best level and give it points relative to the first attribute (Dietrich and Hämäläinen, 2002). The procedure is continued until the weights of all attributes are assessed (Dietrich and Hämäläinen, 2002).

C.4.1.3 Simple multi-attribute rating technique (SMART)

SMART (**S**imple **M**ulti **A**ttribute **R**ating **T**echnique) is a technique where scores are standardised to a 0 – 1 scale (Olson, 2001). In this case, 0 represents the worst expected performance on a given criterion, and 1 representing the best expected performance. The weights are elicited in two steps (a) & (b) below (Pöyhönen and Hämäläinen, 1997):

(a) Rank the importance of the changes in the attributes from the worst attribute levels to the best levels.

(b) Make ratio estimates of the relative importance of each attribute relative to the one ranked lowest in importance.

Step b begins by assigning 10 points to the least important attribute (Pöyhönen and Hämäläinen, 2001).

The relative importance of the other attributes are then evaluated by giving them points from 10 upwards (Pöyhönen and Hämäläinen, 2001). The points given by the decision maker are normalised to get the weights (Pöyhönen and Hämäläinen, 2001).

C.4.1.4 SMARTER

In SMARTER, the weights are elicited with the centroid method directly from the ranking of alternatives (Mustajoki et al. 2003).

$$w_i = \frac{1}{n}\sum_{k=i}^{n}\frac{1}{k} \qquad \text{Equation C.6}$$

C.4.1.5 TRADEOFF

In the TRADEOFF procedure the decision maker compares two hypothetical alternatives that differ in two attributes only (Pöyhönen and Hämäläinen, 1997): The other attributes are kept on the same, fixed levels (Pöyhönen and Hämäläinen, 2001). Let *x* and *y* denote these two alternatives and let the indexes 1 and 2 refer to the attributes (Pöyhönen and Hämäläinen, 2001). The decision-maker is asked to consider two hypothetical alternatives with the attribute pairs (x_1, x_2) and (y_1, y_2) and to adjust one of the attributes until the alternatives become equally preferred (Pöyhönen and Hämäläinen, 2001). In order to choose which attribute should be moved one has to know the rank of attributes or which one of the hypothetical alternatives is preferred (Pöyhönen and Hämäläinen, 2001). The indifference statement gives an equation

$$w_1v_1(x_1) + w_2v_2(x_2) = w_1v_1(y_1) + w_2v_2(y_2) \qquad \text{Equation C.7}$$

where w_1 and w_2 are the unknown attribute weights and v_1 and v_2 are the values of the consequences (Pöyhönen and Hämäläinen, 2001). The n-1 indifference statements, known values $v_i(\cdot)$, and the normalisation condition yield n equations that are used to solve the n weights (Pöyhönen and Hämäläinen, 2001). The TRADEOFF procedure is problematic in many decision making problems because the method assumes that the attributes are measured on a continuous scale (Pöyhönen and Hämäläinen, 2001).

C.5 Use of ordinal and imprecise preference information

In this section, we consider the identification of a value function, or a family of value functions, which is in some sense most consistent with imprecise preference information, typically expressed in one or more of the following forms (Belton and Stewart, 2002):

- Ordinal statements, i.e. to the effect that certain outcomes (combinations of attribute values) are preferred to others;
- Classification of outcomes into semantic categories (such as weakly preferred, strongly preferred, etc)
- Interval assessment of magnitudes, for example that the ratio of importance weights for two criteria lie between stated lower and upper bounds.

C.5.1 Ordinal statements

Ordinal attribute scales are represented by one very easy and popular method, the rule of dominance (Moshkovich et al. 2002). This rule states that one alternative is more preferable than another if it has attribute levels that are not less preferable on all attributes and is more preferable on at least one (Moshkovich et al. 2002).

Let *X* be a set of consequences and *x, y* Є *X* (Gustafsson, 1999). It can be shown that there exists an ordinal value function v( ) that satisfies the following equivalence

$$x \succ y \Leftrightarrow v(x) \geq v(y)$$ Equation C.8

Such value functions are unique up positive transformations, i.e. one can multiply the function with a positive number and add an arbitrary number to it without violating equation C.9 (Gustafsson, 1999). Thus, if V( ) satisfies equation C.9 the (Gustafsson, 1999)

$$v(\ ) = \alpha v(\ ) + \beta, \alpha > 0$$ Equation C.9

$$\Rightarrow v(x) \geq v(y)$$ Equation C.10

C.5.2 Classification of outcomes

Category estimation is a variation of the direct rating technique in which the possible responses of the decision maker are reduced to a finite number of semantic categories (Dietrich and Hämäläinen, 2002). The advantage of the categorisation is that relatively few preferences estimates are needed (Dietrich and Hämäläinen, 2002).

C.5.3 Interval assessment

Interval analysis was initially developed to bound computational error and it is a deterministic way of representing uncertainty in values by replacing a number with a range of values (Tung, 2001). The decision maker can capture the subjective uncertainty in preferences and thus avoid the often cumbersome elicitation of exact ratio estimates (Salo and Hämäläinen, 1995). The theory and methodology of preference programming through approximate ratio comparisons using interval judgements is given in Salo and Hämäläinen (1995).

C.5.3.1 Interval SMART/SWING

This technique is further discussed in Chapter 5.

C.5.3.2 PRIME method

The PRIME method supports the elicitation of incomplete information through the use of interval-valued ratio statements (Gustafsson et al. 2000). According to Gustafsson et al, 2000, in PRIME, the decision-makers preferences are assumed to have an additive structure so that the overall value of an alternatives equals the sum of its attribute-specific scores (Equation C.11). Because the representation (equation C.11) is unique up to affine positive transformations, the scores of the least preferred achievement levels can be set to equal zero, i.e. $v_i(x_i^0) = 0$ (Gustafsson et al. 2002). It is customary to normalise the value functions so that (Gustafsson et al. 2002):

(a) The scores of the most single-attribute scores are mapped to one; and

(b) All scores are multiplied by scaling constants, or attribute weights w_i *(I = 1,.....N)* which add up to one.

When doing this, however, care must be taken to ensure that the attribute weight w_i remains proportional to the value difference between x_i^* and x_i^0 (Gustafsson et al. 2000).

$$V(x) = \sum_{i=1}^{N} v_i(x_i) = \sum_{i=1}^{N} \left[v_i(x_i^*) - v_i(x_i^0)\right] \left[\frac{v_i(x_i) - v_i(x_i^0)}{v_i(x_i^*) - v_i(x_i^0)}\right] = \sum_{i=1}^{N} w_i v_i^N(x_i) \qquad \text{Equation C.11}$$

Where $w_i = v_i(x_i^*) - v_i(x_i^0)$, $i = 1, \ldots, N$ denote attribute weights and the normalised scores

C.6 Cognitive biases

Weighting biases often lead to different kinds of results with different methods (Gustafsson, 1999). The following weighting biases exist (Gustafsson, 1999):

- Different weighting methods yield different weights
- Hierarchical (top down) weighting leads to steeper weights
- Division of attributes changes weights, splitting bias
- Range effect

The range effect refers to a phenomenon in which the attribute gains more or less weight than the range between its best and worst achievement levels would imply (Gustafsson, 1999).

Division of an attribute is likely to result in increase of the attribute's total weight; in other words the divided attribute gains overweight (Gustafsson, 1999). This phenomenon is called splitting bias (Gustafsson, 1999).

C.7 Application to water resource management problems

Reynolds and Peets (2001) prioritised watersheds and stream reaches for protection and restoration in the Chewaucan Basin in Oregon, USA. An AHP model prioritised watersheds for protection and restoration, considering watershed condition and the feasibility and efficacy of restoration (Reynolds and Peets, 2001). A second AHP model prioritised reaches for protection and restoration, considering reach condition, watershed restoration priority, and reaches level feasibility and efficacy (Reynolds and Peets, 2001). Lowest-level criteria (e.g. attributes of alternatives were evaluated with the Simple Multi-Attribute Rating Technique (Reynolds and Peets, 2001). Reach index scores were determined which provide a basin-level view of the distribution of reach indices at a single point in time.

Mustajoki et al. (2002) describe the use of Web-based multicriteria decision support software called Web-HIPRE in the case dealing with the evaluation of regulation policies for the Lake Päijänne in Finland. This is the second largest lake in Finland. The lake has been regulated since 1964, with the original objective being to increase hydropower production and to decrease agricultural flood damages (Mustajoki et al. 2002). The main objective of this study was to identify the values and opinions of representatives in a steering group and in this way enhance their overall understanding of the problem (Mustajoki et al. 2002). Problems recognised included the low water levels during spring, changes in the littoral zone vegetation and negative impacts of the regulation on the reproduction of fish stocks (Mustajoki et al. 2002).

Interviews were conducted with stakeholders. The interviews were based on a common value tree. Three different sets of parameters were used, one for normal, one for dry and one for wet seasonal rain conditions (Mustajoki et al. 2002). The analyst presented the impacts of various regulation alternatives and the pre-assigned ratings of the alternatives were evaluated (Mustajoki et al. 2002). The participants had the opportunity to change the pre-assigned ratings. The relative weights of the attributes were determined following the SWING procedure (Mustajoki et al. 2002). The most important attribute was given 100 points and the other attributes were given points between 0-100, depending on their relative importance from the point of view of the respondent (Mustajoki et al. 2002). The last phase of the interviews was the analysis of the obtained priorities and overall value score of the alternatives (Mustajoki et al. 2002).

The main results of the interviews were the following (Mustajoki et al. 2002):

- The stakeholders had large differences in the perceptions of the importance of the ecological, social and economic impacts, which naturally affected the preference order of the regulation alternatives.
- The importance of the objectives depends on the water seasonal conditions considered. For example, during the wet spring the original objectives of the regulation, hydropower and flood protection, were more acceptable objectives than under the other water conditions.
- The interviews improved the stakeholders overall picture of the problem, gave them new information of the impacts of regulation and encouraged them to think and analyse their own values more carefully than before.

The results of the interviews were applied to prioritise the objectives of regulation in the different water conditions (Mustajoki et al. 2002). This information was further used when the final consensus recommendation for the sustainable regulation strategy for the Lake Päijänne was created (Mustajoki et al. 2002).

C.8 Discussions and conclusions

Value function methods were discussed in this chapter. Theoretical considerations for decision support by interval SMART/SWING are discussed in Chapter 5. The selection of this methodology for further analysis in the study is given in section 4.5. Application to water resources problems is given in section C.7.

Value function methods create a systematic framework for developing an analytic understanding of a problem. As result it provides a tool that can assist in the sustainable management of groundwater resources.

Appendix D Water quality of boreholes close to communities in Namaqualand

Table D.1 Water quality of boreholes near Leliefontein. (taken from Titus et al. 2002).

LELIEFONTEIN				
SOURCE	DRINKING/DOMESTIC	LIVESTOCK	IRRIGATION	REMARKS
100475 wind pump	marginally suitable	suitable	marginally suitable	* F content poses slight risk for long-term users of drinking water. * Medium salinity hazard for sensitive plants or poorly drained soils.
12759 2/5 windmill	suitable	suitable	unsuitable unless salinity is controlled	* Salt content could cause slightly adverse taste effects, but poses no health risk. * Mn content could cause slight staining of laundry. * High salinity hazard for sensitive plants. Soils may require salinity control.
90LF54 borehole	suitable	suitable	unsuitable unless salinity is controlled	* Salt content could cause slightly adverse taste effects, but poses no health risk. * F content poses slight risk for long-term users of drinking water. * High salinity hazard sensitive plants. Soils may require salinity control.
131414/3 wind pump	suitable	suitable	marginally suitable	* F content poses slight risk for long-term users of drinking water. * Medium salinity hazard for sensitive plants or poorly drained soils.
N110 well	suitable	suitable	marginally suitable	* Good quality drinking water. * Medium salinity hazard for sensitive plants or poorly drained soils.
90LF68 well	suitable	suitable	suitable	* Good quality water for all purposes. * Iron content may cause slight staining of laundry.

90LF59 well	suitable	suitable	suitable	* Good quality water for all purposes.
Fountain 1	suitable	suitable	suitable	* Good quality water for all purposes.
Fountain2	suitable	suitable	suitable	* Good quality water for all purposes.

Table D.2 Water quality of boreholes near Rooifontein. (taken from Titus et al. 2002)

ROOIFONTEIN				
SOURCE	DRINKING/DOMESTIC	LIVESTOCK	IRRIGATION	REMARKS
91LF101 wind pump	unsuitable	suitable for ruminants, unsuitable for monogastrics	unsuitable	* Water is brackish. * Na, Cl, F, B and EC exceed "no risk" guideline limits (See Appendix E). * F content poses high risk for long-term users of drinking water and livestock. * Salt content will cause adverse taste effects, but health risks are rare. * Salt content could lead to corrosion of appliances with long-term use. * High salinity hazard for sensitive plants. Soils may require salinity control. * Medium sodium hazard for poor soils.
N118975/0 wind pump	marginally suitable	suitable for ruminants, marginally suitable for monogastrics	unsuitable unless salinity is controlled	* Cl, F and EC exceed "no risk" guideline limits (See Appendix E). * Salt content could cause adverse taste effects, but health risks are rare. * Salt content could lead to corrosion of appliances with long-term use. * F content poses slight risk for long-term users of drinking water and livestock. * High salinity hazard for sensitive plants. Soils may require salinity control.

45N119 borehole	unsuitable	unsuitable	unsuitable	* Water is brackish. * Na, Ca, Mg, SO_4, Cl, F, B and EC exceed "no risk" guideline limits (See Appendix E). * Na and Cl levels are too high for infants and sensitive users, causing dehydration and nausea. Mg and SO_4 levels are likely to induce diarrhoea in most new users. * F content poses high risk for long-term users of drinking water and livestock. * Hard water will require softening to facilitate lathering of soap. * Cl content poses low risk of adverse chronic effects for monogastrics and poultry. * High salinity hazard for sensitive plants. Soils may require salinity control.
91LF99/ G55515 wind pump	marginally suitable for short-term use	suitable for ruminants, marginally suitable for monogastrics	unsuitable unless salinity is controlled	* Water is brackish. * Na, K, Mg, SO_4, Cl, F and EC exceed "no risk" guideline limits (See Appendix E). * Na and Cl levels are too high for infants and sensitive users, causing dehydration and nausea. Mg and SO_4 levels are likely to induce diarrhoea in some new users. * F content poses moderate risk for long-term users of drinking water and livestock. * Hard water will require softening to facilitate lathering of soap. * High salinity hazard for sensitive plants. Soils may require salinity control.
G143684/8 wind pump	marginally suitable for short-term use	suitable for ruminants, marginally suitable for monogastrics	marginally suitable	* F content poses moderate risk for long-term users of drinking water and livestock. * Medium salinity hazard for sensitive plants or poorly drained soils

G143685/6 wind pump	marginally suitable	suitable for ruminants, marginally suitable for monogastrics	unsuitable unless salinity is controlled	* Water is brackish * Na, K, Mg, Cl, F and EC exceed "no risk" guideline limits (See Appendix E). * Salt content will cause adverse taste effects, but health risks are rare. * Salt content could lead to corrosion of appliances with long-term use. * F content poses moderate risk for long-term users of drinking water and livestock. * Hard water will require softening to facilitate lathering of soap. * High salinity hazard for sensitive plants. Soils may require salinity control.
91LF102 well	marginally suitable for long-term use	suitable	unsuitable unless salinity is controlled	* Na, K, Cl and EC exceed "no risk" guideline limits (See Appendix E). * Salt content could cause adverse taste effects, but health risks are rare. * Salt content could lead to corrosion of appliances with long-term use.. * High salinity hazard for sensitive plants. Soils may require salinity control.

Table D.3 Water quality of boreholes near Nourivier. (taken from Titus et al. 2002)

NOURIVIER				
SOURCE	DRINKING/DOMESTIC	LIVESTOCK	IRRIGATION	REMARKS
G103429 borehole	unsuitable	marginally suitable	unsuitable	* Water is brackish * Na, K, Mg, Ca, Cl, SO_4, F, Mn and EC exceed "no risk" guideline limits (See Appendix E). * Na and Cl levels are too high for infants and sensitive users, causing dehydration and nausea. Mg and SO_4 levels are likely to induce diarrhoea in most new users. * Salt content could lead to corrosion of appliances with long-term use * F content poses slight risk for long-term users of drinking water and livestock. * Mn content may cause severe staining of laundry. * Hard water will require softening to facilitate lathering of soap. * Very high salinity hazard. * Medium sodium hazard for poor soils.

G87655 wind pump	unsuitable	marginally suitable	unsuitable	* Water is brackish * Na, Ca, Mg, SO_4, Cl, F, NO_3 and EC exceed "no risk" guideline limits (See Appendix E). * Na and Cl levels are too high for infants and sensitive users, causing dehydration and nausea. Mg and SO_4 levels are likely to induce diarrhoea in most new users. * Salt content could lead to corrosion of appliances with long-term use * F content poses slight risk for long-term users of drinking water and livestock. * Nitrate content poses health risk for infants under 1 year * Hard water will require softening to facilitate lathering of soap. * Very high salinity hazard. * Medium sodium hazard for poor soils.
G114699 wind pump	marginally suitable	marginally suitable	suitable	* F content poses moderate risk for long-term users of drinking water and livestock. * Medium salinity hazard for sensitive plants or poorly drained soils.
91LF90/91/92 well	suitable	suitable	unsuitable unless salinity is controlled	* High salinity hazard for sensitive plants. Soils may require salinity control.
91LF94 well	marginally suitable	suitable	unsuitable unless salinity is controlled	* Na, Cl, EC exceed "no risk" guideline limits (See Appendix E). * Salt content will cause adverse taste effects, but health risks are rare. * Salt content could lead to corrosion of appliances with long-term use * High salinity hazard for sensitive plants. Soils may require salinity control. * Medium sodium hazard for poor soils.

91LF108 well	unsuitable	suitable	unsuitable	* Water is brackish * Na, Mg, Cl, F and EC exceed "no risk" guideline limits (See Appendix E). * Na and Cl levels are too high for infants and sensitive users, causing dehydration and nausea. Mg levels may cause diarrhoea in new users. * Salt content could lead to corrosion of appliances with long-term use. * Hard water will require softening to facilitate lathering of soap. * Very high salinity hazard. * Medium sodium hazard for poor soils.
91LF97 spring	marginally suitable	suitable	suitable	*Aluminium exceeds "no risk" guideline limits (See Appendix E). * Medium salinity hazard for sensitive plants or poorly drained soils.
Nourivier dam	suitable	suitable	suitable	* Medium salinity hazard for sensitive plants or poorly drained soils.

Table D.4 Water quality of boreholes near Kamassies. ((taken from Titus et al. 2002)

		KAMASSIES		
SOURCE	DRINKING/DOMESTIC	LIVESTOCK	IRRIGATION	REMARKS
G55516 wind pump	marginally suitable	marginally suitable for monogastrics, suitable for ruminants	unsuitable unless salinity is controlled	* Na, Cl, F and EC exceed "no risk" guideline limits (See Appendix E). * Salt content will cause adverse taste effects, but health risks are rare. * Salt content could lead to corrosion of appliances with long-term use * F content poses high risk for long-term users of drinking water and livestock. * High salinity hazard for sensitive plants. Soils may require salinity control. * Medium sodium hazard for poor soils.
G114700 wind pump	marginally suitable	unsuitable for monogastrics, marginally suitable for ruminants	unsuitable	* Na, F and EC exceed "no risk" guideline limits (See Appendix E). * Salt content will cause adverse taste effects, but health risks are rare. * Salt content could lead to corrosion of appliances with long-term use * F content poses high risk for long-term users of drinking water and livestock. * High salinity hazard for sensitive plants. Soils may require salinity control. * High sodium hazard for poor soils

G84197 wind pump	marginally suitable	marginally suitable for monogastrics, suitable for ruminants	unsuitable unless salinity is controlled	* Water is brackish * Na, Mg, Cl, F and EC exceed "no risk" guideline limits (See Appendix E). * Salt content will cause adverse taste effects, but health risks are rare. * F content poses slight risk for long-term users of drinking water and livestock. * High salinity hazard for sensitive plants. Soils may require salinity control. * Medium sodium hazard for poor soils.
G83027 borehole	marginally suitable unsuitable for infants	marginally suitable for monogastrics, suitable for ruminants	unsuitable unless salinity is controlled	* Water is brackish * Na, Mg, Cl, F, NO_3 and EC exceed "no risk" guideline limits (See Appendix E). * Salt content will cause adverse taste effects, but health risks are rare. * Salt content could lead to corrosion of appliances with long-term use * F content poses slight risk for long-term users of drinking water and livestock. * Nitrate content poses health risk for infants under 1 year * High salinity hazard for sensitive plants. Soils may require salinity control. * Medium sodium hazard for poor soils.
G37229 wind pump	marginally suitable unsuitable for infants	marginally suitable for monogastrics, suitable for ruminants	unsuitable unless salinity is controlled	* Cl, F, NO_3 and EC exceed "no risk" guideline limits (See Appendix E). * Salt content will cause adverse taste effects, but health risks are rare. * Salt content could lead to corrosion of appliances with long-term use * F content poses slight risk for long-term users of drinking water and livestock. * Nitrate content poses health risk for infants under 1 year * High salinity hazard for sensitive plants. Soils may require salinity control. * Medium sodium hazard for poor soils.

91LF106 well	suitable	suitable	unsuitable unless salinity is controlled	* Cl and EC exceed "no risk" guideline limits (See Appendix E). * Salt content will cause adverse taste effects, but health risks are rare. * Salt content could lead to corrosion of appliances with long-term use * High salinity hazard for sensitive plants. Soils may require salinity control. * Medium sodium hazard for poor soils.
91LF111 well	marginally suitable	marginally suitable for monogastrics, suitable for ruminants	unsuitable unless salinity is controlled	* Water is brackish * Na, Cl, Mg, F and EC exceed "no risk" guideline limits (See Appendix E). * Salt content will cause adverse taste effects, but health risks are rare. * Salt content could lead to corrosion of appliances with long-term use * F content poses slight risk for long-term users of drinking water and livestock. * Hard water will require softening to facilitate lathering of soap. * High salinity hazard for sensitive plants. Soils may require salinity control. * Medium sodium hazard for poor soils.
91LF107 well	unsuitable	marginally suitable for monogastrics, suitable for ruminants	unsuitable	* Water is brackish * Salt content will cause adverse taste effects, but health risks are rare. * Na, Mg, Cl, SO_4, F and EC exceed "no risk" guideline limits (See Appendix E). * F content poses slight risk for long-term users of drinking water and livestock. * Hard water will require softening to facilitate lathering of soap. * Very high salinity hazard. * Medium sodium hazard for poor soils.

Appendix E Drinking water quality for South Africa

Water Quality Variable	Units	Guideline Limits		
		Maximum limit for no risk	Maximum limit for insignificant risk	Maximum limit for low risk
Physical and Organoleptic variables				
Colour	mg/l Pt	20	-	-
Conductivity	mS/m (20°C)	70	300	400
DOC	mg/l	5	10	20
Dissolved Oxygen	% saturation	70	30	10
Odour	TON	1	5	10
pH	pH units	6.0-9.0	5.5-9.5	>4 or <11
Taste	TTN	1	5	10
Temperature	°C	<25	<30	<40
Turbidity	NTU	1	5	10
Microbiological				
Standard plate count	counts/1ml	<100	1000	10 000
Total coliforms	counts/100ml	0	5	100
Faecal coliforms	counts/100ml	0	1	10
Clostridium perfingens	counts/100ml	0	1	10
Coliphages	counts/100ml	0	10	100
Enteric viruses	$TCID_{50}$/10ml	0	1	10
Macro-variables				
Aluminium	mg/l Al	0.15	0.5	1.0
Ammonia	mg/l N	1.0	2.0	4.0
Barium	mg/l Ba	0.5	1.0	2.0
Boron	mg/l B	0.5	2.0	4.0
Bromide	mg/l Br	1.0	3.0	6.0

Calcium	mg/l Ca	150	200	400
Cerium	mg/l Ce	1.0	2.0	4.0
Chloride	mg/l Cl	250	600	1 200
Copper	mg/l Cu	0.5	1.0	2.0
Fluoride	mg/l F	1.0	1.5	3.0
Hardness	mg/l $CaCO_3$	20-300	650	1 300
Iodide	mg/l I	0.5	1.0	2.0
Iron	mg/l Fe	0.1	1.0	2.0
Lithium	mg/l Li	2.5	5.0	10.0
Magnesium	mg/l Mg	70	100	200
Manganese	mg/l Mn	0.05	1.0	2.0
Nitrates	mg/l N	6.0	10.0	20.0
Potassium	mg/l K	200	400	800
Sodium	mg/l Na	100	400	800
Sulphate	mg/l SO_4^{2-}	200	600	1 200
Uranium	mg/l U	1	4	8
Zinc	mg/l Zn	1	5	10

(Taken from Titus et al. 2002)